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1885

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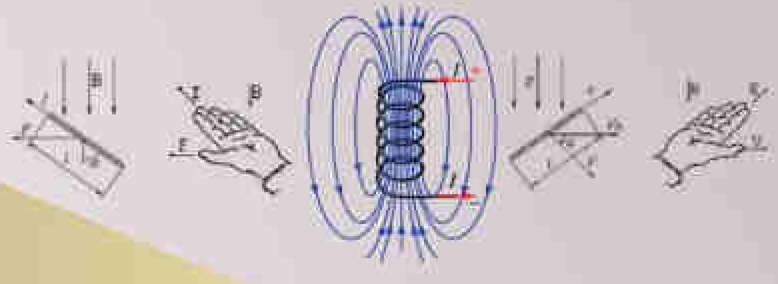
Department of Applied Electrical Engineering

LECTURES ON ELECTRICAL ENGINEERING



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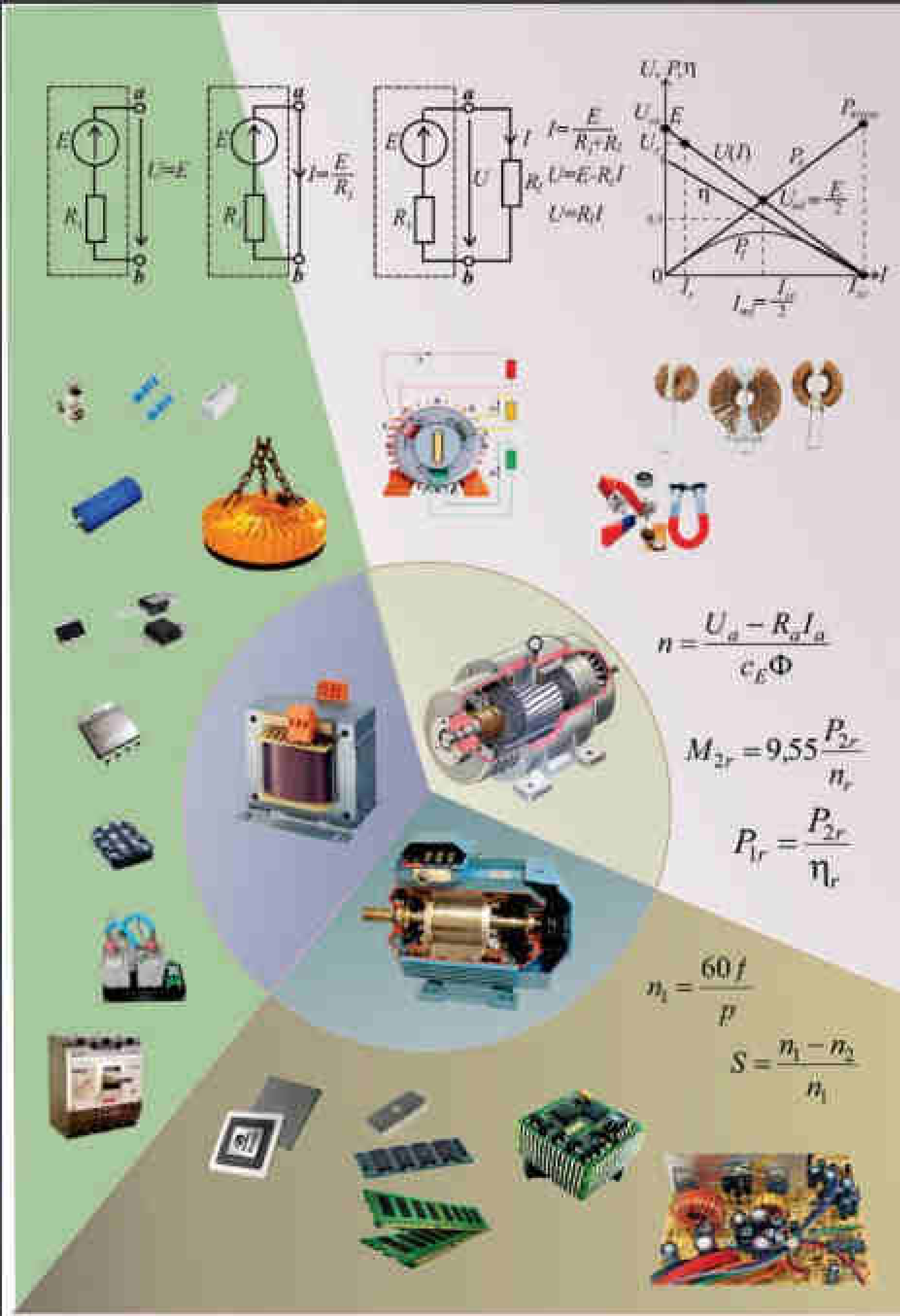

Ministry of Education and Science of Ukraine
National Technical University
“Kharkiv Polytechnic Institute”

Department Of Applied Electrical Engineering

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ISBN

This tutorial contains a course of lectures within the discipline of “Electrical Engineering, Electronics and Microprocessor Technology”. The manual is intended for students of universities to study electrical disciplines in English, and will also be useful to a wide range of specialists and scientists working in the field of electrical engineering and related areas of science and technology.

Fig. 253; Tabl. 6; Bibl. 16

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Theory is when you know everything
and nothing works; practice
is when everything works
and nobody knows why.
Here we combine theory
with practice: nothing works
and nobody knows why.
Albert Einstein

PREFACE

At present, there is a serious necessity for educational and scientific communications among peoples. Proficiency in English for Ukrainian students and scientists becomes such the barest necessity. The given tutorial is the first attempt to create an electrical engineering textbook in English in National Technical University “Kharkiv Polytechnical Institute” (NTU “KhPI”). Besides, the manual would be very useful for Ukrainian and foreign students learning electrical engineering in NTU “KhPI” and Ukraine at all.

At the basis of the given manual there are lectures of professor Volodymyr F. Boliukh. These are the lectures he has been lecturing for non-electric specialties students of NTU “KhPI” at the Department of Applied Electrical Engineering on disciplines: "Electrical engineering and electronics", "Electrical engineering and electromechanics", "Electrical engineering, electronics and microprocessor technology", during last 20 years. That’s why the manual is largely in line with [1].

The lectures are shared on three sections: electric circuits (direct current circuits and alternating current including single-phase and three-phases circuits), electric and magnetic devices, electronics including the microprocessor technology. In the lectures it is given particular attention to the main laws of electrical engineering concerning to solving problems on electric circuits, and construction of different electric devices such as relays, transformers, electric motors, and also different electronic devices: semiconductor diodes, transistors, electronic rectifiers, inverters, electronic amplifiers, logic elements, impulse technology and integrated circuit chip. Graphic symbols of electric circuit elements (resistors, inductors, capacitors and electromotive force and etc.) have been accepted as they are usually presented in the Soviet/CIS/Ukrainian electrical engineering literature.

In the end of each lecture the questions for self-checking are resulted. In the manual the typical questions of an educational course are considered. Also English - Ukrainian dictionary on electrical engineering supplied the manual all needed information for translation and understanding. In the text and in the dictionary of the given manual sometimes a British variant in the electrical engineering terminology is denoted by **UK**, an American one by **US**.

ВСТУП
ДЛЯ УКРАЇНОМОВНОГО ЧИТАЧА
ЧИ
ЧОМУ У НАС ВИНИКЛИ ТРУДНОЩІ ПРИ ПЕРЕКЛАДІ ЕЛЕКТРОТЕХНІЧНИХ ТЕРМІНІВ АНГЛІЙСЬКОЮ МОВОЮ

Використання англомовної електротехнічної термінології у останні роки стає невід’ємною частиною науково-педагогічної діяльності у вищій школі України. Написання наукових статей, монографій, методичної літератури та викладання лекційних та практично-лабораторних занять потребує не тільки володіння англійською мовою на рівні не нижче *Intermediate*, але й знання відповідної науково-технічної термінології.

Англійська мова стає по суті лінгва-франка сучасного світу, в тому числі і у науковій площині. Тому досить дивно, що у науковій бібліотеці НТУ ”ХПІ” практично немає літератури з електротехнічних дисциплін англійською мовою. Там є література німецькою, французською, іспанською, польською, а англійською край обмаль.

В зв’язку з цим, майже винятком є навчальний посібник [2], який був написаний колишнім завідувачем кафедри електричних апаратів НТУ ”ХПІ”, головним редактором журналу «Електротехніка і електромеханіка» до 2020 року проф. Б.В. Клименком. Посібник є фактично англо-українським словником з електромеханіки. В його основі покладений Міжнародний електротехнічний словник (*International Electrotechnical Vocabulary – IEV*), який має статус стандарту Міжнародної електротехнічної комісії (*International Electrotechnical Commission – IEC*), а саме його частин 151 (Електричні та магнітні пристрої), 442 (Електричні аксесуари) та 826 (Електричні установки). Це велика та важлива робота, але вона не охоплює всього різноманіття електротехнічних термінів.

Було б дуже просто скористатися словником *IEV* та не занурюватися у проблему. Вірніше казати, взяти цей словник та взагалі не бачити ніяких проблем. Але не все так просто. Далі ми покажемо, що *IEV* вступає в протиріччя з іншими англомовними джерелами, та сам, певною мірою, має внутрішні протиріччя.

Тоді виникає закономірне питання, яким достовірним англомовним джерелом або можливо декількома навчальними чи науковими джерелами треба користуватися при перекладі?

В 1994 році був затверджений, досі існуючий, **Державний стандарт України з електротехніки (ДСТУ 2843-94 Електротехніка. Основні поняття. Терміни та визначення)** [3]. Цей стандарт дає визначення не тільки українською, але дає переклад англійською, німецькою, російською та французькою. Але стандарт має значні лакуни в термінології. Наприклад, там немає понять *джерело електроенергії*, *навантаження, затискачі*, *контур* та інш. Для понять *схема електричного кола* та *ділянка кола* наведені лише російські варіанти. Таким чином, можна стверджувати, що цей ДСТУ потребує значного доповнення та переробки.

В дев’яності роки минулого сторіччя з'явилося декілька комп’ютерних перекладачів та словників. Найбільш розповсюджений та широко відомий серед них комп'ютерний словник *Lingvo.* Взагалі це дуже гарний, змістовний словник з великою кількістю словникових статей. Переклад будь-якого слова дається з урахуванням галузі використання. Але, на жаль, він може ввести у деяку оману, даючи переклад, наприклад, терміну «активний опір», як один із варіантів – *active resistance*, що невірно, або «індуктивний опір» як *inductive resistance*. Подібні помилки зустрічаються у літературі, яка видається українськими фахівцями, в тому числі і у ХПІ [4]. В англомовній електротехнічній літературі використовується тільки *resistance* та відповідно *inductive reactance*!

Можна користуватися, вже згадуваним словником *IEV* інакше *Electropedia*: *The World's Online Electrotechnical Vocabulary* (Інтернет сайт) [5] та/або літературою, яка видана у Великій Британії [6, 10], США [7, 8] та ЄС [9]. Але несподівано виявляється, що ці поважні джерела не співпадають у деяких важливих моментах. Так, наприклад, поняття «електрорушійної сили» (ЕРС) у [5] трактується як нерекомендоване або застаріле (*deprecated*), в [6] ЕРС використовується та позначається у тексті як e.m.f., а напруга в електричних колах трактується в основному як *potential difference*. В [7,9] ЕРС не згадується, але використовується як позначка джерела напруги (E) в електричних схемах. В [8, 10] загадується та позначається у тексті як emf, а у формулах як E.

Взагалі, як рекомендує *Electropedia*, можна відмовитися від поняття ЕРС, але це призведе до багатьох незручностей при викладанні багатьох різних питань низки електротехнічних дисциплін. А ще можна зауважити, що ЕРС та напруга хоча й можуть бути взаємно замінені, наприклад, при розрахунку електричних кіл, але фізична природа цих понять не зовсім тотожна. Тому, з урахуванням вітчизняних методик викладання електротехніки та інших суміжних дисциплін, вважаємо, що відмовлятися від поняття ЕРС при написанні наукових статей або методичної літератури не варто, та слід писати абревіатуру *electromotive force* великими літерами, як прийнято у нас, тобто *EMF*. Тут треба сказати про протиріччя самої *Electropedia*. В частині 131 «Електричні кола» від ЕРС пропонується відмовитися (стаття 131-12-22) та замінювати її поняттям *source voltage*, тобто «напруга джерела», а в частині 314 «Електричні виміри» існує термін *source e.m.f.* – «ЕРС джерела», яке, як пояснюється в статті 314-08-14, дорівнює напрузі розімкнутого кола. Тоді незрозуміло, чому в частині 131 треба було відмовлятися від поняття ЕРС, або не відмовлятися в частині 314?

Ще безумовно одно з найважливіших понять – «схема електричного кола», який не має перекладу на англійську в українському Державному стандарті [3], як вже було зазначено. Зазвичай «схема електричного кола» та «електричне коло» іноді використовуються як синоніми, хоча це не зовсім одне і теж. Але для певної простоти у вітчизняній та закордонній літературі використовуються у схожому смислі. Тобто в тексті вказується що на такому-то рисунку зображено електричне коло (*electric circuit* або *circuit* або *network*) хоча, строго кажучи, це схема електричного кола, а не само коло. Але інколи автори пишуть точніше, і все ж таки використовують слово «схема». В [6] це *electrical circuit diagram*, в [7, 8] *schematic diagram* або *schematic circuit diagram*. Інколи, використовують просто *schematic* як іменник. Причому, в *Electropedia* цих термінів нема.

Тобто вони не зовсім канонічні з точки зору *IEC*. В [11] ми припустили, що слово *scheme* можна використовувати при перекладі такого слова як «схема», але слід тут уточнити, що *scheme* використовується в англомовній літературі в розумінні «порядок дій вирішення наукової проблеми», «план дій розв'язання інженерної задачі» .

Ще один цікавий нюанс. Як правильно *electric* чи *electrical?* Чи взагалі це одне і теж? Начебто так і є. Але *Electropedia* роз'ясняє, що *electric* «електричний» це те, що безпосереднє відноситься до електричних явищ.

Одже стаття 151-11-03, **electric**, adj - containing, producing, arising from, or actuated by electricity. Note – Examples of usage of the term "electric": electric energy, electric lamp, electric motor, electric quantity, що у перекладі означає «електричний», прикметник – (об'єкти та процеси), що містять, що виробляють, що виникають завдяки або приводяться в дію електрикою. Приклади використання терміну «електричний»: електрична енергія, електрична лампа, електродвигун, кількість електроенергії.

Тобто, коли перекладаємо поняття «електричне коло» це безперечно *electric circuit*, а «електрична потужність» це *electric power*. Так трактує [5], але інші джерела [6, 8] використовують як *electric circuit*, так і *electrical circuit, electrical power, electrical energy.*

Тепер стаття 151-11-04 **electrical** (1), adj qualifies a person involved in electricity. Note – Example of usage of this concept: electrical engineer. Тобто **electrical** кваліфікує особу, пов'язану з електрикою. Приклад використання цього поняття: інженер-електрик.

Наступна стаття 151-11-05 **electrical** (2), adj pertaining to electricity, but not having its properties or characteristics. Note – Examples of usage of this concept: electrical handbook. Це те, що відноситься до електрики, але не має його властивостей або характеристик. Приклади використання цього поняття: довідник з електротехніки.

Тобто *electrical* – це або «електрик» (за фахом) або те, що має відношення до електрики, але не має фізичних властивостей, які характеризують електричні явища. Наприклад, само поняття «електротехніка» (наука, навчальна дисципліна) пишеться як *electrical engineering* або *electrical science або electrical technology*.

Але чому частина 151 називається *Electrical and magnetic devices*? Чому не *electric devices*? Що електричні прилади та пристрої не приводяться в дію електрикою? Безпосередньо не перетворюють електричну енергію, зокрема, не перетворюють її у теплову, механічну, не характеризуються електричними величинами, як то напруга, струм, опір, потужність тощо? Не зрозуміло!

А у частині 411 *Rotating Machinery* – про обертові електричні машини є стаття 431-01-11 **(electrical) rotating machine** виникає слово *electrical*, як бачимо, ще чомусь у дужках. Теж дивно. Раніш воно було згадане у вигляді *electric motor*, що безумовно і є електричною ротаційною або обертовою машиною.

Знов якась неузгодженість, та ще в рамках одного джерела, яке начебто є стандартом.

Коли ми читаємо англомовну електротехнічну літературу, то безперечно звертаємо увагу на позначення резисторів або активного опору в схемах електричних кіл, яке значно відрізняється від звичного нам (рис.1, *а,б*)

Рис.1 Позначення резисторів в електричних схемах

Дійсно в [7 - 10] ми бачимо, що резистори позначені так, як на рис.1, *б*. Взагалі, колись на початку та всередині минулого століття у вітчизняній науковій та навчальній літературі позначали резистор так само. Тільки в [6] резистор позначений так, як на рис.1, *а.* Треба сказати, що *IEC* вимагає позначати резистор як звикли ми, тому позначати інакше можливо зовсім не варто. Та і взагалі, таке позначення складніше звичного нам, тому і незручно при написанні та кресленні на комп'ютері.

Декілька слів про закони Кірхгофа. В [5] вони називаються *Kirchhoff law for nodes* та *Kirchhoff law for meshes*. В інших джерелах [6 - 10] відповідно *Kirchhoff's current law* та *Kirchhoff's voltage law* . Ніякого першого та другого закону у назвах немає. Тому, мабуть, не слід при перекладі писати *first Kirchhoff's law* та *second Kirchhoff's law,* або додатково пояснювати до чого відноситься тій чи інший закон. Тим більше, що в деяких джерелах [6, 8] першим по тексту іде *Kirchhoff's current law*, другим *Kirchhoff's voltage law*, а в [7, 9] навпаки. Артиклі в цих назвах теж на вживаються!

Щодо перекладу понять «контур» та «контурний струм». Контур в теорії електричних кіл це *loop* або *mesh* [5]. Тут же зазначається, що при аналізі електричної схеми за законами Кірхгофа використовують саме *loop,* а при аналізі з використанням теорії графів – *mesh.* Хоча коли розглядають контурний струм його називають *mesh current* [5, 6, 9], а в американських виданнях [7, 8] *loop current*.

Ще приклади. «Фазовий зсув» або «фазовий кут» або «кут зсуву фаз» φ у [5] пишеться як *displacement angle* або *phase difference angle,* у інших джерелах [6 - 10] тільки *phase angle.* Український стандарт [3] дає переклад як *phase difference*.

«З'єднання зіркою» у європейських джерелах пишеться як *star-connected* (прикметник) або без дефіса *star connection* (**UK**), дещо рідше *Y-connection,* а у американських джерелах *wye-connection, "Y" connection* або теж *Y-connection*. «З'єднання трикутником» – *delta connection* або Δ *connection,* а з'єднанний трикутником – *delta-connected*.

Для трифазних кіл, поряд зі «з'єднанням зіркою» або «трикутником», важливі поняття «лінійна» та «фазна напруга». В [6 - 9] це відповідно *line voltage* та *phase voltage*. Тут все зрозуміло, а в *Electropedia* «лінійна напруга» подається як *line-to-line voltage* або *phase-to-phase voltage.* Хоча другий термін має примітку *deprecated*. «Фазна напруга» подається як *line-to-neutral voltage* або *phase-to-neutral voltage* (цей термін теж нерекомендований як застарілий, тобто *deprecated*). Така термінологія теж цілком логічна, але задовга на письмі. Тому без шкоди, на наш погляд, можна користуватися *line voltage* та *phase voltage*.

Таке важливе в електротехніці поняття як «потокозчеплення» ψ у [5] представлене як *protoflux* або як *total flux*, тобто дослівно «протопотік» або «повний потік». Інший термін у [5], що ближче до нашого розуміння *linked flux* має примітку *deprecated.* В [10] використовується варіант *flux linkage,* що цілком відповідає нашому «потокозчепленню». [7] не дає варіанта англійською взагалі, просто обмежується тільки «магнітним потоком» – *magnetic flux*.

Поняття «вузол» в електричному колі перекладається в [3, 5] як *node* або *vertex* (**US**). В [6, 8] використовують слово *junction*, в [7] використовують *junction*, так і *node*, а ще й *common point*. Цікаво, що *vertex* в американських виданнях [7, 8] не зустрічається. В свою чергу *junction* є в [5] – Частина 442 «Електричні аксесуари» в схожому з *node* смислі, та в Частині 551 «Напівпровідникові прилади та інтегральні схеми» має зовсім інше значення. Хоча в *Electropedia* само визначення «вузол» – *node* пояснюється досить дивно. Цитуємо [5] *node is endpoint of a branch , that is or is not connected to one or more other*. Що у перекладі означає «вузол – кінцева точка вітки, яка з'єднана або не з'єднана з однією чи кількома іншими вітками». В вітчизняній електротехнічний літературі слово «вузол» – це точка в електричному колі, яка з'єднує три та більше віток електричного кола.

Загалом робимо висновок, що *node* та *junction* однаково припустимо використовувати, наприклад, при аналізі електричних кіл за допомогою законів Кірхгофа.

Також таке поняття як «втрати потужності» цілком можливо використовувати в однині *loss* [5, 6, 8, 10] або множині *losses* [5, 7]. Тобто

Electropedia не виключає обидва варіанти, хоча однину рекомендує для електричних кіл, а множину для електричних машин.

Поняттю «номінальне значення» відповідають два англомовних терміни в *Electropedia: rated value* стаття 151-16-08, *nominal value* стаття 151-16-09.

Перший відноситься для точного розрахунку параметрів пристрою. Цитата – «значення величини, яка використовується для цілей специфікації, встановлена для визначеного набору робочих умов компонента, пристрою, обладнання або системи», тоді як другий – «значення величини, яка використовується для позначення та ідентифікації компонента, пристрою, обладнання чи системи. Номінальне значення, як правило, округлене». З цього виходить, що *nominal value* цілком можливо використовувати в методичній або науковій літературі, коли ми не стикаємось з жорсткими умовами виробництва продукції або експлуатації в промислових або побутових умовах. Хоча загальна тенденція при написанні наукових статей англійською мовою у світі направлена в бік використання в усіх випадках тільки *rated value*. Тому і в даному посібнику ми використовуємо в основному *rated.*

Повертаючись ще раз до абревіатур, як то ЕРС або МРС – «магніторушійна сила», «середньо-квадратичне значення» (діюче значення), має смисл писати їх в англомовному тексті великими літерами, тобто *EMF, MMF – magnetomotive force, RMS – root-mean-square* або *effective value,* як ми пишемо будь-яку абревіатуру українською.

Декілька слів про поширену помилку при перекладі слова «вектор», «векторна величина» англійською при написанні статей українським фахівцями. В математиці, фізиці та радіотехніці використовують при перекладі слово *vector*, а в електротехніці, коли мова йде про синусоїдальну величину, яка представлена комплексним числом або вектором, тільки *phasor*!

Можна навести ще чимало прикладів термінологічних розбіжностей. Більш того, відомо [6 - 10], що в США та Великій Британії діють різноманітні галузеві стандарти з електротехнічного обладнання, з певними термінологічними розбіжностями.

Доволі велика проблема – це переклад на англійську мову понять у яких майже нема аналогій в англомовній літературі. Наприклад, «ділянка електричного кола». Хоча *Lingvo* дає переклад *subcircuit,* в [5 - 10] він не зустрічається взагалі. А [5, 7] у подібному з нашим вітчизняним розумінням наведені варіанти, відповідно: *a circuit element* та *an element of a circuit,* тобто «елемент кола». Іноді у літературі зустрічається *a part of a circuit*. Або такі поняття як «баланс потужностей» або «режим узгодженого навантаження». Вони в англомовній британсько-американської літературі не зустрічаються. С балансом все зрозуміло, можливо писати *power balance*, а ось переклад «режим узгодженого навантаження» як *matched load* чи *matched load operation* (*mode*, *condition*) може бути незрозумілий англомовному читачу та вочевидь потребує додаткового роз'яснення.

Створення Міжнародного електротехнічного словника *IEV* на початку XX сторіччя та подальша робота над ним безумовно сприяє більшому порозумінню серед фахівців з електротехніки в різних державах, але з'ясовується, що цей поважний словник має деякі вади і не може бути, як-то кажуть, істиною в останній інстанції.

Бачимо, що і дотепер зберігаються деякі регіональні розбіжності в термінології, поняттях та позначеннях, методиках викладання електротехніки, обумовлені місцевими традиціями. Крім цього, мова, сама по собі, постійно розвівається, деякі слова та поняття застарівають, деякі з'являються. Тому робота над словниками йде постійно, але вони цілком природно вимушені відставати від життя. Таким чином, при перекладі електротехнічних термінів англійською, виникають певні складнощі.

Вважаємо, що треба брати, все ж таки, за основу словник *IEV* з деяким корегуванням на основі ще кількох достовірних джерел. Якщо якесь поняття не має точної відповідності в англомовній літературі, то автор перекладу бере на себе певний ризик бути незрозумілим, тому це поняття необхідно в тексті додатково роз'яснювати. Взагалі, головне при використанні іноземної мови в усіх аспектах життя є те, щоб вас максимально вірно зрозуміли.

Безсумнівно потрібна подальша стандартизація та міждержавна термінологічна узгодженість стосовно електротехніки, а також потрібен, що дуже актуально і є нагальною необхідністю, оновлений та доповнений український державний стандарт з електротехніки.

Основні думки, які викладені в цьому вступі, були більшою частиною опубліковані в статті [11], але ми вважаємо, що тут доречно їх повторити.

Ми, як автори цього посібника, усвідомлюємо, що можемо теж помилятися у перекладі або використанні тих або інших англомовних термінів, і зовсім не претендуємо на якийсь-то беззаперечний авторитет у області англомовної електротехнічної термінології. Тому будемо вдячні за обгрунтовану критику або доречні поради, якщо такі виникнуть у нашого читача. Прохання писати на електронну пошту **vladyslav.markov@khpi.edu.ua**

ABBREVATION

AC – alternating current

BJT – bipolar junction transistor

CB – common base

CC – common collector

CE – common emitter

DC –direct current

DCEM – direct current electric machine

DCG – direct current generator

DCM – direct current motor

EMF, e.m.f., emf – electromotive force

EW – excitation winding

FET – field-effect transistors

HV – high voltage

IEC – International Electrotechnical Vocabulary

IEV – International Electrotechnical Commission

LED – light-emitting diode

LV – low voltage

MMF, mmf – magnetomotive force

NFb – negative feedback

NL – no-load

OL – on-load

PFb – positive feedback

Q-factor – quality factor

rpm – revolutions per minute

SC – short circuit

SG – synchronous generator

SM – synchronous machine

TIM – three-phase induction motor

UK – British terminology

US – American terminology

CONTENTS

SECTION

I

ELECTRIC CIRCUITS THEORY

LECTURE 1

THE BASIC CONCEPTS AND LAWS OF ELECTRICAL ENGINEERING. DIRECT CURRENT CIRCUITS

Electrical engineering is the area of science and engineering connected with practical application of electric power, including its manufacture, transfer, distribution and consumption.

An electric power carrier is *an electromagnetic field* produced by moving electric charges or, in other words, created by an electric current in a conductor.

An electromagnetic field represents a kind of matter, which is characterized by its two parties – an electric field and a magnetic field, and has power influence on charged particles, depending on their speed and a charge.

Electric circuits of a direct current and their structure

The electric circuit is a set of devices and the objects forming a path for an electric current and intended for generating, transfer and electric power transformation.

The electric circuit includes: sources, loads, power converters, switching devices, measuring devices and connecting wires.

Electric circuits elements can be subdivided on:

– power sources or generating devices (generators; galvanic cells (or accumulators (**UK**), rechargeable cells, storage cells, batteries, storage batteries (**US**)); thermocouples, photovoltaic cells);

– electric power loads (electric motors, filament lamps, heaters, etc);

– transmission lines (two - three - four-wire) or connecting wires;

– electric power converters (transformers, rectifiers, inverters);

– switching devices (switches, connection, protective equipment).

In the sources there is a conversion of other (not electric) kinds of energy in electrical one (generators, batteries, photovoltaic cells, etc.).

In the loads electric energy will be converted to other kinds of energy: thermal, light, mechanical (resistors, filament lamps, electric motors, etc.).

A schematic diagram is a conditional representation of real elements of a circuit (Fig.1.1, Fig.1.2).

Electric power sources are characterized by *electromotive force* (EMF) E and an internal resistance R_i (Fig.1.1).

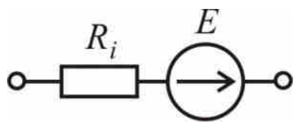


Figure 1.1

Electromotive force is numerically equal to work which is made by non-coulomb forces on moving an individual charge in a source. It is measured in volts (V), i.e. $[E] = [V]$.

A load is characterised by resistance R measured in ohms, $[R] = [\Omega]$.

If a source connects to a load, in a closed loop an electric current will proceed. *An electric current* is a stream of charged particles, such as electrons or ions, moving through an conductor or medium. *An invariable current on value and direction is called a direct current denoted by I.* Current is measured in amperes, $[I] = [A]$.

Across the terminals of a source a *potential difference* appears (Fig.1.2). In other words, a *potential difference* is *voltage U*. It is measured in volts, $[U] = [V]$.

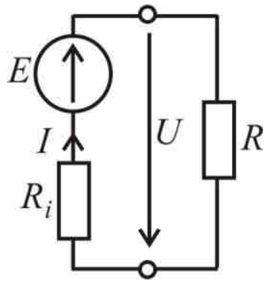


Figure 1.2

The *current strength* or just *current* in an electric circuit is defined by quantity of an electric charge for one second of time

$$i = \frac{dq}{dt}, \tag{1.1}$$

where q is a charge (the quantity of electricity) passing through cross-section of a conductor.

According to **Ohm's law** the current in a circuit is directly proportional to the applied voltage (or EMF) and inversely proportional to the circuit resistance (Fig.1.2).

$$I = \frac{U}{R} = GU\,, \tag{1.2}$$

where $G = \frac{1}{R}$ is conductance in siemens, [G] = [S].

Ohm's law for a complete circuit considers all resistance of a circuit

$$I = \frac{E}{R_i + R}\,. \tag{1.3}$$

$$E = R_i I + RI = R_i I + U\,, \tag{1.4}$$

where U is a voltage across the load or across the source terminals.

A voltage drop or simply *voltage U* across the given element of a circuit numerically equals to work executed by an electric field on moving an individual positive charge (from the plus terminal to the minus one).

From (1.4) we received the voltage on the source terminals

$$U = E - R_i I\,, \tag{1.5}$$

which means that it is less than EMF value by the voltage drop R_iI in the internal resistance R_i. The external characteristic of the EMF source is shown in Fig.1.3. At I = 0, U = E – a circuit is open. U_r, I_r – rated (nominal) value of voltage U and current I respectively.

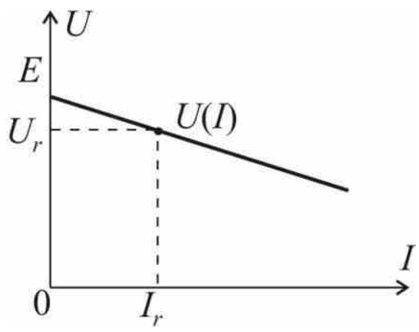
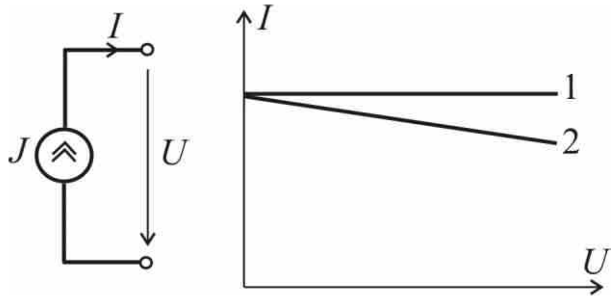


Figure 1.3

It is possible to present electric power sources in the form of an EMF source and a current source. At an EMF source an internal resistance R_i is not enough and voltage across its terminals, at a current change from 0 to I_r, changes slightly. These are generators, accumulators, etc. At the ideal EMF source resistance is equal to zero $R_i = 0$ and EMF value is equal to voltage value $E = U$.

Sources of electric power include current sources with high internal resistance in which the circuit current weakly depends on the voltage across the load at its change from 0 to the rated value. These are radioactive sources, semiconductor devices, vacuum tubes.

The equivalent circuit of an ideal current source (denoted as J, $[J]$ = [A]) is shown in Fig.1.4, *a* and the external characteristic of ideal (1) and real (2) current sources (Fig.1.4, *b*).



a *b*

Figure 1.4

Resistance R characterises a property of an electric circuit element to transform irreversibly the electric power to other kinds of energy, for example, to the thermal energy. The current-voltage graph of a resistive element can be a linear (Fig.1.5, R = const), i.e. its value does not depend on the applied voltage, and a non-linear one (R = var).

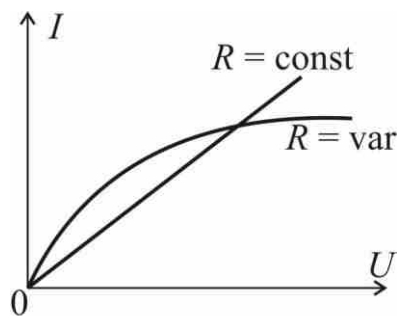


Figure 1.5

A linear resistance depends only from $R = \rho \frac{l}{s}$, where ρ – resistivity. It is measured in ohm· metres

[Ω·m]; l, s – length (m) and cross-sectional area (m^2) of a conductor.

A nonlinear resistance is characterised by the volt-ampere characteristic (Fig.1.5) and for it the dependence *U (I)* is nonlinear. A nonlinear resistance has a symbol shown in Fig.1.6.

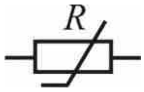


Figure 1.6

The circuit, which contains only resistors with a linear resistance, is called as linear. If in a circuit there is at least one nonlinear resistance, such a circuit is called as nonlinear.

Ohm's law for an element of a circuit with EMF

As stated before a potential difference between two points of this element (Fig. 1.7)

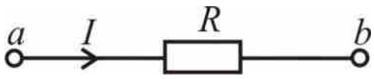


Figure 1.7

By definition $U_{ab} = \varphi_a - \varphi_b = RI$, whence $\varphi_a = \varphi_b + RI$.

Therefore, Ohm's law for an element of the circuit without EMF

$$I = \frac{U_{ab}}{R}. \tag{1.6}$$

Let's consider an element of the circuit (Fig.1.8) where the source EMF *E* and the current *I* coincide in direction.

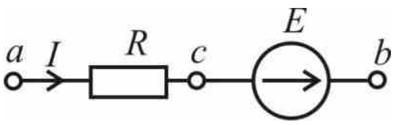


Figure 1.8

$$U_{ab} = \varphi_a - \varphi_b,$$

but $\varphi_a = \varphi_c + RI$, and $\varphi_b = \varphi_c + E$. Then $U_{ab} = \varphi_c + RI - \varphi_c - E$, i.e.

$$U_{ab} = RI - E$$

Ohm's law results

$$I = \frac{U_{ab} + E}{R}. \tag{1.7}$$

The element of the circuit (Fig. 1.9) consists of the EMF source E and the resistance R. The current does not coincide in direction with the EMF.

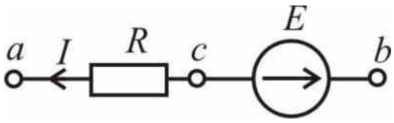


Figure 1.9

$\varphi_a = \varphi_c + I \cdot R; \varphi_b = \varphi_c - E$.

Then Ohm's law becomes

$$I = \frac{U_{ab} - E}{R}. \qquad (1.8)$$

Generally, Ohm's law for a part of a circuit with EMF looks like

$$I = \frac{U_{ab} \pm \sum_{k=1}^{n} E_k}{R}, \qquad (1.9)$$

Where E_k is positive «+» if an EMF and a current coincide in a direction if don't coincide a sign «–». R is the resistance of an element of a circuit.

Kirchhoff laws (Kirchhoff's laws)

Kirchhoff laws concern a *node* of an electric circuit, a *branch* and a *loop*. *A node* is a point of an electric circuit in which are connected not less than 3 branches. *A branch* is a part of an electric circuit where all elements are connected in series, i.e. one current proceeds on them. Any closed way which is passing on several branches, is called *a loop* of electric circuits.

Current law (law for nodes) or **(** *in Ukraine we call it as* 1st *Kirchhoff law***):**

the algebraic sum of all currents is equal to zero in a node of an electric circuit. (Fig. 1.10).

$$\sum_{k=1}^{n} I_k = 0. \qquad (1.10)$$

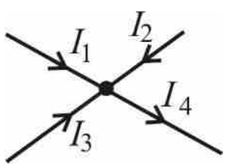


Figure 1.10

This consequence of a conduction current continuity principle (charges do not collect in a node). Currents which flow to a node are positive, and leaving currents are negative. So that, according to Fig. 1.10

$$I_1 + I_2 + I_3 - I_4 = 0$$

Voltage law (law for loops or meshes) or **(**2nd *Kirchhoff law***):**
the algebraic sum of electromotive forces (EMF) acting in any closed loop of an electric circuit is equal to the algebraic sum of the voltages (voltage drops) across the elements of this loop

$$\sum_{k=1}^{n} E_k = \sum_{k=1}^{m} I_k R_k \,. \tag{1.11}$$

For equation drawing up according to the 2nd law of Kirchhoff it is necessary:

1) to choose the positive direction of currents;
2) to choose the positive direction of a loop bypass.

Voltage law is a consequence of the energy conservation law.

Power balance of an electric circuit

According to the energy conservation law, we can state that quantity of heat power releases in loads in unit of time must equal to quantity of the power given for the same time by sources.

$$\sum_{k=1}^{n} I_k^2 R_k = \sum_{k=1}^{m} E_k I_k \tag{1.12}$$

The algebraic sum of powers of all sources is equal to the arithmetic sum of all loads powers in an electric circuit.

$P = I_k^2 R_k$ is the power consumed by resistance R_k according to *Joule law*. It measured in watts, i.e. [P] = [W].

$E_k I_k$ – the power of a source. The product $E_k I_k$ is assumed positive if an EMF and a current coincide in a direction (a source gives power to a circuit). The product $E_k I_k$ is assumed negative if EMF and a current do not coincide in a direction (a source consumes energy) the accumulator, for example, is charged.

Joule law defines quantity of the electrical power W transformed in thermal on an element of a circuit with resistance R. It is measured in kilowatt-hours $[W]$ = [kWh].

$$W = RI^2t. \tag{1.13}$$

Generally, electric energy is equal to electric power multiply by time, then the unit of energy is watt-second or joule.

Operation conditions of an electric circuit

A double wire circuit with a wire resistance R_w is shown in Fig. 1.11.

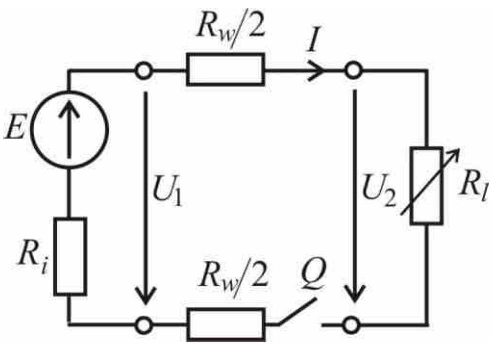


Figure 1.11

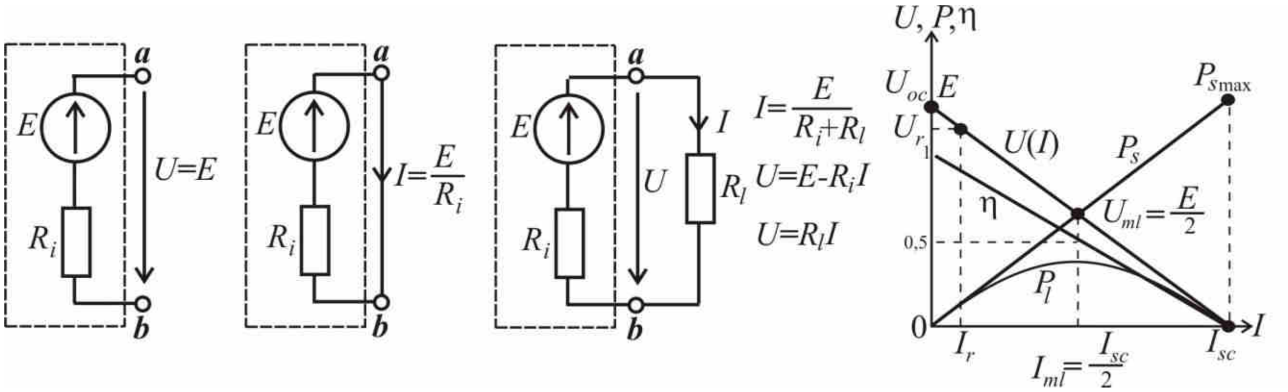
With change of the load resistance R_l, the current I, the voltage U_1 across terminals of the power source E and the voltage U_2 across the load terminals will change.

They distinguish four basic operating conditions (duties) of an electric circuit:

1) *open circuit* or *no-load* (operation) is the condition, at which the circuit is broken off also a current is absent I = 0. The load R_l is disconnected by the switch Q (Fig. 1.11).

$$U_1 = U_2 = E.$$

The circuit in such a condition can be shown as well as in Fig. 1.12, *a*. The voltage across the terminals ***a*** and ***b*** is equal to the E value. The open circuit voltage is shown in a volt-ampere characteristic as U_{oc} in Fig. 1.12, *d*. Powers of the source and the load are zero: $P_S = EI = 0$, $P_l = U_{oc}I = 0$.



a *b* *c* *d*

Figure 1.12

2) *short circuit* (*operation*) is the condition at which a resistance of the load R_l comes nearer to zero, or the wire closes its terminals, and also when line wires or source terminals are closed. The condition is characterized by the voltage across the load $U_2 = 0$ (Fig.1.11), and the current of short circuit I_{sc} is considerably bigger than the rated current $I_{sc} >> I_r$ (as shown in Fig 1.12, *b*).

$$I_{sc} = \frac{U_1}{R_w} = \frac{E}{R_i + R_w}. \tag{1.14}$$

If we neglect the wires resistance $R_w = 0$ (Fig 1.12, *b*) then

$$I_{sc} = \frac{E}{R_i} \tag{1.15}$$

So that the maximum current in a circuit will be at short circuit condition. It is an emergency condition. It should be avoided.

Power of the source is $P_s = EI_{sc} = \frac{E^2}{R_i} = P_{s\max}$.

Power of the load is zero $P_l = UI_{sc} = 0$.

3) *rated or full load* (*operation*) (sometimes it is called *nominal*) is the condition at which all elements of an electric circuit in normal conditions of environment can carry out the functional purpose long enough (time is defined by the registration certificate or equipment certificate) with specified reliability. The condition is characterized by the rated: voltage U_r, current I_r, power P_r and efficiency η_r which are specified in the registration certificate or on a device

plate. On these data plate the isolation, section of wires and condition of their limiting heating are presented.

4) *matched load* (or *matched load operation*) called the condition at which the power given by a source in an external circuit is maximum. The condition is possible at certain parities of the circuit parameters.

If the voltage across terminals ***a*** and ***b*** is $U = E - R_l I$ and power of the load is $P_l = UI = EI - R_i^2 I$, then the maximum power value of the load corresponds to the condition $\frac{dP_l}{dI} = 0$, whence the current of the condition is

$$I_{ml} = \frac{E}{2R_i} = \frac{I_{sc}}{2} \qquad (1.16)$$

The matched load current $I_{ml} = 0{,}5 I_{sc} >> I_r$ (Fig.11.2, *d*).

As at *open circuit*: power $P_l = 0$, since $I = 0$, and at *short circuit* $P_l = 0$, since $R_l = 0$ between them there is a maximum under the condition $R_l = R_i + R_w$.

Efficiency of the *matched load*

$$\eta = \frac{P_l}{P_s} = \frac{EI - R_l I}{EI} = 1 - \frac{R_l I}{E} = 1 - \frac{I}{I_{sc}} \qquad (1.17)$$

Thus, at $I = I_{ml}$ efficiency $\eta = 0{,}5$. Thus, this is not a very favourable energetic condition. The *matched load* is usually used in low-power devices or radio and control devices.

Test questions

1. *What is an electric circuit?*
2. *What sources of electric power do you know?*
3. *Name the loads in electric circuit?*
4. *What is an electric current?*
5. *What are voltage, EMF and resistance?*
6. *What does it mean a nonlinear resistance?*
7. *State Ohm's law.*
8. *State Ohm's law for an element of a circuit with EMF.*
9. *State Kirchhoff laws and say about a node, a branch and a loop.*
10. *What do you know about operation conditions of an electric circuit?*
11. *State Joule law.*
12. *What is efficiency?*

LECTURE 2

FUNDEMENTALS OF SINUSOIDAL CURRENT CIRCUITS

Now an alternating current is widespread as:

1) it is easier generating than a direct current;

2) it can be easily converted to another value;

3) it can be transmitted over long distances with little loss as $U_1 I_1 \approx U_2 I_2$ and loss $P = I^2 R$, it is possible to transfer a small current.

An alternating current is the current which periodically changes on a value and direction. The most widespread form of an alternating current is sinusoidal, as: the most simply to obtain such form; relative simplicity of calculation of circuits of a sinusoidal current; efficiency of electric motors and devices is above at a sinusoidal current.

Principle of generating a sinusoidal EMF is shown in Fig. 2.1., where *N*, *S* – north and south poles of a permanent magnet, *B* – magnetic induction, ω– angular velocity of a conductor, *V* – linear speed of a conductor α – angle between vectors *V* and *B*.

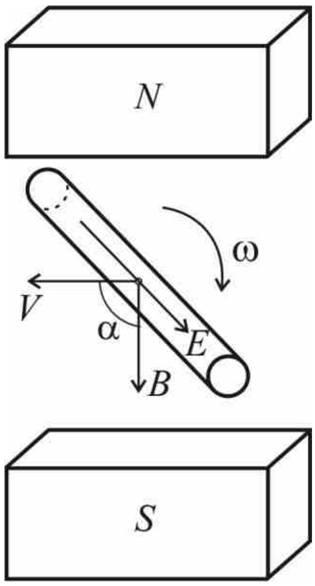


Figure 2.1

In a vector form in physics, equation for EMF is **E = [B x V].**

In an algebraic form $E = BVl\sin\alpha$, where *l* is the length of a conductor.

Characteristics and parameters of a sinusoidal current

It is possible to release the next 4 forms of representation of a sinusoidal current: a mathematical; a graphic; a phasor, in the form of complex numbers.

Mathematical expressions for a sinusoidal voltage and current:

$$u = U_m \sin\left(\frac{2\pi}{T}t + \psi_u\right); i = I_m \sin\left(\frac{2\pi}{T}t + \psi_i\right), \qquad (2.1)$$

where:

u, i – instantaneous values of voltage and current, i.e. values at any moment of time;

U_m, I_m – peak values – maximum values of voltage and current;

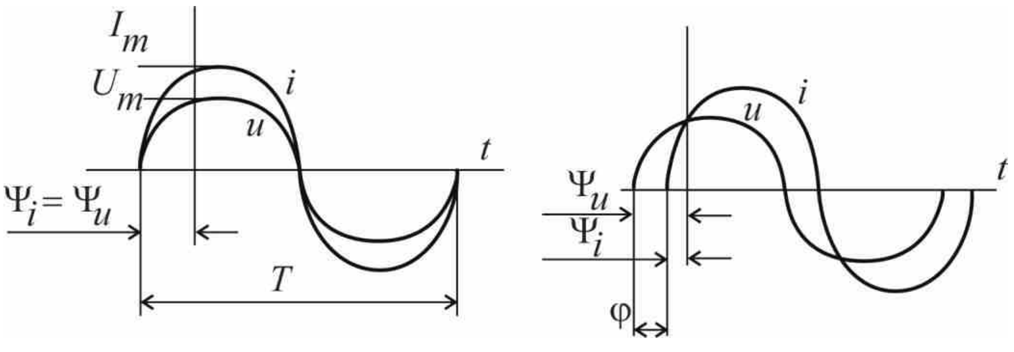
T – period (wave period, cycle), a time interval during which there is a full cycle of change of the considered quantity in seconds, s;

$f = \frac{1}{T}$ – frequency of a current in hertz, [Hz] or number of the periods in a second; on default – 50 Hz;

$\omega = \frac{2\pi}{T} = 2\pi f$ – angular frequency – one turn for the period, rad/s;

$(\omega t + \psi_u)$ – argument of a sine – the phase, characterises value of function at present time;

A graphic form of a sinusoidal current and voltage represents in Fig. 2.2



a *b*

Figure 2.2

ψ_u, ψ_i – an initial phase of voltage and current (at $t = 0$);

$\varphi = \psi_u - \psi_i$ – a phase difference angle (phase angle) between the voltage *u* sinusoid and the current *i* sinusoid.

If $\psi_u = \psi_i$, φ = 0 both the current and the voltage coincide in phase (Fig. 2.2, *a*). If $\psi_u > \psi_i$, φ > 0 the voltage phase leads the current by an angle of φ (Fig. 2.2, *b*).

Average and RMS (root mean square) values of a sinusoidal current (sometimes *"effective value"* is in literature**)**

The average value of any sinusoidal function for the period is equal to zero. Therefore, as the average value of a sinusoidal current we can understand the average value of a sinusoidal current for a half-period.

For any form of a current

$$I_{av} = \frac{\int_0^{T/2} i dt}{T/2} = \frac{2}{T}\int_0^{T/2} i dt. \tag{2.2}$$

If $i = I_m \sin \omega t$, hence $I_{av} = -\frac{2}{T}\frac{I_m}{\omega}\cos\omega t \Big|_0^{T/2}$, as $\omega T = 2\pi$, then

$$I_{av} = -\frac{2}{2\pi} I_m \left[\cos\frac{2\pi}{T}\frac{T}{2} - \cos 0\right] = \frac{2}{\pi} I_m \approx 0{,}637 I_m,$$

as $[\cos\pi] = -1$ and $[\cos 0] = 1$.

Then the average value of a sinusoidal current

$$I_{av} = \frac{2}{\pi} I_m \approx 0{,}637 I_m. \tag{2.3}$$

But the most widespread characteristic is the RMS (root mean square) value. At measurements a sinusoidal current they compare with a direct current on thermal action.

The RMS value of an alternating current is equal to such a value of a direct current which releases the same quantity of heat $Q_{\_}$, as well as the given alternating current $Q_{\sim}$ across the same resistance R per the same time t = T.

Let's receive expression for RMS value of an alternating current for part of a circuit shown in Fig.2.3.

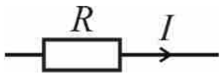


Figure 2.3

As a direct current I flows, the energy will release as heat

$$Q_{-} = I^2 RT .$$

If an alternating current I flows via the same resistance R, the energy of heat will release

$$Q_{\sim} = \int_0^T i^2 R dt$$

Let's equate the released energy of direct and sinusoidal currents

$$Q_{-} = Q_{\sim}.$$

$$I^2 RT = \int_0^T i^2 R dt,$$

whence an expression for the RMS value of an alternating current

$$I = \sqrt{\frac{1}{T}\int_0^T i^2 dt} . \qquad (2.4)$$

If a current is sinusoidal $i = I_m \sin \omega t$,

$$I = \sqrt{\frac{I_m^2}{T}\int_0^T \sin^2 \omega t dt}\text{, as } \sin^2 \omega t = \frac{1}{2}(1 - \cos 2\omega t),$$

$$I = \sqrt{\frac{I_m^2}{2T}\int_0^T dt - \frac{I_m^2}{2T}\int_0^T \cos 2\omega t dt}\text{, as} \int_0^T dt = T\text{, and} \int_0^T \cos 2\omega t dt = 0,$$

The RMS value of a sinusoidal current

$$I = \sqrt{\frac{I_m^2}{2T} T} = \frac{I_m}{\sqrt{2}} = 0{,}707 I_m . \qquad (2.5)$$

It is similarly possible to write down: $U = \dfrac{U_m}{\sqrt{2}}$; $\quad E = \dfrac{E_m}{\sqrt{2}}$.

If the RMS value of voltage U is 220 V, then the peak value $U_m \approx$ 311 V.

Representation of sinusoidal functions by phasors and complex numbers

At calculation circuits of an alternating current Ohm and Kirchhoff laws are used. They are valid for instantaneous values of currents and voltages.

At calculation it is necessary to carry out difficult trigonometric operations.

Calculation becomes simpler, if currents and other parameters are presented as rotating phasors as shown in Fig. 2.4.

$$i = I_m \sin\left(\omega t + \psi_i\right).$$

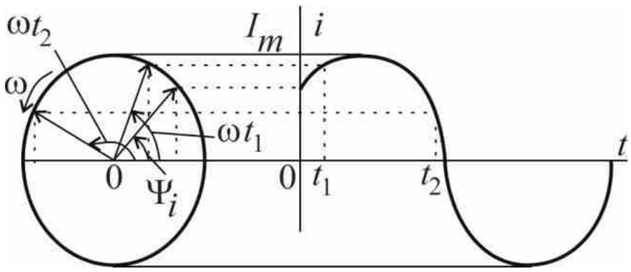


Figure 2.4

At the moment t = 0 I = I_m sinψ_i – a perpendicular (a vertical axis). Let the radius-phasor in length i = I_m rotates with constant angular frequency $\omega = \dfrac{2\pi}{T} = 2\pi f$ against an hour hand direction – one turn for the period.

At the moment t_1 the phasor will turn on an angle ωt_1 and the length of a perpendicular will be $I_m\sin(\omega t_1 + \psi_i)$. Application of rotating phasors allows to present compactly in one drawing set of the various sinusoidal changing values of identical frequency at the analysis of electric sinusoidal current circuits. The phasor can be spread out on two components and be written down in the form of complex number (Fig. 2.5).

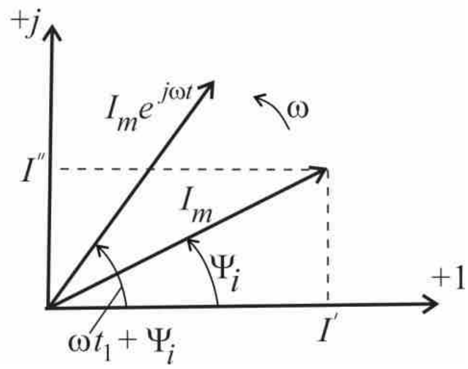


Figure 2.5

On a complex plane the complex number $\underline{I_m} = I_m e^{j\psi_i}$ at t = 0 corresponds to a current $i = I_m \sin(\omega t + \psi_i)$. The valid length of a phasor is equal in certain scale to the peak value of a current.

At t = 0 the projection of a phasor to an imaginary axis is equal to an instantaneous value of a current $i(0) = I_m \, sin \psi_i$.

Thus, if a radius-phasor rotates counter-clockwise with angular speed ω at any moment the projection of this phasor to an imaginary axis will be equal to an instantaneous value of a current during the considered moment of time.

There are 3 forms of record of a complex number

$$\underline{I} = I_m e^{j\psi_i} = I_m(\cos\psi_i + j\sin\psi_i) = I' + jI'' \qquad (2.6)$$

Let's have agreed that a sinusoidal current, EMF and voltage are to be designated for time moment t = 0, i.e. the phasor $\underline{I} = I_m e^{j\psi_i}$ corresponds to the current $i = I_m \sin(\omega t + \psi_i)$.

I_m is the complex peak value of a current. Having divided by $\sqrt{2}$, we receive a complex RMS value of a current

$$\underline{I} = \frac{I_m}{\sqrt{2}} e^{j\psi_i} = I e^{j\psi_i}. \qquad (2.7)$$

If two currents are given: $i_1 = I_{m1} \sin(\omega t + \psi_1)$ and $i_2 = I_{m2} \sin(\omega t + \psi_2)$, their sum is defined by a rule of addition of phasors or complex numbers (Fig.2.6).

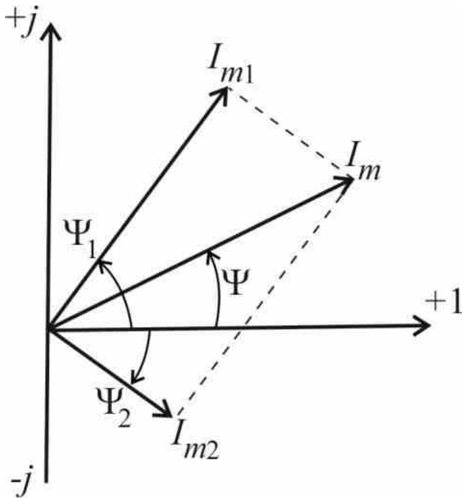


Figure 2.6

The algebraic sum of the currents corresponds to the geometric sum of the phasors representing the indicated functions.

Set of phasors on a complex plane is called as a *phasor diagram*. Usually, in the phasor diagram we don't use the peak value, but the RMS values of the quantities.

The method of calculation based on representation of functions by complex numbers, is called as complex or symbolical.

Elements of an alternating current circuit

In the course of calculation and the analysis a real circuit is replaced with an equivalent schematic diagram which contains a number of elements. Passive elements of an electric circuit are referred to:

1) *Resistance R*

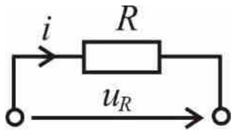


Figure 2.7

Resistance R (Fig.2.7) characterizes a resistive element (a resistor) property to transform irreversibly electric energy into thermal energy. Relationship between current and voltage across resistance is expressed so

$$u_R = Ri \,. \qquad (2.8)$$

Thus, it is necessary to mention, resistance at a sinusoidal current is bigger than resistance at a direct current because of current replacement in conductors at a sinusoidal current circuit. It is measured in ohms, [Ω].

2) *Inductance L*

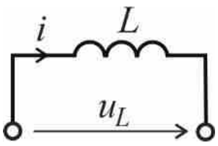


Figure 2.8

Inductance L (Fig.2.8) characterizes a property of an electric circuit inductive element (an inductor or a coil), under the influence of a sinusoidal current in it to create own magnetic field. It is measured in henri, [H].

$$L = \frac{\Psi}{i}, \tag{2.9}$$

where ψ – *protoflux* (*linked flux* or *total flux*) of an element self-induction.

At changing of protoflux ψ in windings of an inductor according to law of electromagnetic induction (Faraday's law), EMF of self-induction is induced

$$e_L = -\frac{d\Psi}{dt}. \tag{2.10}$$

Inductance stores the magnetic field energy $W_m = \frac{Li^2}{2}$ and the phenomenon of self-induction, i.e. when a current flows in the inductance, an EMF is induced

$$e_L = -L\frac{di}{dt}. \tag{2.11}$$

In order for a current to flow through inductance, a voltage must be applied to it, at each moment in time it is opposite in direction to EMF of self-induction

$$u_L = -e_L = L\frac{di}{dt}.$$

3) *Capacitance C*

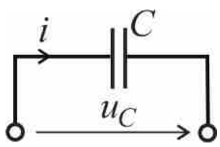


Figure 2.9

Capacitance C (Fig.2.9) characterizes a property of an electric circuit element, for example a capacitor, to accumulate electric charges q and to create the electric field energy $W_e = \frac{Cu_C^2}{2}$.

$$C = \frac{q}{u_C}. \tag{2.12}$$

It is measured in farads, [F]. But as current is equal to speed of change of charges in time $i = \frac{dq}{dt}$, and $q = C \cdot u_C$, then $i = \frac{d(C \cdot u_C)}{dt} = C\frac{du_C}{dt}$.

From here we receive the expression for voltage across capacitance

$$u_C = \frac{1}{C}\int idt. \tag{2.13}$$

Relationship of a sinusoidal current and a voltage across ideal *R, L, C* - elements

A sinusoidal current circuit with a resistance R (Fig. 2.10).

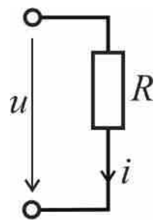


Figure 2.10

The voltage $u = U_m \sin \omega t$ is applied to the resistance R (Fig. 2.10) The current is $i = \frac{u}{R} = \frac{U_m}{R}\sin \omega t = I_m \sin \omega t$, where $I_m = \frac{U_m}{R}$ – peak value of the current.

Phase difference angle between the current i and the voltage u across the resistance R is equal to zero, i.e. $\varphi = 0$ (Fig. 2.11). Having divided U_m by $\sqrt{2}$, we receive Ohm's law

$$I = \frac{U}{R}; \qquad \underline{I} = \frac{\underline{U}}{R}. \tag{2.14}$$

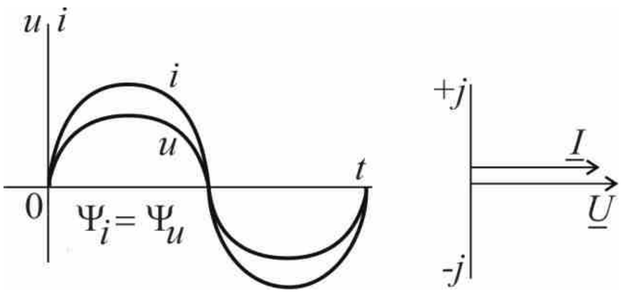


Figure 2.11

The current change is sinusoidal and coincides in phase with the voltage across resistance (an active element).

A sinusoidal current circuit with an inductance L (Fig. 2.12)

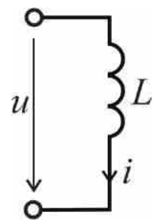


Figure 2.12

The voltage $u = U_m \sin \omega t$ is applied to the inductance L (Fig. 2.12).

If $u_L = -e_L = L\dfrac{di}{dt}$, from here we find a sinusoidal current

$$i = \frac{1}{L}\int u dt = \frac{1}{L}\int U_m \sin \omega t dt = -\frac{U_m}{\omega L}\cos\omega t = \frac{U_m}{\omega L}\sin\left(\omega t - \frac{\pi}{2}\right) = I_m \sin\left(\omega t - \frac{\pi}{2}\right),$$

(2.15)

where $I_m = \dfrac{U_m}{\omega L} = \dfrac{U_m}{X_L}$.

Ohm's law for a circuit with inductance

$$I = \frac{U}{\omega L} = \frac{U}{X_L}. \quad (2.16)$$

The current varies sinusoidally, but it lags behind the voltage across inductance by π/2 in phase. (Fig. 2.13)

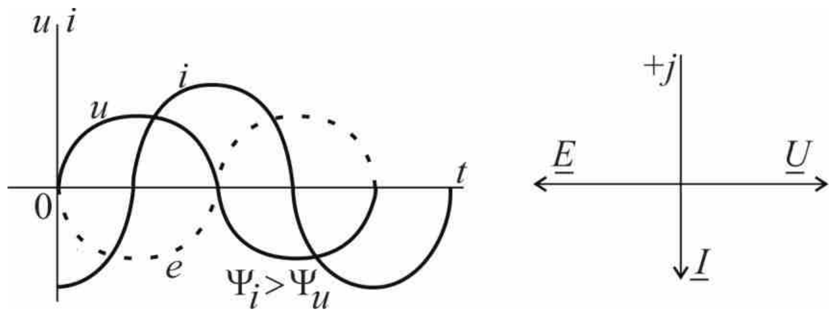


Figure 2.13

An inductive reactance is determined as

$$X_L = \omega L = 2\pi f L\,. \qquad (2.17)$$

It is measured in ohms, [Ω].

The EMF of self-induction $e_L = -L\dfrac{di}{dt} = -u = -U_m \sin\omega t = E_m \sin\omega t$.

A complex form of voltage across inductance looks like

$$\underline{U}_L = U_L e^{j\left(\psi_i + 90^\circ\right)} = x_L I \cdot e^{j\left(\psi_i + 90^\circ\right)} = x_L I e^{j\psi_i} e^{j90^\circ} = j x_L \underline{I}$$

As under Euler formula $e^{j90^\circ} = \cos 90^\circ + j\sin 90^\circ = j$.

Then Ohm's law for an inductive element is

$$\underline{I} = \frac{\underline{U}}{j\omega L} = \frac{\underline{U}}{jX_L}\,. \qquad (2.18)$$

A sinusoidal current circuit with a capacitance C (Fig. 2.14)

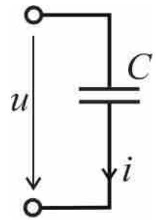


Figure 2.14

The voltage $u = U_m \sin\omega t$ is applied to the capacitance C (Fig. 2.14) , then the current in capacitance

$$i = C\frac{du_C}{dt} = \omega C U_m \cos\omega t = \frac{U_m}{\dfrac{1}{\omega C}}\sin\left(\omega t + \frac{\pi}{2}\right) = I_m \sin\left(\omega t + \frac{\pi}{2}\right), \qquad (2.19)$$

where $I_m = \dfrac{U_m}{\dfrac{1}{\omega C}} = \dfrac{U_m}{X_C}$. Ohm's law for capacitance $I = \dfrac{U}{\dfrac{1}{\omega C}} = \dfrac{U}{X_C}$.

A capacitive reactance is

$$X_C = \frac{1}{\omega C}, \qquad (2.20)$$

measured in ohms, $[X_C] = [\Omega]$.

The current varies sinusoidal, but it leads the voltage across capacitance by π/2 in phase (Fig.2.14). A complex form (a phasor) of voltage across capacitance

$$\underline{U}_C = Ue^{j\left(\psi_i - \frac{\pi}{2}\right)} = X_C I^{j\left(\psi_i - \frac{\pi}{2}\right)} = Ie^{j\psi_i} X_C e^{-j\frac{\pi}{2}} = -jX_C \underline{I}\ .$$

Ohm’s law for capacitance in a complex form

$$\underline{I} = \frac{\underline{U}}{-j\omega C} = \frac{\underline{U}}{-jx_C}\ . \qquad (2.21)$$

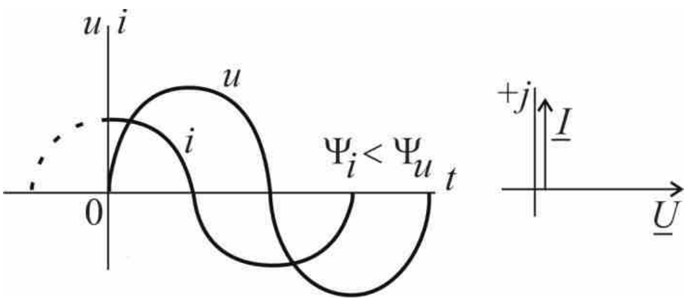


Figure 2.15

Test questions

1. What are the advantages of an alternating current?

2. What the forms of representation of a sinusoidal current do you know?

3. What are instantaneous values of voltage and current?

4. What are the peak-values of voltage and current?

5. What is the RMS value of a sinusoidal quantity?

6. What is the average value of a sinusoidal quantity?

7. What elements of an alternating current circuit do you know?

8. What is the phase difference angle between current and voltage across resistance?

9. What is the phase difference angle between current and voltage across inductance?

10. What is the phase difference angle between current and voltage across capacitance?

LECTURE 3

RELATIONSHIPS OF SINUSOIDAL VOLTAGES AND CURRENTS IN THE CIRCUIT WITH A SERIES CONNECTION OF ELEMENTS. ENERGY AND POWER IN A SINUSOIDAL CURRENT CIRCUIT WITH IDEAL *R, L, C* ELEMENTS

A series connection of elements in an electric circuit is shown in Fig. 3.1.

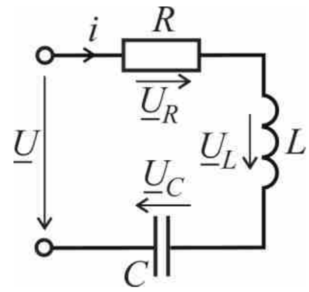


Figure 3.1

The voltage is applied to the circuit (Fig. 3.1) $u = U_m \sin(\omega t + \varphi)$. According to Kirchhoff's Voltage Law we can write down for instantaneous values of quantities

$$u = u_a + u_L + u_C = Ri + L\frac{di}{dt} + \frac{1}{C}\int idt. \qquad (3.1)$$

The complex of RMS voltage values is equal to the sum of the complex values of voltage drops

$$\underline{U} = \underline{U}_a + \underline{U}_L + \underline{U}_C = \underline{I}R + jX_L\underline{I} - jX_C\underline{I}. \qquad (3.2)$$

Let's draw a phasor diagram for this circuit (Fig. 3.2).

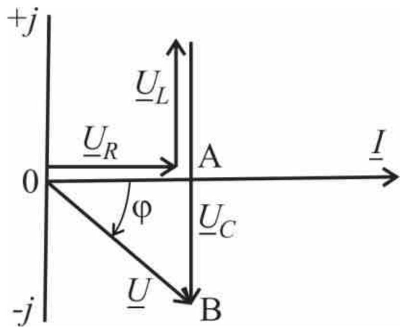


Figure 3.2

From the phasor diagram (triangle Δ 0AB) we will find

$$U^2 = U_a^2 + (U_L - U_C)^2 = (IR)^2 + (IX_L - IX_C)^2 = I^2\left[R^2 + \left(X_L - X_C{}^2\right)\right].$$

From here Ohm's law for an alternating current circuit

$$I = \frac{U}{\sqrt{R^2 + (X_L - X_C)^2}} = \frac{U}{Z}. \quad (3.3)$$

Impedance of the circuit

$$Z = \sqrt{R^2 + (X_L - X_C)^2}. \quad (3.4)$$

If it is the impedance of the circuit in Fig. 3.1

$$Z = \sqrt{\left(\sum R\right)^2 + \left(\sum X_L - \sum X_C\right)^2},$$

it's similarly possible to write down from the initial equation

$$\underline{Z} = R + j(X_L - X_C) = R + jX, \quad (3.5)$$

where $X = X_L - X_C$ is the reactance of the circuit.

From the triangle Δ 0AB (Fig.3.2) we have a voltage triangle (Fig. 3.3)

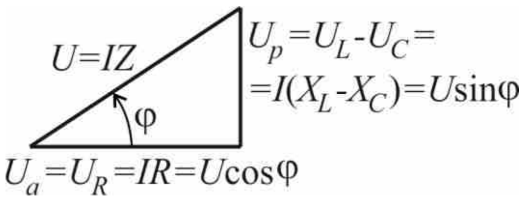


Figure 3.3

Having divided each line of the voltage triangle by a current, we will receive an impedance triangle (Fig. 3.4)

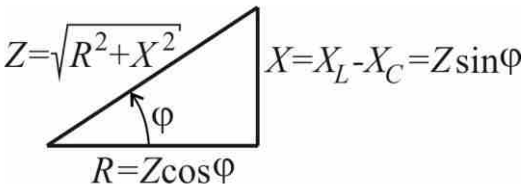


Figure 3.4

The angle φ represents a phase difference angle between a current and a voltage in a circuit

$$\varphi = \mathrm{arctg}\frac{U_L - U_C}{U_a} = \mathrm{arctg}\frac{X_L - X_C}{R}. \quad (3.6)$$

Conductance, susceptance and admittance

Complex admittance of the circuit is

$$\underline{Y} = \frac{1}{\underline{Z}} = \frac{1}{Ze^{j\varphi}} = \frac{1}{Z}e^{-j\varphi} = Ye^{-j\varphi}$$

$$\underline{Y} = \frac{1}{\underline{Z}} = \frac{1}{R+jX} = \frac{1}{R+jX}\cdot\frac{R-jX}{R-jX} = \frac{R-jX}{R^2+X^2} = \frac{R}{R^2+X^2} - j\frac{X}{R^2+X^2} =$$

$$= \frac{R}{Z^2} - j\frac{X}{Z^2} = G - jB, \tag{3.7}$$

where conductance of the circuit (at $X = 0$, $G = 1/R$) is

$$G = \frac{R}{R^2+X^2} = \frac{R}{Z^2}, \tag{3.8}$$

susceptance of the circuit is

$$B = \frac{X}{R^2+X^2} = \frac{X}{Z^2}. \tag{3.9}$$

At $X = X_L - X_C > 0$, $B > 0$, and at $X = X_L - X_C < 0$, $B < 0$.

Subject to a complex admittance, Ohm's law becomes

$$\underline{I} = \frac{\underline{U}}{\underline{Z}} = \underline{U}\,\underline{Y} \tag{3.10}$$

$$\underline{I} = \underline{U}\,\underline{Y} = \underline{U}(G - jB) = \underline{U}G - j\underline{U}B = \underline{I}_a + \underline{I}_p,$$

where I_a is an active component of a current I, I_p is a reactive component of the current I. The phasor diagram looks like (Fig. 3.5)

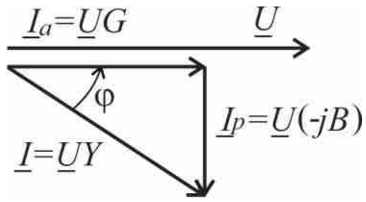


Figure 3.5

Then an admittance-conductance-susceptance triangle is shown in Fig. 3.6.

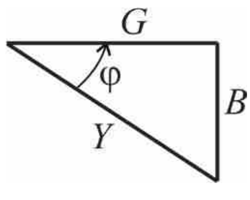


Figure 3.6

Kirchhoff's laws for sinusoidal current circuits

Kirchhoff's current law (1st law): the algebraic sum of instantaneous values of currents is equal to zero in a node of an electric circuit. Or the geometrical sum of the phasors representing currents in a node is equal to zero.

For instantaneous values $\sum_{k=1}^{n} i_k = 0$. (3.11)

For complex values or phasors $\sum_{k=1}^{n} \underline{I}_k = 0$. (3.12)

Kirchhoff's voltage law (2nd law):

If each part of the loop of the electric circuit contains *R, L, C* elements, then the algebraic sum of instantaneous values of the EMF, acting in a closed loop, are equal to the algebraic sum of the instantaneous values of the voltage drops on the elements of this circuit

$$\sum_{k=1}^{n} e_k = \sum_{k=1}^{m}\left(i_k R_k + L_k \frac{di_k}{dt} + \frac{1}{C_k}\int i_k dt \right). \qquad (3.13)$$

The sum of EMF complex values, operating in the closed loop, is equal to the sum of the complex values of voltage drops on parts of this loop

$$\sum_{k=1}^{n} \underline{E}_k = \sum_{k=1}^{m} \underline{I}_k \underline{Z}_k \,. \qquad (3.14)$$

Energy and power in a sinusoidal current circuit with ideal *R, L, C* elements

In a circuit of a direct current power was defined by the expression of $P = UI$.

Let's consider a sinusoidal current circuit with a series connection *R, L, C* elements (Fig. 3.7).

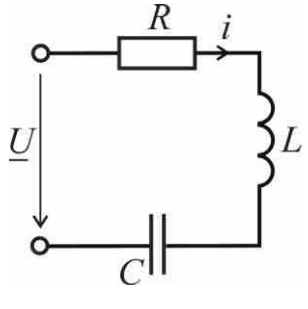


Figure 3.7

Let's write down the applied voltage U as $u = U_m \sin(\omega t + \varphi)$ and the current I as $i = I_m \sin \omega t$.

It’s known $\varphi = \psi_u - \psi_i$ at $\psi_i = 0$ then $\psi_u = \varphi$.

If $X_L > X_C$, $\varphi > 0$ and vice versa $X_L < X_C$, $\varphi < 0$.

For instantaneous values the next expression represents

$$p = ui = U_m \sin(\omega t + \varphi) I_m \sin \omega t. \qquad (3.15)$$

Separately here, we write down $U_m I_m = \sqrt{2}U\sqrt{2}I = 2UI$.

$$\sin(\omega t + \varphi) \cdot \sin \omega t = \frac{1}{2}[\cos(\omega t + \varphi - \omega t) - \cos(\omega t + \varphi + \omega t)] = \frac{1}{2}[\cos\varphi - \cos(2\omega t + \varphi)]$$

.

The expression for the instantaneous power is

$$p = UI \cos\varphi - UI \cos(2\omega t + \varphi). \qquad (3.16)$$

Energy, which arrives in a circuit, defined by the average value of power for the period

$$P = \frac{1}{T}\int_0^T p\,dt = \frac{1}{T}\int_0^T UI \cos\varphi\,dt - \frac{1}{T}\int_0^T UI \cos(2\omega t + \varphi)\,dt, \qquad (3.17)$$

but $\frac{1}{T}\int_0^T UI \cos(2\omega t + \varphi)\,dt = 0$, therefore

$$P = UI \cos\varphi, \qquad (3.18)$$

where $\cos\varphi$ is called a power factor.

From a triangle of voltage $U \cos\varphi = IR$, therefore an active power

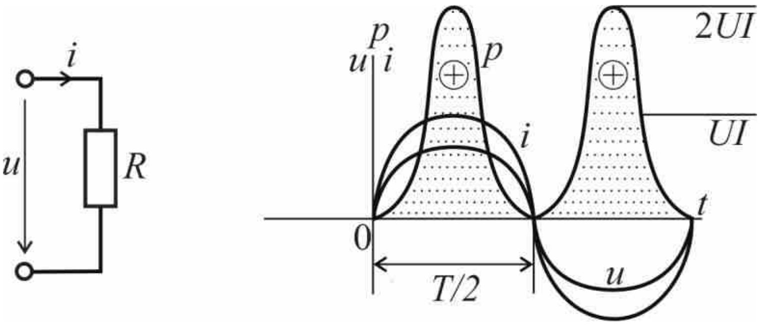
$$P = UI \cos\varphi = I^2 R. \qquad (3.19)$$

Thus, an average power for the period is called the active power P.

Let's consider a circuit with an active element, i.e. $\varphi = 0$ (Fig. 3.8, a).

$$p = ui = UI(1 - \cos 2\omega t) = UI - UI \cos 2\omega t. \qquad (3.20)$$

Let's plot the function graph of this power (Fig.3.8, *b*)



a *b*

Figure 3.8

The power is more than zero (Fig. 3.8, *b*), electric energy arrives from a source in a circuit, here it is spent. What is this energy? This is a thermal energy

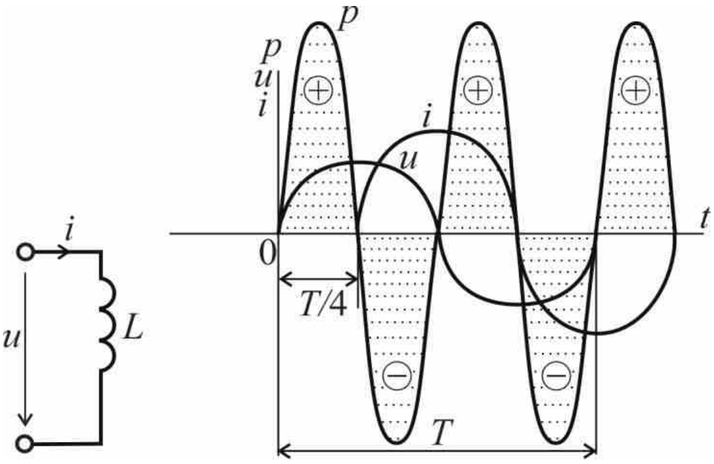
$$W = \int_{0}^{T/2} p dt = \int_{0}^{T/2} u i dt = \int_{0}^{T/2} i r i dt = I^2 R \frac{T}{2}. \tag{3.21}$$

Let's consider a circuit with an inductive element, i.e. φ = π/2. (Fig. 3.9, a)

$$P = \frac{1}{T}\int_{0}^{T} p dt = \frac{1}{T}\int_{0}^{T} UI\cos\varphi dt - \frac{1}{T}\int_{0}^{T} UI\cos(2\omega t + \varphi) dt. \tag{3.22}$$

But also the first and second expressions in (3.22) are equal to zero, i.e. the average value of the power for the period is equal to zero (Fig. 3.9, *b*). From the general expression for the instantaneous power

$$p = -UI\cos\left(2\omega t + \frac{\pi}{2}\right) = UI\sin 2\omega t. \tag{3.23}$$



a *b*

Figure 3.9

In inductance (in the ideal inductive element) the current lags behind the voltage by 90°.

For the period power is changing a sign twice. A positive value of power corresponds to the condition at which energy arrives in a circuit. A negative value of power corresponds to the condition at which energy comes back to a source. Thus, the ideal inductive element does not consume energy. Let's find value of the energy arriving about a circuit for a quarter of the period. This the expression for the energy of a magnetic field

$$W = \int_0^{T/4} p dt = \int_0^{T/4} u i dt = \int_0^{T/4} L \frac{di}{dt} i dt = L \int_0^{I_m} i di = \frac{L I_m^2}{2}. \tag{3.24}$$

Here we have made replacement of the limits of the integral: at $t = 0$, $i = 0$; at $t = T/4$, $i = I_m$.

Thus, the energy which has arrived in a circuit with an ideal inductive element, will be transformed to the energy of a magnetic field. Power is positive, when the current rises in an absolute value. During this moment energy arrives in a circuit and will be transformed to the energy of a magnetic field.

When current decreases, the reserved energy in an inductive element comes back to a source, i.e. in such a circuit between the source and the load there is a continuous exchange of energy.

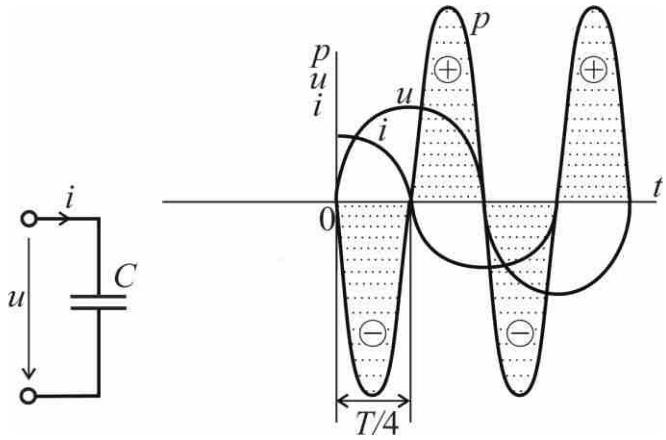
Let's consider a circuit with a capacitive element, i.e. $\varphi = -\pi/2$.

From the general expression for the instantaneous power

$$p = -UI \cos\left(2\omega t - \frac{\pi}{2}\right) = -UI \sin 2\omega t. \tag{3.25}$$

Here the voltage lags behind the current by 90°. The same drawing, but the current and the voltage have changed in places (Fig. 3.10). This is the energy of an electric field

$$W = \int_0^{T/4} p dt = \int_0^{T/4} u i dt = \int_0^{T/4} u \cdot C \frac{du}{dt} dt = C \int_{U_m}^{0} u du = -\frac{C U_m}{2}. \tag{3.26}$$



a *b*

Figure 3.10

Thus, in a circuit with capacitance (the ideal capacitive element) the processes are similar to processes in a circuit with an inductive element, but the energy of an electric field here fluctuates.

In a real electric circuit both phenomena take place simultaneously: and irreversible transformations of energy of a source to heat and an exchange a source and loads.

Apparent, active and reactive power

In Fig. 3.5 the phasor diagram has been shown in which the current I lags behind the applied voltage U by angle of φ. In Fig. 3.11 the triangle of voltage is shown, where the active (horizontal) component of U is $U\cos\varphi$ and the reactive (vertical) component of U is $U\sin\varphi$.

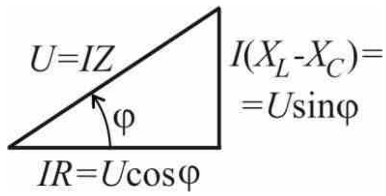


Figure 3.11

If each of the voltage phasors is multiplied by I, Fig. 3.12 is obtained and is known as the power triangle.

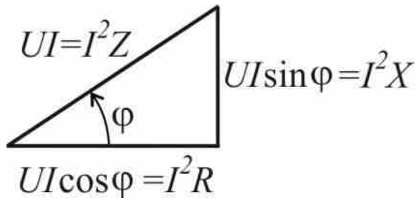


Figure 3.12

Active power (true power) is irreversibly converted into heat or mechanical work. It is measured in watts, [W].

$$P = I^2 R = UI\cos\varphi. \tag{3.27}$$

Reactive power, which is spent for creation magnetic and electric fields, and then comes back to a source

$$Q = I^2 X = I^2 X_L - I^2 X_C = UI\sin\varphi, \tag{3.28}$$

It is measured in reactive volt-amperes, [var].

Apparent (total power) is the product of the RMS voltage U across the terminals of a two-terminal element or two-terminal circuit and the RMS electric current I in the element or circuit

$$S = UI = I^2 Z = \sqrt{P^2 + Q^2}. \tag{3.29}$$

Apparent (total power) is measured in volt-ampers, [VA]

Then, active and reactive power: $P = S\cos\varphi$, $Q = S\sin\varphi$.

Power in the symbolical form

Let's take $u = U_m \sin(\omega t + \psi_u)$; $i = I_m \sin(\omega t + \psi_i)$.

In the complex form these expressions:

$$\underline{U} = \frac{U_m}{\sqrt{2}} e^{j\psi_u} = Ue^{j\psi_u};\ \ \underline{I} = \frac{I_m}{\sqrt{2}} e^{j\psi_i} = Ie^{j\psi_i};\ \ \varphi = \psi_u - \psi_i.$$

The complex conjugate value of a current $\underline{I}^* = Ie^{-j\psi_i}$.

Let's write down the expression

$$\underline{U}\underline{I}^* = Ue^{j\psi_u} \cdot Ie^{-j\psi_i} = UIe^{j(\psi_u - \psi_i)} = UIe^{j\varphi} = UI\cos\varphi + jUI\sin\varphi = P + jQ = \underline{S}.$$

The apparent complex power

$$\underline{S} = \underline{U}\underline{I}^* = P + jQ. \tag{3.30}$$

The real part of this complex represents the active power, and the imaginary part is the reactive power.

Power balance equations

In an electric circuit the sum of the active powers given by sources is equal to the sum of the active powers consumed by loads. The statement for reactive powers is similar to active ones.

For active powers (the real part of the complex)

$$\sum_{k=1}^{n} \mathrm{Re}\left(\underline{E}_k \overset{*}{\underline{I}}_k\right) = \sum_{k=1}^{m} \mathrm{Re}\left(\underline{U}_k \overset{*}{\underline{I}}_k\right); \qquad (3.31)$$

For reactive powers (the imaginary part of the complex).

$$\sum_{k=1}^{n} \mathrm{Im}\left(\underline{E}_k \overset{*}{\underline{I}}_k\right) = \sum_{k=1}^{m} \mathrm{Im}\left(\underline{U}_k \overset{*}{\underline{I}}_k\right). \qquad (3.32)$$

Test questions

1. What is conductance of a circuit?

2. What is susceptance of a circuit?

3. What is admittance of a circuit?

4. State Kirchhoff's laws for circuits of a sinusoidal current.

5. What are powers and the phase difference angle in a circuit with resistance?

6. What are powers and the phase difference angle in a circuit with inductance?

7. What are powers and the phase difference angle in a circuit with capacitance?

8. What is active power in sinusoidal current circuits?

9. What is reactive power in sinusoidal current circuits?

10. What is apparent power in sinusoidal current circuits?

LECTURE 4

CIRCUIT WITH PARALLEL CONNECTION OF IDEAL *R, L, C* ELEMENTS. RESONANCE PHENOMENA IN AC CIRCUITS

Currents in the branches of an alternating current (AC) circuit (Fig .4.1) are defined by Ohm's law, but the current *I* in not branched out part of the circuit we find with help by of Kirchhoff's Current Law in the complex form:

$$\underline{I}_1 = \frac{\underline{U}}{R}; \quad \underline{I}_2 = \frac{\underline{U}}{jX_L}; \quad \underline{I}_3 = -\frac{\underline{U}}{jX_C}, \tag{4.1}$$

$$\underline{I} = \underline{I}_1 + \underline{I}_2 + \underline{I}_3. \tag{4.2}$$

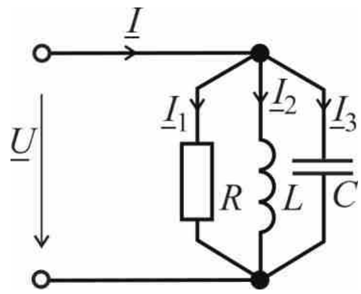


Figure 4.1

It is possible to express currents in the branches by complex admittance. To remind the general expression for admittance, conductance and susceptance:

$$\underline{Y} = G - j(B_L - B_C) \tag{4.3}$$

$$\underline{I}_1 = G\underline{U}; \quad \underline{I}_2 = -jB_L\underline{U}; \quad \underline{I}_3 = jB_C\underline{U}.$$

Hence an active component of the current *I* is

$$\underline{I}_a = \underline{I}_1 = G\underline{U}. \tag{4.4}$$

A reactive component of the current *I* is

$$\underline{I}_p = \underline{I}_2 + \underline{I}_3 = -j(B_L - B_C)\underline{U} = -jB\underline{U}. \tag{4.5}$$

The total complex current is

$$\underline{I} = \underline{I}_a + \underline{I}_p. \tag{4.6}$$

The module of this current is

$$I = \sqrt{I_a^2 + I_p^2}\,. \tag{4.7}$$

The phasor diagram is shown in Fig. 4.2.

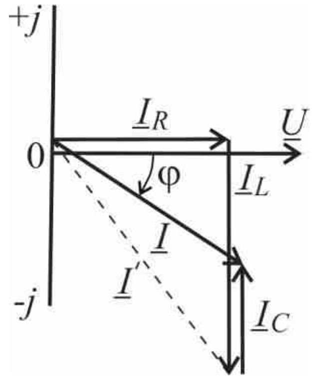


Figure 4.2

The currents in the branches with inductive and capacitive elements are in antiphase (opposite each other), and the reactive current of the circuit is equal to their difference. This phenomenon is used to compensate for a phase difference.

Thus, a compensating capacitor is connected in parallel to the circuit with active-inductive elements in parallel, which provides:

1) reducing the phase difference angle between the current source and its voltage;

2) increases $\cos\varphi$ (the power factor) of the circuit;

3) reduces the source current ($I < I'$).

Resonance phenomena in alternative current (AC) circuits

As resonance we understand such a condition in which the impedance of the circuit (Fig. 4.3) with *R, L, C* elements relative to the source is purely resistive. In this case, φ = 0, the current and the source voltage coincide in phase, the reactive power $Q = UI\,sin\,\varphi = (X_L - X_C)I^2 = 0$, i.e. the circuit consumes only an active power $P = RI^2$.

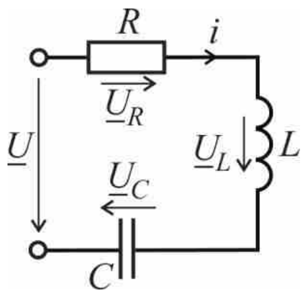


Figure 4.3

Series resonance (Voltage resonance)

Series resonance is possible in an electric circuit with series *R, L, C* elements connection. For this circuit impedance is $Z = \sqrt{R^2 + (X_L - X_C)^2}$.

If $X_L = X_C$ then $Z = R$ and the impedance of the circuit will be purely active.

Thus, a necessary and sufficient condition of series resonance is the condition

$$X_L = X_C \text{ or } \omega L = \frac{1}{\omega C}. \qquad (4.8)$$

From here we obtain the resonance frequency or resonant frequency

$$f = \frac{1}{2\pi\sqrt{LC}}. \qquad (4.9)$$

At resonance the impedance of an AC circuit becomes minimum, and the current becomes the maximum value I_0, which is shown in Fig.4.4.

$$I_0 = \frac{U}{Z} = \frac{U}{R}. \qquad (4.10)$$

As $X_L = X_C$, $I \cdot X_L = I \cdot X_C$ and $U_L = U_C$.

Voltages across inductive and capacitive elements can exceed many times over the voltage of the source, from here and the phenomenon name is voltage resonance.

The voltage across a coil (inductance) U_L is equal to the voltage across capacitor (capacitance) U_C, but they are opposite on a phase, therefore the input voltage U is equal to the voltage across a resistor (resistance) element U_R. This situation is shown in Fig. 4.5.

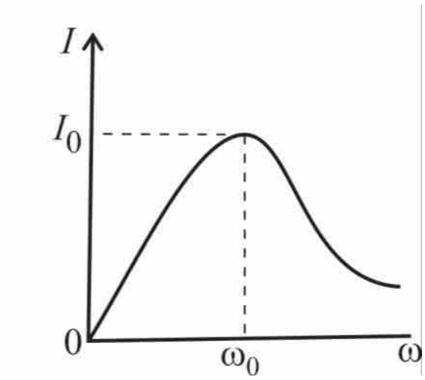


Figure 4.4

Parallel resonance can be obtain, changing φ, L, C.

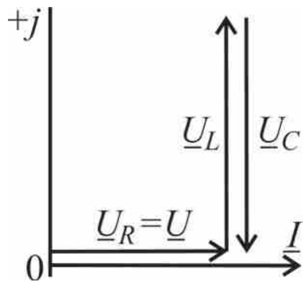


Figure 4.5

A current in the circuit in common case can be found as

$$I = \frac{U}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \qquad (4.11)$$

At the resonance the voltages across inductance and capacitance have the same value:

$$U_L = U_C = I_0 X_L = I_0 X_C = \frac{U}{R} X_L = \frac{U}{R} X_C .$$

Q-factor or quality factor of a circuit is

$$Q^/ = \frac{U_L}{U} = \frac{U_C}{U} = \frac{U}{R \cdot U}\omega L = \frac{X_L}{R} = \frac{X_C}{R} . \qquad (4.12)$$

Q-factor shows how many times the voltage across inductance or capacitance exceeds the input voltage of a circuit.

Parallel resonance (Current resonance)

Parallel resonance appears at parallel connection of reactive elements (Fig. 4.6).

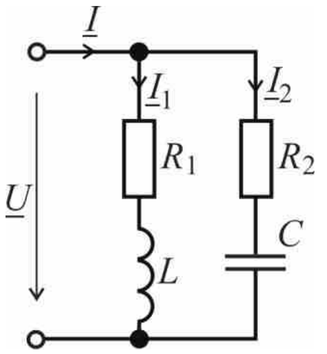


Figure.4.6

Therefore, we can write down

$$\underline{I} = \underline{I}_1 + \underline{I}_2 = \underline{Y}_1\underline{U} + \underline{Y}_2\underline{U} = \underline{U}(G_1 - jB_1) + \underline{U}(G_2 + jB_2) =$$
$$= \underline{U}\left[(G_1 + G_2) - j(B_1 - B_2)\right].$$

The resonance of currents will be, when $B_1 - B_2 = 0$.

Parallel resonance condition is

$$B_1 = B_2 . \qquad (4.13)$$

Or

$$\frac{X_L}{R_1^2 + X_L^2} = \frac{X_C}{R_2^2 + X_C^2}\,. \qquad (4.14)$$

Also it's possible to write down

$$\frac{\omega L}{R_1^2 + \omega^2 L^2} = \frac{\dfrac{1}{\omega C}}{R_2^2 + \dfrac{1}{\omega^2 C^2}}\,.$$

And we obtain the phasor diagram of parallel resonance shown in Fig. 4.7, where φ = 0.

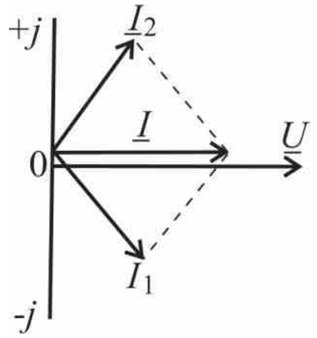


Figure 4.7

Test questions

1. How can we sum the currents in a circuit with a parallel connection of R, L, C elements?

2. What is a series resonance?

3. What is the series resonance condition?

4. What is the resonant frequency?

5. What is the condition of a parallel resonance?

6. What is Q-factror?

7. Compare the phasor diagrams of a series resonance and a parallel resonance.

LECTURE 5

THREE-PHASE CIRCUITS. PRINCIPLES OF GENERATION. THE REPRESENTATION FORMS. THREE-PHASE EMF SYSTEM AT CONNECTION OF THREE-PHASE SOURCES AND LOADS

The multiphase circuit is a set of single-phase circuits in which several EMF operate with the identical frequency, shifted by a certain angle. The separate circuits, entering into a multiphase circuit, are called as phases.

Three-phase circuits are wide spread occurrence. The source of a three-phase circuit is a three-phase synchronous (usually) generator. The three-phase generator is shown in Fig. 5.1. The rotor is shown as a permanent magnet for simplicity.

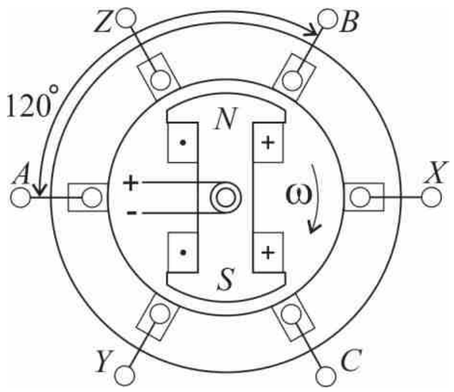


Figure 5.1

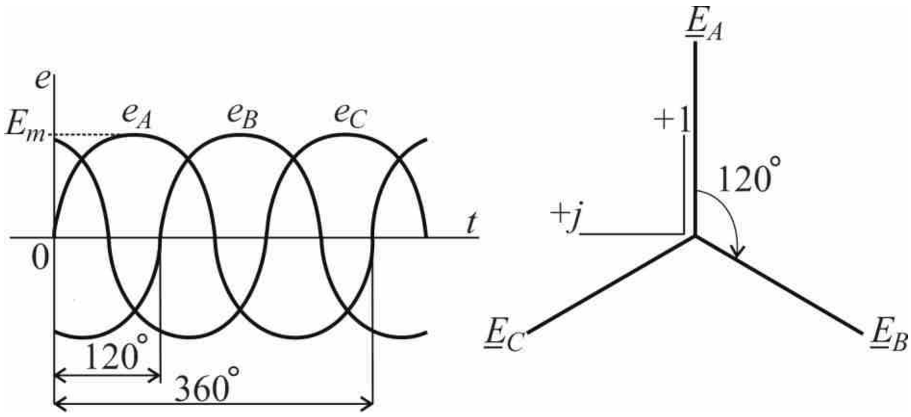
There are three windings *A-X, B-Y, C-Z* in the stator of a generator. The axes of the windings are shifted in space by 120°. At the rotor rotation a sinusoidal EMF will be induced in each winding. Figure 5.1 shows the rotor as a permanent magnet for simplicity. Let's accept for the moment of readout time when EMF in a phase *A*, it is equal to zero, i.e.: $e_A = E_m \sin \omega t$, then:

$$e_B = E_m \sin\left(\omega t - 120^{\circ}\right)$$

$$e_C = E_m \sin\left(\omega t - 240^{\circ}\right) = E_m \sin\left(\omega t + 120^{\circ}\right).$$

In view of that symmetry the peak EMF values E_m of all three phases are equal to each other (Fig. 5.2):

$$\underline{E}_A = Ee^{j0^\circ};\ \ \underline{E}_B = Ee^{-j120^\circ};\ \ \underline{E}_C = Ee^{j120^\circ} = \underline{E}_C = Ee^{-j240^\circ}. \qquad (5.1)$$



a *b*

Figure 5.2

The algebraic sum of the instantaneous values is

$$e_A + e_B + e_C = 0. \qquad (5.2)$$

The RMS values of electromotive forces are summed up as

$$\underline{E}_A + \underline{E}_B + \underline{E}_C = 0. \qquad (5.3)$$

Such EMF system, in which all the EMF are equal by value and shifted relatively to each other by the same angle of 120°, is called *symmetric*.

Having connected three phases of a source to a three-phase load, we obtain a three-phase circuit shown in Fig. 5.3. The circuit is called uncoupled.

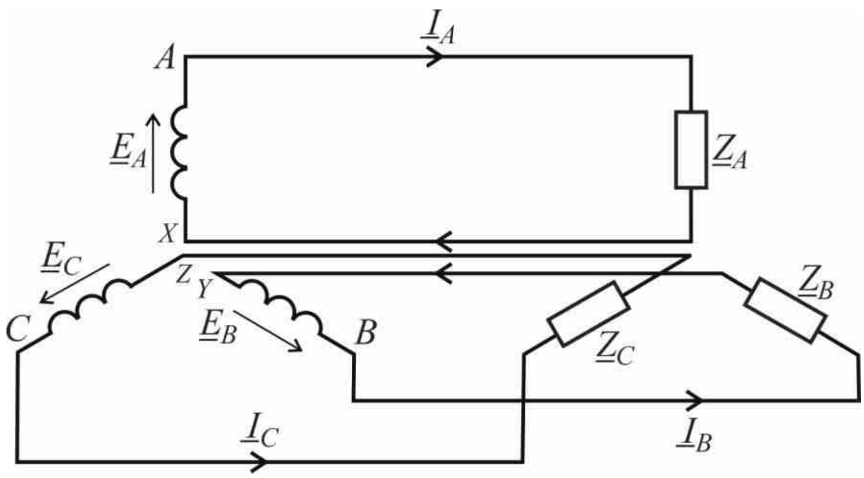


Figure 5.3

The phasor diagram of this three-phase uncoupled circuit is shown in Fig. 5.4.

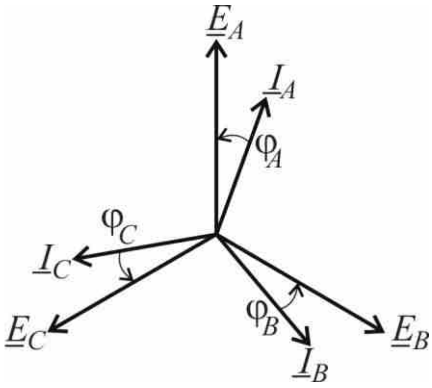


Figure 5.4

The load is called *balanced* if the complex impedances of all the loads in all the phases are the same

$$\underline{Z}_A = \underline{Z}_B = \underline{Z}_C . \tag{5.4}$$

Since $\underline{Z} = Ze^{j\varphi}$ both the modules and the phase difference angles should be equal

$$Z_A = Z_B = Z_C ; \quad \varphi_A = \varphi_B = \varphi_C . \tag{5.5}$$

At a balanced load the currents are equal to each other in the phases

$$I_A = I_B = I_C . \tag{5.6}$$

Star connection (wye or Y connection) of the generator phases and loads

At a star connection the ends of the phases *X*, *Y*, *Z* are united in one general point which is called neutral (*N*, *n*).

The wire, connecting these two neutral points of the power supply and the load, is called a neutral conductor (Fig. 5.5).

Conductors connect a power supply to loads called *lines* in a three-phase circuit.

There are *phase* and *line currents* and *voltages*.

Phase voltage is a voltage between the beginning and the phase end. It is the voltage between a line and the neutral wire: U_A, U_B, U_C. Other names of phase voltage are *phase to neutral voltage* or *line to neutral voltage* (**US**).

A phase voltage of a source is accepted equal to EMF.

Line voltage is a voltage between phases or line wires U_{AB}, U_{BC}, U_{CA}. Currents in the phases are called *phase currents*. Currents in line wires are called *line currents* I_A, I_B, I_C.

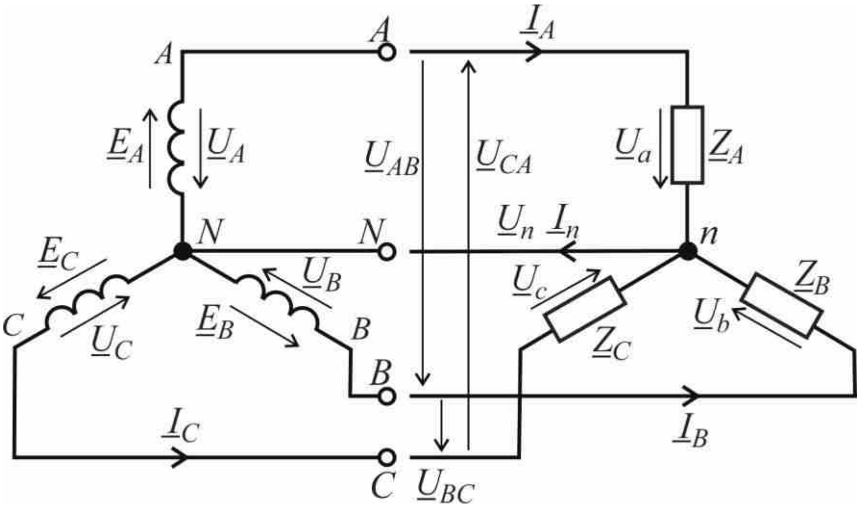


Figure 5.5

At star connection the line currents are equal to the phase currents $I_L = I_{Ph}$

According to Kirchhoff's voltage law $\underline{U}_{AB} + \underline{U}_B - \underline{U}_A = 0$.

From here:

$$\underline{U}_{AB} = \underline{U}_A - \underline{U}_B; \ \underline{U}_{BC} = \underline{U}_B - \underline{U}_C; \ \underline{U}_{CA} = \underline{U}_C - \underline{U}_A. \quad (5.7)$$

The following phasor diagram (Fig. 5.6) corresponds to these relationships.

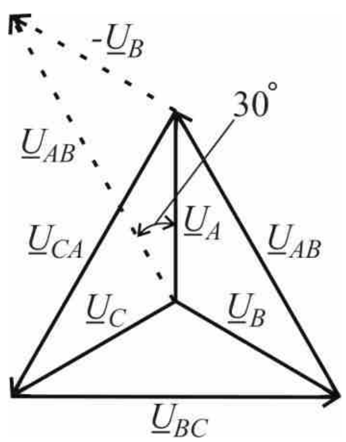


Figure 5.6

The system of voltage source is always symmetric. From the triangle shown in Fig. 5.6 we have

$$\frac{U_L}{2} = U_{Ph} \cos 30^{\circ} = U_{Ph} \frac{\sqrt{3}}{2},$$

From here we receive

$$U_L = \sqrt{3} U_{Ph}. \tag{5.8}$$

Thus, if the system of voltages is symmetric, then the line voltages are greater than the phase voltages by $\sqrt{3}$ times when the loads is star-connected.

$$\frac{U_L}{U_{Ph}} = \sqrt{3} = \frac{220}{127} = \frac{380}{220}.$$

According to Kirchhoff's current law we find the neutral conductor current

$$\underline{I}_N = \underline{I}_A + \underline{I}_B + \underline{I}_C, \tag{5.9}$$

and according to Ohm's law

$$\underline{I}_N = \frac{\underline{U}_N}{\underline{Z}_N} = \underline{U}_N \underline{Y}_N, \tag{5.10}$$

where: $\underline{U}_N$ is the neutral bias voltage, $\underline{Y}_n = \frac{1}{\underline{Z}_N}$ is the admittance of the neutral conductor.

The phases voltages across the loads U_a, U_b, U_c can be defined as follows from the of Kirchhoff's voltage law $\underline{U}_A = \underline{U}_a + \underline{U}_N$:

$$\underline{U}_a = \underline{U}_A - \underline{U}_N; \;\; \underline{U}_b = \underline{U}_B - \underline{U}_N; \;\; \underline{U}_c = \underline{U}_C - \underline{U}_N. \tag{5.11}$$

Then the currents are equal in the phases:

$$\underline{I}_A = \frac{\underline{U}_a}{\underline{Z}_a} = \underline{U}_a \underline{Y}_a = \left(\underline{U}_A - \underline{U}_N\right)\underline{Y}_a. \tag{5.12}$$

We will similarly write down for other phases:

$$\underline{I}_B = \left(\underline{U}_B - \underline{U}_N\right)\underline{Y}_b;$$

$$\underline{I}_C = \left(\underline{U}_C - \underline{U}_N\right)\underline{Y}_c.$$

Substituting these currents and (5.10) in the equation (5.9) it results

$$\underline{U}_N \underline{Y}_N = (\underline{U}_A - \underline{U}_N)\underline{Y}_a + (\underline{U}_B - \underline{U}_N)\underline{Y}_b + (\underline{U}_C - \underline{U}_N)\underline{Y}_c . \qquad (5.13)$$

From here definitively we obtain the expression for the neutral bias voltage:

$$\underline{U}_N = \frac{\underline{U}_A \underline{Y}_a + \underline{U}_B \underline{Y}_b + \underline{U}_C \underline{Y}_c}{\underline{Y}_a + \underline{Y}_b + \underline{Y}_c + \underline{Y}_N} . \qquad (5.14)$$

In the absence of the neutral conductor $Z_N = \infty \;\Rightarrow\; \underline{Y} \to 0$

From the equation (5.14) follows that if *the load is balanced*, i.e.

$$\underline{Y}_a = \underline{Y}_b = \underline{Y}_c = \underline{Y} ,$$

that $\underline{U}_N = 0$ and $\underline{I}_N = \underline{U}_N \underline{Y}_N = 0$; $\underline{I}_N = \underline{I}_A + \underline{I}_B + \underline{I}_C = 0$.

From expression (5.12) follows that phase voltage of loads will be equal to corresponding phase voltage of a source:

$$\underline{U}_a = \underline{U}_A ;\; \underline{U}_b = \underline{U}_B ;\; \underline{U}_c = \underline{U}_C . \qquad (5.15)$$

At *an unbalanced load and absence of the neutral conductor*, i.e.: $\underline{Y}_a \neq \underline{Y}_b \neq \underline{Y}_c$; and $\underline{U}_N \neq 0$.

If the load is *unbalanced and the neutral conductor is absent*, $\underline{U}_N \neq 0$ also the phase voltage across loads are not equal to the phase voltages of the source (see 5.11):

$$\underline{U}_a \neq \underline{U}_A ;\; \underline{U}_b \neq \underline{U}_B ;\; \underline{U}_c \neq \underline{U}_C .$$

At *an unbalanced load and presence of the neutral conductor*, equality of the phase voltage across loads and the source voltages (5.15), as

$Z_N \approx 0$, then $\underline{U}_N = \underline{I}_N \underline{Z}_N$, and $\underline{U}_a = \underline{U}_A$; $\underline{U}_b = \underline{U}_B$; $\underline{U}_c = \underline{U}_C$.

Thus, the neutral conductor provides equality of the phase voltage of a source and phase voltage across loads if the three-phase load is unbalanced.

Delta connection of the generator and the phase loads

At a delta connection of the source phases or the phase loads are connected in a closed loop (Fig. 5.7). Such closing of the generator three phases is not short circuit as between instantaneous EMF there are the phase difference angles of 120°.

The way of connection of the phase loads does not depend on a way of connection of source phases. Each phase of the load inserts between two line wires, therefore $U_L = U_{Ph}$.

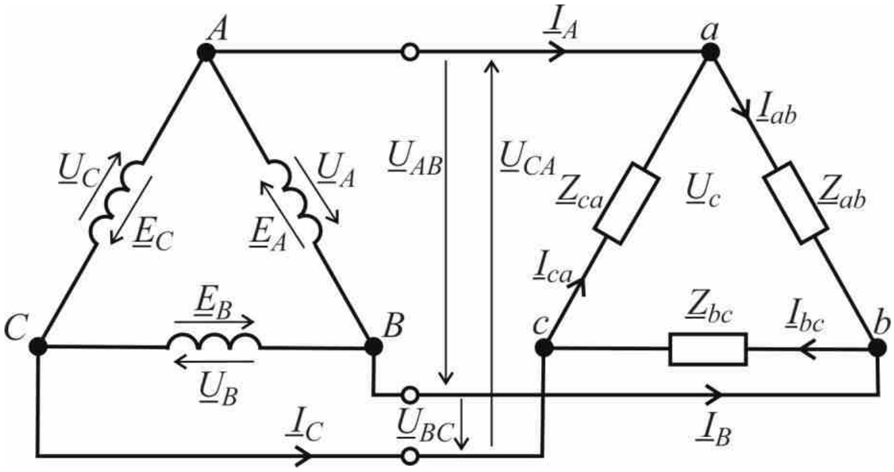


Figure 5.7

The phase currents can be found as follows:

$$\underline{I}_{ab} = \frac{\underline{U}_{AB}}{\underline{Z}_{ab}}; \quad \underline{I}_{bc} = \frac{\underline{U}_{BC}}{\underline{Z}_{bc}}; \quad \underline{I}_{ca} = \frac{\underline{U}_{CA}}{\underline{Z}_{ca}}. \qquad (5.16)$$

The line currents can be defined according to Kirchhoff's current law $\underline{I}_A + \underline{I}_{ca} = \underline{I}_{ab}$, from here:

$$\underline{I}_A = \underline{I}_{ab} - \underline{I}_{ca}; \underline{I}_B = \underline{I}_{bc} - \underline{I}_{ab}; \underline{I}_C = \underline{I}_{ca} - \underline{I}_{bc}. \qquad (5.17)$$

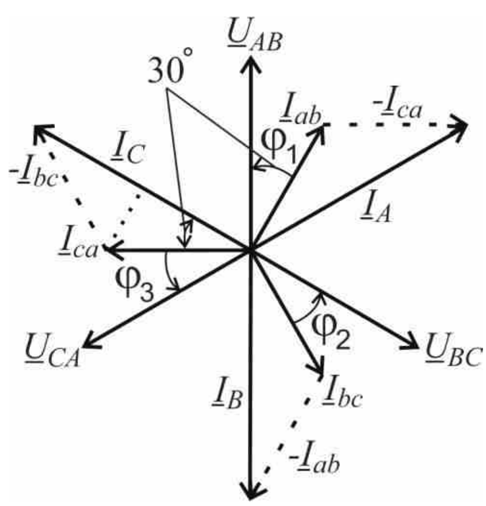


Figure 5.8

Since the angles φ_1, φ_2, φ_3 are given (depending on the load), the line current phasors can be drawn using the equation 5.17. The phasor diagram is shown in Fig. 5.8.

1) If the load is balanced, i.e. $\underline{Z}_{ab} = \underline{Z}_{bc} = \underline{Z}_{ca}$, $\underline{I}_{ab} = \underline{I}_{bc} = \underline{I}_{ca}$ and $\underline{I}_A = \underline{I}_B = \underline{I}_C$.

Let's consider one of triangles in Fig. 5.8. From here we will obtain

$$\frac{I_L}{2} = I_{Ph} \cos 30^{\circ}.$$

We'll receive at a balanced load $I_L = \sqrt{3} I_{Ph}$.

At a balanced load a line current is more than a phase current in $\sqrt{3}$ *times.*

2) If the load is non-balanced, this condition is not carried out, however currents in phases will not depend on impedance of other phases. Therefore, a delta connection is often applied at unbalanced load.

Power of a three-phase circuit

Generally, the active power of a three-phase circuit is equal to the sum of the power consumed by each phase

$$P = P_A + P_B + P_C. \quad (5.18)$$

At a balanced load $P = 3P_{Ph}$. As $P_{\mathrm{Ph}} = U_{Ph} I_{Ph} \cos \varphi_{Ph}$,

where φ_{Ph} is a phase difference angle between a phase voltage and phase current.

At a star connection: $U_{Ph} = \frac{U_L}{\sqrt{3}}$; $I_L = I_{Ph}$, then

$$P = 3U_{\mathrm{Ph}} I_{Ph} \cos\varphi = 3\frac{U_L}{\sqrt{3}} I_L \cos\varphi = \sqrt{3} U_L I_L \cos\varphi.$$

At a delta connection : $I_{Ph} = \frac{I_L}{\sqrt{3}}$; $U_L = U_{Ph}$, then

$$P = 3U_{Ph} I_{Ph} \cos\varphi = 3\frac{I_L}{\sqrt{3}} U_L \cos\varphi = \sqrt{3} U_L I_L \cos\varphi.$$

Therefore, without dependence from a way of connection, the active powers of a circuit with a balanced load are equal to

$$P = 3U_{Ph} I_{Ph} \cos\varphi = \sqrt{3} U_L I_L \cos\varphi. \quad (5.19)$$

It is similarly possible to write down for the reactive power and the apparent power accordingly:

$$Q = 3U_{Ph}I_{Ph}\sin\varphi = \sqrt{3}U_L I_L \sin\varphi; \tag{5.20}$$

$$S = 3U_{Ph}I_{Ph} = \sqrt{3}U_L I_L. \tag{5.21}$$

Test questions

1. What is the angle between the axes of windings in the stator of a synchronous generator?

2. What is a symmetric EMF system?

3. What is an asymmetric or an unbalanced load in a three- phase circuit?

4. What connection of the phases do you know in a three-phase system?

5. What is a line voltage, current?

6. What is a phase voltage, current?

7. What is a neutral bias voltage?

8. What is the ratio between a line voltage and a phase voltage when the load is connected in star?

9. What is the ratio between a line voltage and a phase voltage when the load is connected in delta?

10. What is the ratio between a line current and a phase current when the load is connected in star?

11. What is the ratio between a line current and a phase current when the load is connected in delta?

12. What are formulae for active, reactive, apparent powers in a three-phase circuit?

LECTURE 6

TRANSIENTS IN LINEAR ELECTRIC CIRCUITS

Electromagnetic processes appearing in an electric circuit at transition from one steady-state condition to another are called *transients or transient response*. Generally speaking, in science a *transient response* is the system's response to changes in parameters. In circuits with only resistive elements transients don't appear, in them the stationary operation condition is established instantly.

Inductive and capacitive elements are inertial, i.e. variation of magnetic and electric fields energy can't physically occur instantaneously.

Laws of switching

Changes of parameters of electric circuits causing transients are called *switching*. Accumulation of energy of a magnetic field $W_m = \frac{Li^2}{2}$ in an inductor and energy of an electric field $W_e = \frac{Cu^2}{2}$ in a capacitor takes some time, because increase of a current i in an inductor is interfered by EMF of self-induction $e_L = -L\frac{d}{dt}$, and the charge of a capacitor which is accompanied by voltage u increase, is interfered by a field of accumulated electric charges.

These positions are formulated in the form of two *laws of switching*:

1) *in a branch with an inductive element, the current cannot change abruptly, i.e. a current at the last moment before switching* $i_L(0-)$ *and a current immediately after switching* $i_L(0+)$ *are equal to each other*:

$$i_L(0-) = i_L(0+), \tag{6.1}$$

$i_L(t)$ – a continuous function.

In other words:

The current in an inductor (coil) cannot change immediately (with discontinuity of the derivative).

$i_L(-0)=i_L(+0)$ at $t=0$, at that t = – 0 и t = +0 is the same point in time, but before and after switching.

It is known that an inductive element stores magnetic energy as $W_m=\dfrac{LI^2}{2}$, while the instantaneous power of such a process $p_m=\dfrac{\partial W_m}{\partial t}=Li\dfrac{di}{dt}$. Assuming that the current may change abruptly, i.e. $\dfrac{di}{dt}\to\infty$, it means that $p_m\to\infty$. However, in nature there are no sources of an infinite power, so the current spike in the inductive element is impossible;

2) *voltage across a capacitive element cannot change abruptly, i.e. during the first moment of transient* $u_C(0+)$ *it keeps the value which had prior to the beginning of transient* $u_C(0-)$:

$$u_C(0-)=u_C(0+), \tag{6.2}$$

$u_C(t)$ – a continuous function.

In other words:

The voltage across a capacitor can't change instantly $u_C(-0)=u_C(+0)$ at $t=0$.

A capacitive element stores electric energy $W_e=\dfrac{CU_C^2}{2}$ consuming instantaneous power p_e. If the voltage is changed instantaneously $p_e=\dfrac{\partial W_e}{\partial t}=Cu_C\dfrac{du_C}{dt}$, i.e. $\dfrac{du_C}{dt}\to\infty$, it would mean $p_e\to\infty$ that it is impossible.

The general principles of the transient analysis

Transients in linear electric circuits are described by linear differential equations compiled on the basis of Ohm's law and Kirchhoff's laws for in instantaneous values of electric quantities, applied to any state of a circuit.

The current and voltage across *R, L, C* elements are related by the expressions:

$$u_R=i\cdot R;\;\; u_L=L\frac{di}{dt};\;\; u_C=\frac{1}{C}\int idt \;\Leftrightarrow\; i=C\frac{du_C}{dt}. \tag{6.3}$$

The current or voltage is defined by the solution of a differential equation with an absolute term.

The solution of a differential equation is the sum of the particular solution of this equation and the general solution of the equation without an absolute term.

The desired value of a current (or voltage) according to the principle of superposition is conveniently presented as the sum of two components: steady-state and free, i.e.

$$i(t) = i_{ss} + i_f \,. \qquad (6.4)$$

In the steady-state condition which theoretically comes at $t \to \infty$, and practically at reduction i_f to zero, a resultant current $i = i_{ss}$. The steady-state value of a current i_{ss}, called a forced component, is defined by the particular solution of a differential equation, i.e. the solution with an absolute term.

The free component of a current i_f is defined by the general solution of a differential equation without an absolute term and, it's equal to 0.

Connection of an inductor (coil) to a direct current (DC) voltage source

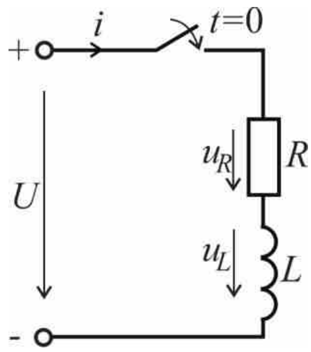


Figure 6.1

After a key closing in the circuit, as shown in Fig. 6.1, according to Kirchhoff's voltage law, we'll obtain

$$u_R + u_L - U = 0 \,. \qquad (6.5)$$

The solution of the differential equation looks like

$$i(t) = i_{ss} + i_f \,. \qquad (6.6)$$

The steady-state value of the current i_{ss} is as the particular solution of the equation (6.5)

$$i_{ss} = \frac{U}{R} = I \tag{6.7}$$

For the free component of the current i_f a general homogeneous differential equation of the first order is valid

$$L\frac{di_f}{dt} + R \cdot i_f = 0. \tag{6.8}$$

The general solution of the equation (6.8) is an exponential function,

$$i_f = Ae^{pt}, \tag{6.9}$$

where A is a constant of integration; p is a root of the characteristic equation

$L \cdot p + R = 0$, whence

$$p = -\frac{R}{L}. \tag{6.10}$$

Substituting (6.7) and (6.9) in the equation (6.6) we obtain

$$i(t) = i_{ss} + i_f = \frac{U}{R} + Ae^{-\frac{R}{L}t}. \tag{6.11}$$

The constant A we find from the initial condition at $t=0$.

Before closing of the circuit $i(0-) = 0$

After closing of the circuit from the equation $i_L(0+) = \frac{U}{R} + A$.

As $i_L(0-) = 0$, that $0 = \frac{U}{R} + A$, whence we find

$$A = -\frac{U}{R}. \tag{6.12}$$

Substituting the equation (6.12) in (6.11) we obtain

$$i = \frac{U}{R} - \frac{U}{R}e^{-\frac{R}{L}t} = \frac{U}{R}\left(1 - e^{-\frac{R}{L}t}\right) = \frac{U}{R}\left(1 - e^{-\frac{t}{\tau}}\right), \tag{6.13}$$

where $\tau = \frac{L}{R}$ is the time constant of the circuit.

The larger τ, the current more slowly changes. τ is a measure electromagnetic inertia of an electric circuit. It is equal to the time interval during which the free component of the current i_f decreases in *e* (*Euler number*) times.

τ is equal to a time interval for which the current reaches 0,632 steady-states values. Practically a transient comes to the end through *t* = 4....5τ and the current reaches $i = i_{ss} = I = \frac{U}{R}$ (Fig. 6.2).

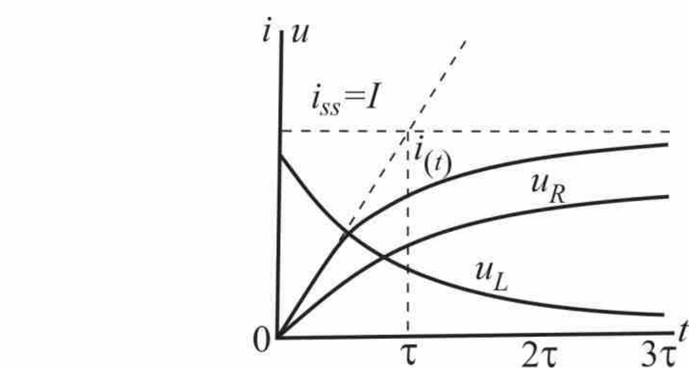


Figure 6.2

The voltages equations are:

$$u_R = R \cdot i = U\left(1 - e^{-\frac{R}{L}t}\right); \tag{6.14}$$

$$u_L = L\frac{di}{dt} = L\frac{U}{L}e^{-\frac{R}{L}t} = Ue^{-\frac{R}{L}t}, \tag{6.15}$$

as $\frac{di}{dt} = +\frac{U}{R}\frac{R}{L}e^{-\frac{R}{L}t} = -\frac{U}{L}e^{-\frac{R}{L}t}$.

An inductor switching off in the circuit with a DC voltage source

Switching-off of the inductor from a source of constant voltage (Fig. 6.3), as a result of occurrence EMF of the self-induction interfering reduction of a current, it can be accompanied by voltage substantial increase across the circuit parts. The arc discharge (flash) between disconnected contacts is possible.

That the arc discharge wouldn't appear, it is necessary in parallel for the coil to connect a discharge resistor R_p as shown in Fig. 6.3.

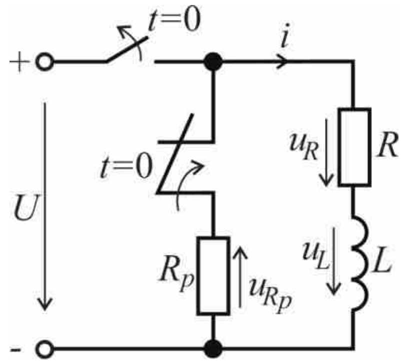


Figure 6.3

After simultaneous disconnection of one key and switching on of another key according to Kirchhoff's voltage law of we can write down

$$u_R + u_{Rp} + u_L = 0.$$

After substitution it is obtained

$$Ri + R_p i + L\frac{di}{dt} = 0. \qquad (6.16)$$

Let's rewrite $L\frac{di}{dt} + R_e i = 0$, where the equivalent resistance of the circuit $R_e = R + R_p$.

From the equation (6.16) it's obvious that $i_{ss} = 0$. Therefore,

$$i = i_f = Ae^{-\frac{t}{\tau}}, \qquad (6.17)$$

where $\tau = \frac{L}{R_e} = \frac{L}{R + R_p}$.

We need to find a constant A. Before the key disconnection $i_L(0-) = \frac{U}{R}$, after switching of keys from (6.17) $i_L(0+) = A$.

According to the first law of switching: $i_L(0-) = i_L(0+) \;\Rightarrow\; A = \frac{U}{R}$.

We substitute in the equation (6.17) and obtain

$$i = \frac{U}{R} e^{-\frac{t}{\tau}}. \qquad (6.18)$$

Transient EMF of self-induction in the coil:

$$e_L = -u_L = -L\frac{di}{dt} = -L\frac{d}{dt}\left(\frac{U}{R} e^{-\frac{R+R_p}{L}t}\right) = L\frac{U}{R}\frac{R+R_p}{L} e^{-\frac{R+R_p}{L}t} =$$

$$= U\frac{R+R_p}{R} e^{-\frac{t}{\tau}} = \left(1 + \frac{R_p}{R}\right) U e^{-\frac{t}{\tau}}. \qquad (6.19)$$

At the moment t =0 EMF instantly increases from 0 to the maximum value

$$e_{L\max} = \left(1 + \frac{R_p}{R}\right) U . \qquad (6.20)$$

CONCLUSIONS:

1) if R_p= 0 process proceeds until energy of the coil $W_m = \frac{Li^2}{2}$ doesn't turn to heat in resistance R.
2) if a resistance of the resistor R_p is big (for example, air interval), EMF of self-induction reaches a great value that leads to a breakdown of an air interval; there is an electric arch across contacts.
3) we must choose R_p = (4... 8) R in practice.

Transient curves of the current are shown in Fig. 6.4.

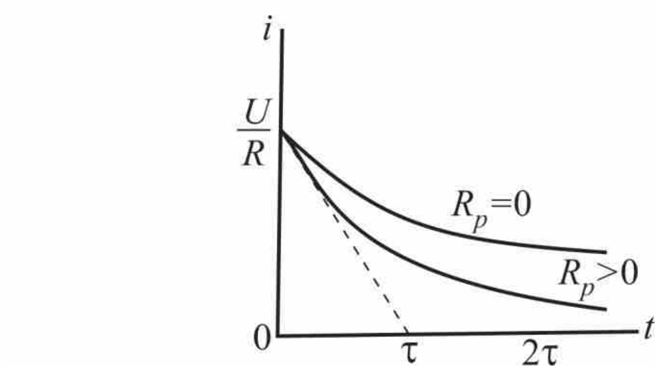


Figure 6.4

Capacitor connection to a DC voltage source (charging a capacitor)

On a capacitor plates (Fig.6.5) electric charges starts collecting with a simultaneous increase of voltage u_C across them till the moment when balance $u_C = U$ reaches equilibrium.

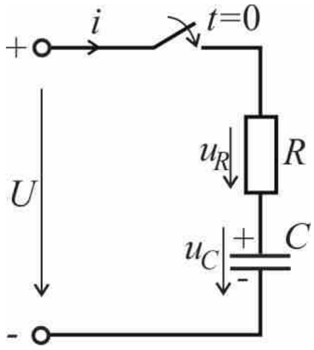


Figure 6.5

According to Kirchhoff's voltage law $u_R + u_C = U$ or $Ri + u_C = U$, but as $i = C\dfrac{du_C}{dt}$, then

$$RC\frac{du_C}{dt} + u_C = U. \tag{6.21}$$

The solution of the non-homogeneous differential equation

$$u_C = u_{Css} + u_{Cf} \tag{6.22}$$

When $u_{Css} = U$, the charging of capacitor will stop at the same time.

For a free component of the voltage we will write down the homogeneous differential equation (without the absolute term U)

$$RC\frac{du_{Cf}}{dt} + u_{Cf} = 0. \qquad (6.23)$$

This differential equation of the first order has the general solution $u_{Cf} = Ae^{pt}$ and the characteristic equation $RCp + 1 = 0$, whence the root of the characteristic equation

$$p = -\frac{1}{RC}. \qquad (6.24)$$

Substituting in the equation (6.23) its components, we obtain

$$u_C = U + Ae^{pt}. \qquad (6.25)$$

For finding of a constant A the 2nd law of switching is used. Before the key closing $u_C(0-) = 0$; after the key closing (from the equation (6.25)) $u_C(0+) = U + A$.

As $u_C(0-) = u_C(0+) \;\Rightarrow\; U + A \;\Rightarrow\; A = -U$.

Let's definitively write down

$$u_C = U - Ue^{-\frac{t}{RC}} = U\left(1 - e^{-\frac{t}{\tau}}\right), \qquad (6.26)$$

where $\tau = RC$ – time constant defines speed of transient.

Let's define the current i

$$i = C\frac{du_C}{dt} = C\frac{d}{dt}\left(U - Ue^{-\frac{t}{RC}}\right) = --CU\frac{1}{RC}e^{-\frac{t}{RC}} = \frac{U}{R}e^{-\frac{t}{\tau}}. \qquad (6.27)$$

And voltage is equal to

$$u_R = Ri = R\frac{U}{R}e^{-\frac{t}{\tau}} = Ue^{-\frac{t}{\tau}}. \qquad (6.28)$$

Transient curves of the voltages and current are shown in Fig. 6.6. We can see growth of the voltage u_C and decay of the voltage u_R and the current i.

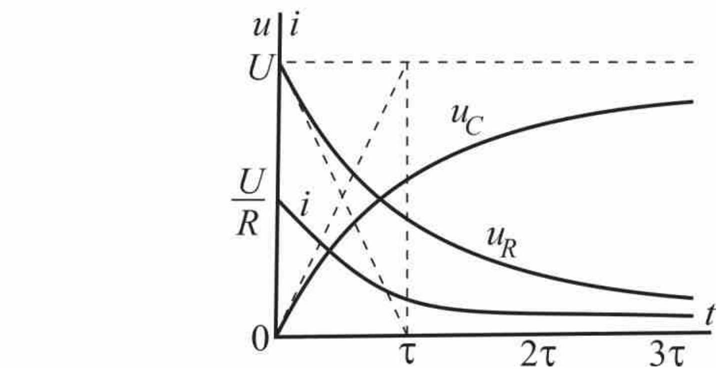


Figure 6.6

At the first moment of time the current $i(0+)=\dfrac{U}{R}$ and the capacitor is as though closed in a short circuit, i.e. the current i is very high at a small resistance. Thus, the resistor limits a current surge, but charging time increases.

The capacitor discharge across resistor (discharging a capacitor)

After short circuit of the capacitor, charged to the voltage $u_C = U$, is across the resistor, in the circuit (Fig. 6.7) there is a discharge current

$$i = -C\frac{du_C}{dt}, \tag{6.29}$$

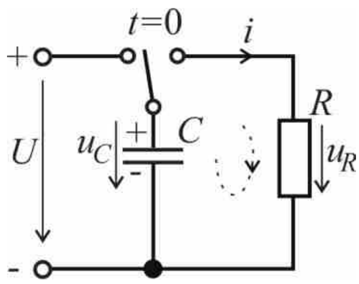


Figure 6.7

where a minus the sign specifies that the discharge current is in the opposite direction to the voltage u_C.

According to Kirchhoff ‘s voltage law:

$$u_R - u_C = 0 \qquad \text{or} \qquad Ri - u_C = 0. \tag{6.30}$$

Substituting in this equation (6.29), we obtain

$$RC\frac{du_C}{dt} + u_C = 0. \tag{6.31}$$

As the equation (6.31) is homogeneous, i.e. 0 is in the right part, $u_{C\text{ss}} = 0$

$$\text{and } u_C = u_{Cf} = Ae^{-\frac{t}{RC}} \qquad (6.32)$$

Let's find the constant A.

Before switching: $u_C(0-) = U$; after switching (from the equation (6.32) at $t = 0$, $u_C(0+) = A$, as $u_C(0-) = u_c(0+) \Rightarrow A = U$.

We substitute it in the equation (6.32) $u_C = Ue^{-\frac{t}{RC}} = Ue^{-\frac{t}{\tau}}$. (6.33)

We'll find the current as

$$i = C\frac{du_C}{dt} = CU\left(-\frac{1}{RC}\right)e^{-\frac{t}{RC}} = -\frac{U}{R}e^{-\frac{t}{\tau}}. \qquad (6.34)$$

Transient curves of the voltage and current are shown in Fig. 6.6. We can see decay of the voltage u_C and the current i.

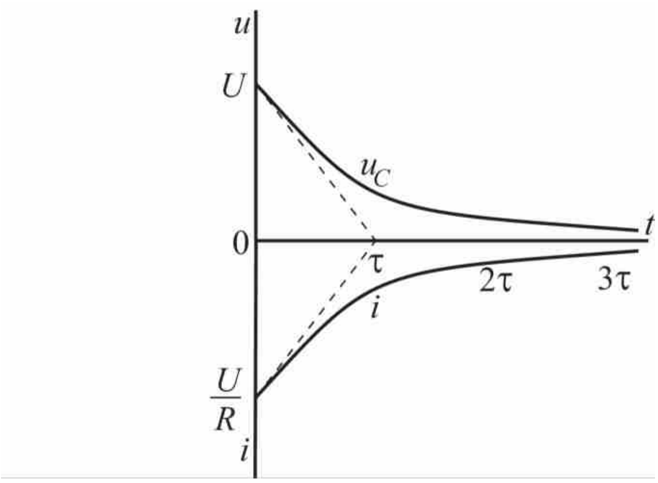


Figure 6.8

Connection of an inductor (coil) to a sinusoidal EMF source

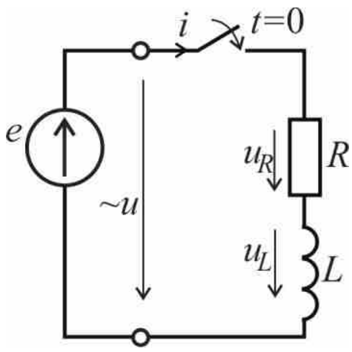


Figure 6.9

The voltage of a source u (Fig. 6.9) is

$e = u = U_m \sin(\omega t + \psi_u)$, where ψ_u – the initial phase of the source EMF.

The steady-state current will be equal $i_{ss} = I_m \sin(\omega t + \psi_u - \varphi)$,

where $I_m = \dfrac{U_m}{\sqrt{R^2 + X_L^2}}$ – amplitude of the current i;

the reactance of the circuit and the phase difference angle respectively:

$$X_L = \omega L = 2\pi f L\,; \qquad \varphi = \mathrm{arctg}\frac{X_L}{R}.$$

According to Kirchhoff's voltage law:

$u_L + u_R = e$ or $L\dfrac{di}{dt} + Ri = e$ is a differential equation of 1st order, therefore a free component of the current is equal to $i_f = Ae^{pt}$, where $p = -\dfrac{R}{L}$ – the root of the characteristic equation.

The solution of a differential equation

$$i = i_{ss} + i_f = I_m \sin(\omega t + \psi_u - \varphi) + Ae^{-\frac{R}{L}t} \qquad (6.35)$$

Before the key closing $i(0-) = 0$; after the key closing (from the equation 6.35) $i(0+) = I_m \sin(\psi_u - \varphi) + A$. According to the 1st law of switching $i(0-) = i(0+)$ it is obtained:

$I_m \sin(\psi_u - \varphi) + A = 0$, whence, we find $A = -I_m \sin(\psi_u - \varphi)$.

Substituting this value in (6.35) we obtain the general solution

$$i = I_m \sin(\omega t + \psi_u - \varphi) - I_m \sin(\psi_u - \varphi) e^{-\frac{R}{L}t}. \qquad (6.36)$$

Let's graph this function. It is shown in Fig. 6.10.

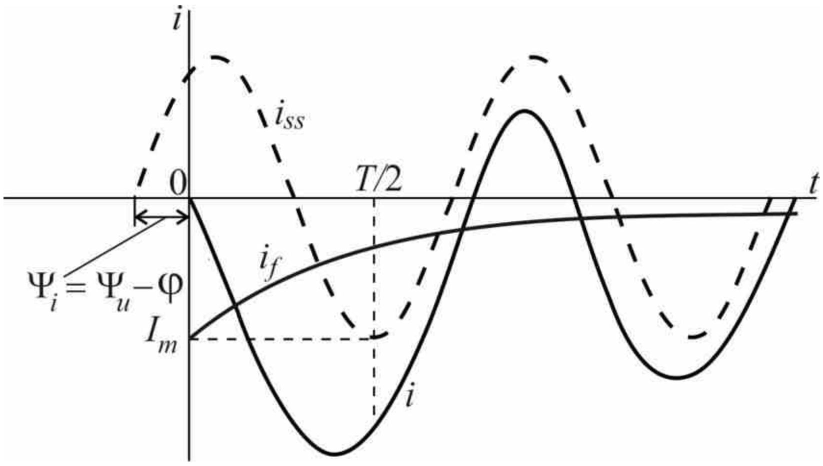


Figure 6.10

CONCLUSIONS:

1) if at the moment of switching (t=0) $\psi_u = \varphi, i_f = 0$ also transient is not present right after switching the sinusoidal current is steady-state;

2) if $\psi_u = \varphi + \frac{\pi}{2}$ during the moment t = T/2 the peak value of the current can reach double maximum value $i \approx 2I_m$.

Test questions

1. *What is a transient?*
2. *State the 1st switching law.*
3. *State the 2nd switching law.*
4. *Prove the 1st switching law.*
5. *Prove the 2nd switching law.*
6. *What is a steady-state component of the electrical quantity value?*
7. *What is a free value of the electrical quantity value?*
8. *What is the time constant of a transient?*
9. *What is a constant of integration of a differential equation solution?*
10. *What is a transient characterized by?*

SECTION
II

MAGNETIC CIRCUITS AND ELECTRIC DEVICES

LECTURE 7

MAGNETIC CIRCUITS. QUANTITIES AND LAWS CHARACTERIZING MAGNETIC FIELDS IN MAGNETIC CIRCUITS

Magnetic field and its demonstration

A magnetic field is a vector field that describes the magnetic influence on moving electric charges, electric currents, and magnetic materials.

The magnetic field proves as follows:

1) in a conductor which moves in a steady-state magnetic (magnetostatic) field, it is induced EMF;
2) in a motionless conductor which is in a variable magnetic field, it is induced EMF;
3) a mechanical force operates on a conductor, on which the current flows and which is in the magnetic field.

The parameters characterizing the magnetic field

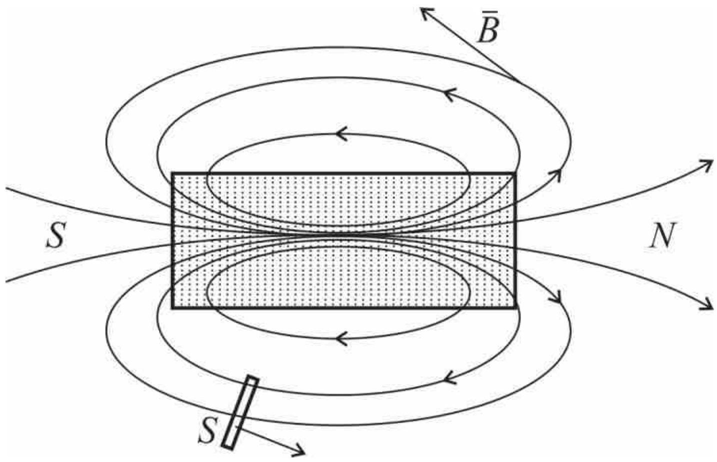


Figure 7.1

A magnetic flux Φ is characterized by number of the lines of force penetrating a surface by area *S*. The magnetic field can be represented the power lines directed from the northern magnet pole *N* to the southern pole *S*.

$$\Phi = BS\cos\alpha, \tag{7.1}$$

where α is an angle between a normal to a platform and the direction of the field lines (force lines). A magnetic flux is measured in weber [Φ] = [Wb] = [V·s].

Magnetic field induction $\overline{B}$ characterizes intensity of a magnetic field in the set point of space. It is a vector quantity. Its direction coincides with a tangent to the field lines.

$$B = \frac{\Delta\Phi}{\Delta S}. \tag{7.2}$$

If the magnetic field is uniform $B = \frac{\Phi}{S}$. [B] = [Wb/m^2] = [T] (tesla).

The flux of a vector of magnetic field induction through the closed surface is equal to zero

$$\Phi = \oint_s \overline{B} d\overline{s} = 0. \tag{7.3}$$

The lines of magnetic force are always closed. It is a principle of continuity of the lines of force.

Magnetic field strength (*intensity*) $\overline{H}$ is a vector quantity which coincides with the direction of induction and characterizes intensity of the magnetic field in vacuum (in the absence of magnetic substances). It is measured in Ampere per meter[H] = [A/m].

$$\overline{B} = \mu_a \overline{H}, \tag{7.4}$$

where μ_a – absolute permeability of environment;

$\mu_r = \mu_a / \mu_0$ – relative permeability;

$\mu_0 = 4\ \pi \cdot 10^{-7}$ H/m (henry per meter) – permeability of vacuum is equal to absolute permeability in vacuum.

In 1831 Faraday disclosed law of (electromagnetic) induction or simply **Faraday's law**:

electromagnetic induction is called the phenomenon of EMF excitation in a loop at change of the magnetic flux linked to it. An induced EMF is equal to speed of change of the flux linked to a loop

$$e = -\frac{d\Phi}{dt}. \tag{7.5}$$

The sign "minus" expresses ***Lenz's rule:*** *the current, created in the closed loop by an induced EMF, always has such a direction that the magnetic flux created by the current counteracts change of the external field magnetic flux, that caused the current.*

As $L = \dfrac{\Phi}{i}$, then $e = \dfrac{d(Li)}{dt} = -L\dfrac{di}{dt}$. (7.6)

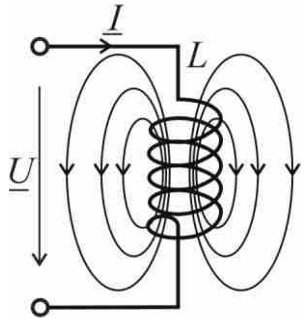


Figure 7.2

The EMF, which is induced in the coil, is equal to the sum of an EMF of each turn

$$e = \sum_{k=1}^{w} e_k ,$$

where w is a number of turns in the coil.

$$e = \sum_{k=1}^{w} e_k = -\frac{d}{dt}\left(\Phi_1 + \Phi_2 + ... + \Phi_w\right), \tag{7.7}$$

where Φ_1, Φ_2, …, Φ_w are fluxes which cover, accordingly, the first, the second and w – a number of turns in the coil. $\Psi = \left(\Phi_1 + \Phi_2 + ... + \Phi_w\right)$ – the full magnetic flux is the protoflux (linked flux) of the coil.

Then for the coil

$$e = -\frac{d\Psi}{dt}. \tag{7.8}$$

If each turn of the coil is captured by the same flux, then $\Psi = w\Phi$ and

$$e = -w\frac{d\Phi}{dt}. \tag{7.9}$$

If a magnetic field is created by the current of the same coil, then such an EMF created by this field is called *self-induction* EMF.

If the magnetic field is created by a current of another coil such an EMF is called EMF *of mutual induction*. (Fig.7.3)

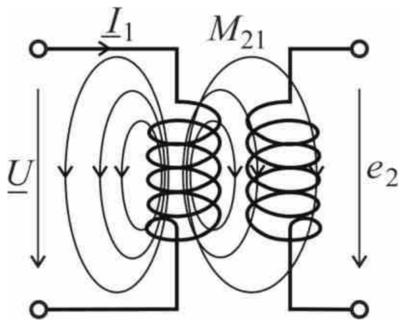


Figure 7.3

$$e_2 = -M_{21}\frac{di_1}{dt}, \qquad (7.10)$$

where $M_{21} = \frac{\Psi_2}{i_1}$ is mutual induction.

If a conductor moves in a steady-state magnetic field, the induced EMF is equal to

$$E = BlV\sin\alpha, \qquad (7.11)$$

where l – active length of a conductor;

V – speed of moving of a conductor;

B – induction of a magnetic field;

α – an angle between the direction of the lines of a magnetic force and the direction of moving of a conductor (Fig. 7.4).

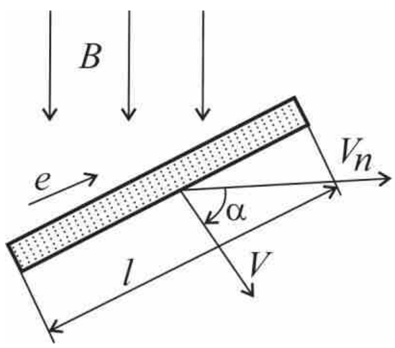


Figure 7.4

By the right-hand rule the EMF direction is determined as shown in Fig. 7.4. The thumb is the moving direction.

If the conductor with the current I is in a magnetic field with induction B, Ampère force operates on a conductor as shown in Fig. 7.5.

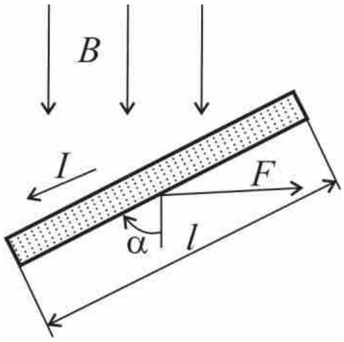


Figure 7.5

Ampère law

$$F = BIl\sin\alpha, \tag{7.12}$$

where α is an angle between the lines of force and the conductor direction of movement. By the left-hand rule Ampère force is determined (the thumb is the force F) as shown in Fig. 7.5.

Magnetic properties of materials

In electrical engineering all materials are divided on not magnetic and magnetic. *Non-magnetic materials* (para- and diamagnetics): copper, aluminium, insulators, air, water, etc. have relative permeability $\mu_r \approx 1$. *Magnetic materials* (ferromagnetics) have $\mu_r >> 1$: iron, nickel, cobalt, alloys – steel, cast iron, etc.

Feature of ferromagnetic materials is that *relative permeability* $\mu_r \neq$ const, and depends on magnetic field strength (intensity) H.

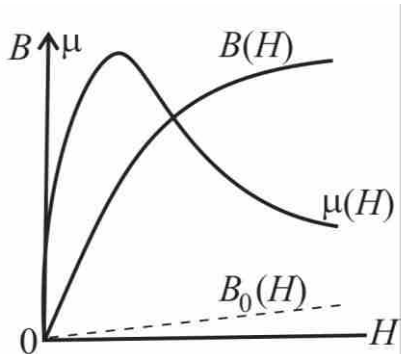


Figure 7.6

Ferromagnetic dependences $B(H)$, $\mu(H)$ are non-linear.

$B(H)$ – magnetization curve.

In vacuum $B = \mu_0 H$,

where $\mu_0 = 4\pi\times10^{-7}$ *H/m (henry per metre)* $\approx 1{,}2566\cdot10^{-6}$ *H/m is absolute permeability or magnetic constant* or *permeability of vacuum*

At cyclic magnetization reversal the *hysteresis loop* is formed as shown in Fig. 7.7, where: B_r – *residual magnetic induction*, H_c -– *coercivity*.

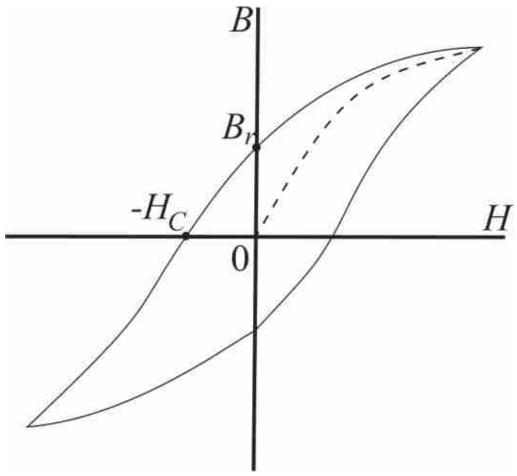


Figure 7.7

Ferromagnetic materials are divided to *soft magnetic* materials ($H_c < 4$ kA/m) and *high coercivity* (*hard-magnetic*) materials. At *soft magnetic* materials have a narrow hysteresis loop. They are used for cores of electrotechnical equipment. The area of a hysteresis loop characterizes losses on hysteresis. *High coercivity* have a wide loop of a hysteresis (are used for constant magnets, systems of data carriers – computer disks).

Ampère 's circuital law

Ampere's circuital law state a relationship between of the magnetic field intensity and the current by which this field is created.

The line integral from a vector of magnetic field strength (*intensity*) *along any closed loop is equal to the total current covering the given loop.*

$$\oint \overline{H} d\bar{l} = \sum I_k \, . \qquad (7.13)$$

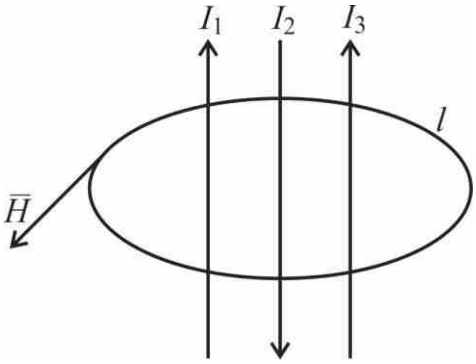


Figure 7.8

The total current is an algebraic sum of all the currents of the loop. In space around these conductors with a current the magnetic field is formed. According to the total current law

$$\oint \overline{H} d\bar{l} = I_1 - I_2 + I_3. \qquad (7.14)$$

The currents, which at the chosen direction of path tracing coincide with a direction of *a right-handed screw*, are considered as the positive.

For a multi-turn coil (Fig. 7.9) the integration loop is captured by a current in *w* times

$$\oint \overline{H} d\bar{l} = wI. \qquad (7.15)$$

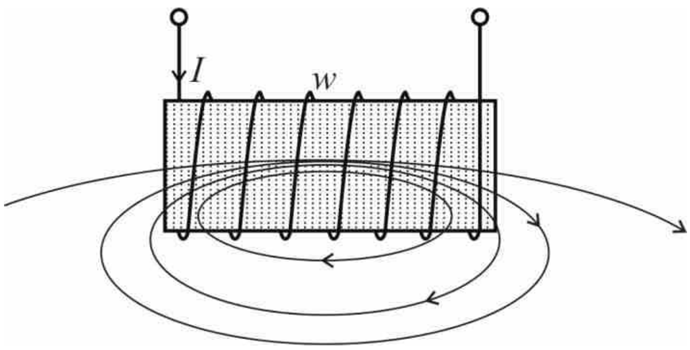


Figure 7.9

The quantity $F = wI$ is called a *magnetizing force* or *magnetomotive force* or MMF.

At practical calculations the integration loop can be divided into a number of parts so that magnetic field intensity throughout a part remained invariable and its direction coincided with a direction *dl*. In this case the integral changes for the sum:

$$\oint \overline{H} d\bar{l} = \sum_{k=1}^{n} H_k l_k \text{ and } \sum_{k=1}^{n} H_k l_k = \sum_{k=1}^{m} I_k w_k \,. \tag{7.16}$$

Classification of magnetic circuits

A magnetic circuit is a set of magnetizing forces, ferromagnetic parts and other environments on which the magnetic flux becomes isolated.

Magnetic circuits can be divided: *simple and complex* (one or the several MMF); *uniform and non-uniform* (magnetic field strength is constant or changeable); *multi-path and single-path (*the flux branches or not), etc.

Let's consider the simple, single-path magnetic circuit with constant MMF.

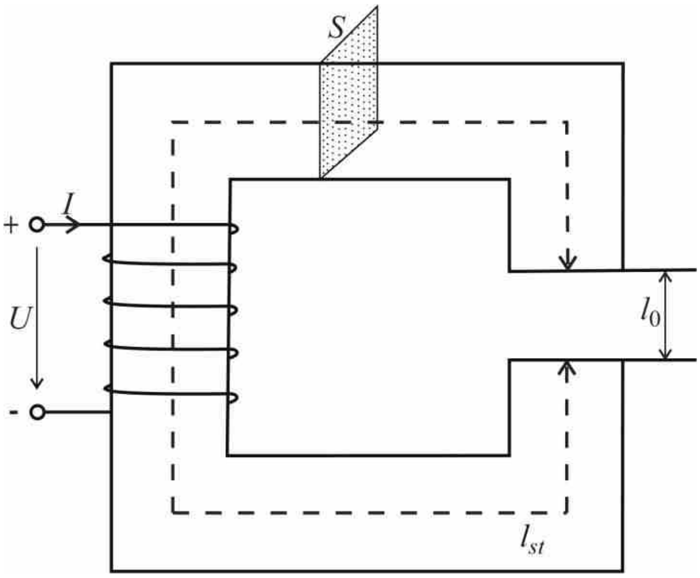


Figure 7.10

l_{st} – length of the lines of force throughout all parts in steel;

l_0 – length of the air gap.

For the given magnetic circuit, we can write down

$$H_{st} l_{st} + H_0 l_0 = Iw \,. \tag{7.17}$$

But $H = \dfrac{B}{\mu_a}$; $\Phi = BS$, therefore, $B = \dfrac{\Phi}{S}$. From here $H = \dfrac{\Phi}{\mu_a S}$;

Then we write down

$$\frac{\Phi l_{st}}{\mu_{st} S_{st}} + \frac{\Phi l_0}{\mu_0 S_0} = Iw, \tag{7.18}$$

and Ohm's law is for a magnetic circuit

$$\Phi = \frac{Iw}{\frac{l_{st}}{\mu_{st} S_{st}} + \frac{l_0}{\mu_0 S_0}} = \frac{Iw}{\sum R_M}. \qquad (7.19)$$

$R_{M\,st} = \frac{l_{st}}{\mu_{st} S_{st}}$ – reluctance of a steel part (to compare with $R = \rho \frac{l}{S}$);

$R_{M\,0} = \frac{l_0}{\mu_0 S_0}$ – reluctance of the air gap.

As $\mu_{cm} >> \mu_0$, $R_{M\,st} << R_{M\,0}$.

Therefore, a ferromagnetic material (a core with a small magnetic resistance) is introduced into a magnetic circuit, that allows to obtain a large magnetic flux at the same magnetizing force.

Table 7. 1 Analogy between electric and magnetic circuits

Electric quantities		Magnetic quantities	
Current	I	Flux	Φ
EMF	E	MMF	F
Resistance	$R = \rho \frac{l}{S}$	Reluctance	$R_M = \frac{l}{\mu_a S}$
Voltage	$U = I \cdot R$	Voltage	$U_M = H_k l_k = \Phi R_{M_k}$
Conductor		Ferromagnetic	
Insulator		Non- magnetic substance	
Conductivity	$\gamma = \frac{1}{\rho}$	Magnetic permeability	μ_a

By analogy it is possible to write down Kirchhoff's laws for magnetic circuits.

1st Kirchhoff's law: *the algebraic sum of magnetic fluxes of branches of a multipath magnetic circuit in a node is equal to zero*

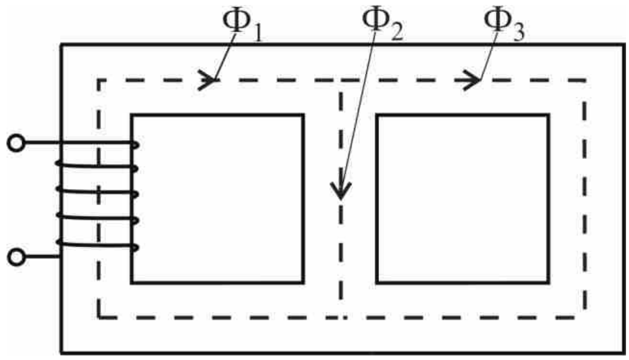


Figure 7.11

$$\sum_k \Phi_k = 0. \qquad (7.20)$$

2nd Kirchhoff's law: *the algebraic of MMF of a single-path non-uniform magnetic circuit is equal to the algebraic sum of magnetic voltages on its separate parts.*

$$\sum_k U_{M_k} = \sum_k F_k\ . \qquad (7.21)$$

Principle of calculation of magnetic circuits of a direct current

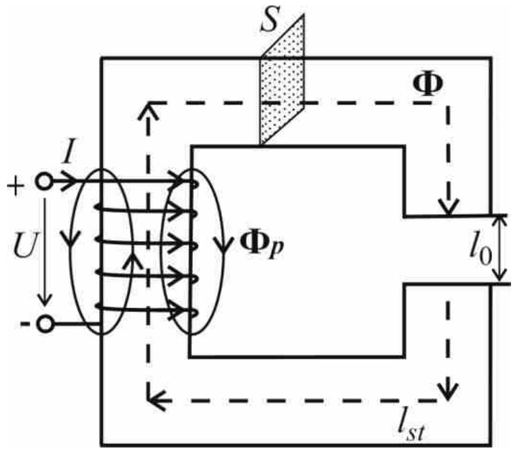


Figure 7.12

Φ_p – a leakage flux (it is usually small).

It is set: a flux Φ, the sizes of a magnetic circuit, a core material, a steel mark, a curve of magnetization B (H).

PROBLEM: to find $F = wI$ – the magnetomotive force of a coil, which is necessary for creation of the magnetic flux Φ.

Sequence of calculation:

1. The circuit is divided into parts so that an induction B and of a magnetic field intensity H throughout a part remain invariable; l_k and S_k are defined by the constructive sizes of magnetic circuits; it is supposed that flux Φ on each part is identical;

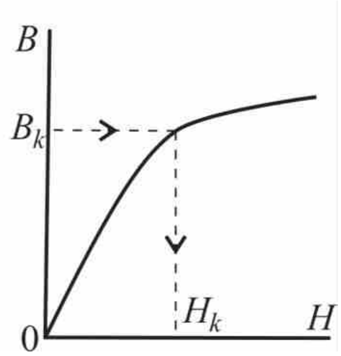


Figure 7.13

2. If we know a magnetic flux Φ, we'll define an induction B_k across each site $B_k = \frac{\Phi}{S_k}$.

Then, knowing B_k on a magnetization curve it is defined H_k as shown in Fig.7.13.

3. Knowing H_k, according to Ampere's circuital law, we find MMF $F = Iw = \sum_{k=1}^{n} H_k l_k$. Also we find the current $I = \frac{F}{w}$.

Test questions

1. What are the parameters characterizing a magnetic field?

2. State Faraday's law of electromagnetic induction.

3. State Lenz's rule.

4. What is mutual induction?

5. State Ampère law.

6. State Ampere's circuital law?

7. What is a magnetic circuit?

8. What is classification of magnetic circuits?

9. State Ohm's law for a magnetic circuit.

10. State 1st Kirchhoff's law for magnetic circuits.

11. State 2nd Kirchhoff's law for magnetic circuits.

12. State the sequence of calculation of a magnetic circuit.

LECTURE 8
MAGNETIC CIRCUITS WITH ALTERNATING MAGNETOMOTIVE FORCE

Physical processes and relationships of the basic quantities

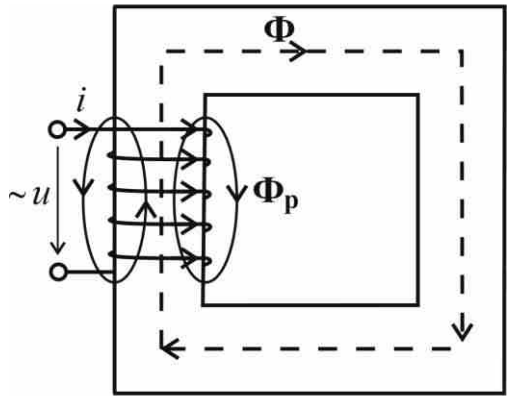


Figure 8.1

Let's consider an inductor (a ferromagnetic-core coil or iron-core coil) in an AC circuit (Fig. 8.1). Such system is a widespread element in many systems since in most cases the winding is powered by a sinusoidal voltage network. Alternating current creates an alternating magnetic flux. Thus, the core continuously re-magnetized.

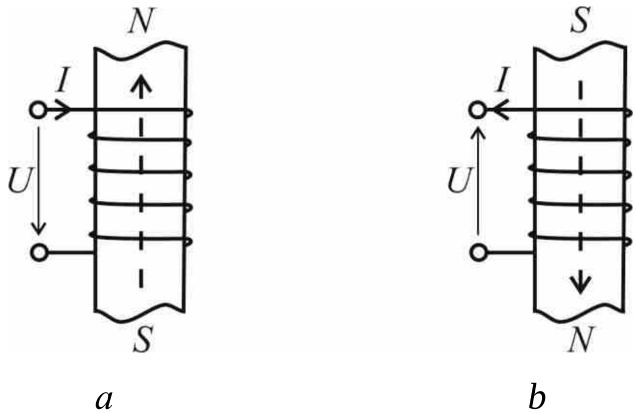


Figure 8.2

The first half-period we can see the picture shown in Fig. 8.2, *a*, through the second the half-period the picture changes (Fig. 8.2, *b*).

Cyclic magnetization reversal of the core causes in it energy of hysteresis loss.

According to Faraday's law of induction each flux creates the EMF of self-induction:

$$\Phi \Rightarrow e = -w\frac{d\Phi}{dt}; \qquad (8.1)$$

$$\Phi_p \Rightarrow e_p = -w\frac{d\Phi_p}{dt}, \qquad (8.2)$$

where Φ – basic magnetic flux;

Φ_p – leakage flux closes through the air:

w – a number of turns in the inductor.

According to Kirchhoff’s Voltage law the applied voltage creates two EMF of self-induction and voltage drop across resistance R of the inductor

$$u = -e - e_p + Ri, \qquad (8.3)$$

or we can rewrite

$$u + e + e_p = Ri. \qquad (8.4)$$

Usually, the peak value of a self-induction EMF E_m over exceeds an leakage EMF E_{mp} many times, and a voltage drop $I_m R$ across the inductor is

$$E_m >> E_{mp} \text{ and } E_m >> I_m R. \qquad (8.5)$$

The main resistance to the flowing current is EMF of self-induction E_m.

The inductor can be presented the following schematic diagram (Fig. 8.3).

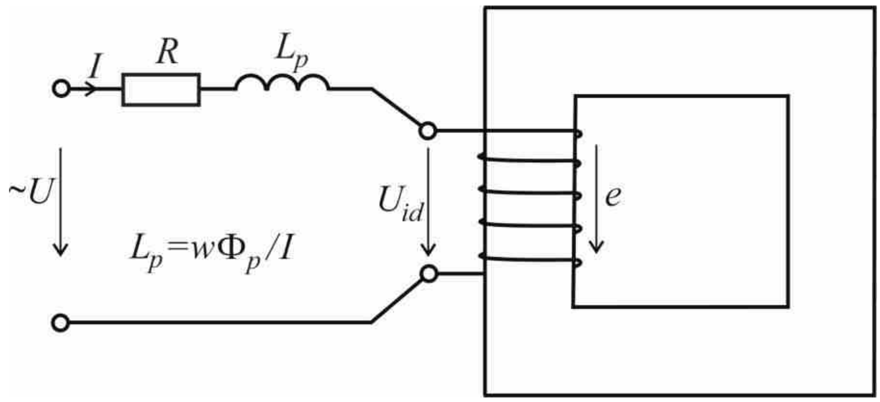


Figure 8.3

id – index of the ideal inductor (inductor without resistance, capacitance, or energy dissipation and without a leakage flux).

Graph curves of the EMF and current dependences of the ideal inductor

The ideal inductor at which R = 0 and a leakage flux Φ_p is absent. The sinusoidal voltage is applied to such an inductor $u_{id} = U_{mid}\sin\left(\omega t + \frac{\pi}{2}\right)$.

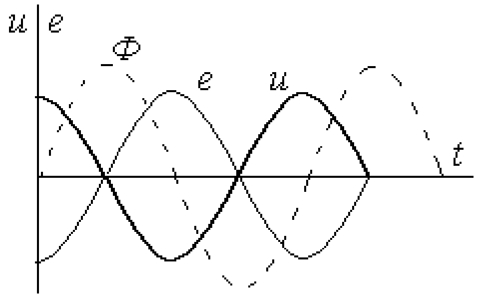


Figure 8.4

But thus, $u_{id} = -e = w\frac{d\Phi}{dt}$ means EMF is in antiphase:

$e = E_m \sin\left(\omega t - \frac{\pi}{2}\right)$ and $E_{\mathrm{m}} = U_{mid}$.

$$e = -w\frac{d\Phi}{dt} = E_m \sin\left(\omega t - \frac{\pi}{2}\right) = -E_m \cos\omega t\,.$$

We find the flux from here:

$$\Phi = -\frac{1}{w}\int edt = --\frac{1}{w}\int E_m \cos\omega t dt = \frac{E_m}{w\omega}\sin\omega t = \Phi_m \sin\omega t\,, \qquad (8.6)$$

where $\Phi_m = \frac{E_m}{\omega w}$. (8.7)

Thus, at a sinusoidal voltage across the ideal inductor a voltage, EMF and current change is sinusoidal. But at the same time, the current and flux lag in phase from the voltage by the angle of $\pi/2$. The phasor diagram of the ideal inductor looks like in Fig. 8.5

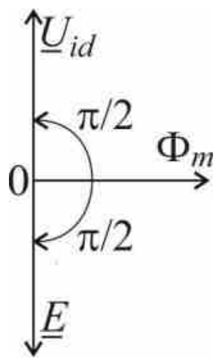


Figure 8.5

From (8.7) we will write down $E = \frac{\omega w}{\sqrt{2}}\Phi_m$.

Considering that $\omega = 2\pi f$, we will obtain

$$E = \frac{2\pi f w}{\sqrt{2}} \Phi_m = \sqrt{2}\pi f w \Phi_m = 4{,}44 w f \Phi_m . \qquad (8.8)$$

This is the equation of a transformer EMF.

Dependence of a magnetic flux on a current represents a hysteresis loop (was $B=f(H)$). But $B = \Phi / S$, and according to Ampere's circuital law $\oint H dl = I w$, i.e. $B \sim \Phi,\ H \sim I$.

At a sinusoidal change of the voltage U so also the flux Φ, we will look as the current *i(t)* changes. On dependence Φ *(i)* and Φ *(t)* we draw *i (t)* in Fig.8.6.

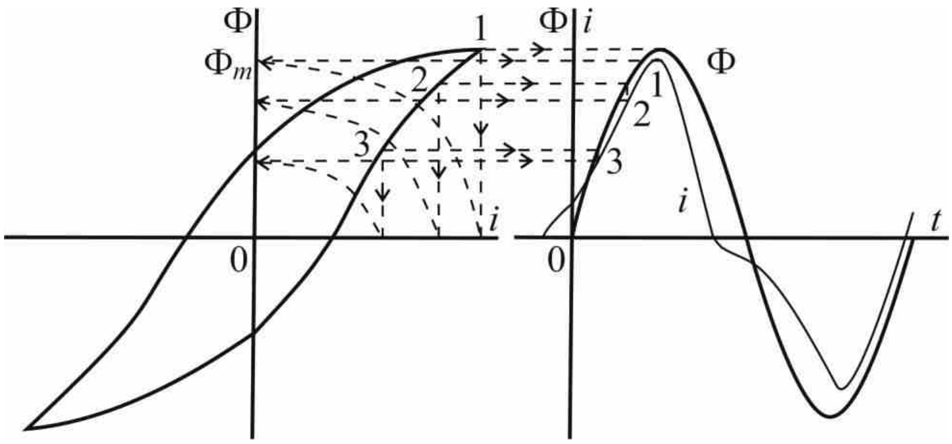


Figure 8.6

At $t = 0$ $\Phi = 0$ and $i \neq 0$.

In the inductor the current I changes is not sinusoidal. The current and the magnetic flux reach the maximum value not simultaneously. The flux, because of a hysteresis, don't have time to change in a phase with the current.

At calculation not sinusoidal current replace sinusoidal, which RMS (effective) values are identical.

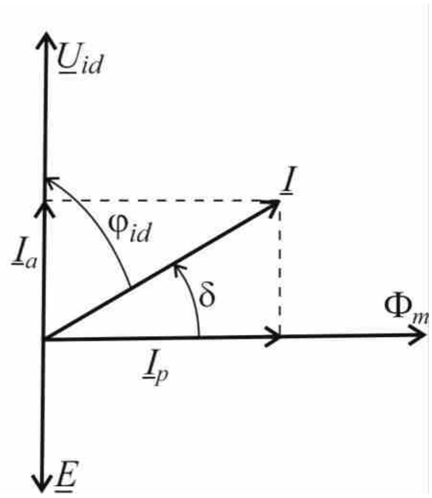


Figure 8.7

Taking into account it the phasor diagram looks like as shown in Fig. 8.7.

$I_p = I\cos\delta$ – the reactive component of the current I;

$I_a = I\sin\delta$ – the active component of the current I.

φ_{id} – the phase difference angle between U_{id} and I.

The angle δ is caused by a hysteresis presence, i.e. magnetic loss.

The angle δ is called as a magnetic delay angle of or magnetic loss angle.

The active power consumed by the ideal inductor:

$P_{id} = U_{id} I\cos\varphi_{id} = U_{id} I\sin\delta = U_{id} I_a$. This power is spent for core heating.

The reactive power consumed by the inductor:

$Q_{id} = U_{id} I\sin\varphi_{id} = U_{id} I\cos\delta = U_{id} I_p$. The reactive power is spent for creation of the basic magnetic flux.

The phasor diagram of the real inductor

Let's use the equation

$$u = -e - e_p + iR.$$

In the form of the RMS values of phasor quantities it becomes

$$\underline{U} = -\underline{E} - \underline{E}_p + \underline{I}R. \tag{8.9}$$

The leakage flux of Φ_p closes through the air (linear environment), therefore its dependence on the current linear Φ *(i)*. But then both inductance of leakage:

$L_p = \dfrac{w\Phi_p}{i}$ and inductive reactance of leakage $X_p = \omega L_p$ do not depend on the current, so and leakage EMF $e_p = -L_p \dfrac{di}{dt}$ is directly proportional to the current.

Let's express EMF leakage through voltage drop $\underline{E}_p = \underline{U}_p = -jX_p \underline{I}$

Let's substitute in the formula (8.9) this expression

$$\underline{U} = -\underline{E} + jX_p \underline{I} + \underline{I}R \tag{8.10}$$

This is a electric state equation of the iron-core inductor.

Let's transform this equation $\underline{U} = -\underline{E} + \underline{I}\,\underline{Z}$, where $\underline{Z} = R + jX_p$ is impedance of the inductor.

According to the equation (8.10) we draw the phasor diagram

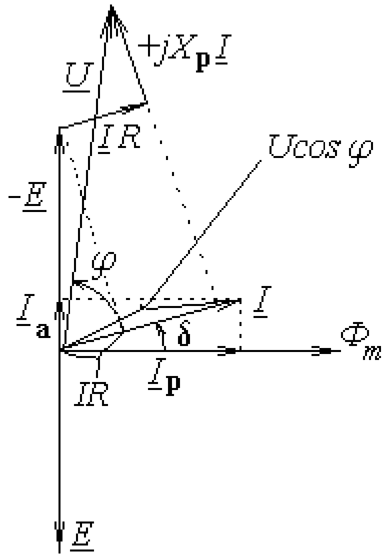


Figure 8.8

From the phasor diagram it follows that the active power consumed by the inductor, is equal $P = UI\cos\varphi$.

But $U\cos\varphi = IR + E\cos\varphi_{id} = IR + E\cos(90^\circ - \delta)$.

Then $P = UI\cos\varphi = I^2R + IE\cos\varphi_{id} = \Delta P_{el} + \Delta P_m$,

where:

$\Delta P_{el} = I^2R$ – electric power losses, i.e. the active power is spent in the inductor resistance;

$\Delta P_m = IE\cos\varphi_{id} = EI\sin\delta$ – magnetic loss of the core, i.e. the active power absorbed from a time-varying magnetic field by a substance, which it is possible to present as $\Delta P_m = P_h + P_{ec}$,

where :

P_h – hysteresis loss, i.e. the active power absorbed by a material due to magnetic hysteresis;

P_{ec} – eddy-current loss, i.e. the active power absorbed by a material due to eddy currents.

When a cyclic magnetization occurs, a hysteresis loss occurs, which is the energy expended in eliminating the previous magnetization. These loss is proportional to the area of a hysteresis loop and can be defined as

$$P_h = \sigma_h f B_m^n G, \qquad (8.11)$$

where σ_h – hysteresis factor which depends on a steel mark (magnetic properties of a material);

f – frequency of the applied voltage;

B_m – maximum value of an induction;

n – an empirical factor;

G – weight of the core.

At $B > 1$ T, $n = 2$, and $\Delta P_m \sim B_m^2$.

When an alternating current flows through an inductor, EMF is induced not only in the inductor, but also in the core. Under the action of EMF, currents flow through the core, which are called eddy currents (Fig.8.9, *a*).

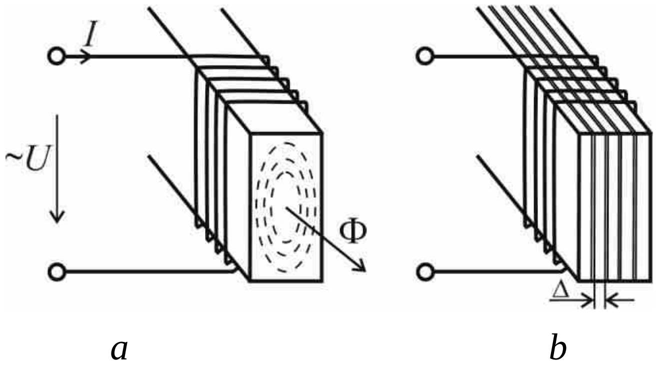


Figure 8.9

According to Lenz's rule, eddy currents create their own magnetic flux, which is directed oppositely to the main flux, i.e. it demagnetizes the core.

The resulting flux is unevenly distributed: it is forced out onto the surface of the core. This phenomenon is called a magnetic surface effect (skin effect).

To reduce eddy currents and magnetic loss in the core, it is carried out laminated, i.e. typed of single sheets in the thickness Δ = 0,15 - 0,5 mm, isolated from each other, it is for example, varnish (Fig. 8.9, *b*).

To calculate the eddy current loss, we can use the next expression

$$P_{ec} = \sigma_{ec} f^2 B_m^2 G\gamma, \qquad (8.12)$$

where σ_{ec} – an empirical factor;

$\gamma = 1/\rho$ – conductivity of a material of the core.

To reduce the conductivity of the core, and hence eddy-currents, silicon Si is added to steel. Thus, resistance increases, and magnetic properties do not worsen. Thus, it is possible to consider that magnetic loss $\Delta P_m \sim B_m^2$.

The equivalent circuit of the iron-core inductor

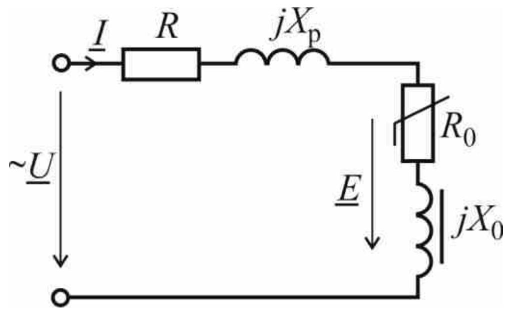


Figure 8.10

It is possible to present in the form of the circuit (Fig.8.10) with series connection of elements. The basis for replacement is equation (8.10).

R_0 and jX_0 depend on voltage U (Flux Φ ~ U). These are variable parameters of the circuit;

R and jX_p – the constant parameters considering a magnetic circuit of the inductor.

Equivalent circuit parameters can be found as follows:

$$R = \frac{\Delta P_m}{I^2}; \quad R_0 = \frac{\Delta P_{st}}{I^2}; \quad X_p = L_p\omega; \quad Z_0 = \frac{E}{I}; \quad X_0 = \sqrt{Z_0^2 - R_0^2}.$$

Equivalent circuit elements have the following physical sense:

X_p – inductive reactance by means of which inducing action of a leakage flux Φ_p is replaced;

R – resistance by means of which active power loss P_{el} in wires of the inductor is replaced;

X_0 – inductive reactance which inducing action of the basic magnetic flux is replaced;

R_0 – resistance by means of which losses of power in the iron core of the inductor are replaced.

Test questions

1. What kind of the power loss does cyclic magnetization of the iron core cause?

2. Write down the equation electric balance according to Kirchhoff's voltage law for an inductor.

3. What is the phasor diagram of the ideal inductor?

4. Are sinusoidal changes of a current in an inductor?

5. What is the angle δ called?

6. What is the phasor diagram of a real inductor?

7. What are the electric power losses and magnetic loss?

8. What are the components of magnetic loss?

9. How can eddy currents influence be reduced?

10. What is the equivalent circuit of the iron-core inductor?

LECTURE 9

ELECTROMAGNETIC DEVICES. SMOOTHING INDUCTOR

Smoothing inductor (*choke* – deprecated terms according to *Electropedia) is called a ferromagnetic-core coil with a variable inductance, switched on in an AC circuit in series with the load for current or voltage regulation.*

In comparison with a regulating rheostat with a big resistance *R*, smoothing inductors are more economic, as they have small resistance R_{sc}, so also small loss $R_{sc}I^2$.

Impedance of a smoothing inductor is

$$Z_{sc} = \frac{U_{sc}}{I} = \sqrt{R_{sc}^2 + X_{sc}^2}\,, \tag{9.1}$$

defined basically by the inductive reactance $X_{sc} = \omega L_{\mathrm{sc}}$,

where U_{sc}, I – a voltage and a smoothing inductor current; L– inductance of a smoothing inductor with number of turns *w*, inversely proportional to its reluctance.

It is distinguished as:

1) smoothing inductor with an adjustable air gap;

2) saturable reactor.

Smoothing inductor with an adjustable air gap

Its symbolic notation is shown in Fig. 9.1.

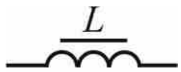


Figure 9.1

The magnetic circuit consists of two parts: the iron core with a small reluctance R_{Mst} and an air gap with a big reluctance R_{M0}.

Full reluctance is

$$R_M = R_{Mst} + R_{M0} \approx R_{M0} = \frac{2\delta}{\mu_0 S}\,. \tag{9.2}$$

As $L = \frac{\Psi}{i} = \frac{w\Phi}{i}$, and $\Phi = \frac{F}{R_M} = \frac{iw}{R_M}$, then $L = \frac{w^2}{R_M}$.

It is possible to write down inductance of a smoothing inductor as

$$L_{sc} \approx \frac{\mu_0 S w^2}{2\delta}, \tag{9.3}$$

and its inductance $X_{sc} = \omega L_{sc} \approx \frac{\mu_0 w^2 S\omega}{2\delta}$, (9.4)

i.e. $X_{sc} \sim \frac{1}{\delta}$ – in inverse proportion to an air gap (Fig. 9.2, *a*).

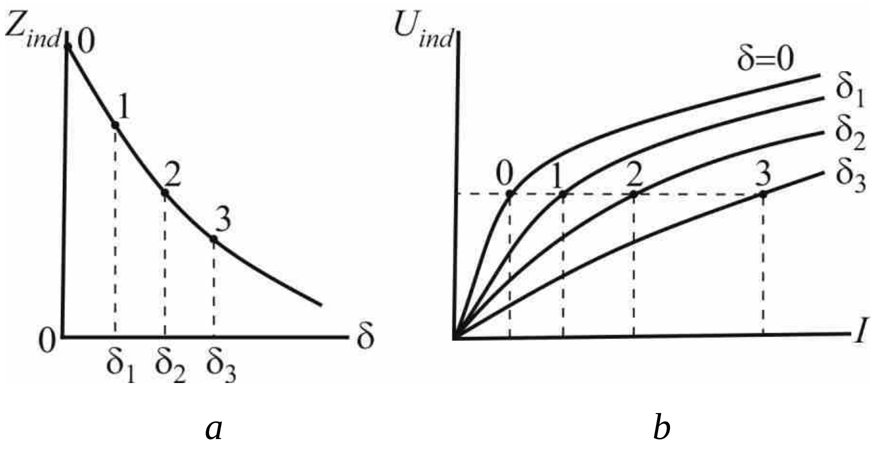


Figure 9.2

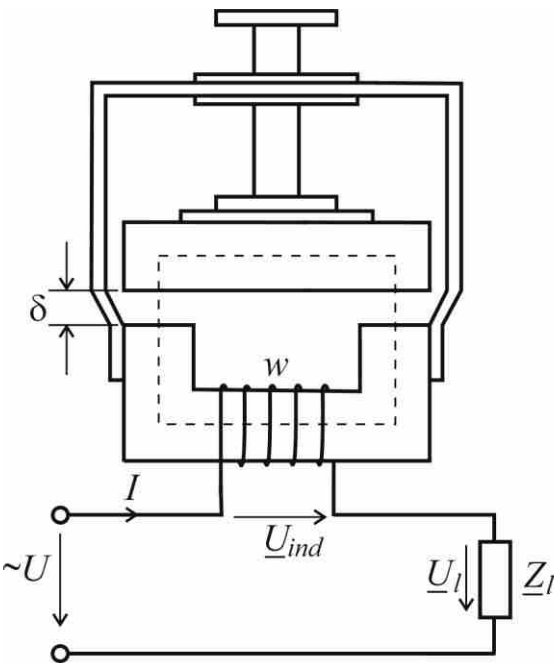


Figure 9.3

At increase of the air gap δ and the invariable voltage of the source U=const (Fig. 9.3) the current I in the circuit and the voltage across the load $U_l = IZ_l$ increase, and the voltage decreases across the winding of the smoothing inductor $U_{sc} = IZ_{sc}$

$$\underline{U}_{sc} = \underline{U} - \underline{U}_l = \underline{U} - \underline{Z}_l \underline{I}\,. \tag{9.5}$$

Dependence $U_{sc}(I)$ is called a volt-ampere characteristic of the smoothing inductor: the increase of the air gap more and more straightens it, as it shown in Fig. 9.3, since the reluctance increases and the magnetic flux decreases. These smoothing inductors are applied to change of a load current in welding transformers and AC electric furnaces. Their lack is construction complexity of the regulation device of a gap.

Saturable reactor

A saturable reactor represents a coil with the closed core made from a soft magnetic steel which inductance is easily regulated by change of the control DC current I_c in an additional control winding (Fig. 9.4, *a*).

Change of the current I_{con} by means of an adjusting rheostat changes degree of saturation of the core, i.e. its absolute magnetic permeability μ_a (decreases with increase of the current I_c) on which value inductance of a reactor depends on

$$L_{sc} = w^2 \frac{\mu_a S}{l}, \tag{9.6}$$

where l is the length of an average line of a magnetic circuit.

$$I_c \uparrow \Rightarrow \mu_a \downarrow \Rightarrow L_{sc} \downarrow \Rightarrow X_{sc} = \omega L_{sc} \downarrow \Rightarrow Z_{sc} \downarrow \Rightarrow I\,.$$

It is projected, so that in the absence of the control current ($I_c = 0$), in an alternating current circuit a reactor works with a non-saturated core. Thus, inductance of reactor L_{sc} and its inductive reactance X_{sc} are maximum, and the working current I is minimum.

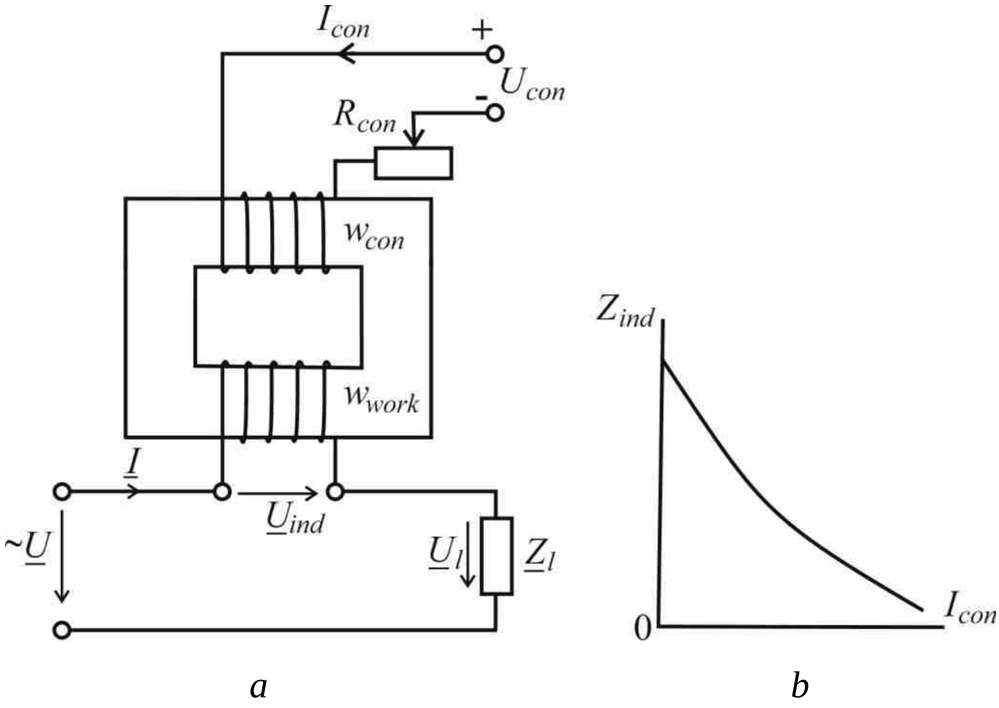


Figure 9.4

Saturable reactors with an adjustable nonlinear impedance Z_{sc} though reduce cosφ of installations, are widely applied to current regulation in such loads as arc electric welding, electric furnaces, lighting installations, etc.

They are made on total power from 0,1 VA to kVA. Their power is commensurable with power of installations in which they are used.

Their advantages are absence of mobile parts, simplicity of construction, safety in operation and high efficiency in regulation circuits of a working current.

Power electromagnets

Traction, load-lifting and braking electromagnets transform electric energy into mechanical.

Traction electromagnets with linear (reciprocating) moving of an armature are applied to control of hydraulic or pneumatic gates, cranes, executive device of machine tools and mechanisms.

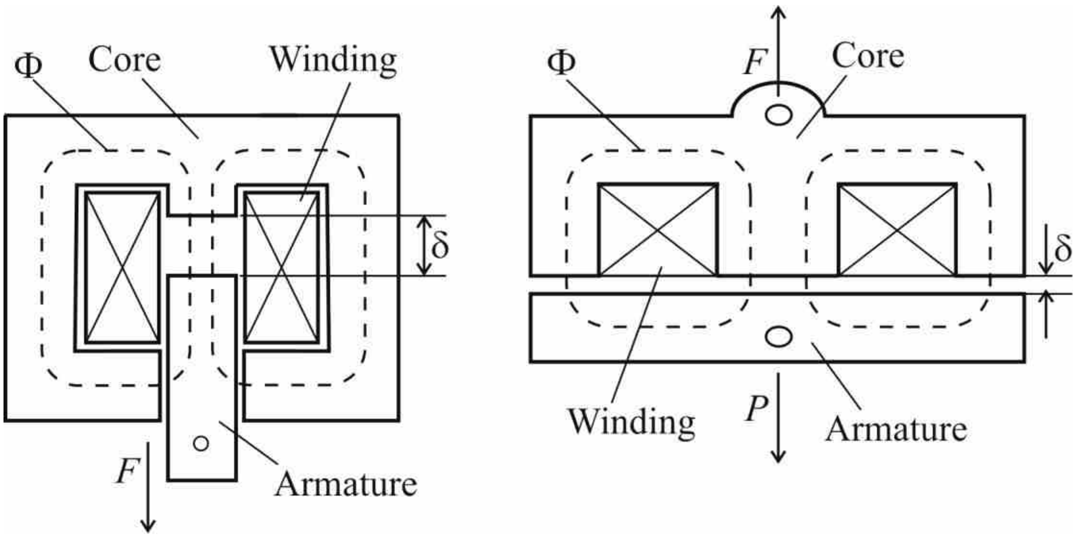


Figure 9.5

Energy of a magnetic field $W_m = \frac{LI^2}{2}$.

Volume density of energy $w_m = \frac{W_m}{V}$,

where $V = Sl$ – the core volume, S, l – section and length of the core.

$w_m = \frac{LI^2}{2}\frac{1}{Sl}$, but inductance is equal to $L = \frac{w^2}{R_m} = \frac{w^2\mu_a S}{l}$,

then $w_m = \frac{w^2\mu_a S}{2l}\frac{I^2}{Sl} = \frac{\mu_a w^2 I^2}{2l^2}$.

But from Ampere's circuital law $Hl = wI$, it is obtained $H = \frac{wI}{l}$, then

$$w_m = \frac{\mu_a H^2}{2} = \frac{BH}{2} = \frac{B^2}{2\mu_a}. \qquad (9.7)$$

Let's find a driving force or traction force of an electromagnet.

If under the influence of external force P the armature departs on distance dx the volume of the space occupied with a magnetic field, will increase by size:

$dV = Sdx$, where S *is* the cross-sectional area of a pole.

Thus, there will be a change of mechanical energy on a value $dW_{mech} = Pdx$.

As change of magnetic energy $dW_m = w_m dV = dW_{mech}$,

$Pdx = w_m dV = 2\frac{B^2}{2\mu_0}Sdx$, (a multiplier 2 as we have 2 poles).

The driving force of a pole of an electromagnet is equal to

$$F = \frac{P}{2} = \frac{B^2 S}{2\mu_0} = \frac{\Phi^2}{2\mu_0 S}. \tag{9.8}$$

Protective relay

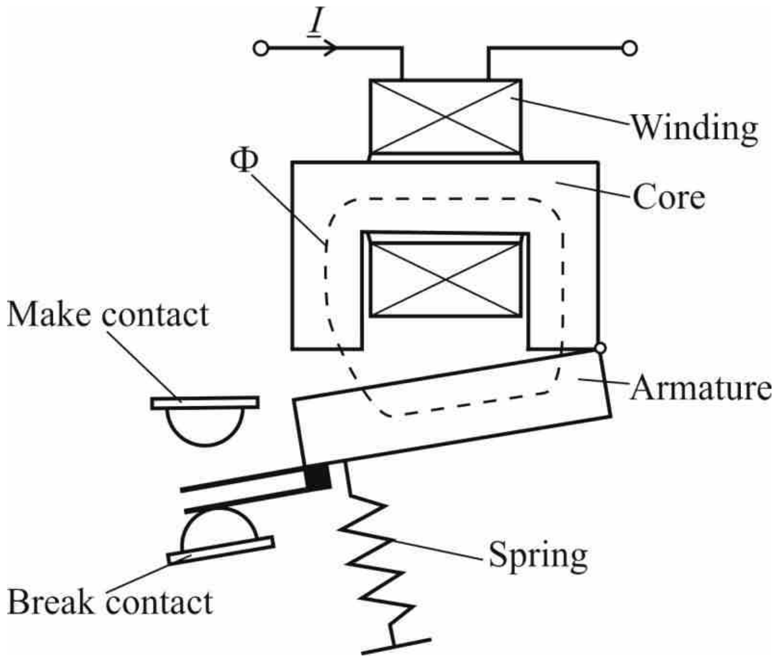


Figure 9.6

An electric relay is called the device intended for automatic operation at change of electric or not electric parameter to which relay should react.

A maximum-current relay

If a working current exceeds a certain maximum value, driving force of the electromagnet exceeds mechanical force of the spring, providing the armature moving. The make contacts close, and break contacts open (Fig. 9.6).

A thermal relay is for protection of electric equipment against long overloads (Fig. 9.7).

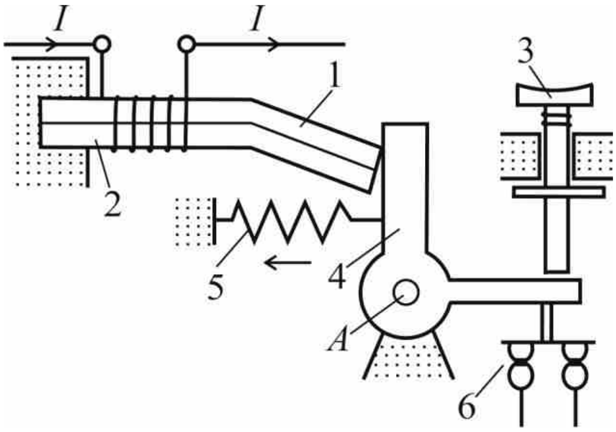


Figure 9.7

At heating the bimetallic plate (1) in the special heater (2) (nichrome wire) is deformed, its bent end rises and releases the lever (4) at operation. The lever (4) turns the spring (5) to the left concerning the axis *A* and the end disconnects break contacts (6) of the motor control circuit. After cooling of the plate during 3 - 5 minutes the initial condition of the relay can be restored pressing the button of return (3).

Test questions

1. *What is a smoothing inductor?*
2. *What is the principle of operation of a smoothing inductor with an adjustable air gap?*
3. *What is the principle of operation of a saturable reactor?*
4. *What dependence is called volt-ampere characteristic of a smoothing inductor?*
5. *What is the formula of the driving force of a pole of an electromagnet?*
6. *Where is power electromagnets applied to?*
7. *What is the construction and principle of operation of a protective relay?*
8. *What is the construction and principle of operation of a thermal relay?*

LECTURE 10

TRANSFORMERS. APPOINTMENT, CONSTRUCTION, PRINCIPLE OF OPERATION

A transformer is a static electromagnetic device intended for transformation of alternating current and voltage into alternating current and voltage at the same frequency, as a rule, but other value for the purpose of transmitting electric power.

Since the invention of the first constant-potential transformer in 1885, transformers have become essential for the transmission, distribution, and utilization of AC electric power. Transformers are distinguished as power transformers of the general application and special, single-phase and three-phase, core-type and shell-core, with laminated or the twisted core, etc. The symbolic representation of transformers is shown in Fig. 10.1.

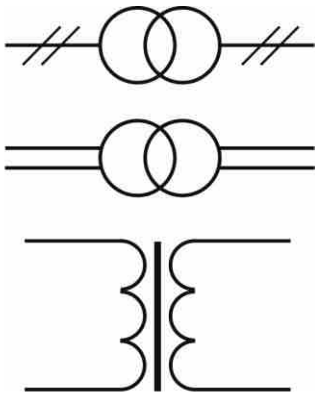


Figure 10.1

By electric power transfer on distances the demanded section of wires and loss in them the less, than it is less a current value and more a voltage value. Therefore, in a place of production of the electric power, a voltage value is raised to hundreds thousand volts, and in a current consumption place this voltage is step-downed to usually applicable values.

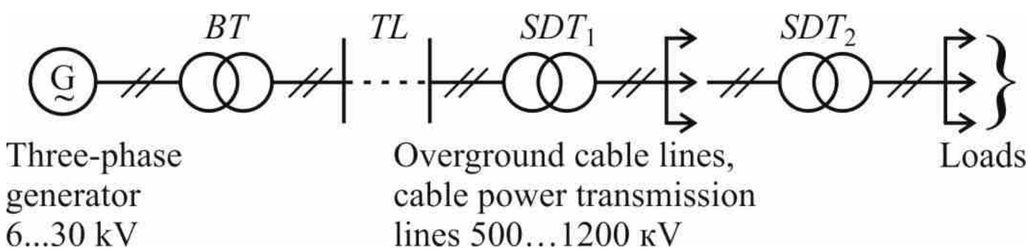


Figure 10.2

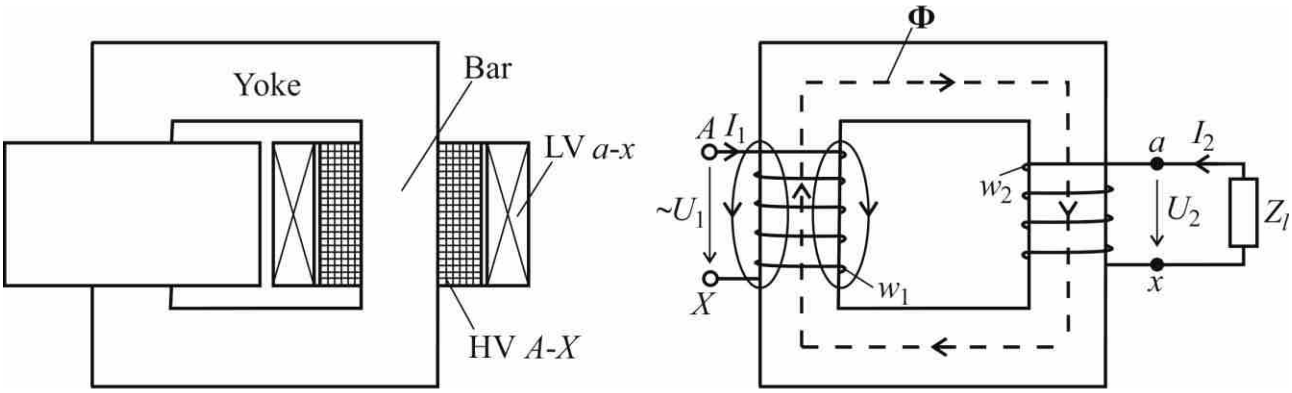
In Fig. 10.2 the structural diagram of a power transmission line with transformers is shown, where: *G* – three-phase generator, *BT* – booster (step-up) transformer; *TL* – power line (over ground cable lines, cable power transmission lines); $SDT_{1,2}$ – step-down transformers; *C* – consumers.

Let's consider the construction of a single-phase power transformer. It consists of two basic parts:

1) magnetic circuit is representing a ferromagnetic (steel) laminated core. It consists of thin plates (0,3 - 0,5 mm) of electrical steel. A horizontal part of the core is called a yoke. A vertical part is called a bar. The core is to spend a magnetic flux and fastening for the windings;
2) One winding is primary, incorporating to a source, and the secondary winding to which a load is connected. Transformer winding are divided to the high-voltage winding (HV) and the low-voltage winding (LV).

The construction and a schematic drawing of the transformer has been shown in Fig.10.3, *a, b*.

Principle of operation: in the primary circuit with the winding w_1 electric power of the source will be transformed to energy of a magnetic field, transferred across the core, which in the secondary circuit with the winding w_2, on the contrary, turns to electric power at the same frequency, but with other values of current and voltage.



a *b*

Figure 10.3

At alternating current flows in the primary winding the variable magnetic flux Φ, which basic part closing in the core, is created, i.e. covers the turns of the primary and secondary windings.

According Faraday's law of induction EMF are induced in the windings. Their instantaneous values are $e_1 = -w_1 \dfrac{d\Phi}{dt}$; $e_2 = -w_2 \dfrac{d\Phi}{dt}$ and

The RMS values: $E_1 = 4{,}44 w_1 f \Phi_m$, $E_2 = 4{,}44 w_2 f \Phi_m$.

Transformation ratio of the transformer:

$$k = \frac{e_{HV}}{e_{LV}} = \frac{E_{HV}}{E_{LV}} = \frac{w_{HV}}{w_{LV}}. \qquad (10.1)$$

If $w_1 > w_2$ – step-down transformer;

If $w_1 < w_2$ – step-up transformer.

If to neglect losses it is possible to consider, the total power of a transformer $S_1 \approx S_2 \Rightarrow U_1 I_1 \approx U_2 I_2$ as

$$\frac{U_1}{U_2} \approx \frac{I_2}{I_1}. \qquad (10.2)$$

Transformer operation duties

They distinguish three basic operating conditions (duties): no-load (NL), short-circuit operation (SC) and on-load (OL).

No-load is a such duty when the alternating voltage is applied to the primary winding, and the secondary winding is opened (Fig.10.4).

In this duty the current in secondary winding is I_2=0, and on the primary winding current is I_{10} ≈ (3... 5 %) I_{1r}, where I_{1r} is the rated current of the winding.

I_{10} is a reactive current creating a magnetic flux of the transformer:

$$\Phi = \frac{F_1}{R_m} = \frac{I_{10} w_1}{R_m}, \qquad (10.3)$$

where F_1 – MMF of the primary winding; R_m – reluctance; w_1 – number of turns in the primary winding.

The equation of voltage and current for the primary winding of the transformer same as was for the iron-core coil:

$$\underline{U}_1 = -\underline{E}_1 + \underline{I}_{10} R_1 + j\underline{I}_{10} X_1 = -\underline{E}_1 + \underline{I}_{10}\underline{Z}_1, \qquad (10.4)$$

where R_1 – resistance of the primary winding;

X_1 – inductive reactance caused by the leakage flux linked to the primary winding;

$Z_1 = R_1 + jX_1$ – impedance of the primary winding.

As the reactive current I_{10} is small, $U_1 \approx E_1$.

For definition of parameters of the transformer we can carry NL test. The circuit is shown in Fig.10.4.

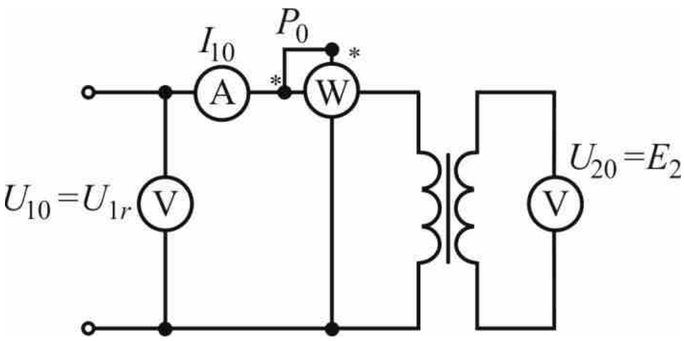


Figure 10.4

The voltage $U_{10} = U_{1r}$ is applied to the primary winding.

By results of measurements (U_{10}, I_{10}, P_0, U_{20}) we can define:

1) *transformation ratio of the transformer*

$$k = \frac{E_1}{E_2} \approx \frac{U_{10}}{U_{20}}.$$

As the no-load current I_{10} is too small, $E_1 \approx U_{10}$, and voltage $E_2 = U_{20}$. Thus, most precisely transformation ratio is defined by NL test.

2) *losses in the ferromagnetic core*.

We will show that measured power P_0, as magnetic losses, almost completely is equal to the losses in the core.

$$P_0 = \Delta P_{el1} + \Delta P_{m}.$$

But electric losses in the winding $\Delta P_{el1} = I_{10}^2 R_1$ are small since

$I_{10} \approx$ (3... 5 %) I_{1r}, and consequently $\Delta P_{el1} \approx 0$.

But, magnetic losses $\Delta P_m \sim B_m^2$; $B_m \sim \Phi_m$; $\Phi_m \sim U_1$.

As $U_{10} = U_{1r}$, ΔP_m correspond to the rated load. Therefore, $P_0 \approx \Delta P_m$.

$$\cos\varphi_0 = \frac{P_0}{U_{10} I_{10}}; \tag{10.5}$$

3) *parameters of the transformer*:

$$Z_0 = \frac{U_{10}}{I_{10}}; \quad R_0 = \frac{P_0}{I_{10}^2}; \quad X_0 = \sqrt{Z_0^2 - R_0^2}. \tag{10.6}$$

Short-circuit

As the short-circuit e understand such a duty at which the secondary winding is in a short circuit, and the voltage U_{1k} is applied to the primary windings, as shown in Fig. 10.5. If $U_1 = U_{1r}$ such a duty is emergency, as the currents in 10... 20 times can exceed the rated values. It can appear in an operation duty. We can carry short circuit test under the schematic diagram in Fig. 10.5

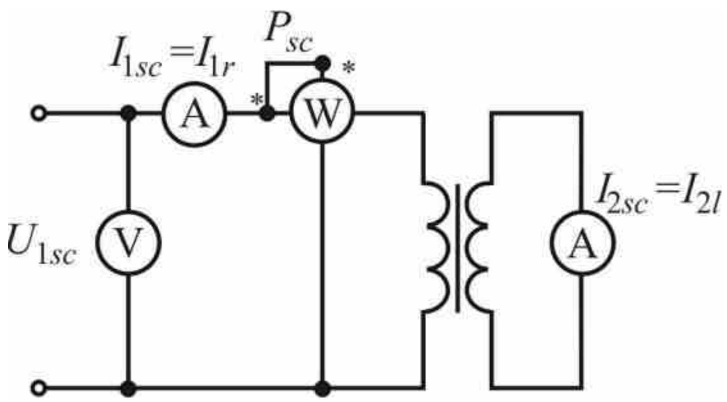


Figure 10.5

Lowered voltage U_{1k} at which in the both windings the rated currents proceed is applied to the primary winding.

By results of the SC test we define:

1) the short-circuit voltage u_k

$$u_k = \frac{U_{1k}}{U_{1r}}; \qquad u_k = (3...7)\,\%; \tag{10.7}$$

2) the power P_k was consumed by transformer. Generally, short-circuit losses

$$P_k = \Delta P_{el} + \Delta P_m . \tag{10.8}$$

$\Delta P_m \sim U_1^2$, but also $U_1 = U_{1k} = (3...7)\% \cdot U_{1r}$. Therefore, $\Delta P_m \approx 0$.

Electric losses $\Delta P_{el} = R_1 I_{1k}^2 + R_2 I_{2k}^2$ are the rated. Therefore, $P_k = \Delta P_m$.

3) emergency duty of SC:

From the relationship $\dfrac{I_{1sc}}{I_{1r}} = \dfrac{U_{1r}}{U_{1k}}$ we obtained $I_{1SC} = I_{1r}\dfrac{U_{1r}}{U_{1k}}$

On-load operation

The load duty appears, when the secondary winding is closed by the load resistance Z_l (Fig.10.3, *b*), and the rated voltage U_{1r} is applied across the primary windings. Then, currents I_1, I_2 flow in the windings.

The voltage U_1 is applied to the transformer

$$\underline{U}_1 = -\underline{E}_1 + \underline{I}_1 \underline{Z}_1 . \tag{10.9}$$

An induced EMF appears across the secondary winding which according to Kirchhoff's voltage law is equal to:

$$\underline{E}_2 = \underline{I}_2 \underline{Z}_l + \underline{I}_2 \underline{Z}_2 = \underline{U}_2 + \underline{I}_2 \underline{Z}_2 ,$$

where $Z_2=R_2+jX_2$ – impedance of the secondary winding;

R_2 – resistance of the secondary winding;

X_2 – inductive reactance caused by a leakage flux linked to the secondary winding.

From here we find

$$\underline{U}_2 = \underline{E}_2 - \underline{I}_2 \underline{Z}_2 \tag{10.10}$$

this is an equilibrium voltages equation of the secondary winding.

In NL the magnetic flux is created by the MMF $F_0 = I_{10} w_1$ and corresponds to Ohm's law for a magnetic circuit

$$\underline{\Phi}_m = \sqrt{2}\Phi = \sqrt{2}\frac{F_0}{R_m} = \sqrt{2}\frac{I_{10} w_1}{R_m} . \tag{10.11}$$

In OL the magnetic flux is created by the MMF of the both windings: $\underline{F}_1 = \underline{I}_1 w_1$ and $\underline{F}_2 = \underline{I}_2 w_2$, which are connected by the main magnetic flux:

$$\underline{\Phi}_m = \sqrt{2}\Phi = \sqrt{2}\,\frac{\underline{I}_1 w_1 + \underline{I}_2 w_2}{R_m}. \qquad (10.12)$$

But it is known that $\underline{E}_1 = 4{,}44\underline{\Phi}_m w_1 f$, from here

$$\underline{\Phi}_m = \frac{\underline{E}_1}{4{,}44 w_1 f} \approx \frac{\underline{U}_1}{4{,}44 w_1 f}. \qquad (10.13)$$

As applied voltage remains invariable, i.e. $U_1 = U_{1k} = \text{const}$, from (10.13) the magnetic flux also it is possible to consider is invariable $\Phi = \text{const}$.

Thus, the flux does not depend on load. We will equate (10.11) and (10.12):

$$\sqrt{2}\,\frac{\underline{I}_{10} w_1}{R_m} = \sqrt{2}\,\frac{\underline{I}_1 w_1 + \underline{I}_2 w_2}{R_m}.$$

We obtain $\underline{I}_{10} w_1 = \underline{I}_1 w_1 + \underline{I}_2 w_2$. Having divided by w_1, we obtain $\underline{I}_{10} = \underline{I}_1 + \underline{I}_2 \frac{w_2}{w_1}$, or the currents equation of the transformer

$$\underline{I}_1 = \underline{I}_{10} + \left(-\underline{I}_2'\right). \qquad (10.14)$$

The reduced secondary current of transformer $I_2' = \frac{w_2}{w_1} I_2$.

The phasor diagram of transformer

In NL (Fig.10.6, *a*) it is graphed on the basis of the equation

$$\underline{U}_1 = -\underline{E}_1 + \underline{I}_{10} R_1 + j\underline{I}_{10} X_1. \qquad (10.15)$$

If a load, for example, is active-inductive the current in the secondary winding $\underline{I}_2 = \frac{\underline{E}_2}{\underline{Z}_l}$ lags E_2 by an angle Ψ_2.

The voltage across the secondary winding can be found as

$$\underline{U}_2 = \underline{E}_2 - \underline{I}_2 R_2 - jX_2 \underline{I}_2, \qquad (10.16)$$

and the current of the primary winding $\underline{I}_1 = \underline{I}_{10} + \left(-\frac{w_2}{w_1} \underline{I}_2 \right)$ (Fig.10.6, *b*).

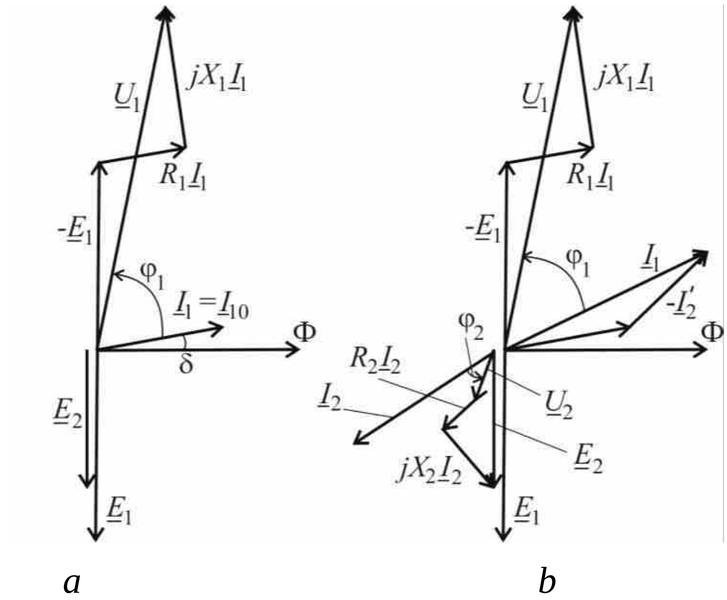


Figure 10.6

From the phasor diagram and equation of currents it follows that any change of the current I_2 leads to a respective change of the current I_1.

The current I_1 has two components: I_{10} creates the basic magnetic flux; the current I_1 compensates demagnetization action of the current I_2.

According to Lenz rule, the current I_2 creates a magnetic flux directed counter-relative to the main flux, i.e. demagnetizes the transformer. But the flux does not depend on the load, therefore, the demagnetizing effect of the current I_2 leads to an increase of the current I_1.

Transformer characteristics

1) *the load characteristic or the voltage regulation characteristic* is dependence $U_2(I_2)$ at $U_1 = U_{1r}$=const, $\cos\varphi_2$ = const.

From the equation $\underline{U}_2 = \underline{E}_2 - \underline{I}_2 \underline{Z}_2$ it follows that at the load changing, i.e. the current I_2, the voltage U_2 across the load changes because of a voltage drop $I_2 Z_2$.

With a resistive-inductive load, the core is demagnetized, i.e. the main magnetic flux decreases, which means that E_2 decreases. With an resistive-capacitive load, the core is magnetized, which leads to increase of the load voltage with increase in the load current.

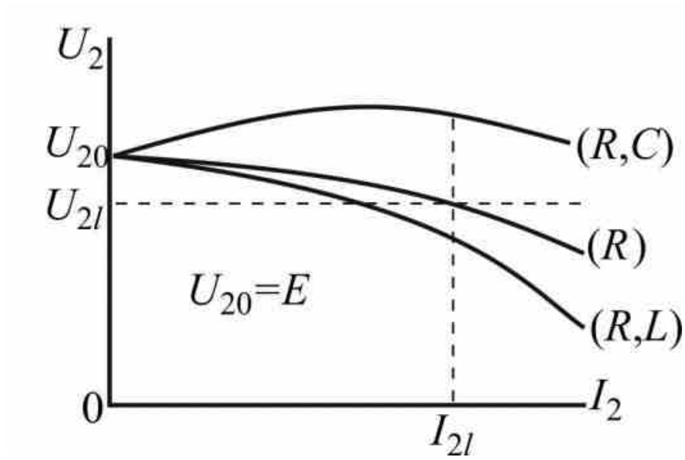


Figure 10.7

If the load is resistive, quantity Δu is change of voltage of the transformer:

$$\Delta u = \frac{U_{20} - U_{2'}}{U_{20}} = \frac{\Delta U}{U_{20}} 100\% . \tag{10.17}$$

It makes $\Delta u \approx (5...7)\%$. The external characteristic of a transformer is rigid.

2) *losses and efficiency of the transformer* depending on useful power. The characteristic transformer characteristic can be drawn by the dependence $\eta(P_2)$ at $U_1 = U_{1r}$; $\cos\varphi_2 = \text{const}$.

Efficiency is $\eta = \dfrac{P_2}{P_1}$, (10.18)

where $P_1 = U_1 I_1 \cos\varphi_1$ – the input active power;

$P_2 = U_2 I_2 \cos\varphi_2$ – the active useful power in the load.

Difference between these powers are power losses in the transformer:

$P_1 - P_2 = \Delta P_{el} + \Delta P_m$, or $P_1 = P_2 + \Delta P_{el} + \Delta P_m$.

Then we can write down

$$\eta = \frac{P_2}{P_2 + \Delta P_{el} + \Delta P_m} . \tag{10.19}$$

At the rated load the efficiency is possible to define by an indirect method

$$\eta = \frac{P_2}{P_2 + \Delta P_{\mathrm{NL}} + \Delta P_{\mathrm{SC}}}. \qquad (10.20)$$

The character of the loss change: as $U_1 = U_{1r} = \text{const}$, magnetic losses are constant $\Delta P_m \sim U_1 = \text{const}$.

Electric losses $\Delta P_{el} = R_1 I_1^2 + R_2 I_2^2 \sim I_2^2$ depend on a load in square-law dependence and are variables.

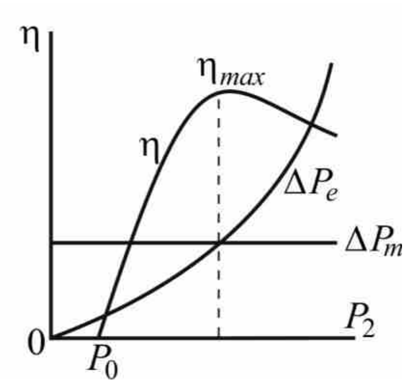


Figure 10.8

At a small load, the efficiency is low due to relatively large magnetic loss, at high loads, the efficiency decreases due to relatively large electric loss. The maximum value of efficiency is achieved when these losses are equal. The efficiency increases with increasing the transformer power.

$\Delta P_{el} = \Delta P_m \Rightarrow \eta = \eta_{max}$; $\eta_{max} \approx (97...99{,}5)\ \%$

Test questions

1. What is called a transformer?

2. What is the construction of a single phase transformer?

3. What is the principle of operation of a single-phase transformer?

4. What is the transformer ratio?

5. What is the no-load duty of a transformer?

6. What is the short-circuit duty of a transformer?

7. What is the on-load duty of a transformer?

8. What are the losses in the transformer?

9. What is the efficiency of the transformer?

10. Draw the load characteristic of the transformer.

LECTURE 11

DIRECT CURRENT ELECTRIC MACHINES

Assignment, application area and construction of direct current electric machines (DCEM)

DCEM are applied, as a rule, in controlled electric drives in transport, mechanical engineering, and other areas.

Operation duties of DCEM are generator and motor. A generator is an electric power source in which mechanical energy (of an external motor or an engine, a gas or a wind turbine, etc) will be converted into electric energy, and in a motor, on the contrary, electric energy will be converted into mechanical energy.

Construction of DCEM

DCEM consists of three basic parts: a fixed stator is a stationary portion of a machine, a rotating armature (rotor) and a commutator assembly.

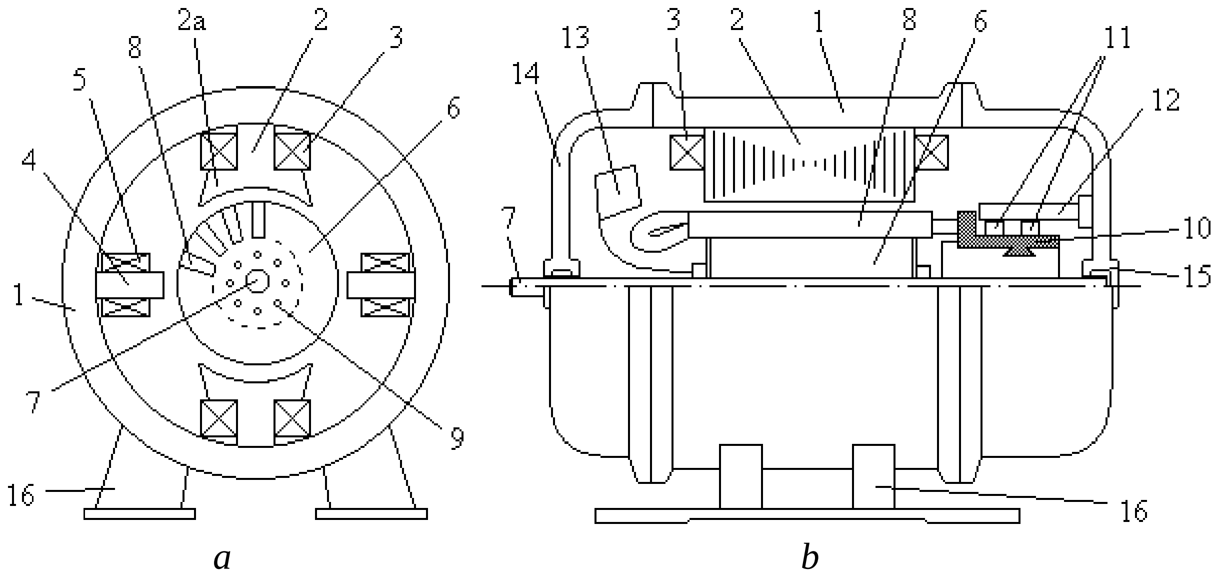


Figure 11.1

As shown in Fig. 11.1:

The STATOR includes: 1 – the frame (a hollow steel cylinder), 2 – the main poles which fasten to the frame yoke (they are always laminated) with pole pieces (tips) 2*a*; 3 – the excitation winding mounted on the main poles; 4 – commutating [compensating] poles; 5 – the winding of an commutating pole.

The ARMATURE includes: 6 – a laminated core mounted on the shaft 7; 8 – the armature winding laid in the slots of the core; in the core there are channels for cooling 9.

The COMMUTATOR ASSEMBLY includes: 10 – a commutator made of separate commutator copper plates; 11 – brushes (made of carbon) in the brush holder; 12 – traverse (brush finger).

In addition, DCEM includes: 13 – the fan mounted on the shaft; 14 – bearing shields; 15 – bearings; 16 – lugs intended for fastening of the motor.

A direct current flows through the excitation winding. In this case, the core of the pole is an electromagnet. The excitation winding current creates the main magnetic flux.

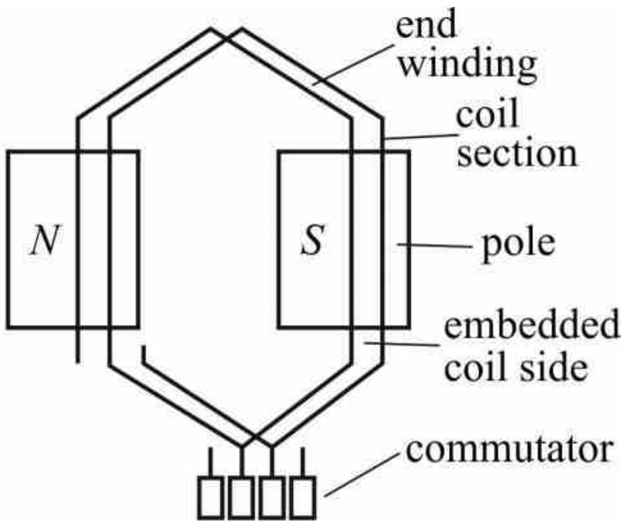


Figure 11.2

The armature winding is executed in the form of sections (end coil, embedded coil side) as shown in Fig. 11.2. All these sections are connected in series. The end of the subsequent winding section is connected to the beginning of the previous one. The armature winding is closed. The winding is divided into parallel branches by the brushes, $2a$ is the number of parallel branches (Fig. 11.3).

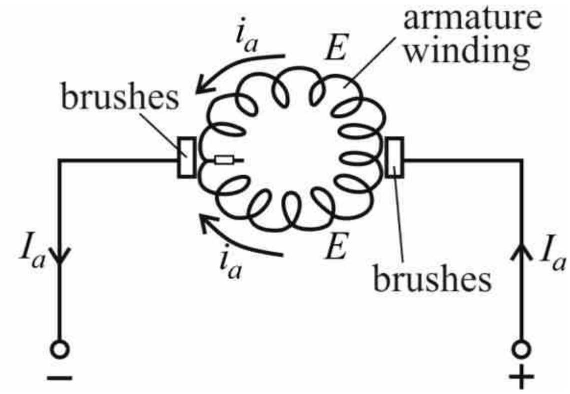
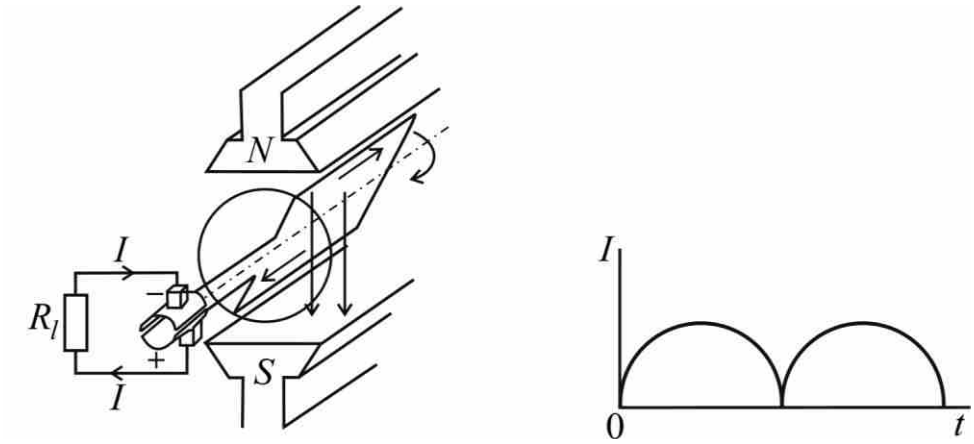


Figure 11.3

Current of a parallel branch

$$i_a = \frac{I_a}{2a}. \tag{11.1}$$

The principle of operation of DCEM can be understood under the following scheme (Fig. 11.4).



a *b*

Figure 11.4

The direction of the EMF and current in the armature winding is determined by *right-hand rule*.

The commutator is made in the form of a cylinder composed of a large number of commutator plates. In the *generator duty* the commutator serves to rectify the currents.

In the *motor duty* the commutator provides the flow of current in the conductors, which lie under one pole in one direction.

The principle of operation of DCEM is based on the laws of electromagnetic induction and Ampere. The magnetic field of the DCEM is created by the excitation winding. The main magnetic flux passes through the frame, the core of the poles, the core of the armature and twice overcomes the air gap.

In the generator duty a small direct field current is applied to the excitation winding, and the armature is rotated by a primary motor (turbine, engine, etc.). The armature winding wires are crossed by the magnetic field lines of the poles and the EMF is induced in the wires.

With the help of the commutator and brushes, which are a mechanical rectifier, these pulsating variables EMF are summed up in a direct value and direction of the machine EMF. If the load is connected to the brushes, then a direct current will appear in it and in the entire armature circuit.

In the motor duty the direct current is applied simultaneously to the armature and to the excitation winding. The interaction of the magnetic field of the stator poles with the current of the armature winding leads to the action on the conductors of a force that generates the electromagnetic torque of the armature.

EMF and electromagnetic torque of DCEM

When the armature rotates in the magnetic field of the excitation winding, the EMF is induced in each conductor of the armature winding

$$e = B_{av} l_a v \,, \qquad (11.2)$$

where B_{av} – the average value of an of the magnetic field induction by a pole pitch;

l_a – active length of a conductor.

The pole pitch is an arch of a circle of the armature by one pole

$$\tau = \frac{\pi D_a}{2p}, \tag{11.3}$$

where D_a – diameter of the armature circle;

p is the pairs number of the main poles.

An angular speed of the armature rotation or just armature speed

$$v = \frac{\pi D_a n}{60}. \tag{11.4}$$

All sections are connected in series, so the EMF of one parallel branch is equal to

$$E = \sum_{i=1}^{N/2a} e_i = l_a v \sum_{i=1}^{N/2a} B_{avi} = \frac{N}{2a} l_a v B_{av}, \tag{11.5}$$

where N is the number of conductors of the armature winding.

It is known that magnetic flux

$$\Phi = B_{av} S = B_{av} \tau l_a = B_{av} l_a \frac{\pi D_a}{2p}. \tag{11.6}$$

We substitute (11.4) in (11.5) and subject to (11.6) we obtain:

$$E = \frac{N}{2a} l_a v B_{av} = \frac{N}{2a} l_a B_{av} \frac{\pi D_a n}{60} \cdot \frac{2p}{2p} = \frac{N}{2a} l_a B_{av} \tau \cdot n \frac{2p}{60} = \frac{p}{a} \frac{N}{60} \Phi n,$$

or finally

$$E = c_E \Phi n, \tag{11.7}$$

where $c_E = \frac{p}{a} \frac{N}{60}$ – the coefficient, constant for a given motor.

So to change the sign of the EMF, you can change the polarity of the excitation flux or the direction of rotation of the machine.

When the current flows through the armature winding, a force is applied to each conductor

$$F_c = B_{av} l_a i_a \ . \tag{11.8}$$

The electromagnetic torque is $M = F_c N \frac{D_a}{2}$

The current in an armature is equal $i_a = \frac{I_a}{2a}$, and the magnetic flux is $\Phi = B_{av} l_a \tau$, and the pole pitch is $\tau = \frac{\pi D_a}{2p}$.

Then $F_{\text{пр}} = B_{\text{ср}} l_a \frac{I_a}{2a}$, and the electromagnetic torque

$$M = F_c N \frac{D_a}{2} = N \frac{D_a}{2} B_{av} l_a \frac{I_a}{2\text{a}} \cdot \frac{\pi \cdot 2p}{\pi \cdot 2p} = \frac{N}{2} \tau \cdot B_{av} l_a \frac{I_\text{a}}{2\text{a}} \frac{2p}{\pi} = \frac{Np}{2a\pi} \Phi I_\text{a} .$$

Finally, quantity of the electromagnetic torque is equal to

$$M = c_M \Phi I_a , \qquad (11.9)$$

where $c_M = \frac{Np}{2a\pi}$ – a machine constant.

If the machine operates in generator duty, then this torque is braking. The primary motor should exceed it.

If the machine operates in motor duty, then under the influence of this torque the armature will rotate.

For the generator, according to Kirchhoff's voltage law, the voltage U is less than the EMF E by the value of the voltage drop in the armature circuit with a resistance R_a,

$$U = E - R_a I_a . \qquad (11.10)$$

This is the equation of an electrical state of a loaded generator.

For the motor the induced EMF in the armature winding, during rotation of the armature in the stator magnetic field, is a secondary phenomenon. This EMF is directed counter to the current and the applied voltage

$$U = E + I_a R_a \qquad (11.11)$$

This is the equation of the electrical state of the motor.

Electromagnetic power

We multiply the equations of electric state by the armature current:

$UI_a = EI_a - I_a^2 R_a$ (for the generator duty);

$UI_a = EI_a + {I_a}^2 R_a$ (for the motor duty).

Where $P_{em} = EI_a$ is the electromagnetic power of machine. (11.12)

$P = UI_a$ – load power;

$P_a = {I_a}^2 R_a$ – power losses in the armature circuit.

Losses and efficiency of DCEM

In DCEM there are electric, magnetic, mechanical and additional losses.

Magnetic losses are consist of the hysteresis losses and the eddy currents losses

$$\Delta P_m = \Delta P_h + \Delta P_{ec}. \qquad (11.13)$$

Basically, these losses take place in the armature core, and practically do not depend on load.

Electric losses (*copper losses*) are power loss in the armature and excitation windings

$$\Delta P_{el} = I_a^2 R_a + I_{ew}^2 R_{ew}.$$

These losses depend on a current, therefore they are variables.

Mechanical losses ΔP_{mec} are caused by all types of friction.

Stray-load (*added*) *losses* ΔP_{sl} are losses in the pole pieces due to jaggedness of the armature, losses from eddy currents in the wires of the windings, etc.

These losses, as a rule, amount to 1% of the useful power P_2. The difference between the supplied and the useful power is made up of loss

$$P_1 - P_2 = \Delta P_m + \Delta P_{el} + \Delta P_{mec} + \Delta P_{sl},$$

it is possible to write down $P_1 = P_2 + \Delta P_m + \Delta P_{el} + \Delta P_{mec} + \Delta P_{sl}$. (11.14)

DCEM efficiency

$$\eta = \frac{P_2}{P_1} = \frac{P_2}{P_2 + \Delta P_m + \Delta P_{el} + \Delta P_{mec} + \Delta P_{sl}}. \qquad (11.15)$$

The maximum efficiency of the machine is η_{max} = 0,8 (for small machines) ... 0,95 (for large machines) (Fig. 11.5).

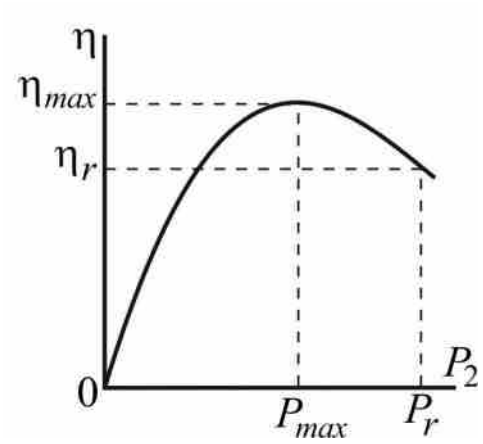


Figure 11.5

Concept about armature reaction and switching (commutation) of DCEM

The main magnetic flux is created by the field current (in no-load duty). The main magnetic flux is symmetrical concerning to the poles and brushes.

Under load the current flows through the armature, creating its own magnetic field, distorting the symmetry of the machine magnetic field.

The complex of phenomena associated with the influence of the magnetic field of the armature on working properties of the machine is called the *armature reaction*.

Under the influence of an armature reaction the magnetic field increases under one edge of the pole, and decreases under the other. Since the increase is less due to saturation of the core, the resulting field decreases.

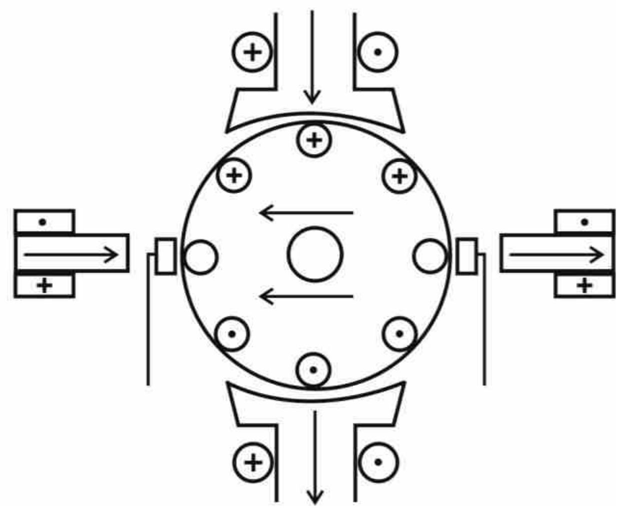


Figure 11.6

An armature reaction is undesirable. They are struggling with it by installing commutating poles which create a magnetic field directed opposite to the armature reaction field as shown in Fig. 11.6.

Switching (commutation) is the process of switching sections of the windings of the rotating armature from one parallel branch to another. At the same time, the direction of the current changes in a short time in these sections during short-circuit with their brushes (Fig. 11.7). If the switching process is incorrect, the entire process of switching current from one parallel branch to another is accompanied by sparking on the commutator. This is an avalanche-like process and ultimately sparking can damage the machine.

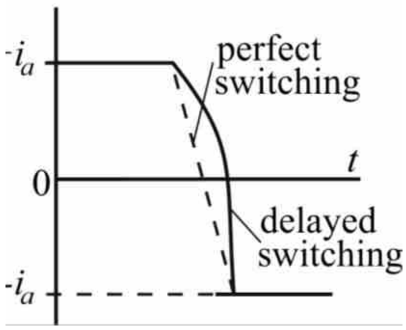


Figure 11.7

Sparking at a certain intensity can have a progressing character.

The reasons of sparking: mechanical; electric (~ 80 %).

The mechanical reasons: attrition of copper on the commutator, eccentricity of the commutator, buckling of the commutator, local breakage, etc.;

The electric reasons: a rapid change in the current in the section creates a reactive EMF of self-induction $e = -L\dfrac{di}{dt}$, which prevents the current in the section from changing, the delayed switching is obtained (Fig.11.7). Opening the section with a significant energy reserve leads to electric breakdown of the air gap between the brush and the commutator.

To improve switching, commutating poles are used, the magnetic field of which in the switched section induces an additional EMF that compensates for the reactive EMF.

Test questions

1. What are the main parts of DCEM?

2. What is the principle of operation of DCEM?

3. *What are the formulae for EMF and electromagnetic torque of DCEM?*

4. What are the losses and efficiency of DCEM ?

5. *What is the armature reaction of DCEM ?*

6. What are the reasons of sparking in DCEM?

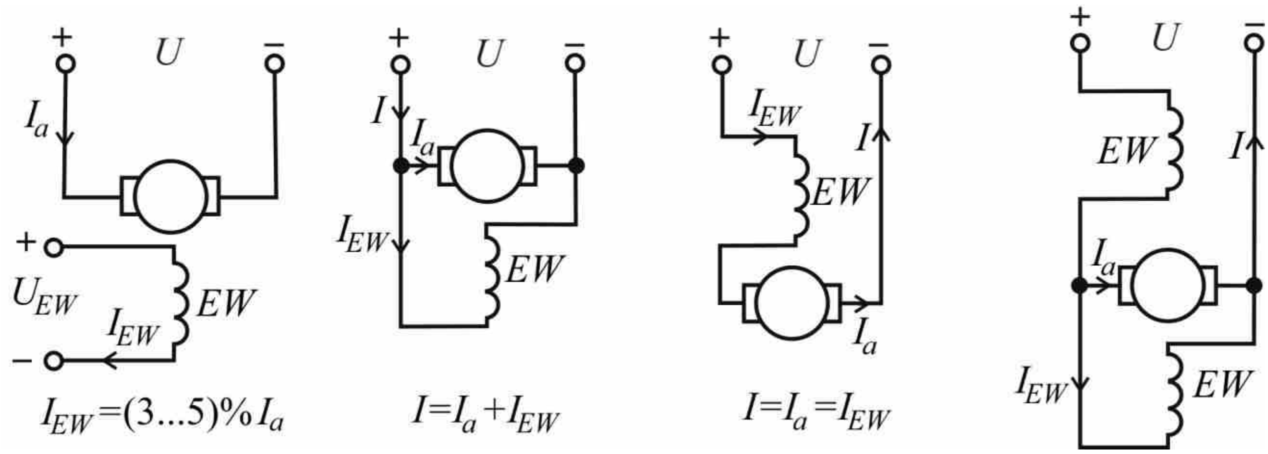
7. How can we improve the switching of DCEM?

LECTURE 12

DC GENERATORS AND MOTORS

Methods of excitation of DC electric machines (DCEM)

According to the method of excitation, DCEM are divided into: separately-excited (*a*), shunt-wound (*b*), series-wound (*c*) and compounding-wound (*d*) ones. In Fig. 12.1 their equivalent schemes are presented, where EW is the excitation winding, I_a is the armature current, I_{EW} is the excitation current winding, I is the total DCEM current.



a *b* *c* *d*

Figure 12.1

Characteristics of direct current generators (DCG)

DCG with the series-wound, shunt-wound excitation and compound-wound excitation are called as generators with self-excitation as DCG is a source for EW. The separately-excited DCG is shown in Fig. 12.2, where R_l is a load variable resistor.

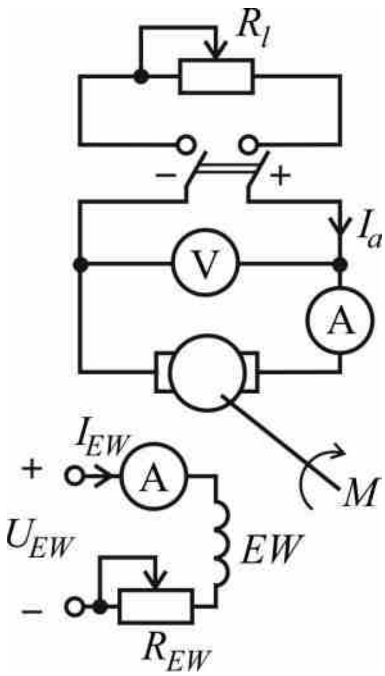


Figure 12.2

No-load characteristic (Fig. 12.3) is the EMF dependence on the excitation current E (I_{EW}) on condition: n = const, I_a = 0. The external circuit of the DCG is open.

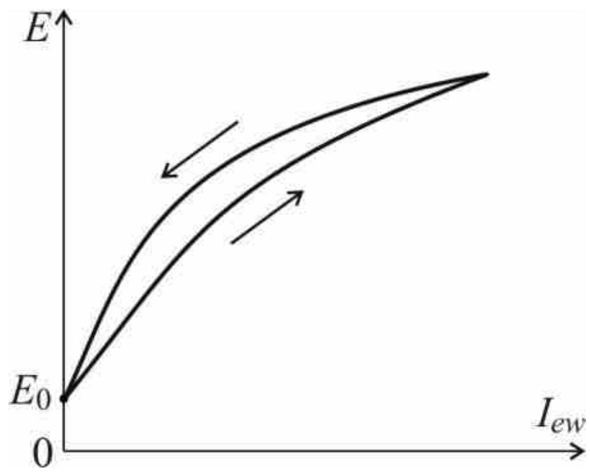


Figure 12.3

From the equation of an electrical equilibrium $U = E - I_a R_a$ it follows that $U = E$.

But $E = c_E \Phi n$. At $I_{EW} = 0$ then $E_0 \Rightarrow \Phi_0$.

Usually, the poles have previously been magnetized from a previous work. They create a small magnetic flux of residual magnetization. During of the armature rotation EMF E_0 is induced with increasing of the excitation current: $I_{EW} \uparrow \Rightarrow \Phi \uparrow \Rightarrow E \uparrow$.

At low excitation currents the magnetic flux is proportional to the current $\Phi \sim I_{EW}$. Due to saturation of the core steel, this dependence becomes non-linear.

Because of hysteresis, this characteristic, with a decrease in the excitation current, is located higher (a falling characteristic) than an ascending one (with an increase in the excitation current).

The external (*load*) *characteristic* (Fig.12.4) is the dependence of the terminal voltage (voltage across the armature winding terminals) of DCG on its current *U* (*I*) on condition: *n* = const, I_{EW} = const.

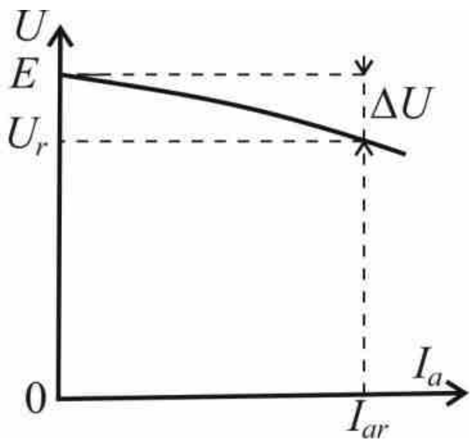


Figure 12.4

The DCG voltage $U = E - I_a R_a$ will decrease due to the following reasons:

1) because of increase of the voltage drop $I_a R_a$ in the armature;

2) because of the armature reaction the resulting magnetic flux decreases, and hence EMF ($E = c_E \Phi n$), $\Delta U \approx 10\ \% E$.

The adjusting characteristic (Fig. 12.5) is the dependence of the excitation current on the armature current delivered to the external circuit I_{EW} (I_a) on condition: n = const, U = const.

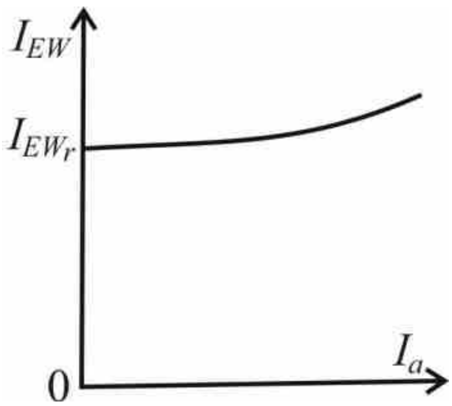


Figure 12.5

From the external characteristics it follows, that with increasing load, the voltage of the generator decreases. But it must be kept constant. Therefore, it is necessary to increase the EMF $E = c_E \Phi n$ by the excitation current (from the equation $U = E - I_a R_a$).

The adjustment characteristic shows how it is necessary to regulate the excitation current, when the generator load changes so that the voltage at its terminals remains invariable.

The shunt-wound DCG (shunt DC generator)

The self-excitation principle: if the armature rotates, then the remanent magnetization flux Φ_0 will induce E_0. Under the influence of EMF E_0 the current I_{EW0} flows, which will increase the flux Φ etc.: $I_{EW0} \Rightarrow \Phi_1 > \Phi_0$. If $\Phi_1 \Rightarrow E_1 > E_0$, through the excitation winding the current flows $I_{EW1} > I_{EW0}$.

Process will proceed until $I_{EW}(R_{EW} + R_p) = E$,

where R_{EW} – resistance of the excitation winding;

R_p – adjusting resistance in circuit of the excitation winding.

Self-excitation conditions:

1) presence of a remanent magnetization flux Φ_0;
2) the current in the excitation winding should strengthen the flux Φ_0;
3) resistance R_{EW} + R_p should be less the critical (Fig. 12.6).

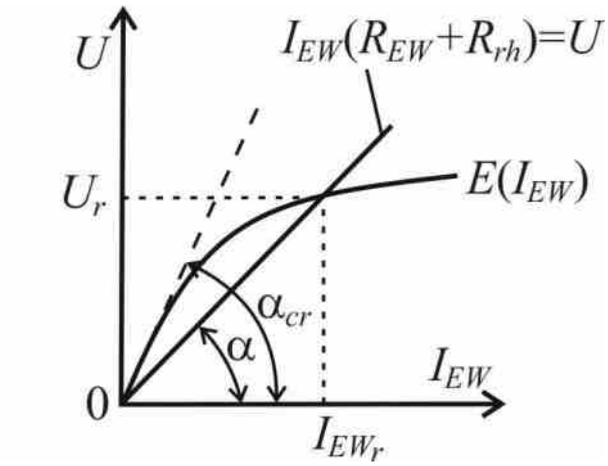


Figure 12.6

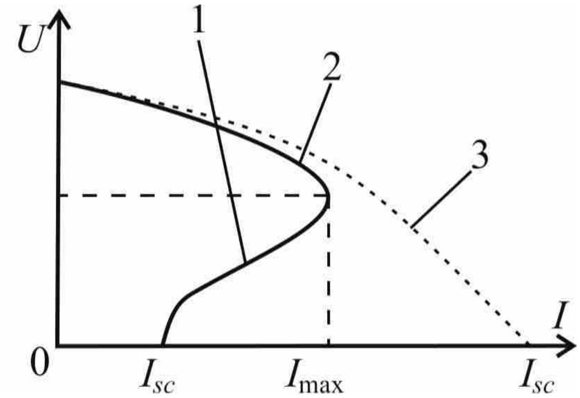


Figure 12.7

The no-load and adjusting characteristics are exactly the same as those of the separately-excited generator.

However, the external characteristics U (I) of generators with different excitation on condition R_p = const; n = const are significantly different (Fig.12.7):

1 – an unstable part of the characteristics;

2 – shunt-wound generator;

3 – separately-excited.

The voltage of the shunt-wound DCG decreases faster than that of the DCG with separately excitation, since there are three reasons why the voltage decreases with increase of load:

1) with increase of the load current I, due to decrease in the voltage U, the excitation current I_{EW} decreases: $I_{EW} = \dfrac{U}{R_{EW} + R_p}$ and decrease in the current I_{EW} reduces the flux Φ, and hence the EMF E;

2) a demagnetizing effect of the armature reaction;

3) the voltage drop in the armature circuit increases $I_a R_a$;

At the critical current $I_{\max}$ the generator is demagnetized.

Overload factor is $K_{ov} = \dfrac{I_{cr}}{I_r} \approx 2{,}0...2{,}5$, (12.1)

where I_r – the rated current.

As $I_{\max} < I_{sc}$, the generator is not sensitive of the short circuit duty, but only with a gradual increase in the load current. And with a sudden short circuit, a very high short circuit current occurs, because the stator magnetic flux remains almost the same (cannot instantly disappear) and creates the same EMF in the armature of a short-circuited generator as with the rated value duty.

The *series-wound* DCG is not applied in practice because of the bad external characteristic.

The compound-wound DCG (compound DC generator)

The main is the shunt-wound excitation winding, and the series-wound winding is auxiliary.

Series-wound excitation winding could be aiding connected or opposite connected to EW. At aiding connection the magnetic fields are added, and at opposite connection they are subtracted.

At this generator the no-load characteristic is the same as at the previous ones.

The external characteristic: (Fig. 12.8) *U (I) on condition: R_p* = const*;* *n* = const.

The DCG with a opposite series EW is used in welding generators: the current constancy is provided by arc oscillations.

If the series EW is aiding connected, then with increasing load, the resulting magnetic flux will increase.

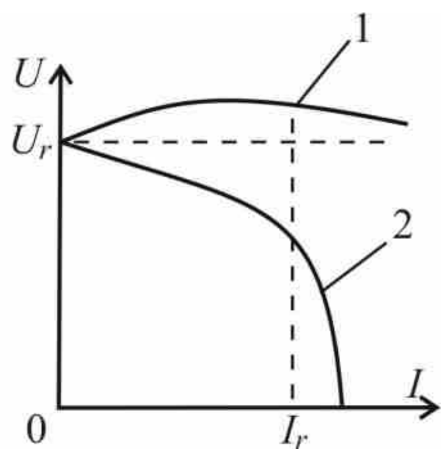


Figure 12.8

The series EW is selected so that a flux increase compensates for the voltage drop in the armature and the armature reaction:

$$U = c_E(\Phi + \Phi_{com})n - R_a I\ , \qquad (12.2)$$

where Φ_{com} – a compensating flux.

If this winding is connected in the opposite direction, then with increasing load, the resulting magnetic flux will sharply decrease, demagnetizing the machine, which will lead to a rapid decrease in the generator voltage:

$$U = c_E(\Phi - \Phi_{com})n - R_a I\ . \qquad (12.3)$$

Direct current motors

Direct current motors (DCM) are used much more widely than generators.

When the DCM is in motor duty, a direct current is supplied to the armature winding and the excitation winding. In this case, a force (according to Ampere's law), causing the electromagnetic torque, acts on each conductor of the armature

$$M = c_M \Phi I_a\ , \qquad (12.4)$$

under the influence of which the armature begins to rotate. In this case, EMF is induced in the winding of the armature

$$E = c_E \Phi n, \qquad (12.5)$$

which is directed against the current and is called counter-EMF.

The equation of electrical balance for the motor

$$U = E + I_a R_a . \qquad (12.6)$$

The armature current is determined by both the braking torque $I_a = \dfrac{M}{c_M \Phi}$ and the voltage applied $I_a = \dfrac{U - E}{R_a}$.

Having substituted the EMF value in the formula of electric balance, we obtain

$$U = c_E \Phi n + I_a R_a, \qquad (12.7)$$

whence we find $n = \dfrac{U - I_a R_a}{c_E \Phi}$. (12.8)

When the motor is running, we can distinguish the torques:

1) electromagnetic M created by the motor;

2) braking M_b created by the working mechanism; this torque also includes the braking torque of the motor itself.

When $M = M_\text{b}$, then motor speed n = const;

At $M > M_b$, motor speed n increase;

When $M < M_b$, the motor speed n decreases.

Principle of self-regulation of the DCM

The motor creates the electromagnetic torque M, which is equal to a braking torque M_b.

Let there was an equality of the torques $M = M_b$, but then the braking torque has grown, i.e. $M_b > M$. Then:

$$n \downarrow \Rightarrow E \downarrow (E = c_E \Phi n) \Rightarrow I_a \uparrow \left(I_a = \frac{U - E}{R_\text{a}} \right) \Rightarrow M \uparrow (M = c_M \Phi I_\text{a}).$$

This process will occur until again there will come equality of the torques.

Problem of the DCM start-up

The problem of the DCM start-up consists in the following:

as the armature current is equal to $I_a = \dfrac{U - E}{R_a}$, at the moment of start $n=0$ and $E = c_E \Phi n$=0. The starting current is

$$I_{as} = \frac{U}{R_\text{a}}. \tag{12.9}$$

Since the resistance of the armature circuit is very small (Ohm fraction), the starting current can exceed the rated current by 10 ... 30 times.

Method of the DCM start-up*:*

1) DIRECT start-up. In this case, there are: problems for the supply network, circular fire on the collector, a big push of the torque to the working mechanism, which can lead to breakage of the shaft.

The method is applicable for low-power motors (up to 1 kW) with high resistance of the armature circuit.

2) RHEOSTATIC start-up. With the help of a rheostat R_s in the armature circuit. It is selected so that the starting current does not exceed the rated one in 1.5 – 2,0 times.

$$I_{as} = \frac{U}{R_a + R_s}. \tag{12.10}$$

3) START-UP AT LOW VOLTAGE. This method requires a regulated voltage source. It is used in the generator-motor system.

Methods of the DCM speed control

From the formula (12.8) it follows that motor speed can be regulated:

1) *voltage change*. This method is widely used in generator-motor installations, where the motor is powered by a special generator. By regulating the excitation current of the generator, the voltage supplied to the DCM is changed.

2) *rheostat adjustment*. Turn on the adjusting rheostat R_{rha} in the armature circuit. Thus, the motor speed is

$$n = \frac{U - I_a\left(R_a + R_{ad}\right)}{c_E\Phi}. \tag{12.11}$$

When the rheostat resistance R_{ad} increases, the numerator and motor speed decreases. This method is uneconomical, because the big loss $I_a^2 R_{ad}$ released in the adjusting rheostat due to the big current I_a. These losses are commensurate with the motor power.

3) *changing of the magnetic flux* Φ. The realization is switching on of adjusting rheostat R_{rhEW} in the circuit of the excitation winding. Changing the excitation current ($I_e \approx (3...5)\% I_a$), we change also the magnetic flux. At increase of resistance of this rheostat: $R_{rhEW}\uparrow \Rightarrow I_{EW}\downarrow \Rightarrow \Phi\downarrow \Rightarrow n\uparrow$.

This is the main method of the motor speed adjusting.

With a significant decrease in the excitation current, the motor speed increase significantly, and mechanically the motor can be damaged. Therefore, it is equipped with automatic protection, which disconnects the motor from the network with a strong decrease in the excitation current.

Operation characteristic of the DCM

In practice motors with shunt-wound and series-wound excitation, and also with compound-wound excitation are used. Their characteristics vary significantly.

The shunt-wound DCM (shunt DC motor)

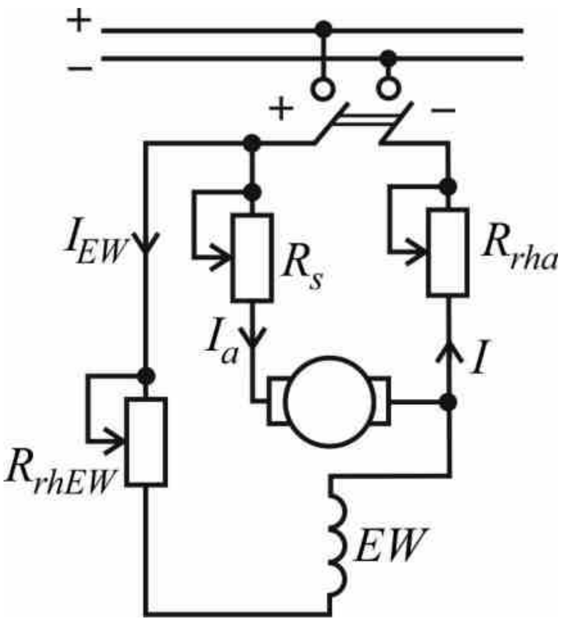


Figure 12.9

With increase of useful power on the shaft P_2 the excitation current I_{EW} does not change and, if the armature reaction is not taken into account, the magnetic flux Φ remains unchanged.

$I_a \sim P_2$, i.e. with increasing load, the armature current also increases.

The useful torque of the DCM

$$M_2 = \frac{P_2}{\omega}, \tag{12.12}$$

where ω – angular frequency of rotation.

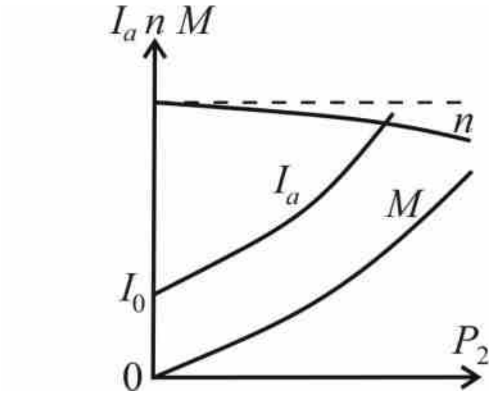


Figure 12.10

The mechanical characteristic n (*M*) at I_{EW}*=const*.

$$n = \frac{U - I_a R_a}{c_E \Phi} = \frac{U}{c_E \Phi} - \frac{I_a R_a}{c_E \Phi} = n_0 - \frac{I_a R_a}{c_E \Phi}, \tag{12.13}$$

where $n_0 = \dfrac{U}{c_E \Phi}$ – the no-load duty speed.

But the torque $M = c_M \Phi I_a$, from here $I_a = \dfrac{M}{c_M \Phi}$ after substitution in (12.13):

The equation of the natural mechanical characteristic (Fig. 12.11)

$$n = n_0 - \frac{M R_a}{c_E c_M \Phi^2}. \tag{12.14}$$

When the resistor R_{ad} is switched on into the armature circuit, artificial mechanical characteristics are obtained (Fig. 12.11).

$$n = n_0 - \frac{M\left(R_a + R_{ad}\right)}{c_E c_M \Phi^2}. \tag{12.15}$$

The natural mechanical characteristic of that DCM is rigid. When the load changes, the operation speed changes a little. At rated load, the operation speed makes 5 … 10 % change of n_0. on

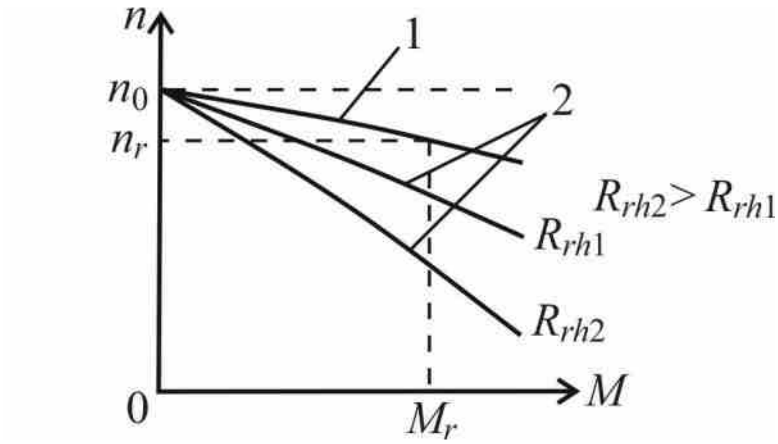


Figure 12.11

The series-wound DCM (series DC motor)

The peculiarity of DCM with series-wound excitation is that the armature current is equal to an excitation current $I_a = I_{EW}$.

When the load changes, the excitation current cannot remain constant. Those. a change in load leads to a change of the magnetic flux.

At change of the load the excitation current can't remain constant. I.e. the load changing leads to change of the magnetic flux. When the machine's magnetic system is unsaturated, the magnetic flux $\Phi \sim I_{EW} = I_a$, i.e. $\Phi = k_\Phi I_a$.

But $M = c_M \Phi I_a$, it means that

$$M = c_M k_\Phi I_a^2. \tag{12.16}$$

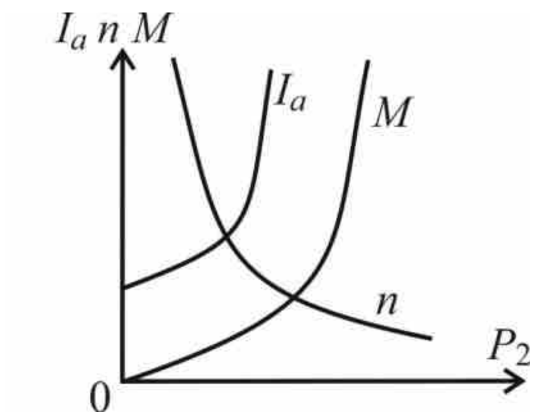


Figure 12.12

This motor is capable to create the large torques and to maintain considerable overloads. Since with increasing of load, the armature current and magnetic flux increase, the motor speed varies over a wide range.

The mechanical characteristic n (M) (Fig. 12.13)

$$n = \frac{U - I_a R_a}{c_E \Phi}. \qquad (12.17)$$

But $M = c_M k_\Phi I_a^{\,2}$, whence $I_a = \sqrt{\dfrac{M}{c_M k_\Phi}}$.

Since $\Phi = k_\Phi I_a$ then $\Phi = k_\Phi \sqrt{\dfrac{M}{c_M k_\Phi}} = \sqrt{\dfrac{k_\Phi M}{c_M}}$.

Substituting in the initial formula (12.17) for operation speed, we obtain the hyperbola equation

$$n = \frac{U - I_a R_a}{c_E \Phi} = \frac{U}{c_E \sqrt{M \dfrac{k_\Phi}{c_M}}} - \frac{I_a R_a}{c_E k_\Phi I_a} = \frac{U}{c_E \sqrt{M \dfrac{k_\Phi}{c_M}}} - \frac{R_a}{c_E k_\Phi} = \frac{A}{\sqrt{M}} - B. \qquad (12.18)$$

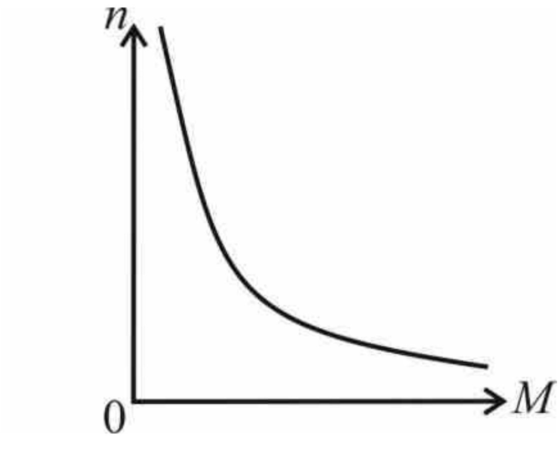


Figure 12.13

But as the load on the motor shaft decreases, the speed rises sharply. Theoretically it rises to infinity. The motor is overrunning. No-load duty is not allowed for this motor. Therefore, the motor with series-wound excitation must be rigidly connected to the working mechanism using a gear transmission, clutch, etc., and not a belt drive.

The compound-wound DCM (compound DC motor)

The main excitation winding is shunt (parallel connected), and the series is auxiliary. The series winding can be switched on aiding or opposite connection (magnetic fluxes are added or subtracted).

When an opposite connection is switched-on, the fluxes are subtracted and the mechanical characteristic is "more rigid" than that of the motor with shunt-wound excitation. When an aiding connection is switched-on, the fluxes add up and the motor has the properties of both DCM: the shunt wound and the series-wound DCM. But at low loads and even at no-load, such the motor has a limited speed. In Fig. 12.14: 1 –aiding connection; 2 – opposite connection.

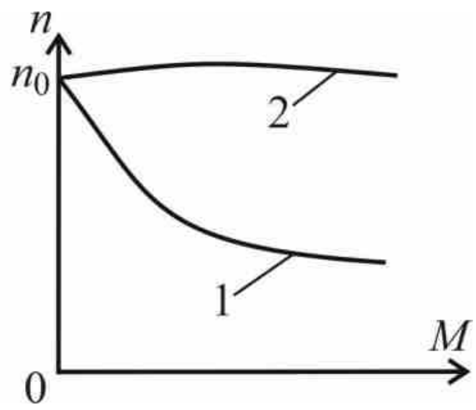


Figure 12.14

Test questions

1. *What are methods of excitation of DC electric machines?*
2. *What are the characteristics of a DC generator?*
3. *What are the self-excitation conditions of the shunt-wound generator?*
4. *What is principle of self-regulation of DCM?*
5. *What is the problem of DCM start-up?*
6. *What are the methods of DCM motor speed control?*
7. *What is the equation of the natural mechanical characteristic of the shunt-wound DCM?*
8. *What is the equation of the natural mechanical characteristic of the series-wound DCM?*
9. *What are peculiarities of the compound-wound DCM?*
10. *What is the formula for the no-load speed of DCM?*

LECTURE 13

THREE-PHASE INDUCTION MOTORS

Appointment and the construction of a three-phase induction motor (TIM)

Among motors the TIM have received the greatest (up to 80 %) distribution because of their low cost and reliability.

Induction machines (asynchronous machine) are referred to alternating current machines, the rotational speed of the rotor n_2 of which, at a constant frequency f of an alternating current of the source, varies with load and differs from the synchronous frequency, i.e. from the rotational frequency of the stator magnetic field n_1.

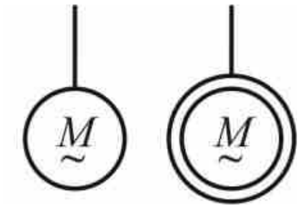


Figure 13.1

The TIM symbolic notation is shown in Fig. 13.1. Another name of the TIM is an asynchronous motor, asynchronous means non-simultaneous.

As well as all electric machines, the TIM are reversible, i.e. can work as both a generator and a motor. But induction generators are practically not applied.

The TIM consists of a fixed stator and a rotating rotor, separated by an air gap as shown in Fig. 13.2.

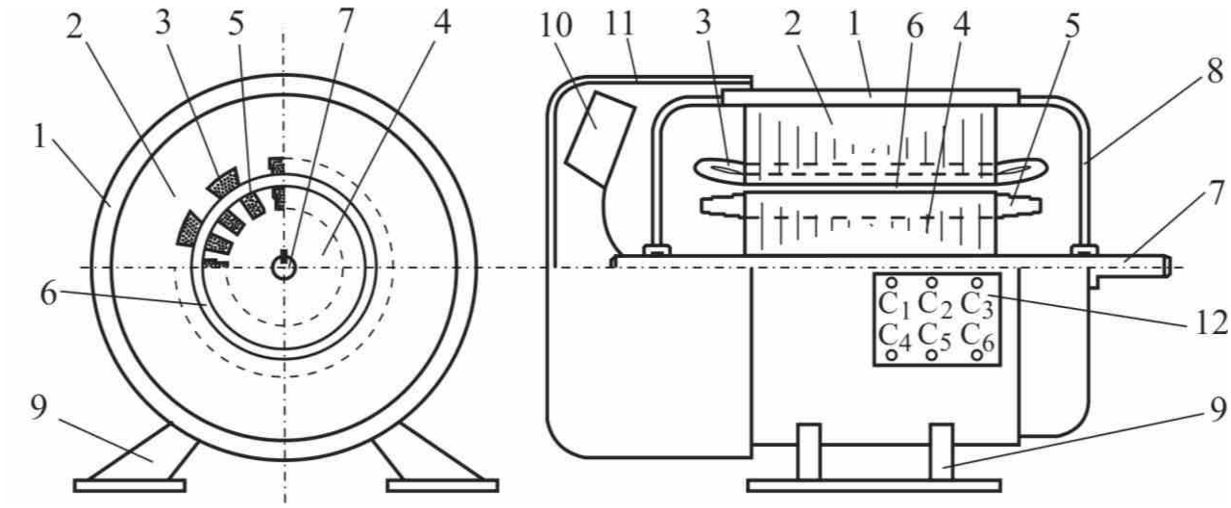


Figure 13.2

The STATOR consists of: 1 – enclosure (housing) is made from aluminum alloys with fins for cooling; 2 – stator core, stacked up from sheets of electrical steel and pressed into the frame; slots are stamped on the inner surface of the core, into which the three-phase stator winding 3 is placed;

The ROTOR consists of: 4 – laminated core, in the slots of which the rotor winding 5 is laid; a small air gap is executed between the rotor and the stator 6. The core of the rotor 4 is mounted on the shaft 7. The stator is supported by the bearing shields 8, and the enclosure 1 is fastened to the base with the help of the lugs 9. On one side of the rotor, the fan 10 is fixed on the shaft, closed by a thin fan case 11.

The leads of the stator winding 3 are connected to the terminal box 12. This winding is three-phase. Actually we can consider it as three connected windings. The axes of the individual windings (phases) are located relative to each other at an angle of 120°. Between themselves the windings are connected in "star" or "delta" (Fig. 13.3).

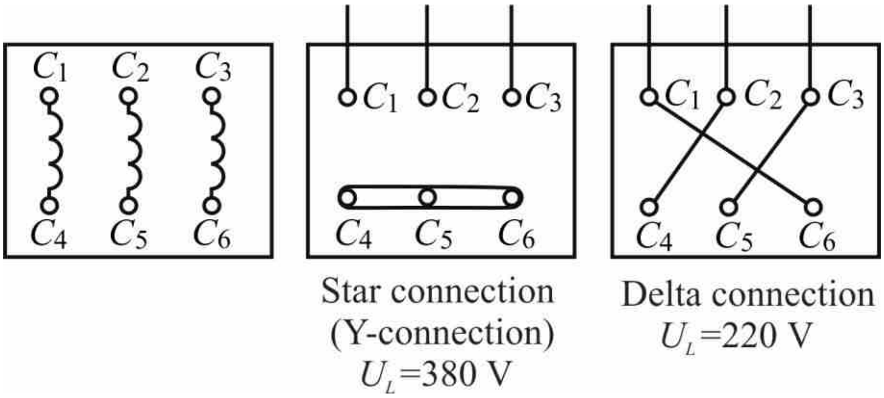


Figure 13.3

The rotor can be made as a squirrel-cage rotor (cage rotor) (Fig. 13.4) or a wound-rotor (Fig. 13.5).

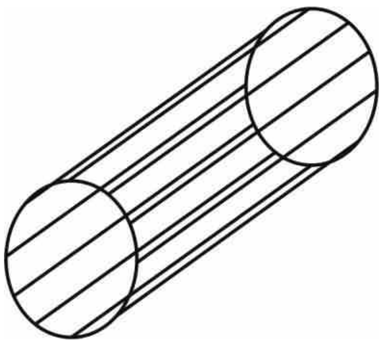


Figure 13.4

In a *squirrel-cage* rotor, the winding is executed like a squirrel cage. In the slots of the rotor core are placed (poured) aluminum or brass rods, which are connected at the ends by rings.

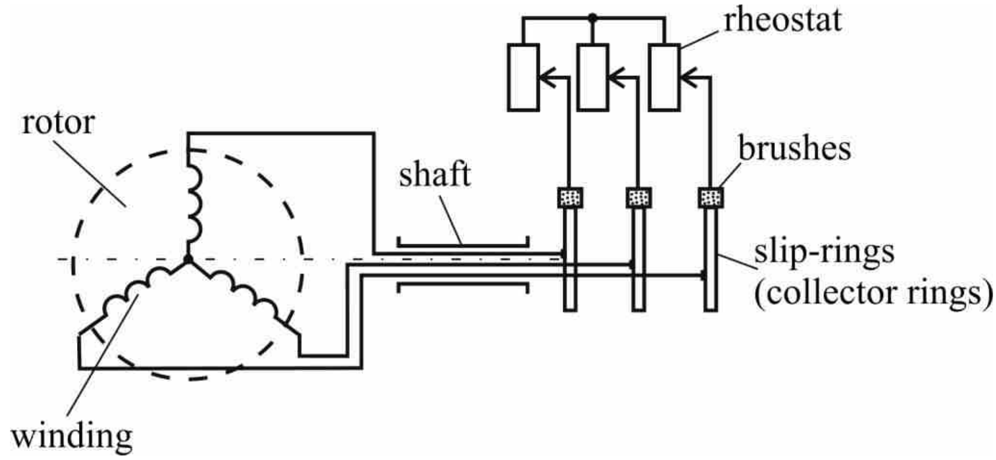


Figure 13.5

In a *wound-rotor* TIM with contact (slip) rings, a three-phase winding is laid in the slots of the rotor, which is usually connected in star. The beginnings of each phase are connected to three contact rings that are mounted on the rotor shaft. Thus, with the help of brushes, the rotor winding can be connected to an external circuit, namely, a start-regulating rheostat.

Rotating magnetic field

Inherently of the TIM work is use of a rotating magnetic field which is created by the three-phase stator winding. To create the rotating magnetic field, two conditions are necessary:

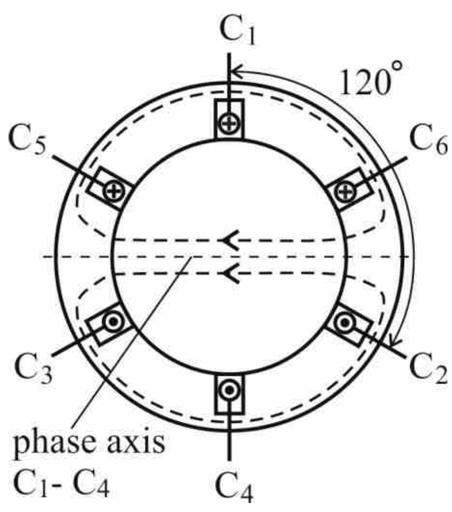


Figure 13.6

1) *a spatial shift* between the phases creating a magnetic field;

2) *a phase* (*time*) *shift* between the phases.

In the TIM structurally the phases axes rotated relative to each other by 120°. A phase shift between the currents, and hence the fields of the phases, occurs when these phases are connected to a three-phase network. When connected to a three-phase network, the currents of the phases are shifted by 120° (Fig. 13.7):

$$i_A = I_m \sin \omega t\,;\; i_B = I_m \sin\left(\omega t - 120^{\circ}\right);;\; i_C = I_m \sin\left(\omega t + 120^{\circ}\right). \qquad (13.1)$$

The same can be written for their magnetic fields:

$$B_A = B_m \sin \omega t\,;\; B_B = I_m \sin\left(\omega t - 120^{\circ}\right);\; B_C = I_m \sin\left(\omega t + 120^{\circ}\right). \qquad (13.2)$$

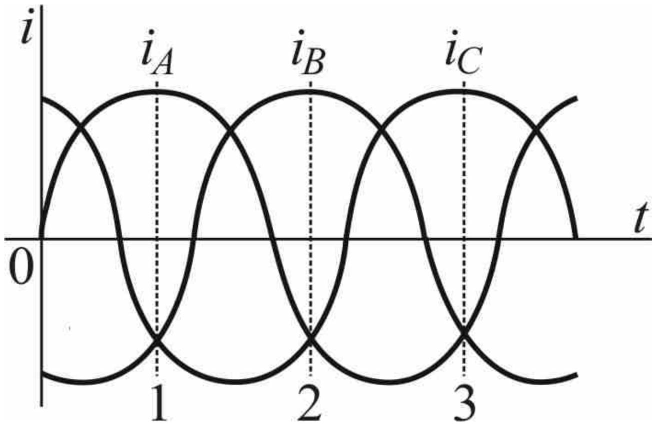


Figure 13.7

Fig. 13.8 shows the distribution of the magnetic field at three moments of time at the maximum currents in the phases. The resulting magnetic field phasor is $1{,}5B_m$ (where B_m is the field amplitude of one phase) and rotates with an angular speed ω towards a lagging phase. Such a rotating field is called a circular magnetic field.

To change the direction of the magnetic field rotation and the TIM rotor, it is necessary to change the phase sequence in two windings.

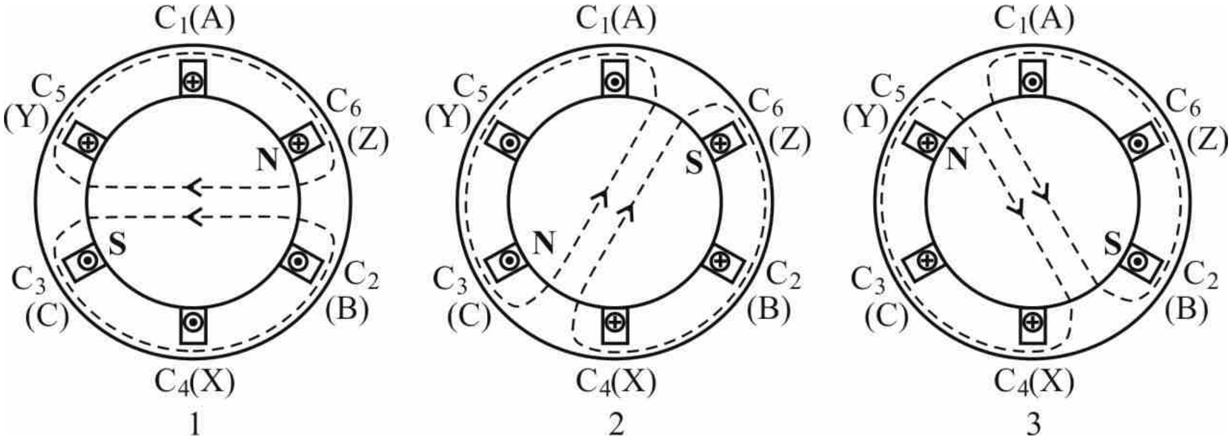


Figure 13.8

Generally, the speed (rotational frequency) of the stator magnetic field, rpm,

$$n_1 = \frac{60f}{p}, \tag{13.1}$$

where f is the frequency of a current in the stator winding;
p is a number of poles pairs of the stator.

The movement of the magnetic wave is accompanied by the movement of the magnetic poles N and S in the inner surface of the stator. The dependence of the magnetic field in the air gap is close to sinusoidal.

Principle of operation of the TIM

An alternating three-phase voltage is supplied to the stator windings, under the influence of which an alternating current flows in the windings (phases).

As currents in the phases are shifted in space and in time by 120° relative to each other, the magnetic field is formed, rotating with synchronous speed n_1 (13.1).

Under the action of this field, EMF will be induced in the conductors of the stator and rotor windings, respectively E_1 and E_2.

Since the rotor circuit is closed, under the influence of EMF E_2, current I_2 flows through the rotor winding. According to Ampere's law, a force will act on each rotor conductor, as a result of which the rotor will start to rotate.

Note that when the rotor is stationary, then each of its conductors is crossed by the field lines of force the maximum number of times.

Parameters of the TIM

All stator parameters have an index of 1, and the rotor has an index of 2. The rotor speed n_2 by the definition of the TIM is not equal to the speed of rotation of the stator magnetic field n_1, i.e. between them there is a relative speed $n_1 - n_2$. The concept of slip is introduced to estimate the relative speed

$$s = \frac{n_1 - n_2}{n_1}. \qquad (13.2)$$

The slip is a dimensionless quantity measured in %. The slip is approximately 5...7 %in the TIM.

Let's consider EMF in the windings. The rotating magnetic field of the stator induces EMF in each turn of its winding:

$$E_1 = 4{,}44\, f_1 \Phi_m w_1 k_{wc1}, \qquad (13.3)$$

where f_1 – the frequency of the applied voltage;

Φ_m – the maximum value of the magnetic field;

w_1 – the number of turns in the stator winding;

k_{wc1} – the winding coefficient (0,9... 0,8).

The winding coefficient arises due to the fact that usually the conductors are not in one but in several slots and the flux does not intersect them at the same time; there is a bevel of the slots – the inclination of their axis to the axis of the machine, and there is a shortening of the windings.

In the rotor the EMF has the form

$$E_2 = 4{,}44\, f_2 \Phi_m w_2 k_{wc2}, \qquad (13.4)$$

But the frequency of the current in the rotor is determined from the expression

$$n_1 - n_2 = \frac{60 f_2}{p}.$$

From here we obtain

$$f_2 = \frac{(n_1 - n_2)p}{60} \cdot \frac{n_1}{n_1} = \frac{pn_1}{60} \cdot \frac{n_1 - n_2}{n_1} = f_1 s$$

$$f_2 = f_1 s. \qquad (13.5)$$

Generally, for the TIM the slip is in the range 0... 1.

If the rotor is stationary: $n_2 = 0$, then $s = 1$ (*start-up of the TIM*).

If the rotor rotates at a speed of $n_2 = n_1$, then $s = 0$ (*ideal no-load duty*).

From the expression it follows that in a stationary rotor the EMF frequency will be equal to the frequency of the voltage applied.

The TIM is similar to a transformer, but with a rotating secondary winding.

$$E_2 = 4{,}44\, f_2 \Phi_m w_2 k_{wc2} = 4{,}44\, f_1 s \Phi_m w_2 k_{wc2} = E_{20} s, \qquad (13.6)$$

where $E_{20} = 4{,}44\, f_1 \Phi_m w_2 k_{wc2}$ –the EMF of a stationary rotor.

When the rotor is stationary (at the time of start-up), then s = 1 and the maximum EMF is induced in the rotor winding, and in the ideal no-load duty, when $n_2 = n_1$, this EMF is zero.

Resistance of the TIM windings

The resistance of the rotor R_2 does not change, while the inductance changes during operation

$$X_2 = \omega_2 L_2 = 2\pi f_2 L_2 = 2\pi f_1 s L_2 = X_{20} s, \qquad (13.7)$$

where $X_{20} = 2\pi f_1 L_2$ is the inductance of a stationary rotor (s = 1).

Thus, both E_2 and X_2 vary with speed.

For the transformer was and for the stator winding is saved

$$\underline{U}_1 = -\underline{E}_1 + \underline{I}_1 \underline{Z}_1 = -\underline{E}_1 + \underline{I}_1 (R_1 + jX_1). \qquad (13.8)$$

For the secondary winding of a transformer was $\underline{U}_2 = \underline{E}_2 - \underline{I}_2 \underline{Z}_2$.

But since this winding is short-circuited, then $\underline{U}_2 = 0$, and for the rotor winding

$$\underline{E}_2 = \underline{I}_2 \underline{Z}_2 = \underline{I}_2 R_2 + j \underline{I}_2 X_2. \qquad (13.9)$$

We rewrite the last expression:

$$\underline{E}_{20} s = \underline{I}_2 R_2 + j \underline{I}_2 X_{20} s \text{ or}$$

$$\underline{E}_{20} = \underline{I}_2 \frac{R_2}{s} + j \underline{I}_2 X_{20} = \underline{I}_2 \left(\frac{R_2}{s} + jX_{20} \right) = \underline{I}_2 \underline{Z}_2, \qquad (13.10)$$

where $\underline{Z}_2 = \dfrac{R_2}{s} + jX_{20}$.

From here we find the current in the winding of the TIM rotor in a complex form

$$\underline{I}_2 = \frac{\underline{E}_{20}}{\frac{R_2}{s} + jX_{20}}. \qquad (13.11)$$

Let's write down the module of this current

$$I_2 = \frac{E_{20}}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_{20}^2}}. \qquad (13.12)$$

Let's plot the dependence of this current on the slip in Fig.13.9

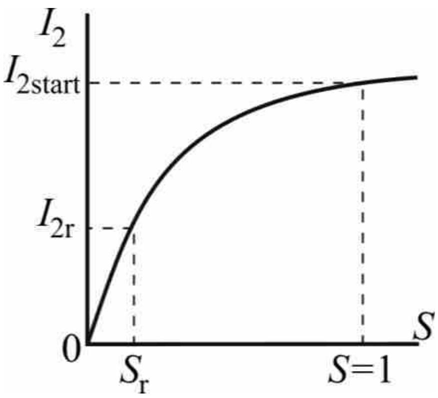


Figure 13.9

CONCLUSIONS:

1) the rated slip is not enough (5…8 %) and the rated current is small;

2) the starting current (at $s = 1$) is large – in 5 - 8 times higher than the rated current.

Thus, one of problems the TIM is a big starting current.

We plot a triangle of resistances for the TIM and its dependence on the slip (angle ψ_2 between the current and EMF).

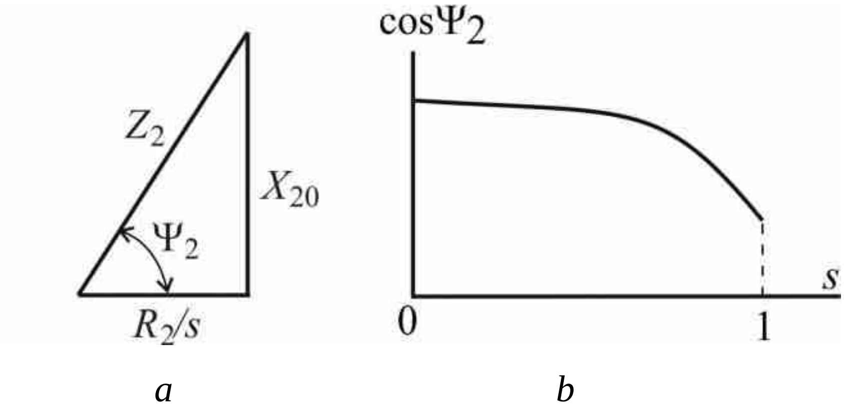


Figure 13.10

The power diagram of losses and efficiency of the TIM

The conversion of energy into the TIM is accompanied by power loss. The power diagram is shown in Fig. 13.11.

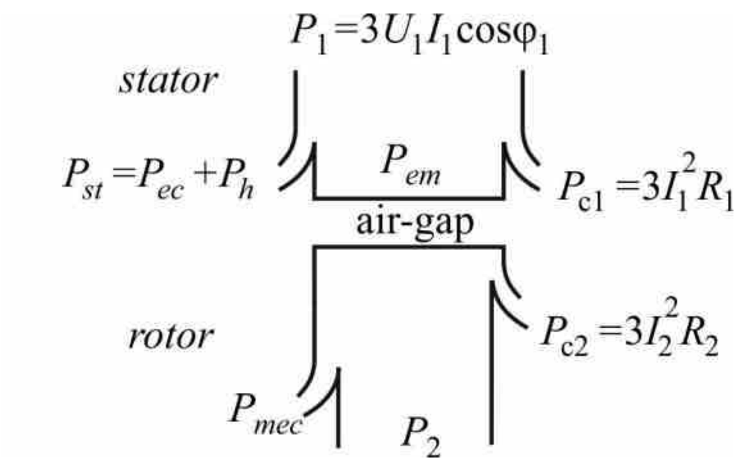


Figure 13.11

Electric power is applied to the TIM

$$P_1 = 3U_1 I_1 \cos\varphi_1 . \tag{13.13}$$

Magnetic losses P_{st} in the stator concern to eddy currents and hysteresis. Copper or electric losses in the stator winding are

$$P_{c1} = 3I_1^2 R_1 \tag{13.14}$$

Electromagnetic power is transmitted from the stator to the rotor through the air gap

$$P_{em} = P_1 - \left(P_{st} + P_{c1}\right) = E_{20} I_2 \, cos\,\Psi_2 . \tag{13.15}$$

P_2 is useful mechanical power on the shaft

$$P_2 = P_1 - \left(P_{st} + P_{c1} + P_{c2} + P_{mec}\right) \tag{13.16}$$

The mechanical losses P_{mec} caused by all kinds of friction

$P_{st} + P_{mec}$ – permanent loss, which is independent of the load. They are found out from the no-load duty test.

$P_{c1} + P_{c2}$ – variable losses depending on the load. They are found out from the test of short-circuit with a braked rotor and the rated currents of the stator and rotor.

The TIM efficiency

$$\eta = \frac{P_2}{P_1}. \qquad (13.17)$$

The dependence $\eta(P_2)$ is plot in Fig. 13.12

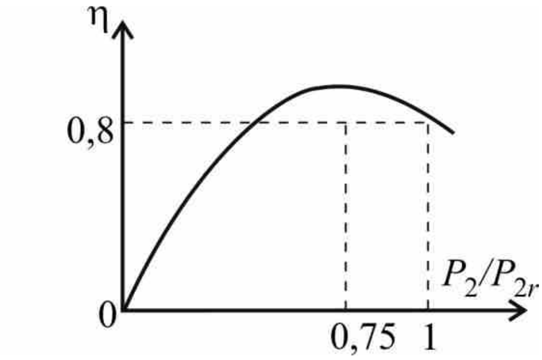


Figure 13.12

The TIM is designed so that the efficiency is maximum at load of 75 %, because more often they work with underloading.

Test questions

1. *What is the design of the TIM?*
2. *What are the kinds of the TIM rotor?*
3. *What can we get the rotating magnetic field?*
4. *What is the principle of operation of the TIM?*
5. *What is the slip of the TIM?*
6. *What is the formula for resistance of windings of the TIM?*
7. *What is the formula for inductance of windings of the TIM?*
8. *What is the formula for the rotor current?*
9. *What is the dependence of this current on the slip?*
10. *What is the power diagram of losses and efficiency of the TIM?*

LECTURE 14

TORQUE AND MECHANICAL CHARACTERISTIC OF THREE-PHASE INDUCTION MOTOR (TIM)

The rotating torque of the TIM is formed as a result of the interaction of the rotating magnetic field of the stator winding and the induced current flowing through the rotor winding.

Electromagnetic torque is equal to

$$M = \frac{P_{em}}{\omega_1}, \qquad (14.1)$$

where $\omega_1 = 2\pi f_1 = 2\pi \frac{n_1 p}{60}$ is the angular speed of rotation of the magnetic flux.

Electromagnetic power is equal to

$$P_{em} = E_{20} I_2 \cos\Psi_2, \qquad (14.2)$$

where $E_{20} = 4{,}44 w_2 f_1 \Phi_m k_{w2}$.

We substitute these values in the formula (14.1):

$$M = \frac{4{,}44 w_2 f_1 \Phi_m k_{w2}}{\frac{2\pi n_1 p}{60}} I_2 \cos\Psi_2 = C_M^{'} \Phi_m I_2 \cos\Psi_2$$

$$M = C_M^{'} \Phi_m I_2 \cos\Psi_2. \qquad (14.3)$$

The rotating torque of the TIM is proportional to the magnetic flux of the stator and the active component of the rotor current.

Let's make the further transformations. We represent the input quantities into this formula like that:

$$\cos\Psi_2 = \frac{R^{'}}{Z^{'}} = \frac{R_2/s}{\sqrt{\left(R_2/s\right)^2 + X_{20}^2}}; \qquad (14.4)$$

$$\Phi_m = \frac{E_1}{4{,}44 w_1 f_1 k_{w1}} \approx \frac{U_1}{4{,}44 w_1 f_1 k_{w1}}; \tag{14.5}$$

$$I_2 = \frac{E_{20}}{\sqrt{\left(R_2/s\right)^2 + X_{20}^2}}. \tag{14.6}$$

But $E_{20} = 4{,}44 w_2 f_1 \Phi_m k_{w2}$ and $E_1 = 4{,}44 w_1 f_1 \Phi_m k_{w1}$, from here $E_{20} = \frac{w_2 k_{w2}}{w_1 k_{w1}} E_1$.

As $E_1 \approx U_1$, we obtain

$$I_2 \approx \frac{w_2 k_{w2}}{w_1 k_{w1}} \cdot \frac{U_1}{\sqrt{\left(R_2/s\right)^2 + X_{20}^2}}. \tag{14.7}$$

We substitute values (14.4), (14.7) in (14.3), and we obtain

$$M = C_M U_1^2 \frac{R_2/s}{\left(R_2/s\right)^2 + X_{20}^2}. \tag{14.8}$$

From the given formula follows that the torque of the TIM is proportional to a square of the applied voltage. Having substituted a sequence of values s, we will obtain the dependence $M(s)$ which is called a mechanical characteristic (Fig. 14.1).

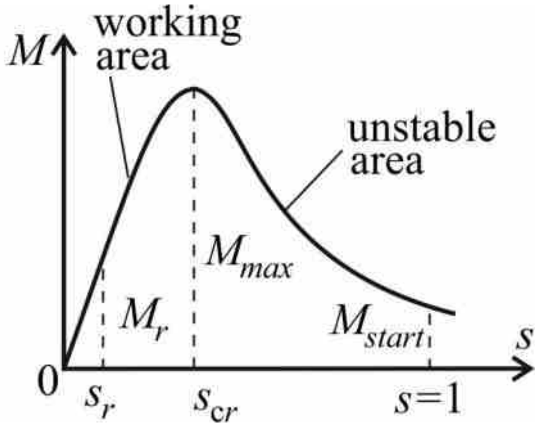
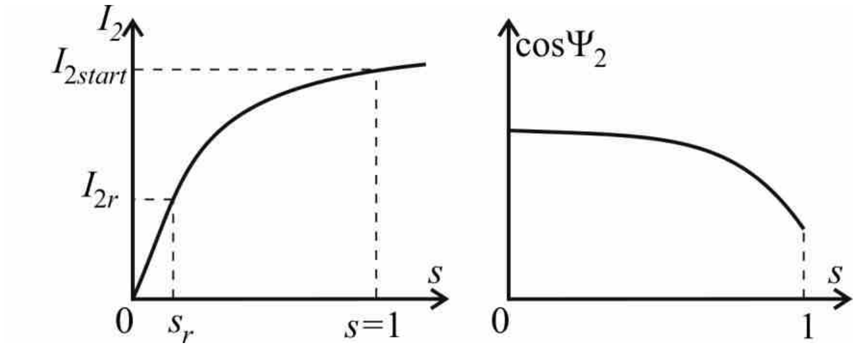


Figure 14.1



a *b*

Figure 14.2

At the time of start-up at s = 1, the starting torque generated by the TIM M_s is small, although the rotor current is maximum. The small starting torque is caused by the large inductance of the rotor and low value $\cos\Psi_2$.

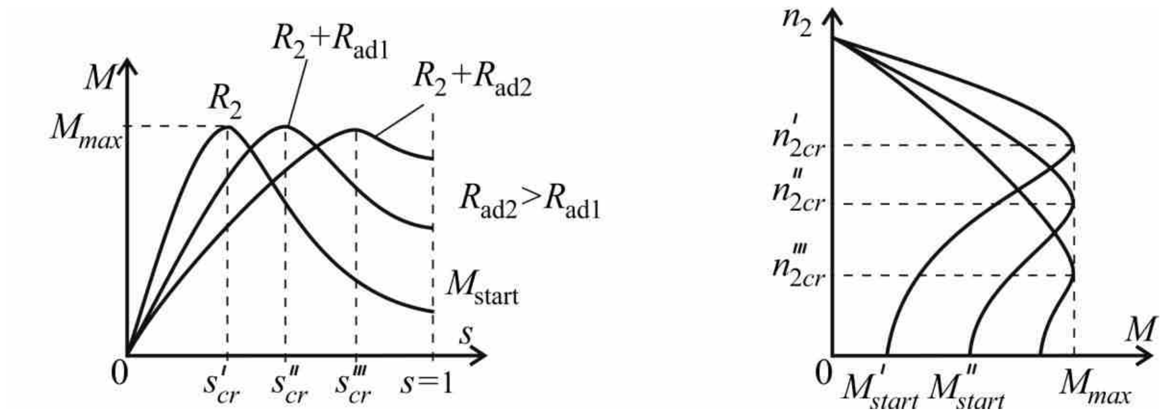
If $M_s > M_b$, then the rotor starts to rotate.

As the rotor accelerates, the slip decreases, and therefore, the inductance decreases and $\cos\Psi_2$ increases.

At some $s = s_{cr}$ the motor generates the greatest torque $M_{\max}$.

With a further decrease in the slip s, the value $\cos\Psi_2$ changes little and the torque decreases due to a decrease in the rotor current.

The magnitude of the maximum torque (breakdown torque) $M_{\max}$ does not depend on the value of the rotor resistance, therefore, if you add additional resistance to the rotor circuit, the maximum torque will not change, but the maximum will come at a larger slip value.



a *b*

Figure 14.3

$$s = \frac{n_1 - n_2}{n_1} \;\Rightarrow\; n_2 = n_1(1 - s) \qquad (14.9)$$

It is possible to change the resistance of the rotor circuit in the TIM with a phase rotor. By changing the resistance of the rotor circuit, we can choose such value of the auxiliary resistance R_d so that when a starting motor generates the most maximal torque.

Ways of start-up of induction motors

The TIM at start-up has two problems:

1) a small starting torque M_s;

2) a big starting current I_s.

If the starting (peak) torque M_s the motor accelerates for a long time that reduces its productivity. The big starting current I_s badly influences an external network – a voltage drop is possible.

1. *DIRECT START-UP*

When starting a squirrel-cage rotor, direct start-up is used (Fig. 14.4). Voltage of a network is equal to the rated voltage of the TIM directly supplied to the stator winding.

This starting method is used for a low power TIM.

If the TIM power P > 100 kW, then the TIM start is carried out at low voltage.

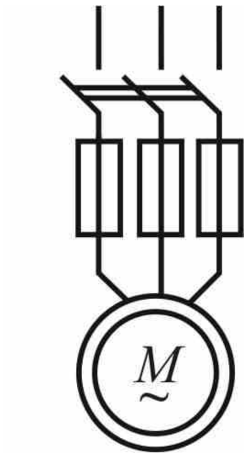


Figure 14.4

2. *AUTOTRANSFORMER WAY OF START-UP*

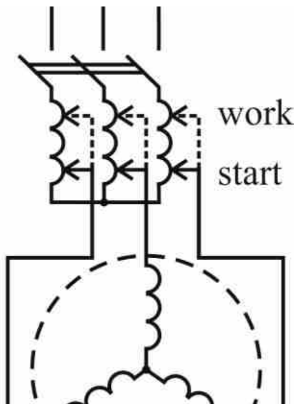


Figure 14.5

An autotransformer is connected to the stator winding (Fig. 14.5). At the time of the start-up stator voltage of the TIM

$$U_{TIM} = \frac{U_{network}}{k_A}, \qquad (14.10)$$

where $U_{network}$ – network voltage; k_A – transformation ratio of an autotransformer.

Accordingly, the starting current

$$I_s = \frac{I_{TIM}}{k_A} = \frac{1}{k_A}\frac{U_{TIM}}{Z_{TIM}} = \frac{1}{k_A}\frac{1}{Z_{TIM}}\frac{U_{network}}{k_A} = \frac{1}{k_A^2}\frac{U_{network}}{Z_{TIM}}, \qquad (14.11)$$

where I_{TIM} – a stator current of the TIM, A; Z_{TIM} – impedance of the TIM, Ω.

Hence the starting current decreases in k_A^2 time.

Let's notice that as $M \sim U^2$, hence the starting torque also decreases in k_A^2 time.

Therefore, such way of start-up is possible only at start-up of the TIM without a load, i.e. a no-load duty.

3. *START-UP BY SWITCHING OF STATOR WINDING FROM STAR TO DELTA*

If during the operation of the TIM the stator winding should be connected by delta, then during start-up it is connected by star as shown in Fig. 14.6.

In this case, the voltage of the TIM decreases in $\sqrt{3}$ times, and the starting current and starting torque are reduced by 3 times.

In position 1, the stator winding is connected by star at start-up. When the speed of the TIM is approximately equal to the nominal, the switch is switched to position 2.

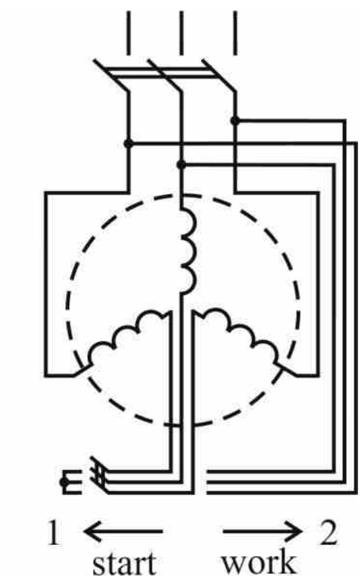


Figure 14.6

4. *START-UP OF THE TIM WITH A WOUND-ROTOR*

To improve the starting characteristics, the TIM is performed with a phase rotor (see Fig. 13.5).

The start of the TIM with a phase rotor is performed manually or automatically.

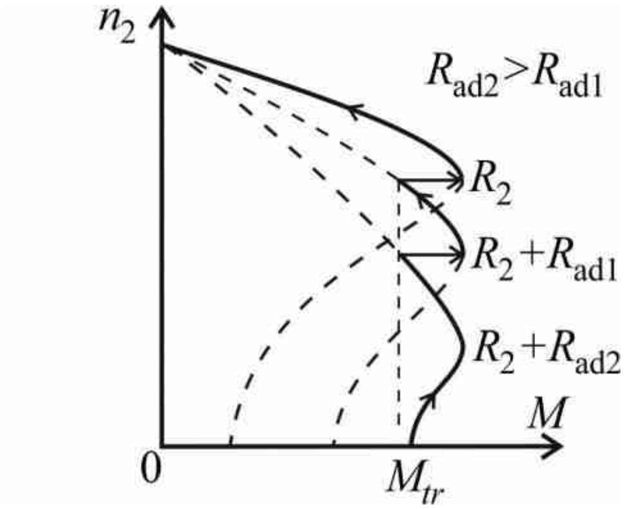


Figure 14.7

Manual start is carried out using a starting rheostat. At the given M_{tr} torque (Fig. 14.7), the transition from one characteristic to another occurs when the corresponding rheostat stage is excluded (its resistance decreases).

When starting the TIM, the resistance of the starting rheostat R_{ad2} is selected so that the starting current does not exceed the allowable value and that the starting torque of the TIM is equal to the maximum.

Then the first stage of the starting rheostat is displayed and its resistance decreases to R_{ad1}. In this case, the motor moves to the next characteristic, etc. to the complete exclusion of the starting rheostat $R_{ad} = 0$.

The rheostat setting into the rotor circuit allows:

1) to reduce the starting current of the motor;

2) to increase the starting torque of the motor.

Speed control (regulation of rotational frequency) of the TIM

Reverse of a motor is a change of the direction of rotation on the opposite.

The rotor is carried away by a rotating field, the direction of which is determined by the order of phase rotation of the three-phase stator winding.

Therefore, in order to reverse the TIM, it is necessary to change the direction of rotation of its magnetic field. For this purpose, it is enough to change places of any two wires connecting the three-phase stator winding to the network.

To select a method of the speed control, we use the formulas:

$$s = \frac{n_1 - n_2}{n_1} \text{ and } n_1 = \frac{60 f_1}{p},$$

whence

$$n_2 = n_1(1-s) = \frac{60 f_1}{p}(1-s). \quad (14.12)$$

1) frequency regulation (changing the frequency of the applied voltage mains). We have a network frequency of 50 Hz. It can be carried out:

a) by changing the speed of the synchronous generator - possibly in self-contained units.

b) using a frequency converter (thyristor and transistor frequency converters). The most promising but also is quite expensive way. The reliability of these converters is still insufficiently high.

2) poles regulation (by changing the number of pole pairs).

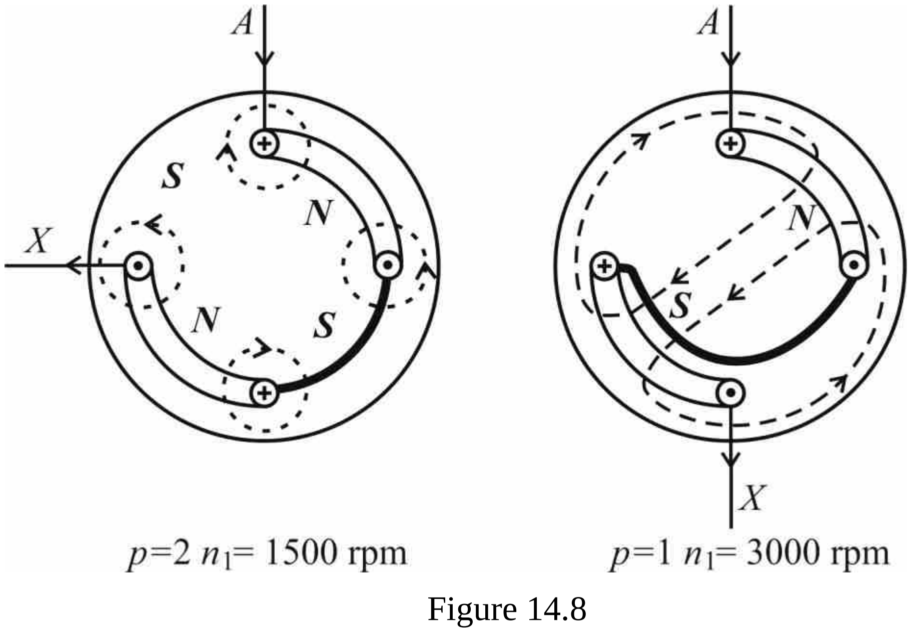


Figure 14.8

Technically this method is implemented:

a) in the slots two windings with different numbers of *p*. But this is disadvantageous, because increases the cost and size of the TIM;

b) by switching the coils to change the width of the poles of the stator field (Fig.14.8). In the first case, the coils of each phase are connected in series, and in the second, in parallel. As a result, the direction of the current in the conductors that make up the phase winding changes, and the topography of the magnetic field becomes different.

These are the so-called multi-speed motors.

3) rotary regulation (an auxiliary way).

It is implemented by a rheostat introducing with resistance R_d into the rotor winding circuit.

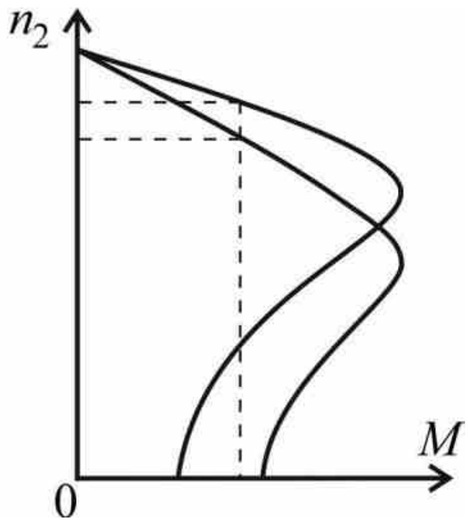


Figure 14.9

At $R_d \uparrow \Rightarrow n_2 \downarrow$ as shown in Fig.14.9. It is possible to change the speed in the range of 3... 5 %.

3) changing of applied voltage to the motor. At $U \downarrow \Rightarrow n_2 \downarrow$. But, thus, $M \sim U^2$ that leads to electromagnetic torque decrease (Fig. 14.10).

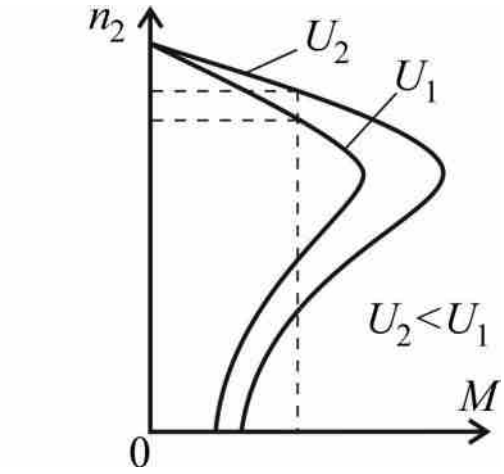


Figure 14.10

Brake duties of the TIM

Consider electrical braking methods:

1) *an opposition switch*;

It occurs when the rotor, under the influence of an external torque, rotates against the magnetic field of the machine. Switching on the motor two phases of the stator winding, which leads to a rapid change in the direction of field rotation, acting against the inertia-rotating rotor. At a rotational speed equals to zero, it is necessary to disconnect the motor from the network. Disadvantage of the method is increased power consumption from the network and possible overheating of the motor windings.

2) *a generator braking*;

It is accompanied by return of the motor energy in the network, and therefore it is also called as recuperative. It is possible under a condition if the rotor overtakes the stator magnetic field field статора ($n_2 > n_1$) that corresponds to negative slip.

Probably also, if the TIM to be switched on the move to smaller number of pairs poles: it was for example ($p = 1$, $n_1 = 3000$ rpm), and becomes ($p = 2$, $n_1 = 1500$ rpm). This is incomplete braking. Kinetic energy of a rotating rotor is given to the network in the form of electric power.

3) *a dynamic braking*;

It is made by disconnecting the stator winding from the network and connecting it to a DC source. The winding wires of an inertia-rotating rotor (short-circuited) will intersect the stator's constant and non-space-moving magnetic field, and induction currents will appear in them, the interaction of which with the machine field creates a braking torque.

4) a capacitor braking;

For a low power TIM. The motor operates in a generator duty with self-excitation from a parallel capacitor bank (Fig. 14.11).

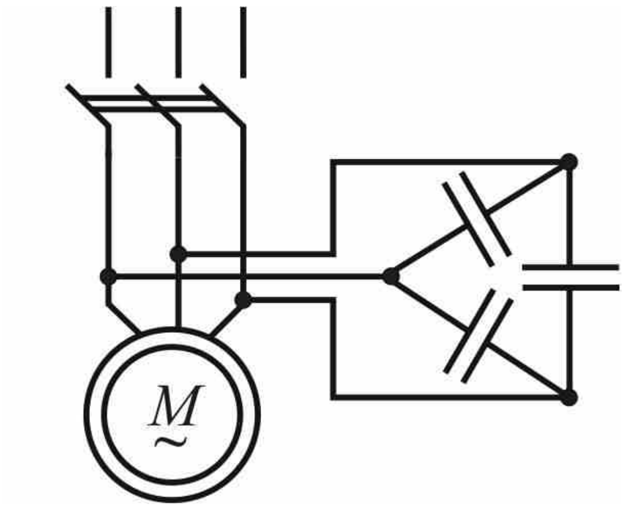


Figure 14.11

Braking does not occur until it stops completely (up to 0,2 ... 0,6 n_1). Finally, it can be braked by a dynamic braking or short-circuited winding of the stator.

Test questions

1. *What is the formula for electromagnetic torque of the TIM?*
2. *What is called the mechanical characteristic of the TIM?*
3. *What are the problems of the TIM at start-up?*
4. *What are the ways of start-up of induction motors?*
5. *How do speed control methods of the TIM realize?*
6. *What brake duties of the TIM do you know?*

LECTURE 15

THREE-PHASE SYNCHRONOUS MACHINES. APPOINTMENT, CONSTRUCTION AND PRINCIPLE OF OPERATION. SYNCHRONOUS GENERATOR

Synchronous machines (SM) are used as generators, motors and AC compensators. Synchronous compensators are used to compensate for the inductive phase shift, where they are capacitive reactive power generators. Synchronous (Greek "simultaneous") is called an electric machine of alternating current, a speed of rotation of the rotor of which is equal to the frequency of stator magnetic field. The last one n_0 is called a synchronous speed:

$$n_0 = \frac{60\,f}{p}; \;\; f = \frac{n_0\,p}{60}, \text{ since } f\text{=50 Hz}$$

$$n_0 = \frac{3000}{p}, \tag{15.1}$$

where p is a number of poles pairs.

The construction of the synchronous machine

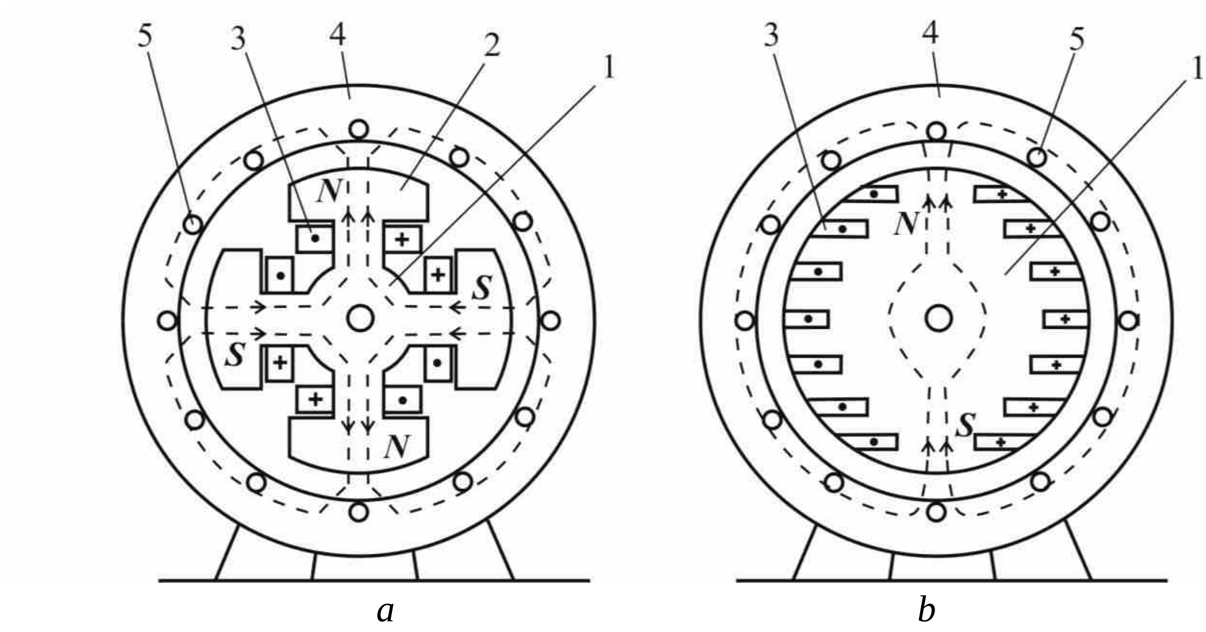


Figure 15.1

The synchronous machine consists of a rotating rotor (inductor) (1) and a fixed stator (armature) (4) as it shown in Fig. 15 *a*, *b*. The SM stator is made exactly the same as the stator of an induction motor. According to the construction of the rotor, the machines are divided into (Fig. 15.1, *a*) salient-pole machines and (Fig. 15.1, *b*) non-salient pole ones.

The SM with a salient pole rotor is a slow-moving machine (the number of pole pairs is p ~ 100). The generator is driven by a water turbine. This is a hydro-generator.

The SM with a non-salient pole rotor is a high-speed machine (the number of pole pairs $p = 1$). The generator is driven by a steam turbine. This is a turbo-generator.

Thus, depending on the type of drive motor, synchronous generators (SG) are divided into turbo-generators and hydro-generators.

The salient pole rotor consists of the rotor housing (1), which is mounted on the shaft. Poles (2), which are always made laminated, are fastened to the housing. An excitation winding (3) is wound around the poles. The stator consists of a laminated steel core (4), in the internal slots of which a three-phase winding (5) is laid.

A direct current is supplied to the excitation winding through rings and brushes mounted on the shaft. The poles are electromagnets that create the main magnetic flux. A non-salient pole rotor is a massive forged cylinder.

Excitation of the SM

a) a separate excitation is powered by an exciter (a direct current generator) (Fig. 15.2);

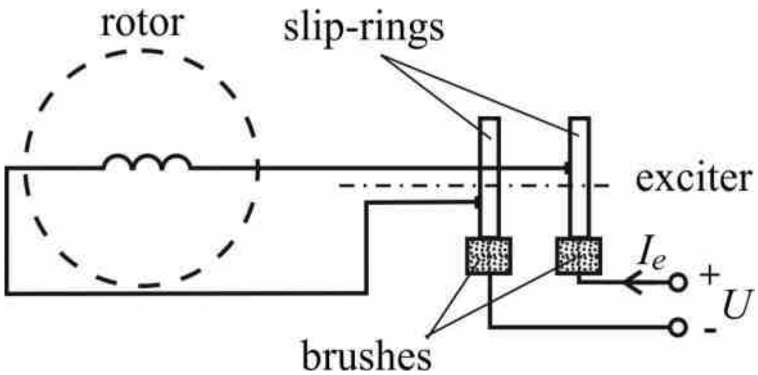


Figure 15.2

b) self-excitation – a three-phase voltage supply is at the stator winding, the voltage is rectified by a three-phase rectifier and supply the rotor excitation winding.

Operating principle of the SG

The excitation winding creates the main magnetic flux Φ. The pole pieces are designed so that the induction in the air gap has a sinusoidal character. In this case, when the rotor rotates, a sinusoidal EMF will be induced in the three-phase stator winding according to Faraday's law of induction.

The effective value of the EMF of one phase of the stator winding is determined by the expression

$$E = 4{,}44 w f \Phi_m k_{w1} \,, \qquad (15.2)$$

where k_{w1} is the winding coefficient;

w is the number of turns of the stator winding;

Φ_m is the peak value of the magnetic flux.

In the SG the frequency is strictly constant $f = \dfrac{pn}{60}$. Then $E = 4{,}44 w \dfrac{pn}{60} \Phi_m k_{w1}$, or

$$E = c_E n_0 \Phi_m , \qquad (15.3)$$

where c_E – coefficient, constant for a given motor

Since the rotor speed n_0 = const , the EMF E is determined by the magnitude of the magnetic flux Φ and the sinusoidal character of a magnetic induction in the air gap of the machine.

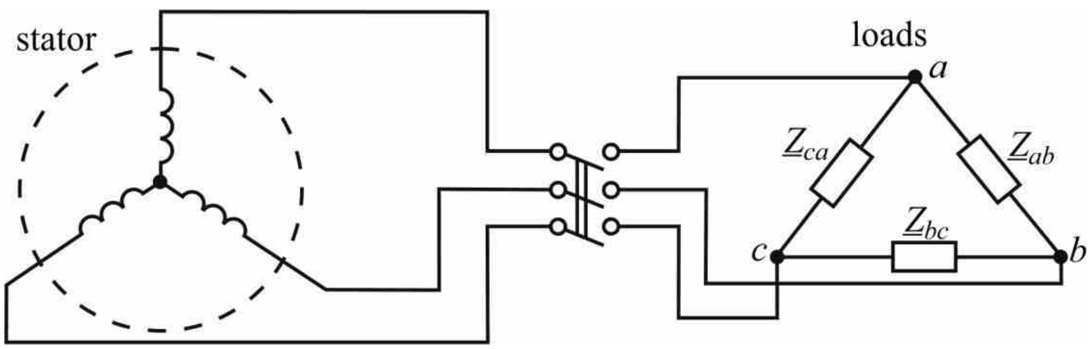


Figure 15.3

No-load of the SG is such a duty of its operation, in which the external circuit of the stator winding is open and I = 0. Current flows only in the excitation winding. In this duty, I_{EW} creates the main magnetic flux Φ_0.

Under load, a current will flow through the stator winding, which creates a rotating magnetic field. This field rotates at the synchronous speed

$$n_0 = \frac{60\,f}{p}, \tag{15.4}$$

and therefore, the rotor field and the field created by the stator winding are motionless relative to each other.

Armature reaction in the synchronous generator

By the armature reaction we mean the effect of the magnetic field of the stator on the main magnetic field of the machine. In DC machines, the response of the armature depends only on the magnitude of the armature current. In the SG, the reaction of the armature depends not only on the magnitude of the stator current, but also on the nature of the load.

A resistive load (Ψ = 0°)

Ψ is the phase angle between the EMF E and the stator current I. A quadrature-axis armature reaction is relative perpendicular to the axis of the poles of the rotor as shown in Fig. 15.4 *a*.

A resistive-inductive load (Ψ = 90°)

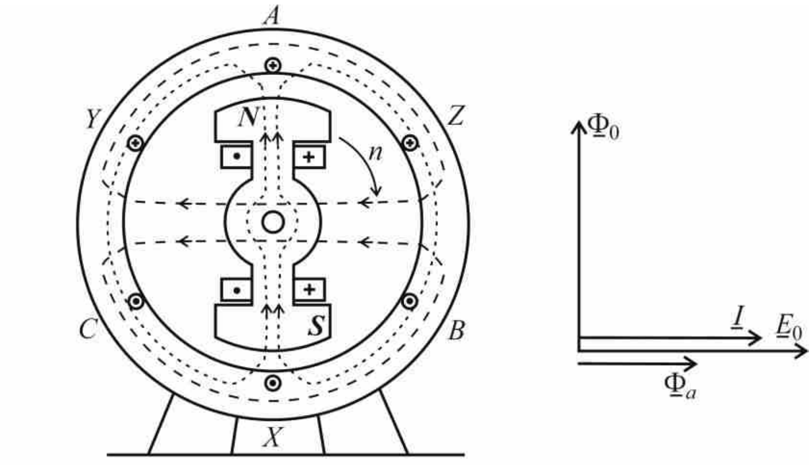
EMF E will be the same, and current I will lag behind E by 90°. This is a longitudinally demagnetizing reaction of the armature (Fig. 15.4, *b*). The axes of the fields coincide, but the stator field acts counter to the rotor field. The resulting field, the flux and the EMF of a SG phase are significantly reduced.

A resistive-capacitive load (Ψ = – 90°)

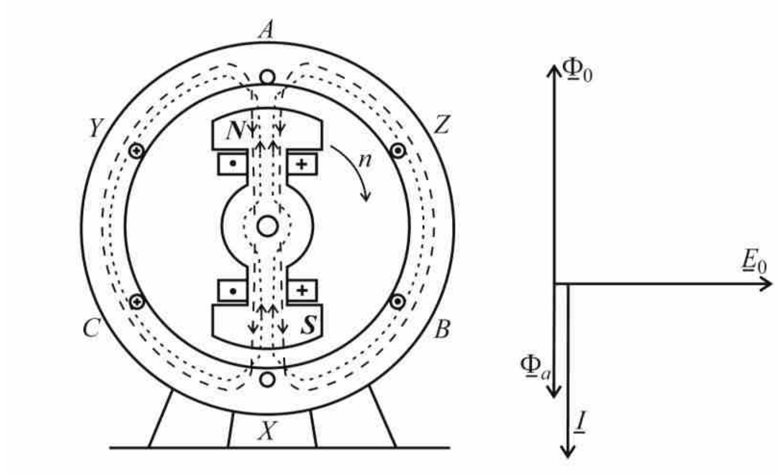
EMF E will be the same, and current I will be ahead of E by 90°. This is the longitudinally magnetizing reaction of the armature (Fig. 15.4, *c*).

The axes of the fields coincide, but the stator field acts according to the rotor field. The resulting field, the flux and the EMF of a SG phase increase significantly. Thus, in a synchronous generator, the nature of the reaction of the armature is determined by the nature of the load.

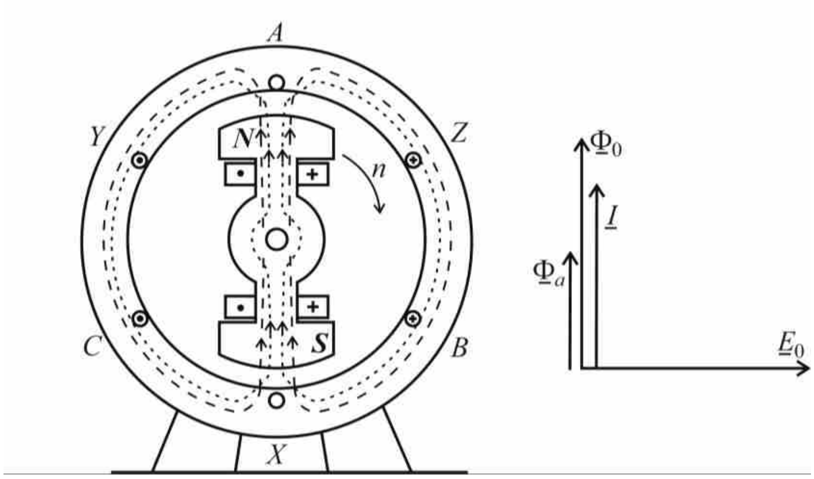
In the general case, a SG load is mixed, therefore, the active component of the current provides the flux of a quadrature-axis armature reaction, and the reactive component of the current provides the flux of a longitudinal reaction of the armature.



a



b



c

Figure 15.4

The equation of electrical state and phasor diagram of the SG

The most important thing in the SG is to generate voltage, which is induced in the conductors of the stator windings. Although physically in the SG the rotor field and the stator field form a single resulting machine field, and the stator has a leakage flux, when determining the voltage across the generator poles, it is advisable to consider their action separately, and the phenomenon of armature reaction without taking into account core saturation.

Each of the SG magnetic fields is coupled to a three-phase stator winding and creates its own EMF.

The following fluxes are distinguished:

- the excitation winding flux Φ_0 induces E_0;

- the armature reaction flux Φ_a induces $\underline{E}_a = -j\underline{I}\,\underline{X}_a$, where $\underline{X}_a$ is the inductance of the armature reaction;

- leakage flux Φ_s induces a leakage flux EMF $\underline{E}_s = -j\underline{I}\,\underline{X}_s$, where $\underline{X}_s$ is dissipation inductance of the stator winding.

According to voltage Kirchhoff's law for one phase of the stator winding, we can write

$$\underline{E}_0 + \underline{E}_a + \underline{E}_s = \underline{I}R + \underline{I}\,\underline{Z}_l = \underline{I}R + \underline{U}\,, \qquad (15.5)$$

where Z_l is the load resistance, R is the stator winding phase resistance.

$$\underline{U} = \underline{E}_0 + \underline{E}_a + \underline{E}_s - \underline{I}R = \underline{E}_0 - j\underline{I}\left(X_a + X_s\right) - \underline{I}R = \underline{E}_0 - j\underline{I}X_c - \underline{I}R, \qquad (15.6)$$

where $X_c = X_a + X_s$ is the synchronous inductance of the stator winding;

Usually $R << X_c$. The voltage drop of the stator winding IR can be neglected. Finally, we obtain

$$\underline{U} = \underline{E}_0 - j\underline{I}X_c\,. \qquad (15.7)$$

This equation corresponds to the equivalent circuit and phasor diagram shown on Fig. 15.5, *a,b*, where the Φ_a, Φ_s phasors are in phase with the I current phasor. The Φ_0 phasor is ahead of EMF E_0 by 90°. The phasor diagram is based on the E_0 EMF of the SG.

To construct the voltage U phasor from the end of the phasor E_0, we lay the phasor jXI is perpendicular to the current I phasor. Between the U voltage phasor and the I current phasor is an angle φ.

Between the E_0 phasor and the U phasor the angle θ is the angle of departure of the SG. The physical sense of the angle of departure is the angle between the axis of poles of the rotor and the axis of conditional poles of the stator (Fig. 15.6).

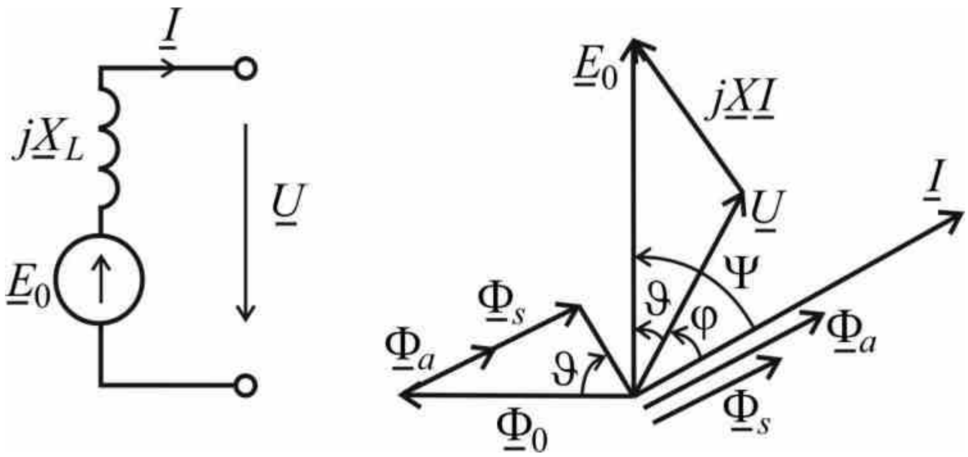


Figure 15.5

$$\Psi = \theta + \varphi. \tag{15.8}$$

For an active-inductive load, I phase lags from E_0 by an angle:

$$\Psi = \mathrm{arctg}\frac{X + X_l}{R + R_l}, \tag{15.9}$$

where R, X is the internal resistance and reactance of the SG (indicated in the catalogue). R_l, X_l are load resistance and reactance.

In a generator duty, the rotor is leading, and the driven one is the resulting magnetic flux of the air gap along the stator surface, rotating synchronously with the rotor.

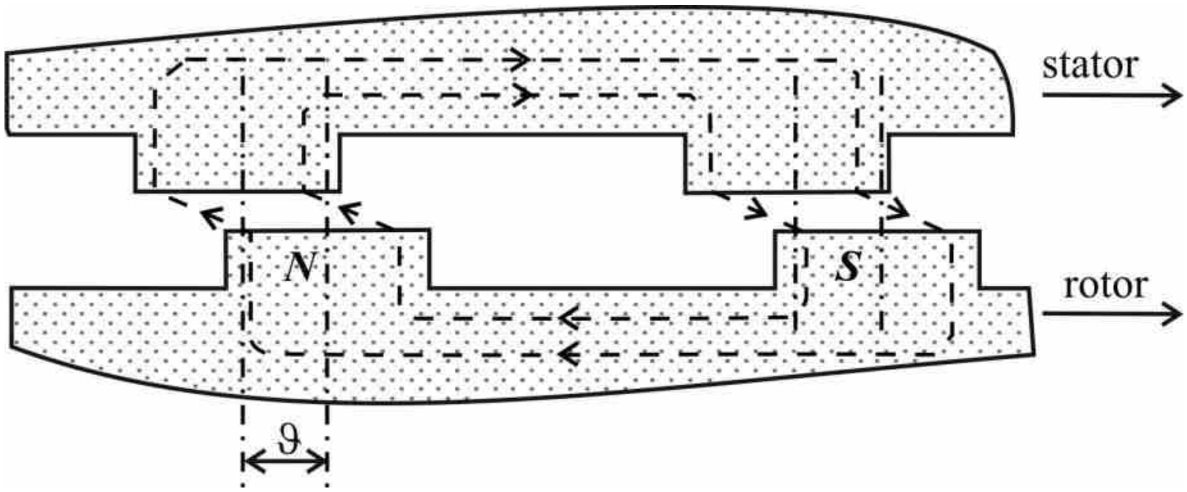


Figure 15.6

Test questions

1. What is called as a synchronous machine?

2. What is the construction of a synchronous machine?

3. What kinds of excitation of a synchronous machine do you know?

4. What is formula for the synchronous speed?

5. *What is the principle of operation of synchronous generators?*

6. What are the equation of an electrical state and the phasor diagram of the SG?

LECTURE 16

CHARACTERISTICS OF THE SYNCHRONOUS GENERATOR. ELECTROMAGNETIC POWER. REGULATION OF ACTIVE AND REACTIVE POWER

The properties of the synchronous generator (SG) are judged by its characteristics.

1. *No-load characteristic* (Fig. 16.1):

$E\ (I_{EW})$ at $I = 0$ and *at* $n = n_r$.

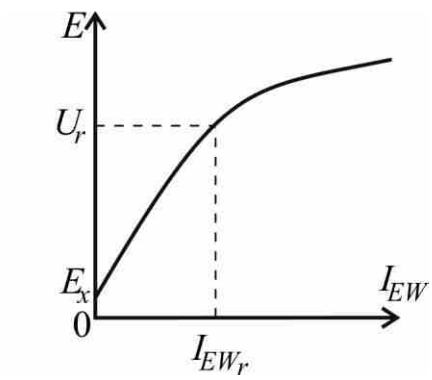


Figure 16.1

At $I_{EW} = 0$, a small EMF E_x is induced by the residual magnetic flux. When $I_{EW}\uparrow \Rightarrow \Phi_0 \uparrow \Rightarrow E\uparrow$, because $E = c_E n\Phi$.

There comes a saturation of the magnetic circuit – a curve break. The point (U_r, I_r) (the rated values) is located before saturation. That's the way the SG is designed.

2. *External characteristic* (Fig. 16.2):

$U\ (I)$ *at* $I_{EW} = I_{EWr}$ (rated); $\cos\varphi = \text{const}$; $n = n_r$. for $I = 0$, $U = U_0$.

$$\underline{U} = \underline{E}_0 + \underline{E}_a + \underline{E}_s - \underline{I}R$$

$$\underline{U} = \underline{E}_0 - j\underline{I}X_S - \underline{I}R,$$

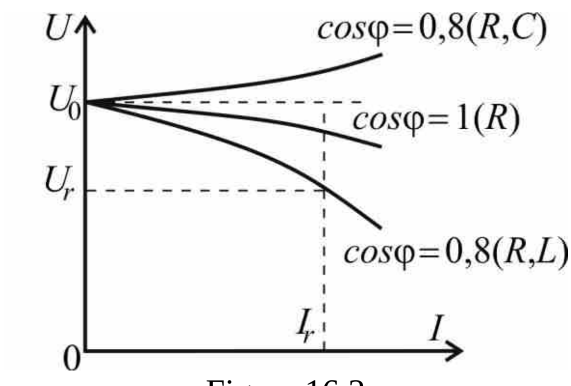


Figure 16.2

where X_S – synchronous reactance of stator windings of the SG.

With increasing current I at an active load, the voltage U drops.

The change in voltage occurs mainly due to the armature reaction. If the load is active, then the flux changes slightly. With an active-inductive load, the armature reaction is longitudinally demagnetizing. The flux varies significantly, which leads to a strong change in voltage. With an active-capacitive load, the armature reaction will be longitudinally magnetizing, the flux will increase, which leads to a small increase in voltage. Voltage stabilization is achieved by regulating the excitation current $I_{EW.}$

3. *Adjusting characteristic* (Fig. 16.3):

I_{EW} (I) at U = const; cosφ = const; $n = n_r$. $U = U_r$.

This characteristic shows how to regulate the excitation current I_{EW} when the SG load changes, so that the voltage at its terminals remains unchanged (artificial characteristic).

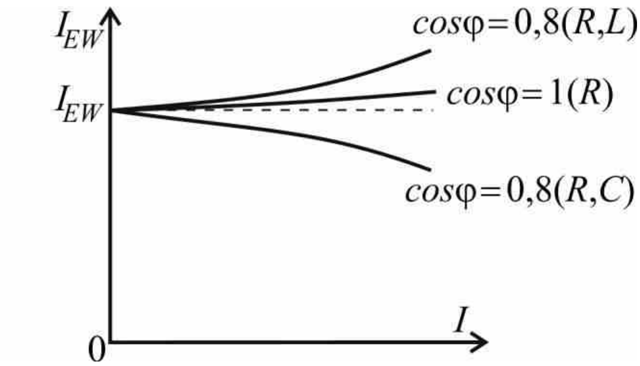


Figure 16.3

Typically, voltage adjustment, so that U = const remains unchanged when the load current I changes, is carried out automatically according to the scheme (Fig. 16.4), where *CT* is a current transformer; *T* – step-down transformer.

Regulation principle: when the load current I increases, the voltage U drops (according to the external characteristic), but the current I_{EW} increases, which leads to an increase in the excitation current I_{EW} and to an increase in the magnetic flux Φ, EMF, and voltage U.

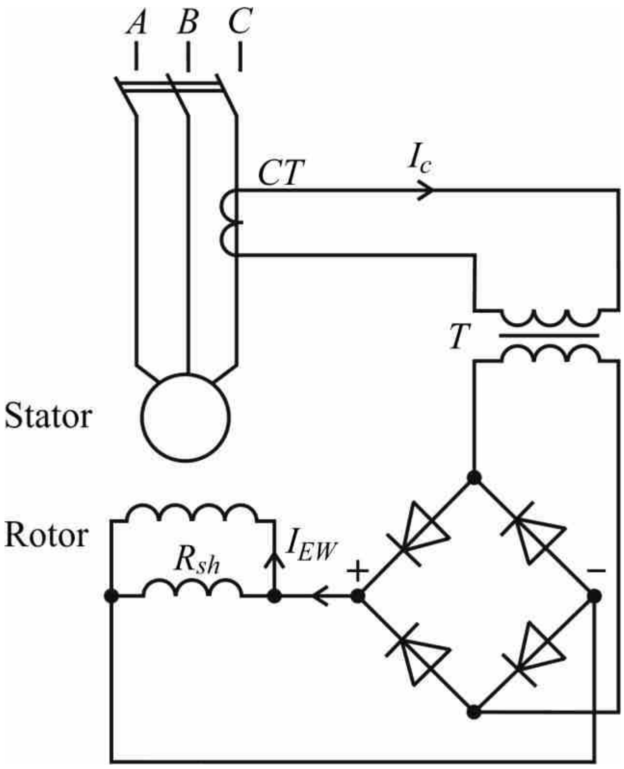


Figure 16.4

Electromagnetic power and electromagnetic torque of SG

Power of losses and efficiency of the synchronous generator

In the SG, the conversion of mechanical energy into electric energy is accompanied by energy losses. The mechanical power P_1 (input power) is delivered to the synchronous generator from the shaft side.

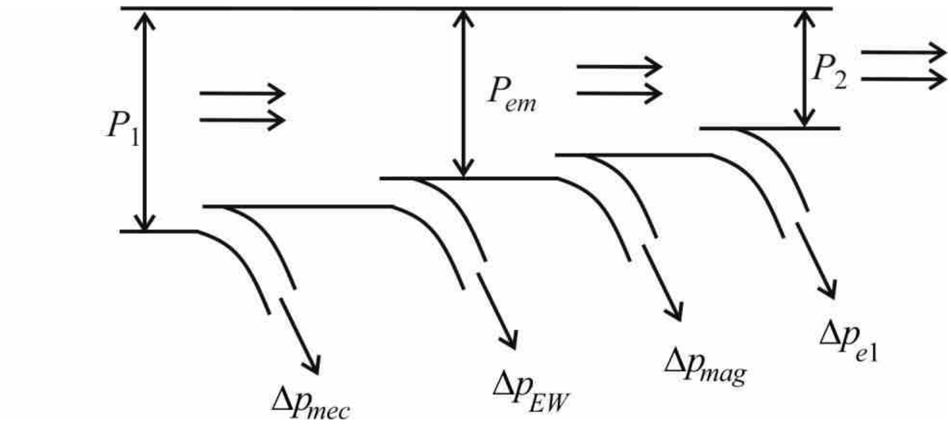


Figure 16.5

The rotor and stator have the following losses:

1) $\Delta P_{EW} = I_{EW}^2 R_{EW}$ – excitation losses; R_{EW} – resistance of the excitation circuit:

$$\Delta P_{EW} = I_{EW}^2 R_{EW}; \tag{16.1}$$

2) ΔP_{mec} – mechanical losses caused by all types of friction;

3) ΔP_{mag} – magnetic losses in the stator core (magnetization reversal and eddy currents);

$$P_1 - \left(\Delta P_{EW} + \Delta P_{mec}\right) = P_{em} = 3E_0 I \cos\Psi, \tag{16.2}$$

("3" in the formula means 3 phases). This electromagnetic power is transmitted to the stator.

4) ΔP_{e1} – electric losses in the stator winding:

$$\Delta P_{e1} = 3I^2 R. \tag{16.3}$$

The $\Delta P_{EW}, \Delta P_{mec}, \Delta P_{st}$ losses are constant (not depend on the load) and consist of no-load loss of SG.

Efficiency of the SG is

$$\boxed{\eta = \frac{P_2}{P_1} = \frac{P_2}{P_2 + \Delta p}}, \qquad (16.4)$$

where P_2 is the net power delivered to the network, ΔP is sum of all losses.

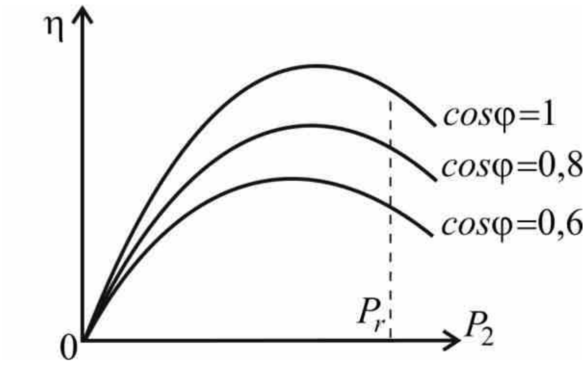


Figure 16.6

$$P_2 = 3U_{ph}I_{ph}\cos\varphi = \sqrt{3}U_l I_l \cos\varphi.$$

(16.5)

From this formula it follows that the efficiency depends on cosφ.

The SG efficiency depends not only on the load power, but also on the power factor cosφ. SG efficiency reaches 98 – 99 %. For these generators, cooling is used with hydrogen gas, water, etc.

Active power regulation. Angular characteristics

Electromagnetic power is equal to

$$P_{em} = 3E_0 I \cos\Psi. \qquad (16.6)$$

But from the likeness of triangles, we arrange the angles in the phasor diagram (Fig. 16.7). The side (cathetus) of *bd* is:

$$jX_S I \cos\varphi = E_0 \sin\theta.$$

ac ⊥ E_0, *bc* ⊥ *I*, then the angle *bca* is equal to Ψ. From here:

$$\cos\Psi = \frac{ac}{bc} = \frac{U\sin\theta}{jX_S I}.$$

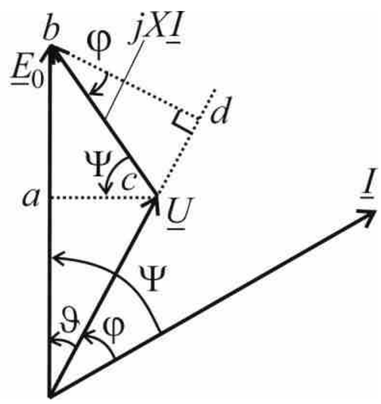


Figure 16.7

Substitute this value in the formula (16.6) we get:

$$\boxed{P_{em} = 3\frac{E_0 U}{X_S} sin\,\theta} \tag{16.7}$$

With a direct excitation current I_{EW} = const.

SG is included in the network and provides $U = U_{\mathrm{network}}$ = const.

The torque is

$$M_{em} = \frac{P_{em}}{\omega_r}, \tag{16.8}$$

where $\omega_r = \frac{2\pi n}{60}$ is an angular rotor speed. But $n = \frac{60\,f}{p}$, therefore

$$\omega_r = \frac{2\pi}{60}\frac{60\,f}{p} = \frac{2\pi f}{p} = \frac{\omega}{p}, \tag{16.9}$$

where ω is the angular rotor speed of the SG; f is the frequency of the current; p is the number of pairs of SG poles:

$$M_{em} = \frac{P_{em}}{\omega_r} = \frac{P_{em}\,p}{\omega}, \tag{16.10}$$

$$\boxed{M_{em} = 3\frac{p}{\omega}\frac{E_0 U}{X_S}\sin\theta}. \tag{16.11}$$

Dependence $P_{em}(\theta)$ or $M_{em}(\theta)$ are called power-angle curves of the SG. The angle θ characterizes the stability of the SG.

$$0 \le \theta \le 90^\circ; \qquad \boxed{\theta_r \approx 15...20^{\mathrm{o}}}.$$

A positive value of θ corresponds to the generator duty.

At θ = const, an increase in the excitation current I_{EW} in the SG leads to an increase in the electromagnetic power P_{em}.

If the angle θ is negative, this corresponds to the operation of the synchronous machine in a motor duty.

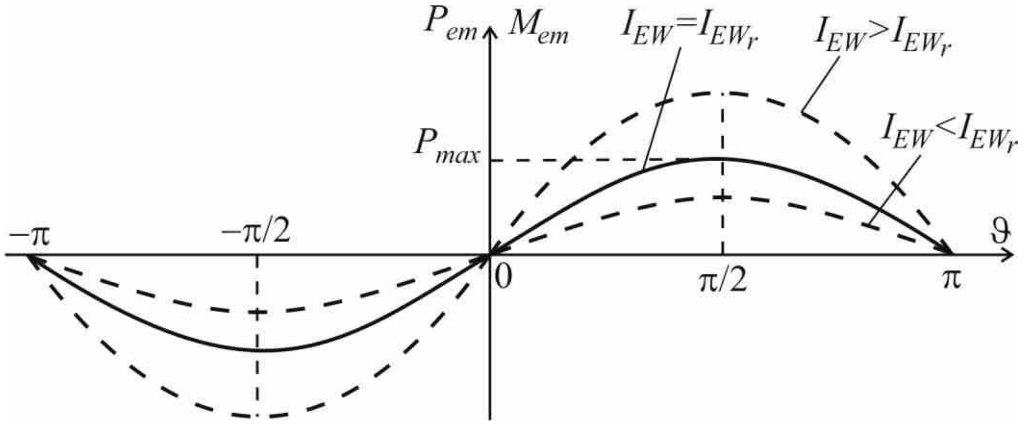


Figure 16.8

In a generator duty, M_{em} counteracts the rotation of the rotor, i.e. it is braking.

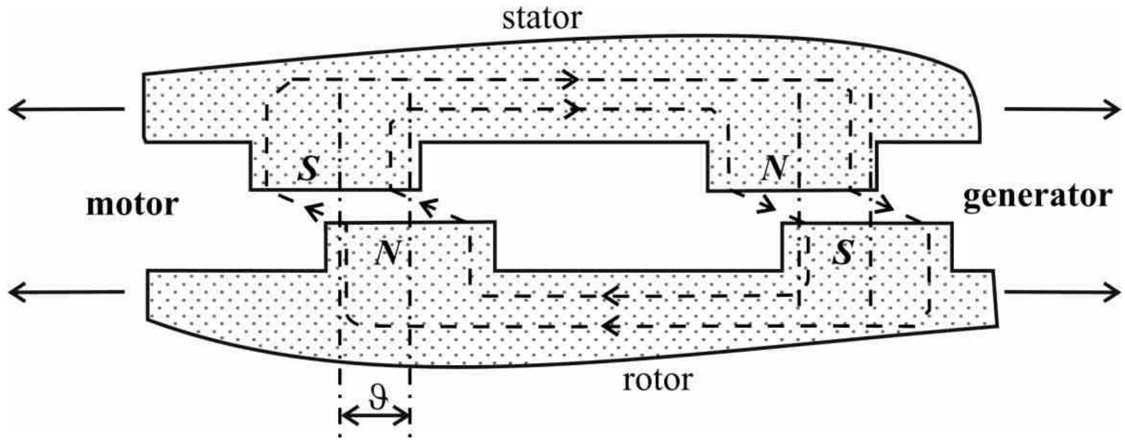


Figure 16.9

In a generator duty, the rotor field is leading, and the stator field is driven. In motor duty it is vice versa.

As the torque increases, the lines of force become more deformed (stretched), and the angle θ grows.

If $\theta > 90^{\circ}$, then the lines of force break, the magnetic force between the rotor and the stator breaks down, the rotor rotates like a blank (ingot), because he does not rotate anything. This phenomenon is called loss of synchronism (dropout, breaking step).

When $0 \le \theta \le 90^{\circ}$ the synchronous generator operates stably.

The change in power in parallel with the SG network is achieved by acting on the primary drive motor.

Let the SG work at angle θ_1 as shown in Fig. 16.10. After increasing the steam supply, the rotor accelerated, and the angle θ increased, because increased a torque of the drive motor.

When the angle θ increased, the braking torque increased, and at a certain angle θ_2, the torque equilibrium again comes at a new power. So we increased the power.

With an excessive increase in the torque of the drive motor, the braking torque does not reach such a large value, i.e. they will not be balanced and the SG will fall out of synchronism. (loss of synchronism, dropout, breaking step).

Synchronizing power is

$$\boxed{P_x = \frac{dP}{d\theta}}.$$

It shows how stable the SG is at a given angle θ.

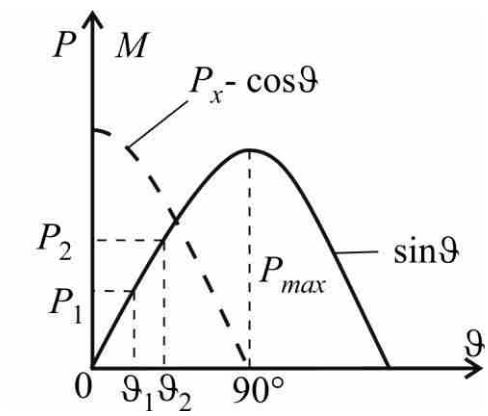


Figure 16.10

Stability of a synchronous generator

It depends on us at what angle θ the SG we will operate. For a small angle θ, the power P is small; if θ is large, then we can overload the SG, and it will fall out of synchronism. Usually they choose $\theta_r \approx 20^{\text{o}}$.

Static overload capacity of SG

$$\boxed{k_s = \frac{P_{\max}}{P_r}} \qquad (16.13)$$

Since maximal power $P_{\max} = 3\dfrac{E_0 U}{X_S}$, then $k_S = \dfrac{3\dfrac{E_0 U}{X_S}}{3\dfrac{E_0 U}{X_S}\sin\theta}$ or $\boxed{k_s = \dfrac{1}{\sin\theta}}$.

Usually, $k_s \approx 3$.

Thus, in order to increase the static overload capacity k_s, it is necessary to increase the maximum power P_{max}. And for this we need to reduce X_c.

But inductive reactance, $X_S = \omega L = \omega w^2 \lambda_a$,

where w is the number of turns of the winding;

λ_a – conductivity of the air gap.

So it is necessary to increase the gap between the stator and the rotor. In this case, both λ_a and inductive reactance X_c decrease.

That is why in synchronous generators a large gap has been made, to increase stability, i.e. to increase overload capacity.

With a very large air gap the dimensions of the SG increase and you need a lot of amp-turns on the rotor (large magnetomotive force, MMF).

We can raise P_{max} by forcing. Forcing EMF E_{for} is caused by current I_{EW} this increases the dynamic stability of the generator.

Parallel operation of the SG

In parallel operation, several generators are switched on one line.

Connecting the SG to the network

For trouble-free switching on of SG in the network, it is necessary that:

1) EMF produced by the SG is equal to the voltage of the network, and at the time of switching on is in antiphase to this voltage. Otherwise, a compensating current will occur.

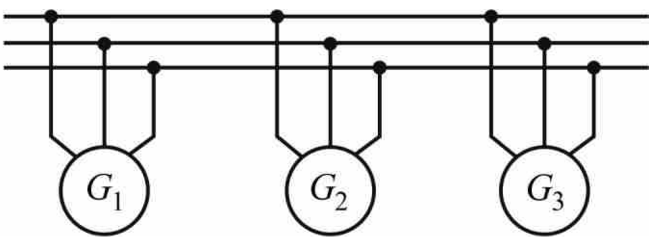


Figure 16.11

The EMF E is adjusted by the excitation current I_{EW}.

2) the EMF frequency of the SG must be equal to the frequency of the network. In this case, we need to adjust the rotor speed of the SG.

3) phase interlacing of the SG and the network corresponded to each other. Otherwise, a short circuit will occur.

4) the shape of the EMF SG and the shape of the network voltages are the same – sinusoidal.

Active power regulation we have already considered $P_{em} = 3\frac{E_0 U}{X_S}\sin\theta$.

Any change in active power with a constant EMF E_0 is possible with a change in the angle θ. It regulated by the primary drive motor.

In order to transfer part of the load from one SG to another, it is necessary to reduce the rotating torque of the primary motor of SG and increase the torque for the second. Then, after redistribution, the generators will operate at a constant speed. Otherwise, the rotational speed of all units, the voltage and a frequency of the current in the network will change.

SG reactive power regulation

After fulfilling the synchronization conditions, the synchronous generator operates in no-load duty. We use the equation

$$\underline{U} = \underline{E}_0 - j\underline{I}X_S - \underline{I}R \tag{16.14}$$

Since $R << X_S$, then $\underline{U} \approx \underline{E}_0 - j\underline{I}X_S$, from here

$$\boxed{\underline{I} = \frac{\underline{E}_0 - \underline{U}}{jX_S}}. \tag{16.15}$$

The power of the SG is constant P = const. But, and the excitation current changes I_{EW} = var. Since U = const, we change the excitation current. In this case, the EMF changes (see the dependence E (I_{EW})).

The imbalance between the EMF E_0 and the voltage U in the formula (16.15) should be suppressed due to the current I. But since U and P are constant, the product $UI\cos\varphi = \text{const}$ must be constant, i.e. the active current remains constant, and a reactive current appears, which affects the cosφ of the network (when I_{EW} changes).

If $\cos\varphi = 1$, then the generator is normally excited (Fig. 16.12). When the excitation current I_{EW} changes, the reactive current will flow $P_1 < P_2 < P_3$.

This is a set of *U*-shaped characteristics at various capacities. They show the dependence of the SG current on the excitation current at constant power, and the angle θ. When the excitation current I_{EW} changes, an inductive or capacitive compensating current will flow.

Modern SGs work with over-excitation.

$$\cos\varphi = 0{,}8 \ldots 0{,}9, \qquad \varphi_{rated} > 0.$$

In this case, the SG provides the network receivers (induction motors, transformers, etc.) with the necessary inductive energy.

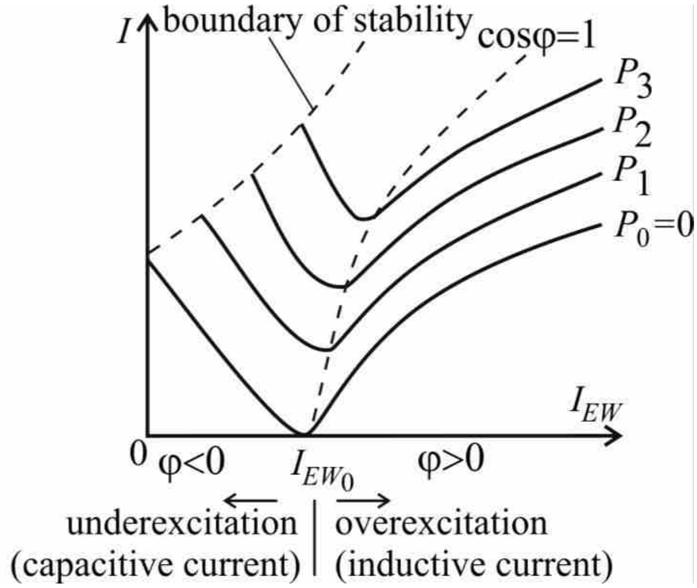


Figure 16.12

Test questions

1. What characteristics of the synchronous generator do you know?

2. What is regulation principle of the synchronous generator?

3. What are principles of connecting the SG to the network?

4. At what the θ angle does the synchronous generator operate stably?

5. What is the SG reactive power regulation?

SECTION

III

ELECTRONICS

LECTURE 17

SEMICONDUCTORS AND THEIR PROPERTIES. PHYSICAL PROCESSES IN SEMICONDUCTORS

Semiconductors are substances that occupy an intermediate position between conductors and dielectrics in terms of their electric resistivity.

CONDUCTORS: $\rho < 10^{-7}$ Ohm·m (copper, aluminum, silver, etc.);

DIELECTRICS: $\rho > 10^{8}$ Ohm·m (glass, mica, plastics, polystyrene, etc.);

SEMICONDUCTORS: $10^{-7} < \rho < 10^{8}$ Ohm·m (Si, Ge, As, In, etc.).

Semiconductors differ from conductors in the strong dependence of the resistivity ρ on temperature and the concentration of impurities. With increasing temperature, resistivity ρ increases in conductors and decreases in semiconductors.

Electrons in isolated atoms can only be at resolved energy levels.

When isolated atoms come closer, their energy levels overlap and energy bands form.

Energy bands are: allowed and forbidden, i.e. values of energies that an electron of an ideal crystal cannot possess.

Allowed bands are divided into filled and free ones (Fig. 17.1).

In the filled band at a temperature of absolute zero T = 0 K, all energy levels are occupied, and in the free band, the electrons are absent.

The band of highest energies of free levels is the conduction band. Lower in energy is the valence band – the upper of the electron-filled bands.

In semiconductors, the conduction band and the valence band are separated by a wide (0,5... 3 eV) prohibited band (Fig. 17.1).

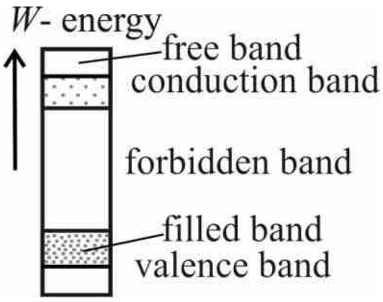


Figure 17.1

In semiconductors, due to the small prohibited band, the transition of an electron from the valence band to the conduction band under the action of an external electric field is possible. In this case, a free electron appears in the conduction band, and a hole in the valence band appears a free energy level. Such a transition process is called generation of a pair of charge carriers.

Charge generation leads to the fact that in the conduction band, electrons can move to nearby levels, and holes can move in the valence band.

The electric conductivity due to the generation of pairs of charge carriers "electron-hole" is called intrinsic conductivity.

The return of electrons to the valence band is called recombination and is accompanied by the release of an energy quantum in the form of a photon.

A dynamic equilibrium is established between generation and recombination.

In real crystals, due to defects in the crystal lattice and impurities in the band gap of the semiconductor, the arrangement of local energy levels is possible.

Impurity levels can be located near both the conduction band and the valence band.

In the first case (Fig. 17.2, *a*) an electron is likely to transition from a busy impurity level to the conduction band. This type of crystal lattice defect is called a donor, and the impurity that creates it is called a donor.

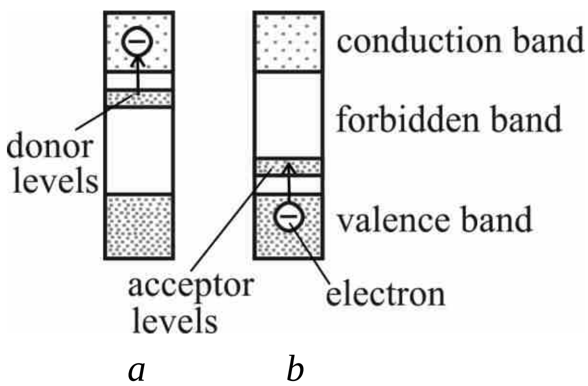


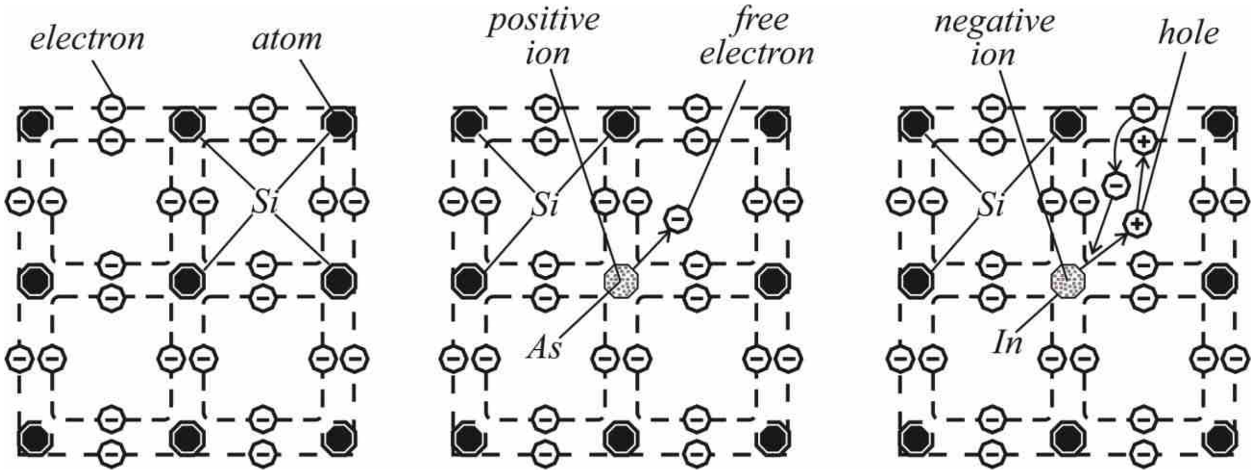
Figure 17.2

In the second case (Fig. 17.2, *b*), the electron is likely to transition from the valence band to the unoccupied impurity level, it’s an acceptor, and the impurity that creates it, also the acceptor is.

The electric conductivity of a semiconductor, due to the ionization of atoms by donor or acceptor impurities, is called impurity conduction.

Possible electronic or hole conduction, due to the type of impurity.

The basic semiconductor materials used are germanium Ge and silicon Si, the elements of group IV of the periodic table. In them, each atom is bonded to four neighboring atoms by pair-electron (covalent) bonds (Fig. 17.3, *a*).



a *b* *c*

Figure 17.3

If we introduce an impurity as an element of group V of the periodic table, for example, arsenic As, then the impurity atom becomes a donor. In this case, a free electron appears, and the atom becomes a positive ion (Fig. 17.3, *b*).

If we introduce an impurity as an element of group III, for example, indium In, then this impurity atom becomes an acceptor. For a covalent bond, one electron is lacking, which is filled with an electron from the valence band, where a hole is formed. An impurity atom becomes a negative ion (Fig. 17.3, *c*).

CONCLUSIONS:

1) positive ions are formed in a semiconductor with a donor impurity, and electrons are the majority of charge carriers. These are N-type semiconductors. Holes in such a semiconductor are the minority carriers of charge.

2) negative ions are formed in the semiconductor with an acceptor impurity, and holes are the main charge carriers. These are P-type

semiconductors. In such a semiconductor, electrons are non-basic charge carriers.

Electron-hole p-n junction (PN junction)

An electron-hole or *p-n* junction is formed between two types of a semiconductor, one of which has an N-type conductivity, and the other has a P-type conductivity.

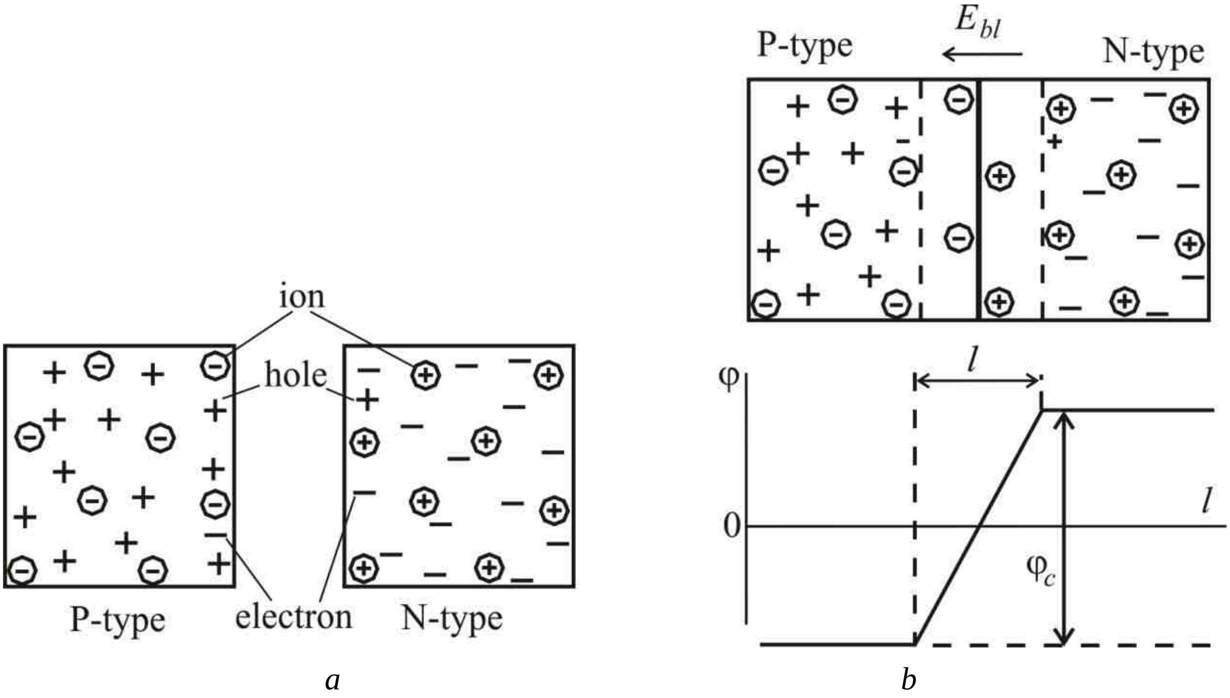


Figure 17.4

At the boundary, a carrier concentration gradient *p* and *n* arises, which results in diffusion of holes from the P-type and electrons from the N-type (Fig. 17.4, *b*). A diffuse current arises through the *p-n* junction. A blocking electric field is formed in the boundary layer, causing drift of minority carriers (*n* from the P-type to the N-type and vice versa), and forming a drift current, which is opposed to the diffusion current.

Since the resulting current is zero, the drift current is equal to the diffusion current (if the external circuit is open). A contact potential difference φ_c arises. (φ_c = 0,1 ... 0,8 V in Ge and Si).

The width of the blocking layer l = 0,01 ... 1,0 μm.

If an external direct voltage source E_{ex} is connected to such a semiconductor so that (+) is applied to *p* and (-) to *n*, then:

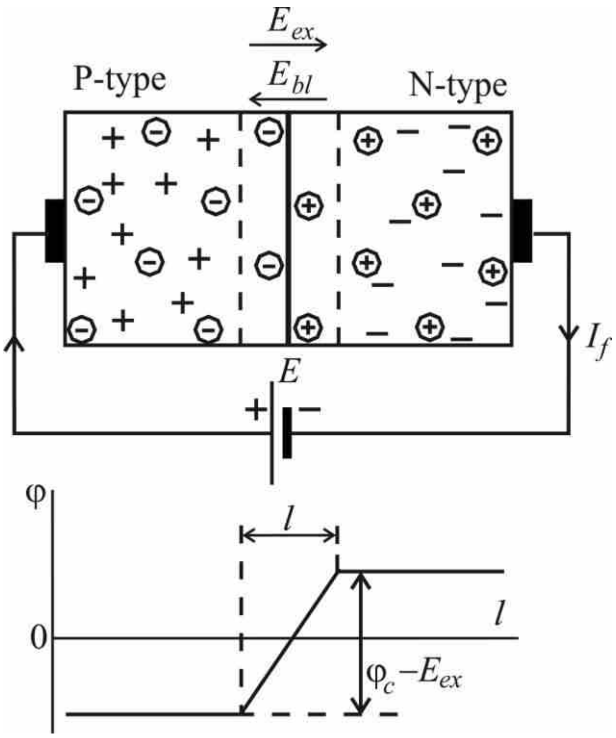


Figure 17.5

an external field is opposite to blocking EMF. Resulting EMF E_{res} is equal to blocking (turn-off) EMF E_{lock} minus external EMF E_{ex} type (Fig. 17.5).

$$E_{res} = E_{bl} - E_{ex}.$$

The diffusion current increases, and a forward diffusion current I_f arises. This switching on is called forward.

With the reverse switching on

$$E_{res} = E_{bl} + E_{ex},$$

the potential barrier increases: $\varphi = \varphi_c + E_{ex}$ and its width l increases (Fig. 17.6).

The diffusion current to the majority carriers decrease, and the drift current due to the movement of minority charge carriers of charge increases.

Once in the blocking layer, they are picked up by its field and moved through the *p-n* junction. This is the reverse current of the drift I_{rev}.

Since minority carriers are much smaller than majority ones, I_{rev} is several orders of magnitude smaller than I_f. It determines the gate properties of the *p-n* junction.

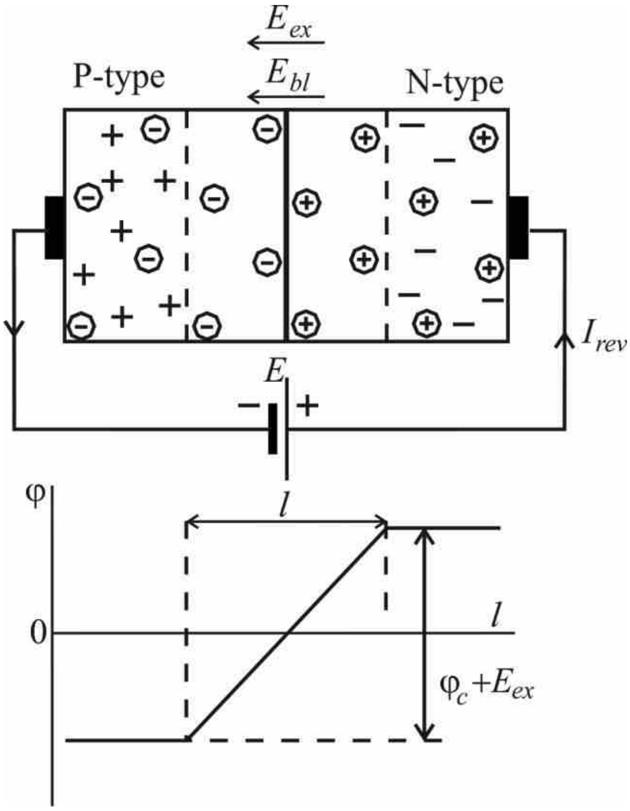


Figure 17.6

Current-voltage characteristic of p-n junction

Distinguish between electric and thermal breakdown.

Electrical (*avalanche*) *breakdown* – minority charge carriers with high energy shock ionize the semiconductor atoms, which leads to an avalanche-like multiplication of charge carriers. It is convertible.

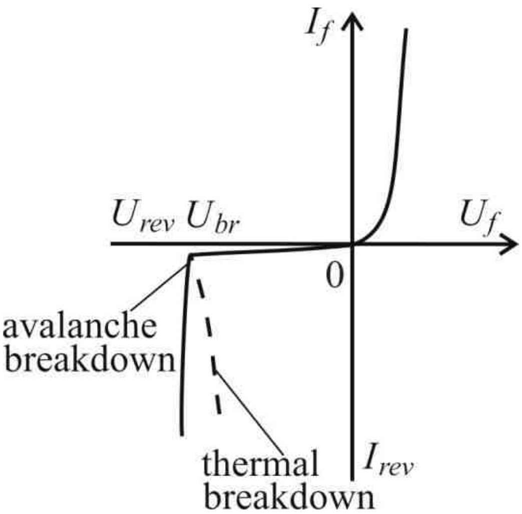


Figure 17.7

Thermal breakdown – the temperature of the semiconductor increases due to the reverse current, which leads to an increase in the process of generation of charges. This breakdown is irreversible.

Table 17.1 Classification of semiconductor devices

№	Type of device	Quantity *p-n* junctions	Quantity electrodes
1.	Semiconductor resistors	no	2
2.	Semiconductor diodes	1	2
3.	Bipolar transistors	2	3
4.	Field-effect transistors	1	3
5.	Thyristors	3 and more	2, 3
6.	Integrated circuits	many	many

Test questions

1. What are semiconductors?

2. What are energy bands existing in substance?

3. What impurities in semiconductors do you know?

4. What are the N-type semiconductors?

5. What are the P-type semiconductors?

6. What is p-n junction?

7. What are peculiarities of a forward switching on of p-n junction?

8. What are peculiarities of a reverse switching on of p-n junction?

9. What breakdowns in p-n junction do you know?

LECTURE 18

SEMICONDUCTOR RESISTORS AND DIODES.
DESIGNATION, APPOINTMENT, TYPES AND CHARACTERISTICS

A semiconductor resistor is a two-electrode device that uses the dependence of the electric resistance of a semiconductor on voltage or other factors. These devices have no *p-n* junction, i.e. they are uniformly alloyed with impurities. Legend has been shown in Fig. 18.1.

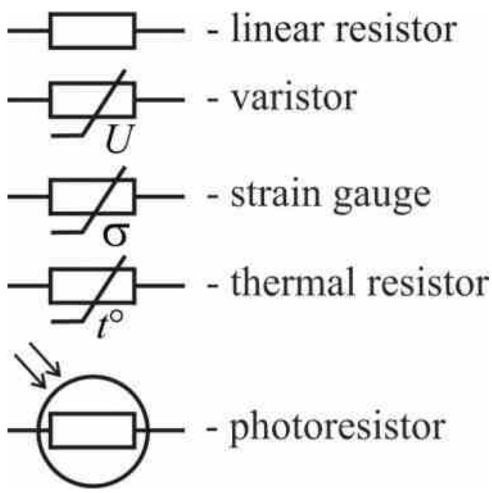


Figure 18.1

Types of semiconductor resistors

1) LINEAR RESISTOR. Its resistance depends only slightly on voltage and current density, i.e. it has almost constant resistance. It is used for integrated microcircuits.

2) VARISTOR. Its current-voltage characteristic (CVC) is non-linear, but symmetrical. It is used to protect circuits against overvoltage, in stabilization systems, automatic gain controllers, etc. The volt-ampere characteristic of varistor is shown in Fig. 18.2.

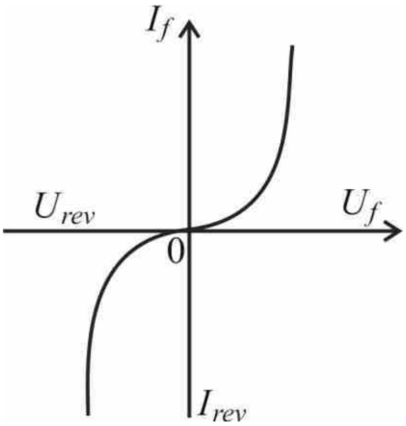


Figure 18.2

3) RESISTANCE STRAIN GAUGE is a semiconductor device, the resistance of which depends on the linear deformation of the actuating medium. Deformation characteristics of the resistance strain gage is shown in Fig. 18.3. During deformation, the regularity of the crystal lattice is violated, which leads to a change in resistance. It used to measure the deformation of solids.

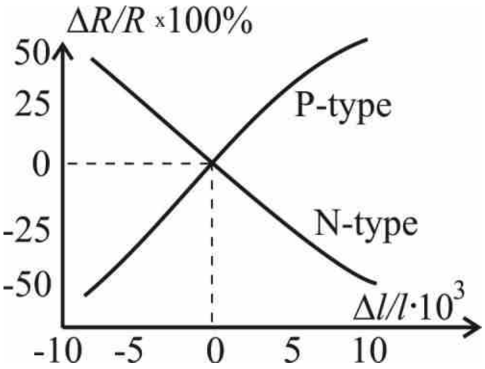


Figure 18.3

4) THERMISTOR is a semiconductor device, the resistance of which changes depending on the temperature. Thermistors are divided based on their conduction model. Negative temperature coefficient thermistors have much less resistance at higher temperatures, while positive temperature coefficient thermistors (posistors) have much more resistance at higher temperatures. Temperature characteristics of thermistors are shown in Fig. 18.4.

Thermistors are used for thermal protection, signaling, temperature measurements, stabilization of semiconductor devices.

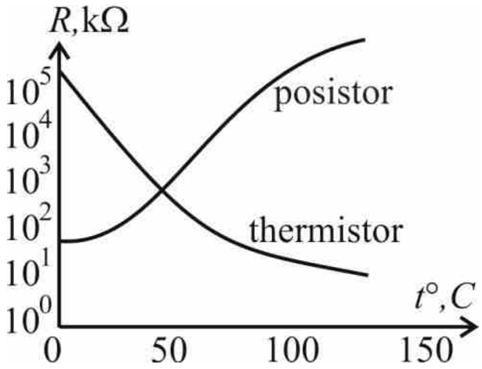


Figure 18.4

5) PHOTORESISTOR is a semiconductor device, the resistance of which depends on the illumination or light flux. They are made on the basis of cadmium sulfide, cadmium selenide, sulphurous lead, etc. The photosensitive element is usually in a plastic case, used in various areas of the spectrum.

The characteristic of the photoresistor is shown in Fig. 18.5, where the Φ is a light flux.

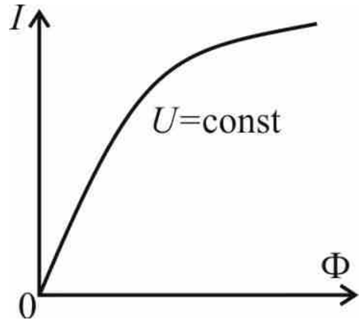


Figure 18.5

SEMICONDUCTOR DIODES.

Designation, appointment, types and characteristics

A semiconductor diode is a device with one *p-n* junction and two electrodes. They distinguish: point-contact and planar diodes. A point-contact diode uses a germanium plate with N-type electric conductivity, a thickness of 0,1 ... 0,6 mm and an area of 0,5 ... 1,5 mm^2. A pointed steel wire is in contact with the plate, forming a *p-n* junction at the point of contact. These are low-current diodes.

In a planar diode, the *p-n* junction is formed by two semiconductors with different types of electric conductivity, and the junction area can be up to several tens of square centimeters. These are power diodes. Symbols of various diodes are shown in Fig. 18.6.

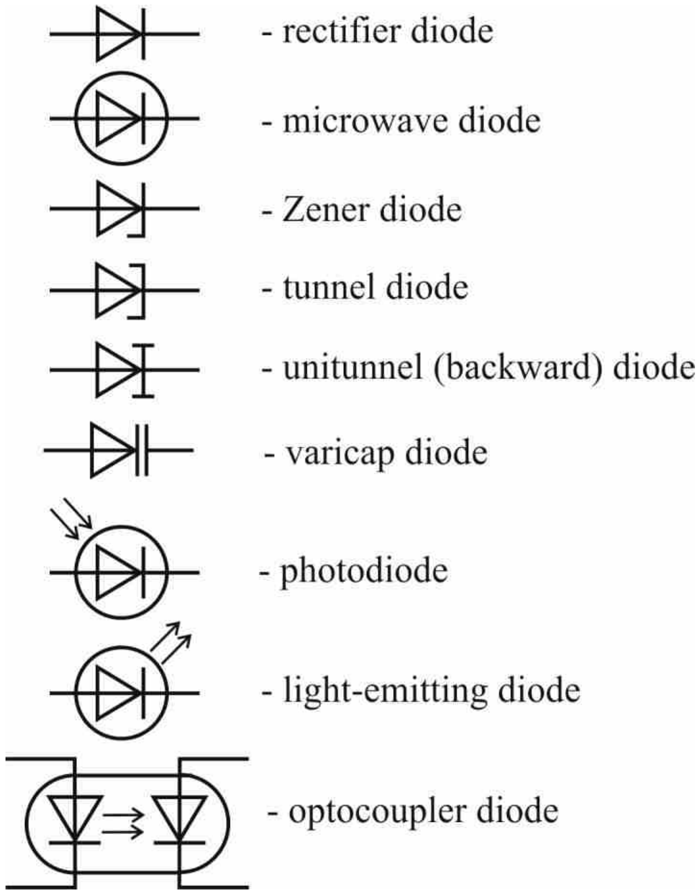


Figure 18.6

1) RECTIFIER DIODE

Usually forward voltage U_f does not exceed 1 ... 2 V. In this case, the current density reaches 1 ... 10 A/mm^2. Reverse voltage U_{rev} is up to several hundred volts. It is allowed U$_r$ = (0,7 ... 0,8) U_{br} (breakdown voltage). Permissible temperature T is up to 85 ... 100°C (germanium). T is up to 150 ... 200° C (silicon). Diodes are mounted on radiators, blowing, etc. is used for cooling.

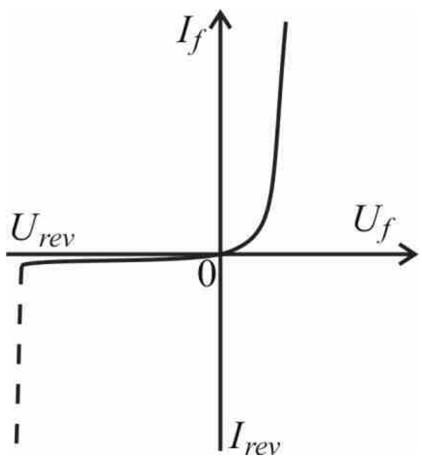


Figure 18.7

It has a thermal irreversible breakdown. It is allowed 50 ... 100 times current overload for 0,1 s. The volt-ampere characteristic of a rectifier diode is shown in Fig. 18.7.

2) MICROWAVE DIODE works at very high frequencies.

3) ZENER DIODE (voltage-reference diode) is a semiconductor diode, the voltage on which in the type of electric breakdown weakly depends on the current (Fig. 18.8). They are used to stabilize voltage. It works in the area of reversible electric breakdown. Stabilizing voltage U_{st} = 1 ... 1000 V;
Minimum Zener current $I_{st\min}$ = 1 ... 10 mA;
Maximum Zener current $I_{st\max}$ = 50 ... 2000 mA.

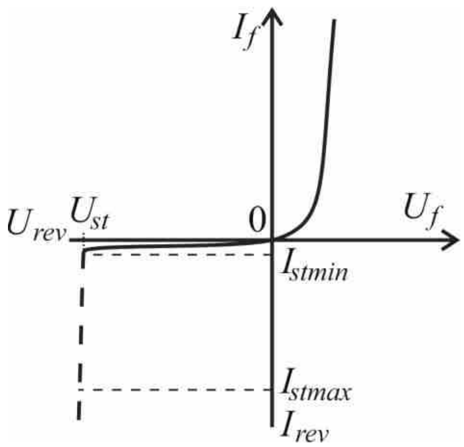


Figure 18.8

A semiconductor Zener diode, in which the stabilization area is a direct branch of the $I - U$ characteristic, is called a stabistor (a forward reference diode).

4) TUNNEL DIODE is a diode in which the tunneling effect leads to the appearance of negative differential conductivity on the $I - U$ characteristic in the forward direction. Incremental resistance of a tunnel diode

$$R_{\text{inc}} = \frac{dU}{dI} \approx \frac{\Delta U}{\Delta I} \quad .$$

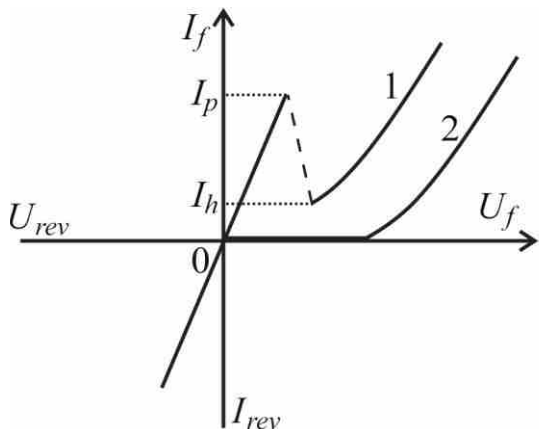


Figure 18.9

The work area is a forward branch of volt-ampere characteristic (Fig. 18.9), where I_p is the peak current; I_h is the current of the hollow. It is used for generators of high-frequency oscillations and high-speed pulse switches.

5) INVERSED (unitunnel) DIODE is a type of tunnel diode in which the peak current I_p = 0. It has valve properties at low voltages. The highest conductivity is in the opposite direction.

6) VARICAP (variable capacitance diode) is a semiconductor diode in which the dependence of the *p*-*n* junction capacitance on the reverse voltage is used and which is intended for use as an element with an electrically controlled capacitance value. The characteristic of varicap is shown in Fig.18.10, where *C* is the varicap capacitance.

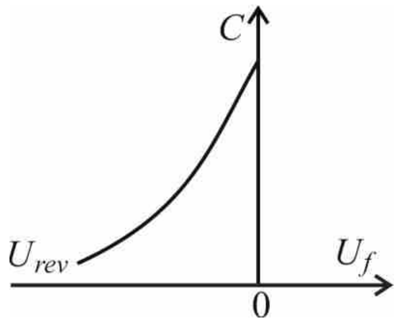


Figure 18.10

The photodiode and light-emitting diode are semiconductor diodes that use the effect of the interaction of visible, ultraviolet and infrared radiation with charge carriers in the blocking layer of the *p*-*n* junction.

7) PHOTODIODE is a photovoltaic radiation detector without internal amplification. I_0 is the black current. The characteristics of photodiode are shown in Fig. 18.11 *a*, *b*.

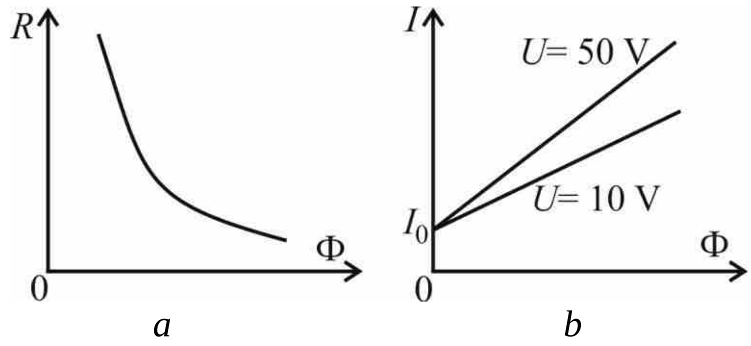


Figure 18.11

8) LIGHT-EMITTING DIODE (LED). LED is a diode that converts electricity to energy of incoherent light radiation. The most common LEDs emitting in the visible part of the spectrum: yellow, red and green light. The characteristic of LED is shown in Fig. 18.12, where *B* is brightness.

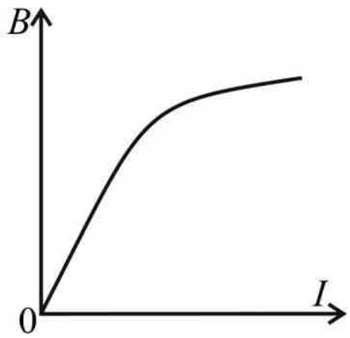


Figure 18.12

9) OPTOCOUPLER or PHOTOCOUPLER is an optoelectric semiconductor device containing emitting and photodetector elements, between which there is optical communication and electric isolation is provided. The diode optocoupler has the following characteristic which is shown in Fig. 18.13.

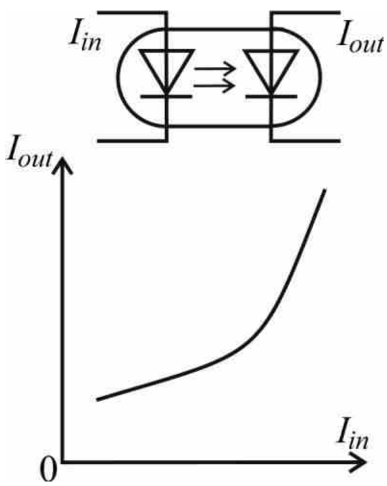


Figure 18.13

In a source of light radiation (SLR), the energy of an electric signal is converted into light radiation. Light radiation is transmitted through an optical channel (OC) to a photodetector (FD), in which it is converted into electricity.

<u>Opto-coupler block diagram</u>

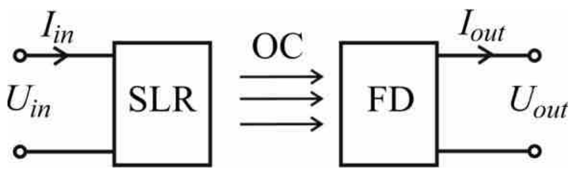


Figure 18.14

SLR is usually a LED. OC uses polymer optical adhesives, varnishes, fiber optic fibers, etc. Opto-couplers use photoresistors, photodiodes, phototransistors, and photo thyristors as FD.

Depending on the type of FD, resistor, diode, transistor and thyristor opto-couplers are distinguished.

Test questions

1. What is a semiconductor resistor?
2. What types of semiconductor resistors do you know?
3. How many p-n junctions are contained in semiconductor resistors?
4. What is the difference between negative and positive temperature coefficient thermistors?
5. What are the characteristics of varistor, photoresistor, resistance strain gage, varicup?
6. What is a semiconductor diode?
7. What types of semiconductor diodes do you know?
8. What is the volt-ampere characteristic of a rectifier diode?
9. What is electrical breakdown?
10. What is the difference between a thermal breakdown and an electrical breakdown?

LECTURE 19

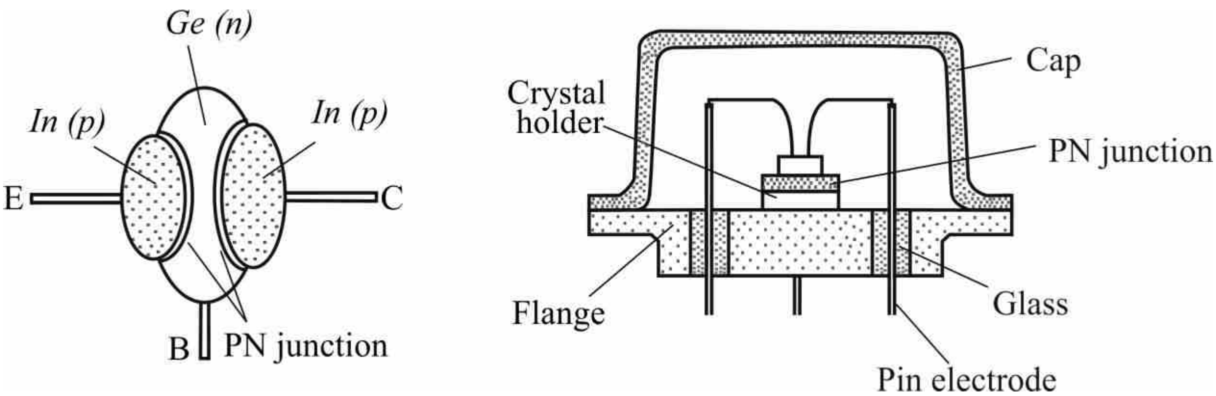
BIPOLAR JUNCTION TRANSISTORS
DESIGN, TYPES AND DESIGNATIONS

A transistor is an electro-converting semiconductor device with one or two interacting *p-n* junctions and three terminals, which has amplifying properties.

A transistor with two *p-n* junctions is called a bipolar junction transistor (BJT). "Bi" means two types of charge carriers: electrons and holes.

There are silicon and germanium transistors.

Three-layer semiconductor structure: principal (*a*) and structural (*b*) embodiment is shown in Fig. 19.1.



a *b*

Figure 19.1

Electrodes: *E* – emitter; *B* – base; *C* – collector.

In BJT, the central layer is called BASE.

The outer layer, which is the source of charge carriers (electrons or holes), which mainly creates the current of the device, is called EMITTER.

The outer layer receiving charges coming from the emitter is called a COLLECTOR.

The “base-emitter” transition is called EMITTER junction.

The “base-collector” transition is called COLLECTOR junction.

There are two classes of BJT: *n-p-n* type and *p-n-p* types (Fig. 19.2).

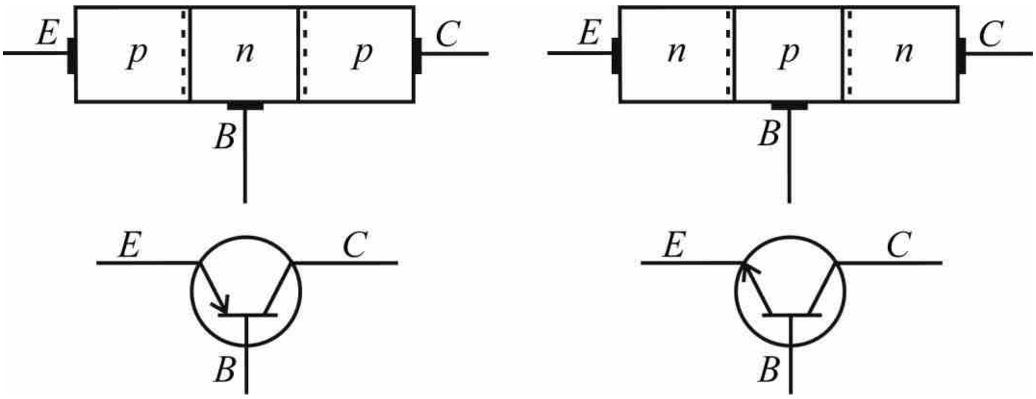


Figure 19.2

BJT Switching Circuits

When we switch on the transistor in the circuit, one of its leads is made common to the input and output circuits. Therefore, the transistor switching circuits are (Fig. 19.3):

a with a common-base (CB);

b with a common-emitter (CE);

c with a common-collector (CC).

Relative to the general lead, on which the potential φ = 0 is considered, the voltage of the input and output circuits of the transistor is measured.

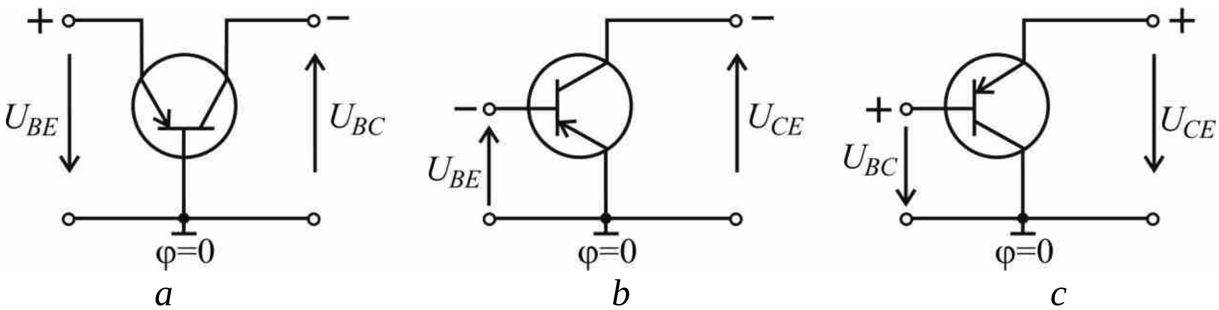


Figure 19.3

Modes of BJT

Depending on the polarity of the voltages applied to the emitter and collector junctions, 4 modes of operation of the transistor are distinguished.

Consider a bipolar junction transistor with a common-base (CB).

1. Active mode – forward voltage is applied to the emitter junction, and the reverse is applied to the collector junction. (Fig. 19.4).

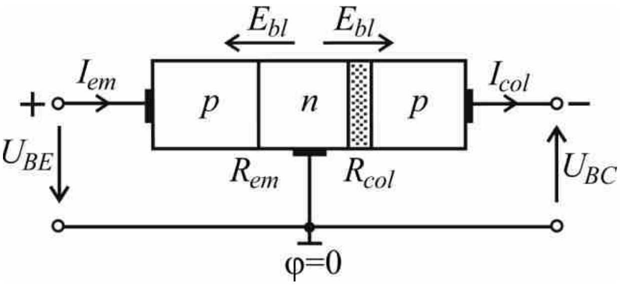


Figure 19.4

In this case, the resistance of the emitter junction is much smaller than the resistance of the collector junction:

$R_{em} << R_{col}$.

Since currents: $I_{em} \approx I_{col}$, then $U_{em} = I_{em}R_{em} << U_{col} = I_{col}R_{col}$

With this power: $P_{em} = I_{em}^2 R_{em} << P_{col} = I_{col}^2 R_{col}$, i.e. $P_{in} = P_{em} << P_{out} = P_{col}$.

The output power P_{out} (collector circuit) is many times higher than the input power P_{in} (emitter circuit).

Active mode is used in amplifier circuits and in generating devices where the transistor is an active element.

2. Cut-off mode – reverse voltages are applied to both junctions (Fig. 19.5). Therefore, the current through them is very small and is due only to minority carriers. The transistor is almost locked.

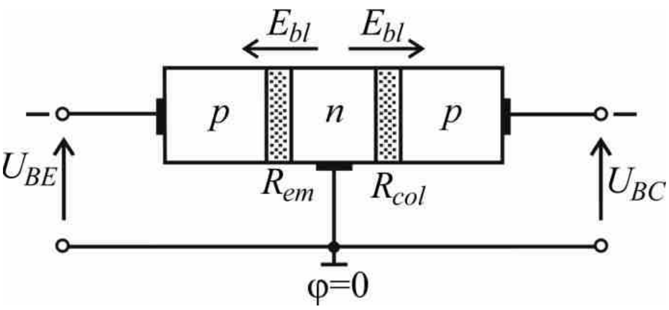


Figure 19.5

The cut-off mode is used in key modes: the state is “Closed” or “Disabled”.

3. Saturation mode – forward voltages are applied to both transitions. The current in the output circuit of the transistor is maximum and is practically not regulated by the current of the input circuit. The transistor is totally opened. The saturation mode is used in key modes: the state "Enabled" or "Open".

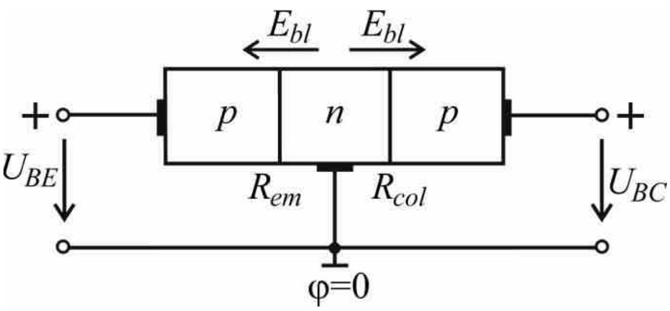


Figure 19.6

4. Inverse mode: reverse voltage is applied to the emitter junction, and direct voltage is applied to the collector junction. The emitter and collector functionally switch places. This mode does not correspond to the normal operation conditions of the transistor.

The principle of operation of a BJT

Let's consider the operation of a BJT with a *p-n-p* structure at a forward current, switched on according to the circuit with CB in an active mode (Fig. 19.7).

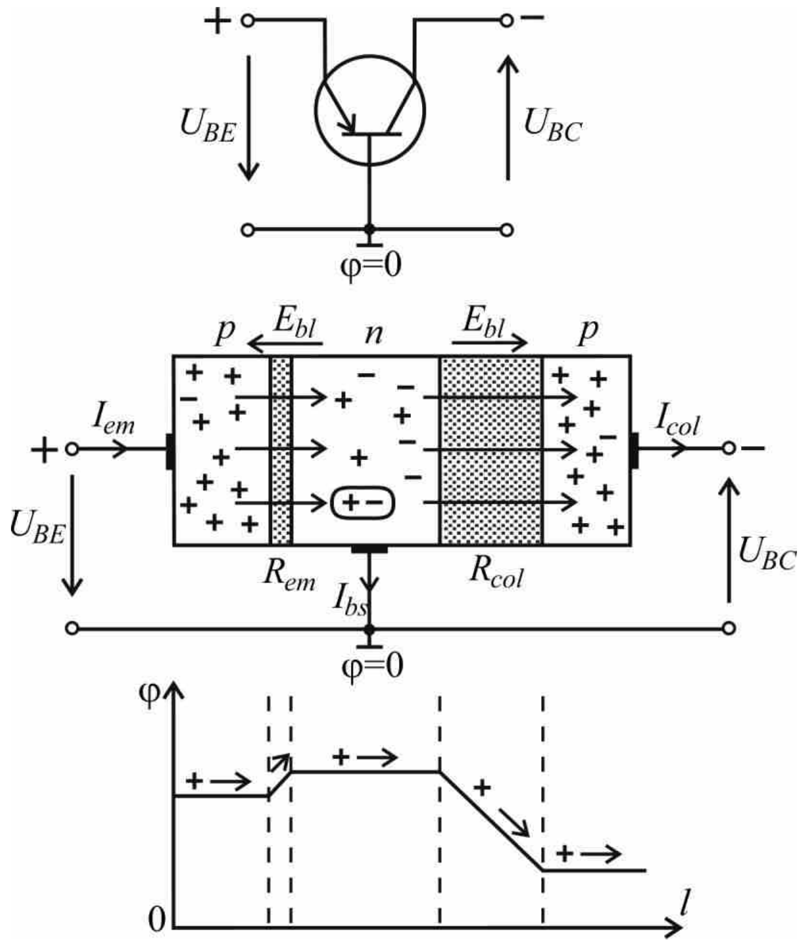


Figure 19.7

The source of the U_{BE} voltage creates a direct bias of the emitter junction. The source of U_{BC} voltage creates a reverse bias of the collector junction. The potential barrier due to sources at the emitter junction decreases, and at the collector junction it rises.

The emitter holes (majority carriers) are injected (penetrate) into the base, and the base electrons are injected into the emitter due to diffusion.

Holes due to the difference in density along the length of the base diffuse and reach the collector, some of them recombine with the base electrons. The base is made very thin.

Since the blocking (turn-off) field E_{bl} of the collector junction for holes is accelerating, they are drawn into the collector, i.e. holes are extracted into the collector. Propagating along the collector due to a difference in their density over the collector, the holes reach the contact and recombine with the electrons of the source.

The majority carriers (holes) of the collector, due to the high potential barrier, do not pass into the base.

A part of the base electrons, which has recombined with the emitter holes, is filled up by the source electrons, forming the base current. The relationship between the increments of the emitter and collector currents is characterized by the current transfer coefficient (for a circuit with CB is equal to):

$$\boxed{\alpha = \frac{\partial I_{col}}{\partial I_{em}} \approx \left(\frac{\Delta I_k}{\Delta I_{em}} \right)_{U_{CB}=const}}\ .$$

Since $\Delta I_{col} < \Delta I_{em}$ and α = 0,9 ... 0,995.

When $I_{em} = 0$ there is an initial collector current I_{col0} created by minority carriers of the charge.

When $I_{em} \neq 0 \quad I_{col} = I_{col0} + \alpha I_{em} \approx I_{em}$.

In a circuit with CB, a low current transfer coefficient. By changing the emitter current (input) I_{em}, you can control the collector current (output) I_{out}. In the circuit with CB, there is no current gain, but there is only voltage gain.

The main circuit of amplifier is a circuit with CE (*n-p-n* transistor).
The circuit is shown in Fig. 19.8, where base current I_b is input current, and collector current I_{col} is output current.

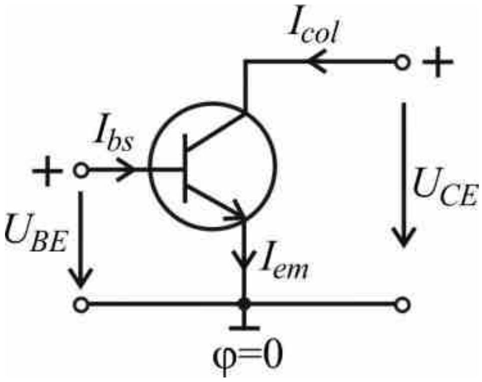


Figure 19.8

According to Kirchhoff's law for nodes

$$I_{em} = I_b + I_{col} \tag{19.1}$$

$$I_{col} = I_{col0} + \alpha I_{em} \tag{19.2}$$

From

$$I_b = I_{em} - I_{col} = I_{em} - I_{col} - \alpha I_{em} = I_{em}(1-\alpha) - I_{col0} << I_{em} \approx I_{col} \quad (19.1)$$

Since α = 0,9 ... 0,995, then

$$\boxed{I_b << I_{col}}.$$

The small value of the input (control) current I_b caused a wide application of the circuit with CE.

Base current transfer coefficient (increment of currents of input and output circuits):

$$\boxed{\beta = \left.\frac{\partial I_{col}}{\partial I_b}\right|_{U_{\mathrm{CE}}=const} \approx \frac{\Delta I_{col}}{\Delta I_b}}.$$

But $\Delta I_b = \Delta I_{em} - \Delta I_{col}$.

Therefore $\beta \approx \dfrac{\Delta I_{col}}{\Delta I_{em} - \Delta I_{col}} = \dfrac{\dfrac{\Delta I_{col}}{\Delta I_{em}}}{1 - \dfrac{\Delta I_{col}}{\Delta I_{em}}} = \dfrac{\alpha}{1-\alpha}$.

$$\boxed{\beta = \frac{\alpha}{1-\alpha}}.$$

β = 50 ... 100.

Thus, in a circuit with CE, amplification occurs both in current and in voltage.

Amplifying properties of a BJT

Basic indicators:

1) Current gain $K_I = \dfrac{\Delta I_{out}}{\Delta I_{in}}$;

2) Voltage gain $K_U = \dfrac{\Delta U_{out}}{\Delta U_{in}}$;

3) Power gain $K_P = K_I K_U$;

4) Input impedance $R_{in} = \dfrac{\Delta U_{in}}{\Delta I_{in}}$.

Table 19.1 Amplifying coefficients in active mode

Circuits of switching	R_{in}, Ohm	K_I	K_U	K_P
CB	Units - Tens	1	Up to 1000	Up to 1000
CE	Hundreds	10…100	100	Up to 10000
CC	Tens of thousands	10…100	1	Up to 100

A common-collector amplifier is built on the circuit with CC. It has a low output resistance R_{out} and a large input resistance R_{in}.

It is used in cases where:

1) it is required to separate the previous part of the circuit from the load, which has a small resistance R_l;

2) it is used as matching (buffer) cascades: it is connected between cascades with high output and low input resistances.

Static characteristics of a BJT with CE

Static characteristics describe the relationship between input and output currents and transistor voltages. This is the volt-ampere characteristic of the transistor.

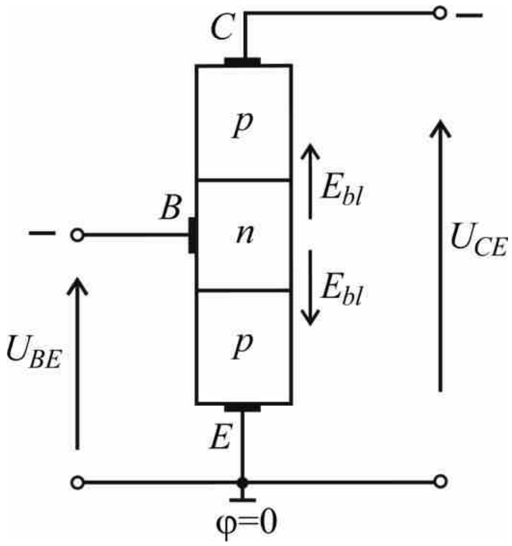


Figure 19.9

Input BJT characteristic

$$\boxed{I_b(U_{BE}) / \text{ at } U_{CE} = const}$$

It is shown in Fig. 19.10. The more U_{BE}, the greater the current base I_b, tk. with an increase in the forward voltage at the emitter junction, the potential barrier decreases. It can be overcome by a larger number of the main charge carriers of the emitter (holes), and a larger number of them will be able to recombine with the base electrons.

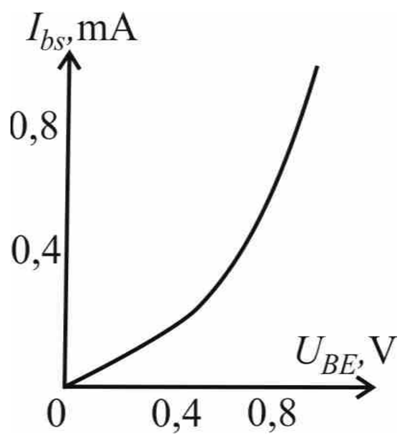


Figure 19.10

Output BJT characteristics

(set of characteristics are shown in Fig. 19.11):

$$\boxed{I_{col}(U_{CE}) / \text{ at } I_b = \text{const}}$$

At the initial moment, the characteristics are very steep, because at the collector voltage $|U_{CE}| < |U_{BE}|$, the collector junction is turned on in the forward direction and the resistance is small, i.e. the collector current I_{col} varies strongly at a low voltage U_{CE}.

Subsequently, with increasing voltage $|U_{CE}|$, the collector junction is shifted in the opposite direction and the output resistance is large, as a result of which the current changes slightly.

Load limits:

1) $I_{col} \approx I_{em} \le I_{col\,\max}$ – overheating of the open emitter junction;

2) $U_{CE} \le U_{CE\,\max}$ – breakdown of a closed collector junction;

3) $P_{col} = I_{col} U_{CE} \le P_{col\,\max}$ – overheating of the closed collector junction.

BJT are semiconductor amplifying and key devices for universal use.

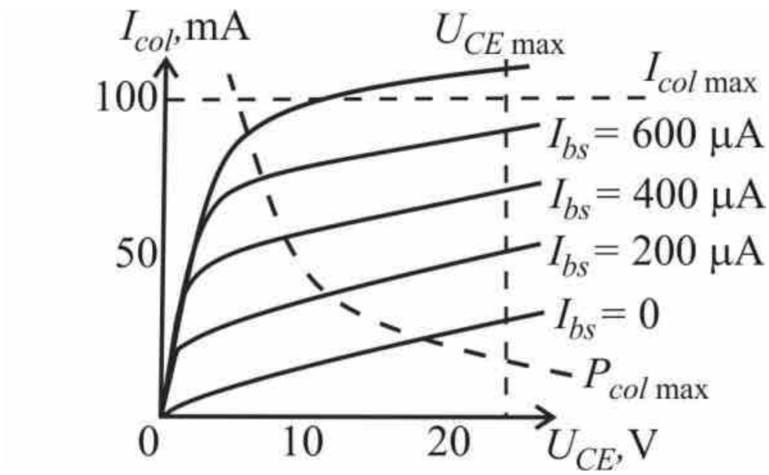


Figure 19.11

Test questions

1. What is a bipolar junction transistor?

2. How many p-n junctions and electrodes are in a bipolar junction transistor?

3. What are the names of electrodes in a bipolar junction transistor?

4. What are the transistor switching circuits?

5. What are the modes of operation of a bipolar junction transistor?

6. What is the principle of operation of a bipolar junction transistor?

LECTURE 20

FIELD-EFFECT TRANSISTORS. THYRISTOR. PURPOSE, TYPES, DESIGNATIONS, PRINCIPLE OF OPERATION AND CHARACTERISTICS

Field-effect (unipolar) transistors (FET) are used:

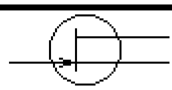
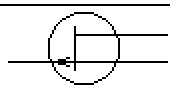
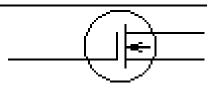
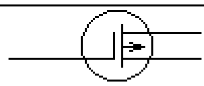
1) in amplifier stages with high input impedance;

2) in gating and logical circuits.

Field effect transistors can operate at low temperatures (up to 0 K), have high stability of parameters in time under the influence of various adverse factors, have high radiation stability, work in space, etc.

FET is a semiconductor device, the amplifying properties of which are due to the flow of the main charge carriers of the same sign flowing through a conducting channel, and which is controlled by an electric field.

Table 20.1 Symbolic notation of FET

Gate type	Канал	Symbolic notation
p-*n* junction	N-type	
	P-type	
Isolated	N-type	
	P-type	

In the field effect transistor there are:

A CHANNEL is a region in a transistor which resistance depends on the potential at the gate.

GATE (G) is an electrode used to control the cross section of the channel.

SOURCE (I) is an electrode from which the majority carriers of charge enter the channel.

DRAIN (D) is an electrode through which the majority carriers of charge escape from the channel.

FET are divided into transistors with N-type and P-type channels.

By the method of isolating gate, FET are divided into transistors with a control *p-n* junction and transistors with an isolated gate.

FET with a gate in the form of *p-n* junction

Block diagram (Fig. 20.1, *a*) and the switching circuit (Fig. 20.1, *b*) of a field effect transistor with an N-type channel and a gate in the form of *p-n* junction.

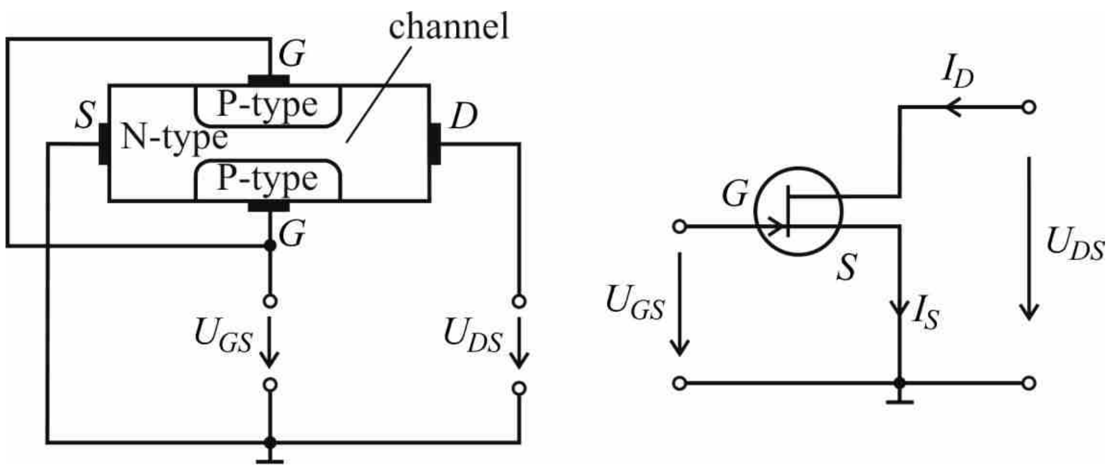


Figure 20.1

At $U_{GS} = 0$, the channel thickness is greatest and its resistance is minimal.

If a negative voltage $U_{GS} < 0$ is applied to the gate with respect to the source, then the *p-n* junctions will expand, the channel thickness will decrease, and its resistance will increase.

If the source U_{GS} is turned on, then the drain current I_D flowing through the channel can be controlled by the voltage U_{GS} supplied to the gate.

Current-voltage characteristics of the FETr

1) DRAIN-GATE (TRANSITION) characteristic: $I_D(U_{GS})|_{U_{DS}=const}$. .

U_{GScut} – gate voltage at which the channel completely overlaps.

I_{Din} at the start at U_{DS} = 0 is the initial drain current in Fig.20.2.

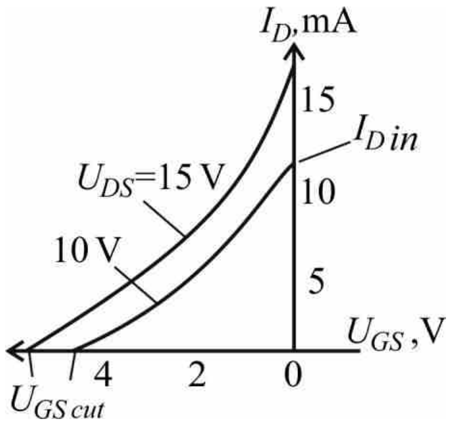


Figure 20.2

2) DRAIN (OUTPUT) characteristics: $I_D(U_{DS})|_{U_{GS}=const}$ are in Fig. 20.3.

In the initial section:

$U_{DS}+|U_{GS}|<U_{turn-off}$ and the current I_D increases with increasing U_{DS}.

With a further increase in voltage U_{DS} to the value: $U_{DS}+|U_{GS}|=U_{turn-off}$.

The channel are closed, and the current growth I_D ceases (saturation section).

With a further increase in the voltage U_{DS}, a breakdown of the *p-n* junction occurs between the gate and the channel.

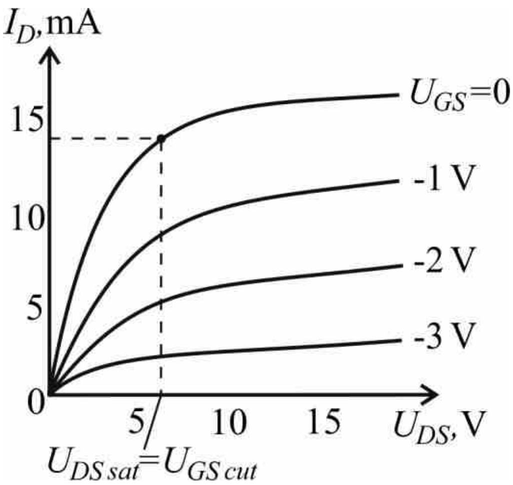


Figure 20.3

Insulated Gate Field-Effect Transistor

An insulated gate field-effect transistor is a semiconductor device in which a thin layer of dielectric (usually silicon oxide) is located between the metal gate and the channel to reduce the gate leakage current I_G. The scheme of an insulated gate FET is shown in Fig.20.4. These transistors are called MOS transistors (metal - oxide - semiconductor) or MDS transistors (metal - dielectric - semiconductor).

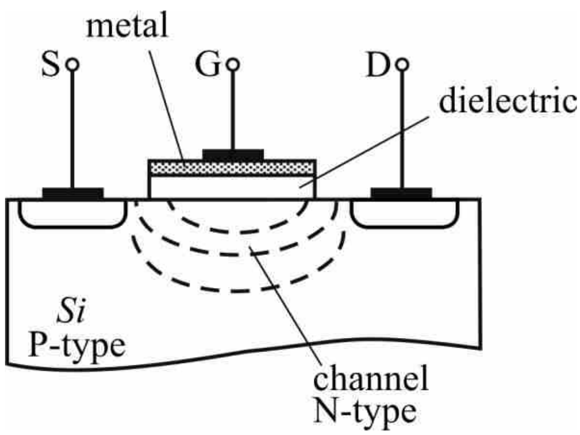


Figure 20.4

The I – U characteristics of these FET transistors are similar, but they can operate at U_{GS}> 0, when the channel expands and the drain current I_c increases.

Depending on the polarity of the voltage, the U_{GS} channel can be depleted or enriched with charge carriers (electrons).

At a negative voltage $U_{GS} < 0$, conduction electrons are pushed out of the channel region into the semiconductor volume, the channel is depleted in charge carriers, and the drain current I_D decreases.

With a positive voltage $U_{GS} > 0$, conduction electrons are drawn into the channel from the semiconductor. The enrichment of the channel occurs, and the drain current I_D increases.

Thyristors. Purpose, types, designations, device,
Principle of operation and characteristics

A thyristor is a semiconductor device with two stable states, which has 3 or more *p-n* junctions, in the current-voltage characteristic of which there is a section of negative differential resistance $-\frac{\Delta U}{\Delta I}$, and which can switch from a closed state to an open state and vice versa.

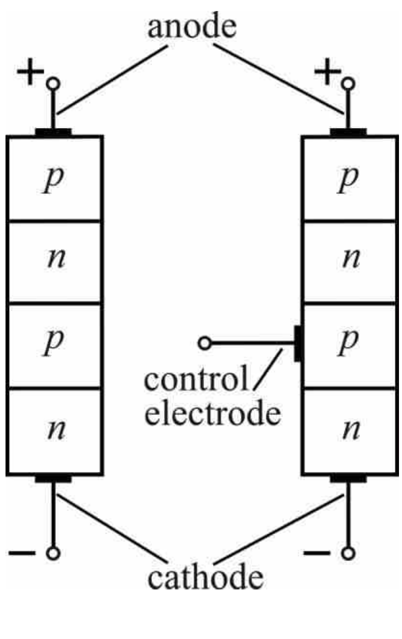


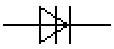
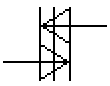
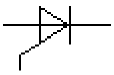
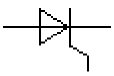
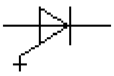
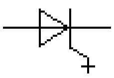
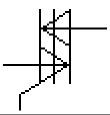
Figure 20.5

Applications of thyristors: uncontrolled and controlled rectifiers, inverters - DC-to-AC converters, voltage regulators, proximity switches, electric drives and automation devices, telemechanics and computer equipment, etc.

Thyristors are divided into with two-leads thyristors (Fig. 20.5, *a*), and with three-leads thyristors (Fig. 20.5, *b*). Two-leads thyristors are uncontrolled keys, and three-leads thyristors are controlled keys.

The electrode providing electrical connection with the external N-type is called the CATHODE, and the electrode connected in the external P-type is called the ANODE.

Table 20.2 Thyristor symbols

Symbol	Designation Name
	- two-lead thyristor
	- Symmetric two-lead thyristor
	- three-leads thyristor with anode control (the control lead (gate) is closer to the anode)
	- three-leads thyristor with cathode control (the control lead(gate) is closer to the cathode)
	- lockable anode three-leads thyristor
	- lockable cathode three-leads thyristor
	- Symmetric three-leads thyristor

Lockable thyristors are closed with a short pulse of reverse voltage supplied to the control electrode.

Principle of operation

P_1, P_2, P_3 are three *p-n* junctions which are shown in Fig. 20.6. With a direct voltage U_f, junctions P_1 and $P3$ are open, and junction P_2 is closed.

Moreover, all the forward voltage U_f applied to the junction P_2. Since the resistance of this junction is large, the current through the thyristor is small (section A on the $I – U$ characteristic is shown in Fig. 20.7).

After reaching $U_f = U_{in}$ (input voltage), an avalanche-like increase in the number of charge carriers in the P_2 junction occurs.

Due to this, the current increases rapidly, because electrons from the n_2-type and holes from the p_1-type rush into the p_2–type and n_1–type, and saturate them with non-basic charge carriers. The thyristor resistance drops significantly. The thyristor switches because the voltage on it drops, the current rises and the voltage increases on the resistance R_l.

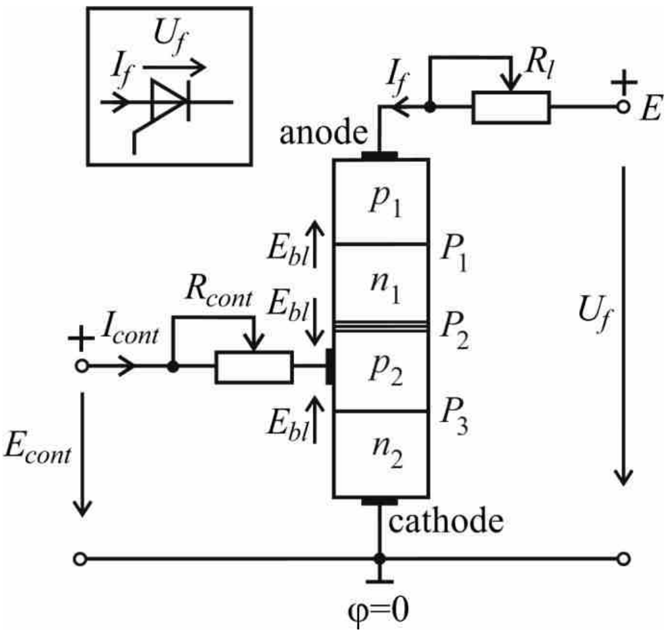


Figure 20.6

Sections A, B are two stable conditions in Fig. 20.7.

After switching, in point of opening (U_{op}, I_{op}), the voltage on the thyristor decreases to 0,5 ... 1,0 V. With a further increase of EMF of the source or a decrease in R_l, the current in the device increases in section *B*.

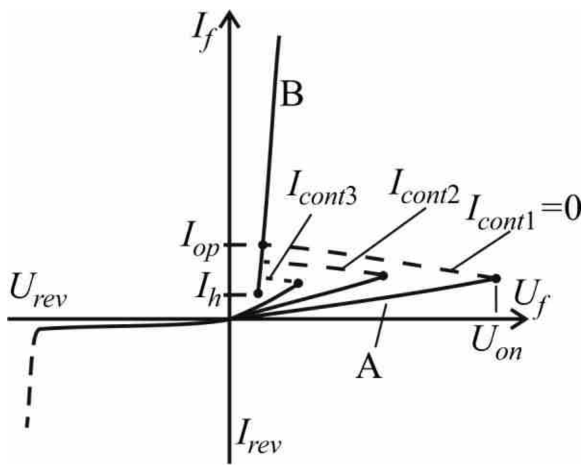


Figure 20.7

With a decrease of the forward current I_f below the holding current I_h, the high resistance of the P_2 junction is restored (off-state). The recovery time is 10 ... 30 μs.

The turn-on (on-state) voltage U_{on}, at which an avalanche-like increase of a current begins, can be reduced by introducing minority carriers of charge into any of the layers adjacent to the P_2 junction.

These additional charge carriers increase the number of atomic ionization events in the junction, and therefore U_{on} decreases.

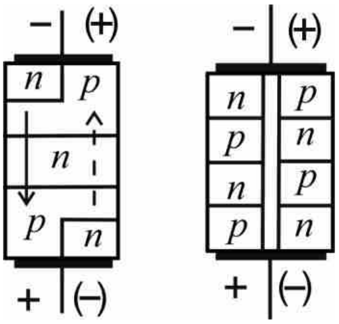
Additional carriers in the three-lead thyristor are introduced into the *p*2 layer by a controlled circuit from an independent source E_{cont}.

When a reverse voltage U_{rev} is applied to the thyristor, a small current I_{rev} appears, since in this case two junctions P_1 and P_3 are closed. To avoid breakdown of the thyristor, it is necessary to provide $U_{rev} < U_{rev\ \max}$.

Symmetric Thyristor Structure

In the five-layer thyristor design (Fig. 20.8, a) with the initial polarity of the applied voltage (without brackets), the left half of the device works (the direction of electron motion is indicated by a down arrow).

With reverse voltage polarity (shown in parentheses), the current flows in the opposite direction through the right half. The role of a symmetric thyristor can be performed by two diode thyristors connected in opposite directions (Fig. 20.8, *b*).



a *b*

Figure 20.8

Controlled symmetrical thyristors have leads from the corresponding base areas.

Test questions

1. What is a field-effect transistor?

2. What is the main region in a field-effect transistor?

3. What are the names of electrodes in a field-effect?

4. What are the current-voltage characteristics of a field-effect transistor?

5. What is an insulated gate field-effect transistor?

6. What is the design and principle of operation of a thyristor?

LECTURE 21

RECTIFIER DEVICES

Block diagram and parameters of rectifiers

RECTIFIER is a device that converts alternating current into direct current. The rectifier block diagram is shown in Fig. 21.1.

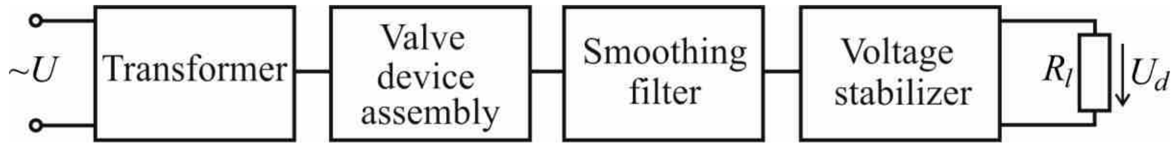


Figure 21.1

The transformer regulates the voltage to the required value.

The valve device assembly (*valve group*) contains elements with one-sided conductivity: rectifier diodes in uncontrolled rectifiers and thyristors in controlled rectifiers.

Smoothing filters are designed to reduce the ripple of the rectified voltage.

The voltage stabilizer (*voltage regulator*) keeps the constant voltage across the load resistor R_l.

There are single-phase and three-phase, controlled and uncontrolled rectifiers.

Single phase rectifiers

Schemes of circuits, principle of operation, parameters and characteristics

To rectify a single-phase alternating voltage, three circuits are used:

1) half-wave circuit;

2) bridge circuit (Grets circuit);

3) double half-wave circuit (with the lead of the midpoint of transformer).

One-half-wave circuit in which the current passes through the valve only for one half-period of the alternating voltage of the source. Double half-wave circuits in which the current passes through the valve group for two half-periods of the alternating voltage of the source.

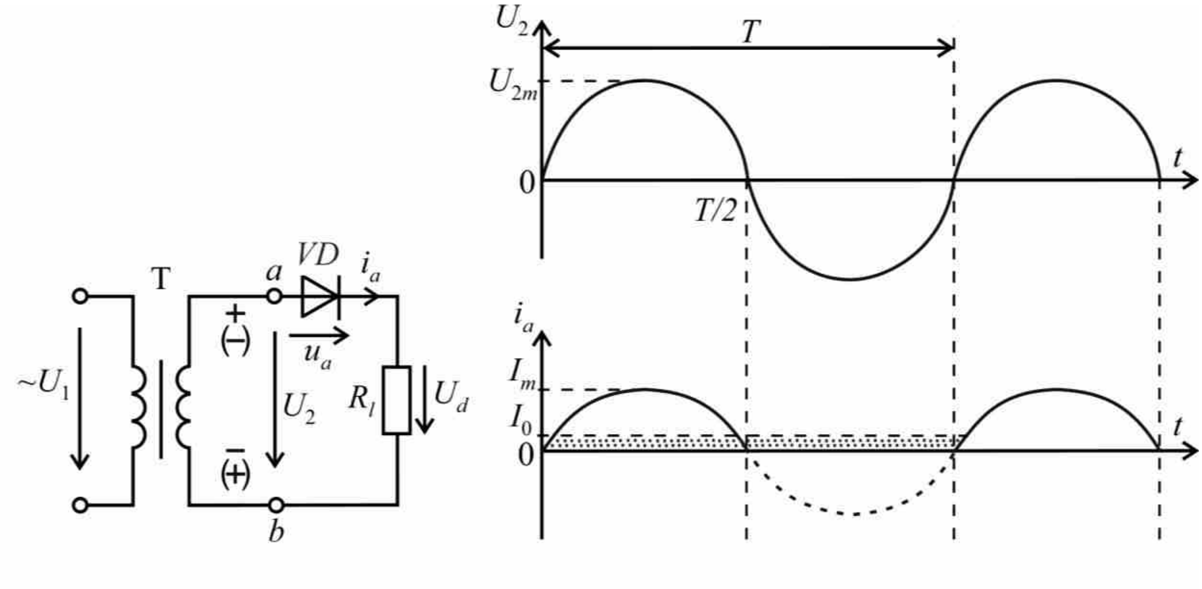
Consider the ratio of the parameters in the rectifiers under the following assumptions:

1) the leakage inductance of the transformer and the resistance of its windings are equal to zero;

2) the resistance of the valve in the forward direction is equal to zero, and in the opposite direction it is equal to infinity.

Single phase half wave rectifier. Time diagrams of voltages and currents

The circuit of the rectifier and time diagram are shown in Fig. 21.2, *a*, *b*.



a *b*

Figure 21.2

Define the constant component of the rectified current:

$$I_0 T = \int_0^{T/2} i_2 dt$$

Since, $i_2 = I_m \sin \omega t$ then

$$I_0 T = \int_0^{T/2} I_m \sin \omega t dt = -I_m \frac{\cos \omega t}{\omega}\Bigg|_0^{T/2} = 2\frac{I_m}{\omega}$$

$$I_0 == 2\frac{I_m}{\omega T}.$$

But since $\omega = \frac{2\pi}{T}$, i.e. $\omega T = 2\pi$, then

$$I_0 = 2\frac{I_m}{\omega T} = \frac{2I_m}{2\pi} = \frac{I_m}{\pi} \text{ or } \boxed{I_0 = \frac{I_m}{\pi} \approx 0{,}318 I_m}.$$

The constant component of the voltage, expressed in terms of the maximum value

$$U_0 = I_0 R_l = \frac{I_m}{\pi} R_l = \frac{U_m}{\pi} = 0{,}318 U_m \ .$$

The constant component of the voltage, expressed in terms of the actual value

$$U_0 = \frac{U_m}{\pi} = \frac{\sqrt{2}U}{\pi} \approx 0{,}45 \cdot U$$

Thus, in this circuit, the maximum voltage on the diode

$$U_m = U_{rev} = \pi U_0 = 3{,}14 U_0 \ ,$$

the voltage across the diode is three times higher than on the load.

The average value of the diode current in this circuit $I_{av} = I_0$.

The ripple value of the rectified voltage is characterized by the ripple factor

$$\boxed{K_r = \frac{U_{1m}}{U_0}},$$

where U_{1m} is the amplitude (peak value) of the variable component of the voltage, changing with the pulse repetition rate, i.e. amplitude of the first harmonic.

For a half-wave circuit

$$U_{1m} = \frac{U_{2m}}{2} = \frac{\pi U_0}{2} = 1{,}57 \cdot U_0, \quad \text{and } K_r = 1{,}57 .$$

The disadvantages of the circuit:

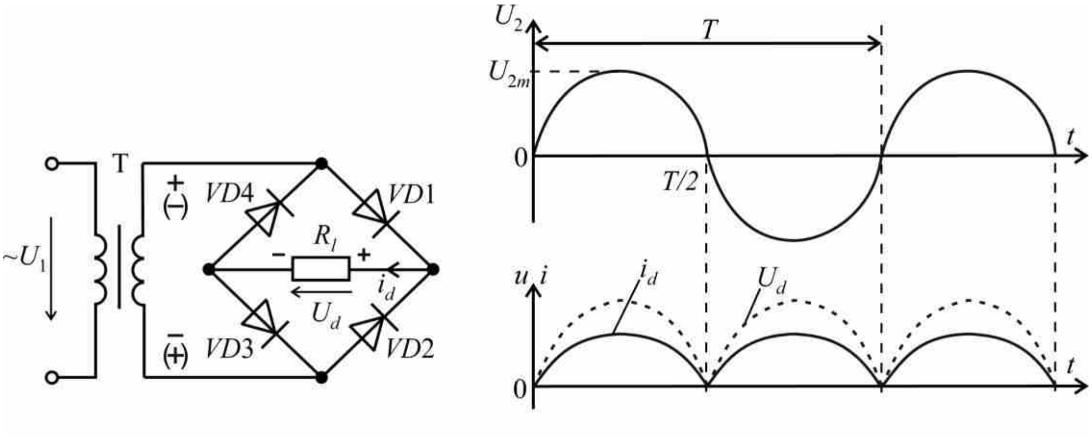
1) a large value of the ripple coefficient;

2) the voltage across the load is almost 3 times less than on the diode;

3) the constant component of the rectified current is much less than the current in the secondary winding of the transformer, which leads to its insufficient current use.

Bridge circuit (Grets circuit)

The circuit of the rectifier and the time diagram are shown in Fig. 21.3 *a, b*.



a *b*

Figure 21.3

I_0 is 2 times greater than in a half-wave circuit. Therefore:

$$\boxed{I_0 = 2\frac{I_m}{\pi} \approx 0{,}636 I_m}$$

$$U_0 = I_0 R_l = 2\frac{I_m}{\pi} R_l = \frac{2 \cdot U_m}{\pi} = 0{,}636 \cdot U_m;$$

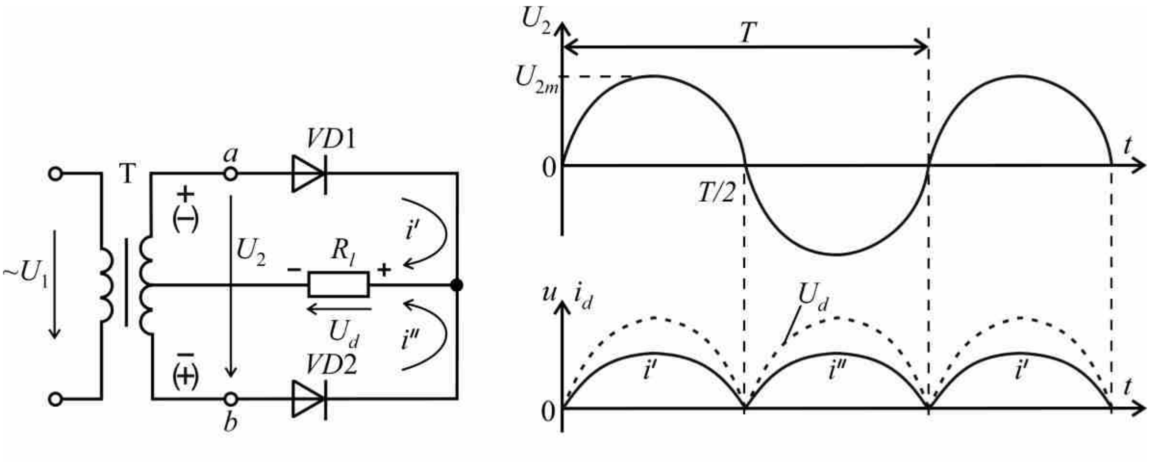
$$U_0 = 2\frac{U_m}{\pi} = \frac{\sqrt{2} \cdot 2 \cdot U}{\pi} \approx 0{,}9 \cdot U\ ;$$

$$K_r = 0{,}67\ .$$

The frequency of the rectified current is 2 times higher than that of the network.

Double half-wave circuit with transformer midpoint output

The circuit of the rectifier and time diagram are shown in Fig. 21.4, *a, b*.



a *b*

Figure 21.4

This is actually a combination of two half-wave rectifiers connected to the load resistor R_l in different phases.

The ratio of the parameters in this circuit are the same as in the bridge circuit.

Advantages of double half-wave rectifiers over single-half-wave rectifiers:

The average value of the rectified current and voltage is 2 times greater, and the ripple is less. But double half-wave rectifiers have a more complex design and cost.

Comparison of double half-wave circuits:

1) the bridge circuit is structurally simpler, its dimensions, weight and cost are lower than the transformer circuit;

2) the maximum reverse voltage on the closed diodes in the bridge circuit is 2 times less (each of the two diodes accounts for half the voltage);

3) but in the bridge circuit, 2 times more diodes are needed.

When rectifying the currents $I > I_{fr\max}$ for one diode, in parallel, diodes of the same type with additional resistances are included.

The values of the currents are determined by the resistance in the forward direction. But the resistance of the diodes in the forward directions R_f even for the same type of diodes are different. To equalize the currents of the diodes, additional resistances are sequentially included. Moreover, R_d is 5 ... 10 times more than R_f (Fig. 21.5).

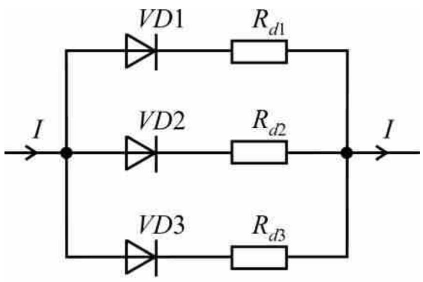


Figure 21.5

When rectifying a voltage exceeding the maximum allowable for the diode $U_{rev.\max}$, a serial connection of diodes shunted by resistors are used. In this case, the reverse voltage across the diodes is distributed in accordance with their inverse resistances R_d. To align the reverse voltages parallel to the diodes, we can include shunt resistors R_{sh}, the value of which is equal to R_{sh} = (0,1 ... 0,2) R_d. (Fig. 21.6).

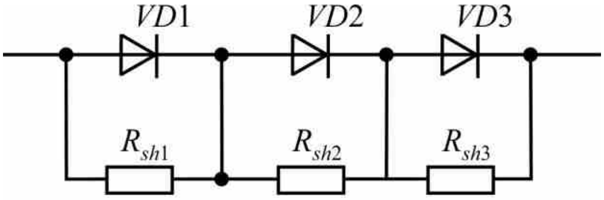


Figure 21.6

Smoothing filters. Schematic diagrams, principle of operation, parameters and characteristics

To reduce the ripple of the rectified voltage, smoothing filters (SF) are used. Ripple reduction is estimated by a smoothing coefficient

$$\boxed{q = \frac{K_r}{K_r^{'}}},$$

where K_r and $K_r^{'}$ are the ripple coefficients before and after the filter.

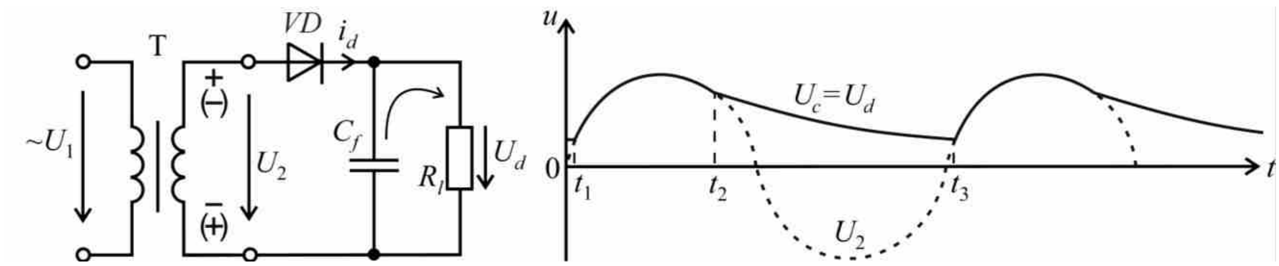
The main requirements for smoothing filters are the maximum reduction of the high-frequency components of the currents in the load resistance.

The inductive element $L \Rightarrow X_{Lk} = \omega kL$, and the capacitive element $C \Rightarrow X_{Ck} = \frac{1}{\omega kC}$, where k is the harmonic number.

Therefore, the inductance is set in series, and the capacitance is parallel to the load.

Capacitive filter

The schematic diagram of the filter is shown in Fig. 22.7, *a*.



a *b*

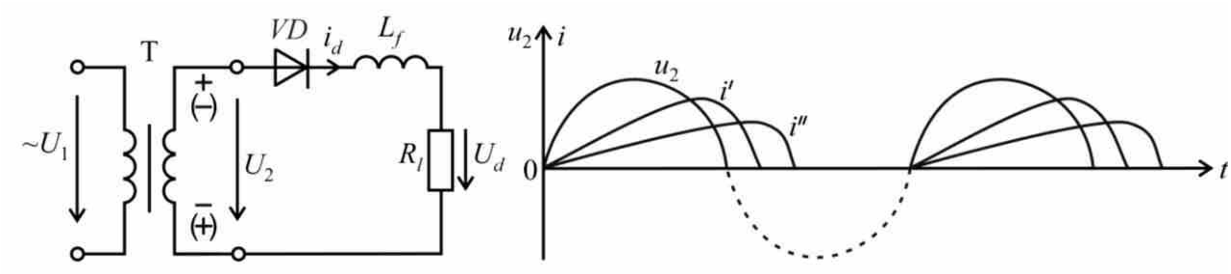
Figure 21.7

The capacitor is charged to voltage U_2 when $U_2 > U_c$ (interval $t_1 - t_2$) as it shown in Fig. 21.7, *b*. During the time interval ($t_2 - t_3$), the voltage $U_c > U_2$ – the diode is closed, and the capacitor is discharged through the resistor R_l with a time constant.

From the moment of time t_3 $U_c < U_2$ – the capacitor is charging, etc. That is, when the diode passes the current, the capacitor is charged, and when the reverse voltage is applied to the diode, the capacitor is discharged to the load R_l.

Inductive filter

The schematic diagram of the filter is shown in Fig. 21.8, *a*.



a *b*

Figure 21.8

During the positive half-cycle of voltage u_2, when the current i rises, the inductive coil L_f stores energy, and in the negative half-period, energy is spent on maintaining the current.

The duration of the current i_l pulses in is determined by the time constant $\tau = \dfrac{L_f}{R_l}$. The larger the inductance L_f, the more the pulse is pulled and its amplitude decreases due to inductive resistance $X_L = \omega L_f$. The average current value also falls.

Typically, the inductance L_f in half-wave circuits is not used, but used in double half-wave.

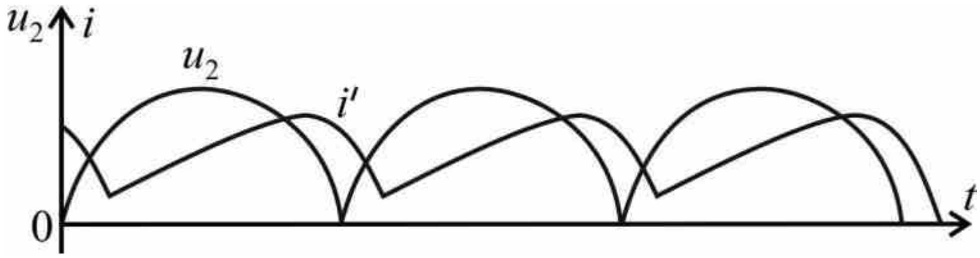
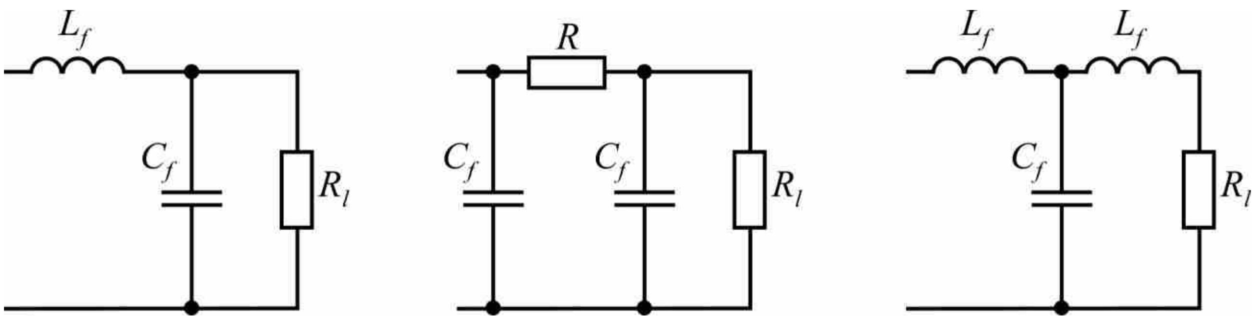


Figure 21.9

Varieties of smoothing filters (*LC*-*RC* filters; *L*-, *P*-, *T*- shaped) filters are shown in Figure 21.10, *a*, *b*, *c*.



a *b* *c*

Figure 21.10

External characteristics of rectifiers

The load resistance R_l changes during operation, which causes a change in the load current I_l.

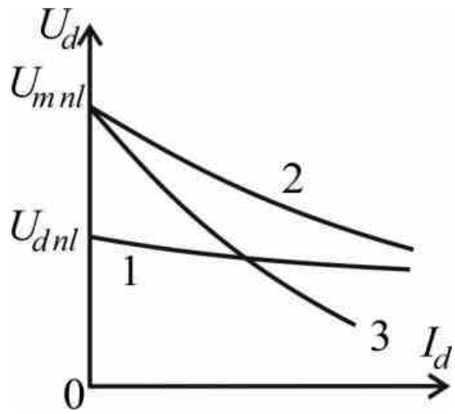


Figure 21.11

Transformers and valves (diodes) have certain values R_{tr} and R_f of resistances. At these resistances, the voltage drops from the current I_l, resulting in a change in the load voltage U_l.

External characteristic of the rectifier U_l (I_l)

$$U_l(I_l) = U_{nl} - (R_f + R_{tr})I_l = U_{nl} - R_f I_l - R_{tr} I_l \ ,$$

where U_{nl} is the rectified voltage at $I_l = 0$;

$R_f I_l$ – the average value of the voltage drop across the diode resistance in the forward direction;

$R_{tr} I_l$ – the average value of the voltage drop across the resistance of the secondary winding of the transformer.

The external characteristic defines the boundaries of the change in the load current at which the rectified voltage does not decrease below the permissible value.

1 – rectifier without filter (characteristic is non-linear due to R_f);

2 – rectifier with capacitive filter;

In the idle (no-load) mode ($I_l = 0$), the rectified voltage is equal to the amplitude value $U_{m\,nl}$, and without a filter, to the average value.

For a half-wave rectifier – $U_{l\,nl} = \dfrac{U_m}{\pi} = 0{,}318U_m$;

For the double half-wave – $U_{l\,nl} = 2\dfrac{U_m}{\pi} = 0{,}636U_m$.

With an increase in the load current, curve 2 drops more sharply, since the drop also occurs due to a faster discharge of the capacitor to a lower resistance, which reduces the voltage on the load.

3 – rectifier with a *L*-shaped *RC* filter. An additional decrease in voltage is caused by a voltage drop across the series-connected resistor R_f.

Test questions

1. *What is a rectifier?*
2. *What does the rectifier block diagram consist of?*
3. *What do you know about single phase rectifiers?*
4. *What are the schematic diagram, time diagram and the parameters of a half wave rectifier?*
5. *What are the schematic diagram, time diagram and parameters of a double half wave rectifier?*
6. *What are the schematic diagram, time diagram and parameters of a bridge circuit rectifier?*
7. *What the smoothing filters do you know?*
8. *What external characteristics of rectifiers do you know?*

LECTURE 22

CONTROLLED RECTIFIERS

In practice, rectifier installations often must provide smooth regulation of the rectified voltage U_0. In uncontrolled rectifiers with diodes, adjustment is difficult to carry out. In controlled rectifiers, a three-lead thyristor is used as a valve element.

Single Phase Half-Wave Controlled Rectifier

The circuit and time diagram of a single-phase one-half-wave rectifier is shown in Fig. 22.1:

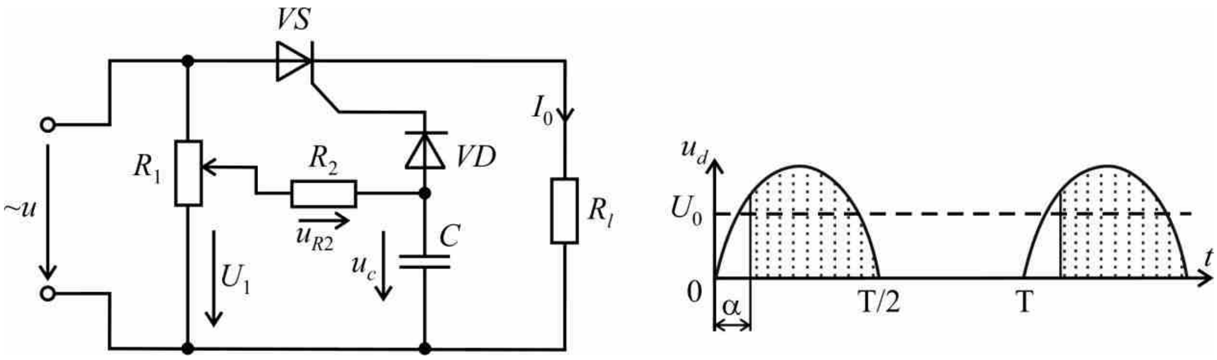


Figure 22.1

The control of the rectified voltage reduces to a time delay of the moment of turning on the thyristor *VS* with respect to the moment of natural turning on due to the voltage applied between its anode and cathode. This is done by adjusting the phase angle between the anode voltage and the voltage supplied to the thyristor control electrode.

This phase shift is called the control angle α. The angle α is controlled using the phase-shifting circuit R_1, R_2, C.

Depending on the resistance of the variable resistor R_2, the angle α can vary from от 0° to 90°, which allows you to smoothly adjust the rectified voltage from the largest value to half.

The average rectified voltage is

$$U_0 = \frac{1}{T}\int_{\alpha}^{T/2} u(t)dt = \frac{1}{T}\int_{\alpha}^{T/2} U_m \sin\omega t dt = -\frac{U_m}{\omega T}\cos\omega t\Big|_{\alpha}^{T/2} = \frac{U_m}{2\pi}(1+\cos\alpha).$$

Disadvantage: at $\alpha\uparrow \Rightarrow U_0\downarrow$. But at the same time, the ripple of the rectified voltage increases, and the efficiency of the rectifier decreases. Control characteristic U_0 (α) (with active load R_l) is shown in Fig. 22.2.

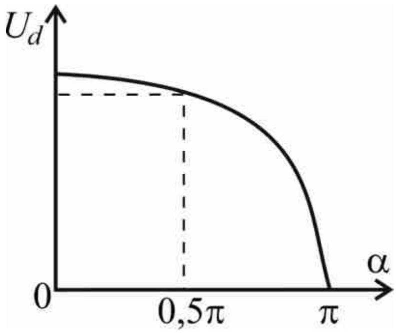


Figure 22.2

Voltage multipliers

Provide rectification with multiplying the output voltage any number of times.

Parallel voltage doubler

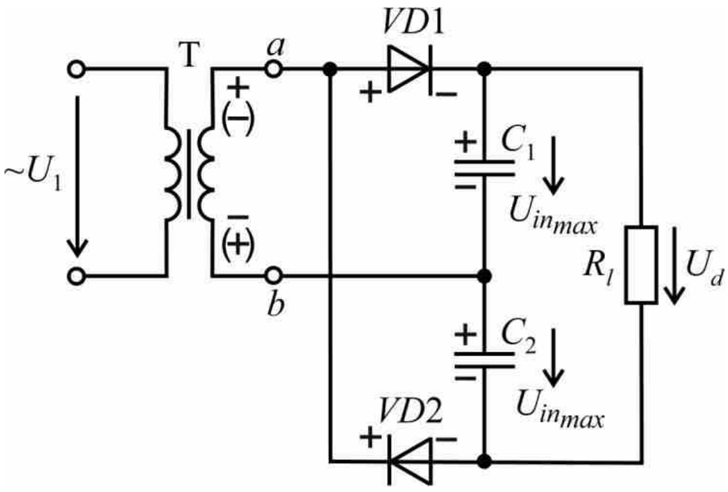


Figure 22.3

In the first half-cycle (Fig. 22.3), when *a* (+) and *b* (-), the diode *VD*1 is open, and the diode *VD*2 is closed and the capacitor C_1 is charged to the amplitude value of the input voltage $U_{in\ \max}$.

In another half-cycle, when *a* (-) and *b* (+), the diode *VD*1 is closed, and the diode *VD*2 is open and the capacitor C_2 is charged to the amplitude value of the input voltage $U_{in\ \max}$.

Since the capacitors C_1 and C_2 are connected in series with respect to the output terminals, and the polarity of the plates is such that the output voltage $U_{out} = U_l$ is equal to the sum of the voltages on the capacitors, the voltage across the load resistor is approximately equal to $2U_{in\ \max}$ (decreases at low R_l due to discharge capacitor to this resistor).

Series voltage doubler

The series voltage doubler has lower ripple and higher stability.

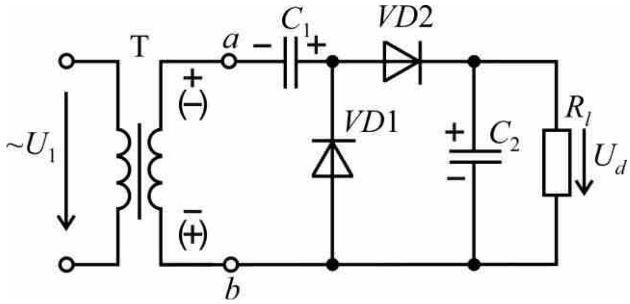


Figure 22.4

In one of the half-periods (Fig. 22.4), when the potential of point *b* (+), point *a* (-), capacitor C_1 is charged through diode *VD*1 to the amplitude input voltage $U_{in\ \max}$. In this case, the diode *VD*2 is closed.

In another half-period, when the potential of point *b* (-), *a* (+), the voltage across capacitor C_1 is summed with the input voltage. Due to this, the capacitor C_2 is charged through the diode *VD*2 to double the input voltage.

The combination of multipliers provides multiplication any number of times. With the help of voltage multipliers, you can get any voltage at the output when using small-sized and inexpensive devices and parts with low rated voltages.

The voltage balancer (quadruplicater) is a 2 series-connected voltage doubler shown in Fig. 22.5.

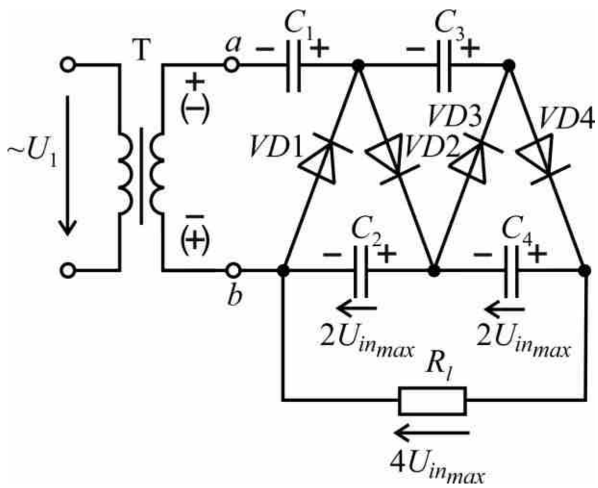


Figure 22.5

Inverter

To convert DC to AC, an autonomous inverter is used. It converts to alternating current with any number of phases, and the magnitude and frequency can be adjusted over a wide range.

Single phase self-commutated inverter

Thyristors are opened alternately with the help of triggering pulses supplied from the Control Unit to the control electrodes (Fig. 22.6).

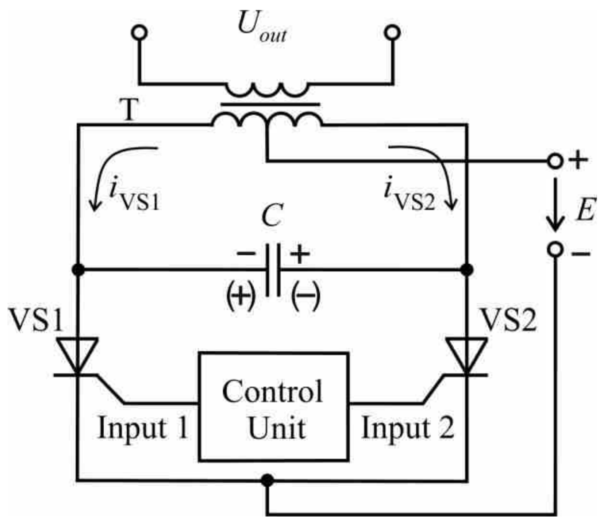


Figure 22.6

The pulse to the thyristor T_1 (Fig. 22.7) opens it and the current i_{T1} flows, inducing EMF in the secondary winding of the transformer and charging the switching capacitor C to the maximum voltage of the primary winding.

The next positive pulse arrives at thyristor T_2 and opens it. In this case, the capacitor C through the open thyristor T_2 is connected to the thyristor T_1. Such a reverse voltage seeks to close it.

The capacitor C is discharged through both thyristors, creating a forward current in the open thyristor T_2 and a counter current in the thyristor T_1.

The discharge of the capacitor C ends after the thyristor T_1 is turned off and it immediately starts recharging from the power source E through the left half

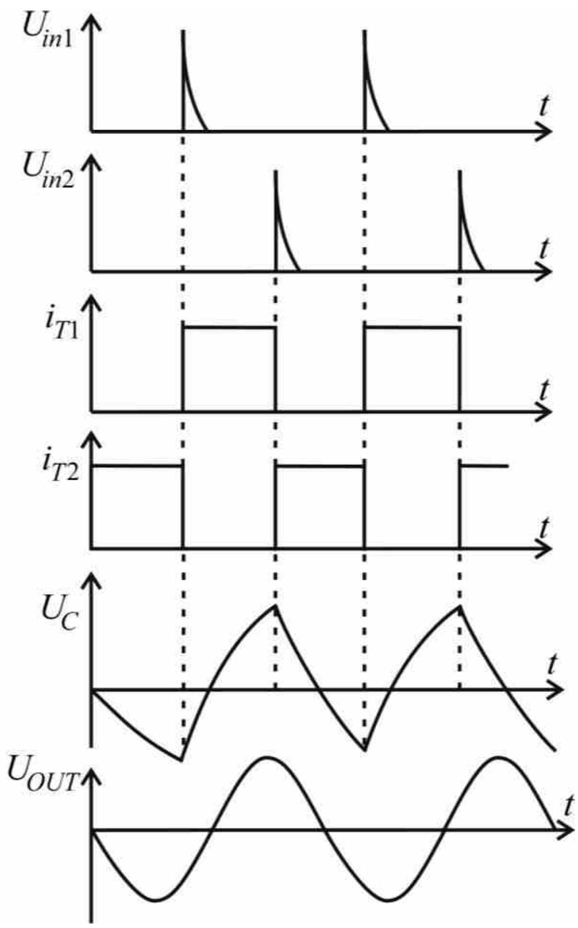


Figure 22.7

of the transformer primary winding and the thyristor T_2. In this case, the voltage across the capacitor reverses the polarity.

Changing the direction of the current in the primary winding of the transformer T changes the voltage on the secondary winding U_{out}. With a large value of capacitance C, the output voltage becomes close to sinusoidal.

Voltage stabilizer (Potentiostats or Surge Protectors)

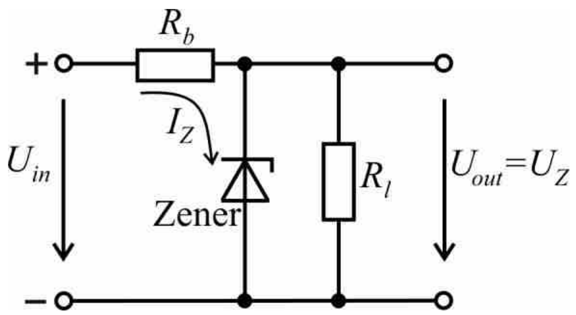


Figure 22.8

They distinguish between parametric and compensation stabilizers.

Parametric stabilizer

For a parametric voltage stabilizer on a Zener diode (Fig. 22.8), within a certain portion of the I – U characteristic, the voltage is practically independent of the current (Fig. 22.9).

We solve the problem graphically (Fig. 22.9).

With $R_l = \infty$: $U_{in1} = U_{Z1} + R_b I_{Z1}$

If the voltage at the input of the stabilizer has increased by Δu_{in}, for example, due to an increase in the network voltage, then the I – U characteristic of the ballast resistor R_b will move parallel to itself and take position 2:

$$U_{in2} = U_{in1} + \Delta U_{in} = U_{Z2} + R_b I_{Z2} \ .$$

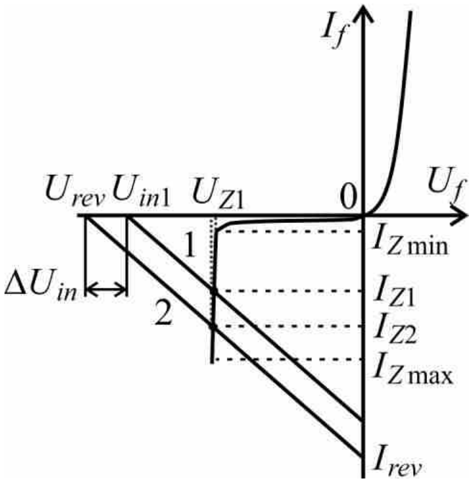


Figure 22.9

The voltage at the Zener diode will practically not change. The current of the Zener diode must not go beyond $I_{Z\max}$ ... $I_{Z\min}$.

The value of the ballast resistor R_b is chosen so that the I – U characteristic of the resistor crosses the Zener diode at a point in the middle of the working section 0,5 ($I_{Z\max}\ldots I_{Z\min}$).

The quality of work of voltage stabilizers is evaluated by the *stabilization coefficient* – the ratio of the relative change in the input voltage to the relative change in the output voltage at R_l = const.

$$\boxed{K_{st} = \frac{\Delta U_{in} / U_{in}}{\Delta U_{out} / U_{out}} = \frac{\Delta U_{in} U_{out}}{\Delta U_{out} U_{in}}},$$

where U_{in}, U_{out} – rated voltage values.

K_{st} for a parametric stabilizer is up to 100 (this is not much).

Advantages: simplicity of design and reliability.

Disadvantages: low coefficient of stabilization and efficiency, narrow and unregulated stabilized voltage range.

Compensation stabilizer

The compensation stabilizer (Fig. 22.10) work is based on comparing the input voltage with a given stable.

Depending on the difference between the stable and output voltages (mismatch), automatic control is carried out to reduce this mismatch.

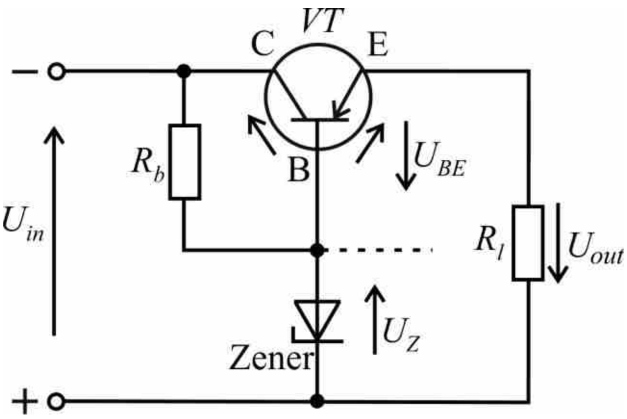


Figure 22.10

Stable (reference) voltage U_{st} is created on the Zener diode *VD*. The bipolar junction transistor *VT* plays the role of a comparing and regulating element. There is a slight positive voltage between the emitter and the base $U_{BE} = U_{st} - U_{out}$, since $U_{out} \approx U_{st}$. Suppose the input voltage U_{in} has increased. This will increase $U_{out.}$ Consequently, the voltage U_{BE} decreases and the current I_e, equal to I_{out}, decreases. Because of this $U_{out} = R_l I_{out}$, it will decrease to the previous value, and the voltage on the transistor will increase

$$U_{in} \uparrow \Rightarrow U_{out} \uparrow \Rightarrow U_{BE} \downarrow \Rightarrow I_b \downarrow \Rightarrow I_{col} \downarrow \approx I_{em} \downarrow \Rightarrow U_{CE} \uparrow \Rightarrow U_{out} \downarrow .$$

U_{CE} – voltage across collector-emitter.

The stabilization coefficient K_{st} is up to several thousand.

Test questions

1. What are controlled rectifiers?

2. What is the circuit and time diagram of the single phase half wave controlled rectifier?

3. What is the principle of operation the parallel voltage doubler?

4. What the voltage multipliers do you know?

5. What is the principle of operation of the single phase self-commutated inverter?

6. What are the parametric stabilization and compensation stabilizers?

7. What is the stabilization coefficient?

LECTURE 23

THE GENERAL CONCEPTS ABOUT AMPLIFIERS

The amplifier block diagram

An electronic amplifier is a device that provides an increase in the power of electric signals supplied to its input.

The amplifier includes:

1) an amplifying (active) element is a nonlinear element (transistor, electron lamp, etc.);
2) passive elements: resistive, capacitive, oscillatory circuit, etc .;
3) power supply (direct current, less often alternating current).

The source of input signals are: microphone, photocell, thermocouple, chemical current source, previous amplifier, etc.

Load of the amplifier can be: a resistor, an oscillating circuit, a transformer, an electric motor, a speaker, etc.

The purpose of the amplifier element is to convert the electric energy of the power source into the energy of amplified signals.

The simplest amplifier contains one active element with passive elements attached to it, and it is called an ***amplifier stage***.

Block diagram of the amplifier stage

Block diagram is shown in Fig. 23.1. The amplification process is to convert the energy of the power source into the energy of the output signal.

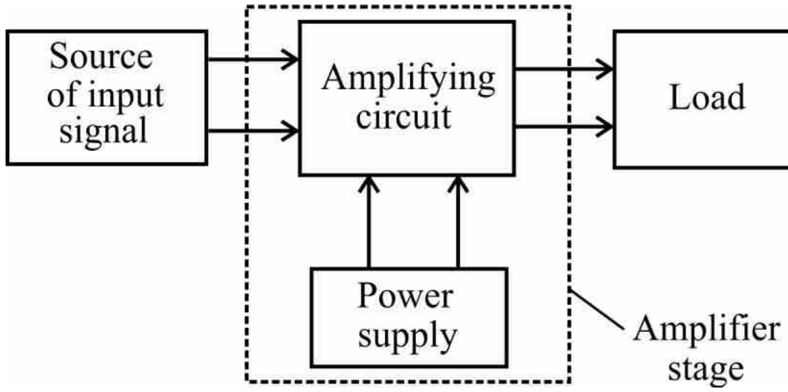


Figure 23.1

The input signal is a function of the input signal, and the power of the output signal due to the energy of the power source is much greater than the power of the input signal.

Amplifier Classification

By the nature of the amplified signals:

1) harmonic signal amplifiers;

2) pulse amplifiers.

By appointment:

3) voltage amplifiers;

4) current amplifiers;

5) power amplifiers.

By the nature of the amplifying elements:

6) transistor amplifiers (on bipolar or field effect transistors);

7) tube amplifiers (electronic tubes);

8) magnetic amplifiers, etc.

According to the frequency range of electric signals:

9) amplifiers of low frequency; from tens of Hz to tens of kHz.

11) DC amplifiers; more precisely, amplifiers of slowly changing signals: from 0 Hz to tens and hundreds of kHz.

12) selective or selective amplifiers - amplifying signals in a very narrow frequency band. They are characterized by a small ratio of the upper to lower frequencies

$$f_h / f_l < 1,1.$$

13) broadband amplifiers amplifying a very wide frequency band (from a few kHz to several MHz).

According to the type of interstage connections:

14) amplifiers with galvanic coupling;

15) amplifiers with resistive-capacitive coupling;

16) transformer coupled amplifiers;

17) amplifiers with communication through an oscillatory circuit.

Amplifier Key Features

1. *Gain* is the ratio of the signal at the output to the signal at the input of the amplifier.

We can distinguish between gains:

voltage gain $\boxed{K_U = \dfrac{U_{out}}{U_{in}}}$; current gain $\boxed{K_I = \dfrac{I_{out}}{I_{in}}}$;

power gain $\boxed{K_P = \dfrac{P_{out}}{P_{in}} = \dfrac{U_{out}}{U_{in}} \dfrac{I_{out}}{I_{in}} = K_U K_I}$.

These are dimensionless coefficients. There are very large values and this is inconvenient. Therefore, gain factors are used in logarithmic units – decibels (dB).

The relationship between dimensional and dimensionless coefficients is as follows:

$$\boxed{K_{P,\mathrm{dB}} = 10 \lg K_P}.$$

Since $P \sim I^2$ or U^2, then $\boxed{K_{U,\mathrm{dB}} = 20 \lg K_U}$ $\boxed{K_{I,\mathrm{dB}} = 20 \lg K_I}$

$$\boxed{K_U = 10^{\frac{K_{U,\mathrm{dB}}}{20}}}.$$

Reverse transition

If $K_{U,\ \mathrm{dB}}$ = 1 dB, then $K_U = 10^{1/20}$ = 1,12, i.e. gain of 12%.

The values of the coefficients K_U or just K are tens ... hundreds. Sometimes this is not enough. Then a series connection of amplification stages is used.

Block diagram of a multistage amplifier is shown in Fig. 23.2.

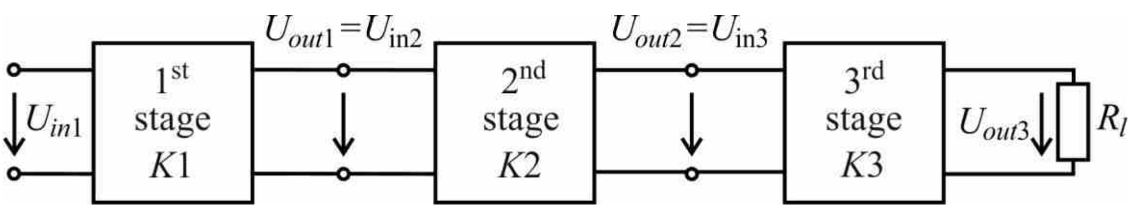


Figure 23.2

Total gain $K = K_1 \cdot K_2 \cdot K_3$ or $\boxed{K = \frac{U_{out3}}{U_{in1}} = \prod_{i=1}^{n} K_i}$.

Indeed $K = \frac{U_{out1}}{U_{in1}} \cdot \frac{U_{out2}}{U_{in2}} \cdot \frac{U_{out3}}{U_{in3}} = \frac{U_{out3}}{U_{in1}}$,

because $U_{out1} = U_{in2}$; $U_{out2} = U_{in3}$.

For dimensional coefficients

$$K_{\text{dB}} = K_{1,\text{dB}} + K_{2,\text{dB}} + K_{3,\text{dB}} = \sum_{i=1}^{n} K_{i,\text{dB}}.$$

2. *Output power*. With an active load, the output power of the amplifier

$$P_{out} = \frac{U_{out}^2}{R_l} = \frac{U_{m\,out}^2}{2R_l}$$

This is the net power developed by the amplifier in the load resistance. Its increase is limited by distortions due to the nonlinearity of the characteristics of the amplifying elements at large signal amplitudes.

The power at which the distortion does not exceed the allowable value is called the rated output power.

3. *Efficiency*

$$\boxed{\eta = \frac{P_{out}}{P_0} 100\%}$$

where P_0 is the power consumed by the amplifier from all power sources.

4. *Rated input voltage* – sensitivity. This is the voltage that must be brought to the input of the amplifier in order to obtain a given power output. Otherwise, there will be strong signal distortions.

5. *The range of amplified frequencies or bandwidth* – that region of frequencies in which the gain does not change more than is allowed by the technical conditions.

The expansion of the bandwidth leads to an increase in cost and complexity of the equipment.

Low frequency amplifier on common emitter bipolar transistor.

The transistor is *n-p-n* type. The polarity of the power supply E_{col} depends on this. Its value is usually taken 10 ... 15 V.

$E_{CE} > U_{BE}$; $I_{col} \approx I_{em}$; $R_{col} >> R_{em}$, so $U_{in} = I_{em}R_{em} << U_{out} = I_{col}R_{col}$.

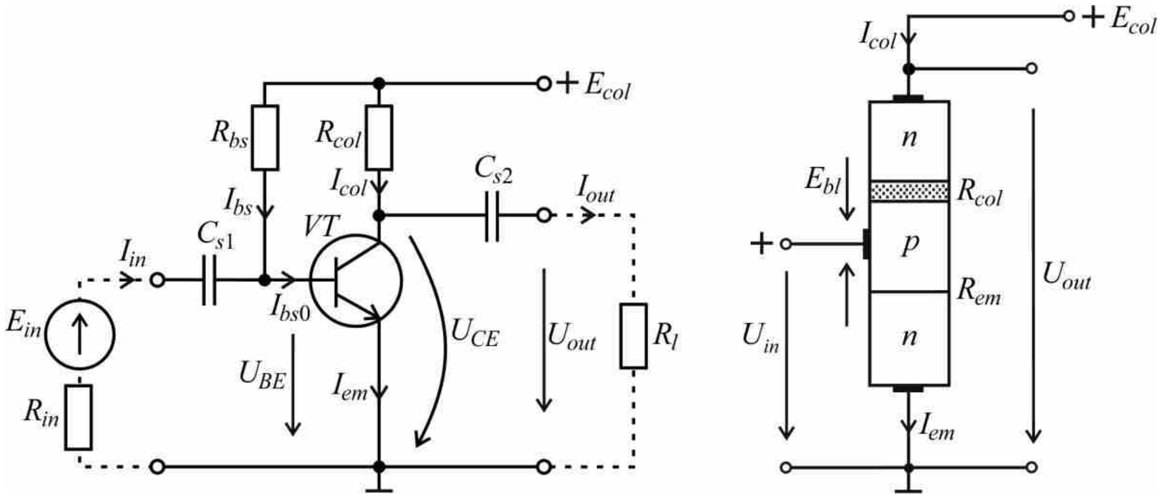


Figure 23.3

The input signal arrives at the base and changes its potential relative to the grounded emitter. This leads to a change in the base current, and, consequently, to a change in the collector current and the voltage at the load resistance R_{col}.

The separation capacitor C_{s1} serves to prevent the DC component of the base current from flowing through the input signal source (without C_{s1}, the source will heat up and the transistor will change its operation mode).

Using a capacitor C_{s2}, an alternating voltage component U_{CE} is supplied to the output of the cascade, which varies according to the law of the input signal, but significantly exceeds it in magnitude.

The resistor R_b provides the choice of the initial operation point on the characteristics of the transistor and determines the mode of operation of the cascade of direct current.

For the collector circuit according to Kirchhoff's voltage law

$$E_{col} = U_{CE} + I_{col}R_{col}$$

I - U characteristic of R_{col}: $I_{col}(U_{CE})$ – linear,

I - U characteristic of VT: $I_{col}(U_{CE})$ – non-linear.

We build a load line $U_{CE} = E_{col} - I_{col} R_{col}$ for the resistor

We can build on two points:

1) $I_{col} = 0;$ $\Rightarrow$ $U_{CE} = E_{col}$; 2) $U_{CE} = 0 \Rightarrow I_{col} = {E_{col}}/{R_{col}}$.

For this and base currents I_b, you can find the current I_{col} and voltage U_{CE} (along the intersection of the curves). Fig. 23.4 shows the characteristics.

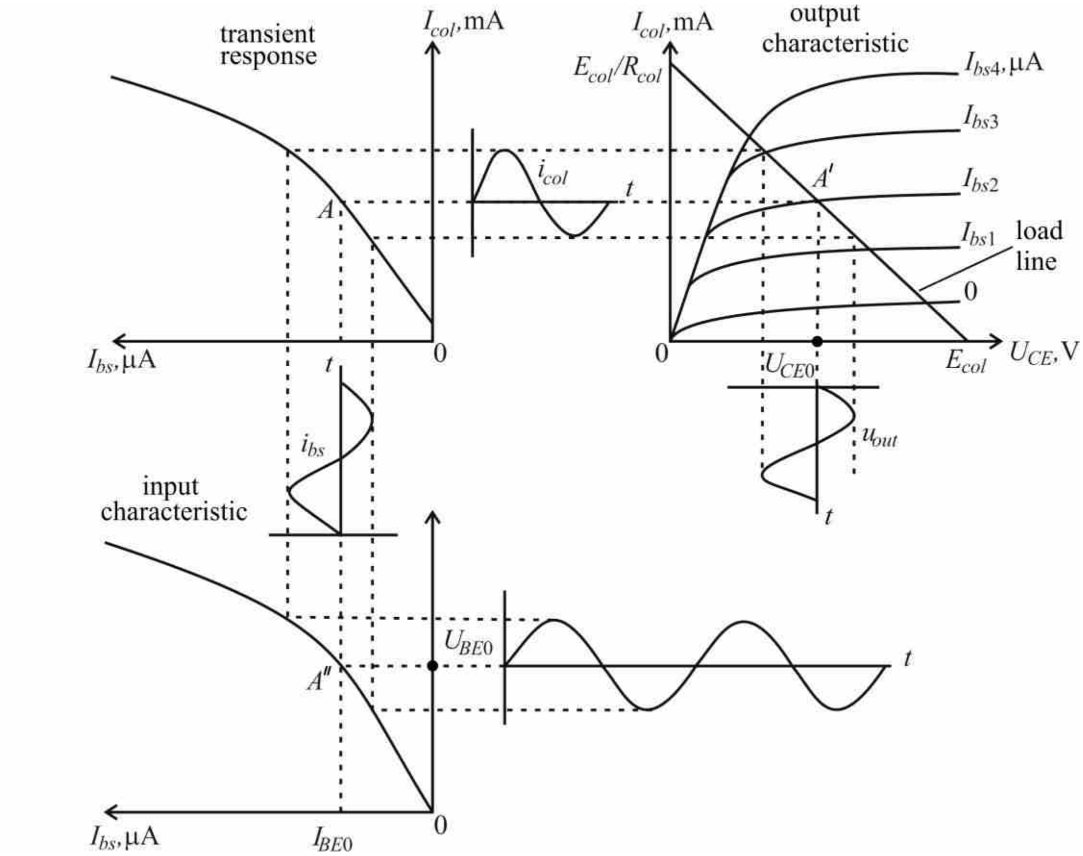


Figure 23.4

Using the resistor R_b, it is possible to obtain in the absence of an input signal a current I_{BE0} and a voltage U_{BE0} corresponding to the middle of the linear portion of the input characteristic (point A).

The resistance of the resistor R_b is selected from the equation:

$$E_{col} = U_{BE0} + I_{BE0} R_b \text{ – at the idle mode.}$$

$$R_b = \frac{E_{col} - U_{BE0}}{I_{BE0}}$$

The resistor R_b provides the bias current in the base circuit. Such a shift of the emitter junction is provided by a fixed base current. This is a fixed base current amplifier.

Amplifier temperature stabilization

With increasing temperature, the current I_{col} increases due to an increase in minority charge carriers, which changes the characteristics of the transistor (the operation point shifts from point A).

In this amplifier, the offset of the emitter junction is provided by a fixed base-emitter voltage, and the amplifier is called a fixed base voltage.

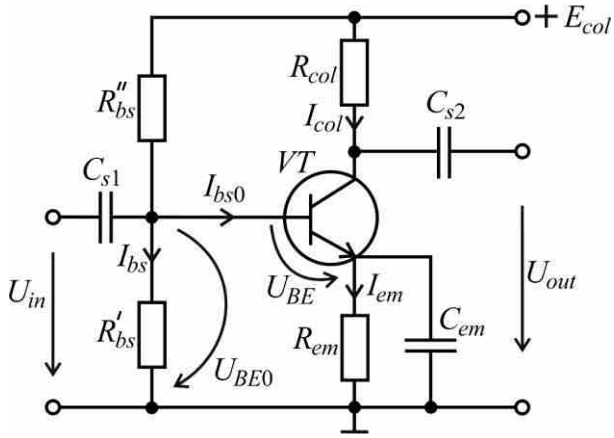


Figure 23.5

The idle mode is ensured by the constant bias voltage of the emitter junction using the $R'_{bs} - R''_{bs}$ divider that is shown in Fig. 23.5.

Voltage U_{BE0} (direct current in the absence of U_{in}):

$$U_{BE0} = I_{bs}R'_{bs} = \frac{E_{col}R'_{bs}}{R'_{bs} + R''_{bs}}$$ – initial shift of the base.

According to Kirchhoff's voltage law:

$$U_{BE} = U_{BE0} - I_{em}R_{em} = \frac{E_{col}R'_{bs}}{R'_{bs} + R''_{bs}} - I_{em}R_{em} \quad .$$

In the presence of a resistor R_{em}, an increase in current $I_{em} = I_{b0} + I_{col}$ due to an increase in temperature leads to an increase in the voltage drop $I_{em}R_{em}$ on the resistor R_{em}, which causes a decrease in voltage U_{be}, and therefore currents I_{em} and I_{col}:

$$\boxed{T\uparrow \Rightarrow I_{col}\uparrow \Rightarrow I_{em}\uparrow \Rightarrow I_{em}R_{em}\uparrow \Rightarrow U_{BE}\downarrow \Rightarrow I_{bs}\downarrow \Rightarrow I_{col}\downarrow}$$

Thus, the resistor R_{em} plays the role of DC feedback.

For alternating current in the presence of U_{in}: the introduction of R_{em} creates a voltage drop $u_{em} = i_{em} R_{em}$, which reduces the amplified voltage.

Where i_{em} is the alternating component of the emitter current.

$$U_{BE} = U_{in} - i_{em} R_{em}.$$

To attenuate this negative phenomenon, C_{em} is set in parallel with R_{em}. The capacitance of C_{em} is such that $X_{em} = \frac{1}{\omega C_{em}} << R_{em}$ for all frequencies of the amplifier and then the amplified voltage is almost equal to the input

$$u_{BE} \approx u_{in} ,$$

So that we removed the feedback on alternating current.

Self-interference and distortion of the amplifier

The causes of interference at the amplifier output can be divided into 3 groups:

1) thermal noise;

2) noise of amplifying elements;

3) interference due to ripples in the supply voltage and interference from external electromagnetic fields.

The amount of total noise at the amplifier output should be significantly less than the signal voltage. Typically, the useful signal should exceed the interference level by at least 2 ... 3 times (by 6 ... 10 dB).

Amplitude response (Gain characteristic)

It is dependence $U_{вых}(U_{вх})$ shown in Fig. 23.6. At low voltage or in the absence of a signal input, the output voltage is determined by the level of intrinsic noise and the noise of the amplifier at $U_{in} < U_{in\min}$.

At high input voltages $U_{in} > U_{in\max}$, the characteristic is distorted due to overload of the amplifying elements from the input side.

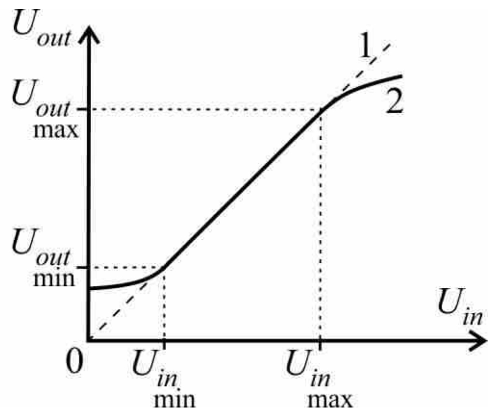


Figure 23.6

1 – ideal characteristic;
2 – a real characteristic

Estimated by the dynamic range of amplitudes in decibels

$$\boxed{D_{dB} = 20\lg\frac{U_{in\max}}{U_{in\min}}}.$$

Amp distortion

Distortions can be: nonlinear, frequency and phase.

Nonlinear distortion is a change in the shape of the curve of amplified oscillations caused by the nonlinear properties of the amplifier circuit (mainly due to the nonlinear characteristics of the transistor).

For example, how do nonlinear distortions appear in the input circuit of an amplifier due to a transistor? It is shown in Fig. 23.7.

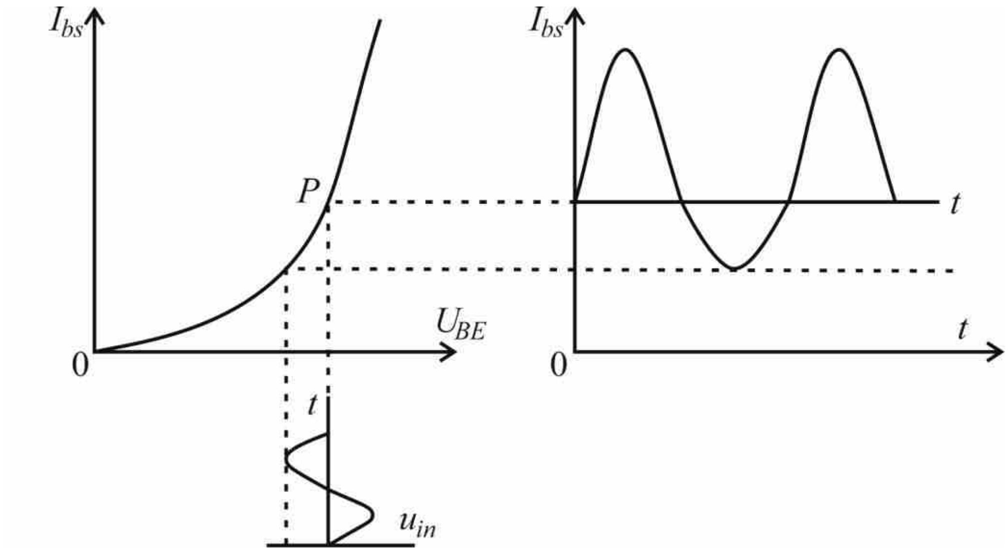


Figure 23.7

A sinusoidal signal is applied to the input of the amplifier. Getting on a non-linear section of the input characteristic of the transistor, this signal causes a change in the input current, the shape of which is not sinusoidal. This means that the output current and output voltage change their shape.

Frequency distortion is caused by a change in the magnitude of the gain at different frequencies. Reason is the presence of reactive elements in the amplifier (capacitors, inductors, mounting capacities, etc.).

Frequency distortion is estimated by the amplitude-frequency characteristic $K(f)$ or $U_{out}(f)$. It is shown in Fig. 2.38, where f_0 is the average transmission frequency; f_{low}, f_{high} are lower and upper boundary frequencies.

In the mid-frequency area or bandwith, the gain K is independent of frequency. The changes in the gain K are determined by the frequency distortion of the signal and are estimated by the frequency distortion coefficient

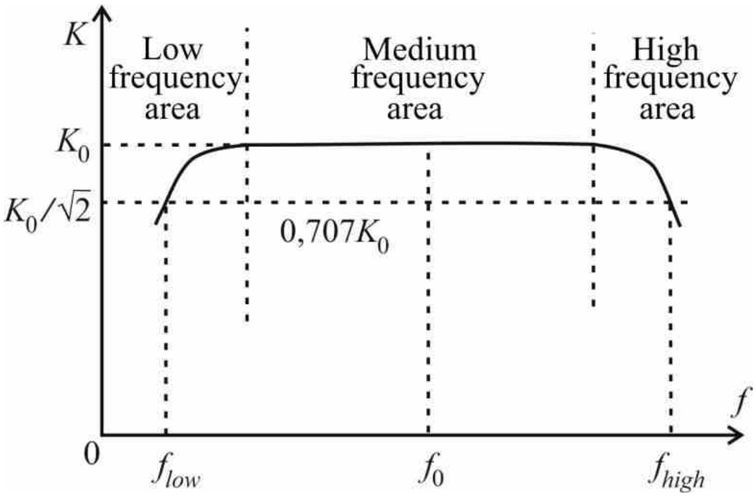


Figure 23.8

$$M(\omega) = \frac{K_0}{K(\omega)},$$

where $K(\omega)$ is the gain modulus at a certain frequency lying outside the mid-frequency region.

Phase distortion of the amplifier is estimated by its phase-frequency characteristic: the dependence of the phase angle φ between the input and output voltages of the amplifier on the frequency $\varphi(f)$ (Fig.23.9).

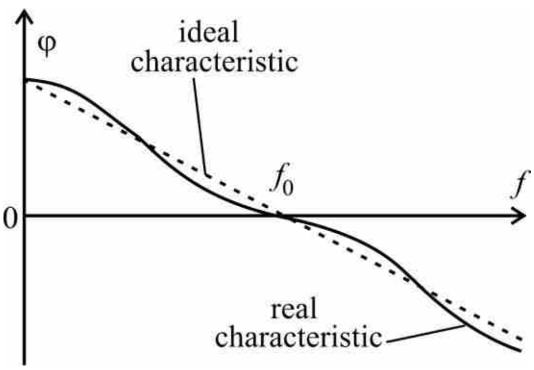


Figure 23.9

There is no phase distortion when the phase shift is linearly dependent on the frequency.

Test questions

1. *What is an electronic amplifier?*
2. *What is block diagram of the amplifier stage?*
3. *What is the amplifier classification?*
4. *What are the amplifier key features*
5. *What is the principle of operation of the* low *frequency amplifier on common emitter bipolar junction transistor?*
6. *What is the amplifier temperature stabilization?*
7. *What are called as intrinsic noise and distortion of the amplifier?*

LECTURE 24

FEEDBACK IN AMPLIFIERS

Types of feedbacks and their influence on amplifier parameters

Feedback (*FB*) *is a transfer of a part of the energy of the amplified signal from the output circuit of an amplifier to the input circuit of the same amplifier.*

Block diagram of a feedback amplifier is shown in Fig. 24.1.

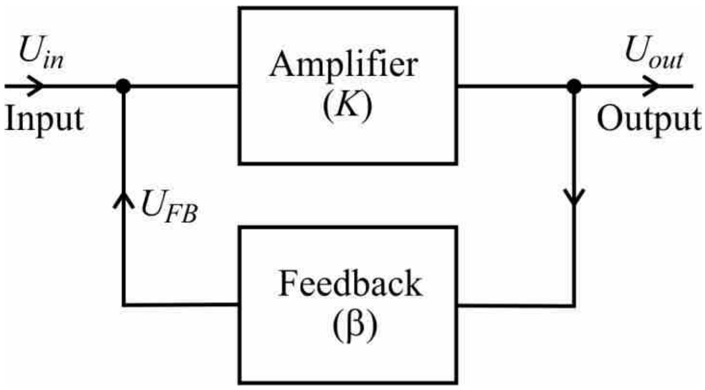


Figure 24.1

The feedback circuit is characterized by a transmission coefficient or feedback coefficient β, showing how much of the output signal is transmitted to the input of the amplifier

$$\beta = \frac{U_{FB}}{U_{out}} .$$

Usually $|\beta| < 1$.

Types of feedbacks

If the voltage at the feedback output U_{FB} is in counter-phase to the input U_{in}, then such feedback is called negative.

If the voltage at the feedback output U_{FB} is in phase to the input U_{in}, then such feedback is called positive (it is used in oscillators to maintain oscillations).

1) internal *FB* – arises due to the physical properties of amplifying elements;

2) parasitic *FB*– arises due to parasitic capacitive and inductive connections between the input and output circuits;

3) artificial *FB* – it is specially created to reduce non-linear distortions, stabilize the position of the operation point, etc.

Various types of feedbacks are shown in Fig. 24.2:

4) input feedback; 5) output feedback; 6) voltage feedback;

7) current feedback; 8) series feedback; 9) parallel feedback.

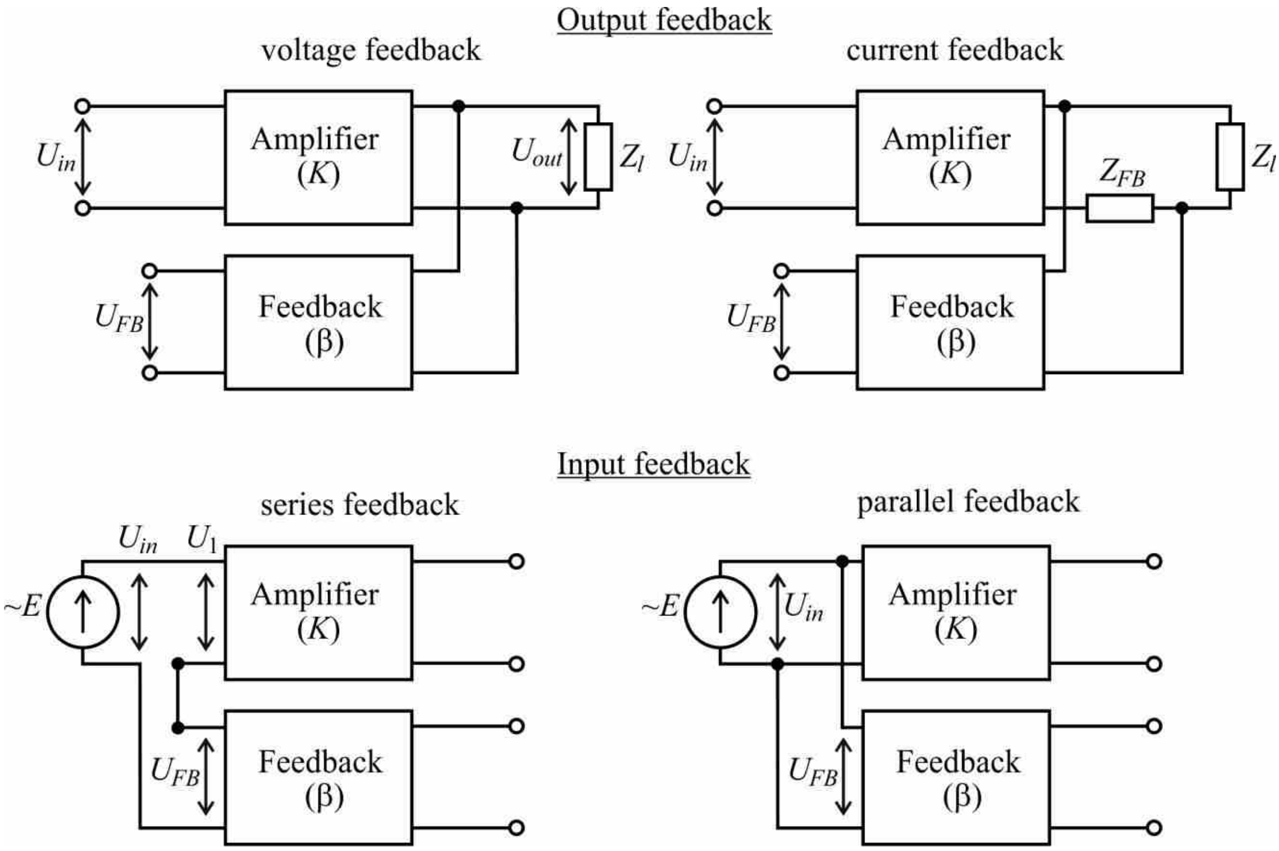


Figure 24.2

Feedback influence on gain

Consider the negative series feedback which is shown in Fig.24.3.

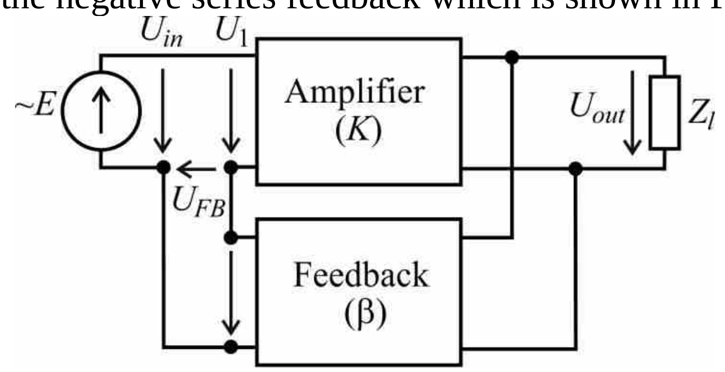


Figure 24.3

Feedback voltage is applied to the input circuit of the amplifier

$$U_{\mathrm{FB}} = \beta U_{out}, \quad \text{because} \quad \beta = \frac{U_{\mathrm{FB}}}{U_{out}}.$$

$$U_1 = U_{in} - U_{\mathrm{FB}} = U_{in} - \beta U_{out},$$

whence we obtain : $U_{in} = U_1 + \beta U_{out}$.

Without feedback: $K = \frac{U_{out}}{U_{in}} = \frac{U_{out}}{U_1}$.

In the presence of a negative feedback (NFb):

$$K_{\mathrm{NFb}} = \frac{U_{out}}{U_{in}} = \frac{U_{out}}{U_1 + \beta U_{out}} \cdot \frac{1}{U_1} = \frac{\frac{U_{out}}{U_1}}{\frac{U_1}{U_1} + \beta \frac{U_{out}}{U_1}} = \frac{K}{1 + \beta K}.$$

$$\boxed{\mathrm{K}_{\mathrm{NFb}} = \frac{K}{1 + \beta K}}.$$

Thus, the NFb reduces the gain by a factor of one $(1 + \beta K)$.

The value $(1 + \beta K)$ is called the NFb depth.

Using of negative feedback:

1) increases the stability of the gain K of the amplifier when changing the mode of the amplifier element (frequency, temperature, signal amplitude, etc.);

2) extends the bandwidth, reduces the level of nonlinear distortion, background and noise.

The frequency response is smoothed (Fig. 24.4):

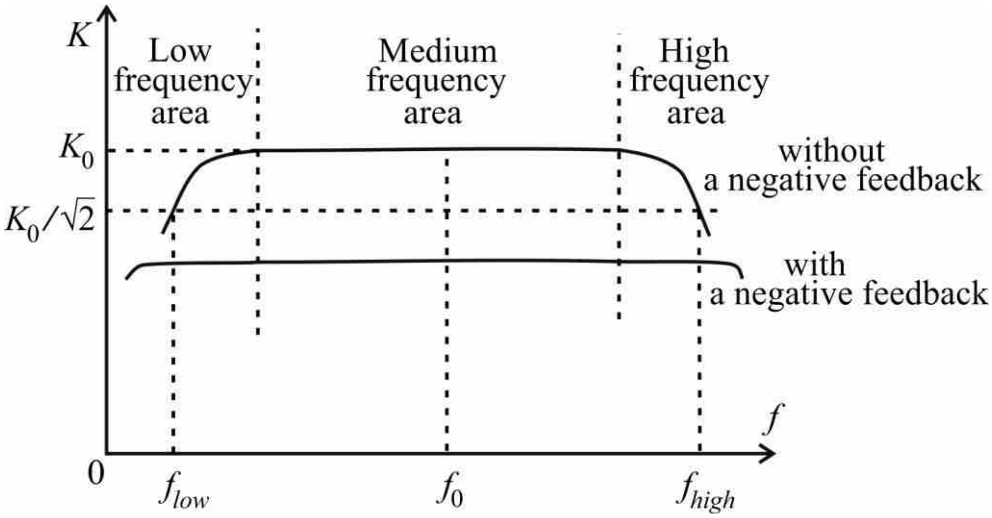


Figure 24.4

3) it is possible to reduce or increase the input and output resistances, for example, when matching loads, amplifying stages, etc.

$$Z_{in} = \frac{U_{in}}{I_{in}}; \qquad Z_{out} = \frac{U_{out}}{I_{out}} \ ; .$$

With a positive feedback (PFb), the gain increases:

$$\boxed{K_{\text{PFb}} = \frac{K}{1-\beta K}}.$$

If $\beta K \approx 1$, then $K_{\text{PFb}} \to \infty$, i.e. the amplifier self-excites and begins to work as an oscillator.

Interstage communications in amplifiers

There are 3 main types of connections between cascades in an amplifier:

1) communication through isolation capacitors (capacitive or resistive-capacitive coupling) – in low-frequency amplifiers.

2) direct communication (galvanic) - in direct current amplifiers.

3) transformer – using transformers.

Schematic diagram of a two-stage low-frequency amplifiers with resistive-capacitive coupling

It is shown in Fig. 24.5.

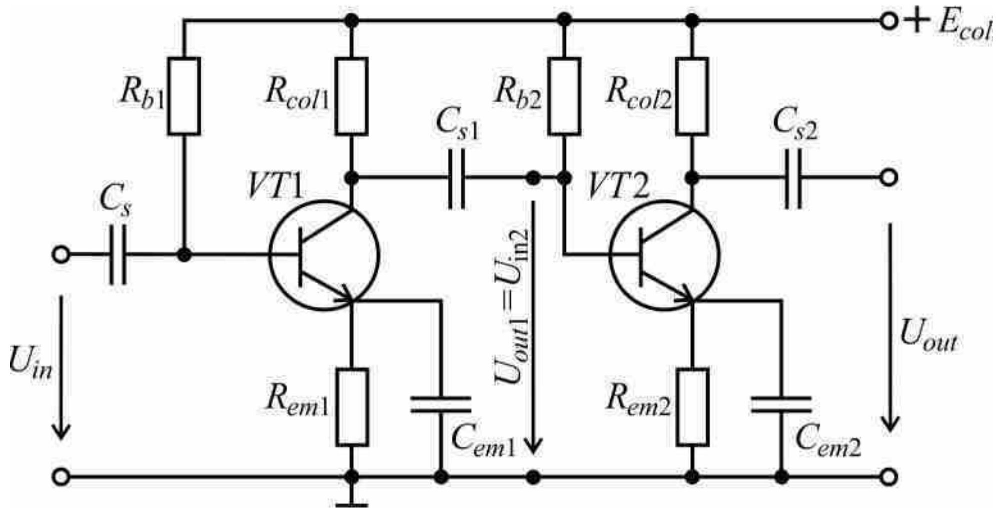


Figure 24.5

The amplifier consists of two amplifier stages with a common emitter on bipolar transistors. The cascades are interconnected using a coupling capacitor C_{c1} connected between the collector of transistor $VT1$ and the base of transistor $VT2$.

The capacitor C_{s1} does not pass the DC component of the collector voltage of the transistor $VT1$ into the base circuit of the transistor $VT2$.

The coupling capacitor C_{s2} does not pass the constant component of the collector voltage of the transistor $VT2$ to the load device of the amplifier, which is connected to the capacitor C_{s2}.

In each amplifier stage, emitter temperature stabilization is applied, provided by the elements of R_{em} and C_{em}.

Test questions

1. What is a feedback in amplifiers?

2. What types of feedbacks do you know?

3. What is difference between a positive and a negative feedback?

4. What is diagram of a two-stage low-frequency amplifiers with resistive-capacitive coupling?

5. *What is appointment of elements in the circuit of a two-stage low frequency amplifier with resistive-capacitive coupling?*

LECTURE 25

PULSE TECHNOLOGY

General concepts and characteristics of pulse devices

Continuous operation requires a long exposure to the signals. The pulse mode of operation is characterized by a short-term influence of the signal, alternating with a pause.

The advantages of pulsed mode in relation to long-term:

1) high power during the pulse with a small average power of the device;

2) the influence of temperature and dispersion of parameters of semiconductor devices is weakened (modes: “on”, “off”);

3) increases the bandwidth and noise immunity of electronic equipment.

Bandwidth is the highest possible speed of information transfer.

Immunity is the ability of the equipment to distinguish signals with a given reliability.

4) to create pulsed devices requires a greater number of simple elements of the same type, easily performed by the methods of integrated technology. This increases reliability, reduces the weight and dimensions of the device.

Pulse devices are used in microprocessor technology, automatic technology, radar, industrial electronics, etc. Pulses (video pulses) of various shapes are used as shown in Fig. 25.1.

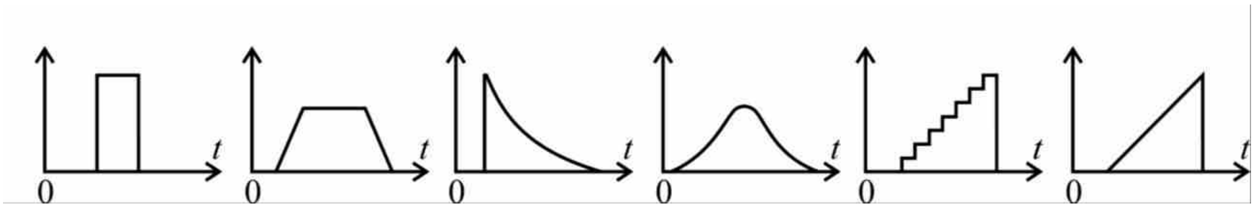


Figure 25.1

Radio pulses are packets of high-frequency modulated oscillations (Fig. 25.2).

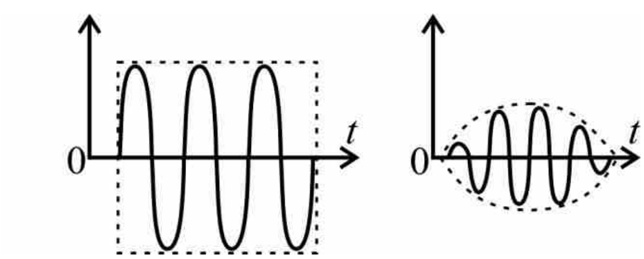


Figure 25.2

Pulse technology typically uses video pulses. Pulses usually follow periodically as shown in Fig. 25.3.

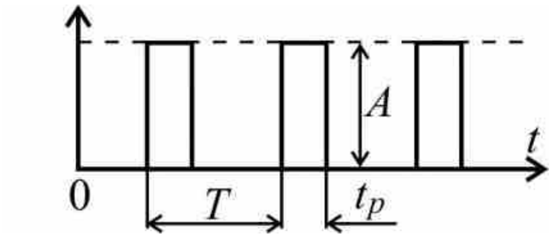


Figure 25.3

T is the pulse repetition period; t_{im} is pulse duration;

$$\boxed{q = \frac{T}{t_{im}}}$$ is pulse duty factor.

(*Electropedia*: *the ratio of the average pulse duration to the reciprocal of the pulse repetition frequency in a pulse sequence*)

In automation, the duty factor is q = 2 ... 10, and in radar, q is up to 10^4 and higher.

Electronic keys and simple shapers pulse signals

Many pulsed devices include electronic keys. The basis of the electronic key is the active element (semiconductor diode, transistor, electronic lamp) operation in the key mode. The key mode is characterized by two key states: “On” but “Off”. The simplest type of electronic key is a diode key.

Circuit of a serial diode switch with a zero level of inclusion and its transfer characteristic are shown in Fig. 25.4.

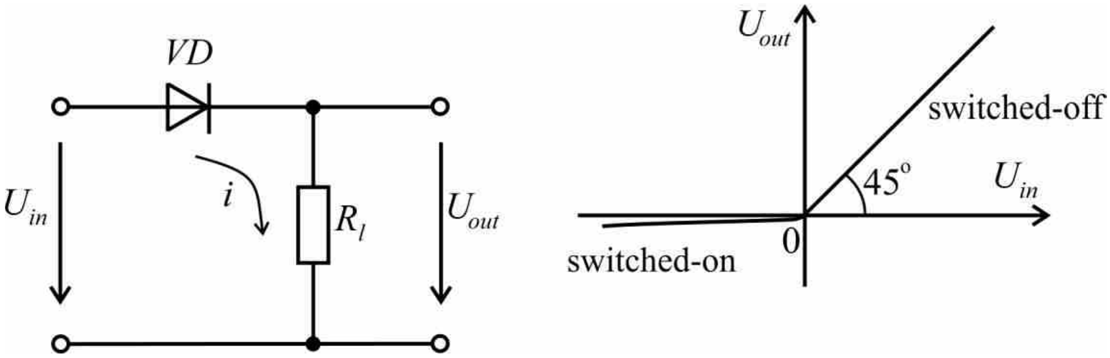


Figure 25.4

With a positive input voltage, the diode is open and the current is:

$$i = \frac{u_{in}}{R_{fr} + R_l}, \qquad u_{out} = R_l \cdot i = R_l \frac{u_{in}}{R_{fr} + R_l},$$

where R_{fr} is diode resistance in the forward direction;

R_l is the resistance of the load.

Usually, $R_{fr} << R_l$ then $u_{out} \approx u_{in}$.

With a negative input voltage:

$$i = \frac{u_{in}}{R_{back} + R_l}, \qquad u_{out} = R_l \cdot i = R_l \frac{u_{in}}{R_{back} + R_l} ,.$$

Since $R_{back} >> R_l$, then $u_{out} \approx \frac{R_l}{R_{back}} u_{in} << u_{in}$,

where R_{back} is the resistance of the diode in the opposite direction.

When the polarity of the diode changes, the function graph $u_{out}(u_{in})$ will rotate by 180°.

To change the level of inclusion in the key circuit, a bias source E_0 is introduced (Fig. 25.5).

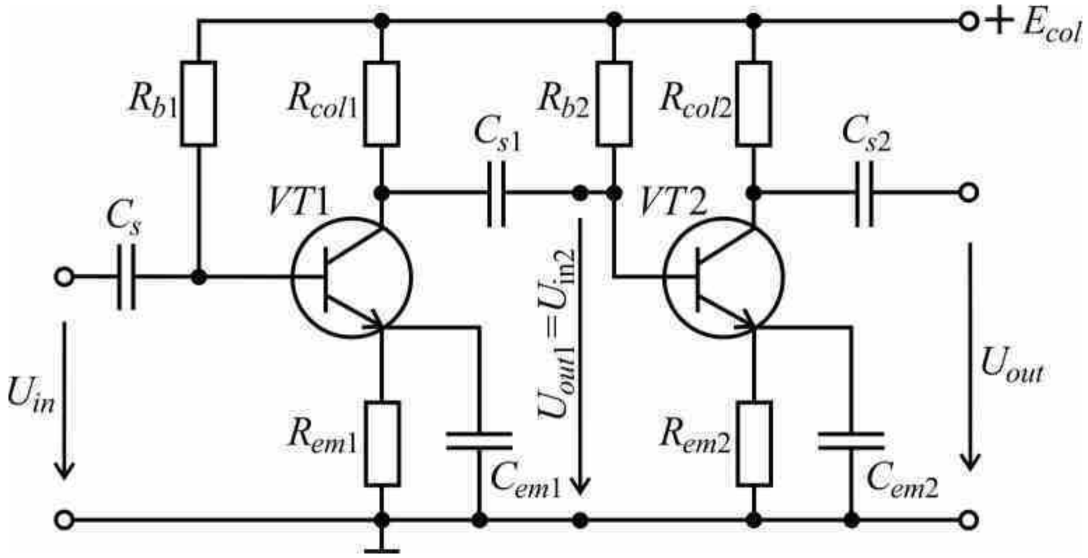


Figure 25.5

When $u_{in} > E_0 \Rightarrow u_{out} \approx u_{in}$ the diode VD is open.

When $u_{in} < E_0 \Rightarrow u_{out} \approx E_0$ the diode VD is closed.

Circuit of a parallel diode key (Fig. 25.6):

With a positive input voltage, the *VD* diode is open (the key is closed) and; at negative voltage the *VD* diode is closed (the key is open) and. When you turn on the source E_0 (the key with a non-zero level of switching), the level of the closed voltage increases.

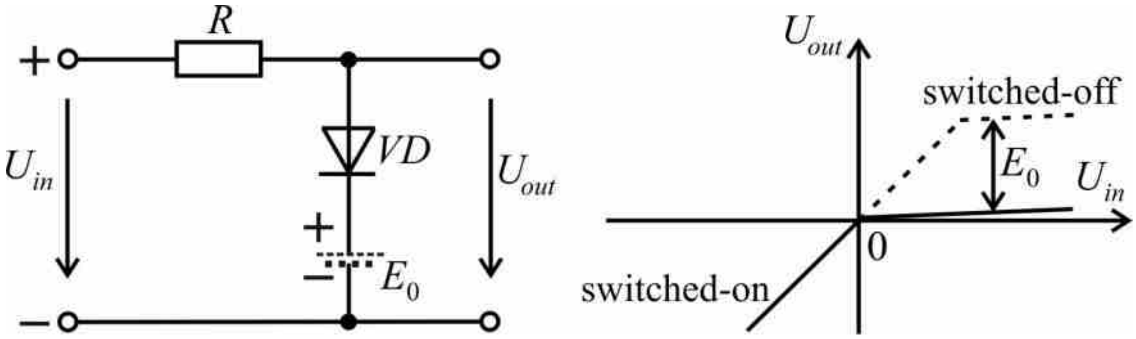


Figure 25.6

Dual diode key circuit (Fig. 25.7)

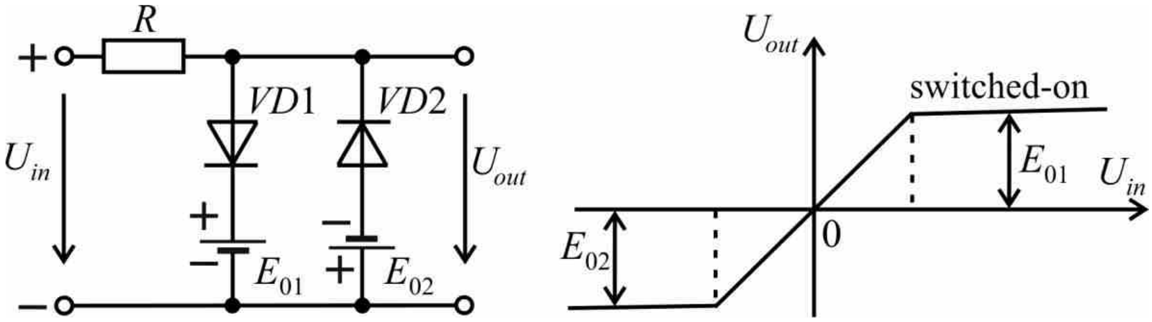


Figure 25.7

Transistor switch

Diode keys do not allow to separate the control and controlled circuits, which is often required in practice. In these cases, transistor switches are used.

The key circuit on a bipolar junction transistor and characteristics of the operation mode is shown in Fig. 25.8.

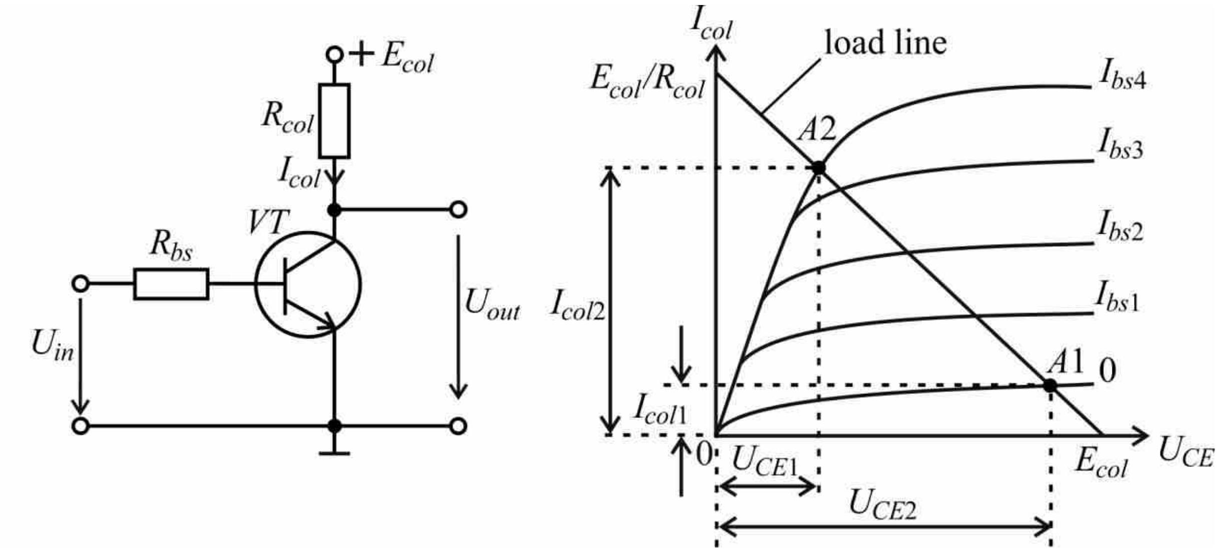


Figure 25.8

The input (control) circuit is separated from the output (controlled) circuit. The transistor operates in a key mode, characterized by two states:

1) The first state is determined by point A_1 on the output characteristics of the transistor. It is called a cut-off mode.

In this case, the base current is $I_b = 0$. The collector current I_{col1} is equal to the initial current I_{col0}, but $U_{col} = U_{col1} \approx E_{col}$. The mode is realized at negative base potentials.

2) The second state is determined by point A_2 on the output characteristics of the transistor. It is called the saturation mode. It is realized with the positive potentials of the base.

The base current is determined mainly by the resistor R_b:

$$I_{b2} = \frac{U_{in}}{R_b} ,$$

because the resistance of the open emitter junction is small. Collector junction is also open $I_{col2} \approx \dfrac{E_{col}}{R_{col}}$ and collector voltage $U_{col2} \approx 0$.

From the cutoff mode to the saturation mode, the transistor is transferred by the action of a positive input voltage. An increase in the input voltage (base potential) corresponds to a decrease in the output voltage (collector potential) and vice versa. Such a key is called an inverting (inverter).

Logical elements

Logical elements form the basis of digital (discrete) information processing devices – computers, etc.

A logical operation converts, according to certain rules, input information into output. Logic elements are built on the basis of electronic devices operation in a key mode. Digital information is used in binary form: 0 (logical zero) and 1 (logical unit), corresponding to two key positions.

Logical conversions of binary signals include three elementary operations:

1) OR – logical addition (disjunction), denoted by the signs "V" or "+":

$$F = X_1 \vee X_2 \vee X_3 \vee ... \vee X_n.$$

2) AND – logical multiplication (conjunction), denoted by the signs "Λ" or "·":

$$F = X_1 \wedge X_2 \wedge X_3 \wedge ... \wedge X_n.$$

3) NOT – logical negation (inversion), denoted by a bar over a variable:

$$F = \overline{X}.$$

Table 25.1 The basic logic operations

OR	AND	NOT	PROHIBIT
$0 \vee 0 = 0$	$0 \wedge 0 = 0$	$\overline{0} = 1$	$F = X_1 \wedge \overline{X_2}$
$0 \vee 1 = 1$	$0 \wedge 1 = 0$	$\overline{1} = 0$	
$1 \vee 0 = 1$	$1 \wedge 0 = 0$		
$1 \vee 1 = 1$	$1 \wedge 1 = 1$		

Symbols of the main logical elements (Fig.25.8):

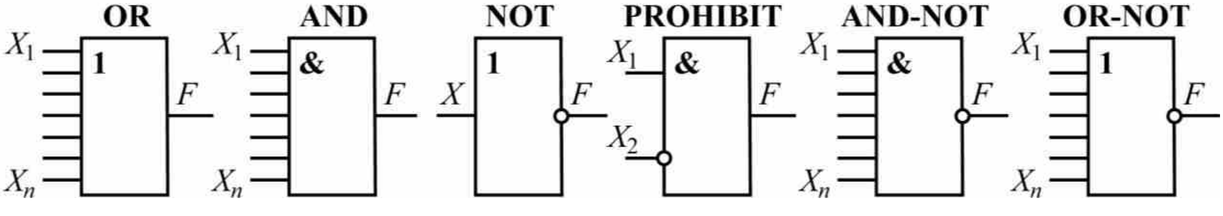


Figure 25.9

Where sign º means that the input (output) is inverse.

Depending on the type of signals used, the logic elements are divided into potential and pulse.

In potential elements, logical “0” and “1” are represented by two different levels of electric potential, and in impulse ones, by the presence or absence of impulses (the most common are potential ones).

OR element (gate). The output signal *F* of the element is equal to one if at least one of the n-inputs has a signal “1”.

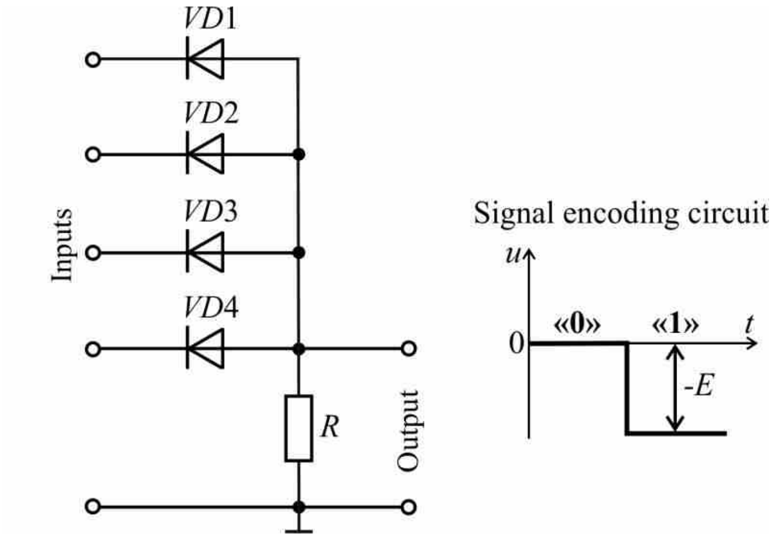


Figure 25.10

When signals “1” (- E) are exposed to at least one input (for example, $X_1 = 1$), the corresponding diode (D_1) opens and the output is connected to the input ($F = 1$).

The remaining diodes are closed, i.e. the output signal does not reach the inputs on which $u_{in} = 0$.

AND element (gate). When the signal is “0”, the diodes are open at all inputs (Fig. 25.11), and a current is generated in them and in the resistor *R*, which is generated by the source *E* and closed through the signal source. Since the resistance of the resistor $R >> R_{fr}$, then all outputs signals are “0”.

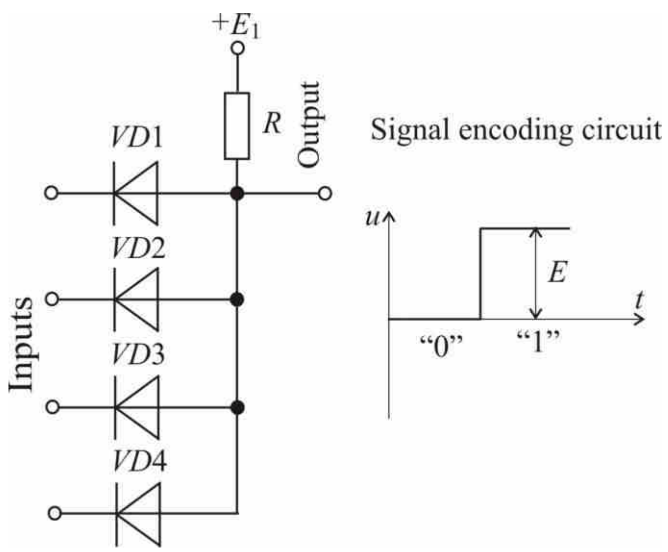


Figure 25.11

If the voltage at one of the inputs corresponds to a logical “1” ($E > E_1$), then the corresponding diode is closed, but the remaining diodes are open and the signal is still “0” at the output.

The signal “1” at the output will be only when the signal “1” will act on all inputs. In this case, all diodes will be closed, the current through the resistor will be zero and $u_{out} = E_{col}$.

NOT element **(gate)**.

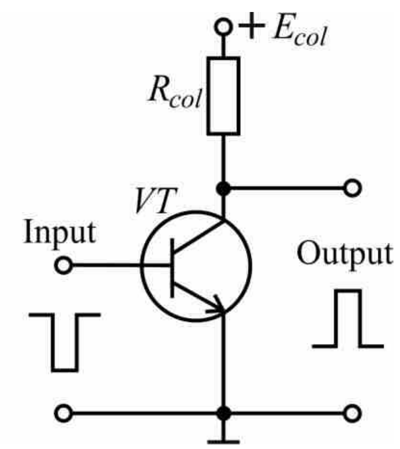


Figure 25.12

A transistor switch with inverting properties is usually NOT used as an element (Fig. 25.12).

In the initial state, the transistor is locked, because the base potential is 0. The output voltage corresponds to a logical “1” ($u_{out} = E_{col}$).

When a high (positive) voltage is applied to the base of the transistor, the transistor is unlocked and a low voltage is set at the output – logical “0”.

Test questions

1. What are the advantages of pulsed mode in relation to long-term?

2. What are the shapes of pulses (video pulses)?

3. What is pulse duty factor?

4. What is the circuit of a serial diode switch?

5. What is the circuit of a parallel diode key?

6. What is dual diode key circuit?

7. What are the logic operation and logic elements?

8. What is the OR *element?*

9. *What is the* AND *element?*

10. What is the NOT *element?*

LECTURE 26

INTEGRATED CIRCUITS. (MICROCHIP)
(MULTI-CHIP INTEGRATED CIRCUIT)

An integrated microcircuit is a microelectronic device consisting of active elements (diodes, transistors), passive elements (resistors, capacitors, smoothing inductors) and connecting wires, which are made in a single technological process, are electrically interconnected, enclosed in a common building and constitute an indivisible whole (Fig. 26.1).

Electropedia: microcircuit in which all or some of the circuit elements are inseparably associated and electrically interconnected so that it is considered to be indivisible for the purpose of construction and commerce.

According to the manufacturing technology, integrated circuits are divided into:

1) HYBRID made in the form of films deposited on the surface of a dielectric material, and mounted frame elements (transistors, capacitors, etc.) attached to the base.

2) SEMICONDUCTOR in which all elements are formed in the volume of the semiconductor.

Hybrid integrated circuits include the following key features:

1) an insulating base made of glass, ceramics, etc., on the surface of which are film conductors, contact pads, resistors, low-power capacitors;

2) mounted open-frame active elements (transistors, diodes);

3) mounted passive elements in a special miniature design, which cannot be made in the form of films (high-capacity capacitors, transformers, smoothing inductors).

4) a plastic or metal case, which serves to seal the circuit and fasten the lead lobes.

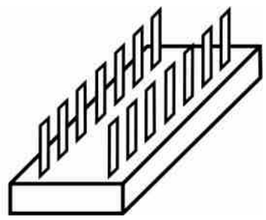


Figure 26.1

Hybrid Integrated Circuit (Chips) Elements

Production technology is a vacuum thermal spraying method. To give the films a given configuration, the free mask method is used, which is based on shielding the substrate using special removable stencils, except for those areas on which the elements of this layer are applied.

Films are up to 1 micron thick.

FILM RESISTOR

With small (Fig. 26.2, *a*) and large (Fig. 26.1, *b*) resistances $R = \rho \frac{l}{s}$.

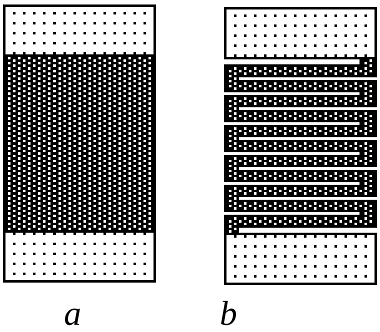


Figure 26.2

In the form of thin films of pure chromium, nichrome or tantalum are applied directly to the insulating base $R = 10^{-4} ... 10^{6}\ \text{Ohm}$.

FILM CAPACITOR. (Fig. 26.3)

Size: 10^{-3} ... $1 cm^2$.

Capacitance : 10^{-1} ... 10^5 pF.

The lower and upper plates of the capacitor in the form of thin films of copper, aluminum, silver, gold.

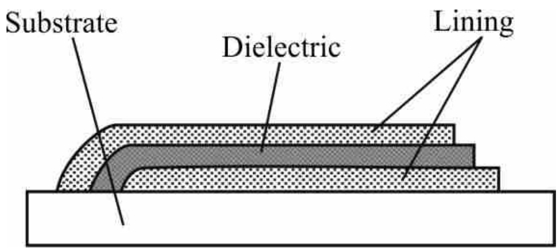


Figure 26.3

Dielectric is a film of aluminum silicate, barium titanate, beryllium oxide, silicon, etc. These films have good electrical strength and high dielectric constant.

THIN FILM INDUCTION is in the form of a single-layer spiral. The material is gold. It has good conductivity. The shape is square as shown in Fig. 26.4.

MOUNTED ELEMENTS with rigid “ball” leads for mounting and electrical connection is shown in Fig. 26.5.

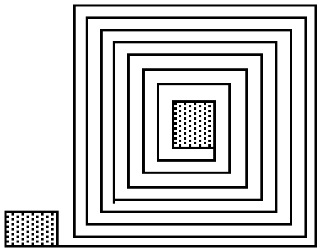


Figure 26.4

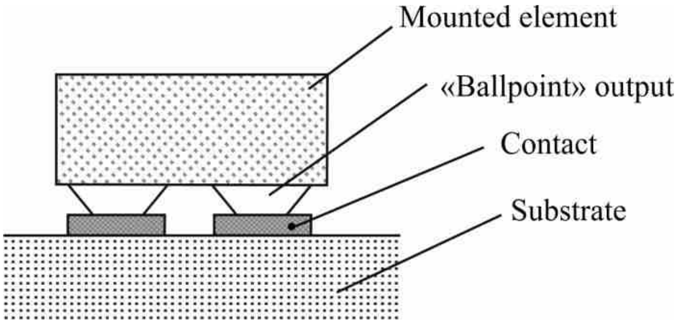


Figure 26.5

Hybrid integrated circuits have high reliability 10^6 hours uptime. Installation density is up to 100 elements per 1 cm^3.

Semiconductor integrated circuits (chips)

They consist of a single semiconductor crystal, separate areas of which serve as a transistor, diode, resistor or capacitor.

The sequence of obtaining isolated sections of silicon N-type is:

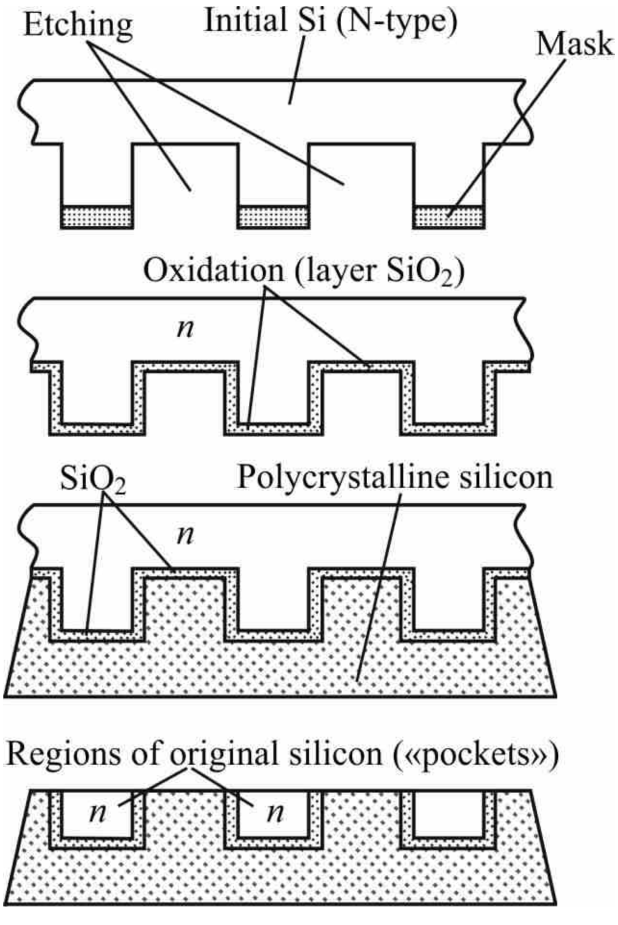


Figure 26.6

A protective mask is applied to the plate of initial N-type silicon by photolithography and selective etching of the initial crystal (Fig. 26.6, *a*) is performed. Then, after washing off the mask, the surface of the silicon crystal is oxidized, on which an SiO_2 insulating layer is formed (Fig. 26.6, *b*).

A polycrystalline silicon layer (Fig. 26.6, *c*) is sprayed onto a surface protected by a SiO_2 layer.

After repeated etching of the initial silicon crystal, isolated regions ("pockets") of the initial N-type silicon are formed (Fig. 26.6, *d*).

In these isolated areas with the help of various impurities (acceptor and donor) create areas with electric conductivity of N-type and P-type, which form different parts of the chip (Fig. 26.7).

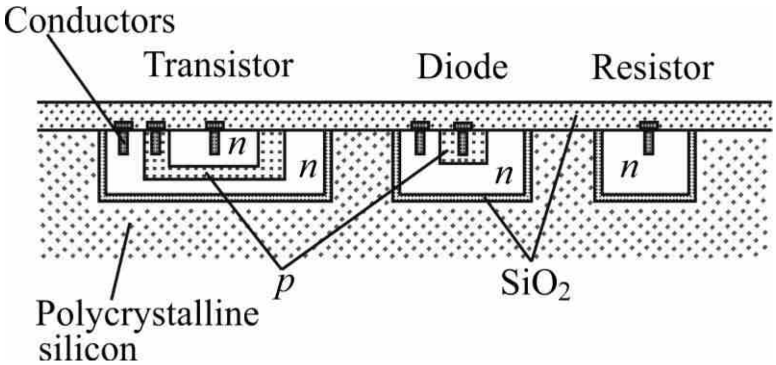


Figure 26.7

A transistor is a three-layer structure with two *p-n* junctions (Fig. 26.8).

A diode is a two-layer structure with one - junction, or diode-type transistors (these diodes are characterized by different speed and breakdown voltage).

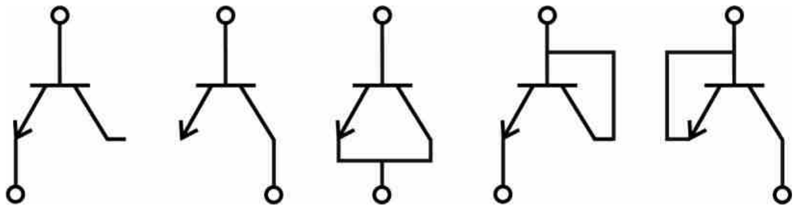


Figure 26.8

In microelectronics there is a multi-emitter transistor (there is no analogue in discrete devices) (Fig. 26.9)

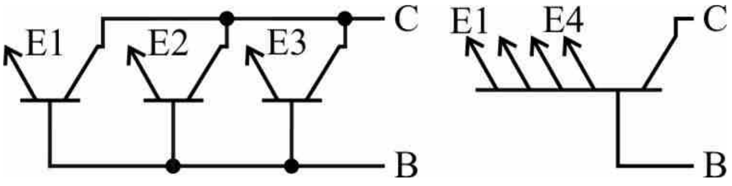


Figure 26.9

A capacitor is implemented at the *p-n* junction, locked by reverse constant voltage.

A resistor is a section of a doped semiconductor with two leads (resistance depends on geometry and resistivity).

Semiconductor integrated circuits are placed in the housing. Reliability is high. Uptime (2 ... 5) 10^7 hours.

Installation density is up to 500 elements per 1 cm^3.

Test questions

1. What is an integrated circuit?

2. What hybrid integrated circuit elements do you know?

3. What are semiconductor integrated circuits?

4. What is the sequence of obtaining isolated sections of silicon N-type?

ENGLISH-UKRAINIAN
ELECTRICAL ENGINEERING DICTIONARY

A

absolute term – вільний член диференційного рівняння

absolute permeability – абсолютна магнітна проникність

accumulator (**UK**) – акумулятор, акумуляторна батарея

active mode – активний режим транзистора

active power – активна потужність

adjusting characteristic – регулювальна характеристика

admittance – повна провідність

aiding connection – узгоджене вмикання

air-core coil – котушка індуктивності без феромагнітного осердя

air gap, air-gap – повітряний проміжок

apparent power – повна (або уявна) потужність

algebraic sum – алгебраїчна сума

arithmetic sum – арифметична сума

alternating current (AC) – змінний струм

Ampere's circuital law – закон повного струму

Ampere's law – Закон Ампера

amplifier (amp) – підсилювач

angle – кут

angular – кутовий

antiphase – проти-фаза

arc discharge – дуговий розряд

argument – аргумент

armature – якір електродвигуна

armature reaction – реакція якоря

asymmetric(al) – асиметричний

asynchronous motor – асинхронний двигун

autotransformer – автотрансформатор

average – середній

B

bandwidth – діапазон підсилення електронного підсилювача, смуга пропускання

base – база (біполярного транзистора)

battery (**US**) – акумулятор, акумуляторна батарея

bar – стрижень трансформатора

bearing – підшипник

belt leakage – потік розсіювання

bias (bias voltage) – напруга зміщення

bipolar junction transistor – біполярний транзистор

booster transformer – трансформатор, який збільшує напругу

blocking layer – запірний шар

brake – гальма

braking – гальмовий

branch – вітка електричного кола

break contacts – нормально-замкнені контакти

breakdown – пробій

breakdown torque – максимальний статичний момент асинхронного двигуна

bridge circuit – мостова схема

brush – щітка

brush holder – щіткотримач

bypass – обхід

C

capacitance – ємність

capacitive – ємнісний

capacitor – конденсатор

cage rotor – короткозамкнений ротор

charge – електричний заряд, заряджання, напр. конденсатора

channel – канал у польовому транзисторі

choke (smoothing inductor) – дросель (***deprecated,*** тобто *Electropedia трактує як застарілий термін*)

circuit – електричне коло
circuitry **(US) –** електрична схема
circular speed – кругова швидкість
clutch – муфта
coercivity – коерцитивна сила
coil – котушка індуктивності, сукупність витків обмотки трансформатора
collector – колектор
common-collector amplifier – емітерний повторювач
complex number – комплексне число
compound-wound (compound) generator/motor – генератор/двигун із змішаним збудженням
commutating [compensating] poles – додатковий полюс
commutation – комутація
commutator – колектор
compensating current – вирівняльний струм
compensating flux – додатковий магнітний потік
compound-wound – зі змішаним збудженням
condition – умови роботи кола, приладу, пристрою,
conductance – провідність, активна провідність
conduction – провідність у напівпровідниках
conduction band – зона провідності у зонній теорії будови речовини
conductivity – питома провідність, провідність у напівпровідниках
conductor – провідник
conjunction – логічне множення
connection (**US**) – з'єднання, електричний контакт, вмикання
constant of integration – стала інтеґрування
construction – конструкція, устрій
consumer – споживач електроенергії (фізичне або юридичне лице)
contact – електричний контакт
control angle – кут керування
control current – струм керування
converter – перетворювач

copper losses – електричні втрати, втрати в міді
core – осердя
core-type transformer – стрижневий трансформатор
counter-EMF – проти-ЕРС
cross-sectional area – площа поперечного перерізу
crystal lattice – кристалічна решітка
current – електричний струм
current resonance – резонанс струмів
current source – джерело струму
current-voltage graph (characteristic) – ампер-вольтна характеристика
current surge – кидок струму
cut-off – відсічка у напівпровідникових приладах та пристроях
cut-off mode – режим відсічки у транзисторах
cycle – період, цикл
cyclic magnetization reversal – циклічне перемагнічування

D

delta – трикутник, вид з’єднання резисторів в електричному колі
delta-connected – з’єднаний трикутником
delta connection – з’єднання трикутником
design – устрій, інженерне-технічне рішення, проект
designation – умовне позначення
differential equation – диференційне рівняння
diffusion current – дифузійний струм
diode – діод
direct current (DC) – постійний струм
discharge resistor – розрядний резистор
discharging – розряджання
disconnection – розмикання
disjunction – диз’юнкція, логічне додавання
displacement angle – кут зсуву фаз
distortion – спотворення

double half-wave – двонапівперіодний

doubler – подвоювач

drain – стік у польовому транзисторі

drift current – струм дрейфу

driving force – сила тяги електромагніта

duty – режим (роботи) пристрою

E

eddy current – вихровий струм

eddy-current loss – втрати на вихровий струм

efficiency – коефіцієнт корисної дії, ККД

effective – діючий

effective value – діюче значення синусоїдної величини

electric – електричний, той, що має фізичні властивості, які характеризують електричні явища (заряд, електричне поле, електричне коло, струм, напруга, енергія, потужність тощо)

electric circuit – електричне коло, електрична схема

electric charge – електричнй заряд

electric current – електричний струм

electric field – електричне поле

electric losses – електричні втрати потужності

electric power – електроенергія

electric power carrier– носій електроенергії

electric power converter – перетворювач електричної енергії

electric motor – електричний двигун

electric machine – електрична машина

electric network – електрична схема, електрична мережа

electrical – електричний, той, що має відношення до електрики, але немає фізичних властивостей, які характеризують електричні явища (навчальна дисципліна, підручник, електрик за фахом, матеріал та ін.)

electrical (avalance) breakdown – електричний пробій

electrical engineering – електротехніка
electrical steel – електротехнічна сталь
electromotive force (EMF, e.m.f., emf) – електрорушійна сила, ЕРС
electron – електрон
electron-hole junction – електронно-дірковий перехід
element of a circuit – елемент електричного кола, участок кола
EMF source – джерело ЕРС
EMF of self-induction – ЕРС самоіндукції
embedded coil side – пазова частина обмотки
emitter – емітер (біполярного транзистора)
enclosure – корпус
energy – енергія
engine – двигун внутрішнього згоряння
energy band – енергетичний рівень
end coil – лобова частина обмотки електродвигуна
entry conditions – початкові умови
equivalent resistance – еквівалентний опір
Euler number – число Ейлера або основа натурального логорифма
excitation – збудження
excitation winding – обмотка збудження

F

fan – вентилятор
Faraday's law of induction or Faraday's law – закон електромагнітної індукції
feedback – зворотний зв'язок
ferromagnetic-core coil (inductor) – котушка з феромагнітним осердям
filament lamp – лампа розжарювання
field-effect transistor – польовий транзистор
flash – дуговий розряд
flux linkage – потокозчеплення
forbidden band – заборонене зона в зонній теорії речовини
force – сила

forced component – вимушена складова

forward voltage – пряма напруга

forward current – прямий струм

frame – станина електродвигуна

frame yoke – ярмо станини (статора) електродвигуна, а саме місце до якого приєднуються полюси станини (статора)

free component – вільна складова

frequency – частота

G

gain – коефіцієнт підсилення електронного підсилювача

galvanic cell – гальванічна батарея, акумулятор, електрохімічне джерело

gas turbine – газова турбіна

gate – затвор у польовому транзисторі, логічний вентиль

general solution – загальне рішення диференційного рівняння

generating device – пристрій, який генерує електроенергію

generator – генератор

H

half-wave – однонапівперіодний

heat – теплота

heater – обігрівач, нагрівник, нагрівальний пристрій

holding current – струм утримання у тиристорі

homogeneous – однорідний

housing – корпус

hysteresis loop – петля гістерезису

hysteresis loss – втрати потужності на гістерезис

I

ideal voltage (tension) source – ідеальне джерело напруги

idle mode – режим холостого ходу або очікування у електронних пристроях

imaginary – уявний

immunity – захищеність від перешкод

impedance – повний опір електричного кола impurity – домішка

in a short circuit – замкнути накоротко

inductance – індуктивність

induction – індукція, індукційний

induction coil – котушка індуктивності Румкорффа

induction machine, motor, generator – індукційна/індукційний (асинхронна/асинхронний) машина, двигун, генератор

inductive – індуктивний

inductive reactance – індуктивний опір

inductor – котушка індуктивності

initial – початковий

in-series – послідовно ввімкнутий

inverse proportion – обернено-пропорційно

instantaneous – миттєве

insulated – ізольований

internal resistance – внутрішній опір

integrated circuit – інтегральна схема

intrinsic conductance – власна провідність напівпровідника

intrinsic conductivity – власна провідність напівпровідника

inverter – інвертор

inverse resonance – резонанс струмів

iron-core inductor (coil) – котушка зі сталевим осердям

J

jaggedness – зубчастість

Joule law – Закон Джоуля-Ленца

joule – джоуль

junction, junction point – з'єднання, контакт, вузол

K

Kirchhoff’s laws – закони Кірхгофа

Kirchhoff’s current Law – закон Кірхгофа для струмів (перший закон)

Kirchhoff's voltage law – закон Кірхгофа для напруг (другий закон) [*Electropedia*]:

Kirchhoff laws – закони Кірхгофа

Kirchhoff current law (Kirchhoff law for nodes) – закон Кірхгофа для струмів (для вузлів)

Kirchhoff voltage (tension) law (Kirchhoff law for meshes) – закон Кірхгофа для напруг (для контурів)

L

lag, lag behind – відставати (синусоїда напруги від синусоїди тока, або навпаки

laminated – шихтований

laminated core – шихтоване осердя

lattice – кристалічні ґрати

laws of switching – закони комутації

lead – вивід для підключення навантаження

leakage flux – магнітний потік розпорошення

length – довжина

Lenz's rule – правило Ленца

light emitting diode – світлодіод

line – лінія

line of force – силова лінія

linear – лінійний

linked flux – потокозчеплення ***(deprecated** in Electropedia*)

longitudinally demagnetizing reaction – продольна розмагнічувальна реакція

load – навантаження

load characteristic – характеристика навантаження

load-lifting – вантажопідйомний

logic(al) addition (disjunction) – логічне додавання

logic(al) multiplication (conjunction) – логічне множення

logic inversion – логічне заперечення

logic(al) operation – логічна операція

logical negation – логічне заперечення
loop – контур електричного кола
loop current – контурний струм
loss(es) – втрата(и) потужності
lugs – лапи електродвигуна

M

magnetic circuit – магнітне коло, магнітопровід
magnetic constant – магнітна константа або абсолютна магнітна проникність
magnetic field – магнітне поле
magnetic field strength (intensity) – напруженість магнітного поля
magnetic flux – магнітний потік
magnetic induction – магнітна індукція
magnetic loss(es) – магнітні втрати
magnetic loss angle (magnetic delay angle) – кут магнітних втрат (кут магнітної затримки)
magnetization curve – крива намагнічування
magnetizing force – намагнічувальна сила
magnetomotive force (MMF) – магніторушійна сила
main poles – головні полюси машини постійного струму
mains – електромережа
make contacts – нормально-розімкнені контакти
matched load – узгоджене навантаження
maximum-current relay – реле максимального струму
mesh – контур
mesh analysis – аналіз електричного кола методом контурних струмів
mesh current – контурний струм
meter (**US**) – метр (одиниця довжини)
metre (**UK**) – метр (одиниця довжини)
mode – режим (режим роботи) електронних приладів і пристроїв
motor – електродвигун
motor speed – частота обертання електродвигуна

multipath – розгалужений
multiplier – помножувач
multichip integrated circuit – багатокристальна інтегральна схема
multi-turn – багатовитковий
mutual induction – взаємоіндукція

N

negative temperature coefficient thermistor – термістор
network – електромережа
neutral – нульовий, нейтральний
neutral bias voltage – напруга зміщення нейтралі
node – вузол
non-linear – нелінійний
no-load, no-load operation – холостий хід, неробочий хід
non-magnetic – немагнітний
nominal – номінальний
non-coulomb force – некулонівська сила
non-uniform – неоднорідний
normally-on – замикальний
normally-off – розмикальний
non-salient – неявно полюсний
N-type - напівпровідник *n*-типу

O

Ohm's law – закон Ома
on-load, on-load operation – режим навантаження
open-circuit, open-circuit operation – холостий хід, неробочий хід для електричних кіл
operating characteristic – робоча характеристика
operating condition – робочі умови
operating mode – режим роботи для електронних приладів і пристроїв, систем управління, систем зберігання електроенергії

operation – дія, робота (експлуатація) приладів та пристроїв

operation duty – режим роботи електротехнічних пристроїв

operation (operating) speed – частота обертання або швидкість обертання двигуна

opposite connection – зустрічне вмикання

opposition circuit – проти вмикання

optocoupler – оптрон, оптопара

overload capacity – перевантажувальна здатність

overrunning – рознос електродвигуна

P

parallel resonance – паралельний резонанс, резонанс струмів

part of a circuit – участок електричного кола

particular(partial) solution – часткове рішення диференційного рівняння

pass-band – смуга пропускання фільтра

path tracing – обхід контуру

peak value – амплітудне значення

permeability of vacuum – відносна магнітна проникність вакууму або абсолютна магнітна проникність

phase – фаза

phase angle – фазовий кут

phase lag – відставати за фазою

phase lead – випереджати за фазою

phase sequence – порядок чергування фаз

phase difference angle – кут зсуву фаз

phase difference – різниця фаз

phase-wound rotor – фазний ротор

phasor – вектор в електротехніці або синусоїдна величина у вигляді комплексного числа, яке може бути представлене вектором

phasor diagram – векторна діаграма в електротехніці

photocoupler – оптрон, оптопара

photoresistor – фоторезистор

photovoltaic cell – фотоелемент, фотоелектричний елемент
period – період
permeability of vacuum – магнітна стала
p-n boundary – *p-n* перехід
PN junction, *p-n* junction – *p-n* перехід
pole – полюс, в тому числі і електродвигуна
pole pitch – полюсний поділ
pole piece – полюсний наконечник
pole tip – полюсний наконечник
positive charge – позитивний заряд
positive temperature coefficient thermistor (posistor) – позистор
potential difference – різниця потенціалів
power – потужність, енергія
power balance – баланс потужностей
power-angle curve – кутова характеристика
power factor – коефіцієнт потужності
power electromagnet – силовий електромагніт
power loss(es) – втрати потужності
power station, power plant – електростанція
power supply – джерело електроенергії, як правило, вторинне
power transformer – силовий трансформатор
power transmission line – лінія електропередачи
principle of operation – принцип дії
product – алгебраїчний добуток
protective equipment – захисна апаратура
protoflux – потокозчеплення
P-type – напівпровідник p-типу
pulse – імпульсний
pulse duty factor – коефіцієнт заповнення, скважність

Q

Q-factor, quality factor – добротність

quadrature-axis armature reaction – поперечна реакція якоря
quantity – фізична величина, кількість

R

radius-vector – радіус-вектор
rated – номінальний, паспортний
rated operation, duty, mode – номінальний режим
reactance – реактивний опір
reactive power – реактивна потужність
real – дійсний
real source - реальне джерело
rechargeable cell – акумулятор, акумуляторна батарея
reciprocating – зворотно-поступальний
rectifier – випрямляч
relative permeability – відносна магнітна проникність
relay – реле
reluctance – магнітний опір
remanent (residual) flux – залишковий магнітний потік
remanent (residual) magnetization – залишкове намагнічування
resistance – опір, активний опір
resistance strain gage – тензорезистор
resistive element – резистивний елемент
resistivity – питомий опір
resistor – резистор
resonance – резонанс
resonant – резонансний
reverse voltage – зворотна напруга
rheostat adjustment – реостатне регулювання
ripple coefficient –коефіцієнт пульсації
root-mean-square (RMS) – середньо-квадратичний, діючий
rotational frequency – частота обертання
rotational (rotation) speed – частота (число) обертів електродвигуна

rotor – ротор

S

salient-pole – явнополюсний

saturation – насичення

saturable reactor – дросель насичення

schematic diagram – схема електричного кола

scheme – схема, як порядок дій розв’язання інженерної або наукової задачі

self-induction – самоіндукція

self-interference – власні перешкоди підсилювача

semiconductor – напівпровідник, напівпровідниковий

separately-excited generator/motor – генератор/двигун з незалежним збудженням

series-connected – послідовно з’єднаний

series-wound (series) generator/motor – генератор/двигун з послідовним збудженням

series connection – послідовне з’єднання

series resonance – послідовний резонанс, резонанс напруг

shaft – вал

short circuit – коротке замикання

shunt-wound (shunt) generator/motor – генератор/двигун з паралельним збудженням

shell-core transformer – панцерний трансформатор

single-path magnetic circuit – нерозгалужене магнітне коло

sinusoidal – синусоїдний

slot – паз в статорі або якорі електричних машин

smoothing inductor (choke – ***deprecated*** in *Electropedia*) – дросель

smoothing filter – згладжувальний фільтр

source – джерело електроенергії, витік у польовому транзисторі

source EMF (e.m.f., emf) – ЕРС джерела

source of EMF – джерело ЕРС

source voltage – напруга джерела

source current – струм джерела

sparking – іскріння
specific conductance – питома провідність
specific resistance – питомий опір
squirrel-cage rotor – короткозамкнений ротор
star – зірка
star connection (**UK**) – з’єднання зіркою
star-connected – з’єднаний зіркою
starting torque – пусковий момент
start-up – вмикання (пуск) двигуна
stator – статор
steady-state, steady state – рівновага або стаціонарний стан
step-up transformer – трансформатор, який збільшує напругу
storage battery **(US) –** акумулятор, акумуляторна батарея
storage cell – акумулятор, акумуляторна батарея
strain gauge – тензодатчик
stray-load (added) losses – додаткові втрати потужності
supply – джерело напруги або електроенергії, в тому числі і вторинне
susceptance – реактивна провідність
swinging choke (***deprecated,*** *Electropedia*) – дросель зі змінною індуктивністю
switch – пристрій для зміни електричних з’єднань між його клемами, ключ
switching device – комутаційний пристрій
switching – вмикання, перемикання, комутація
switching off – вимикання
symbolical – символьний
symbolic notation – умовне позначення
symmetric(al) – симетричний
synchronous – синхронний
synchronous speed – синхронна частота, швидкість ротора при холостому ході

T

tension – напруга

terminal – ввід; вивід; клема
terminal voltage – напруга на виводах електродвигуна, зокрема якірного кола електродвигуна постійного струму
thermal breakdown – термічний пробій
thermal resistance – термічний опір
thermal relay – теплове реле
thermistor – терморезистор
thermocouple – термопара
three-phase – трифазний
thyristor – тиристор
time constant – стала часу
total current – повний струм
total flux – повний потік або потокозчеплення
total loss (of a machine) – повні втрати потужності електричної машини
total power – повна потужність
total resistance – еквівалентний опір
torque – обертальний момент електродвигуна
traction – тяга
transformer – трансформатор
transformation ratio – коефіцієнт трансформації
transmission line – лінія електропередачі
transient – перехідний, перехідний процес
transient response – перехідна характеристика, перехідний процес
tractive force – підйомна сила електромагніта
transformer winding – обмотка трансформатора
transmission line – лінія електропередачі
traverse – траверса
three-lead thyristor – триністор
true power – активна потужність
tunnel diode – тунельний діод
turn – виток котушки, обмотки збудження електричної машини
turn on – вмикати

turn-off – запірний

two-lead thyristor – диністор

U

unbalanced load – несиметричне навантаження

V

vacuum tube – електронно-вакуумна лампа

valence band – валентна зона

value – значення

valve – вентиль, напівпровідниковий прилад із односторонньою провідністю

varistor – варистор

vector – вектор в математиці та фізиці

velocity – лінійна швидкість

volt-ampere characteristic – вольт-амперна характеристика

voltage – напруга

voltage resonance – резонанс напруг

voltage regulation characteristic – зовнішня характеристика електричних машин (генератора та трансформатора)

voltage source – джерело напруги

voltage drop – падіння напруги

voltage-reference diode – стабілітрон

voltage regulator, stabilizer – стабілізатор напруги

W

wave period – період синусоїдної величини

welding transformer – зварювальний трансформатор

wind farm (park), wind power station (plant) – вітроелектростанція

wind turbine – вітротурбіна

winding – обмотка, наприклад, трансформатора або електричної машини wire – провід, дріт

work – робота

wound-rotor – фазний ротор

wye connection (**US**) – з’єднання зіркою

wye-connected – з’єднаний зіркою

X

Y

Y connection, Y-connection (**US**) – з’єднання зіркою

yoke – ярмо

Z

Zener diode – стабілітрон

zero – нуль

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<u>FOR NOTES</u>

F O R   N O T E S

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