

LECTURES ON THE DISCIPLINE
**"Fundamental of Relay Protection and Automation of Power
System"**

For students of specialty G3 «Electrical engineering»

The lecture materials were prepared based on the following sources of information:

1. Relay protection of electric power systems: Textbook. - Lviv: Lviv Polytechnic National University Press, 2013. -533 p.

2. Shelepeten T.M. Protective automation of electrical networks: Study guide for students of specialties 7.090602 and 8.090602 "Electrical Systems and Networks" of all forms of education. - Lviv, 2002, 157 p.

TABLE OF CONTENTS

TABLE OF CONTENTS	3
LIST OF KEY ABBREVIATIONS AND SYMBOLS.....	4
PREFACE.....	6
1.1. Purpose of relay protection.....	7
1.2. Requirements for the implementation of relay protection	7
1.3. Purpose and main characteristics of relay.....	10
1.4. Principle of operation and design features relay.....	11
1.5. Structural and functional diagram of the relay protection device.....	32
1.6. Requirements for relay protection devices	33
Chapter 2 PROTECTION BY FUSES	38
1.5 Main characteristics of fuses	38
1.6 Selection of fuses	39
Chapter 3 PROTECTION BY CIRCUIT BREAKERS.....	42
3.1. Main characteristics of automatic circuit breakers.....	42
3.2. Selection of automatic circuit breakers	47
Chapter 4 Primary CURRENT MEASURING TRANSDUCERS.....	50
4.1. Purpose of primary measuring transducers current	50
4.2. The principle of operation of the transformer current.....	51
4.3. Design diagram and vector diagram of a current transformer	52
4.4. Transformer operating mode current	53
4.5. Transformer error current.....	54
4.6. Conventional and positional designation of the transformer current	55
4.7. Transformer winding connection diagrams current.....	57
4.8. Inspection of transformers current.....	61
Chapter 5 PRIMARY MEASURING VOLTAGE CONVERTERS	63
1.7 Purpose of primary measuring voltage converters	63
1.8 Electromagnetic transformers voltage	63
1.9 Features of transformer modes voltage in networks with isolated and compensated neutral	65
5.5. Features of voltage transformer modes in networks with effectively grounded neutral	69
Chapter 6 OPERATING CURRENT SOURCES	72
Chapter 7 PROTECTION OF TRANSMISSION LINES.....	77

LIST OF KEY ABBREVIATIONS AND SYMBOLS

A	- relay protection device, automation;
ATS	- automatic transfer switch;
NPP	- nuclear power plant;
recloser	- automatic reclosing;
ARC	- automatic excitation control;
AT	- autotransformer;
ADC	- analog-to-digital converter;
AFR	- automatic frequency unloading;
IP	- own needs (substations, power plants);
HF	- high-frequency;
DZ	- differential protection;
DPS	- differential tire protection;
DFZ	- differential-phase high-frequency protection;
EMF	- electromotive force;
CGC	- is the limiting multiplicity curve;
KRZ	- complete distribution agreement;
S.C.	- short circuit;
L,	transmission line - power line;
MSZ	- maximum current protection;
MCCP	- maximum current-directed protection;
n.c.	- normally closed contacts;
n.r.	- normally open contact;
SPR	- single-phase recloser;
RAM	- random access memory;
OTC	- optical current transformer;
PA	- automation device;
PBZ	- switching without excitation;
RBFD	- circuit breaker failure backup device;
ROM	- is a permanent storage device;
ROM	- reprogrammable storage device;
PUE	- electrical installation rules;
RP	- relay protection;
RPA	- relay protection and automation;
CB	- current cut-off;
CCD	- is a current-directed cutoff;
TS	- is the tire section;
TVP	- transformer of own needs;
TV	- voltage transformer;
TPS	- direct current transformer;
TC	- current transformer;
FRP	- ferroresonance process;
FFRP	- frequency recloser;
C	- capacity;
DT	- is a time delay element;
F	- fuse;
K	- relay winding (contacts);
KA	- winding (contacts) of the current relay;
KH	- winding (contacts) of the signal relay;

KL - winding (contacts) of the intermediate relay;
KV - winding (contacts) of the voltage relay;
KZ - winding (contacts) of the resistance relay;
KW - winding (contacts) of the power directional relay;
L - is the inductance;
RA - ammeter;
PV - voltmeter;
T - transformer;
TA - current transformer;
TAL, TVL - intermediate transformers;
TAV - trans reactor;
TLA - throttle;
TV - voltage transformer;
VD - light emitting diode;
VS - rectifier;
VT - is a transistor;
Z - is the complex resistance;
Q - switch;
S - is the switching key;
R - active resistance;
SF - is a circuit breaker with a disconnecter;
w - winding turns;
UVZ - inverter converter;
YAC - switch-on electromagnet;
YAT - is a trip solenoid;
 Φ - is the magnetic flux;
 Ψ - is the flow adhesion;
 ε - is the absolute error.

PREFACE

During the design and operation of power systems, it is necessary to take into account the possibility of damage and special modes. The most common and dangerous damages are short circuits at power system facilities. Such damages cause the destruction of the damaged object by short-circuit currents or an arc that may occur at the point of damage. It is also possible to destroy adjacent objects by currents that exceed the permissible values. In addition, a decrease in voltage at the nodal points of the power system as a result of short circuits may affect the disruption of technological processes and the stability of the power system. Therefore, it is necessary to disconnect the damaged facility from the power system in a fraction of a second or even within milliseconds. Given the rapidity of processes in electric power systems, it is impossible to operate them without automation devices. Of course, humans are unable to perform such actions. Therefore, special automation devices, namely *relay protection* devices, are used to shut down a damaged object, as well as to eliminate some special modes, such as overloads.

Therefore, knowledge of the principles of implementation, features of operation and calculation of the operation parameters of relay protection devices for power system facilities is mandatory for engineers working in the field of electricity.

Section 1 GENERAL PROVISIONS

1.1. Purpose of relay protection

The modern electric power system is a complex set of electrical equipment located over a large area and united by a single mode of electricity generation, transportation and consumption.

The electricity system is subject to constant disturbances. These disturbances can be of a planned nature: switching generators off and on, daily changes in the level of electricity generation at power plants, mode switching in the power grid, etc.

In addition to these planned disturbances, the power system may experience damages and dangerous special modes that have a significant impact on the equipment and operation of the power system as a whole. One of the most dangerous damages in the power system is short circuits (short circuits), occur as a result of damage to the insulation of current-carrying parts of electrical equipment. Short circuits can lead to:

- destruction of the damaged element by overcurrents or an arc that may occur at the point of damage;
- possible destruction of equipment at adjacent power system facilities to the damaged element as a result of thermal and dynamic effects of currents exceeding permissible values;
- lowering the voltage level at the nodal points of the electric power system, which can lead to disruption of technological processes at enterprises as well as to a possible disruption of the stability of the electric power system, which, in turn, will lead to a complete loss of power supply to consumers.

Therefore, after a short circuit occurs in the power system, it is necessary to disconnect the damaged cell from the power supply as soon as possible.

In addition to accidents, special modes may occur in the power system, such as overloading electrical equipment with operating currents, oscillations in the system, voltage increases above the rated value, etc.

One of the most common special modes is the overload mode. During overload, currents occur in the elements of the power grid, which are higher than their nominal values, although not to the same level as during a short circuit. This causes overheating of the equipment and premature aging of the insulation, which in turn can lead to a short circuit.

After the occurrence of special modes, measures must be taken to eliminate such modes, and if such actions are not possible or unsuccessful, the equipment operating in the special mode must be turned off. In this case, the equipment should be disconnected from the power supply, as a rule, with a time delay.

Damaged equipment or equipment operating in a special mode is switched off by special automation devices - relay protection devices (RPDs).

It should be remembered that relay protection does not prevent damage, it operates only after it has occurred and its purpose is to prevent the destruction of the damaged element or reduce the extent of such destruction, as well as to limit the spread of damage to other adjacent elements of the power system, and to eliminate possible danger to people.

1.2. Requirements for the implementation of relay protection

The requirements for relay protection are regulated by the relevant state regulatory documents that comply with international standards.

Relay protection devices are designed so that each of them covers a specific area of the power system. These areas are called *protection zones*. The protection area can be a generator, transformer, power line, etc. The protection zone may also cover several elements of the power grid, for example, a transmission line - a transformer. If a fault occurs within this zone, the relay protection of this zone must operate and act to trip the circuit breakers that supply power to the fault location.

The following conditions must be met when designing relay protection devices:

- relay protection devices must cover all the equipment of the power system, there cannot be any areas, even within a single element, that are not covered by the relay protection zones;
- the areas of operation of relay protection devices of adjacent sections of the electric power system must overlap;
- to increase reliability, the operation of individual relay protection devices should be duplicated, i.e. each section of the power system should be protected by at least two independent relay protection devices (100% redundancy), for critical sections, three independent relay protection devices (200% redundancy) can be used.

Let us explain these requirements with specific examples.

The protection area of *A1* (Fig. 1.1) covers the transmission line *L2* from the busbars of substation *A* and the beginning of line *L3*, and the protection area of *A2* covers the same line *L2* from the busbars of substation *B* and part of line *L1*. Therefore, after the occurrence of fault *F1* on line *L2*, relay protections *A1*, *A2* should operate and act to close circuit breakers *Q1*, *Q2* - the damaged line *L2* will be disconnected from the power sources.

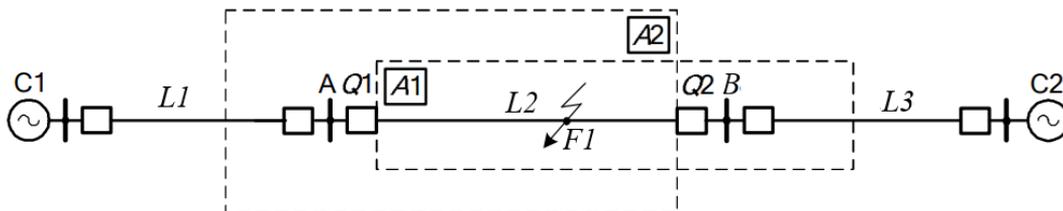


Fig. 1.1. Areas of operation of the RF

Fig. 1.2 shows the areas (highlighted by dashed lines) of incorrectly designed line protection *A1* and busbar protection *A2*. The measuring elements of these protections are connected to different current transformers *TA1*, *TA2*. The line protection does not trip during a short-circuit at point *F1* and does not act to disconnect this line. The busbar protection also does not act on this fault.

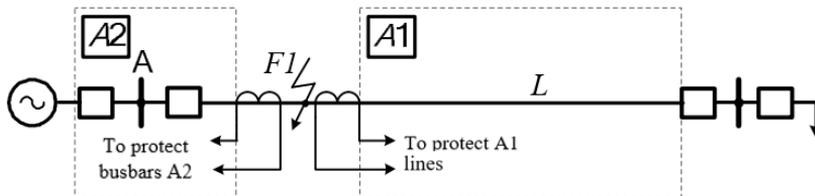


Fig. 1.2. Improperly designed protections

Thus, with this connection of the line and busbar protection measuring devices, there is a section between the current transformers that is neither within the area of coverage of line protection *A1* nor within the area of coverage of busbar protection *A2*. Therefore, during a short circuit in this section at point *F1*, neither of these protections will operate.

For proper functioning of the protections (areas marked with dashed lines) of the line and

busbars, their measuring instruments must be connected according to Fig. 1.3.

In this case, fault point $F1$ falls within the coverage of both line protection $A1$ and busbar protection $A2$.

The diagram in Fig. 1.4 illustrates how the operation of relay protection devices is backed up.

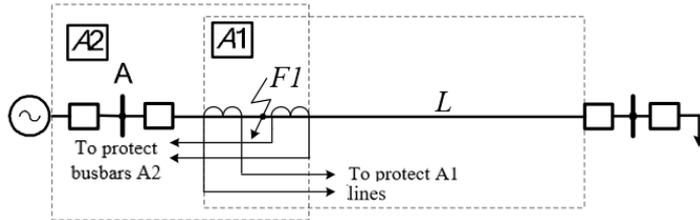


Fig. 1.3. Protection zones overlap

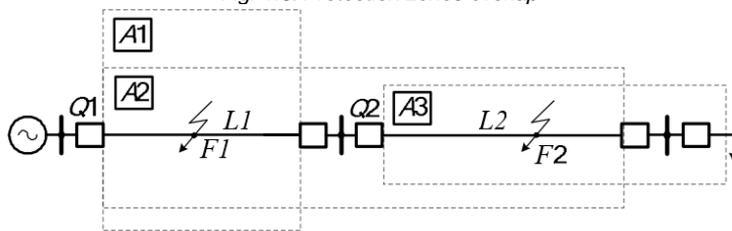


Fig. 1.4. Reservation of protection operation

At the beginning of line $L1$, the main protection $A1$ is installed, the area of operation of which completely covers line $L1$ and protection $A2$, which performs the function of backup protection. In addition to line $L1$, the area of operation of the backup protection $A2$ covers the adjacent line $L2$. If, after a short circuit at point $F1$ on line $L1$, the main protection $A1$ fails, the backup protection $A2$ will operate and act to close the circuit breaker $Q1$. However, unlike protection $A1$, this will be done with a longer time delay. In the event of a short circuit at point $F2$ on the adjacent line $L2$ and the failure of the protection of this line $A3$, protection $A2$ will also trip, because its area of operation also covers the line $L2$. Protection $A2$ will trip the circuit breaker $Q1$. In this case, the damaged line $L2$ and the undamaged line $L1$ will be disconnected. Such a trip is called a *non-selective trip*. In the first case, the protection $A2$ performed the function of *short-term redundancy*, in the second - of *long-term redundancy*.

To implement *near redundancy* at a connection, two protections with different operating principles are usually used. These protections mutually back up each other. Sometimes, three sets of protectors are installed to ensure close redundancy. Such three-protection redundancy is, in particular, used to protect the 750 kV line at Zakhidnoukrainska substation.

In order to increase the reliability of near redundancy, it is advisable to connect the operational circuits of the main and backup protection through different fuses or circuit breakers, and to connect the current circuits to different groups of current transformers. It is also advisable to connect the voltage circuits of the main and backup protection to different voltage transformers. The latter requirement is not always technically feasible.

to implement, because not all substations have two voltage transformers connected to the same busbars or to the same line.

The use of *long-distance redundancy* has significant drawbacks. The main disadvantage is the non-selective tripping of undamaged elements that are switched off simultaneously with the damaged one. In addition, the operating time of the protections that implement long-distance redundancy is significant and, in some cases, the total time of fault tripping can be up to 10 seconds, which may be unacceptable from the point of view of ensuring the stability of the power system. Also, it is not always possible to ensure sufficient sensitivity of the protections that provide long-distance redundancy. The only significant advantage of long-distance redundancy compared to short-distance redundancy is that no additional protection is required - long-distance redundancy is usually provided by separate protection stages that perform the functions of the main protection of the adjacent element. For example, protection A2 (Fig. 1.4) protects line L1, and its individual stages can operate during a short circuit on line L2 (point F2).

From the above, it can be concluded that the use of near redundancy has some advantages over far redundancy.

1.3. Purpose and main characteristics of relay

One of the main elements of relay protection devices is a *relay*. The relay is a device in which the output signal y_{out} changes in a jump-like manner, in depending on the change in the input value y_{input} (Fig. 1.5).

When the output signal changes in a spike-like manner, the relay is said to have tripped. That is, there are two stable states of the relay: the relay is in a fault in the state - output signal $y_{out}=0$, relay in triggered state $y_{out}=1$. The value of input signal y_{input} , at which the relay is triggered is called *the relay trip setpoint*.

A distinction is made between *maximum* and *minimum action* relays. *Maximum-acting* relays operate when the input signal level *increases* to the trip setpoint. *Minimal action* relays are triggered when the input signal level *drops* below the trip setpoint.

Depending on how the relay is switched on (how the input signal is supplied), *primary* and *secondary* relays are distinguished. Primary relays are connected directly to the primary (power) circuit. Secondary relays are connected to the primary circuit through primary current or voltage transducers. Primary measuring transducers are usually *current transformers and voltage transformers*.

Depending on the action on the switchgear, a distinction is made between *direct-acting* and *indirect-acting relays*. *Direct-acting relays* act directly on the switching device's tripping mechanism. *Indirect-acting relays* act on the switchgear through intermediate elements, for example, through the electromagnets of circuit breakers. Another feature of the relay is its *hysteresis characteristic*.

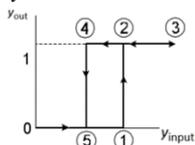


Fig. 1.6. Hysteresis characteristic of the relay

Let's explain the essence of the hysteresis characteristic using the example of a maximum action relay. In the case of increasing of the input signal y_{input} to the value at which the relay is triggered, i.e., up to the relay setpoint - $y_{input}=y_{op}$. (point 1 in Fig. 1.6) the output value y_{out} will change by a jump (points 1, 2). With a further increase in the input signal no change in the output value occurs (points 2, 3). After reducing the input

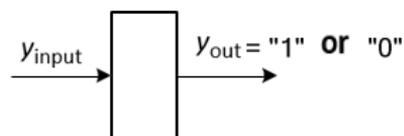


Fig. 1.5. Relay

signal y_{input} to the value of $y_{\text{ret.r}}$ (point 5) of the relay will return to the original value state (points 4, 5). That is, the relay will return to its initial state by the value of the input value $y_{\text{input}} = y_{\text{ret.r}}$ which is less than the value of the input of the signal at which the relay is triggered - $y_{\text{ret.r}} < y_{s.r.}$.

The hysteresis of the relay characteristic is determined by *the relay return coefficient* k_{ret} , the value of which is calculated from the expression

$$k_{\text{ret}} = \frac{y_{\text{ret.r}}}{y_{s.r.}} \quad (1.1)$$

For maximum action relays $k_{\text{ret}} < 1$, for minimum action relays $k_{\text{ret}} > 1$.

1.4. Principle of operation and design features relay

1.4.1. Electromechanical relays

As mentioned in Section 1.3, one of the main elements of relay protection and automation devices (RPA) is a relay. Mostly *electromechanical relays* are used. Although recently, in connection with the introduction of digital RPA devices, the share of electromechanical relays has been gradually decreasing. But even in digital-based relay protection devices, electromechanical relays are used. These are usually output relays. Attempts to replace these output relays with electronic ones (transistor or triac switches) have not yet been successful. Therefore, in the near future, electromechanical relays will be used in both electromechanical and digital reclosers.

The principle of operation of electromechanical relays is based on the mutual conversion of electrical and mechanical quantities.

Depending on the principle of operation, the following electromechanical relays are distinguished:

- *electromagnetic;*
- *induction;*
- *magnetolectric;*
- *electric heat.*

The most common relays in relay protection devices are relays whose operation is based on

electromagnetic principle.

The main element of these relays is an electromagnet to which the moving armature is attracted. Depending on the movement of the moving armature, systems are distinguished:

- with a swivel anchor;
- with transverse movement of the anchor;
- with forward movement of the anchor.

1.4.1.1. Electromagnetic relays

Let's consider the principles and features of electromagnetic relays based on typical relays used in the electric power industry.

The most common electromagnetic relays with a *rotary armature* are current relays of the RT-40 series and voltage relays of the RN-50 series.

Relays of RT-40 series

These relays respond to changes in the current of the current source.

According to the method of switching into the primary circuit, these are secondary relays, they are connected to the secondary circuits of current transformers. By way of action, they are indirect - they act on the circuit breaker actuator through additional intermediate relays.

Electromagnetic current relays are used in current protection (current cut-off, time-delayed current cut-off, maximum current protection, differential protection, ground fault protection, etc.).

RT-40 series relays are manufactured in the following modifications:

- PT-40/ N , where N is the maximum value of the current setpoint;
- RT-40/1D is a relay with a high multiplicity of long-term permissible overcurrent;
- RT-40/F is a relay with reduced sensitivity to higher harmonics in the current;
- RT-40/P-1, RT-40/P-5 are relays with current totalizers for special protections and circuit breaker failure redundancy devices (CBFD).

The following current relays of the RT-40 series are mass-produced: RT-40/0.2; RT-40/0.6; RT-40/2; RT-40/6; RT-40/10; RT-40/20; RT-40/50; RT-40/100; RT-40/200; where the numbers

after the dash indicate the highest tripping current, as well as RT-40/P-1; RT-40/P-5; RT-40/1D; RT-40/F relays.

The design of the relay type RT-40 is shown in Fig. 1.7.

The main element of the relay is an electromagnet 1, consisting of a *U-shaped* core made of steel, on which two coils are located. It is possible to connect these coils in series or in parallel.

The electromagnet attracts the ferromagnetic armature 3, to which the contact bridge 5 is attached. A coil spring 4 is attached to the axis about which the armature rotates, the torque of which is regulated by lever 6, which changes the relay's response parameter (setpoint).

magnetizing force F acting to attract the armature to the core is proportional to the square of the flux Φ penetrating the armature

$$F = k_1 \cdot \Phi^2 \quad (1.2)$$

Given that the magnetic resistance of the core magnetic circuit is much lower than the magnetic resistance of the air gap between the core and the armature, the magnetic flux is directly proportional to the magnetizing force ($I_p \cdot w$) and inversely proportional to the size of the gap between the core and the armature

$$\Phi = k_2 \cdot \frac{i_p \cdot w}{l} \quad (1.3)$$

where w is the number of windings; $i_p = I_{r,max} \cdot \sin w \cdot t_p$ is the value of the current that flowing in the relay winding; l is the distance between the armature and the core; k_2 is the proportionality coefficient.

Substituting the expression for determining the magnetic flux from (1.3) into (1.2), we obtain the expression for determining the armature attraction force F .

$$F = k_3 \cdot \frac{i_p^2 \cdot w^2}{l^2} \quad (1.4)$$

where $k_3 = k_1 \cdot k_2$ is the proportionality coefficient.

Given that the relay winding is alternating current, the armature's attraction force will be determined as:

$$F = k_3 \cdot \frac{w^2}{l^2} \cdot I_{r,max}^2 \cdot \sin^2 w \cdot t \quad (1.5)$$

Considering that $\sin^2 w \cdot t = 0.5 \cdot (1 - \cos 2 \cdot w \cdot t)$, $I_{r.max} = \sqrt{2} I_r$, where I_r is the current value in the relay winding, we obtain

$$F = k_3 \cdot \frac{w^2}{l^2} \cdot I_{r.max}^2 \cdot 0.5 \cdot (\sqrt{2} I_r)^2 - k_3 \cdot \frac{I_p^2 \cdot w^2}{l^2} \cdot 0.5 \cdot (\sqrt{2} I_r)^2 \cdot \cos 2 \cdot w \cdot t \quad (1.6)$$

Expression (1.6) shows that the anchor is attracted with a constant force

$$F' = k_3 \cdot \frac{I_p^2 \cdot w^2}{l^2} \quad (1.7)$$

and with the same effort

$$F'' = k_3 \cdot \frac{I_p^2 \cdot w^2}{l^2} \cdot \cos 2 \cdot w \cdot t \quad (1.8)$$

The second component with a double frequency F'' acts on the anchor and causes it to vibrate. To reduce its effect on the armature, the RT-40 relay has a massive disk 7 (Fig. 1.7), which serves as a dynamic damper. It is a plastic cylinder with an aluminum cover filled with quartz sand.

Let's analyze the expression (1.7), which determines the electromagnetic force F_{em} acting on the relay armature:

- This force is proportional to the square of the current flowing through the relay winding;
- at a constant current, an increase in the number of turns leads to a significant increase in the electromagnetic force, and a decrease leads to a significant decrease in this force, since its constant component F_{em} is directly proportional to the square of the turns. The relay has the ability to change the number of turns by connecting two half-windings in series or in parallel;
- the electromagnetic force is inversely proportional to the square of the distance l between the armature and the core.

In the case of significant changes in l occurring during the armature movement, some characteristics of the relay change significantly, in particular, the relay return coefficient is significantly reduced. Therefore, the PT-40 series relays use a design with a *transverse armature movement* - the so-called *L-shaped armature profile*. For this design air gap in the extreme positions of the armature (respectively l_{start} and l_{end}) differs slightly, as illustrated in Fig. 1.8. In Fig. 1.8, the final position of the anchor is shown by a dashed line.

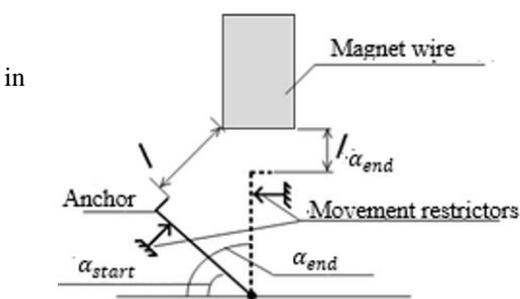


Fig. 1.8. Moving L-shaped relay anchor

The armature has two *movement limiters*. They are necessary to fix the armature its extreme positions and to create a certain pressure on the relay contacts to ensure their reliable closure.

For this relay design, the armature is subjected to a force that creates an electromagnetic torque

$$M_{em} = k_4 \cdot F_{em} \quad (1.9)$$

where k_4 is the proportionality coefficient, which varies according to a rather complex law and depends on the armature angle α , which changes during the armature movement from the value α_{start} to the value α_{end} .

The torque is counteracted by the moment M_{st} , which is created by the spring 4 (Fig. 1.7).

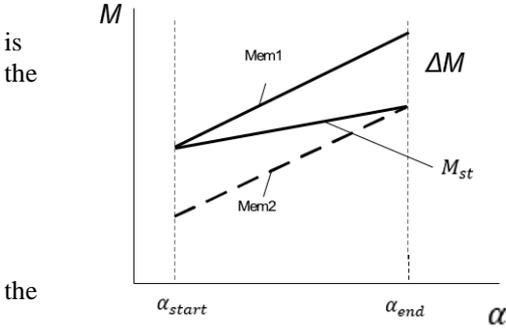


Fig. 1.9. Dependence of electromagnetic torque M_{em} and spring torque M_{st} on the armature rotation angle

Due to the initial excess torque M_p , when there no Mem, the contact bridge 5 is pressed against right pair of contacts.

As the current in the relay winding increases, the electromagnetic force F_{em} (1.7) and, as a result, the electromagnetic torque (1.9) increase. When the electromagnetic torque is equal to the spring moment $M_{em} = M_{st}$, the armature starts to rotate. The current at which armature starts to rotate is called the relay tripping current $I_{s.r.}$. In this case, the mechanical torque M_{st} will increase due to the spring tightening (Fig. 1.9). The electromagnetic torque M_{em1} at a constant current will increase faster than M_{st} due to a decrease in the distance l between the armature and the core - as can be

seen from Fig. 1.8, the initial distance between the armature and the magnetic core at the I_{start} is somewhat greater than the final distance I_{end} , which corresponds to the final position of the armature. Turning the armature will stop the motion limiter.

After moving the armature to the end position, the electromagnetic torque M_{em1} will be greater than the spring moment by $\Delta M = M_{em1} - M_{st}$. Under the armature will be securely pressed against the motion limiter by this excess torque. Therefore, to return the armature relay to the original position, it is necessary to reduce the electromagnetic torque M_{em1} by the value ΔM to the value M_{em2} . This is achieved by reducing the current in the relay winding.

The current at which the relay armature returns to its initial state is called the current relay return $I_{ret.r}$. Therefore, the relay return current is less than the current relay operation $I_{s.r.}$ and the return coefficient of the relay, which defines as the ratio of the return current to the relay trip current according to (1.1) will be less than 1

$$k_{ret} = \frac{I_{ret.r}}{I_{s.r.}} < 1$$

Relay series PH-50

Electromagnetic voltage relays respond to changes in the voltage of the voltage source (increase - maximum action relay, decrease - minimum action relay).

According to the method of switching into the primary circuit, these are secondary relays, they are connected to the secondary circuits of voltage transformers. By way of action, they are indirect - they act on the circuit breaker actuator through additional intermediate relays.

Electromagnetic voltage relays are used in automatic backup transfer switches (ABTS), automatic reclosing devices (ARS), overcurrent protectors with undervoltage start, power supply control circuits for various elements, etc.

Voltage relays of the PH-50 series are manufactured in the following modifications:

- RN-53/N, RN-54/N - for connection to AC circuits, where N is the maximum value of the voltage setpoint;

- RN-51/M - for connection to DC circuits;
- RN-53/60D - used for circuits where a voltage that significantly exceeds the tripping voltage may occur;
- PH-58 is a relay with an increased return coefficient (up to 0.95);
- RNN-57 - has a filter at a frequency of 150 Hz, i.e. it is insensitive to higher harmonic components, used in circuits with a distorted voltage waveform;
- PH-55 - relays used in synchronism control circuits and blocking against asynchronous switching. Unlike the previous relays, these relays have two independent and isolated windings.

The following series of voltage relays are manufactured by the industry: series RN-50: RN-53/60, RN-54/48, , , , , RN-51/M34,

RN-51/M56, RN-51/M78, where the digits after the dash indicate the maximum operating voltage of the relay; RN-58 relay; RN-55 series relay: RN-55/90, RN-55/120, RN-55/130, RN-55/160, RN-55/200, where the number after the dash indicates the rated voltage of the relay.

The design of the relay type PH-50 is the same as the current relay of the RT-40 series (Fig. 1.7). The principle of operation of this electromagnetic relay is similar to the principle of operation of the RT-40 current relay. Only in the relay of the RN-50 series there is no mechanical damper 7 on the armature (Fig. 1.7).

which is two times less than, for example, in a relay of the RT-40 type, in which the alternating force is determined from expression (1.8). Therefore, the anchor will be mainly affected by the force created by the constant component of the induced current, which is determined from expression (1.11).

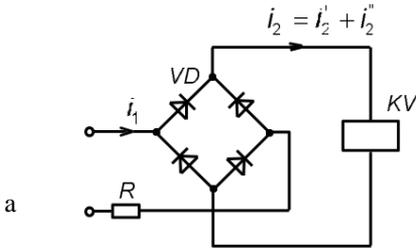


Fig. 1.10. Scheme of switching on the winding of the voltage relay RN-50

This is explained as follows. The second component of the magnetizing force (1.8) F'' acts on the armature with a double frequency and causes its vibration. To reduce vibration, a mechanical damper is installed on the armature of the PT-40 current relay. To reduce the effect of the double-frequency attraction force, rectified voltage circuit is used on the PH-50 series voltage relay (Fig. 1.10). That is, the KV winding of the relay responds to a rectified voltage that is proportional to measured voltage.

With such a connection, a current i_2 flows through the KV relay winding, which has two components: a familiar component, which is determined from the expression

$$i_2' = 0.5 \cdot I_p \cdot \cos 2 \cdot \omega \cdot t \tag{1.10}$$

and the permanent component

$$i_2'' \cong 0.5 \cdot I_p \tag{1.11}$$

In this case, the alternating force that causes the armature vibration according to (1.8) will be generated by the alternating component and determined from the expression

$$F_2'' = 0.25 \cdot k_3 \cdot \frac{\omega^2}{l^2} \cdot I_p^2 \cdot \cos 4 \cdot \omega \cdot t \tag{1.12}$$

which is two times less than, for example, in a relay of the RT-40 type, in which the

alternating force is determined from expression (1.8). Therefore, the anchor will be mainly affected by the force created by the constant component of the induced current, which is determined from expression (1.11).

1.4.1.2. Induction relays

Relay series RT-80

This is the most common *induction type* relay. In addition, the relay combines the electromagnetic principle - *a relay with a rotary armature*.

RT-80 series induction relays (formerly IT-80) have been in operation in power systems for more than 60 years. They are used for current protection of 6-35 kV lines, protection of low-power transformers, and protection of induction motors.

The relay consists of two functional elements - *electromagnetic and induction*. The

electromagnetic element creates a current cut-off without a time delay, and the induction element creates a maximum current protection with a time delay. Thus, a *two-stage current protection* can be created on the basis of one RT-80 relay. In addition, the relay has a signaling body that signals its operation, i.e. the RT-80 relay also contains an indicator relay.

The principle of operation of the RT-80 series relay is based on the electromagnetic and induction principles. Fig. 1.11 illustrates the electromagnetic principle of relay operation. In this relay, the switching of the contacts of the movable 3 and the fixed 4 occurs under the action of the electromagnetic force of attraction of the ferromagnetic armature 2 to the electromagnet. The armature is rotated and attracted to the electromagnet

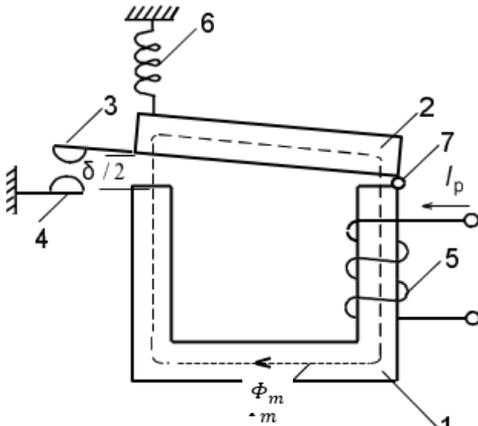


Fig. 1.11. Operating principle of the electromagnetic element of the RT-80 relay

through a hinge 7. On the magnetic circuit of the electromagnet 1 there is a coil 5, through which flows relay current I_r . The current I_r creates a magnet. The flux Φ_m that penetrates the magnetoprop from, air gap, anchor. The direction of the magnetic flux lines is determined by the drill rule. An electromagnetic force of attraction occurs between the armature and the electromagnet, which is determined from the expression

$$\Phi_{em} = k \cdot \left(\frac{I_r w_r}{\delta} \right)^2 \quad (1.13)$$

where k is the proportionality coefficient; w_r is the number of turns of the relay coil; δ is the air gap.

The armature will be attracted to the electromagnet at the corresponding current in the winding $I_{s.r.}$ (relay tripping current), when the magnetizing force Φ_{em} is greater than the force spring tension 6. After the armature is attracted to the electromagnet, contacts 3 and 4 will be closed. After reducing the current I_r in the winding to the value $I_{ret.r.}$ (current relay return), when the spring tension force exceeds the electromagnetic force, the armature will fall off the solenoid and contacts 3 and 4 will open. An increase in the spring tension force leads to an increase in the relay trip current and vice versa. It is obvious from expression (1.13) that by increasing the number of turns, the current can be reduced relay operation. The force of attraction is inversely proportional to the square of the air gap δ . Therefore, as the gap δ decreases, the armature speed

increases sharply and the relay trips in a hundredth of a second.

The trip current of the electromagnetic relay can therefore be adjusted using:

- changing the number of turns;
- changes in the air gap;
- change the spring tension.

Figure 1.12 illustrates the principle of operation of the induction element of the relay.

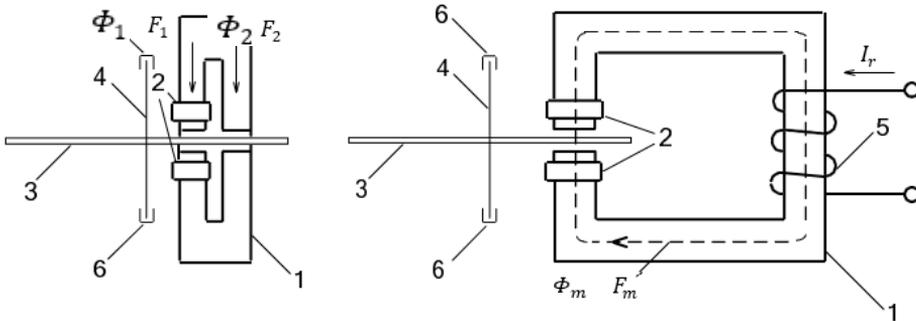


Fig. 1.12. Principle of operation of the inductive element of the RT-80 relay

In Fig. 1.12 the electromagnet and disk are shown in two projections. The relay consists of a magnetic circuit 1, on which the winding 5 is located. The metal disk 3 rotates on the axis 4 and passes through the air gap in the magnetic circuit 1. The disk rotates in the bearings 6. To create a moment that rotates the disk, it is necessary to create two magnetic fluxes shifted in space and time (Φ_1 and Φ_2). Structurally, this is achieved by the fact that part of the upper and lower poles of the electromagnet magnetic circuit is covered by short-circuited copper rings (screens) A part of the flux flows through a magnetic circuit with short-circuited turns $\Phi_m - \Phi_2$, through the rest of the magnetic circuit - the rest of the flux $\Phi_m - \Phi_1$. The flux Φ_1 induces in short-circuited turns the EMF E_s which in turn causes current flow in these turns I_s (Fig. 1.13, a).

The magnetization current \dot{I}_μ , which causes the flux $\dot{\Phi}_1$, and coincides with it by phase, is determined by the relay current and the current in the short-circuited turns \dot{I}_s ,

$$\dot{\Phi}_1$$

$$\dot{\Phi}_1 = k_3 \cdot \dot{I}_m; \quad \dot{I}_m = k_4 \cdot \dot{I}_r + \dot{I}_s, \quad (1.14)$$

where k_3, k_4 are proportionality coefficients; \dot{I}_s is the current in short-circuited turns, is reduced to the number of coils turns. From (1.14) we determine the current in the relay winding \dot{I}_r , which is ahead of the magnetization current \dot{I}_μ by an angle ψ (Fig. 1.13, a).

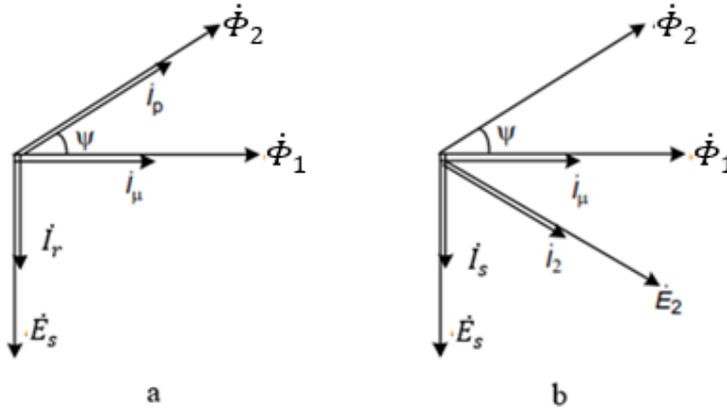


Fig. 1.13. Vector diagrams of the inductive element of the RT-80 relay

The flux $\dot{\Phi}_2$ is caused only by the current in the relay winding \dot{I}_r , proportional to it and coincides with it in phase

$$\dot{\Phi}_2 = k_5 \cdot \dot{I}_r \quad (1.15)$$

As a result of the interaction of the magnetic flux $\dot{\Phi}_1$ with a metal disk in it, the law of electromagnetic induction gives the EMF \dot{E}_1 , under the influence of which circulate vortex currents (Foucault currents) \dot{I}_1 . Similarly, the flux $\dot{\Phi}_2$ causes the \dot{I}_2 (Fig. 1.13, b).

As a result of the interaction of the flux $\dot{\Phi}_1$ with the current \dot{I}_2 , the flux $\dot{\Phi}_2$ with the current \dot{I}_1 , the electromagnetic forces \dot{F}_1 and \dot{F}_2 arise, which form a rotating electromagnetic moment $M_{em} = (|\dot{F}_1| - |\dot{F}_2|) \cdot d$, where d is the shoulder of the force, or

$$M_{em} = k_6 \cdot \dot{\Phi}_1 \cdot \dot{\Phi}_2 \cdot \sin \psi \quad (1.16)$$

The magnetic flux $\dot{\Phi}_1$ and current \dot{I}_1 , as well as the flux $\dot{\Phi}_2$ and current \dot{I}_2 are not created

The electromagnetic forces and, accordingly, the torques, because they are mutually shifted by an angle of 90° . Therefore, in order to generate a torque, it is necessary to create magnetic fluxes crossing the disk that are shifted in phase. For this purpose, short-circuited turns covering a part of the magnetic circuit are introduced.

Taking into account (1.14), (1.15), (1.16), we obtain

$$M_{em} = k_1 \cdot I_r^2 \quad (1.17)$$

that is, the magnetic moment of the induction element is proportional to the square of the current in the relay winding. Expression (1.17) is valid only for an unsaturated relay magnetic circuit. After saturation, with increasing current, the magnetic flux and, consequently, the torque practically do not change.

In addition to the electromagnetic torque M_{em} , the disk is also subjected to a dynamic brake torque. The braking force is determined by the friction in the pads, air resistance and the torque generated by the permanent brake magnet. The permanent braking magnet is created by the permanent magnet that covers the disk. The last component of the braking torque is the decisive one. The braking torque is generated as follows. As the disk rotates between the poles of the

permanent magnet, it crosses its magnetic force lines, results in an emf proportional to the disk rotation frequency ω . Under the action of this emf, current circuits appear, the electromagnetic force of which forms the braking torque

$$M_B = k_2 \cdot \omega \tag{1.18}$$

Considering that at a constant disk rotation frequency ω $M_B = M_{em}$, we obtain

$$k_2 \cdot \omega = k_1 \cdot I_r^2 \tag{1.19}$$

from

$$\omega = \frac{k_1 \cdot I_r^2}{k_2} \tag{1.20}$$

If the relay contacts are connected to the disk through a worm gear (see Fig. rice. 1.1, 6), then as soon as the current in the relay reaches its activation current and the worm pair will enter the clutch, then the relay contacts will close after a fixed amount disk revolutions. Therefore, a delay element is created on the basis of the induction relay time The activation time of such an element is determined from the expression

$$t = \frac{n}{\omega} = \frac{n \cdot k_2}{k_1 \cdot I_r^2} \tag{1.21}$$

where n is a fixed number of revolutions that changes with the initial position of the sector worm pair (position 1 in Fig. 1.15).

From expression (1.21), it is obvious that the greater the current in the relay, the shorter its response time, i.e., the inversely dependent time characteristic of the relay response is obtained (Fig. 1.14).

The characteristic has a current-dependent A and a current-independent B part. The presence of the independent part B is explained by the saturation of the magnetic circuit. In the case of magnetic circuit saturation, a further increase in the current in the relay winding does not lead to an increase in the electromagnetic torque, it practically does not change.

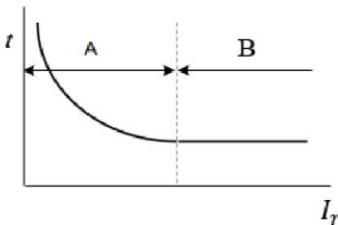


Fig. 1.14. Time characteristic of the inductive element of the RT-80 relay

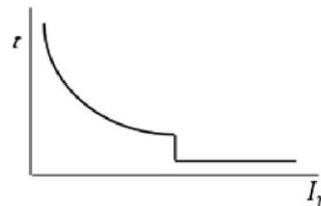


Fig. 1.15. Combined characteristic of induction relay RT-80

The dependent characteristic of the relay, based on the induction part of the relay, in combination with the independent characteristic, based on the electromagnet, provides a combined characteristic that can be used to form a two-stage current protection (Fig. 1.15).

In Fig. 1.16 shows the design of the RT-80 relay:

The electromagnetic element of the relay is formed on the basis of a magnetic circuit 16

with a coil 12 and a cut-off armature 9, and acts on a system of contacts - movable 7 and fixed 6. The gap between the magnetic circuit 16 and the cut-off armature 9 is changed by means of the adjustment screw 10. In this case, the current of the relay electromagnetic element changes.

The magnetic core 16 also serves as the induction element of the relay. The movable part of the induction element is an aluminum disk 18, which rotates between the poles of the magnets, some of which are covered by short-circuited turns 17. The disk axis is mounted on two supports and a frame 29, which rotates on supports 28, 31, fixed in the relay base. The worm 3 is fixed on the disk axis. The second element of the worm pair is the toothed sector 1, which rotates on two axes 30. The sector has a pusher 20 that moves the cutoff anchor 9. The pusher 20 rests on a support 21, the latter being fixed by a screw 24. By changing the position of the support 21, the required relay time delay is set. The rotating frame 29 is fixed with a screw

23. The frame is pulled to the extreme position by a return spring 26, the tension of which is regulated by screw 25.

The permanent magnet 27 is an integral part of the relay's magnetic system. It generates a braking torque proportional to the disk speed, which ensures stable relay performance. In addition, the permanent magnet stops the disk from rotating after the current is released and thus reduces the inertia of the relay runaway.

After the relay current increases to the trip current, the disk 18 is already rotating, the frame 29 turns with the disk and the worm 3 engages with the toothed sector 21. The toothed sector rises together with the pusher 20 and causes the armature 9 to be attracted by the magnetic circuit 16. The speed of rotation of the disk and, accordingly, the speed of lifting of the pusher 20 depends on the amount of current in the relay. After the current in the winding 12 is disconnected, the frame 29 is pulled back by the spring, the worm gear is disconnected and the toothed sector 1 falls on the support 21, the relay contacts open. The RT-80 relay trip current setting is determined by the number of coil turns, which is set by the screw 14 screwed into the corresponding socket of the plug bridge 13.

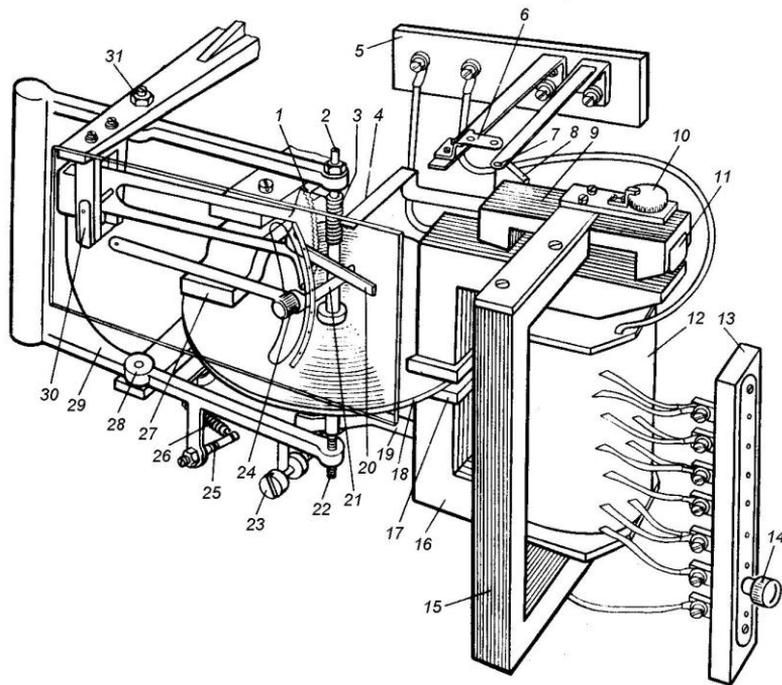


Fig. 1.16. Design of the RT-80 relay:

- 1 - toothed sector; 2 - upper disk support; 3 - worm; 4 - figured lever;
 5 - contact pad; 6 - fixed contact; 7 - movable contact; 8 - textolite plate; 9 - cut-off armature; 10 - cut-off adjusting screw; 11 - short-circuited armature coil; 12 - coil; 13 - plug bridge; 14 - plug screw;
 15 - magnetic circuit shunt; 16 - magnetic circuit; 17 - shields; 18 - disk; 19 - bracket; 20 - pusher; 21 - support; 22 - lower disk support; 23 - support; 15 - screw;
 24 - shaped screw; 25 - spring adjusting screw; 26 - spring; 27 - permanent magnet; 28 - lower frame support; 29 - frame;
 30 - half-axis of the sector; 31 - upper support of the frame

Relays of the RBM series

This is an induction relay with a cylindrical rotor.

The relay is designed to detect the direction of power in the power grid at the place of protection installation.

The relays are manufactured in two versions: single contact relays for determining the direction of power during the short-circuit (relays of RBM-171, RBM-178 types) and double contact relays for bilateral action, when one pair of contacts closes when power is directed in one direction, and the other pair of contacts closes when power is directed in the opposite direction (relays of RBM-271, RBM-277, RBM-278 types).

In addition to these relays, other relays of the RBM series are also produced:

- relays with reverse-sequence current and voltage filtering, which are used in protections against asymmetric short-circuit types - RMOP-2 relays;
- relay with current polarization RMP-272, in which the polarized relay RP-7 is used as an ;

relays that respond to active and reactive power directions - RBM-275 and RBM-276 relays, respectively.

Let's consider the principle of operation of the RBM series relay. The design of the relay is shown in Fig. 1.17.

The square magnetic circuit 1, made of steel, has four protruding poles. A fixed steel core 6 is placed between the poles to reduce the resistance to magnetic flux. In the air gap between the protruding poles and the steel core contains the moving element of the relay - a hollow aluminum cylinder 3, which is fixed to the axis 5.

The movable structure is located on the axis 5 and is held between the lower support 10 and the upper support 11. The movable cylinder is held in place by spring 8. On this axis also contains the moving contact 7 and a spiral spring 9, which is a current conductor of the moving contact 7 and is therefore isolated from the relay body. When the relay is triggered, the moving contact rotates with the axis and closes with the fixed contact 13.

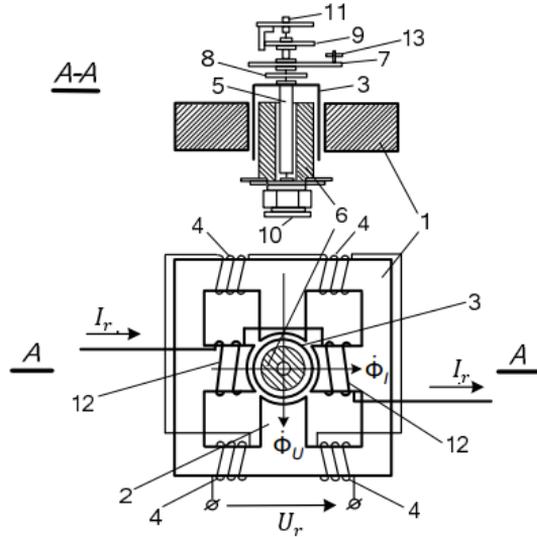


Fig. 1.17. Design of an induction relay of the RBM type

The magnetic circuit has two current windings 12 connected to the current circuits and four windings 4 connected to the voltage circuits. Current I_r is supplied to the current windings, and voltage U_r is supplied to the voltage windings.

Let's consider the processes in the relay under the assumption that the losses in the relay magnetic system are small and can be neglected, and also under the assumption that the magnetization characteristic of the relay magnetic system is linear.

With this winding arrangement, the currents in windings form magnetic fluxes

Φ_U and Φ_I shifted in space by an angle of 90° and shifted in time by a phase angle of ψ . These flows penetrate the aluminum cylinder and induce Foucault currents in it. As a result of the interaction of currents in the relay windings and Foucault currents in the cylinder, an electromagnetic torque arises, the value of which is determined from the expression

$$M_{em} = k_1 \cdot \Phi_U \cdot \Phi_I \cdot \sin \psi \tag{1.22}$$

where k_1 is the proportionality coefficient, the value of which is determined by the design features of the relay design; ψ is the angle of shift between the magnetic flux vectors Φ_U and Φ_I ; Φ_U is the magnitude of the magnetic flux created by the current in the voltage winding; Φ_I is the value of the magnetic flux generated by the current in the current winding.

The vector diagram of the power direction relay is shown in Fig. 1.18.

The current vector in the current

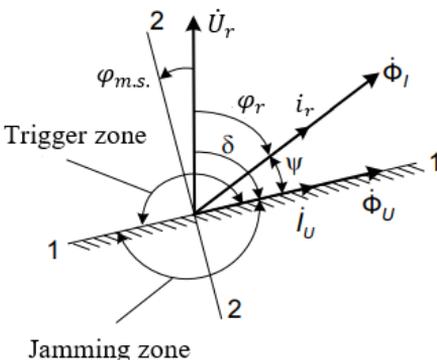


Figure 1.18: Vector diagram induction relay type RBM

winding of the relay \dot{I}_r coincides in phase with the vector of the magnetic flux $\dot{\Phi}_r$ created by this current, because this winding is connected to current source. Instead, the vector current in the relay winding \dot{I}_U , to which applied voltage, lags behind the of the voltage vector \dot{U}_r by an angle δ , whose value is determined by the relay voltage winding resistance. This resistance has active-inductive character, so the current \dot{I}_U lags behind from the voltage by an angle δ . Under the action of this current, a magnetic flux $\dot{\Phi}_U$ is created in the relay.

As can be seen from formula (1.23) at angles between vectors $\dot{\Phi}_U$ $\dot{\Phi}_I$ $\psi = 0^\circ$ and $\psi = 180^\circ$ the magnetic moment is zero. The line 1-1, which corresponds to these angles, is called *the line of zero moments, or the line of change of sign of the moment*. Perpendicular to this line is the line 2-2, which corresponds to the maximum moment, which corresponds to the angle $\psi = 90^\circ$. This line is called *the line of maximum moments*.

The relay contact system is designed so that the relay contacts are closed in the case when the relay current \dot{I}_r and, accordingly, the magnetic flux $\dot{\Phi}_r$ created by this current, outstrips the current \dot{I}_U and, accordingly, the flux $\dot{\Phi}_U$. Therefore, when the angle $\psi > 0$, the relay contacts are closed and the zone that meets this condition is located above the 1-1 line. This zone is called *the relay trip zone*. The zone below this line is called *the relay latching zone*. In this zone, the relay contacts are open. The angle between the vector \dot{U}_r and the line of maximum moments $\varphi_{m.s.}$ is called *the angle of maximum relay sensitivity*.

Substituting in equation (1.22) instead of $\dot{\Phi}_U$ and $\dot{\Phi}_I$ values of the relay voltage U_r and the relay current I_r and expressing the angle ψ in terms of the angles φ_r and $\varphi_{m.s.}$ we obtain formula for calculating the electromagnetic torque of the relay

$$M_{em} = k_2 \cdot U_r \cdot I_r \cdot \sin(90^\circ - (\varphi_r - \varphi_{m.s.})) = k_2 \cdot U_r \cdot I_r \cdot \cos(\varphi_r - \varphi_{m.s.}) \quad (1.23)$$

where k_2 is the proportionality coefficient, the value of which is determined by the design features of the relay design.

1.4.2. Digital devices for relay protection

General characteristics of digital relay protection devices

In recent years, *digital* relay protection devices have been widely used in Ukraine's power systems. Abroad, such devices have been put into operation for more than two decades. Therefore, it is not surprising that foreign companies engaged in the development of digital relay protection and automation devices have a significant advantage over domestic manufacturers of such equipment.

The most well-known foreign companies in the field of digital relay protection and automation are ABB, Siemens, Alstom, General Electric, Schneider, Areva, SEL, NARI, Beckwith, Cooper Power, Orion Italia, VAMP, Woodward, etc. The former USSR is home to such manufacturers as Bresler, Ekra, RELSiS, Kievprylad, Meander, Mehanotronika, Radius Automation, Energomashvin, Cheaz, VNIIR, IMSCOE, and others.

In the literature, digital devices are often referred to as micro-processors. In our opinion, this is not entirely correct. A *microprocessor* is one of the main elements of many relay protection and automation devices. But there are devices that are based on *microcontrollers*. There are more sophisticated relay protection and automation devices that are integrated into a common information network, which is organized by computers with powerful *processors*. Common to all these technical elements is the use of *digital principles of their functioning*. Therefore, it is advisable to call all these devices *digital relay protection devices*.

Compared to traditional electromechanical and semiconductor relay protection devices, digital devices have significant advantages, which makes their use in power systems today

virtually unavoidable. The main ones are:

- generally higher accuracy of reproducing the specified characteristics of the device's functioning. In general, the hardware error of digital protections can reach up to 2%. For example, one of the main parameters of measuring protection devices, the return coefficient, can have a value of 0.99. Achieving such a coefficient value with semiconductor and electromechanical relays requires complex technical solutions. An example of such a relay is the protection against symmetrical overload of the generator stator, which is based on a special RTVK relay. This relay is based on semiconductor elements and allows for a return factor of up to 0.99. However, it is expensive and bulky. The high accuracy of reproducing the characteristics of protections allows you to change some parameters of coordination between the protections of adjacent elements of the electrical network. For example, it is possible to reduce the degree of time selectivity for the maximum current protection of adjacent network elements, which in turn will reduce their operation time and, as a result, the for accident elimination;

- obtaining characteristics of any complexity. This is especially relevant for remote protection, whose measuring elements can have any characteristics and take into account any peculiarities of the modes that may occur in the power system. In addition, changing the shape of the characteristics does not require any additional technical modifications - it changes at the algorithmic level;

- memorizing the mode coordinates when a digital device is tripped. Almost all digital protections memorize the coordinates of the emergency and pre-fault modes, which allows operating personnel to analyze emergency situations in more detail, determine the causes of the accident and, if necessary, refine and change the characteristics of protections and automation;

- the ability to change the device configuration. In the course of network development, it may be necessary to change the characteristics of the protection devices - to change the setpoints, enable or disable certain functions, etc. Such changes do not require any technical costs, as they are made at the program level;

- versatility. This feature of digital devices is more of a concern to developers than to operators. By using a universal processor module, adjusting input and output circuits, and changing the functioning algorithm, we can create various types of protection and automation;

- significantly smaller dimensions and lower consumption of electrical materials. One small digital device can replace a whole group of complex relays based on semiconductors or electromechanical elements. For example, a semiconductor remote protection of the PDE type against interphase short circuits has nine measurable remote bodies, each of which is made as a separate module. In a digital device, the characteristics of all these measuring elements are set at the program level and implemented virtually in the processor;

- The production of electronic components for digital devices based on printed circuit boards is much cheaper than the manufacture of electromechanical relays using high-precision mechanical technologies with a significant amount of manual labor. For example, the Japanese SM402-M/L machine assembles up to 60,000 components per hour on a board. This process is fully automated;

- self-diagnostic capability. The functioning algorithms of modern digital protection devices, especially complex ones, necessarily provide for a self-diagnostic function that periodically monitors the health of all components of the device - input circuits, output circuits, digital elements and, in the event of a malfunction, the device is blocked with automatic notification of the personnel on duty. Traditional relay protection devices, especially electromechanical ones, do not have this capability, and there are many cases in operation when

these devices did not work during an accident and after analysis it turned out that they were faulty, which the operating personnel did not even know about;

- lower power consumption for operation, which significantly reduces the power of the operating current power sources;

- less load on primary current and voltage measuring transformers. The power consumption of modern digital relay protection devices is up to 0.5 VA. This makes it possible to connect a larger number of relay protection and automation devices to primary current and voltage measuring transformers, ensuring that the current and voltage transformers operate in a given accuracy class;

- ease of operation. During scheduled maintenance there is no need to check the characteristics of individual components, as in traditional relay protection devices, because they are not physically present, their characteristics are implemented in software. Therefore, only the general characteristics of functioning are checked. This significantly reduces the scope of work and, accordingly, the time required to test the devices.

The operation of digital relay devices in domestic and foreign power systems has revealed their *negative features*. They primarily include:

- Reduced reliability of relay protection devices by reducing the time between failures of individual modules of digital devices and their components. These include, first of all, failures of processors, ADCs, power supplies, etc. Studies have shown that the reliability of digital relay protection devices is currently somewhat lower than that of electromechanical relay protection devices;

- a significant concentration of protective and control functions on a single digital terminal. For example, ALSTOM's *R3IPT* digital transformer protection performs the functions of differential protection, overcurrent protection

- external overcurrent protection, overload protection, ground fault protection, recloser, change of trip settings depending on the system configuration, sending information to higher control levels via a computer network, control of external devices, etc. With such an organization of protection in the event of a digital terminal fault, the transformer practically loses all main (except for gas protection) and backup protection, as well as some automation and control functions. Only long-distance redundancy remains to protect the transformer. For high-power transformers, due to the long operating times of the backup protections, such redundancy is generally unacceptable;

- Complication of the operation of protection devices due to the presence of digital protection devices of different manufacturers in power systems, each of which has its own design features, different information exchange protocols, different functioning algorithms and, as a result, requires different information for operation. This requires not only high qualification of the personnel in the field of protection, but also high qualification of work with computers, understanding of the functioning of complex information systems, skills of debugging and testing of complex systems, such as modern digital terminals;

- use of functions in digital terminals that are not typical for relay stations, for example, monitoring of electrical equipment;

- the use of "freely programmable logic" in the latest modifications of digital protection devices, i.e., changing the algorithms of protection functioning depending on changes in the modes of the power system or changes in its configuration - "intelligent logic". This can lead to incorrect operation of relay protection devices in general;

- poor protection of digital relay protection devices against electromagnetic

interference. For example, an electromagnetic pulse resulting from a low-power nuclear explosion can disable all digital devices at power plants and substations, including relay protection devices;

- the possibility of hackers disabling digital relay devices through common information networks, which are weakly protected in the energy sector;
- Lack of unified national standards for the design of digital signaling devices, their software, debugging methods and operating conditions.

Block diagram of digital protection

Regardless of the purpose of digital relay protection devices - current, remote, etc. - they have a similar structure, as shown in Fig. 1.32.

The main element of digital protection is the *processor*, which implements the algorithm for a particular protection. Depending on the purpose of the device and the manufacturer, one or more processors can be used.

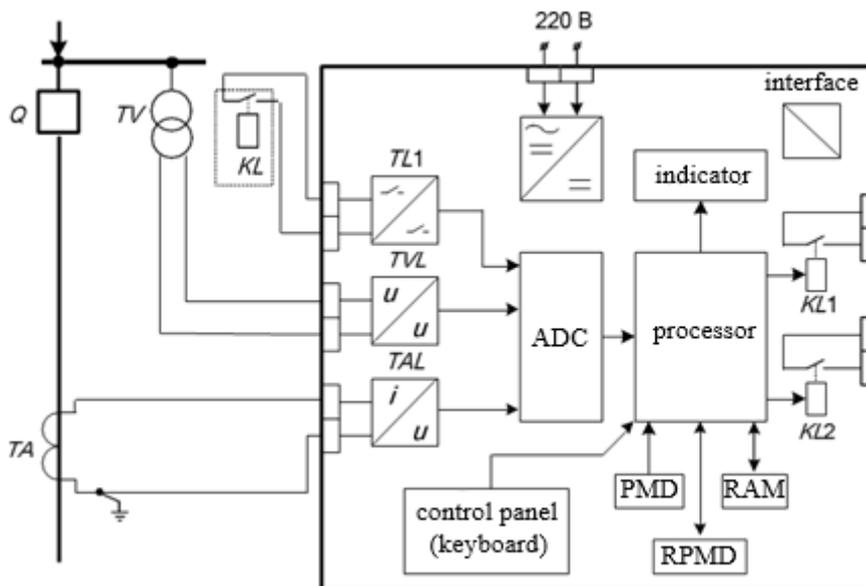


Fig. 1.32. Block diagram of digital protection: TA - current transformer; TV - voltage transformer; Q - switch; KL - output relay of another device; TL1 - binary signal converter; TVL, TAL - input converters of analog signals, respectively, of voltages and currents; ADC - analog-to-digital converter; PMD is a permanent memory device; RAM is an operational memory device; RPMD - reprogrammable memory device; KL1, KL2 - output relays

For example, ABB prefers multiprocessor systems, in which each processor performs specific tasks of the algorithm and these processors work in parallel. This ensures the required speed and accuracy. Other companies use single-processor systems, which require more powerful processors to achieve the required performance. Given the harsh operating conditions of relay protection devices (at many substations, these devices operate in unheated rooms), special processors of the so-called industrial design are used, which can operate at ambient temperatures ranging from -30°C to $+50^{\circ}\text{C}$, and relative humidity up to 80%.

The processor communicates with the object of protection through *input-output* circuits. The input information is usually *analog signals* such as currents, voltages, temperature, etc. and *binary signals* such as the position of switchgear, the state of output relays of other relay protection and automation devices, etc. The output signals of digital protections, like other protections, are traditionally *binary signals*. These signals are sent after the digital protection has tripped to the control and signaling circuits of the controlled objects of the power system.

Conversion of analog signals

The monitored voltages and currents are time-continuous *analog signals* and can take on any values within the limits determined by the operating mode of the electrical network. Digital protection devices do not work with analog signals, but with discrete (digital) signals, which, unlike analog signals, can take on only a finite set of values for specific moments in time. The conversion of analog signals into discrete signals is called *sampling* or *quantization*. The device that performs this conversion (Figure 1.32) is called *an analog-to-digital converter (ADC)*.

The analog signals monitored by the protection devices, i.e. the current from the current transformer *TA* and the voltage from the voltage transformer *TV*, are preliminarily connected to special *input converters (TAL and TVL in the diagram)*. These converters are designed for galvanic isolation of the device from external circuits (current transformers and voltage transformers), as well as for obtaining a normalized output voltage with its subsequent conversion by the ADC into digital signals (Fig. 1.32).

In Fig. 1.33 shows the schematic diagrams of the input current and voltage converters (Fig. 1.33, a and Fig. 1.33, b, respectively).

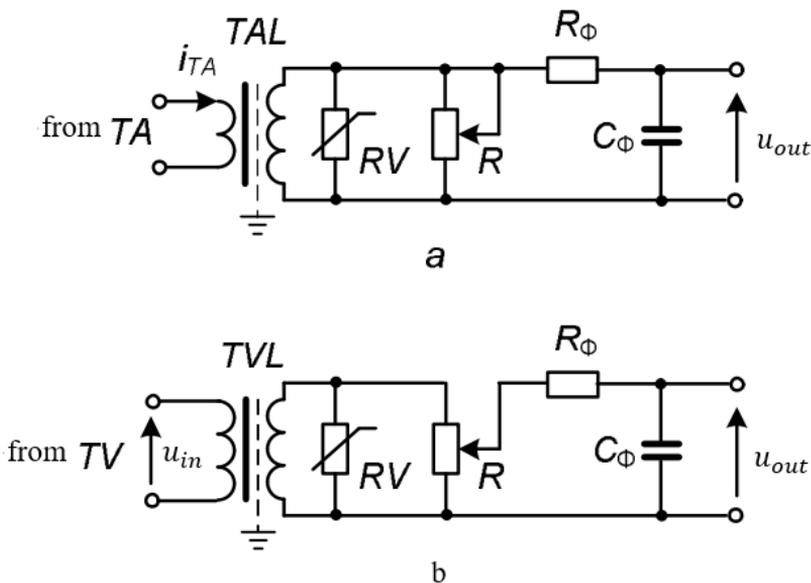


Fig. 1.33. Schematic diagrams of input converters: a - current; b - voltage

The signals from the current transformers *TA* and voltage transformers *TV* are fed to the primary windings of the intermediate transformers *TAL* and *TVL*. On the secondary windings of

these transformers, the current and voltage are converted into voltages proportional to the current and voltage, respectively. In order for the pulse signals that may arise in the secondary circuits of current and voltage transformers do not enter the electronic part of the digital device and do not damage it, a grounded shield is installed between the primary and secondary windings of the *TAL* and *TVL* intermediate transformers. To protect the electronic units of a digital device from overvoltage, *RV* varistors are installed in parallel to the secondary windings of the *TAL* and *TVL* intermediate transformers. In some circuits, Zener diodes are used for protection. To match the secondary voltage at the output of the intermediate transformers with the input signals of the ADC device, variable resistances R are used. For proper operation of the ADC, it is necessary to prevent the high-frequency spectrum of the signal from entering it. Therefore, use a high-pass filter based on the resistance R_f and capacitance C_f . It should be noted that during the implementation of the protection algorithm, digital signal filtering is additionally performed (Fig. 1.34). Output. the signals u_{out} from the input converters *TAL* and *TVL* are sent to the ADC input. For An analog signal is converted into a digital signal using an ADC.

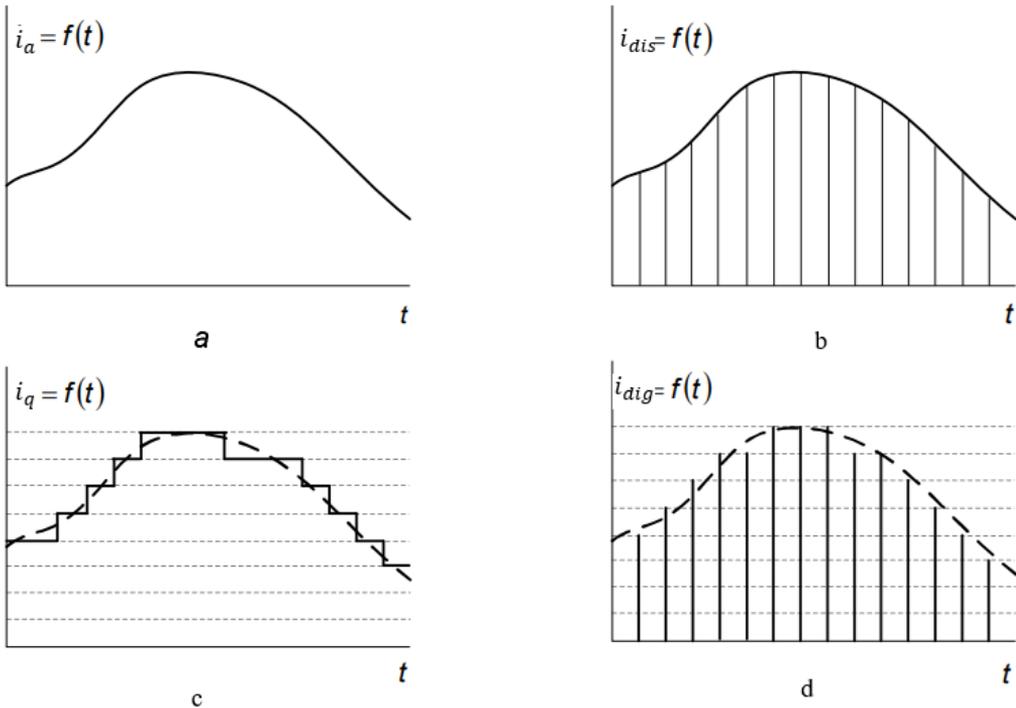


Fig. 1.34. Signals: a - analog, b - discrete, c - quantized, d - digital

The transition from an analog continuous signal to a discrete signal is accompanied by some loss of information. This is due to the fact that the ADC converts the input analog signal into a discrete signal after some time intervals Δt , and between them the value of the input signal is not controlled. By. The smaller this time interval, the more accurately the analog signal is reproduced in digital form. The main characteristics of the ADC are its *bit* depth and the *time sampling interval of the signal*. Time sampling of a signal is also called is called the sample rate, which is associated with the time discretization Δt by the expression

$$f_s = \frac{1}{\Delta t} \tag{1.24}$$

In Fig. 1.34 shows an analog signal (Fig. 1.34, a) and its conversion to digital (Fig. 1.34, d). The time sampling of an analog signal is called sampling. The sampled signal is shown in Fig. 1.34, b. Discretization of an analog signal by value is called quantization. The quantized analog signal is shown in Fig. 1.34, c.

For a periodic signal with period T , the number of samples per period can be determined by a known frequency

$$N = f_s \cdot T \tag{1.25}$$

For a periodic signal, there is a relationship between the upper frequency of the signal being quantized and the number of samples per period. Scientists C. Shannon and V. Kotelnikov proved back in the 1930s that to accurately reproduce a primary periodic signal from its discrete image, it is necessary that the frequency samples f_s should be at least twice the maximum frequency of the input periodic signal f_{max}

$$f_s \geq 2 \cdot f_{max} \tag{1.26}$$

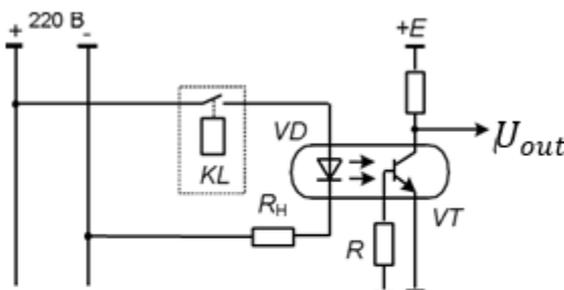
This corresponds to the maximum number of samples for the period

$$N_{max} \geq 2 \cdot f_{max} \cdot T \tag{1.27}$$

According to the given maximum value of the number of samples, N_{max} must be of the input analog signal, remove all signals with a frequency higher than f_{max} . Otherwise, after the inverse conversion of the signal, a signal of lower frequency will appear in it, which will distort the real input signal. Therefore, a high-pass filter with a bandwidth not exceeding than the frequency f_s In the diagram of Fig. 1.33 this filter is realized on the basis of RC elements R_F and C_F .

Modern digital relay protection devices use ADCs with a sampling rate of up to 2000 Hz, which corresponds to 40 samples per period of industrial frequency of 50 Hz. Devices with this sampling rate allow you to monitor the input signal with a frequency of up to 1000 Hz. This corresponds to 20 harmonics at a fundamental frequency of 50 Hz.

U_{out}
Input binary signals



In addition to analog signals, it is also necessary to have information about *binary signals* for the protection to work. These are signals about the operation of intermediate and output relays of other relay protection and automation devices, the position of switchgear, etc. In practice, these signals are also called *discrete signals*.

Figure 1.35. Scheme of binary signal input

In order not to confuse these signals with the discrete signals obtained after quantization of analog signals by an ADC device, they will be called *binary* signals. For example, in order to

For the implementation of the recloser, recloser function, it is necessary to have information about the state of the circuit breaker affected by this protection; to accelerate the action of this protection by a command from busbar protection, it is necessary to have information from the busbar protection output circuits, etc. In Fig. 1.32 binary signal from an external device (conventionally shown as an external relay *KL*)

is fed to the input binary signal converter *TLI*.

In modern digital devices, binary signals from external devices are fed through *optocouplers*. An optocoupler is an electronic key in the form of a transistor *VT* (Fig. 1.35), which is controlled by an LED *VD*. When current flows through the LED (current begins to flow through the LED after the *KL* contact closes), the latter sends a light signal to the photobase of the transistor *VT*, which is triggered (opened) and the signal $U_{out} = 0$ appears at its output, which signals a change in the state of the binary input. The main advantage of optocouplers compared to relay repeaters is a significantly shorter response time. The response time of such a converter is negligible and amounts to fractions of a microsecond.

To organize the flow of current through the LED *VD* after the external contact *KL* is triggered, an external source of operating current is used, usually with a voltage of 220 V (occasionally 110 V). This is a disadvantage of this scheme. This is because even after the external device where the *KL* relay is installed has been switched off from the operating current, the contacts of this relay are still connected to the operating circuits of the device that implements this binary signal input scheme. This is dangerous for the operating personnel. Therefore, in order to prevent electric shock to the operating personnel during scheduled maintenance, a source of operating current with a reduced voltage, for example, a 24 V source (Fig. 1.36), which is implemented on the *UVZ* inverter converter, is used to initialize the binary inputs on other devices that communicate with this device.

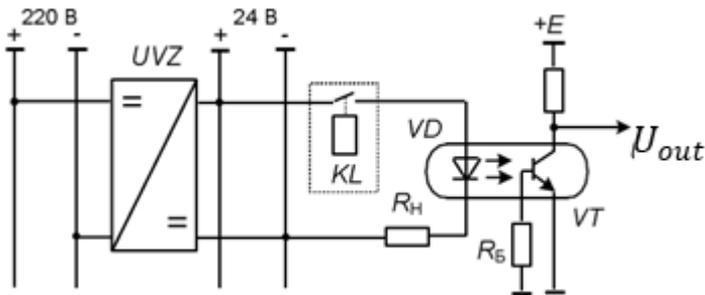


Fig. 1.36. Scheme of binary signal input at low voltage

But this scheme has two significant drawbacks. First, it is less reliable than the scheme shown in Fig. 1.35, due to the presence of an inverter converter *UVZ*. Technically, this is a rather complicated semiconductor element that preliminarily converts a direct current of 220 V into an alternating voltage of increased frequency, for example, 400 Hz. After that, this alternating voltage is converted into a constant voltage of 24 V with appropriate stabilization. The technical realization of such a complex conversion reduces the reliability of the converter and the circuit as a

whole. As the experience of operating circuits with such converters, for example, panels of the PDE series, SGE, has shown, the most unreliable element of such circuits is power supplies that are implemented on the basis of inverter converters.

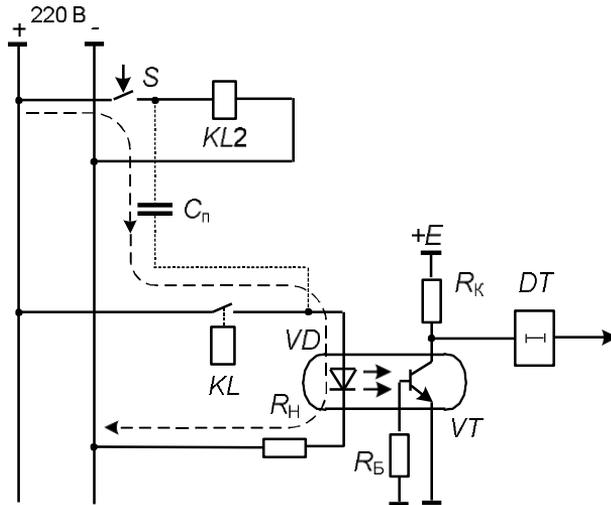


Figure 1.37. False operation of the binary signal input circuit

In addition, the use of undervoltage in the circuits where the KL relay contacts are switched (Fig. 1.36) can lead to an open circuit by the KL relay contacts after its operation. This is explained as follows. Over time, under the influence of the external environment, the surfaces of these contacts oxidize, their resistance increases, and after they close, the current in the circuit through the insulating oxidized layer of contact surfaces from the source of undervoltage will be too low to trigger the circuit. In the case of applying a voltage of 220 V, after the oxidized contacts are closed, the oxidized layer will break through under the influence of this increased voltage and a current sufficient to trigger the binary input signal control circuit will flow in the circuit (Fig. 1.35).

When implementing a binary signal input circuit based on an optocoupler that consumes a small current (up to 5 mA), it is worth remembering that such a circuit may be falsely triggered due to parasitic capacitances (Fig. 1.37) that exist between the cables that communicate between individual devices.

For example, relay $KL2$ is connected to another device with a long cable. Similarly, a long cable connects the relay KL , the state of the contacts of which is controlled by the optocoupler VD (Fig. 1.37). These cables are laid side by side in the same channel. Therefore, there is an electrical connection between them due to the parasitic capacitance C_p (Fig. 1.37 shows the resulting capacitance between the two cables for simplicity, in fact, this capacitance is distributed along the common section between them). During operation of the key S in the transient due to the parasitic capacitance C_p in the circuit optocoupler, a pulse signal appears that can cause the optocoupler to trip. This operation will be false, because according to the scheme, the

optocoupler VD should only monitor the state of the relay contact KL and not be triggered by interference. However, this signal due to the parasitic capacitance C_p will occur only during transient associated with the switching of the key S . Therefore, if you put a time delay element DT of the order of 3 ms at the output of the circuit, you can debug this circuit from malfunctioning.

Output binary signals

The output binary signals in digital relays are organized by means of *intermediate electromechanical relays of the electromagnetic type*. Compared to electronic (thyristor or transistor switches), electromechanical relays are more reliable in operation - they have virtually no false alarms. In addition, the contact system of electromechanical intermediate relays provides a visible break in the switched circuit. However, the use of electromechanical intermediate relays has a significant drawback - they have a longer response time compared to electronic keys. Thus, the response time of modern intermediate electromechanical relays reaches up to 5 ms.

Usually, two types of relays are used in the output circuits of digital relays - more powerful ones for switching switch control circuits and less powerful ones for switching signaling circuits. More powerful relays allow switching circuits with current of 5-30 A and switching circuits with a current of up to 0.2 A in 220 V DC circuits.

Recently, reliable electronic keys based on transistors and thyristors have been developed abroad that can be used to generate binary output signals.

In Fig. 1.32 the output circuits of the digital protection device are shown as intermediate electromechanical relays $KL1$ and $KL2$.

The structure of the digital part of the device

The digital signals from the ADC are sent to the processor (Fig. 1.26), where they are processed according to a certain algorithm implemented in the form of a program. The program itself is stored in a permanent storage device (ROM) (Read Only Memory). This is a reprogrammable permanent storage device with non-volatile memory, which means that the information in it is stored even when the device is disconnected from external power.

A random access memory (RAM) is used to store the results of intermediate calculations. RAM has high performance, but does not retain information after the external power is turned off.

The protection trip settings that need to be changed during operation are stored in a permanent reprogrammable storage device (ROM) that allows multiple changes of settings. In this case, the information about the settings is saved after the external power supply is disconnected.

On the front panel of the device there is a *control panel (keyboard)*, which can be used to set the required device mode and change the trigger settings.

The device results and setpoints are displayed on the liquid crystal *display*, which is also located on the front panel of the device.

1.5. Structural and functional diagram of the relay protection device

The general structural and functional diagram of the relay protection device is shown in Fig. 1.38. It does not depend on the principle of protection operation and on the element base on which it is based.

The relay protection device must continuously monitor *the object of protection* - generator,

transformer, line, etc. For this purpose, it continuously measures the coordinates of the object's mode. These are usually instantaneous values of voltages and currents. The mode coordinates are *transmitted* to the measuring elements of the protection through *primary measuring transducers* (mainly current transformers and voltage transformers). Primary measuring transducers are designed to isolate the relay protection device from the primary high-voltage circuits and to obtain a standard scale of rated secondary voltages and currents - for different primary rated voltages and currents, secondary rated voltages (100 V) and currents (5 A or 1 A) are obtained.

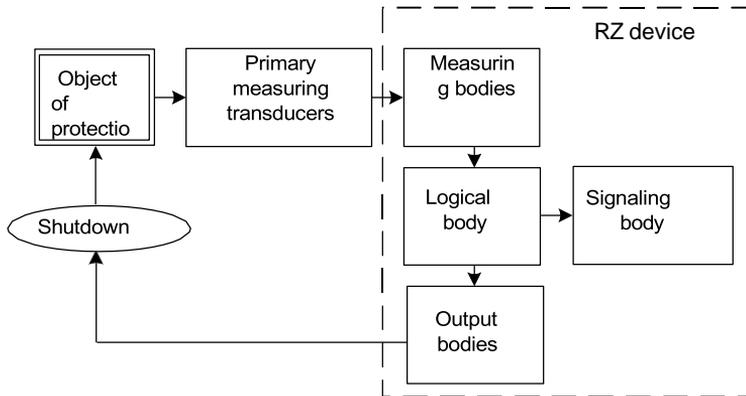


Fig. 1.38. Block diagram of the relay protection device

Measuring elements of protection can be current relays that respond to changes in current, voltage relays that respond to changes in voltage, and resistance relays that respond to changes in complex resistance, i.e., a complex value that is proportional to the ratio of the voltage and current complexes supplied to the relay. When the values controlled by these relays reach their trip settings, the measuring elements are triggered - a signal appears at their outputs. This signal is sent to the *logic protection body*.

The protection algorithm is implemented in the logic body of the relay protection device: additional trip conditions are checked, necessary time delays are performed, etc. If all the conditions for protection operation are met, a signal is generated at the output of the logic body. This signal is sent to the *output protection body*, from which it directly acts to disconnect the object from the power supply.

At the same time, the output signal from the logic body acts to trigger the signaling body, which is designed to signal the operating personnel about the operation of this relay protection device. A characteristic feature of this body is that it remains in the tripped state after the damaged object is disconnected from the power supply, when all other bodies of the relay protection device have returned to their original state. The signaling body can be returned to its original state only manually.

1.6. Requirements for relay protection devices

The main requirements for the operation of relay protection devices are: *selectivity, sensitivity, speed, reliability*.

Selectivity is the ability of a relay protection device to respond to a fault within the power system facility it is designed to protect.

There are *absolute* and *relative selectivity*.

If a protection reacts to damage only to the element it is designed to protect, then this protection is said to have *absolute selectivity*. For example, protection A1 (Fig. 1.39) reacts to damage only in line L1, so it is a protection with absolute selectivity.

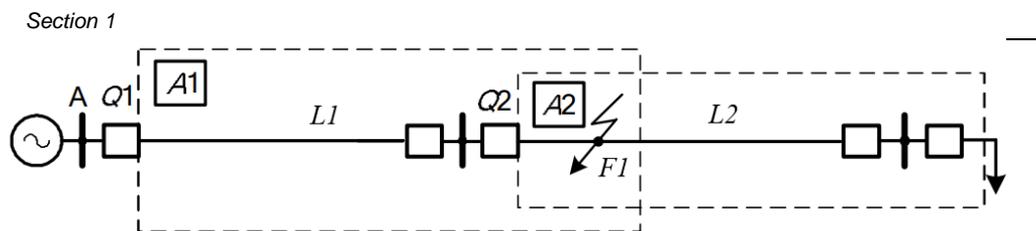


Figure 1.39. Non-selective protection operation

If the protection, in addition to faults on the element it is designed to protect, also responds to faults in an adjacent element, then this protection has *relative selectivity*. An example of protection with relative selectivity is protection A2 (Fig. 1.39), which is designed to protect line L1. In addition to faults on the L1 line, it can also respond to faults in the adjacent L2 line, i.e., perform long-distance redundancy functions.

However, in some cases, the protection is deliberately made non-selective. However, non-selective protection is corrected by special automation devices - *automatic reclosing* devices (ARDs). (ARDs are activated after tripping of the reclosing device and after a certain period of time act to turn on the circuit breaker that was tripped by the relay protection device. When the short-circuit was unstable and it has successfully self-limited (after the circuit breaker has been switched off by the recloser), the network operation will resume. Non-selective protection operation is used for cases when during a fault at the end of the protection zone with a time delay, for example, for line L1 (Fig. 1.39), the residual voltage on the busbars of substation A during a fault at the end of the line is insufficient for stable operation of the asynchronous and synchronous load ($U_{za1} < 0,5 \cdot U_{(nom)}$). Therefore, the line fault must be tripped with the minimum possible time delay. For this purpose, the protection A1 is made high-speed - the speed of protection A1 is commensurate with the speed of protection A2 of line L2, and the area of protection A1 is partially is superimposed on the protection area of A2. Therefore, after the occurrence of a short circuit at the beginning of line L2 (point F1), non-selective operation of protection A1 is possible - it will act to close the circuit breaker Q1, i.e. the damaged line L2 and the undamaged line L1 are disconnected from the power supply.

After that, the non-selective operation of protection A1 is corrected by the operation of the recloser. This happens as follows. After the occurrence of a short circuit at point F1, the high-speed protections A1 and A2 are tripped, which act to close the circuit breakers Q1 and Q2, respectively. After that, the recloser of the line L1 is tripped and opens the circuit breaker Q1. If the fault is not on this line, the A1 protection does not trip, and the line remains in operation. After that, the recloser of line L2 trips, which has a longer response time than the recloser of line L1. The recloser acts to close the circuit breaker Q2. During the operation of the recloser, the non-selective protection A1 is disabled. If the fault was unstable, the system will resume normal operation. Otherwise, protection A2 will operate again and will trip line L2. Thus, the selective operation of the protections will be ensured in general.

Sensitivity. The protection of a power grid element must respond to faults in it in all its possible operating modes, i.e. be sensitive to faults both in the maximum mode, which is characterized by the maximum level of overcurrents, and in the minimum mode, which is characterized by the lowest level of overcurrents.

The protection sensitivity is determined by the sensitivity factor. The sensitivity of the protection is checked for the minimum mode, when the level of fault currents is minimal. If the protection is sensitive to faults in the minimum mode, it will be even more sensitive to faults in all other modes when the level of fault currents is higher.

Depending on the type of protection, this coefficient is determined differently. For example, for maximum current protection (protection that responds to an increase in current), the sensitivity of the protection, or rather the sensitivity of its measuring element, is defined as the ratio of the current in the relay during the fault at the end of the protection zone in the minimum mode to the tripping current of the measuring element (relay setpoint). This ratio is written in the form

$$k_s = \frac{I_{s.s.c.min}}{I_{s.r.}} \quad (1.28)$$

For example, for relay protection A1 (Fig. 1.39), which is designed to protect line L1, *the* design point is the end of line L1. For protection A2, *the* area of operation of which covers line L1 and line L2, the design points of short-circuit are the end of line L1 (protection performs the function of short-term redundancy) and the end of line L2 (protection performs the function of long-term redundancy).

For minimum-action protection that responds to a decrease in the controlled value, the sensitivity coefficient is determined somewhat differently. For example, for a remote protection whose measuring element responds to a change in total resistance, the sensitivity is defined as

$$k_s = \frac{Z_{s.r.}}{Z_l} \quad (1.29)$$

where $Z_{s.r.}$ is the trip setpoint of the measured protection device; Z_l is the resistance from the place setting the protection to the end of the zone covered by this protection.

According to the PUE, the value of the sensitivity factor is regulated as follows. For basic protection, depending on the type of protection, the sensitivity factor should be $k_s \geq 2$ or $k_s \geq 1,5$. For backup protections, the value of the sensitivity factor should be somewhat smaller and should be $k_s \geq 1,2$, $k_s \geq 1,25$.

Reliability. This is the ability of the relay device to perform its functions while maintaining its operational characteristics within the specified limits during the service life guaranteed by the manufacturer.

Functional characteristics of relay protection devices may change during operation, as a result of which RP devices may *not trip* in the event of faults in the protection area, *over-trip* in the event of faults on adjacent elements, or *trip falsely* in the absence of faults in the protection area.

The reliability of relay protection devices depends on many factors. The main ones are a reliable element base of relay protection devices, high-quality installation of equipment and quality of operation.

To check the functional characteristics of relay protection devices during operation, regular maintenance performed. They are carried out at certain intervals during the operation of the

protection devices. This is especially true for relay protection devices based on electromechanical and semiconductor technology. This is explained by the fact that electromechanical protection devices do not have *self-diagnostics* at all. *Self-diagnostics is the ability of a relay protection device to periodically check its main characteristics on its own and, in case of detection of unacceptable deviations, to report this to the operating personnel, and the relay protection device itself is taken out of operation.* As for the protection devices made using semiconductor elements, usually only complex complexes have systems for automated verification of the main functional characteristics of protection. These basic characteristics are checked by the maintenance personnel without disconnecting the power equipment from the network. Modern digital protection devices usually have automatic self-diagnostics, i.e., with a given a special device test program is launched at intervals of up to several seconds to check the device's health. If a device malfunction is detected, it is automatically taken out of operation and the operating personnel are notified of the malfunction.

Speed. Obviously, the faster the damaged element is disconnected from the power supply, the better for the operation of the power system - the area of possible damage to equipment by overcurrents, insulation destruction, the of disruption of technological processes at consumers, the likelihood of disruption of synchronous operation of generators, synchronous compensators, synchronous motors, braking of induction motors, etc.

The fault trip time is determined by the protection trip time and the circuit breaker trip time

$$t_{off} = t_{o.r.} + t_Q \quad (1.30)$$

where $t_{o.r.}$ is the operating time of the relay protection; t_Q is the tripping time of the circuit breaker.

Time of protection $t_{o.r.}$ define as a time interval from the moment the occurrence of a fault before the output contacts of the protection relay trip. The relay protection device cannot trip immediately after a fault occurs. The protection must analyze the mode and recognize the fault mode from all other modes. In addition, there is an inherent response time of the measuring and output protection elements.

The main protections are tried to operate with the shortest possible response time. Backup protection has a delayed response time, taking into account the condition of ensuring selectivity of operation - the main protection must first trip and only when it fails should the backup protection operate, i.e. the backup protection "waits" for the results of the main protection.

The operating time of the circuit breaker t_Q is defined as the time interval from the moment of the signal to the circuit breaker actuator until the arc in the arc suppression chamber is extinguished - until the current in the power circuit is cut off.

The concept of performance in quantitative terms is different for different networks. For example, for power supply systems, high-performance protections are those for which $t_{o.r.} \leq 0.1$ s. For backbone networks (220 kV and above), performance requirements are more stringent - The fastest are protections, which have tripping time $t_{o.r.} \leq 0.02$ s (20 ms). Modern digital protections have even shorter response times. For example, the response time of the differential busbar protection of the ABB company is $t_{o.r.} = 0.005$ s (5 ms).

? Questions for self-examination

1. *What devices operate in the event of a fault in the power ?*
2. *What is the protection area?*
3. *Why do you back up the operation of protectors?*
4. *What is the hysteresis characteristic of a relay?*
5. *What is the relay return factor?*
6. *What are the main structural elements of any relay protection device?*
7. *What is the selectivity of security? What are the types of selectivity?*
8. *What characterizes the sensitivity of protection?*
9. *What factors affect the performance of security systems?*

Chapter 2 PROTECTION BY FUSES

1.5 Main characteristics of fuses

A fuse is an electrical and thermal device used to protect electrical equipment. The protection is provided by burning out the fuse insert under the influence of current and, as a result, breaking the electrical circuit through which the electrical equipment is mainly powered.

Fuses are mainly used to protect electrical equipment in urban and rural power grids, at power plants, substations, and industrial enterprises in electrical installations with voltages up to 1000 V. To a lesser extent, fuses are installed to protect electrical equipment in networks with voltages of 6, 10, 35, and 110 kV.

The advantage of fuses compared to other protective elements is their low cost, simplicity of execution, ease of operation. In addition, in some cases, the fuse provides current-limiting properties - during a short circuit, the fuse insert manages to burn out even before the current reaches its maximum value. This effect is illustrated by the graph shown in Fig. 2.1. After the occurrence of a short circuit at the point of short circuit $t_{s.c.}$, the current in the circuit where the fuse is located will begin to increase sharply and upon reaching point A, the fuse insert will burn out - the current will change according to curve 1 instead of changing according to curve 2.

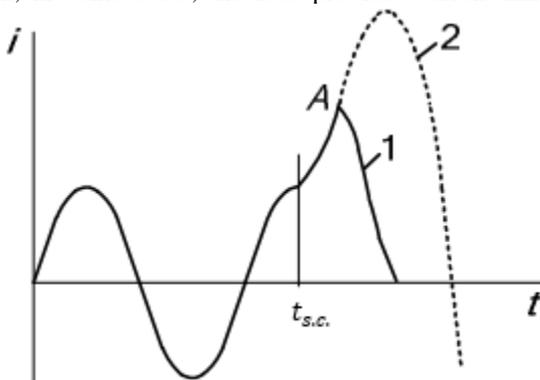


Fig. 2.1. Current limiting effect of a fuse

However, fuses have some drawbacks, the main ones being the following:



Fig. 2.2. Conditional and positional designation of the fuse

- one-time action - after tripping (fuse burnout), the fuse must be replaced manually. This makes it impossible to implement automation devices, such as automatic reclosing, in networks with fuses 50%;
- change in the protective characteristics of fuses due to their aging;
- occurrence of incomplete phase modes. This occurs due to fuses not operating in all three phases;
- insufficient sensitivity to overload currents

The conventional and positional designation of the fuse in the diagram is shown in Fig. 2.2.

Depending on how the arc is extinguished, fuses are divided into two categories:

- *Fuses with a filler.* The filler is usually quartz sand. Such fuses are called quartz. In them, the arc is extinguished between grains of dry quartz sand. The fuse inserts of these fuses do not age over time because they are kept in a sealed porcelain housing surrounded by dry, clean quartz sand;

- fuses with *tubes made of gas-generating material*, for example, vinyl. In such fuses,

the arc is extinguished by compressed gases or by longitudinal blowing, which occurs due to gases released from the gas-generating material by the high temperature of the arc plasma.

Fuses are characterized by the following nominal parameters:

- is the rated voltage of the fuse;
- is the rated current of the fuse;
- rated current of the fuse insert;
- is the maximum current that the fuse can trip;
- protective characteristic of the fuse.

The *rated voltage of a fuse* $U_{fuse\ max}$ is the voltage at which it can to operate for a long time in an electrical installation. The rated voltage of the fuse determines its design and the length of the fuse insert. The actual value of the mains voltage should not exceed the rated voltage of the fuse by more than 10%. Fuses can operate in the network with a voltage less than the rated voltage, but in this case, its main characteristics change.

The *current rating of a fuse* is the maximum current that can flow through the fuse for a long time without causing the fuse components to overheat. This current corresponds to the maximum value of the fuse current that can be installed in the fuse.

The *maximum current that can be cut off by the fuse* $I_{fuse\ max}$ is the maximum value of the periodic component of the current at which the fuse breaks the electrical circuit due to the burnout the fuse, without any damage to its structural elements.

The *current rating* of a fuse insert is the maximum current that can flow through the fuse insert for a long time without causing it to burn out. It is determined by the permissible heating temperature of the fuse insert. As the load current flows through the fuse, the fuse heats up. The heating temperature increases until the heat generated by the fuse is completely released to the environment. The maximum temperature is the temperature at which the fuse does not burn out and determines the rated current of the fuse.

In addition to the rated current of the fuse, there is a so-called *test current* (also called limit current in the literature). This is the minimum current that flows through the fuse and causes the fuse to burn out in one hour.

The *protective characteristic of a fuse* is the dependence of the fuse's tripping time (burnout of its fuse insert) on the amount of current flowing through the fuse. Usually, the protective characteristics of a fuse are plotted on a logarithmic scale to reduce the size of the figure. For example, in Fig. 2.3, b shows the protective characteristics of PN-2 fuse.

1.6 Selection of fuses

The conditions for selecting fuses depend on the type of apparatus they are to protect - line, transformer, motor - and on the type of fault: overcurrent only or both overcurrent and overload. Fuses are selected based on the following conditions. The *fuse* itself and its *fuse insert* are selected.

Two selection conditions are common to all fuses. *These are the rated voltage* of the fuse and the *maximum overcurrent* that it can trip without self-damage.

The rated voltage of the fuse must match the mains voltage

$$U_{fuse.nom} = U_{mains} \quad (2.1)$$

where $U_{fuse.nom}$ is the nominal voltage of the fuse; U_{mains} is the mains voltage, where a fuse is installed.

Most fuses can operate in a network where the voltage is less than the fuse's rated voltage, but in this case, the basic characteristics of the fuse change.

The maximum current that the fuse can disconnect must be greater than the maximum

current during the mains fault

$$I_{fuse.max} \geq I_{s.c.max} \quad (2.2)$$

where $I_{fuse.max}$ is the maximum current that can trip the fuse; $I_{s.c.max}$ is the maximum short-circuit current that can be present in the network.

Let's take a closer look at the conditions for choosing a fuse insert for *line protection*.

When the line is protected only against, the setting is selected provided that the required sensitivity during short-circuits at the end of the protected line is ensured

$$I_{set.nom} \leq \frac{I_{s.c.min}}{k_s} \quad (2.3)$$

where $I_{s.c.min}$ is the minimum current during fault at the end of the line; k_s is the sensitivity factor. The value of the sensitivity coefficient is determined by the neutral mode of the network and the operating conditions of the line. In networks with a grounded neutral, the sensitivity is checked under is the time of single-phase fault at the end of the line and $k_s = 3$. In networks with an isolated neutral sensitivity is tested during two-phase fault at the end of the line and $k_s = 3$. If the line is operated in an explosive environment, then $k_s = 4$.

In addition to short-circuit protection, some lines must also be protected against overloads. According to the Electrical Installation Rules (EIR), such networks include:

- all networks made with openly laid unprotected insulated conductors with combustible insulation inside any premises;
- all lighting networks in residential premises, public buildings, commercial premises, office and household premises of industrial enterprises, fire-hazardous industrial premises, all networks for powering household and portable electrical appliances;
- all power networks in industrial enterprises, residential and public buildings, if the process conditions may cause long-term overloads of conductors and cables;
- networks of all types that are operated in explosive areas and in explosive outdoor installations.

To protect lines from overloads, the rated current of the fuse is selected from the following conditions:

- failure to operate in the maximum operating mode

$$I_{set.nom} \geq k_{with} \cdot I_{oper.max} \quad (2.4)$$

where k_{with} is the drainage coefficient, taken as 1.1-1.25; $I_{oper.max}$ - maximum operating current flowing through the line;

- malfunction during short-term overload, which can occur during start-up or self-start-up of induction motors with a short-circuited rotor, technological overloads of mechanisms, etc.

$$I_{set.nom} \geq \frac{I_{over}}{k_{over}} \quad (2.6)$$

where I_{over} is current short-term overload current; k_{over} is coefficient overload.

Short-term overload current I_{over} is determined by the launch or self-implementation of the start-up of asynchronous motors with a short-circuited rotor, technological overloads of mechanisms, etc. However, this current flows for a short period of 5-10 seconds. Therefore, the rated current of the fuse can be selected less than the short-term overload current I_{over} . Current

reduction of the fusible link is determined by the conditions of starting or self-starting, which in turn are determined by the value of the overload coefficient k_{over} . From the operating experience for of the overload coefficient k_{per} set the following values: $k_{over} = 1.6 - 2$ – for easy start conditions, when engine starts are rare and each start is a single event lasts for less than 10 s; $k_{over} = 2.5$ - for hard start conditions, for which is characterized by frequent motor starts with a significant motor acceleration time of more than 10 seconds. If a fuse insert made of fusible material is used for heavy starts, it is recommended to take a value of $k_{over} = 3.75$.

The overload current I_{over} is selected by the greater of the two conditions:

- conditions for starting the most powerful engine and normal operation of all other consumers

$$I_{over} = I_{st.max} + k_c \cdot \sum_{i=1}^{n-1} I_{oper.max} \quad (2.7)$$

where $I_{st.max}$ is starting current of the most powerful motor; $\sum_{i=1}^{n-1} I_{oper.max}$ is the sum of the maximum operating currents of all consumers except the motor with the highest starting current; k_c – demand coefficient, $k_c < 1$;

- conditions for engine self-starting

$$I_{over} = \sum_{i=1}^m I_{st} \quad (2.8)$$

where $\sum_{i=1}^m I_{st}$ is the sum of the currents of m motors participating in the self-start mode.

? *Questions for self-examination*

1. *What is the purpose of the fuse.*
2. *Give the fuse symbol and position designation.*
3. *What are the main elements of a fuse?*
4. *What is the current-limiting effect of a fuse?*
5. *What are the main characteristics of a fuse?*
6. *What are the conditions for selecting a fuse?*

Chapter 3 PROTECTION BY CIRCUIT BREAKERS

3.1. Main characteristics of automatic circuit breakers

A circuit breaker is a switching device designed to provide rapid switching and protect equipment from overcurrents and overloads.

Compared to fuses, circuit breakers have several advantages, of which the main ones are as follows:

- in normal operation and in case of damage, all three phases are switched off, i.e. there is no possibility of creating partial-phase modes;
- These are reusable devices, which makes it possible to form automation schemes on their basis, in particular, automatic transfer switches and reclosers;
- The characteristics of the current disconnectors are more precise than those of fuse inserts.

The conventional and positional designation of circuit breakers in the diagrams is shown in Fig. 3.1.

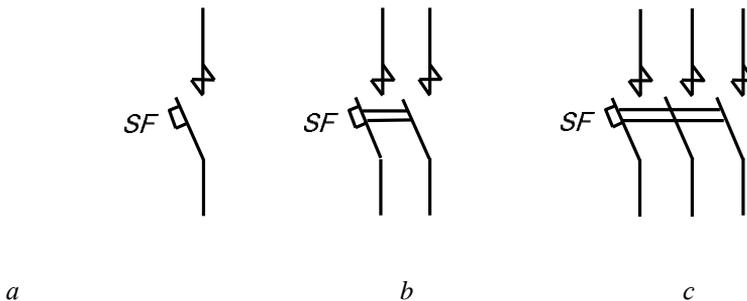


Fig. 3.1 Circuit breaker symbols and positioning

The circuit breakers are manufactured in single-phase, two-phase and three-phase versions for alternating and direct currents.

In Fig. 3.1 shows the conventional and graphical designation of single-phase (*a*), two-phase (*b*), and three-phase (*c*) circuit breakers.

A circuit breaker, unlike a load breaker, which can only switch load currents, can also break currents.

For this purpose, it is equipped with an *arc suppression chamber*. In order to automatically break the electrical circuit during short-circuit or overload conditions, the circuit breaker has a special automatic tripping mechanism - a *release mechanism (disconnecter)*. Release mechanisms can be *electromagnetic, thermal, or semiconductor*. Combined release mechanisms, such as thermal and electromagnetic release mechanisms, can be used in circuit breakers. A trip unit is essentially a direct-acting relay that acts to trip the circuit breaker through a *free release mechanism*. The release mechanism is a combination of levers, springs, latches, etc.

Depending on the type of disconnector, circuit breakers are divided into:

- circuit breakers with overcurrent disconnectors that operate when current increases from the setpoint current;
- circuit breakers with independent trip units that operate independently of the current, usually controlled remotely. The release devices of such automatic

circuit breakers reliably operate at a voltage of $(0,7 - 1,2) U_{nom}$. The response time of such circuit breakers is about 0.04 s;

- circuit breakers with zero or minimum voltage disconnectors that trip when the voltage drops or disappears. Zero-acting disconnectors turn off circuit breakers for lowering voltage less than $(0,1 - 0,35) U_{nom}$, minimum action - for a voltage drop of less than $(0,35 \div 0,7) \cdot U_{nom}$.

The contact system of circuit breakers can be:

- three-stage, with main, auxiliary and arc suppression contacts;
- two-stage, with main and arc suppression contacts;
- single-stage, with a main contact.

The arc suppression chamber of circuit breakers can be designed with narrow slots or in the form of a grille.

In Fig. 3.2 shows diagrams illustrating the principle of operation of the electromagnetic (Fig. 3.2, a) and electromechanical (Fig. 3.2, b) circuit breaker releases.

The main element of the electromagnetic release is the electromagnets 7 installed in each phase (only one phase is shown in Fig. 3.2). The electromagnet coil flows with current I , the core of the electromagnet 8 is held by the spring 6. If the current exceeds a certain value, the electromagnetic force exceeds the tension force of the spring 6, the core starts moving in the direction shown by the arrow, acts on the lever 5, which knocks out the latch 4. The released lever 3 moves under the action of the spring 2 and opens the power contacts 1, which breaks the current flow (after the electric arc between the contacts has died down). This whole process continues 0,015-0,06 s.

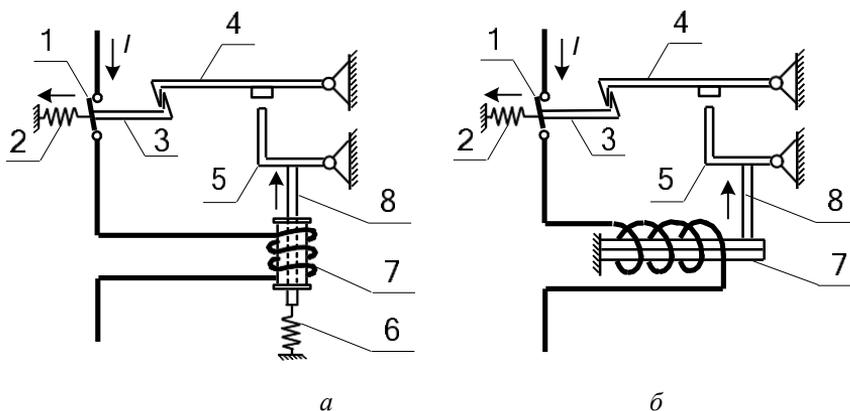


Fig. 3.2. Principle of operation of circuit breaker disconnectors

The circuit breaker disconnecter is made according to the scheme shown in Fig. 3.2, b, is an electro-thermal release. Its main element is two bimetallic plates 7. They are placed in a coil that flows with current I . Under the influence of the current, the bimetallic plates heat up and change their geometry. When heated, the right end of the plates rises upward, pressing in the direction shown by the arrow on the lever 5, which breaks the latch 4. The released lever 3 moves to the left (in the direction of the arrow) under the action of the spring 2 and opens the power contacts I , which breaks the current flow. After cooling, the bimetallic plates return to their original state - the circuit breaker is ready for reclosing.

The protective characteristic (time-current) of the disconnecter is formed from individual stages. Disconnecters are manufactured with one, two, or three stages of this characteristic. Therefore, on the basis of these disconnecters, *one-stage*, *two-stage* or *three-stage current protection* can be realized, respectively. The protection levels can be *current cut-off*, *time-delayed current cut-off*, or *maximum current protection*. The current cut-off and time-delayed current cut-off are performed with independent time delay. With this characteristic, the protection response time does not depend on the current value. Maximum current protection is realized with a dependent time delay, in which case the trip time of the disconnecter depends on the current value.

Fig. 3.3 shows the characteristics of disconnecters. Depending on the type of recloser, the circuit breaker can perform the functions of *current cut-off (time-delayed current cut-off)* (Fig. 3.3, a), *current protection with a dependent characteristic* (Fig. 3.3, b), *protection with a combined two-stage characteristic* (Fig. 3.3, c) and *protection with a combined three-stage characteristic* (Fig. 3.3, d).

The independent characteristic on the basis of which the current cut-off and time-delayed current cut-off are determined can be obtained by means of an electro-magnetic or semiconductor recloser. The dependent characteristic on which the maximum current protection is based can be obtained using an electrothermal or semiconductor release. The characteristics of semiconductor disconnecters can be adjusted during operation. The characteristics of electrothermal release devices are not adjustable during operation. The electromagnetic release, which is the basis for current tripping, is also not adjustable during operation.

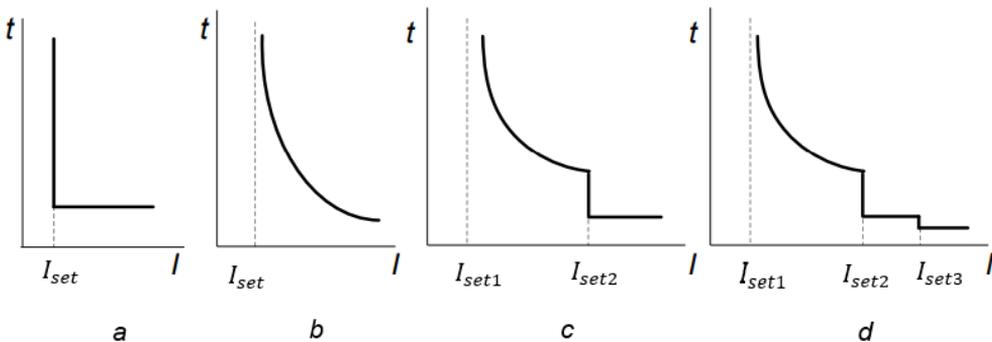


Fig. 3.3. Protective characteristics of circuit breakers

Like fuses, circuit-breaker disconnectors provide *current-limiting* properties in certain cases: during a short-circuit, the disconnecter manages to trip before the current reaches its

maximum value. However, this property is not as important for releases as it is for fuses.

Depending on the amount of current, circuit breakers can be divided into three groups:

- modular circuit breakers for currents up to 125 A;
- medium-current circuit breakers, for currents in the range of 80÷ 630 A;
- powerful circuit breakers for currents from 800 to 6300 A.

Modular switches

Recently, the manufacture of circuit breakers has been regulated by IEC 947.2. This has made it possible to manufacture *modular-type* circuit breakers with *DIN* rail mounting. Modular type circuit breakers are manufactured for currents from 0.5 A to 63 A with a housing width of 18 mm (two modules of 9 mm each) and for one pole for currents from 80 A, and for currents up to 125 A - with a housing width of 27 mm. These are circuit breakers of class of low power. Modular circuit breakers meet the standards of IEC 898, IEC 947.2, GOST R 50345-99, GOST 50030.2-99, DSTU 3025-95. They are manufactured for one, two, three or four poles. The release of a modular circuit breaker is made on the basis of a thermal element realized by means of a bimetallic plate and on the basis of an electromagnet. Therefore, the protective characteristic of the recloser of such a circuit breaker consists of two parts - the dependent part, which forms the thermal element, and the independent part, which forms the electromagnetic element. The protective characteristics of the modular circuit breakers, depending on the settings of these elements, are shown in Fig. 3.4.

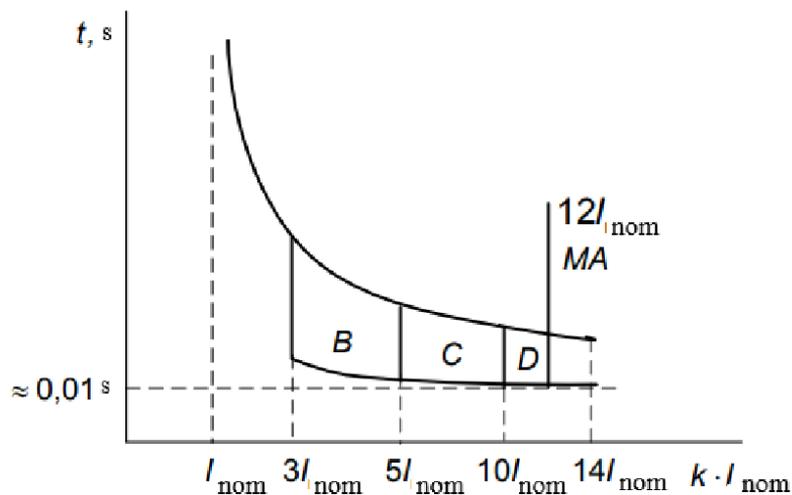


Fig. 3.4. Protective characteristics of modular circuit breakers

The modular circuit breakers for currents up to 125 A, depending on the multiplicity of the cut-off current, have B, C, D and MA characteristics. Type B, C, D circuit breakers have combined protective characteristics - dependent and independent. The independent characteristic of type B circuit breakers is performed for the current multiplicity cutoffs (3–5) I_{nom} , independent

characteristic of type *C* switches - by a factor of cut-off current $(5-10) \cdot I_{nom}$, independent characteristic of type *D* circuit breakers - on multiplicity of the cut-off current $(10-14) \cdot I_{nom}$. The *MA* type circuit breakers are made only with independent characteristics for $12I_{nom}$ current.

Type *B* circuit breakers are used for loads with minimum inrush currents, such as loads with electronic devices. Type *C* circuit breakers are used in general-purpose networks, such as lighting, or to protect loads with short-term overloads. Type *D* circuit breakers are used in power supply circuits for powerful asynchronous motors with infrequent switching.

Medium power circuit breakers

The circuit breakers of this class have thermoelectromagnetic and semiconductor trip units. It is possible to change the characteristics of the trip units of these circuit breakers during operation. Fig. 3.5 shows the typical characteristics of medium-voltage circuit breakers.

Different types of disconnector characteristics can be used for overload protection with a dependent time delay - characteristic 1, protection with a time delay - 3; overcurrent protection with a short time delay - 4; instantaneous trip - 5; adjustable trip for a special disconnector - 6,7. In Fig. 3.5 arrows show the areas of characteristics that can be adjusted.

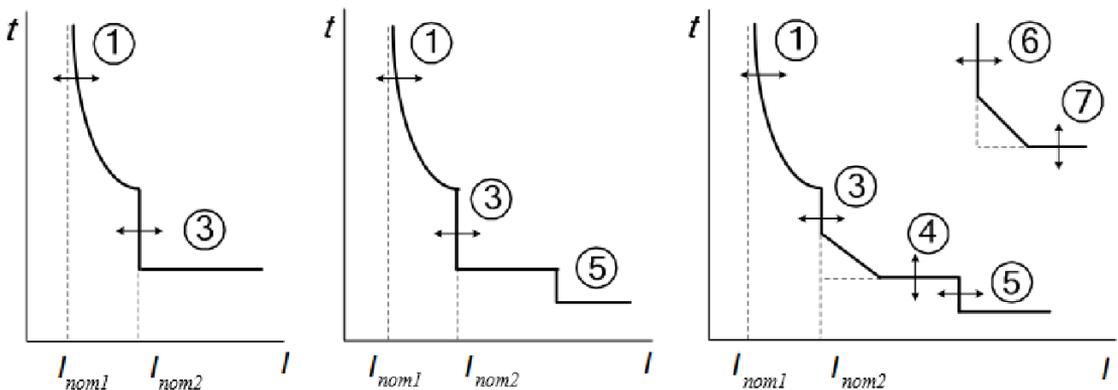


Fig. 3.5. Protective characteristics of medium-voltage circuit breakers

Powerful circuit breakers

These circuit breakers are manufactured for currents from 600 A to 6300 A. They are three-pole or four-pole circuit breakers in fixed or withdrawable versions. Electromagnetic, semiconductor, and electrothermal release devices are used on these circuit breakers. On modern circuit breakers of this classification, it is possible to use release devices based on digital devices.

Electrical characteristics in accordance with the standards and designations according to IEC 947.2 for circuit breakers:

- rated current: 880, 1000, 1200, 1600, 2000, 2500, 3200, 4000, 5000, 6300 A;
- rated voltage 1000 V;
- rated pulse voltage of 8000 V;
- total tripping current (current value) 55, 75, 100, 150 kA;

- permissible through current for 0.5 s - 55, 75, 170 kA;
- permissible switching current at the main circuit (shock) 121, 165, 220, 286 kA;
- electrodynamic resistance 121, 165, 187 kA;
- shutdown time 25-30 ms;
- switch-on time up to 50 ms;
- number of cycles 5000 - 15000.

Powerful circuit breakers that are most commonly used in power systems are circuit breakers of the VA series, A3700 series, and Electron series

3.2. Selection of automatic circuit breakers

The main characteristics of circuit breakers are the *rated voltage* $U_{auto\ nom.}$, *rated current* $I_{auto\ nom.}$, *maximum off-current* $I_{auto\ max.}$

The *rated voltage* $U_{auto\ nom.}$ of the circuit breaker is the voltage that corresponds to the voltage of the network where the circuit breaker is installed.

Nominal current $I_{auto\ nom.}$ of the automatic circuit breaker is this is the maximum current at which the circuit breaker can operate without damage and without changing its performance characteristics for the time guaranteed by the manufacturer.

The *maximum trip current* $I_{auto\ max.}$ is this maximum current which usually occurs during fault and which can trip the circuit breaker without causing any damage to it.

The uncoupler automatic circuit breaker is characterized by *nominal the current of the tripping device* $I_{uc\ nom.}$, *the current* I_{set} *and the time* t_{set} *each stage operation.*

Rated current of the disconnecter $I_{uc\ nom.}$ is called maximum current, the long-term flow of which does not lead to its operation.

The current and trip time of each stage is the minimum current at which the tripping device will trip after reaching the set time t_{set} .

The conditions for selecting a circuit breaker and its disconnecter are determined by the type of object they must protect - line, transformer, motor, as well as the type of fault - overcurrent only or overcurrent and overload, etc.

The circuit breaker is selected according to *the mains voltage, the overcurrent and the maximum operating current of the element it is supposed to protect.*

The rated voltage of the circuit breaker must match the mains voltage

$$U_{auto\ nom} = U_{mains} \quad (3.1)$$

where $U_{auto\ nom}$ is the rated voltage of the circuit breaker; U_{mains} is the voltage in a network where a circuit breaker is installed.

The maximum current that can be tripped by the circuit breaker must be greater than the maximum current during fault conditions in the network

$$I_{auto\ max} \geq I_{s.c.max} \quad (3.2)$$

where $I_{auto\ max}$ is the maximum current that the circuit breaker can trip; $I_{s.c.max}$ - the maximum s.c. current that can be present in the network.

The rated current of the disconnecter $I_{d.s.\ nom}$ is chosen to be greater than the maximum

The long-term operating current of the protected object $I_{o.p. max}$

$$I_{d.s. nom} \geq I_{o.p. max} \tag{3.3}$$

The rated current of the disconnector is selected according to the standard scale of rated currents of this type (series) of disconnector, as the closest to the maximum is the value for the maximum operating current $I_{o.p. max}$.

Let us consider the conditions for selecting circuit breakers for *the protection of power transmission lines*. The peculiarities of calculating the trip settings of circuit breakers for the protection of other objects of the power grid will be given in the relevant sections.

Let's consider the choice of circuit breaker protections that are most commonly used in power systems: circuit breakers of the VA series, A3700 series, and Electron series.

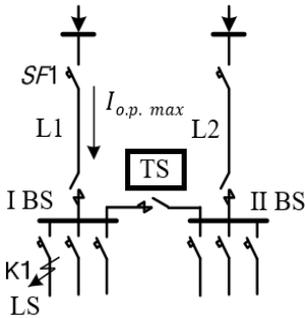


Fig. 3.6. Line protection by circuit breakers

To protect the line L1 (Fig. 3.6), we will use a three-stage current protection made by the disconnector of the circuit breaker SF1.

- 1 stage is a current cut-off without a time delay.
- 2 stage is a current cutoff with a time delay.
- 3 degree - maximum current protection.

In the expressions below, the tripping parameter (current, resistance, etc.) is indicated by an index depending on the zone (time) of the protection:

- I - protection without time delay (current cut-off without time delay, first degree of remote protection, etc.);
- II - second-stage time-delayed protection (time-delayed current cut-off, second-stage remote protection, etc.);
- III, IV, V - time-delayed protection (time-delayed residual current protection and remote time-delayed protection, etc. - of the third, fourth and fifth stages, respectively).

A feature of the calculation three-stage protection circuit breakers is the connection of the tripping current of each stage with the the rated current of the disconnector $I_{d.s. nom}$. This significantly complicates the calculation and selecting the settings of individual circuit breaker trip stages.

Selectivity

To ensure selective operation, the protective characteristics of the disconnectors of two consecutive circuit breakers, for example, SF1 and SF2 (Fig. 3.6) should not intersect for total range of possible short-circuit currents short circuits (Fig. 3.7). In the protective the characteristic of the circuit-breaker release (SF1) located closer to the power supply should be higher than the protective characteristic of

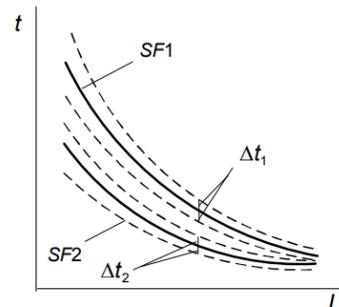


Fig. 3.7. Selectivity of circuit breaker disconnectors

the release located farther from the power supply (SF2). If, after calculating the trip settings of the disconnectors according to expressions (3.4)-(3.10), their selectivity is not ensured, the protective characteristic of the disconnector, I located closer to the source power supply (SF1), it is necessary to raise it higher, i.e. to change the setpoints of the operation the release can be used to disengage. But remember that this will increase the trip time of the release.

In order to ensure selectivity, the characteristics of the disconnectors of the series circuit breakers must not only not overlap, but must also be at the smallest possible distance from each other. This distance is determined by their permissible errors. The average relative error of the time operation of the disconnectors is assumed to be 20%. With such an error, for any possible value of the fault current or overload, the selectivity of is ensured when $(1 - 0.2) \cdot t_{setSF1} \geq (1 + 0.2) \cdot t_{setSF2}$, або $t_{setSF1} \geq 1.5 \cdot t_{setSF2}$.

In networks up to 1000 V, both fuses and circuit breakers are often used to protect network objects. When the circuit breaker is located closer to the power supply and selectivity is not ensured (the protective characteristics of the fuse and the disconnector overlap), selectivity can be achieved by raising the protective characteristic of the circuit breaker. When a fuse is located closer to the power supply, the requirements for selectivity are determined from the condition that $\Delta t = 0.25 \cdot t_{fuse\ nom}$, $t_{fuse\ nom}$ is fuse link operating time. In this case, the selectivity of the fuse and circuit breaker is ensured if the following condition is met: $(1 - 0.25) \cdot t_{set\ nom} \geq (1 + 0.25) \cdot t_{setSF}$, or when the ratio of the fuse and trip settings is $t_{set\ nom} \geq 1.7 \cdot t_{setSF}$.

? *Questions for self-examination*

1. *What is the purpose of a circuit breaker?*
2. *Describe the advantages of circuit breakers compared to fuses.*
3. *Give the conventional and positional designation of the circuit breaker.*
4. *What are the main elements of a circuit breaker?*
5. *Tell us about the principle of operation of the electromagnetic release.*
6. *Tell us about the principle of operation of the thermal release.*
7. *What are the safety characteristics of modular circuit breakers?*
8. *How can the combined protective characteristic of a circuit breaker be obtained?*
9. *What are the characteristics of a circuit breaker?*
10. *What is the current rating of a circuit breaker disconnector?*
11. *What are the conditions for selecting a circuit breaker?*
12. *What parameters are used to test the sensitivity of circuit breakers?*
13. *How is the selectivity of circuit breaker disconnectors ensured?*

Chapter 4 Primary CURRENT MEASURING TRANSDUCCERS

4.1. Purpose of primary measuring transducers current

Primary current transducers are designed to isolate secondary measuring circuits from primary power circuits, as well as to create a standard scale for secondary rated currents.

Primary measuring transducers can be trans reactors, electromagnetic sensors, transformers without magnetic cores, and optoelectronic transducers. Today, electromagnetic sensors - current transformers (CTs) - are the most widely used in power systems.

Isolation of primary power circuits, which are usually high-voltage, is necessary to create safe working conditions in secondary circuits, such as measurement, control, metering, etc. In addition, the isolation of secondary circuits from primary circuits is necessary to protect the equipment of secondary circuits, as it is designed to operate at low voltages (up to 1000 V).

To ensure the unification of secondary equipment, a standard scale of secondary rated currents has been introduced. These are currents of 5 A and 1 A. This means that standard current transformers with different primary rated currents, which, in turn, depends on the voltage class and power of the power equipment, have a rated secondary current of 5 A (1 A). In Ukrainian power systems, current transformers used in electrical installations with a voltage of 330 kV and above are usually used with a rated secondary current of 1 A. For lower voltage classes, current transformers with a rated secondary current of 5 A are used. For networks of a lower voltage class (up to 330 kV), it is possible to use current transformers with a rated secondary current of 1 A in the case of differential busbar protection. In foreign countries, current transformers with a rated secondary current of 5 A are usually used for all voltage classes.

One-ampere current transformers can carry *25 times the load* of five-ampere current transformers with the same primary current rating. Therefore, long conductors with a small cross-section can be used to connect the secondary load for such current transformers.

The primary rated currents of current transformers installed in power grid facilities are also standardized: 15, 20, 30, 40, 50, 75, 100, 150,

200, 300, 400, 500, 600, 750, 800, 1000, 1200, 1500, 2000, 3000 A. Installed in circles

current transformers have higher primary rated currents for stators of synchronous generators (compensators), which depends on the voltage class and power of these synchronous machines.

Information about the current in the primary circuit can be obtained in other ways besides using the electro-magnetic principle. The most promising of these are two areas: the use of optoelectronic transducers and the use of Rogowski coils.

In the first case, special optoelectronic converters - optical current transformers (OCTs) - are located directly in the primary circuit. OCTs use the Faraday effect, which is the effect of the

proportional dependence of the angle of rotation of linearly polarized light on the effect of the magnetic field strength of an electric current. An important feature of the OTC is the ability to measure (record, etc.) instantaneous current values of arbitrary shape, in particular, the DC and ultra-low-frequency components of the current, without contact with the wire. The signal from the OTS is transmitted via an optical fiber cable directly to special converter devices, where it is converted into an electrical signal (digital or analog) that is supplied directly to the recloser devices. Such serial high-voltage OTSs are already manufactured by well-known foreign companies, in particular, NxtPhase.

Rogowski coil is a transformer without a magnetic core, in which the primary current induces an emf in the secondary winding through the air. The power of such transformers is usually small and insufficient for the operation of recloser devices based on electromechanical technology. Modern reclosers are digitally based and do not require high-power information sources. Therefore, recently, especially abroad, the development of primary current converters based on Rogowski coils has been a promising area. The main advantage of this approach is the absence of a magnetic core in the primary converter. Therefore, such a converter has a linear characteristic of the dependence of the voltage on the secondary winding on the primary current, and does not distort the shape of the primary current. That is, it has a significantly lower error compared to a traditional electromagnetic current transformer. Moreover, the primary measuring current converter based on Rogowski coil is smaller and cheaper than traditional electromagnetic current transformers.

converters. Similar serial high-voltage current transformers are already being manufactured by well-known foreign companies, including ABB.

However, in Ukraine, traditional electromagnetic current converters will be used in the near future. Therefore, we will take a closer look at the principles and features of these current converters.

4.2. The principle of operation of the transformer current

The current transformer is a conventional transformer (Fig. 4.1), the core of which is made of transformer steel, the primary winding is connected directly to the current circuit of the power equipment by terminals L_1 , L_2 , and the corresponding load is connected to terminals T_1 , T_2 of the secondary winding - relay protection devices, automation, electricity meters, etc.

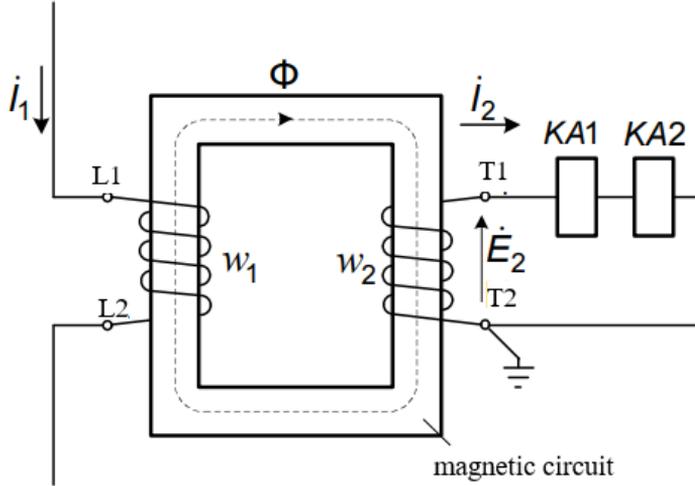


Fig. 4.1: Principle of operation of a current transformer

Current flows through the primary winding (number of turns \$w_1\$) of the transformer current \$\dot{I}_1\$ that creates a magnetizing force \$\dot{F}_1 = \dot{I}_1 \cdot w_1\$. Under the action of this The magnetizing force in the transformer magnetic circuit creates a magnetic flux \$\dot{\Phi}_1\$, which induces in the secondary winding (number of turns \$w_2\$) the electric motor EMF strength. If the secondary winding is closed to the load, then under the action of this emf, a current will flow in the secondary winding, which in turn will create the magnetizing force \$\dot{F}_2 = \dot{I}_2 \cdot w_2\$ and, accordingly, the magnetic flux \$\dot{\Phi}_2\$. The flux \$\dot{\Phi}_2\$ Lenz's law will oppose the magnetic flux \$\dot{\Phi}_1\$. Magnetizing forces, generated by the primary and secondary windings and their corresponding magnetic fluxes are vectorially summed to create the resulting magnetic flux \$\dot{\Phi} = \dot{\Phi}_1 + \dot{\Phi}_2\$

So, the mathematical model of a transformer is described by the equations

$$\begin{aligned} \dot{I}_1 \cdot w_1 + \dot{I}_2 \cdot w_2 &= \dot{I}_\mu \cdot w_\mu \\ \dot{\Phi}_1 + \dot{\Phi}_2 &= \dot{\Phi} \end{aligned} \tag{4.1}$$

As can be seen from (4.1), the resulting magnetic flux \$\dot{\Phi}\$ in the core is created by the magnetizing force \$\dot{I}_\mu \cdot w_\mu\$, i.e., the magnetizing current \$\dot{I}_\mu\$ is a part of primary current \$\dot{I}_1\$. Consequently, the given value of the secondary current is different from the primary current to the magnetization current

$$i_2 = -\left(\frac{i_1}{n_{TA}} - \frac{i_\mu}{n_{TA}}\right) \tag{4.2}$$

-where \$n_{TA} \approx \frac{w_2}{w_1}\$ the transformation ratio of a current transformer, calculated as the ratio of turns of the secondary and primary windings, respectively.

4.3. Design diagram and vector diagram of a current

transformer

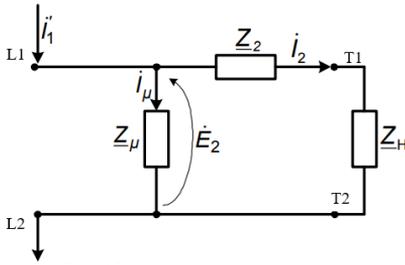


Fig. 4.2. Design diagram of a current transformer

The calculation diagram of the current transformer is shown in Fig. 4.2. In the calculation diagram, the magnetic connection between the primary and secondary windings is replaced by an electrical one. Therefore, the diagram shows the primary current and the magnetizing current introduced into the secondary winding.

As can be seen from Fig. 4.2, in the calculation diagram of the current transformer, unlike the calculation diagram of a classical transformer, there is no resistance of

the primary winding. This is explained by the fact that the current transformer is connected in series with its primary winding to the primary circuit, which is a current source, the internal resistance of which is theoretically infinitely large relative to the current transformer.

According to the principle of operation and the calculation diagram, a vector diagram of the current transformer is built, shown in Fig. 4.3.

The resulting magnetic flux $\dot{\Phi}$ lags behind the magnetization current \dot{I}_μ by an angle γ , which depends on the activity losses in the magnetic circuit of the current transformer. The magnetic flux $\dot{\Phi}$ induces in the secondary winding of the transformer of the EMF formulator \dot{E}_2 , under the action of which the closed to the load Z_H in the second current will flow through the market winding \dot{I}_2 . Secondary current shifted with respect to the EMF \dot{E}_2 by a certain angle φ , the value of which is determined by the total active and reactive resistances of the secondary winding of the current transformer and the load resistance Z_H .

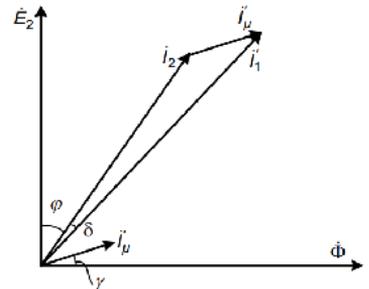


Fig. 4.3. Vector diagram of a current transformer

4.4. Transformer operating mode current

The operating mode of the current transformer is as close as possible to the short-circuit mode of the secondary winding. In this mode, the magnetization current is negligible and reaches up to 10% of the secondary current. When the secondary winding is opened, the magnetization current increases dramatically. In this case, as can be seen from the schematic diagram (Fig. 4.2), the magnetization current is equal to the primary current, the magnetic flux increases sharply, which causes overheating of the transformer magnetic circuit current, its fire is possible. In this case, the emf E_2 on the secondary winding also increases sharply, which poses a danger to the operating personnel.

Therefore, the opening of the secondary winding of the current transformer during its operation (when current flows in the primary winding) is unacceptable!

In accordance with the PUE, current transformers used in recloser circuits must ensure the following operating conditions:

- accurate operation of recloser devices - according to the calculated value of current I_{1deg} (its definition is described in detail in Section 6), the total error of the TS should not exceed 10%;
- to ensure reliable operation of the RCA measuring bodies in case of maximum three-phase fault current flow, when the shape of the secondary current curve may be distorted;
- absence of overvoltage dangerous for secondary equipment and personnel, which can occur on the secondary winding during the maximum power mode.

4.5. Transformer error current

As you can see from the vector diagram, the reduced primary current differs from the secondary current by the magnetization current. The lower the magnetization current, the closer the secondary current will be to the reduced primary current, and the more accurate the current transformer will be. When the primary current is flowing, the magnetization current is determined by the level of the resulting magnetic flux (or, more precisely, the level of magnetic induction of the core material) of the current transformer magnetic circuit. The secondary current of a transformer differs from the reduced primary current both in magnitude and in angle. Therefore, we can talk about three types of current transformer errors: *current, angular, and total*, which are interrelated. Almost all of these errors depend on the value of magnetization current \dot{I}_μ . The greater the saturation of the magnetic circuit, the less value of resistance \underline{Z}_μ (Fig. 4.2), the greater the value of the magnetization current \dot{I}_μ , i.e., the greater the difference between the secondary and reduced primary current of the current transformer.

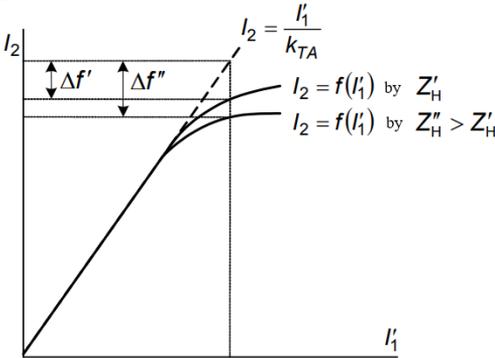


Fig. 4.4. Secondary current dependence of a current transformer from the primary

Saturation can occur when with an increase in primary current, as well as with an increase in load resistance \underline{Z}_H (Fig. 4.4). In the latter case, not only does the magnetization current increase, but also the shape of the secondary current curve is distorted, which can lead to unreliable operation of relays connected to the secondary winding. As can be seen from Fig. 4.4, the error of the current transformer increases with an increase in the primary current $I_1 > I_{nom}$, as well as with an increase in load resistance $Z'_H > Z''_H - \Delta f'' > \Delta f'$.

The relative reduced current error is the relative difference between the values of the reduced primary and secondary currents

$$f = \frac{I_2 - I_1'}{I_1'} \cdot 100\% = \frac{k_{nom} \cdot I_2 - I_1}{I_1} \cdot 100\% \tag{4.3}$$

where $k_{nom} = \frac{I_{1nom}}{I_{2nom}}$ - is the rated transformation ratio of the current transformer.

The angular error shows how much the secondary current is shifted relative to the reduced value of the primary current - in Fig. 4.3 it is the angle δ . Usually, the current and angular errors are quantitatively related - if the current error $f < 10\%$, then $\delta < 10\%$. In case of saturation of the transformer magnetic circuit current, the angular error increases and at large values of angular error ($\delta > 45\%$), some relays, such as remote, power directional, etc., may not operate properly.

The total error of the current transformer is defined as the ratio of the modulus of the difference of the complexes of the secondary and reduced primary current to the modulus of the complex of the reduced primary current

$$\varepsilon = \frac{|\dot{i}_\mu|}{|I'_1|} = \frac{|I_2 - I'_1|}{|I'_1|} \cdot 100\% \quad (4.4)$$

This expression is valid only for sinusoidal secondary current. Therefore, in general, a more complicated expression is used

$$\varepsilon = \frac{100}{|I'_1|} \cdot \sqrt{\frac{1}{T} \int_0^T (k_{nom} \cdot i_2 - i_1)^2 \cdot dt}, \% \quad (4.5)$$

where i_2, i_1 - instantaneous values of secondary and primary currents, T – period industrial frequency of 50 Hz, is 0.02 s.

The total error is always greater than the current error $\varepsilon > f$.

Usually, absolute and angular errors are used to evaluate the operation of a current transformer under rated mode ($I_1 \leq I_{1nom}$). During fault conditions, when the primary current value is greater than the rated value, the total error is used.

Table 4.1 shows the classification of current transformers by accuracy class.

Table 4.1

Classification of current transformers by accuracy class

Accuracy class	Permissible current error, %.	Permissible angular error, el. min	Application area
0,2	± 0,2	± 10	Laboratory measurements
0,5	± 0,5	± 40	Metering of electricity
1,0	± 1,0	± 80	Panel devices
10,0	± 10	± 420 (7 el. g)	RPA

The permissible errors given in Table 4.1 correspond to secondary winding loads not exceeding the rated one and at a primary current not exceeding 120% of the rated one.

4.6. Conventional and positional designation of the transformer current

The conventional and positional designation of the current transformer is shown in Fig. 4.5. The beginning and end of the primary winding are indicated by the letters L_1 and L_2 , the beginning and the end of the secondary winding are marked with the letters T_1 and T_2 , respectively. The polarity marking of the TS windings is carried out so that the direction of current in the primary winding from L_1 to L_2 coincides with the direction of current from I_1 to the relay that is switched on in the secondary winding. That is, the current in the secondary circuit must be in phase with the primary current. This is illustrated in Fig. 4.6. Such marking facilitates the analysis of the operation of RZ devices for which the

directions of currents in the secondary circuit coincide with the directions of currents in the primary circuit (Fig. 4.6).

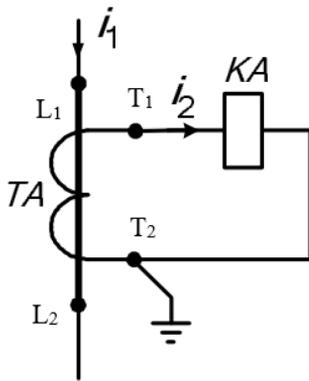


Fig. 4.5. Conventional and positional designation of a current transformer

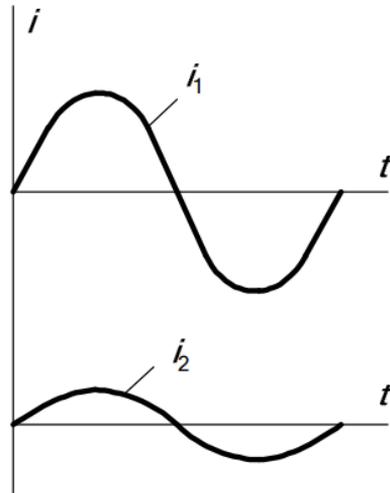


Fig. 4.6. Currents of the current transformer windings

Table 4.2 shows the letter designations of current transformers depending on their design.

Table 4.2

Letter designations of current transformers

TLM	TS is a small-sized unit, which is a cast block with two magnetic cores for different purposes of windings (for measuring and relay protection)
TOLK	Support structure made in the form of a coil
TVLM	Built-in vehicle, made in the form of a coil
TPL	Multi-track pass-through vehicle
TPLU	The vehicle is reinforced in terms of thermal and electrodynamic resistance
TPOL	Single-axle vehicle passing through
TL	TS for complete switchgear
TOL	Vehicles of the support type
TLM	The vehicle, made in the form of a coil, is small in size
TPLC	Vehicles of the support and passage type
TSL	Highly saturated heat transfer medium with molded insulation
TLL	TC for current measurement in laboratories and on test benches of industrial enterprises
TSL	Busbar system with molded insulation
TSN	Tire vehicle of hinged type
TSHMS	Small-sized tire vehicle for the judicial sector
TNS	TC for electromagnetic equipment
TSV	Vehicles with air insulation

TSLO	Vehicle of the tire support type
TUBULAR STEEL PRODUCTS	The TS is installed in the current lines and neutral terminals of turbine generators
TV	Vehicles are mounted in oil circuit breakers
TVT	Vehicles mounted in transformers and autotransformers
TFZM	Outdoor installation with link type windings
TFRM	Outdoor installation transformer with rhyming secondary winding
TFUM	Outdoor installation transformer with U-type primary winding
TZLM	TS for protection schemes against earth faults
TZFL	TS for protection circuits against earth faults with a detachable magnetic circuit

4.7. Transformer winding connection diagrams current

Depending on the purpose of the protection devices, there are different connection schemes of the busbar windings. The winding connection schemes of the busbar windings must be taken into account when calculating the parameters of the protection devices operation - trip settings, as well as when calculating sensitivity coefficients. Therefore, the concept of circuit coefficient is introduced. This coefficient is determined for the symmetrical mode

$$k_{sc}^{(3)} = \frac{I_r}{I_2}, \quad (4.5)$$

where I_r is the current flowing in the relay winding, for example, in normal; I_2 - the value of the current in the secondary winding of the current transformer to which is connected to this relay, in the same mode.

In practice, the following connection schemes are used to connect the windings of the vehicle:

- full star circuit (Fig. 4.7, a). This scheme allows controlling all phase currents, as well as the zero-sequence current (relay $KA4$). Therefore, such a scheme is used for protection devices that respond to all types of faults.

of such a connection of secondary windings and relay is $k_{sc}^{(3)} = 1$. The sensitivity of such a scheme to all types of interphase fault is the same;

- two-phase two-relay circuit (Fig. 4.7, b) allows direct control of currents in phases A and C. Therefore, this circuit is used in networks with an isolated neutral for protection against interphase faults. The coefficient of the circuit, like the previous one, is 1. The sensitivity of such a circuit to all types of interphase faults is the same;

- two-phase three-relay circuit (Fig. 4.7, c) is similar in sensitivity to the full star circuit (Fig. 4.7, a), but can be used only for protection against interphase short-circuits. It is used, like the previous scheme, in networks with an isolated neutral;

- single-relay circuit for switching on the TS on the difference of currents of two phases - the "figure of eight" circuit (Fig. 4.7, d) is used mainly in protection circuits for low-power motors and for powering rectifier devices, which, in turn, are used to supply the operating current to protection devices. The coefficient of the circuit is $\sqrt{3}$. Its sensitivity to different types of short-circuits is different - for two-phase short-circuits between phases A and B or C and B in the relay of the CA, the current of the secondary winding of the TS flows and at two-phase fault of the AC phases - the same double current, and the current of the two-phase fault in power grids is

practically equal to 0.87 of the current of the three-phase fault; at three-phase fault k.s., a current flows in the relay of the CA in $\sqrt{3}$ times higher than the current of the secondary winding of the TS;

– a scheme for connecting the secondary windings of the TS into a triangle (Fig. 4.7, e). This scheme is used in transformer differential protection circuits to eliminate the phase shift between the currents in the protection arms (this is discussed in detail in the section "Differential Transformer Protection"). But in this case, the load resistance in the secondary winding of current transformers increases. In differential protections made on a digital basis, such a phase shift is eliminated algorithmically and a star connection scheme for the secondary windings of the transformers is used. Circuit factors the connection of the secondary windings of the TS in a triangle is $\sqrt{3}$;

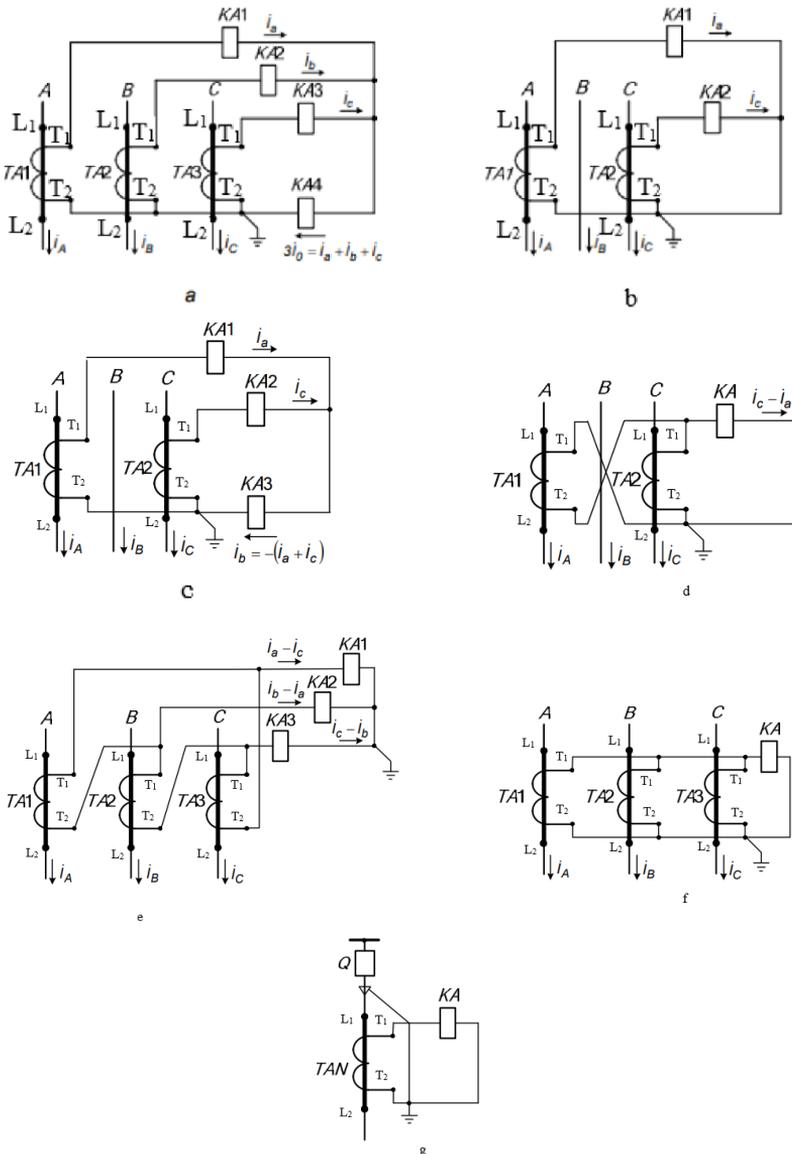


Fig. 4.7. Connection diagrams of secondary windings of current transformers and relays

– connection diagram of the secondary windings of the TS as a neutral current filter (Fig. 4.7, f). When the secondary windings of all three current transformers are connected in parallel, a current proportional to the neutral current will flow in the relay $\dot{I}_r = 3\dot{I}_0 = \dot{I}_a + \dot{I}_b + \dot{I}_c$ sequences. Regarding the zero-sequence current an analog of this scheme (Fig. 4.7) is used for protections that respond to short-circuits to earth in networks from 110 kV with an effectively grounded neutral. In the circuit of Fig. 4.7, f, the neutral sequence current $3\dot{I}_0$ flows in the neutral wire, in when relay *KA4* of the earth fault protection is switched on. Since in such networks significant zero-sequence currents may occur - commensurate with the nominal primary currents of the TS, the errors of the TS in such modes meet the requirements of the RS (current error not more than 10%).

In networks with an isolated neutral, where, as a rule, neutral sequence currents are much lower than the rated primary currents of the TS, the scheme of Fig. 4.7, f is not applicable, because the neutral sequence current obtained in this way contains a significant error. Given that the error of each linear current transformer is 10%, theoretically, the error in determining the neutral sequence current obtained by this scheme can be 30%.

To detect and record zero-sequence currents in the event of earth faults in cable networks with an insulated neutral with a voltage of up to 35 kV inclusive, zero-sequence cable current transformers are used (Fig. 4.7, g) (a detailed description of the application is given in Section 7.8.2). The magnetic core of such a current transformer covers all three phases (cores) of the cable, and these cores are also the primary windings (with a number of turns of 1) of the current transformer. The secondary winding with a larger number of turns is wound on this magnetic core and the relay of *the* control unit is connected to it (by analogy with Fig. 4.7, f). When the mains phase is shorted to ground in the relay of *the* CA will flow only the current $3\dot{I}_0$, in the absence of such a short circuit – only unbalance current, which depends mainly on the level of currents in the cable cores. This design of the cable neutral current transformer makes it possible to record, in the event of a ground fault, small neutral currents (from units of A), significantly less than the line currents (tens of A or more) that simultaneously flow in the phases (cores) of the cable, and meets the requirements of the RS.

Effective primary neutral current sensors (converters) have not yet been developed and are not being mass-produced to detect and record neutral currents that occur earth faults in overhead lines with an insulated neutral voltage of up to 35 kV inclusive.

In addition to the connection schemes shown in Fig. 4.7, in practice, the series connection of the secondary windings of the TS (Fig. 4.8, a) and the parallel connection of the secondary windings of the TS (Fig. 4.8, b) are used.

The series connection of the secondary windings of current transformers *TA1*, *TA2* (Fig. 4.8, a) is a connection in which the end of the secondary winding T_2 of *TA1* is connected to the beginning of the secondary winding T_1 of transformer *TA2*. With a series connection, the equivalent (calculated) load resistance of each transformer is reduced by half. For series connection, it is necessary to use current transformers of the same type with the same rated secondary currents and transformation ratios.

The parallel connection of the secondary windings of current transformers *TA1*, *TA2* (Fig. 4.8, b) is a connection in which the terminals of the secondary windings T_1 , T_2 of these transformers are connected. With a parallel connection, the equivalent (calculated) load resistance of each transformer is doubled.

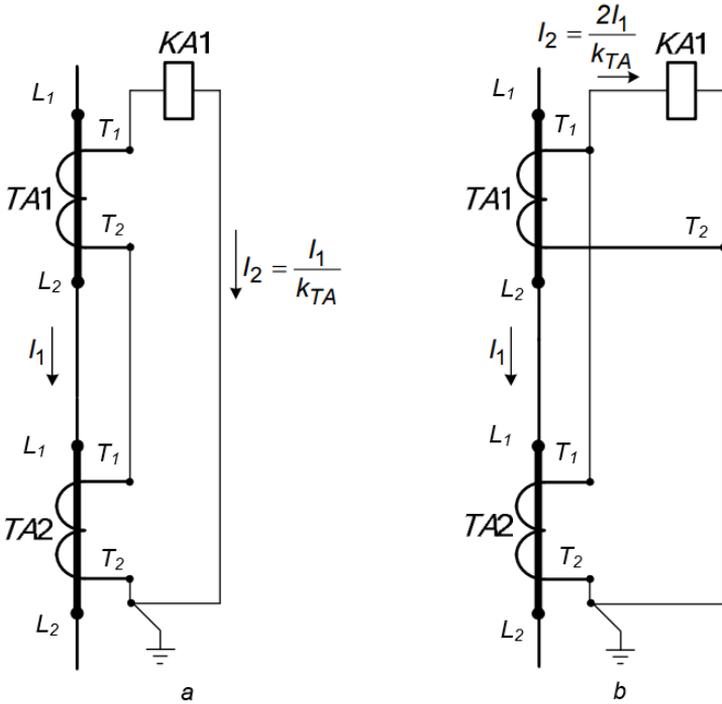


Fig. 4.8. Diagrams of parallel and series connection of secondary windings of current transformers

When setting up relay protection devices, check the correctness of the connection scheme of the secondary windings of current transformers and relays.

Check the complete connection scheme of the current transformers and relays with an independent current source. To do this, connect the primary circuits of the current transformers in the appropriate circuit using temporary connecting conductors and apply current from an independent current source. It is recommended to supply a small current (about 10% of the rated current). After for this purpose, it is necessary to measure the currents and their phases in all branches of the secondary circuits of current transformers with a device, for example, VAF-85. For each particular circuit, the correct connection of the connecting conductors should make it impossible to break the circuits of the secondary windings of the CTs, ensuring free flow (transformation) of the CT secondary currents to the secondary load, i.e., that all secondary windings of all CTs of the circuit are connected to the secondary load.

For example, consider how to check the connection of the current circuits of a two-phase three-relay circuit (Fig. 4.9).

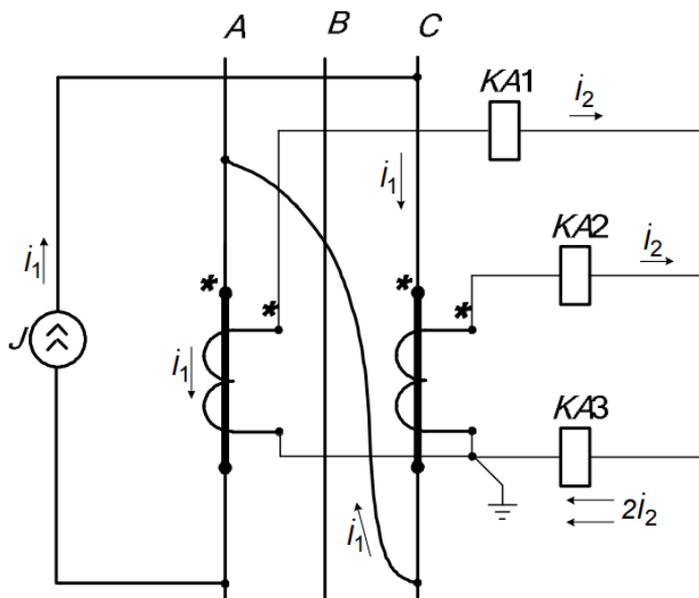


Fig. 4.9. Checking the complete wiring diagram of current transformer windings and relays

The power source J supplies current I_1 , which will flow through the primary windings of the current transformers. In case of correct connection of the TS windings, currents I_2 , in the neutral conductor, where the relay $KA3$ is located, will flow twice the value of this current. For example, if the polarity of the secondary winding of one of the TCs is incorrectly determined, the current in the neutral conductor will be zero. In Fig. 4.9 the unipolar winding terminals of the CTs are marked with an asterisk (*).

4.8. Inspection of transformers current

During operation, current transformers must undergo periodic comprehensive inspections. The most complete inspection of the secondary circuits of the TS is carried out during commissioning and before commissioning of new relay protection devices. Then the following basic routine maintenance is performed during the inspection of current transformers:

- check the unipolarity of the primary and secondary winding leads;
- check the transformation coefficients;
- remove the magnetization characteristics;
- check the vehicle for a 10% error;
- check the connection diagrams of the secondary windings of the vehicle;
- check the insulation of the secondary windings.

? *Questions for self-examination*

1. *What is the purpose of a primary current converter?*
2. *What is the principle of operation of the electromagnetic primary current measuring transducer - current transformer?*
3. *Give the symbol and position of the current transformer.*
4. *Draw a circuit diagram and a vector diagram of a current transformer.*
5. *Why is the operating mode of a current transformer close to the k.c. mode?*
6. *How is the transformation ratio of a current transformer checked?*
7. *What are current transformer errors. What are the errors of a current transformer?*
8. *What methods are used to reduce the error of a current transformer?*
9. *What methods of testing a current transformer for a 10% error are in practice?*

Chapter 5 PRIMARY MEASURING VOLTAGE CONVERTERS

1.7 Purpose of primary measuring voltage converters

Primary measuring voltage converters are designed to isolate secondary measuring circuits from primary power circuits, as well as to create a standard scale of secondary rated voltages.

In the electric power industry today, primary voltage measuring transducers based on the *electromagnetic principle, capacitor-type and optoelectronic* transducers are used. The first two principles are the most widely used in existing electrical installations.

The optoelectronic principle is based on the linear electro-optical effect of Pokkels (1893). This effect consists in the double refraction of polarized light in an optical medium when a constant or alternating electric field is applied. Primary voltage converters based on this principle can record voltages of arbitrary shape with high accuracy, converting them into analog and digital signals. Obviously, they do not have the disadvantages of electromagnetic transducers (magnetic circuit saturation, ferroresonance, etc.). Well-known companies in the world (in particular, General Electric) are already mass-producing and putting into operation such *optoelectronic* primary voltage converters. However, their cost is still much higher than the cost of traditional voltage converters (*electromagnetic, capacitor*), which hinders their use in Ukraine. But the future belongs to *optoelectronic* primary voltage converters in high-voltage networks.

1.8 Electromagnetic transformers voltage

1.8.1 The principle of operation of an electromagnetic transformer voltage

The most common primary voltage measuring transducers are voltage transducers based on the *electromagnetic principle - voltage transformers (VTs)*.

To ensure the unification of secondary equipment, a standard scale was introduced. The secondary rated voltages are as follows. These are the voltages 100 V - linear; $100/\sqrt{3}$ V - phase;

100/3 V - on the secondary windings connected in an open triangle. The primary voltages of voltage transformers are also standardized and have the following values: 3, 6, 10, 15, 20, 24, 27, 35, 110, 150, 220, 330, 500, 750 kV.

Let's take a closer look at the principle of operation of a voltage transformer. A voltage transformer is a transformer whose core is made of high

high-quality transformer steel, the primary winding of which (1) is connected to the high voltage network (A, B, C) (Fig. 5.1), and the secondary winding (2) is connected to the corresponding load - relay protection devices, automation, electricity meters, etc.

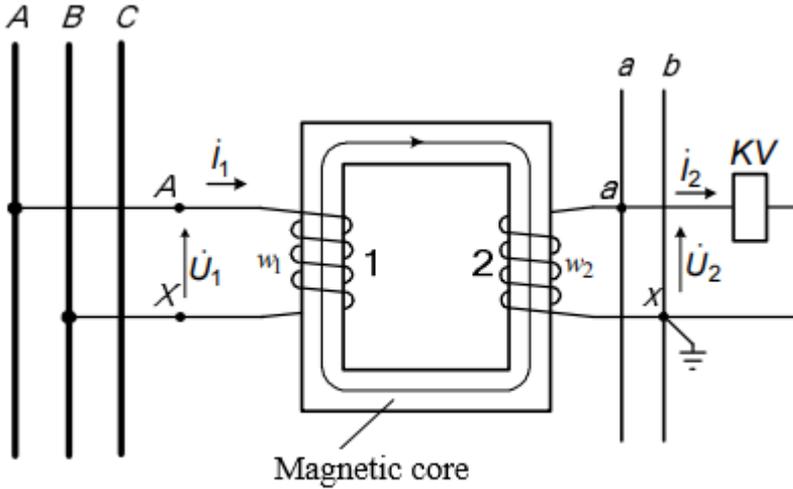


Fig. 5.1. Diagram of a two-winding voltage transformer

On the primary winding (number of turns w_1) of the voltage transformer under the influence of primary voltage \dot{U}_1 , a current \dot{I}_1 , flows, which creates a magnetizing force $\dot{F}_1 = \dot{I}_1 \cdot w_1$. Under the influence of this magnetizing force in the transformer magnetic circuit a magnetic flux Φ_1 is created, which induces an emf \dot{E}_2 in the secondary winding. If the secondary winding is closed to the load, then under the influence of this EMF in the secondary winding (number of turns w_2) will flow current, which, in turn, will create watt magnetizing force $\dot{F}_2 = \dot{I}_2 \cdot w_2$ and, accordingly, magnetic flux Φ_2 . The flux Φ_2 will oppose the magnetic flux Φ_1 according to Lenz's law. Magnetizing forces, generated by the primary and secondary windings and their corresponding magnetic fluxes are summed to create the resulting magnetic flux $\Phi = \Phi_1 + \Phi_2$. If magnetic coupling between the primary and secondary windings is replaced by an electric one, we obtain a design diagram of a voltage transformer (Fig. 5.2). In the diagram are the primary current \dot{I}'_1 , the current of the magnetizing \dot{I}'_μ and the primary voltage \dot{U}'_1 .

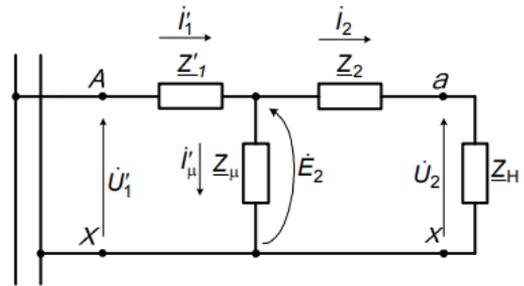


Fig. 5.2. Design diagram of a voltage transformer

The vector diagram of a voltage transformer built according to the design scheme (Fig. 5.2) is shown in Fig. 5.3.

The magnetic flux Φ lags behind the magnetization

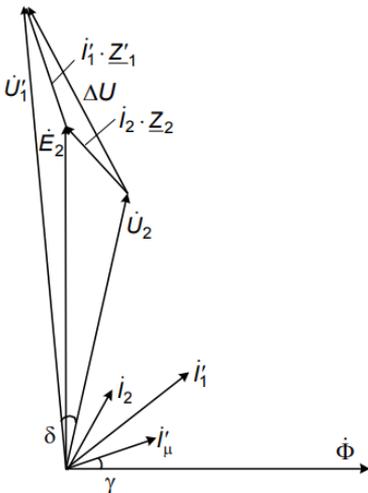


Fig. 5.3. Vector diagram of a voltage transformer

current \dot{I}'_{μ} by an angle γ , which determines active losses in the magnetic circuit of a voltage transformer. For changes flow cohesion $\dot{\psi}_2 (\dot{\psi}_2 = \dot{\Phi} \cdot w_2)$ in secondary winding of the transformer is induced by the EMF \dot{E}_2 , under the action of which the load end for loads with impedance \underline{Z}_H secondary winding will flow current $\dot{\Phi}_2$. The voltage on the secondary winding will differ from the EMF \dot{E}_2 by the amount of voltage drop $\dot{I}_2 \cdot \underline{Z}_2$ on the secondary winding of the voltage transformer. The voltage applied to the primary winding \dot{U}'_1 will differ from the EMF \dot{E}_2 by the amount of voltage drop $\dot{I}_1 \cdot \underline{Z}_1$ on the reduced value of the complex resistance of the primary winding of the voltage transformer. The ratio of turns of the primary and secondary windings is called the transformation ratio of the voltage transformer. In the absence of load on the voltage transformer, when $\dot{I}_2 = 0$, the current in the primary winding is equal to the transformer magnetization current $\dot{I}'_1 = \dot{I}_{\mu}$. We call this mode non-working. In this mode, the reduced value of the primary voltage \dot{U}'_1 differs slightly from the EMF \dot{E}'_2 , because at the nominal primary voltage $U_1 = U_{nom}$ the magnetization current of the TN is not more than 1% of the nominal primary current ($I_m \ll I_{1nom}$), the value $\Delta U \ll U_{1nom}$ and $U_2 \approx U_{2nom}$. Therefore, the transformation ratio of the voltage transformer can be defined as the ratio of the primary and secondary nominal voltages

$$k_{tv} \approx \frac{w_1}{w_2} \approx \frac{U_{1nom}}{U_{2nom}} \quad (5.1)$$

1.9 Features of transformer modes voltage in networks with isolated and compensated neutral

The vast majority of voltage transformers operate in 6-35 kV networks, i.e. in networks with an isolated or compensated neutral. In Ukraine, more than 10 thousand voltage transformers operate in the networks of these voltage classes. There are some peculiarities in the operation of these networks (this is described in detail in Section 7.8, "Protection of lines against single-phase earth faults in networks with insulated or compensated neutrals"). Experience has shown that in such networks, voltage transformers are most often damaged in the event of single-phase earth faults. According to statistics, in networks with earth fault currents of up to 10 A, 6-10% of installed voltage transformers fail annually. Voltage transformers in rural areas are particularly prone to damage - up to 20%. The consequences of damage to voltage transformers include:

- lowering the level of electrical safety, since voltage transformers are used in electrical networks to control the insulation of electrical equipment;
- possible damage to other power equipment of the substation, as damage to voltage transformers is sometimes accompanied by explosions and burning;
- Impossibility of accurate calculation of the consumed electricity, because the voltage circuits of electricity meters are powered by voltage transformers.

Therefore, power grids are constantly working to improve the resistance of voltage transformers to modes that cause damage.

The analysis of accidents and scientific studies have shown that the main causes of damage to voltage transformers are single-phase ground faults accompanied by arc burning and ferroresonance processes in electrical networks.

When metallic single-phase earth faults occur, the currents in the primary windings of voltage transformers increase by 1.5 times the nominal values, but these modes do not lead to voltage transformer failure. Therefore, they are not dangerous for voltage transformers in terms of thermal stability.

A completely different nature of processes occurs during the occurrence of single-phase earth faults accompanied by arc burning. The transient process accompanied by arc burning depends on many factors: the transient resistance of the arc gap, the intensity of its cooling, the duration of burning, the

maximum value of currents, the rate of change of currents during the transition through zero, the values of the critical voltage during arc extinction, etc. However, as the studies have shown, the essential factors that affect the nature of the arc and, as a result, the nature of the transient process are:

- the magnitude and nature of the current at the point of the earth fault;
- breakdown voltage of the arc gap.

Each arc ignition and extinguishment is accompanied by surges in the magnetization current of the VT, which results in an increase in the primary current of voltage transformers to several amperes. If this process continues for a long time, it leads to thermal destruction of the primary winding of the voltage transformer. Phase-to-earth arcing faults in networks with an isolated or compensated neutral cause damage to almost half of all damaged voltage transformers. Moreover, such modes, due to the occurrence of overvoltage, can cause damage to other equipment. According to statistics, 5-12% of complete switchgear systems fail as a result of such damage.

Another danger for electrical networks with an isolated neutral is the occurrence of *ferroresonance processes*. According to the definition given in the physics dictionary, "*ferroresonance is a resonance in the presence of an iron core choke in the circuit, the inductance of which is not a constant value but a function of current*". Ferroresonance is accompanied by an increase in current, which is determined by the voltage from an external source and the ratio of the parameters of the circuit, which consists of inductances and capacitances connected in series or in parallel. In electrical networks, power transformers and electromagnetic voltage transformers with ferromagnetic magnetic cores have variable inductance. The capacitance is the capacitance of the electrical network equipment (lines, busbars, etc.). Therefore, there are parametric conditions for the occurrence of ferroresonance processes. In addition, the dynamic inductance of the transformer winding depends on changes in the flux coupling and current of this winding $L_d = \frac{d\psi}{di}$. Since the magnetization characteristic of the inductance of transformers is nonlinear, this inductance will vary within a wide range (Fig. 5.12). There is always a point on the transformer magnetization curve at which the dynamic inductance of the transformer is equal to the equivalent network capacity, i.e., the conditions for ferroresonance occurrence.

Power transformers of 6/0.4 kV and 10/0.4 kV can resonate with the grid during partial-phase or under-loaded modes. A sequential ferroresonance (voltage ferroresonance) occurs: the nonlinear inductance of the power transformer is the equivalent capacitance of the network. This ferroresonance is accompanied by a significant increase in the phase voltages of the network relative to the ground, which in turn leads to

to growth of currents in primary windings of transformers voltages, that connected to this network. The currents in the primary winding of the CT can reach even 2 A, and if this process occurs for several minutes, it will lead to thermal destruction of the CT primary winding.

Parallel ferroresonance (current ferroresonance) can occur in the voltage transformer - electrical network circuit. The parametric causes of this ferroresonance are the equivalent capacitance of the network relative to ground and the nonlinear dynamic inductance of the voltage transformer.

Parallel ferroresonance in electrical networks is much more common than serial ferroresonance.

Ferroresonance can occur at or above the industrial frequency or below the industrial frequency. Ferroresonance at the industrial frequency or higher frequencies can occur when power transformers or voltage transformers are connected to unloaded busbars. In this mode, when resonance occurs at higher than rated frequencies, the currents in the primary windings of voltage transformers usually do not exceed the rated value. Therefore, they do not pose a direct threat to voltage

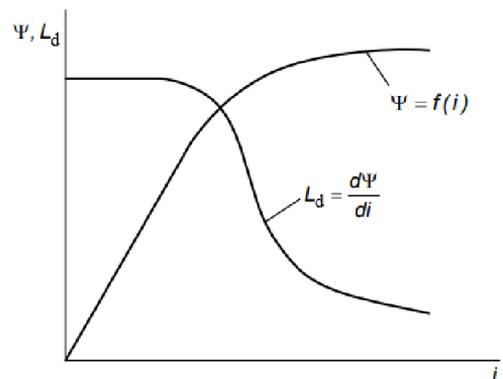


Fig. 5.12. Dependence of the flow coefficient Ψ windings with a ferromagnetic core and the dynamic inductance L_d from the current i

transformers, but in this case, the voltage of the busbar phases (due to the resonant component) relative to ground increases significantly. Then the voltages on the secondary windings of voltage transformers also increase, and the voltage on the open triangle increases, which can lead to false tripping of the protection against single-phase faults on

ground. Such ferroresonant oscillations, as shown by operating experience, occur at frequencies of 50 Hz, 100 Hz and 150 Hz. At a resonant frequency equal to (close to) the industrial frequency of 50 Hz, busbar phase overvoltages occur at this frequency, leading to a significant increase in long-term overcurrents in the primary windings of the CTs and their thermal damage.

Ferroresonance processes at subharmonic frequencies are particularly dangerous for voltage transformers. Such processes are caused by disturbances in electrical networks. Particularly dangerous are the conditions after single-phase earth faults have been disconnected. After disconnection of a single-phase earth fault, ferroresonance processes may occur at frequencies of 16.6 Hz, 25 Hz, accompanied by significant overvoltages (up to four times the nominal phase value), and as a result, the flow of long-lasting overcurrents in the primary windings of voltage transformers, which leads to their thermal damage.

The following measures can be taken to prevent the occurrence of a ferroresonant circuit or its detuning:

- you can turn off the supply. Prolonged shutdown of the power supply after the ferroresonance process has occurred is unacceptable, because the power supply to all consumers powered by the substation busbars is lost;

- To disrupt the ferroresonant process by detuning the ferroresonant circuit, the equivalent capacitance of the electrical network can be changed. To do this, you can turn off parallel lines or turn on additional capacitor banks. It is not advisable to disconnect the lines, as the power supply to consumers is lost. Installing additional capacitor banks requires significant funds, so this method is not widely used in power grids;

- to disrupt the ferroresonance process, it is possible to turn off the voltage transformer if it is the cause of its occurrence. However, this is quite difficult to do, because the HV transformers on the high voltage side do not have switches. Therefore, this method of disrupting ferroresonance processes has not been used in electrical networks either.

To prevent the occurrence of ferroresonance processes in networks with isolated neutrals, other methods, no less effective than the above, and cheaper, are proposed.

One of the methods of preventing ferroresonant processes is to reduce the quality factor of the ferroresonant circuit by introducing an active resistance into the ferroresonant circuit. The active resistance is introduced into the zero-sequence circuit, since this is the ferroresonant circuit. The active resistance can be introduced into both the primary and secondary circuits. Fig. 5.13 shows the schemes of including the active resistance in the primary circuit.

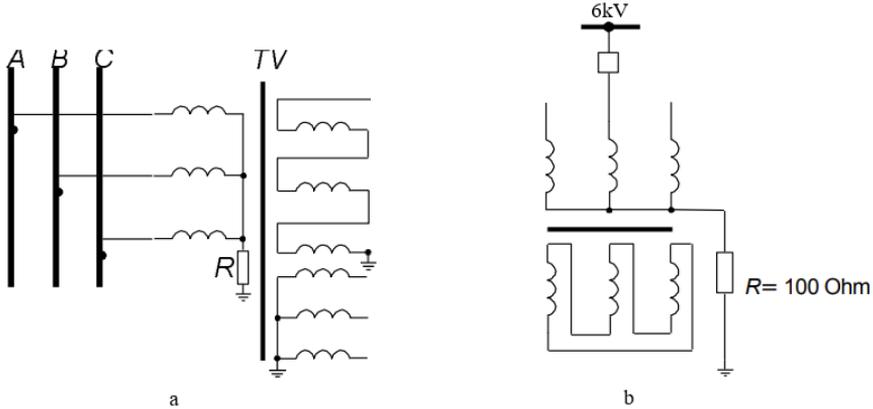


Fig. 5.13. Diagrams of active resistance inclusion in the primary circuit: a - voltage transformer, b - power transformer

For voltage transformers (Fig. 5.13, a), this method is effective, but it has some drawbacks, the main ones being:

- the measurement error of the VT increases, its accuracy class decreases, and this is unacceptable given that VTs feed electricity metering circuits;
- efficiency is not ensured for the entire possible range of capacitive currents of the power grid;
- complexity of execution, since high-voltage resistors must be installed in the primary circuit of the voltage transformer.

Therefore, this method is not widely used.

In some schemes, for example, in the scheme of auxiliary power supply of nuclear power plants (NPPs) use a special additional

A 63 kVA transformer operating without load, the neutral of the primary winding of which is grounded through a resistor (Fig. 5.13, b). However, this method has not found wide application in electrical networks, because it requires the installation of an additional trans and the formulator and high-voltage resistor.

The method of including an active resistance in the secondary winding of a voltage transformer connected in an open triangle is proposed. The PUE

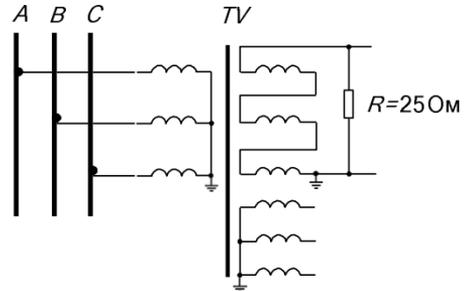


Fig. 5.14. Diagram of the active resistance inclusion in the secondary circuit of a voltage transformer

for this resistor (Fig. 5.14) is recommended to be sized for the required shifting of the neutral (grounded neutral) when measuring voltages with a voltage transformer. This method improves the quality factor of the ferroresonant circuit.

The inclusion of an active resistance of 25 Ohm (Fig. 5.14) in the secondary winding of a transformer prevents ferroresonance processes from developing at the frequencies of the subharmonics, but it cannot significantly affect the nature of the subharmonics.

One of the methods of combating ferroresonance processes is the introduction of a reactor of the NAMI type since the 90s. The schematic diagram of the reactor is shown in Fig. 5.15. In this transformer, two high-voltage windings are connected in series to the \dot{U}_{BC} , and the third winding

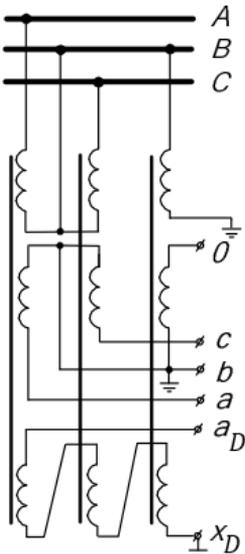


Fig. 5.15. Schematic diagram of an anti-ferroresonant voltage transformer of the NAMI type

The high-voltage line is connected between phase B and ground, i.e. instead of three high-voltage phases, as in traditional voltage transformers such as NTMI, ZNMI, only one phase is grounded. In addition, the number of winding turns was significantly increased, which made it possible to increase the active and inductive resistances of the windings and reduce the operating induction of the transformer magnetic circuit by three times. This design makes it virtually impossible for voltage transformers to fail due to series resonance, and also shifted the zone of occurrence of ferroresonance processes to the area of lower earth fault currents - up to 1 A. Therefore, antiresonant transformers have proven to be more reliable traditional transformers such as NTMI and ZNOL. However, cases of failure of these transformers during ferroresonance processes, especially on subharmonics, have been recorded. Thus, the introduction of such voltage transformers into operation could not completely solve the problem.

The introduction of a non-resonant voltage transformer (VTN) developed by the staff of the Department of Electrical Systems and Networks of Lviv Polytechnic National University has most effectively solved the problem of counteracting the occurrence of ferroresonant processes. The schematic diagram of the nonresonant voltage transformer NTN-10 is shown in Fig. 5.16.

The non-resonant voltage transformer is made on the basis of two single-phase trans voltage formers TV1 and TV 2 and a divider voltage $C_1 - C_2$. High-voltage windings of trans formers voltages on according to incomplete triangle scheme and switched to linear voltages \dot{U}_{AB} and \dot{U}_{BC} . Between the common phase B of both voltage transformers and the ground on non-capacitive capacitive divider $C_1 - C_2$. So, The high-voltage windings of the transformer are isolated from the ground, which makes it impossible to generate ferroresonance processes, as the ferroresonant circuit is eliminated.

The VL arrester prevents high voltages from entering the secondary voltage circuits in the event of loss of capacity of the tank. C_2 , or breaks in the circuit of this/

A non-resonant voltage transformer, as can be seen in Fig. 5.16, allows you to directly control the voltages $u_{ab}, u_{(cb)}, u_b$.

Therefore, to obtain the remaining voltages, an additional module (measuring device) is installed, in which the remaining voltages are obtained from the three voltages above. For this purpose, the following equations are realized using the appropriate algorithm:

$$\begin{aligned} u_a &= u_{ab} + u_b; \\ u_c &= u_{cb} + u_b; \\ u_{ca} &= u_{cb} + u_{ab}; \\ 3 \cdot u_0 &= u_{cb} + u_{ab} + 3 \cdot u_b. \end{aligned} \tag{5.2}$$

The first samples of a non-resonant voltage transformer were obtained as a result of modernization of damaged serial voltage transformers of the NAMI type. Operation of NTN series transformers has shown their high efficiency - none of these transformers has failed in several years of operation

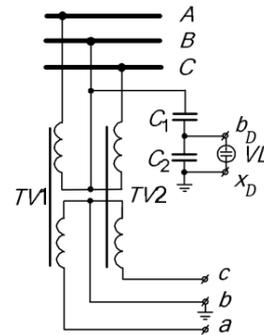


Fig. 5.16. Schematic diagram of a non-resonant transformer voltage NTN-10

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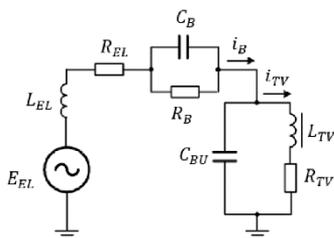


Fig. 5.17. Design scheme of a series-parallel ferroresonant circuit

Ferroresonance processes that damage voltage transformers can also occur in networks with effectively grounded neutrals. Operating experience has shown that phenomena occur when a voltage transformer of the NKF

type is connected to the busbars and all other connections are disconnected, i.e. the busbars are in a non-operational state. However, the busbars are connected to the grid through the capacitive dividers of the switched off circuit breakers of the branches. Under such conditions, the following is created series-parallel ferroresonant circuit (Fig. 5.17). This circuit creates the capacitance of the circuit breaker dividers, the capacitance of the busbars and other equipment connected to these busbars, and also nonlinear inductance voltage transformer.

After switching off the circuit breakers of all busbar connections (differential busbar protection tires etc.), for a certain ratio of parameters schemes Fig. 5.17, there is a long-lasting, usually, *subharmonic* ferroresonance process (FRP). As a result of the FRP, long-lasting subharmonic phase overvoltages occur in the busbar system (BUS) and at the terminals of the primary of the CT windings connected to these busbars. These overvoltages cause prolonged overcurrents in the primary windings of the CTs, which leads to thermal damage (burnout) of the winding insulation (primarily the inter-turn insulation).

In Fig. 5.17, it is denoted: L_{EL} R_{EL} - equivalent active resistance and inductance the power grid; R_B is the active resistance of the circuit breakers in the open state; C_B is the total capacitance of the voltage dividers of the circuit breakers; C_{BU} is the equivalent capacitance tires and connected to them equipment; L_{TV} -nonlinear inductance of the voltage transformer; R_{TV} is the active resistance of the voltage transformer windings.

The existing means of protecting voltage transformers of networks with effectively grounded neutral from damage during FF, such as the introduction of counter emf or the inclusion of an active resistance to the secondary winding of the VT, are not always effective. This is due to the fact that these means begin to act only after the occurrence of ferroresonance processes. The method proposed by the staff of the Department of Electrical Systems and Networks at Lviv Polytechnic National University is more effective. It prevents the occurrence of ferroresonance processes. The bottom line. This method is as follows. The disconnection of the last busbar connection is monitored. As soon as a signal is received to turn off the circuit breaker of the last connection, a signal is simultaneously received to a high-speed electronic device that immediately switches on a low-impedance active resistance in the secondary winding of the voltage transformer. That is, even when the voltage transformer is under the influence of the operating voltage, its secondary winding is shunted by the active resistance. As a result, the initial induction of the VT core at the moment of disconnection of the last connection of the busbar is significantly lower than the nominal induction, especially the saturation induction. After disconnecting the last connection, the induction on the magnetic curve of the core starts to rise towards saturation, but with the correct choice of the active resistance, it does not reach saturation, at which a stable ferroresonance process occurs. The active resistance is switched on in the secondary winding of the heating element for a short time only for the duration of the transient process and until it is completely attenuated (up to 0.5 s). Then this resistance is automatically switched off and the CT switches to normal mode. Thus, the quenching resistance is connected to the CT secondary winding faster than the contacts of the circuit breaker of the last connection open, which leads to the occurrence of a long-lasting FF, thereby preventing the occurrence of overvoltage and overcurrents that can cause damage to the CT.

Based on the proposed principle, a prototype was developed and installed at the Kalush substation of the Western Power System to protect the NKF-220 voltage transformer installed on the 220 kV busbar section from ferroresonance phenomena. Field experiments have shown its high efficiency.

? *Questions for self-examination*

1. *What is the purpose of a primary voltage converter?*
 2. *Tell us about the principle of operation of the electromagnetic primary current converter - voltage transformer.*
 3. *Give the conventional and positional designation of the voltage transformer.*
 4. *Provide a design diagram and a vector diagram of a voltage transformer.*
 5. *Why is the operating mode of a voltage transformer close to the no-load mode?*
 6. *What are the connection diagrams for the secondary windings of voltage transformers?*
 7. *What is the principle of operation of a capacitor voltage transformer?*
 8. *Give the reasons for the occurrence of ferroresonance in networks with an isolated neutral and its effect on voltage transformers.*
- What measures are used to reduce the impact of ferroresonance phenomena on voltage transformers?*

Chapter 6 OPERATING CURRENT SOURCES

Automation, control, alarm, and relay protection devices require power from external sources of electrical energy to operate. These sources are called *operating current sources*. In practice, *sources of alternating and direct operating currents* are used.

Since operating current sources determine the performance of automation, control, relay protection devices, etc., they are subject to increased requirements for reliable operation.

Rechargeable batteries are the most reliable sources of *direct current*. The main advantage of this type of direct current source is its independence from the operating mode of power plants and substations, i.e. even in the event of a complete blackout of power equipment at power plants or substations, their automation, control, alarm, and relay protection devices will continue to function. In addition, the batteries can withstand significant short-term overloads, which is especially important in emergency situations when several protection, automation and control systems are operating simultaneously and consuming a significant amount of electricity.

The schematic diagram of the organization of direct operating current with the use of batteries is shown in Fig. 6.1.

The source of the operating current is the *GB1* and *GB2* batteries. To recharge the batteries, special chargers *UGV1* and *UGV2* are designed, powered by AC sources. The diagram (Fig. 6.1) shows a DC operating current source with two rechargeable batteries that increase the reliability of the source's operation as usual. The switch *SA* is used to switch to power from battery *GB1* or *GB2*. The operating current (+) and (-) busbars supply power to automation, control, relay protection devices, etc. (see diagram *A1 ÷ AN*).

Along with the obvious advantages of a DC-DC power supply with

The use of rechargeable batteries has some disadvantages, the main ones being:

- high cost of rechargeable batteries;
- the need for a special room for placing batteries; the complexity of organizing a DC network over a large area of a power plant or substation;
- the need for highly qualified service personnel.

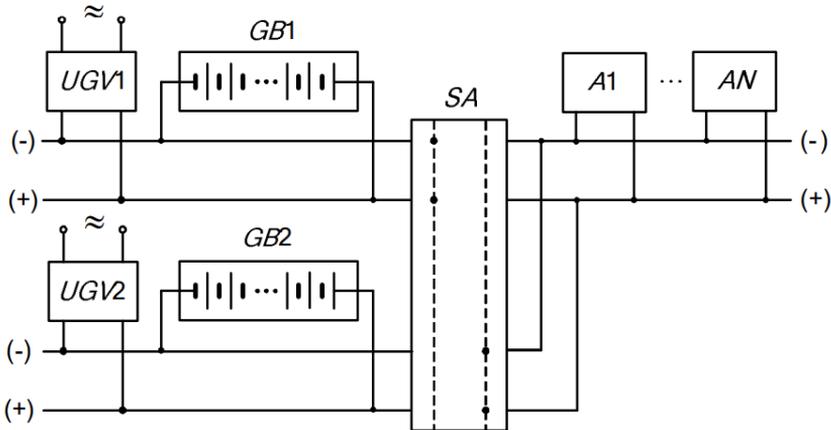


Fig. 6.1. Schematic diagram of the DC operating current with the use of rechargeable batteries

That is why DC-operating current circuits are used at facilities with permanently present operating personnel, such as power plants and powerful substations. Typically, DC circuits are used for voltages of ± 220 V, ± 110 V, occasionally ± 48 V or ± 24 V. At powerful power plants and substations, two identical batteries are used, while smaller substations use a single battery.

This type of operating current is impractical to use at substations with a voltage of 110 kV and below, where there are usually no operating personnel. At these substations, alternating or rectified operating current sources are mostly used.

To obtain *rectified operating current*, special rectifier devices are used, which can be powered by the secondary circuits of measuring transformers - current or voltage, or by the substation's own power supply network. This type of operating current is used to power complex, for example, step protectors, which require a constant operating current to operate.

If the measured operating current is obtained only from a voltage transformer or auxiliary transformer, it must be remembered that it should be used only to power equipment that is not intended for operation at close short-circuit conditions, when deep voltage drops on the ehe devices include overload protection, transformer oil level protection, and transformer oil level protection. Such devices include overload protection, transformer oil level protection, etc.

Therefore, to increase the reliability of RSA and other secondary equipment, such as switchgear trip solenoids, combinations of several sources of operating current are used.

A schematic diagram of the organization of *the combined rectified operating current* is shown in Fig. 6.2. The rectified operating current is obtained from the rectifier units *UGA*, *UGV*, which rectify the alternating current received from the secondary circuits of the measuring transformers - current *TA1*, *TA2* and voltage *TV* or substation auxiliary transformers (AT), respectively.

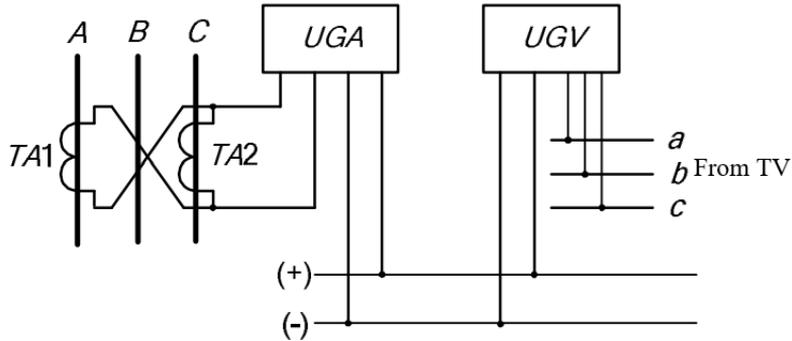


Fig. 6.2. Schematic diagram of the organization of combined operating current

The UGA power supply units connected to the secondary circuits of current transformers consist of an intermediate fast-saturating transformer *TLA* (Fig. 6.3, a), a two-half-period rectifier *VD*. To ensure ferroresonance stabilization, a choke *L* and a capacitance *C* are connected in series to the secondary winding of the intermediate transformer. Ferroresonance occurs in the circuit: magnetization branch of the intermediate transformer *TLA* - choke *L* - capacitance *C*. The input characteristic of the UGA block, taking into account the effect of ferroresonance, is shown in Fig. 6.3, b. As can be seen from Fig. 6.3, b, due to ferroresonance, the voltage of the block changes slightly when the current changes (curve 2). If the ferroresonance effect was not used in the circuit, the voltage-current dependence would have the form 1, i.e., depending on the load, the voltage would vary in a significant range.

The UGV unit (Fig. 6.2) is connected to the secondary circuits of the TV voltage transformer or to the substation's own needs transformer (NTC). The schematic diagram of the UGV unit is shown in Fig. 6.4.

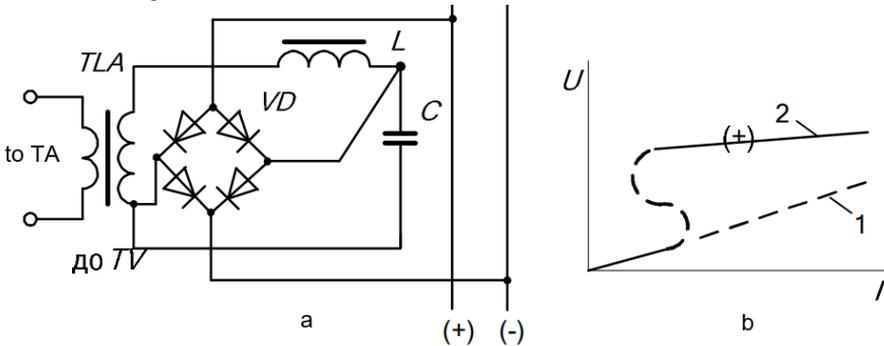


Fig.

6.3. Schematic diagram (a) and input characteristic of the current rectifier block UGA

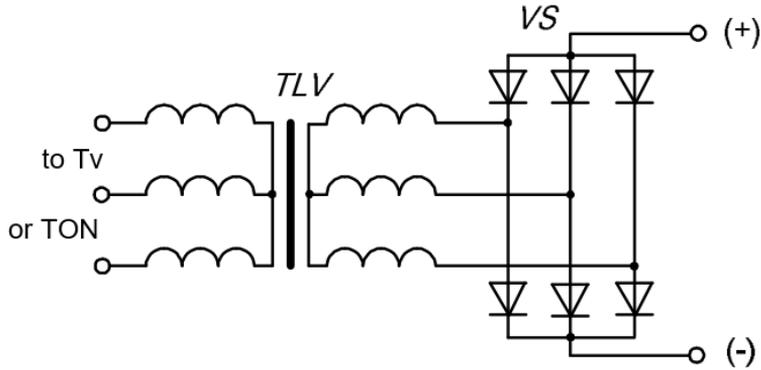


Fig. 6.4. Schematic diagram of the UGV voltage test unit

The UGV device consists of an intermediate transformer *TLV*, a semi-reverse three-phase rectifier bridge *VS*, whose outputs are used to remove the rectified voltage.

To increase reliability, substations use combined schemes for generating rectifier current - simultaneously using rectifier units *UGA*, *UGV*. These units are connected in parallel on the side of the rectified current (Fig. 6.2).

Depending on the power, different types of rectifier units are manufactured and put into operation by the industry. For example, the BPT-11 unit is a rectifier unit designed to be connected to the secondary circuits of current transformers, with a maximum permissible load on the rectified current side of the unit of 20-25 W; BPN-11 is a rectifier unit powered by voltage circuits with the same permissible load (20-25 W). Similar units BPT-1001, BPN-1001 can supply loads with a power of 500-1200 W.

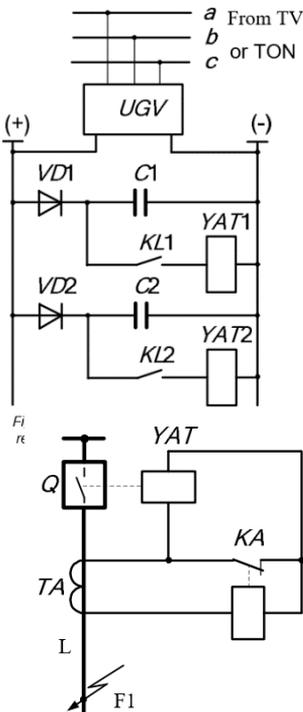


Fig. 6.6. Diagram of direct power supply with alternating operating current

In practice, capacitors are often used together with sources of rectified operating current (Fig. 6.5).

In this scheme, in the pre-failure mode, capacitors *C1* and *C2* are continuously charged from the *UGV* test unit. After a fault has occurred and the relay protection devices have tripped (for example, the output relays of the *KL1* or *KL2* protections have tripped (the windings of these relays are not shown in the diagram), the contacts of the output relays of the *KL1* or *KL2* protections close. After that, the capacitors *C1* or *C2* are discharged to the trip magnets of the circuit breakers *YAT1* or *YAT2* - the circuit breaker of the damaged bay is switched off. The capacitors are selected so that their energy is sufficient to operate the trip solenoids *YAT1*, *YAT2*. Diodes *VD1* and *VD2* are designed to ensure that capacitors *C1* and *C2* are discharged only on their elements and do not discharge on adjacent ones. A significant advantage of this scheme is that even in the event of a complete loss of power at the substation, the substation equipment will be controlled by the energy of pre-charged capacitors.

The simplest and cheapest sources of AC power are

current transformers installed at the substation.

In practice, there are two schemes of alternating operating current obtained from current transformers:

- scheme of direct AC power supply to the operational circuits from the main current transformer of the substation's TS (Fig. 6.6);
- AC power supply circuit of the operational circuits from the intermediate current transformer *TIA* (Fig. 6.7).

The circuit shown Fig. 6.6 works as follows. In normal operation, the trip magnet of the switch *YAT* is shunted by the normally closed contacts of the relay *KA*, so that no current flows through it. After the occurrence of a short circuit at point F1 on line L, when the current in relay

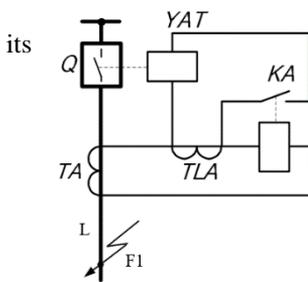


Fig. 6.7. Schematic diagram of the alternating operating current using an intermediate current transformer *TIA*

KA is greater than the relay trip setpoint, the latter will trip and open contact. After that, the secondary current from the current transformer *TA* will flow in the circuit of the series-connected windings of the relay *KA* and the trip magnet *YAT*. The electromagnet will trip and the faulty line circuit breaker *Q* will close.

The scheme shown in Figure 6.7 works like this.

During the fault at point F1, the current in line L increases and, accordingly, in the secondary winding of the current transformer *TA* and the primary winding of the intermediate transformer *TIA* and the relay winding *CA* connected to it in series.

When the current in the relay *CA* winding reaches a value sufficient to trip it, the latter will trip and close the circuit supplying the tripping solenoid *YAT* from the intermediate current transformer *TIA*. The *YAT* solenoid will trip and the *Q* circuit breaker will close.

Although the circuit shown in Fig. 6.6 is simpler than the one shown in Fig. 6.7, it has a significant drawback - it requires a current relay of *the* spacecraft with powerful contacts capable of switching a circuit with significant currents.

? Questions for self-examination

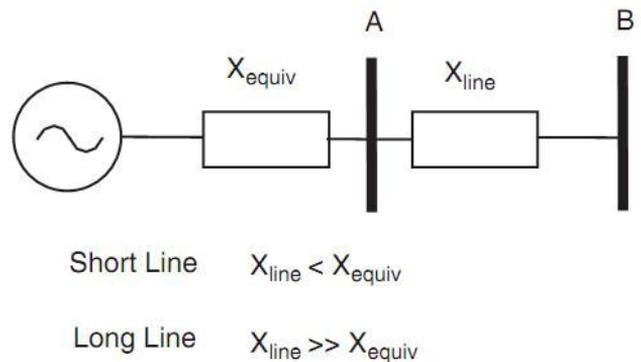
1. What is the purpose of operating current sources?
 2. What are the main types of operating current sources?
 3. Give a comparative characterization of the operating current sources.
- What is the purpose of using ferroresonant stabilization in a current power supply?
?

Chapter 7 PROTECTION OF TRANSMISSION LINES

Transmission lines are primarily exposed to short circuits between phases or from phase to ground. This is also the main source of damage to all other electrical equipment. The range of the possible fault current, the effect of load, the question of directionality and the impact of system configuration are all part of the transmission line protection problem. The solution to this problem, therefore, is a microcosm of all other relaying problems and solutions. Since transmission lines are also the links to adjacent lines or connected equipment, the protection provided for the transmission line must be compatible with the protection of all these other elements. This requires coordination of settings, operating times and characteristics.

A radial system, i.e. one with a single generating source, can have fault current flowing in only one direction: from the source to the fault. In a loop or network, however, fault current can flow in either direction, and the relay system must be able to distinguish between the two directions.

The length of the line, as one would expect, has a direct effect on the setting of a relay, there is no appreciable impedance between the end of one line segment and the beginning of the next. A relay, therefore, cannot be set on fault current magnitude alone in order to differentiate between a fault at the end of one zone or the beginning of the next. The problem is further complicated if the line is short, that is, as shown in Figure, its impedance is much less than the source impedance. In such a case there is very little difference in current magnitude for a fault at one end of the line compared to a fault at the other. It is then difficult to set a relay so that it only protects its own line and does not overreach into the next.



In order of ascending cost and complexity, the protective devices available for transmission line protection are:

- | | |
|----|-----------------------------------|
| 1. | fuses. |
| 2. | sectionalizers, reclosers. |
| 3. | instantaneous overcurrent. |
| 4. | inverse, time delay, overcurrent. |
| 5. | directional overcurrent. |
| 6. | distance. |
| 7. | pilot. |

Fuses, sectionalizers, reclosers:

The distribution system is divided into mains and laterals. The mains are three-phase systems providing the backbone of the distribution service; the laterals are single-phase taps connected to the mains. Industrial and commercial customers that require three-phase service are

fed from the mains. Residential and smaller industrial customers are usually serviced by the laterals. It is the function of the distribution planning engineer to equalize the single-phase loads so the load at the substation is essentially balanced.

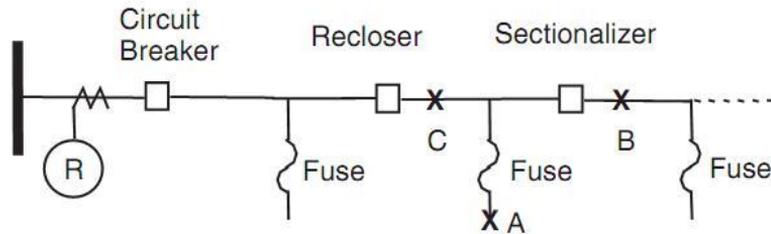
Figure shows a single-line representation of a typical distribution circuit. In practice, the horizontal feeder would be a three-phase main and each tap would be a single-phase load, each load coming from a different phase.

there is some concern over the safety and potential physical damage that could occur from a violent

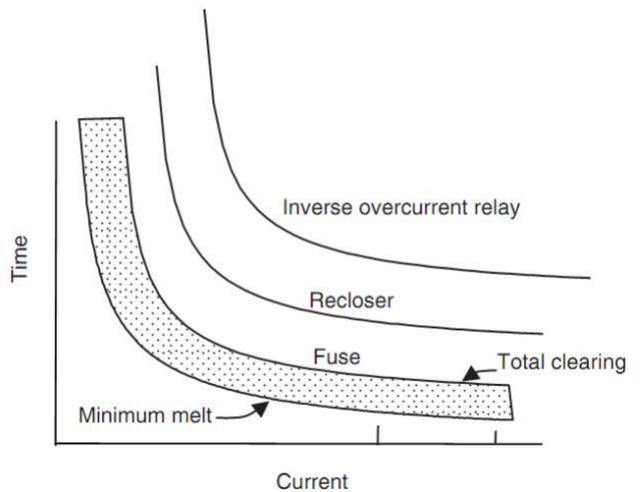
type of failure. This has led to the application of current-limiting (CL) fuses, which drastically reduce the 'let-through' energy for a high-current fault compared to other types of fuse. The most commonly used protective device in a distribution circuit is the fuse. Fuse characteristics vary considerably from one manufacturer to another, and the specifics must be obtained from manufacturers' appropriate literature.

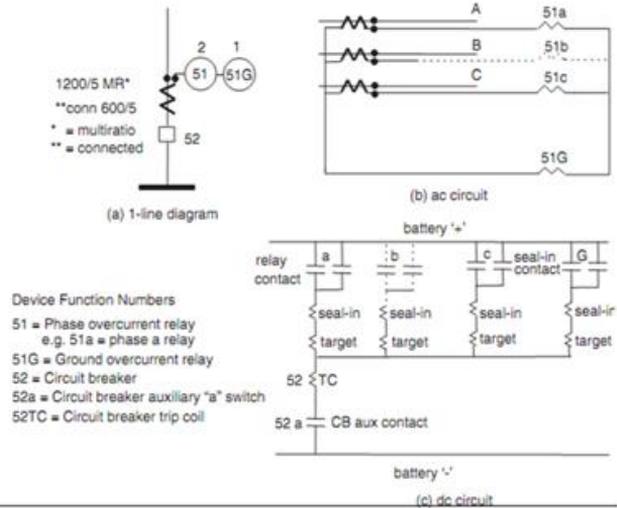
The interrupting devices, in addition to the fuse itself, are sectionalizers and reclosers. A sectionalizer cannot interrupt a fault. It 'counts' the number of times it 'sees' faultcurrent and opens after a preset number while the circuit is de-energized. A recloser has limited fault-interrupting capability and recloses automatically in a programmed sequence.

Referring to Figures, a fault at A should be cleared by the branch fuse, leaving service to the main line and to the other branches undisturbed. A fault at B should be cleared by the sectionalizer, but, since the sectionalizer cannot interrupt a fault, the actual clearing is performed by the recloser.



The sectionalizer 'sees' the fault current, however, and registers one count. The recloser also sees the fault and trips, de-energizing the line. If the sectionalizer setting is '1' it will now open, allowing the recloser to reclose and restore service to the rest of the system. If the sectionalizer setting is more than '1', e.g. '2', the sectionalizer will not open after the first trip. Instead, the recloser recloses a second time. If the fault is still on, the sectionalizer will see a second count of fault current. The recloser will trip again, allowing the sectionalizer now to open, removing the fault, and the recloser will successfully reclose, restoring service up to the sectionalizer. For a fault at C, the recloser trips and recloses as it is programmed to do. The sectionalizer does not see the fault and does not count.





Inverse, time-delay

overcurrent relays:

The principal application of overcurrent relays is on a radial system where they provide both phase and ground protection.

Setting rules:

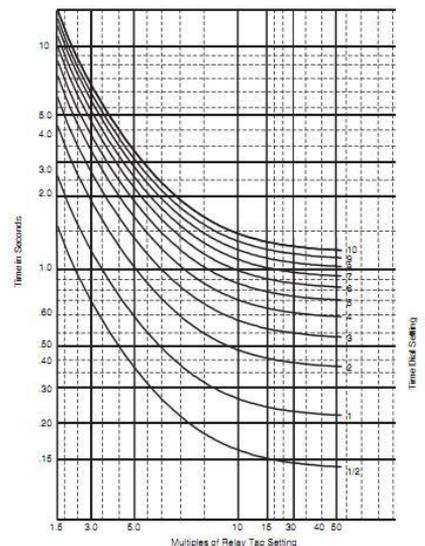
There are two settings that must be applied to all time-delay overcurrent relays: the pickup and the time delay.

1. Pickup setting:

This is a fundamental function and it must be set so it will always operate for faults in that zone of protection. This will require margins above normal operating currents and below minimum fault currents.

If possible, this setting should also provide backup for an adjacent line section or adjoining equipment such as a line-terminated transformer. It should be emphasized, however, that the backup function is a secondary consideration.

The pickup of a relay (as shown in Figure) is the minimum value of the operating current, voltage or other input quantity reached by progressive increases of the operating parameter that will cause the relay to reach its completely operated state when started from the reset condition.



2. Time-delay setting:

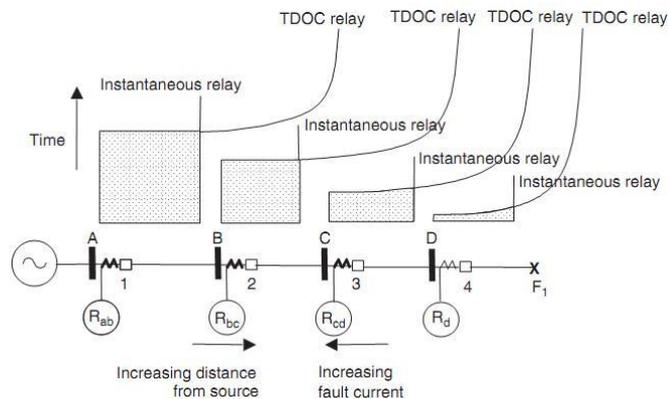
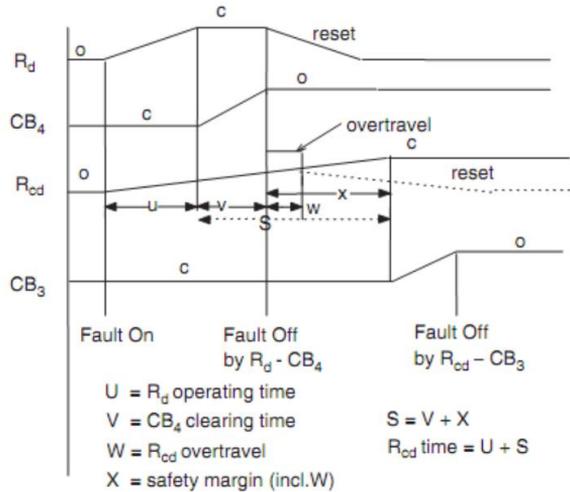
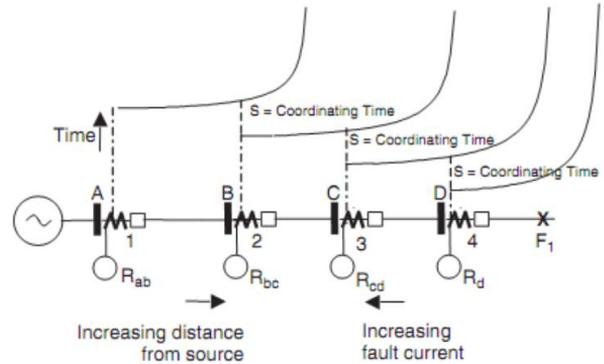
The time-delay feature of the relay is an independent parameter that is obtained in a variety of ways, depending on the design of the relay.

The dial is marked from a setting of 1/2 to 10, This is an inverse time–current relationship, i.e. the greater the operating current, the less time it takes to travel from the reset position to the operating position.

The purpose of the time- delay setting is to enable relays to coordinate with each other. A family of curves must be provided so two or more relays, seeing the same fault as defined by the multiples of pickup, can operate at different times.

The principle of relay coordination can be explained by reference to Figure which shows a series of radial lines and the time–distance characteristics of the associated inverse-time relays. These are relay operating curves selected for each of the relays, plotted as a function of fault location. Since the magnitude of the fault current decreases as the fault moves away from the source.

For fault F1 at the end farthest from the generating source, relay Rd, tripping breaker (4), operates first; relay Rcd at breaker (3) has a higher time lever setting which includes a coordinating time delay S to let breaker (4) trip if it can; similarly, relay Rbc, at breaker (2), coordinates with the relay at breaker (3) by having a still longer time delay (including the same coordinating time S); and finally, relay Rab at breaker (1) has the longest time delay and will not trip unless none of the other breakers trips, provided it can see the fault, i.e. provided the fault current is greater than its pickup setting.



□ Instantaneous overcurrent
relays:

The closer the fault is to the source, the greater the fault current magnitude, yet the longer the tripping time. The addition of instantaneous overcurrent relays makes this system of protection viable. If an instantaneous relay can be set to see almost up to, but not including, the next bus, all of the fault-clearing times can be lowered, as shown in front Figure

Setting rules:

Since the instantaneous relay must not see beyond its own line section, the values for which it must operate are very much higher than even emergency loads. Therefore, load is not usually a consideration for the instantaneous relay settings, As a result, there is no need to set an instantaneous overcurrent relay with margins such as 200% of load and one-third of fault current.

In order to overcome transient overreach problem, It is common to set an instantaneous relay about 125–135% above the maximum value for which the relay should not operate, and 90% of the minimum value for which the relay should operate.

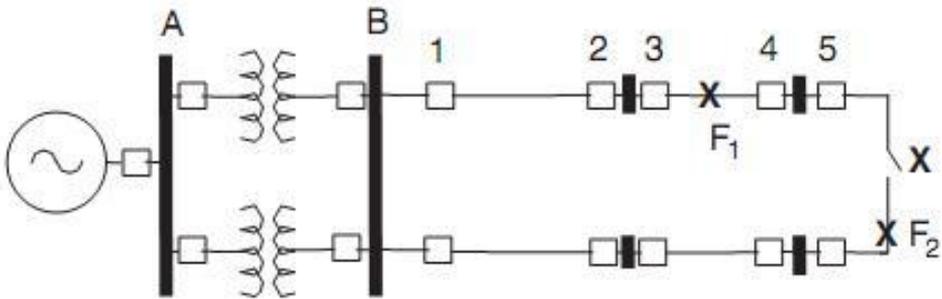
□ Directional overcurrent
relays:

Directional overcurrent relaying is necessary for multiple source circuits, when it is essential to limit relay tripping for faults in only one direction. It would be impossible to obtain correct relay selectivity through the use of a nondirectional overcurrent relay in such cases. If the same magnitude of the fault current could flow in either direction at the relay location, coordination with the relays in front of, and behind, the nondirectional relay cannot be achieved except in very unusual system configurations. Therefore, overcurrent relaying is made directional to provide relay coordination between all of the relays that can see a given fault.

Directional relays require two inputs, the operating current and a reference, or polarizing, quantity (either voltage or current) that does not change with fault location.

Referring to Figure, with switch X closed, assume that the current through (4) and (5) for

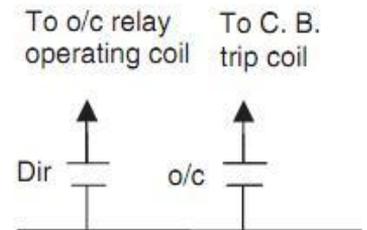
a fault at F1 is 100 A and for a fault at F2 is 400 A. Setting the relay at (4) for pickup at 25 A gives $4 \times pu$ for the fault at F1 and $16 \times pu$ for the fault at F2. This relay must, therefore, be directional to see faults only in the direction from breaker (4) to breaker (3). Setting the relay at (5) at 125 A, however, allows it to have $3.2 \times pu$ for the fault in its protected zone at F2, but less than $1.0 \times pu$ for the fault at F1. It therefore does not have to be directional. However, such a condition may change with system growth and pass unnoticed until a false trip occurs. It is therefore good practice to use directional relays at both locations.



There are two approaches to providing directionality to an overcurrent relay:

1. Directional control.:

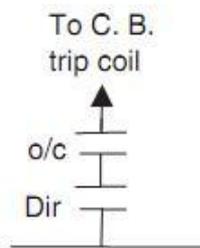
the design of the relay is such that the over-current element will not operate until the directional element operates, indicating that the fault is in the tripping direction.



Directional control (a)

2. Directional overcurrent.:

this relay has independent contacts, connected in series with the circuit breaker trip coil. Both relay contacts must close before a trip output is obtained.



Directional o/c (b)

□

distance protection:

Distance relays are normally used to protect transmission lines. They respond to the

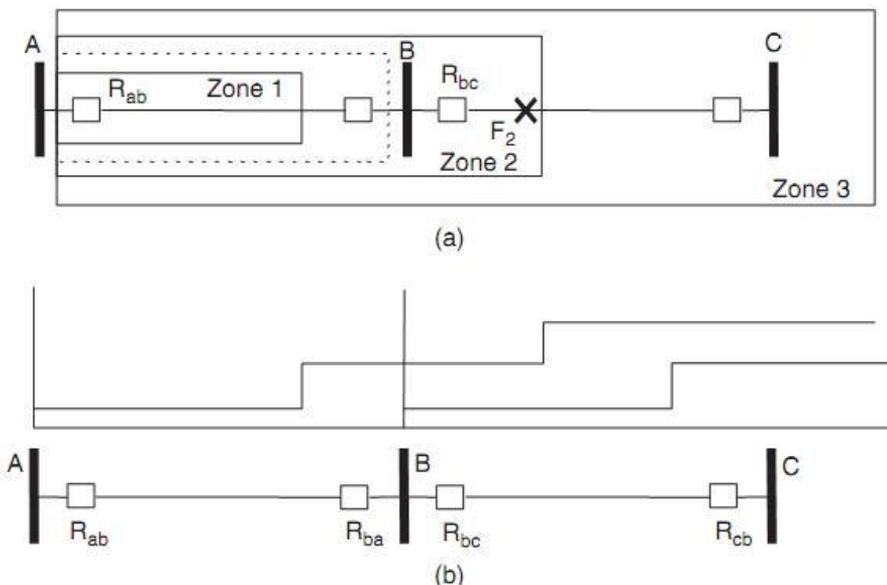
impedance between the relay location and the fault location. As the impedance per mile of a transmission line is fairly constant, these relays respond to the distance to a fault on the transmission line – and hence their name. Similar principles are applicable in case of a three-phase transmission line, provided that appropriate voltages and currents are chosen to energize the distance relay. The R–X diagram is an indispensable tool for describing and analyzing a distance relay characteristic, and we will examine it initially with reference to a single-phase transmission line.

The distance relay is set to underreach the remote terminal. The corollary to this definition, of course, is that the relay will see faults less than the setting. ‘Overreaching’ protection is a form of protection in which the relays at one terminal operate for faults beyond the next terminal. They may be constrained from tripping until an incoming signal from a remote terminal has indicated whether the fault is beyond the protected line section.

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Referring to Figure , the desired zone of protection is shown with a dotted line. The ideal situation would be to have all faults within the dotted area trip instantaneously.

Owing to the uncertainty at the far end, however, to be sure that we do not overreach the end of the line section, we must accept an underreaching zone (zone 1). It is customary to set zone 1 between 85 and 90% of the line length and to be operated instantaneously.

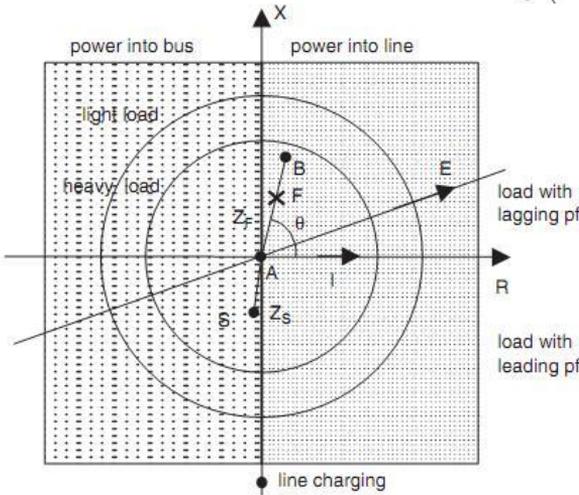
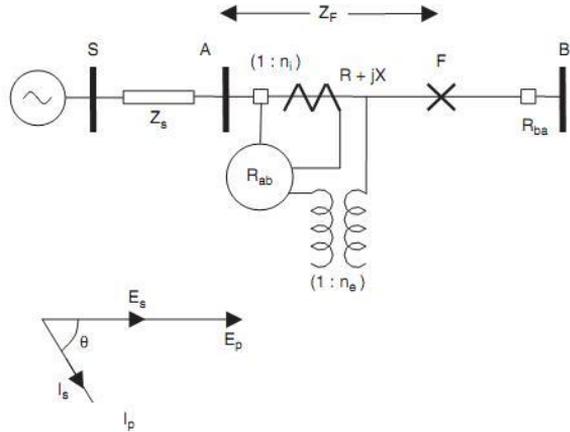


the area between the end of zone 1 and bus B is not protected. Consequently, the distance relay is equipped with another zone, which deliberately overreaches beyond the remote terminal of the transmission line. This is known as zone 2 of the distance relay, and it must be slowed down to be 0.3s, The reach of the second zone is generally set at 120–150% of the line length AB.

In order to provide a backup function for the entire line, it is customary to provide yet another zone of protection for the relay at A. This is known as the third zone of protection, and usually extends to 120–180% of the next line section. The third zone must coordinate in time and distance with the second zone of the neighboring circuit, and usually the operating time of the third zone is of the order of 1 s.

□ R–X diagram

For the product-type relay, such as the distance relay, analyzing the response of the relay for all conditions is difficult because the voltage varies for each fault, or varies for the same fault but with different system conditions. To resolve this difficulty, it is common to use an R–X diagram to both analyze and visualize the relay response. By utilizing only two quantities, R and X (or Z



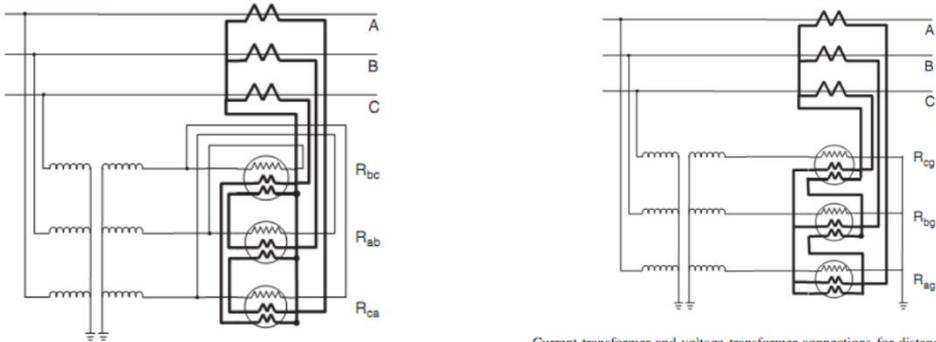
and θ), we avoid the confusion introduced by using the three quantities E, I and θ . There is an additional significant advantage in that the R–X diagram allows us to represent both the relay and the system on the same diagram. Consider an ideal (zero resistance) short circuit at location F in the single-phase system shown in Figure.

Now consider the fault at location F as shown in previous Figure . The corresponding apparent impedance is shown at F in Figure . As the location of the fault is moved along the transmission line, the point F moves along the straight

line AB in Figure 5.5. Thus, the transmission line as seen by the relay maps into the line AB in the R–X plane. The line AB makes an angle θ with the R axis, where θ is the impedance angle of the transmission line. (For an overhead transmission line, θ lies between 70° and 88° , depending upon the system voltage, the larger angles being associated with higher transmission voltages.) When the fault is on the transmission line, the apparent impedance plots on the line AB; for all other faults or loading conditions, the impedance plots away from the line AB.

□ for distance relay (3-ph)

Connections of c.t. and v.t.



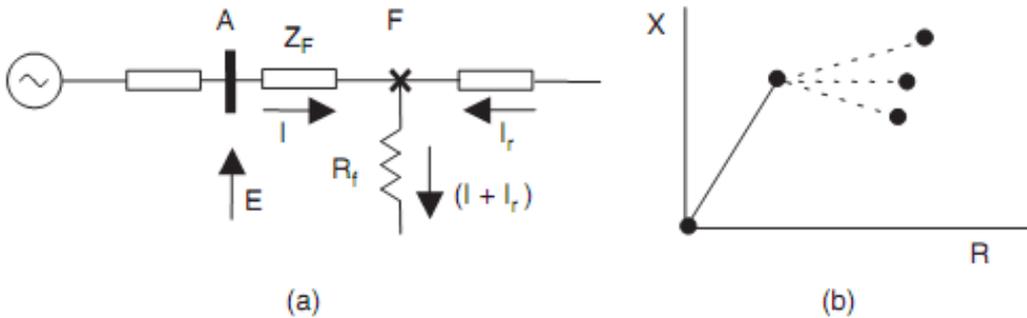
Current transformer and voltage transformer connections for distance relays for ground faults

Current transformer and voltage transformer connections for distance relays for phase faults

□

Fault resistance:

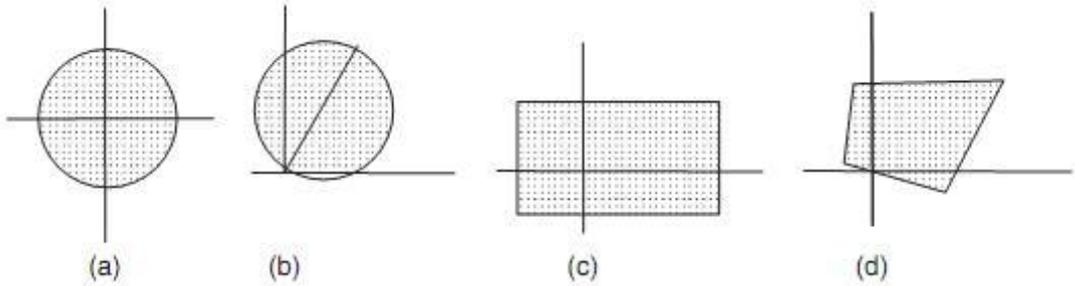
the fault path will have a resistance in it, which may consist of an arc resistance or an arc resistance in series with the tower footing resistance in the case of a ground fault. The tower footing resistance is practically constant during the fault (and ranges between 5 and 50), whereas the arc resistance changes in time as the fault current continues to flow. During the early period of the arc, say in the first few milliseconds, the arc resistance is negligible, and as the arc channel gets elongated in time, the arc resistance increases. the fault arc resistance for a 345 kV transmission line fault at a place with short-circuit capacity of 1500 MVA is $(76 \times 3452/1500 \times 103) \sim = 50$. The fault resistance introduces an error in the fault distance estimate, and hence may create an unreliable operation of a distance relay.



Fault path resistance, and its effect on the R-X diagram

Distance relay types:

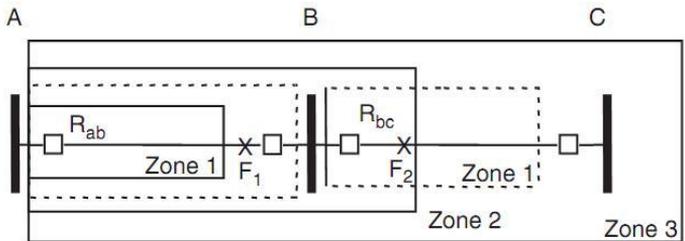
Four general relay types are recognized according to the shapes of their operating zones: (1) impedance relays, (2) admittance or mho relays, (3) reactance relays and (4) quadrilateral relays. These four relay characteristic shapes are illustrated in Figure:



The impedance relay has a circular shape centered at the origin of the R–X diagram. The admittance (or mho) relay has a circular shape which passes through the origin. The reactance relay has a zone boundary defined by a line parallel to the R axis. The zone extends to infinity in three directions as shown in Figure (c). The quadrilateral characteristic, as the name implies, is defined by four straight lines. This last characteristic is only available in solid-state or computer relays.

Pilot protection of transmission lines:

nonpilot protection using overcurrent and distance relays, contain a fundamental difficulty. It is not possible to instantaneously clear a fault from both ends of a transmission line if the fault is near one end of the line. This is due to the fact that, in detecting a fault using only information obtained at one end, faults near the remote end cannot be cleared without the introduction of some time delay. there is always an uncertainty at the limits of a protective zone. to avoid loss of coordination for fault at F₂, the relays at terminal B trip



instantaneously by the first zone and the relays at terminal A use a time delay for second zone or backup tripping. This results in slow clearing for a fault at F₁. The ideal solution would be to use the differential principle.

The communication channels generally used are:

- power line carrier
- microwave
- fiber optics
- communication cable.

The relaying schemes can be classified as directional comparison, phase comparison, current differential or pilot wire depending on the type of sensing used, and are further described as blocking, unblocking or transfer trip depending on how the transmitted signal is used.

The transfer trip schemes are again divided into direct, permissive underreaching and permissive overreaching. There are, of course, advantages and disadvantages associated with each

scheme and the specific application depends on all of the individual factors and conditions involved.

Directional distance relaying is the most commonly used throughout the world, but it has application and setting problems when series capacitors are present. Phase comparison and current differential are immune to such problems, and only require current inputs, eliminating the need for potential sources.

4.2. ROTATING MACHINERY PROTECTION:

The protection of rotating equipment involves the consideration of more possible failures or abnormal operating conditions than any other system element. Although the frequency of failure, particularly for generators and large motors, is relatively low, the consequences in cost and system performance are often very serious.

Some of the abnormal conditions that must be dealt with are the following:

1. Winding faults: stator – phase and ground fault
2. Overload
3. Overspeed
4. Abnormal voltages and frequencies.

For generators we must consider the following.

5. Underexcitation
6. Motoring and startup. For motors we are concerned with the following.
7. Stalling (locked rotor)
8. Single phase
9. Loss of excitation (synchronous motors).

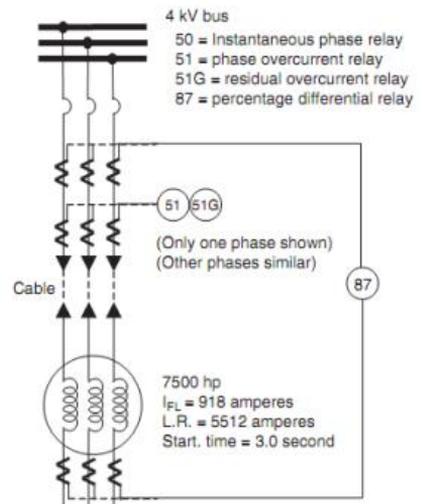
4.2.1. Stator faults:

Phase fault protection:

For short circuits in a stator winding, it is standard practice to use differential protection on generators rated 1000 kVA or higher and on motors rated 1500 hp or larger or rated 5 kV and above. Rotating equipment provides a classic application of this form of protection since the equipment and all of the associated peripherals such as current transformers (CTs), breakers, etc. are usually in close proximity to each other, thereby minimizing the burden and possible error due to long cable runs.

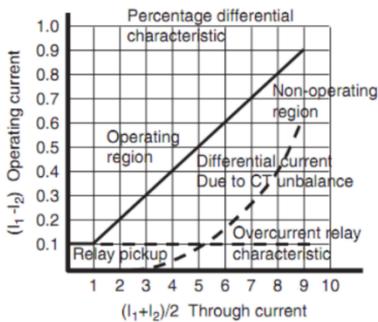
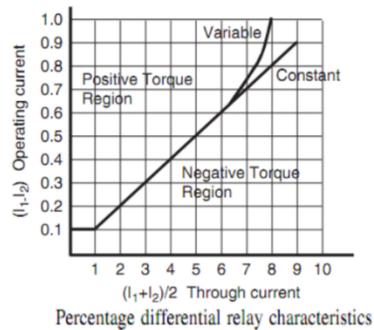
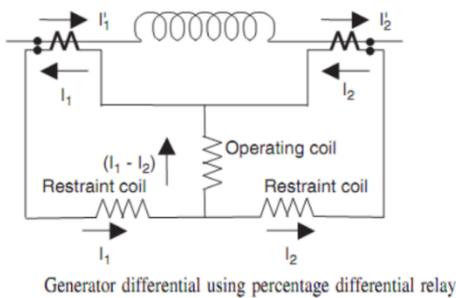
The CTs used for the generator differential are almost invariably located in the buses and leads immediately adjacent to the generator winding. This is done to limit the zone of protection so a fault in the generator is immediately identifiable for quick assessment of damage, repair and restoration of service.

In motor differential circuits, three CTs should be located within the switchgear in order to include the motor cables within the protection zone. The other three CTs are located in the neutral connection of the motor. Six leads must be brought out of the motor: three on

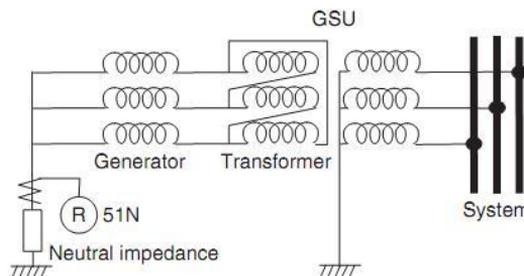


the incoming cable side to connect to the switching device and three on the motor neutral to accommodate the CTs before the neutral connection is made (refer to Figure). Above 1500 hp this is standard manufacturing practice. Below 1500 hp the provision and connections for the CTs must be specified when the motor is purchased. This arrangement would be ideal if the CTs always reproduced the primary currents accurately. Actually, however, the CTs will not always give the same secondary current for the same primary current, even if the CTs are commercially identical. The difference in secondary current, even under steady-state load conditions, can be caused by the variations in manufacturing tolerances and in the difference in secondary loading, i.e. unequal lengths of leads to the relay, unequal burdens of meters and instruments that may be connected in one or both of the secondaries. What is more likely, however, is the ‘error’ current that can occur during short-circuit conditions.

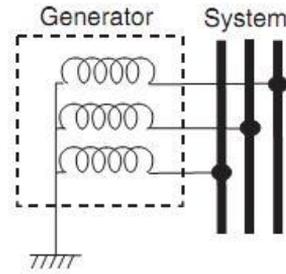
The percentage differential relay solves this problem without sacrificing sensitivity. The schematic arrangement is shown in Figures □



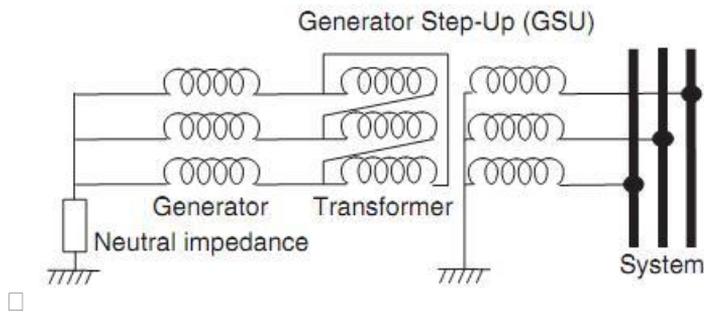
Ground fault protection:



The affects the that is by solidly phase fault to relay, as in Figure method of grounding amount of protection provided differential relay. When the generator is grounded, there is sufficient current for a phase-to-ground operate almost any differential



If the generator has a neutral impedance to limit ground current, there are relay application problems that must be considered for the differential relays that are connected in each phase. as shown in Figure



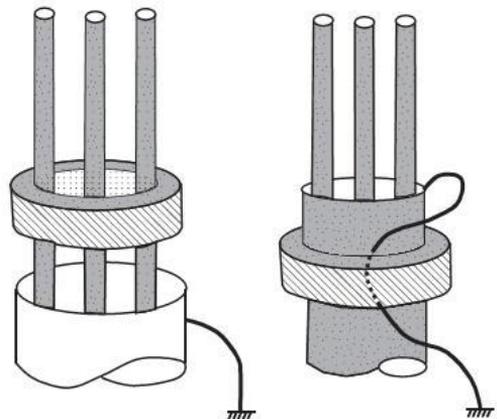
The higher the grounding impedance, the less the fault current magnitude and the more difficult it is for the differential relay to detect low-magnitude ground faults.

If a CT and a relay are connected between ground and the neutral point of the circuit, , sensitive protection will be provided for a phase-to-ground fault since the neutral relay (51N) sees all of the ground current and can be set without regard for load current.as shown in Figure □

As the grounding impedance increases, the fault current decreases and it becomes more difficult to set a current-type relay. The lower the relay pickup, the higher is its burden on the CT and the more difficult it is to distinguish between ground faults and normal third harmonic unbalance. This unbalanced current that flows in the neutral can be as much as 10–15% of the rated current. Other spurious ground current may flow due to unbalances in the primary system. The total false ground.

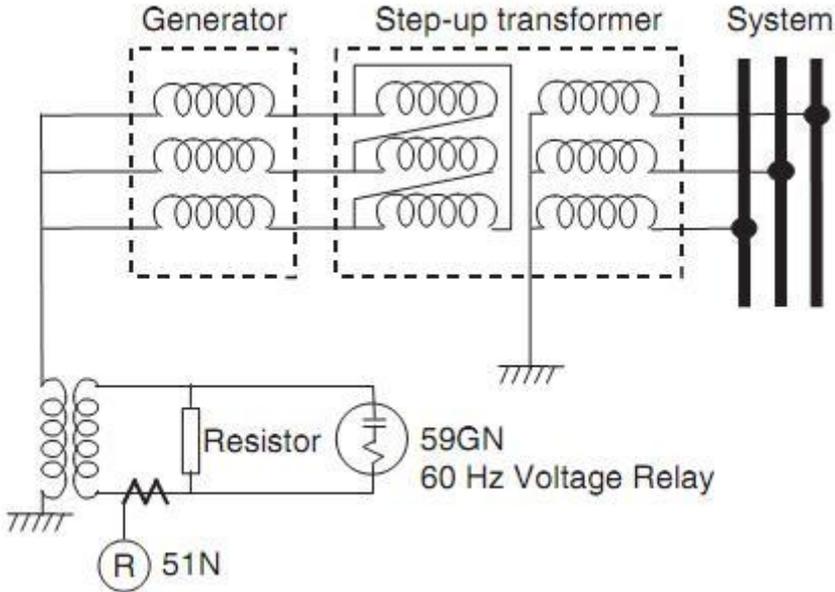
An alternative to the residually connected ground relay in motor applications is the toroidal CT, shown in Figure

The CT ratio can be any standard value that will provide the relay current from the available



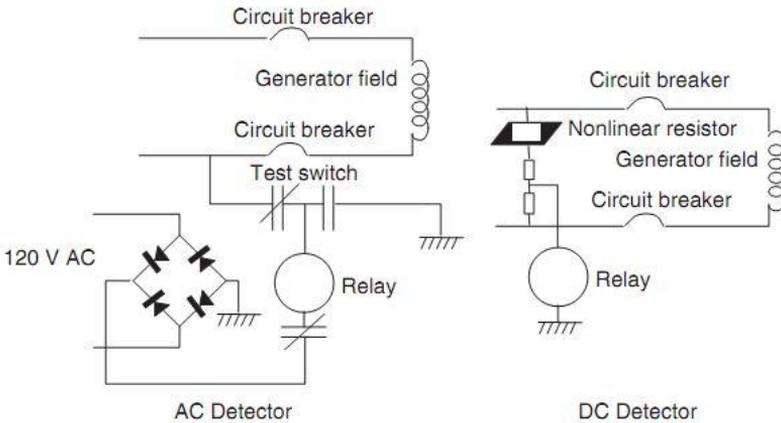
ground current for adequate pickup. Since there will be no error current, the relay can be an instantaneous relay set at a low value.

If a generator is connected directly to a grounded transmission system, as shown before, the generator ground relay may operate for ground faults on the system. It is therefore necessary for the generator ground relay to coordinate with any other relays that see the same fault. If the generator is connected to the system through a wye-delta transformer, zero sequence current cannot flow in the generator bus beyond the delta connection of the step-up transformer. Faults on the wye side will, therefore, not operate ground relays on the delta side. as shown in Figure □



4.2.2. Rotor faults:

The field circuits of modern motors and generators are operated ungrounded. Therefore, a single ground on the field of a synchronous machine produces no immediate damaging effect. However, the existence of a ground fault stresses other portions of the field winding, and the occurrence of a second ground will cause severe unbalance, rotor iron heating and vibration.



Two commonly applied field ground detection schemes. The ground in the detecting circuit is permanently connected through the very high impedance of the relay and associated circuitry. If a ground should occur in the field winding or the buses and circuit breakers external to the rotor, the relay will pick up and actuate an alarm. as shown in Figure □

The primary concern with rotors in squirrel-cage induction motor construction or insulated windings in wound-rotor induction or synchronous motor construction involves rotor heating. In almost all cases, this is the result of unbalanced operation or a stalled condition. Protection is therefore provided against these situations rather than attempt to detect the rotor heating directly.

4.2.3. Unbalanced currents:

Unsymmetrical faults may produce more severe heating in machines than symmetrical faults or balanced three-phase operation. The negative sequence currents which flow during these unbalanced faults induce 120 Hz rotor currents which tend to flow on the surface of the rotor forging and in the nonmagnetic rotor wedges and retaining rings. The resulting I²R loss quickly raises the temperature.

Typical conditions that can give rise to the unbalanced generator currents are:

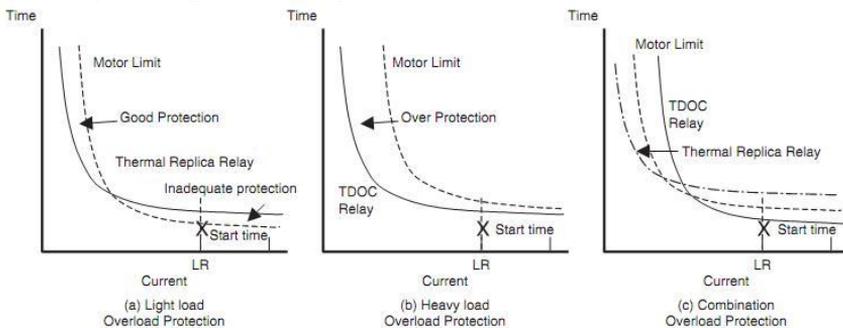
- accidental single-phasing of the generator due to open leads or buswork;
- unbalanced generator stepup transformers;
- unbalanced system fault conditions and a failure of the relays or breakers;
- planned single-phase tripping without rapid reclosing.

When such an unbalance occurs, it is not uncommon to apply negative sequence relays on the generator to alarm first, alerting the operator to the abnormal situation and allowing corrective action to be taken before removing the machine from service.

4.2.4. Overload:

Overload protection is always applied to motors to protect them against overheating. Fractional horsepower motors usually use thermal heating elements such as bimetallic strips purchased with the motor starter

Thermal overload relays offer good protection for light and medium (long-duration) overloads, but may not be good for heavy overloads as shown in (a) □



A long-time induction overcurrent relay offers good protection for heavy overloads but overprotects for light and medium overloads (b)

A combination of two devices can provide better thermal protection as in (c)

Digital relays take advantage of the ability to model the rotor and the stator mathematically and use algorithms that calculate the conductor temperature resulting from operating current, add the effect of ambient temperature, and calculate the heat transfer and the heat decay. They are therefore responsive to the effects of multiple starts.

A motor that is rotating dissipates more heat than a motor at standstill, since the cooling medium flows more efficiently. When full voltage is applied, a motor with a locked rotor is particularly vulnerable to damage because of the large amount of heat generated. If the motor fails to accelerate, stator currents may typically range from 3 to 7 or more times full load value depending on motor design and supply system impedance. Digital relays are particularly suited to this type of logic combined with temperature sensing.

Two approaches are possible to solve this dilemma.

1. Use a motor zero-speed switch which supervises an additional overload relay set for locked rotor protection.
2. Use a relay that incorporates temperature change and discriminates between the sudden increase during locked rotor and the gradual increase during load increases.

Protective practices are different for generators and motors. In the case of generators, overload protection, if applied at all, is used primarily to provide backup protection for bus or feeder faults rather than to protect the machine directly. A voltage-controlled overcurrent relay or an impedance relay can be used to distinguish between full-load and overcurrent.

4.2.5. Overspeed:

In practical situations, overspeed cannot occur unless the unit is disconnected from the system. Overspeed protection for generators is usually provided on the prime mover. Older machines use a centrifugal device operating from the shaft. More modern designs employ very sophisticated electrohydraulic or electronic equipment to accomplish the same function.

During overspeed the turbine presents a greater danger than the generator. Overspeed is not a problem with motors since the normal overcurrent relays will protect them.

4.2.6. Abnormal voltages and frequencies:

Overvoltage:

The voltage at the terminals of a generator is a function of the excitation and speed.

Overvoltage may result in thermal damage to cores due to excessive high flux in the magnetic circuits. Excess flux saturates the core steel and flows into the adjacent structures causing high eddy current losses in the core and adjacent conductor material. Severe overexcitation can cause rapid damage and equipment failure.

Overvoltage exists at 105% of rated voltage and per unit frequency or per unit voltage and 95% frequency.

Transformer can withstand up to 110% of rated voltage at no load and 105% at rated load with 80% power factor.

Undervoltage:

Undervoltage presents a problem to the generator only as it affects the auxiliary system, Low voltage prevents motors from reaching rated speed on starting or causes them to lose speed and draw heavy overloads. the overload relays will eventually detect this condition.

Overfrequency:

Overfrequency is related to the speed of the unit and is protected by the overspeed device. It is possible to use an overfrequency relay as backup to mechanical devices. overfrequency relays can alert the operator. the governing devices will protect the unit from overspeed.

Underfrequency:

Operation at reduced frequency should be at reduced kVA. Underfrequency is a system condition that affects the turbine more than the generator. The turbine is more susceptible because of the mechanical resonant stresses which develop as a result of deviations from synchronous speed.

System load shedding is considered the primary turbine underfrequency protection The amount of load shed varies with coordinating regions and individual utilities but varies from 25 to 75% of system load. additional protection is required to prevent steam turbine damage. In order to have the unit available for restart, it is desirable to trip the turbine to prevent damage. This action in itself is considered as a last line of defense and is sure to cause an area blackout.

4.2.7. Loss of synchronism:

The primary difference in the protection requirements between induction motors and synchronous motors is the effect of the excitation system. Loss of synchronism of a synchronous motor is the result of low excitation exactly as with the synchronous generator.

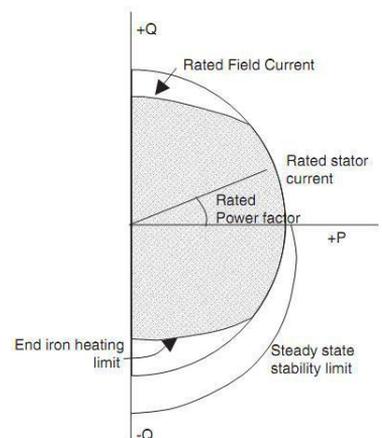
4.2.8. Loss of excitation:

When a synchronous generator loses excitation it operates as an induction generator running above synchronous speed with the system providing the necessary reactive support.

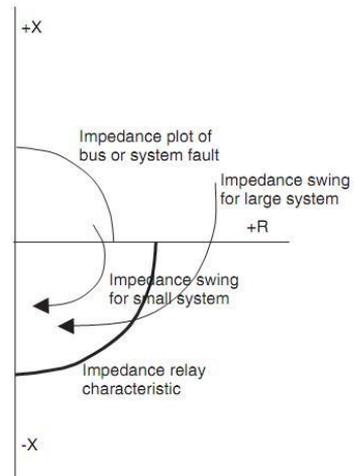
Salient-pole generators, which are commonly used with hydro machines have such damper windings and do not have the problem.

However, in addition to overheating, both salient-pole and round-rotor synchronous machines require a minimum level of excitation to remain stable throughout their load range.

The typical generator capability curve, hews the various limits associated with over- and underexcitation. The generator manufacturer supplies all of the temperature characteristics shown in Figure



How the impedance varies with loss of excitation for several system sizes. Despite the complexity of the phenomenon and the variation in conditions, the end result is surprisingly simple. Since the final impedance lies in the fourth quadrant of the R–X diagram, any relay characteristic that will initiate an action in this quadrant is applicable. Figure



In almost every case, an alarm is provided early in the locus of the impedance swing so the operator can take the appropriate corrective action. Whether this is followed by a trip after a time delay or further advance in the swing path is a utility’s decision.

4.2.9. Inadvertent energization:

A common, catastrophic mis-operation that has been reported many times involves the inadvertent closing of high-voltage breakers or switches while a unit is on turning gear or at some speed less than synchronous speed.

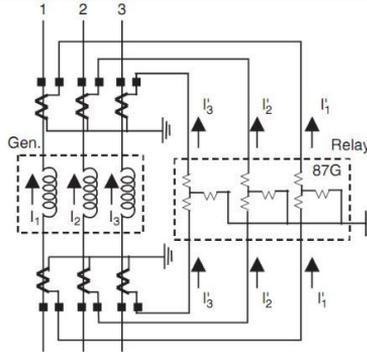
When energized in this fashion, if field has been applied, the generator behaves as a synchronous motor or generator that has been badly synchronized. The result can destroy the shaft or other rotating element. There are several causes for this incorrect switching. The same protection provided for startup can be used in this case. Some utilities use dedicated protective circuits that are activated when the unit is taken out of service.

4.2.10. Torsional vibration:

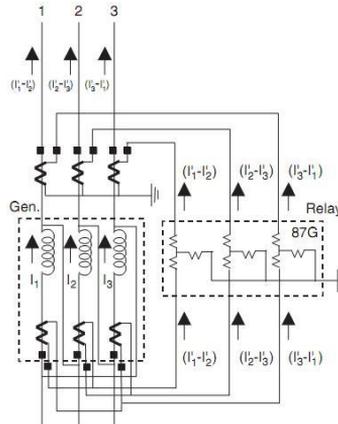
The potential for shaft damage can occur from a variety of electrical system events. In addition to short circuits or bad synchronizing, studies have indicated that subsynchronous resonance or automatic reclosing, particularly high-speed reclosing, can produce torque oscillations leading to fatigue and eventual damage.

4.2.11. Winding connections:

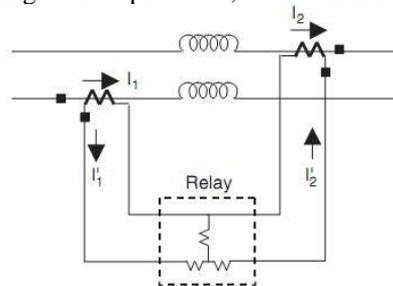
Most machines have star (wye) connections. So three relays that are connected to star-connected CTs provide both phase and ground protection. as shown in Figure.



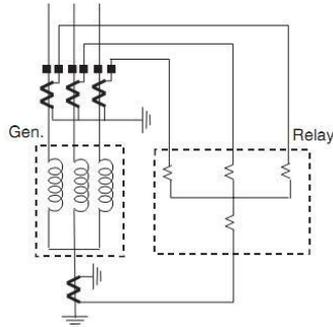
With delta-connected windings there is no connection to ground and the phase currents differ from the winding currents by $\sqrt{3}$ and a phase shift of 30° . Care must be taken to obtain correct current flow, as shown in Figure



Similarly, split-phase windings can be protected, as shown in Figure



If the neutral connection is made inside the machine and only the neutral lead is brought out, differential relays can only be provided for ground faults, as shown in Figure



4.2.12. Sequential tripping:

The purpose of sequential tripping a synchronous generator is to minimize the possibility of damaging the turbine as a result of an overspeed condition occurring following the opening of the generator breakers.

Sequential tripping is accomplished by tripping the prime mover before tripping the generator and field breakers. Reverse-power relays, pressure switches and/or valve limit switches are used to determine that the steam input has been removed and then to complete the trip sequence.

Sequential tripping is essential because overspeeding the turbine is a more damaging operating condition than motoring.

4.3. TRANSFORMER PROTECTION:

Transformer faults – i.e. short circuits – are the result of internal electrical faults, the most common one being the phase-to-ground fault. Somewhat less common are the turn-to-turn faults. Unlike a transmission line, the physical extent of a transformer is limited to within a substation, and consequently differential relaying, the most desirable form of protection available, can be used to protect transformers. In general, a transformer may be protected by fuses, overcurrent relays, differential relays and pressure relays, and can be monitored for incipient trouble with the help of winding temperature measurements, and chemical analysis of the gas above the insulating oil. Which of these will be used in a given instance depends upon several factors as:

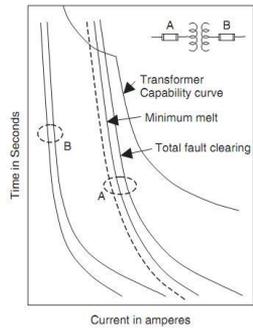
Transformer size, Location and function, Voltage, Connection and design.

4.3.1. Overcurrent protection:

As in all protection applications with overcurrent relays, the external faults or steady-state load currents must be distinguished from the currents produced by the internal faults. The effect of external faults that are not cleared promptly, or steady-state heavy loads, is to overheat the transformer windings and degrade the insulation.

Protection with fuses:

Fuses are not used to protect transformers with ratings above 2.5 MVA. The basic philosophy used in the selection of fuses for the high-voltage side of a power transformer is similar to that used in other applications of fuses. Clearly, the fuse interrupting capability must exceed the maximum short-circuit current that the fuse will be called upon to interrupt. The continuous rating of the fuse must exceed the maximum transformer load. Typically, the fuse rating should be greater than 150% of the maximum load.

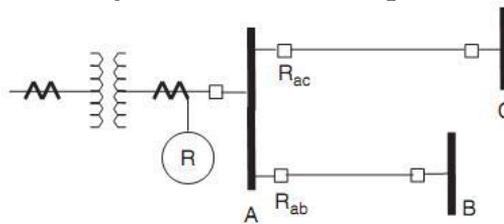


Protection of a transformer fuse: coordination principles

The minimum melt characteristic of the fuse must coordinate with (i.e. should be well separated from) the protective devices on the low side of the power transformer.

Time-delay overcurrent relays:

Protection against excessive overload, or persisting external fault, is provided by time-delay overcurrent relays. The pickup setting is usually 115% of the maximum overload acceptable. The time-delay overcurrent relays must coordinate with the low-side protective devices. These may include low-voltage bus relays for phase-to-phase faults, phase-directional relays on parallel transformers and the breaker failure relay timers on the low-voltage breakers.



Coordination of transformer overcurrent relay with feeder protection on low side

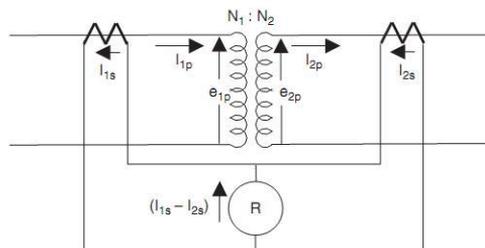
As shown in Figure, the time dial selected for the relay should coordinate with overcurrent relays Rab and Rac, which protect the feeders on the low-voltage side.

Instantaneous relays:

There are several constraints imposed upon the use of instantaneous relays; some of them depend upon the design of the relay. In all cases, of course, the relay must not operate on inrush, or for low-side faults. Peak magnetizing current in a transformer can be as high as 8–10 times peak full-load current. Since the relay will see low-side faults, one must consider these faults when they are fully offset.

4.3.2. Percentage differential protection:

Consider the single-phase, two-winding power transformer shown in Figure 8.3. During normal operation of the transformer, the algebraic sum of the ampere-turns of the primary and the secondary windings must be equal to the MMF required to set up the working flux in



Differential relay connections

the transformer core. if an internal fault develops, this condition is no longer satisfied, and the difference of i_{1s} and i_{2s} becomes much larger; in fact, it is proportional to the fault current. The differential current: $I_d = i_{1s} - i_{2s}$ provides a highly sensitive measure of the fault current. If an overcurrent relay is connected as shown in Figure, it will provide excellent protection for the power transformer.

Several practical issues must be considered before a workable differential relay can be implemented:

First, it may not be possible to obtain the CT ratios on the primary and the secondary side which will satisfy the condition $N_1n_1 = N_2n_2$.

Second, the errors of transformation of the two CTs may differ from each other, thus leading to significant differential current when there is normal load flow, or an external fault.

Finally, if the power transformer is equipped with a tap changer, it will introduce a main transformer ratio change when the taps are changed.

A percentage differential relay provides an excellent solution to this problem. In a percentage differential relay, the differential current must exceed a fixed percentage of the 'through' current in the transformer. The through current is defined as the average of the primary and the secondary currents: $i_r = (i_{1s} + i_{2s}) / 2$. The current (i_r) is known as the restraint current – a name that comes from the electromechanical relay design, where this current produced a restraint torque on the moving disc, while the differential current produced the operating torque. The relay operates when: $i_d \geq K \cdot i_r$

K: slope of the percentage differential characteristic.

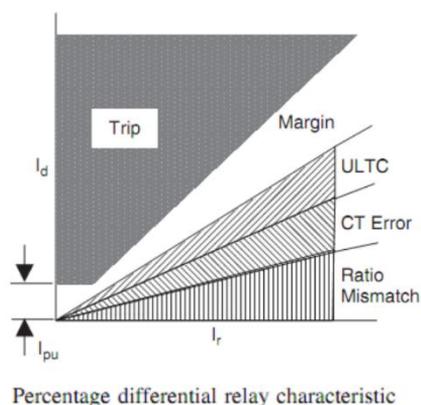
The relay has a small pickup current setting, i.e. the relay does not operate unless the differential current is above this pickup value. The pickup setting is usually set very low: typical values are 0.25 A secondary. This accounts for any residual CT errors at low values of transformer load current.

Causes of false differential currents:

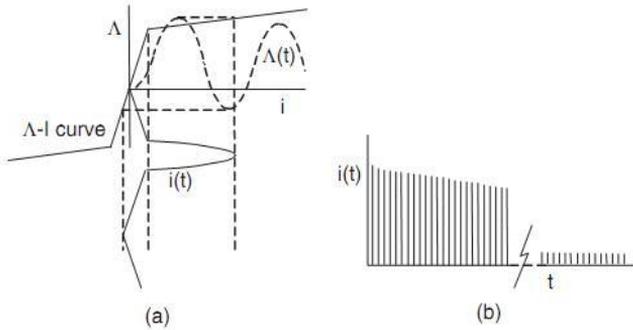
certain other phenomena cause a substantial differential current to flow, when there is no fault, and these false differential currents are generally sufficient to cause a percentage differential relay to trip, unless some special precautions are taken.

1. Magnetizing inrush current during energization:

Consider the two-slope approximation of a magnetizing characteristic shown in Figure (a). As the flux linkages go above the saturation knee point, a much larger current is drawn from the source. The magnitude of this current is determined by the slope of the magnetizing characteristic in the saturated region, and by the leakage inductance of the transformer.

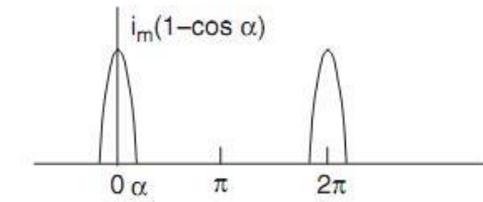


It should be clear that in most modern transformers very large inrush currents are possible, depending upon the instant of energization, and the remnant flux in the transformer core. Since the inrush current flows only in the primary and not in the secondary winding of the transformer, it is clear that it produces a differential current which is 200% of the restraining current, and would cause a false operation.



2. Harmonic content of the inrush current:

Let the magnetizing characteristic be a vertical line in the V - i plane, and be a straight line with a finite slope in the saturated region. This makes the current waveform of Figure(a) acquire the shape shown in Figure □



As we will see shortly, the false operation of a percentage differential relay for a transformer is prevented by taking advantage of the fact that the inrush current is rich in harmonic components, while the fault current is a pure fundamental frequency component (except for a possible decaying DC component).

The relative magnitude of various harmonic components with respect to the fundamental frequency component from Table up to the 13th harmonic, and for saturation angles of 60° , 90° and 120° .

Table 8.1 Harmonics of the magnetizing inrush current

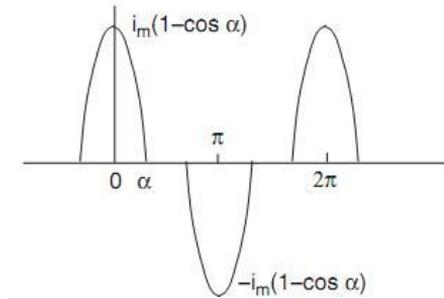
Harmonic	a_n/a_1		
	$\alpha = 60^\circ$	$\alpha = 90^\circ$	$\alpha = 120^\circ$
2	0.705	0.424	0.171
3	0.352	0.000	0.086
4	0.070	0.085	0.017
5	0.070	0.000	0.017
6	0.080	0.036	0.019
7	0.025	0.000	0.006
8	0.025	0.029	0.006
9	0.035	0.000	0.008
10	0.013	0.013	0.003
11	0.013	0.000	0.003
12	0.020	0.009	0.005
13	0.008	0.000	0.002

3. Magnetizing inrush during fault removal:

As the voltage applied to the transformer windings jumps from a low prefault value to the normal (or larger) postfault value, the flux linkages in the transformer core are once again forced to change from a low prefault value to a value close to normal. Depending upon the instant at which the fault is removed, the transition may force a DC offset on the flux linkages, and primary current waveforms similar to those encountered during energization would result. It should be noted that as there is no remnant flux in the core during this process; the inrush is in general smaller than that during the transformer energization.

4. Transformer overexcitation:

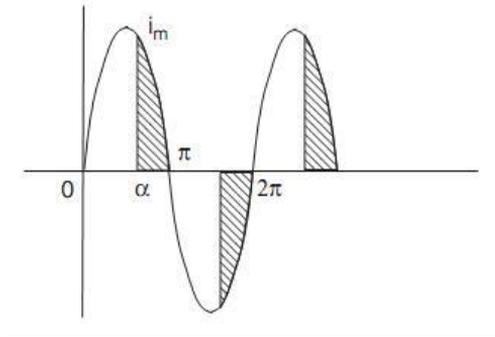
During overexcitation, the transformer flux remains symmetric, but goes into saturation for equal periods in the positive and the negative half periods of the waveform. This condition is illustrated in Figure



5. CT saturation:

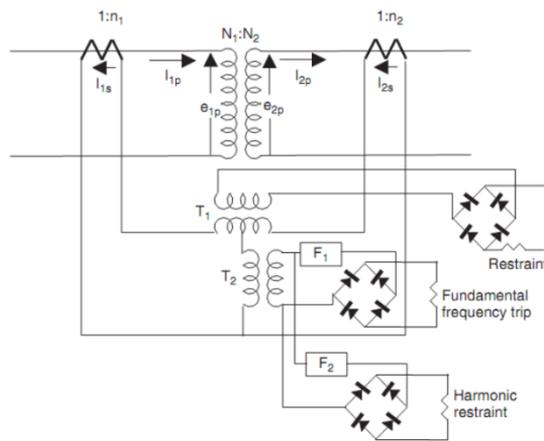
For certain external faults, where the fault currents are large, it is likely that one of the CTs may saturate.

The resulting current waveform of that CT secondary winding is shown in Figure 1. The differential current in the relay will then equal the shaded area, which is the difference between the unsaturated current waveform and the saturated current waveform.



Supervised differential relays:

left inside or around the transformer desensitizing (or disabling) the differential relay during energization is a poor practice, as it is precisely during the initial energization of the transformer, when the transformer is first energized, or some repair work on the transformer may have been completed, that the transformer is in need of protection. This is to ensure that the repair work has been successfully completed, and no maintenance tools inadvertently.



Harmonic restraint percentage differential relay. F₁ is a pass filter and F₂ is a block filter for the fundamental frequency

The method currently in use on large transformers is based upon using the harmonic characterization of the inrush and overexcitation currents. The differential current is almost purely sinusoidal when the transformer has an internal fault, whereas it is full of harmonics when the magnetizing inrush current is present, or when the transformer is overexcited. Thus, the differential current is filtered with filters tuned to an appropriate set of harmonics, and the output of the filters is used to restrain the differential relay.

A harmonic restraint function that uses all the harmonics for restraint may be in danger of preventing a trip for an internal fault if the CTs should saturate, saturated CTs produce a predominant third harmonic in the current. Care should be taken to make sure that the third harmonic component produced in a saturated CT secondary current during an internal fault is not of sufficient magnitude to block tripping of the differential relay. Some modern relays use second and fifth harmonics for restraint so that the relay is prevented from tripping for inrush and

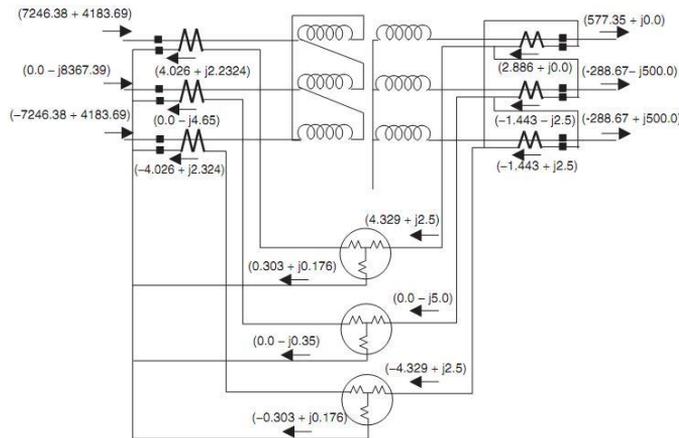
overexcitation, but is not blocked from tripping for internal faults with CT saturation.

4.3.3. Three-phase transformer protection:

Under normal load conditions, the currents in the primary and secondary windings are in phase, but the line currents on the wye and delta sides of the three-phase transformer are out of phase by 30°.

This phase shift causes a standing differential current, even when the turns ratio of the main transformer is correctly taken into account.

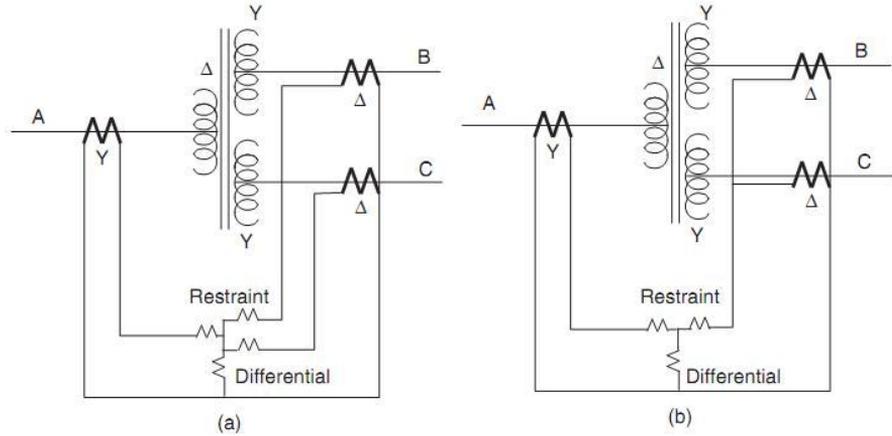
Solution is that the current transformers on the wye side of the power transformer are connected in delta, and the current transformers on the delta side of the power transformer are connected in wye. It is also necessary to adjust the turns ratios of the CTs so that the delta connection on the wye side of the power transformer produces relay currents that are numerically matched with the relay currents produced by the wye-connected CTs. Thus, the delta CT winding currents must be $(1/\sqrt{3})$ times the wye CT currents. It should be noted that the CTs on the wye side of the power transformer are connected in such a manner that the currents in the relays are exactly in phase, and very small currents flow in the differential windings the three relays during normal conditions. The currents are calculated with due attention given to the polarity markings on the CT windings.



Connections for a three-phase differential relay. Note the polarity markings on the CTs. Relay taps will further reduce the differential currents

4.3.4. Multi-winding transformer protection:

Three-phase transformers, similar considerations hold for single-phase transformers as well. Consider the three-winding transformer shown in Figure □. One winding is assumed to be delta connected, while the other two are assumed to be wye connected.



Protection of a three-winding transformer with (a) a three-winding relay and (b) a two-winding

The CTs must of course be connected in wye on the delta side and in delta on the wye side of the power transformer.

The CT ratios are chosen so that when any two windings are in service, equal secondary currents are produced.

It is interesting to note that under certain conditions a two-winding differential relay can be used to protect a three-winding transformer. If the transformer is connected to a source only on one side, the other two winding CTs could be paralleled to produce a net secondary current, which can then be used in a two-winding protection scheme.

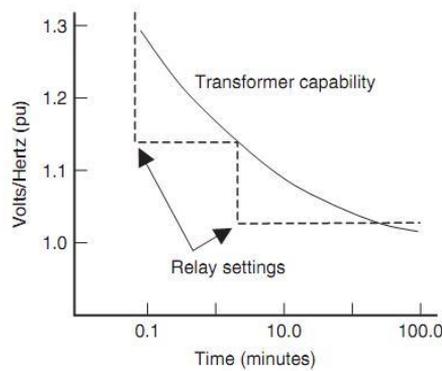
4.3.5. Volts-per-hertz protection:

Transformer cores are normally subjected to flux levels approaching the knee point in their magnetizing characteristic. Typically, the rated voltage at rated frequency may be 10% below the saturation level. If the core flux should exceed the saturation level, the flux patterns in the core and the surrounding structure would change, and significant flux levels may be reached in the transformer tank and other structural members. As these are not laminated, very high eddy currents are likely to result, producing severe damage to the transformer.

As the flux is proportional to the voltage, and inversely proportional to the operating frequency, the significant relaying quantity is the ratio of the per unit voltage to the per unit frequency.

A typical capability curve is shown in Figure □.

Many volts/hertz relays have two settings, a lower setting for alarm and a higher setting which may be used for tripping.



Volts/hertz capability of transformers, and relay settings

4.3.6. Nonelectrical protection:

Pressure devices:

A very sensitive form of transformer protection is provided by relays based upon a mechanical principle of operation:

When a fault occurs inside an oil-filled transformer tank, the fault arc produces gases, which create pressure waves inside the oil. In the 'conservator' type of tank construction, which is more common in Europe, the pressure wave created in the oil is detected by a pressure vane in the pipe which connects the transformer tank with the conservator. The movement of the vane is detected by a microswitch, which can be used to sound an alarm, or trip the transformer. This type of a relay is known as a Buchholz relay, named after its inventor.

In the presence of gas pressure relays, the differential relays can be made less sensitive. Indeed, one may attempt reclosing on those faults which cause the operation of the differential relay, but not of the pressure relay.

Temperature devices:

The temperature devices actuate alarms to a central dispatching office, to alert the operators, who can either remotely unload the transformer by opening the circuit breaker, or can dispatch an operator to the station. The hot-spot sensors are also commonly used to start and stop cooling fans and pumps. In extreme cases, when it is not possible to remotely remove the load, or send an operator to the station, an extreme high alarm will trip the bank.

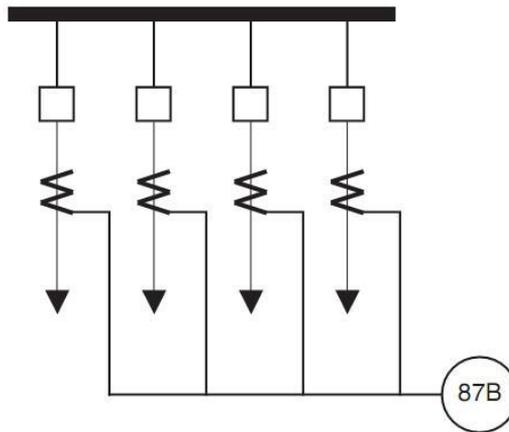
4.4. INTRODUCTION TO BUS PROTECTION:

bus protection has been the most difficult protection to implement because of the severity of an incorrect operation on the integrity of the system. A bus is one of the most critical system elements. It is the connecting point of a variety of elements and a number of transmission lines, and any incorrect operation would cause the loss of all of these elements. This would have the same disastrous effect as a large number of simultaneous faults. However, without bus protection, if a bus fault should occur, the remote terminals of lines must be tripped. In effect, this could create a worse situation than the loss of all of the elements at the bus itself for two reasons:

1. The loss of the remote ends will also result in the loss of intermediate loads.
2. As systems become stronger it is increasingly difficult for the remote ends to see all faults owing to infeeds.

The major problem with bus protection has been unequal core saturation of the current transformers (CTs). This unequal core saturation is due to the possible large variation of current magnitude and residual flux in the individual transformers used in the system. In particular, for a close-in external fault, one CT will receive the total contribution from the bus while the other CTs will only see the contribution of the individual lines. The basic requirement is that the total scheme will provide the degree of selectivity necessary to differentiate between an internal and an external fault.

Protection of substation buses is almost universally accomplished by differential relaying.



Differential with overcurrent relays

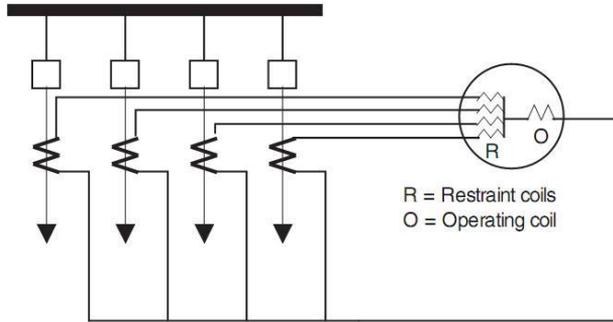
Differential relaying with overcurrent relays requires connecting CTs in each phase of each circuit in parallel with an overcurrent relay for that phase as Figure.

- When conditions are normal, the bridge is balanced and no current flows through the relay operating coil.
- When an external fault occurs, if all of the CTs reproduce the primary current accurately, the bridge is balanced as in normal case and no current flows in the relay operating coil.
- When an internal fault occurs, this balance, as we would expect, is also disrupted and current flows through the operating coil.

To minimize possible incorrect operations, the overcurrent relay may be set less sensitive and/or with time delay.

it is common to use a percentage differential relay. These relays have restraint and operating circuits as shown in Figure □ Only one operating coil per phase is required, but one restraint winding for each phase of each circuit is necessary.

The required current to operate the relay is proportional to the current flowing in the restraint windings.

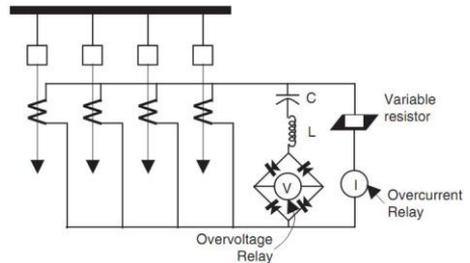


Percentage differential relay

Even with the use of percentage differential relays, the problem of the completely saturated CT for a close-in external fault still exists. To overcome this problem, the most commonly used bus differential relay, particularly on extra high voltage (EHV) buses, is the high-impedance voltage differential relay.

This relay design circumvents the effects of CT saturation during external faults by assuming complete saturation for the worst external fault and calculating the error voltage across the operating coil. The connection for this relay is the same as shown in Figure

The L-C circuit in series with the overvoltage relay is tuned to 60 Hz to prevent the overvoltage relay from mis-operating on DC offset or harmonics.



Directional comparison:

there are a number of directional relays that can compare the direction of current flow in each circuit connected to the bus. If the current flow in one or more circuits is away from the bus, an external fault exists. If the current flow in all of the circuits is into the bus, an internal bus fault exists. The timer is required to provide contact coordination. Since all of the directional relays are connected in series, it is essential that they all have an opportunity to close before a trip signal is initiated.

particularly at high-magnitude fault currents. The relay application and settings must be reviewed whenever system changes are made near the protected bus.

Partial differential protection:

Figures show a variety of bus configurations that have significant impact on the connections and settings of the bus differential.

