FIGURE 10.66
(a) Three-phase current relay of the RSZ 3gk type, with integrated clockwork (AEG, 1975). (b) RSZ 3gk relay construction. 1 — Coils of the electromagnet of the clockwork; 2 — clockwork; 3 — scale of the clockwork; 4 — magnetic core of the electromagnet; 5 — turning flag opening the red sector when the relay pick-ups; 6 — scale of adjustments of the current unit \( I_1 \). (c) Magnetic system of a current unit \( I_1 \), with a turning Z-shaped armature. 1 and 2 — Terminals of the \( \Pi \)-shaped magnetic core; 3 — Z-shaped turning armature; 4 — rotation axis of the armature; 5 — spring; 6 — contacts holder; 7 — coil.

(Continues)
Such signs can be usually found on the relay itself, near the corresponding element of adjustment. They are also indicated on schemes, where the letters $R$, $S$, $T$ (Figure 10.66a) are used to indicate the three phases of AC systems.

As can be seen from the scheme, when the current unit $I>$ picks up, it switches ON the electromagnet of the clockwork by its contacts, and the contacts of the current unit $I\geq$ go out directly to the terminal block where they are used for switching of external circuits.

The magnetic system of the current unit $I>$ (Figure 10.66b) is constructed with a Z-shaped turning armature, which has been known and in use for more than 70 years now and which continues to give a good account of itself in current relays (the peculiarities of relays with such armatures were considered above).

The placement of the both current units, $I>$ and $I\geq$, in constructions, are on both sides of the same plastic carcass, in the form of a common block. All these blocks, relating to all three phases, are installed on a common heelpiece. Unlike relays with a Z-shaped armature described above, which were supplied with a very soft spiral spring requiring protection from mechanical effects, in this construction quite a heavy coil spring of cylindrical shape is used and its power is transmitted to the armature with the help of a simple and reliable mechanical system, with the possibility of slide and regulation of its tension degree (Figure 10.66d).

To adjust the required pick-up current the limb (11) is turned and the proper section of its scale placed in front of the stationary pointer. When the limb turns the finite element of the spring (13) moves in the notch of the post (14) and the tension of the spring changes.

The instantaneous current unit $I\geq$ works only under high current ratios and has a considerably simpler construction, of the clapper type (Figure 10.66e). When the lever (17) changes its position, the armature (15), together with the spring (20), turns, so the pick-up current is adjusted not by changing of the spring tension as in the previous case, but by the reducing of the air gap between the armature and the terminal of the magnetic core.
10.4.2 Current Relays with Electronic Time-Delay

As it can be seen from Figure 10.66d, the clockwork, together with the electromagnet, occupies half of the inner space of the relay. This is the heaviest element of the construction: it weighs about 2 kg. It is probably also worth mentioning that this is the most expensive unit of the relay. That is why it would be only natural to look for the solution to replace this unit with a semiconductor time unit.

This solution was accepted and production of the RSZ3yk-type current relays was arranged. These relays were very much like the relay considered above, except that the clockwork and the powerful electromagnet were replaced with a simple (and light) printed circuit board with an electronic time relay based on the RC-circuit and electronic amplifier, already well known to us (Figure 10.67b). Another difference of this relay from

![Diagram of RSZ3yk-type current relay with semiconductor element](image)

**FIGURE 10.67**
(a) RSZ3yk-type current relay with a semiconductor element of TD (T) instead of a mechanical one. Produced by AEG. (b) Circuit diagram of the TD element of the RSZ3yk-type current relay (AEG 1975).
the previously considered one is an additional indicating relay (M) opening the colored flag at the pickup.

The use of a simple and light TD element enabled installation of two such elements with different TDs in the same case of the current relay (Figure 10.68). One of them (with a longer TD) runs from the current relay $I_1 > I_2$ as in all previously considered cases, and the other (with a shorter TD) runs from the relay $I_{12}$, allowing for adjustment of the pick-up time of the relay $I_{12}$ within some narrow limits at the stable value of this TD.

This development of current relays, that is the transition from a heavy and expensive mechanical time element to a one based on a semiconductor, seems quite logical. The only astonishing fact is that all of these modifications of relays have been produced by the AEG Company, parallel to each other for many years!

Analyzing the tendencies of development of protective relays from the appearance of transistors and then chips, one notices that not only the AEG Company but also many other companies produced in parallel both mechanical relays designed tens of years ago, and the most modern (for that time) transistor relays, than microelectronic ones, and finally microprocessor ones. How can this phenomenon be explained? The answer to this question is probably evident: constant demand for electromechanical relays. Why should such a demand still remain high, is another question requiring separate treatment and we will return to it later. Logically, if one follows tendencies of technical developments in the 1960–70’s, right after the hybrid relays considered above (containing both mechanical and electronic elements), fully electronic relays without electromechanical sensitive current units should have appeared.

10.4.3 Electronic Current Relays with Independent Time-Delay

We have already considered principles of construction of electronic relay circuits turning from one stable state to another when the input value of the given pick-up threshold is
exceeded. Semiconductor current relays are based on the similar principles. The construction of such relays contains a metal or plastic case with input CTs (as a rule there are three of them) and several printed circuit boards with electronic components. Usually, the auxiliary neutral electromagnetic relay is used as an output element (Figure 10.69).

It should be noted that production of the relay is a high-quality one. The output electromagnetic relay (in Figure 10.69 at the upper left) is used in its sealed modification. Printed circuit boards with discrete elements are covered (by dipping) with a thick layer of high-quality varnish protecting the board from humid air (Figure 10.70). As it can be seen from the circuit shown in Figure 10.71, the three-phase current converted to voltage

\[
\begin{align*}
I_2 & \text{ scale of TD in seconds; } \\
I_1 & \text{ scale of pick-up currents in amperes (for the unit } I_2); \\
I_2 / I_1 & \text{ ratio of the pick-up current (for the unit } I_2). 
\end{align*}
\]
with the help of the input transformers WR, WS, and WT is rectified and applied to two current relays: \( I > \) placed on the printed circuit board LP1, and \( I > \) placed on the second printed circuit board LP2. Pick-up currents of these relays are adjusted by potentiometers P1 and P4, respectively. On the third printed circuit board LP3, there are stabilizers St1 and St2, allowing internal circuit supply from an external source with voltage of 24, 60, 110, and 220 V. The TD is provided by units Z1 (for \( I > \)) and Z2 (for \( I > \)), working on the principle of RC-circuit charging. Charging time (that is TD) is adjusted by potentiometers P2 and P3 (it is only potentiometer P2 that is brought out to the front panel).

The author had a chance to test such a relay after it had been used in an electric power station. The results were good for a relay which had served for 29 years, without repair, and show that a well-proven circuit, use of high-quality electronic components and properly chosen modes of operation for them allow even relatively simple electronic devices without modern chips or microprocessors, to remain quite competitive, at least from the point of view of stability of parameters and reliability of operation. Moreover, according to the personal experience of the author, modern microprocessor relays do not always provide as reliable protection of electric units as these old relays based on discrete elements.

Because of this and some other reasons quasi-electronic current relays on discrete electronic elements of the “Quisitron” series considered above, still remain promising, and a TD feature can also be added to this promising construction (Figure 10.72). The TD body in this construction is made not on the basis of an RC-circuit as in the

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**FIGURE 10.71**

Circuit diagram of RSZ-3my type current relay (AEG 1975).
constructions considered above, but in the form of a pulse generator (multivibrator) on the chip D1 (elements D1.1 and D1.2) and a counter on the chip D2 counting these pulses. The time dial is adjustable, with a range of 0.1 to 25 sec (±2.0%), with a grade of 0.1 sec.

10.5 Current Relays with Dependent Time-Delays

The types of secondary relays considered above have an independent on current (fixed) TD, which is not always enough for effective protection from overloading. Much better protection would be provided by a TD that depends inversely on the current value of overloading. At small ratios of overloading the time will be just a few or tens of seconds.
and at higher ones — fractions of a second. The transition must be smooth: the greater the current, the quicker the relay pick-ups. This is how effective and widely used thermal relays work (see above).

Realization of this problem led to the appearance of relays with inverse dependent time–current characteristics. Nowadays such characteristics are implemented in two types of relays: induction ones (with a disk or a cup rotating in the magnetic field), and electronic ones. However, from the very first years of relay development up to the 1970s and 1980s, there were attempts to create relays with inverse time–current characteristics based on other principles (Figure 10.73).

10.5.1 Relays with a Liquid Time-Delay Element

The Bulletin 810 (produced by the Allen Bradley Company in 1976) has inverse time–current characteristics that are dependent on the viscosity of the fluid in the dashpot; however, unlike thermal relays minimum operating current is independent of ambient temperature change or cumulative heating. Current through the Bulletin 810 operating coil imparts an electromagnetic force on the movable core. The vertical position of the core in the coil is adjustable, thereby providing an adjustable trip point. When the coil current increases to the trip point, the core raises to operate the contact mechanism. TD is provided by a silicone fluid dashpot mounted below the core and coil assembly. An adjustable valve in the dashpot piston provides for TD adjustment. Upward motion of core and piston is dampened through the use of the silicon fluid dashpot. The core rises slowly until the piston reaches an increased diameter in the dashpot, where it is free to trip the contact with quick action. The time and current required to complete this cycle are inversely related as shown by the time–current curves (Figure 10.74).

Standard models of the Bulletin 810 are automatically released as soon as the current through the coil is decreased to approximately 20% of the pick-up current. The core is

---

FIGURE 10.73
designed to drop quickly, returning the contacts to their normal position. A check valve allows the position to bypass the fluid in its return to the bottom of the dashpot so there is no waiting period as with thermal relays.

The minimum operating current (100% on the time–current characteristics graph) is independent of ambient temperatures at the relay; however, the operating time at over-current varies directly according to the viscosity of the silicone fluid. Since the viscosity varies inversely with ambient temperature, the operating time is also inversely affected. The time–temperature table shows the proper correction factors to be applied to the operating times for various temperatures (Table 10.1).

<table>
<thead>
<tr>
<th>Ambient temperature (°C)</th>
<th>0</th>
<th>-10</th>
<th>-20</th>
<th>-30</th>
<th>-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating time correction factor</td>
<td>2.25</td>
<td>1.80</td>
<td>1.45</td>
<td>1.20</td>
<td>1.0</td>
</tr>
</tbody>
</table>

10.5.2 Induction Relays: Design and Characteristics

Induction relays are based on a different principle than the other devices considered above. As it is known, if one places a conducting element in an alternating magnetic field an electric current will be created in this element. This current creates its own magnetic field, biased on 90° from the external field that has created it.

These two magnetic fields can interact with each other and as a result a torque appears that can be used for closing of contacts. In induction relays, a coil serves as a source of an alternating magnetic field and the conducting element is made in the form of a light aluminum disk, a hollow rotor in the form of a cup or a frame that is free to rotate around its axis. In order for the torque to appear, the movable elements must start moving, and for
that it must be affected by not less than two alternating magnetic fluxes displaced in space and in time from each other (that is out of phase). These requirements can be implemented in different ways. For example, if one places two coils, one on each side at the edge of the aluminum disk, and switches one of them with a greater number of turns (that is with greater inductance) directly to the source of the input voltage ($U$) and the other one with a less number of turns in series to the additional active resistance ($R$) (Figure 10.75), the magnetic fluxes created by the upper and lower coils will be biased in phase.

One can also obtain magnetic fluxes biased in phase by arranging the windings in space in some special way (Figure 10.76). It should be noted that Westinghouse already

**FIGURE 10.75**
An induction magnetic system of the tangential type with a rotating disk.

**FIGURE 10.76**
(a) Construction of the magnetic system of a CO-type induction relay (Westinghouse). 1 — Secondary current; 2 — upper pole flux; 3 — pole electromagnet; 4 — direction of disk rotation; 5 — disk; 6 — main pole flux; 7 — main pole current. (b) Magnetic fluxes in the induction magnetic system of the so-called "tangential" type with a rotating disk.
produced the first induction relays of this type in 1901, and CO-type relays have a history dating back to 1914. Relays of this type have been produced for decades and were a kind of standard on which new projects were based until the 1950s (Figure 10.76b).

This arrangement allows the magnetic fluxes of the coils (Figure 10.76c) to run through the disk edge, causing disk rotation as a result of the interaction with its magnetic field, occurring on the section near the disk edge.

Another example is the so-called shielded magnetic system (Figure 10.77). The shield here is a copper-shading ring put on the shaded pole of the magnetic core. We have already considered this construction in the section devoted to magnetic systems of the electro-
magnetic relays. In a standard clapper-type AC relay, this ring prevents the armature from vibrating because the magnetic flux created by this ring is biased by 90° from the main magnetic flux, which is why the total magnetic flux affecting the armature never reaches zero as the main flux changes sinusoidaly. The induction magnetic system uses the property of this ring to create additional flux biased by 90°, for torque on the aluminum disk. As the rotating disk crosses the magnetic fluxes (setting it in motion), there a so-called cutting current appears, preventing disk movement according to the Lenz law. It not only prevents movement, but also takes on a stabilizing affect at higher rotation rates of the disk, the greater the cutting current is. To intensify this effect an additional permanent magnet, the poles of which cover the disk edge, is used in some induction relays. The exposure degree of the magnet on the disk depends on its power and position on the disk. In relays with a permanent magnet, there is usually an adjusting mechanism providing radial displacement of this magnet within some limits.

Instead of a disk, a hollow rotor in the form of a cup can be used in induction relays. This rotor has a much smaller diameter and arm of force than the disk, which is why two sources of the magnetic field biased in space and in time are not enough for its rotation, unlike the case with a disk. A magnetic system of at least with four poles is used for rotor rotation (Figure 10.78). Such a magnetic system implies the use of two coils arranged on the core arms in such a way that the pole axes of these coils intersect at the right angle. This means that the magnetic fluxes of these coils are also biased at this angle in space. The phase shift between currents in these coils is determined either by parameters of current (voltage) sources, to which these windings are connected or created artificially with the help of a capacitor (if only one source is used).

FIGURE 10.78
(a) Construction diagram of the induction magnetic system of a four-pole type with a rotating rotor. (b) External design of the unit of the induction magnetic system of a four-pole type with a rotating rotor. 1 — Coils; 2 — ferromagnetic core; 3 — normally open stationary contact; 4 — moving contacts; 5 — spring adjusting ring; 6 — upper pivot assembly; 7 — upper control spring; 8 — normally closed stationary contact.
As the torque in induction systems is the function of frequency, amplitude of magnetic fluxes, and phase angle between them, these systems can be applied in relays of different purposes:

- Current and voltage relays
- Frequency relays
- Active and reactive power relays
- Impedance relays, etc.

It should be noted that protective relays based on these principles have been in existence for 75 years already. Apparently current relays were the first application of induction magnetic systems. Earlier constructions (Figure 10.79) already contained practically all the elements of modern relays but were not good enough.

For example, early models (Figure 10.79) had quite a primitive reduction gear with a large gear ratio, allowing a great number of disk revolutions until the relay picked up. This construction is made in the form of a thread (2), which is wound around the axis while the disk is rotating and which pulls the movable contact to the stationary one.

Also in the 1940–50’s, relays based on an induction system of tangential type were also produced (Figure 10.80). The principle of operation of them has been considered above. In this relay, the thread has already been replaced with a real worm-gearing.

Induction relay RIK type with very complex kinematics to have no parallel, designed by ASEA (Sweden) in 1930’s was a model for modern Russian RT-80 series relays (Figure 10.81).

The disk axis in this construction is fixed with the help of bearings (4 and 5) in the frame (5), which can also rotate in bearings 7 and 8. That is, the disk in this construction can move. In the initial position the spring draws off the frame (6) in such a way that the worm (3) does not touch the toothed quadrant (17).

At a certain current value in the winding, due to the factors described above, the disk begins to rotate. When the disk reaches a certain rotation speed, depending on the

![FIGURE 10.79](image-url) Induction current relay with a vertical rotating disk, produced by Siemens in the 1930s. 1 — Permanent magnet; 2 — thread; 3 and 4 — setting handles of pickup current and TD; 5 and 6 — contacts of the relay.
current value in the winding, all forces affecting the disk including the magnetic field (2) lead to some resultant mechanical force applied to the disk axis. This force is transmitted to the frame (6), which rotates quite quickly in bearings 7 and 8, together with the rotating disk until the worm (3) touches and hooks the toothed quadrant (17). At that moment the TD of the relay starts counting. When the frame (6) rotates and the ferromagnetic plate (12) approaches the magnetic core, it is picked up by the magnetic field of dispersion and pressed to the magnetic core, thus providing fixation of the position of the frame (6) and reliable operation of the worm-gearing. When the disk rotates further, the toothed quadrant (17) with the pusher raises and closes the main contacts (15 and 16) affecting the lever (14). As the lever (14) is linked not only with the contacts, but also with the left end of the rotating armature (19) this end also goes up, bringing(202,684),(797,781) near the special ledge of the magnetic core. At a certain gap the right end of the armature is taken by the magnetic field and safely engages with the magnetic core, providing reliable fixation and good pressure on the main contacts.

When the current in the winding increases, the working torque affecting the disk increases proportionally to the current square, and then considerably more slowly because of saturation of the magnetic core (when the magnetic core is saturated, the increase of current in the coil does not lead to an increase of the magnetic flux in the working gap). Accordingly, the pick-up time of the relay is sharply reduced at first when the current goes up (the dependent part of the characteristic: \( I > \)), and then...
becomes practically constant (the independent part of the characteristic) (Figure 10.82). For relays of this type, the independent part of this characteristic starts approximately at an eight-to-tenfold pick-up current.

At such current ratios the right end of the armature (19) is immediately attracted to the magnetic core, providing closing of the main contacts long before the disk starts to rotate. The pick-up current of this part of the relay ($I_{C29}$) is adjusted by changing the air gap with the help of the screw (21).

There are 12 modifications of relays of the PT-80 series, for currents ranging from 2 to 10 A, and time settings from 0.5 to 16 sec.

Induction current relays with dependent characteristics, of the IAC and IFC series (a modernized IAC relay with its size reduced by 25%) produced by General Electric Co. for many years, have considerably simpler constructions (Figure 10.83). According to GE statistics, the total working time of these relays, used in various power units all around the world, is 15 million relay-hours.!

Unlike the previous construction, with complex kinematics in which the disk made many revolutions until the contacts closed, IAC relays are very simple (Figure 10.84) and do not contain any mechanical transmission. The required TDs at low currents are provided due to the very small rotation of the disk. Instantaneous cut-off is provided by a separate relay (8) of the clapper type. The contact, closed by the disk, switches the auxiliary relay (3) with its powerful output contacts, and a drop-out flag signals the pick-up of the relay.

The nominal pick-up current is fixed with the help of a simple switch of coil taps (tap setting). The current at which the disk begins to move (pick-up) is adjusted by changing the tension of the spiral spring. The time dial setting is chosen in accordance with the initial position change of the unit with the spring and the movable contact. The distance that the movable contact must travel before closing, and therefore the operate time of the relay, also changes. One can make an additional adjustment of the operate time by shifting the permanent magnet along the disk radius. A lot of credit goes to the designers of this relay who created a reliable construction, having stable characteristics, that has been used all over the world for decades, with a minimal set of elements.

The protective properties of induction current relays are determined by the form of their time–current characteristics, which may differ (the slope of the characteristic, its curvature) in various relays of different types. The characteristics of protective relays

![Figure 10.82: Time–current characteristics of the PT-80 relay. 1 — For setting $t = 2$ sec and multiple cut-off setting of 8; 2 — for setting $t = 4$ sec (without cut-off unit).]
must be well matched with the parameters of the protected object, which is why it is important to distinguish between these characteristics. Western producers apply a special classification that includes six types of characteristics: inverse (or normal inverse); very inverse; extremely inverse; short-time inverse; medium-time inverse; long-time inverse (British Standard 142). The most commonly used and popular are the first three.

The normal inverse (or inverse) characteristic is most suitable for systems where there is a large variation of fault-current for different fault locations (i.e., the source impedance is much smaller than the line impedances). The inverse characteristic enables improved utilization of the protected object’s overload capacity, and increased cold-load pick-up capability compared with the definite-time characteristic.

**Very inverse characteristic:** The operating time is more dependent on fault-current magnitude; therefore this characteristic is suited for systems where there is a fairly large variation of fault-current.
FIGURE 10.85
(a) Time–current characteristics of the “inverse” type (the example used here is an IFC-51 relay, produced by GE). K — time dial setting. (b) Time–current characteristics of the “very inverse” type (this example is an IFC-53 relay, also produced by GE). (c) Time–current characteristics of the “extremely inverse” type (another example of a IFC-53 relay, produced by GE).
variation in fault-current for different fault locations (i.e., the source impedance is less than the line impedances). Where line impedance has a large influence on the fault-current level the very inverse characteristic often permits faster overall fault clearance than do normal inverse characteristics.

The use of inverse-time or very-inverse-time relays for the protection of long lines is generally more satisfactory than for short lines. This is because on a long line there are substantial differences in short-circuit currents, and hence the operating time (depending on whether the fault is near the remote end or the local end of the protected line). This makes it easier to obtain proper time coordination.

**Extremely inverse characteristic:** The operating time is very dependent on fault-current magnitude. These characteristics are intended for coordinating with fuses on distribution or industrial circuits, and where an extended service outage results in a heavy accumulation of loads of automatically controlled devices (such as water pumps, refrigerators, water heaters, oil burners, etc.). Such load accumulations often produce inrush currents considerably in excess of the full-load feeder current for a short time after the feeder is re-energized. The extremely inverse time relay characteristic permits successful pick-up of these loads and at the same time provides adequate fault protection which can be made selective with fuses and cut-outs in other parts of the circuit.

They are used in situations requiring a high degree of overload capacity utilization, and where cold-load pickup or energizing transient currents could be a problem. They are also suitable for providing coordination in networks where current changes for different fault locations are small but finite and distinguishable.

It is interesting to compare the efficiency of a protection relay having such characteristics, to that of a relay having definite-time (independent) characteristics (see above). Let us remind ourselves that a relay with a definite-time characteristic will have an operating time independent of the fault-current magnitude. This characteristic is mainly suitable for use in systems where the fault-current magnitude is relatively constant for different fault locations (i.e., source impedance is much larger than line impedances). It also simplifies selectivity planning in conjunction with other relays having instantaneous or definite-time characteristics (Figure 10.87). TD selection should be begun at the farther-
most circuit section and finally completed at the power source (Figure 10.87). Let us select the minimum possible TD $t_1$ for the far-end circuit section $L-1$. By reason of selectivity considerations, in order that a fault at point $K-1$ will not lead to disconnection of circuit section $L-2$, the TD for circuit section $L-2$ must be somewhat greater:

$$t_2 = t_1 + \Delta t$$

where $\Delta t =$ time-delay step or increment necessary as a reliable margin against operation of protection on the succeeding circuit section.

On circuit section $L-3$ the overcurrent protection should operate in a similar fashion with the TD:

$$t_3 = t_2 + \Delta t,$$

etc.

Figure 10.87 shows a diagram with the TDs selected for a system of power circuits and a generator. We can point out here that in order to increase the reliability, the generator protection has a TD setting which includes a double time-delay step, that is

$$t_G = t_4 + 2\Delta t$$

generally $\Delta t = 0.4$ to 0.5 sec.

The major advantage afforded by use of overcurrent relays having inverse-time characteristics is that their TDs are approximately inversely proportional to the short-circuit current or overload current. This property provides the possibility of obtaining simple and quick-acting protections for individual radial circuits against short circuits.

Figure 10.88 shows a system of protection time-delay characteristics in the form of a function $t = f(t)$. They clearly show with what TD the faults are cleared at the various circuit points, not only by the individual protection of a given circuit section (main protection) but also by the protection of the next power-supply-side circuit section (back-up protection). This is another advantage of these relays.
Any comparison of Figure 10.87 and Figure 10.88 makes it evident that the nature of the TDs is identical in both cases. In protections using relays with inverse-time characteristics, a fault at the far end of the circuit section is cleared with a greater TD than a fault at the near end (refer to Figure 10.88). To provide an allowance for the greater inertia error of induction-type relays, the time-delay step \( \Delta t \) is equal to 0.7 to 0.8 sec.

As a whole, the application of inverse-time relays results in higher TD levels. This is a disadvantage of these relays. As can be seen, the relay with an extremely inverse characteristic (1) has a smaller effective area than the relay with a normal inverse characteristic (4).

Induction systems with a rotating disk have a certain inertia (because of the large diameter of the disk) which plays no role when these systems are used for relays with a dependent TD; however, these systems cannot be applied in relays with a small TD because the minimum pick-up time of the system with a disk exceeds 0.1 sec.

A modern induction magnetic system (Figure 10.89) of the four-pole type with a rotating rotor of small diameter (as the so-called “Ferraris motor”) provides a minimum pick-up time of 0.02 to 0.04 sec and is used for current relays with small TDs.

In May–June 1885 Galileo Ferraris (Figure 10.90a) conceived the idea that two out-of-phase, but synchronized, currents might be used to produce two magnetic fields that could be combined to produce a rotating field without any need for switching or for moving parts. This idea, which is common place to electrical engineers now, was a complete novelty in the 1880s. Ferraris published it in a paper to the Royal Academy of Sciences in Turin in 1888.

Ferraris devised motor (Figure 10.90b) using coils (as electromagnets) at right angles and powered by alternating currents that were 90° out of phase, thus producing a revolving magnetic field. The motor, the direction of which could be reversed by reversing its polarity, proved the solution to the last remaining problem in alternating-current motors. The principle made possible the development of the asynchronous, self-starting electric motor that is still used today.

At the time Ferraris seems not to have thought that his principle would lead to a motor for industrial purposes, but he suggested that it could be used as the basis of a meter for alternating current measurements. Ferraris did not want to take out a patent on his inventions and refused a large sum from an American company, because he thought that the discovery can be put in the service by everyone: “I am a professor, not...”
an industrialist,” he said with regard to the offer (now, there are several International Patent Classification indices for devices with Ferraris motor principles: H01H53/12, G01R11/36, G01R5/20).

A typical case of application of such a magnetic system with a rotor is a relay of the CHC11A type, produced by General Electric. When using the CHC11A relay in circuit-breaker-failure back-up schemes, the relay may be called on to carry maximum fault current for some fraction of a second before the fault is cleared. For this reason, the short-time current capability of the relay should be noted. This is particularly true of the hinged-armature unit (without an inverse TD). CHC11A relays have inverse time characteristics for very short TDs (Figure 10.91a).
The short-time rating of the cup unit is so high that it will probably never be a limiting factor. While the 2 to 8 A cup unit is continuously rated for 5 A, it is capable of carrying 8 A continuously. This is important in multi-breaker bus arrangements, where bus current that the relay may be connected to receive can exceed 5 A during maximum load conditions.

The phase bias required for torque in the four-pole induction magnetic system of the CHC11A-type relay is created with the help of capacitors (C1, C2, and C3 in Figure 10.91b). The induction cup unit is intended for multiphase faults and the small hinged-armature for ground faults.

10.5.3 Electronic Current Relays with Dependent Characteristics

TDs dependent on current are implemented in such relays with the help of the RC-circuit considered above. The charging rate of the capacitor with constant power supply voltage is known to be determined by the so-called time constant \( \tau = RC \). If one switches a threshold element picking up at a certain voltage level parallel to the capacitor, one can change the TD value by changing the resistance of the resistor \( R \) and the value of the capacitor \( C \) until this threshold element picks up. This principle is basic for the operation of the time elements with independent characteristics in current relays. Mind the words above in italics “with constant power supply voltage.” This is the requirement for a fixed TD determined only by the parameters \( R \) and \( C \). The voltage on the capacitor \( U_C \) (that is on the threshed element) increases according to the exponential law (Figure 10.92):
where is the $U_{INP}$ is the input voltage applied to the RC-circuit; $t$ is the charging time of the capacitor to the voltage $U_C$.

The threshold element picks up when the voltage on the capacitor $U_C$ reaches the pick-up voltage of the threshold element $U_P$, and the TD ($t_P$) to the pick-up equals:

$$t_P = RC \ln \frac{U_{INP}}{U_{INP} - U_P}$$

As can be seen from the latter formula, the TD depends not only on the time constant value (that is on parameters R and C), but also on the input voltage value $U_{INP}$, which is why special means of stabilization of the input voltage are applied in relays with an independent TD.

On the contrary relays with a dependent TD make use of this property of the RC-circuit. In the latter case, current is converted to voltage (for example, with the help of the input transformer) and is applied to the RC-circuit with the threshold element. The greater the input current (that is the voltage applied to the capacitor) is, the quicker it is charged and the smaller the TD will be until the pickup of the threshold element. This is what is needed for protective current relays with a dependent TD (Figure 10.93). In the initial mode, when current is lesser than a certain threshold value, the contact (S.R.) of the start relay short-circuits the winding ($w_2$) of the transformer ($T_3$) through the current-limiting resistor ($R_4$). As a result, there is no voltage, neither on the charging RC-circuit nor on the winding ($w_3$) of this transformer. The start relay picks up at the certain value of the input current and de-shunts (by its contact S.R.) the rectifier (VD2), through which the capacitor (C2) is charging. As the capacitor is charging, the current used by it from the winding ($w_2$) decreases and the voltage on the winding ($w_3$), which is rectified, filtered and applied to
the winding of the output relay, increases. At a certain voltage level this relay picks up. If
the input current is great, the voltage drop on the resistor \((R_1)\) becomes great enough for
pick up of the output relay before the capacitor \((C_2)\) is charged. This forms the indepen-
dent part of the characteristic. The dependent part of it is formed when the voltage applied
to the capacitor \((C_2)\) is proportional to the input current. At very high current values the
transformer \((T_2)\) is saturated and the voltage in the RC-circuit does not increase further,
while the current goes up. This allows stabilization of the dependent part of the charac-
teristic.

If one cut in an additional converter of the input voltage on Zener diodes, for instance,
with different voltages at the input of those devices (Figure 10.94), it is possible to
make the voltage applied to the capacitor charge change, depending on the input
current (voltage) according to a specific low. If the input voltage is less than the drop-
out voltage of the Zener diodes it is applied to the charging RC-circuit through the
resistor \((R_1)\), which corresponds to the first section on the curve. If the input voltage
(current) increases and reaches the drop-out voltage of the Zener diodes \((VD_1)\), resistor
\(R_2\) appears to be switched parallel to resistor \(R_1\). At that point the resultant resistance
decreases and the curve passes to the second section, and so on. As a result of this process
it is possible to obtain different forms of time–current characteristics of the relay. This
principle has been in use for quite a long time already, since the 1960s and 1970s
(Figure 10.95).

The relay’s input has a built-in CT with several secondary windings with taps. Over the
switch for the setting of the operating current, the voltage is taken out across a resistor.
When this voltage, rectified, smoothed, and compared with above-mentioned voltage,
exceeds the reference voltage, the starting relay picks up. At the same time, the RC circuit
starts charging up. For the inverse time lag relay the required time characteristic is
obtained through a combination of Zener diodes and resistors used in the mentioned
RC circuit. When the capacitor in the RC circuit is charged up to a certain voltage level,
the tripping relay also picks up. In the three-phase design, the measuring circuit acquires
a voltage that is proportional to the largest of the three currents.

*FIGURE 10.94*
Principle of forming of a specific characteristic with the help of Zener diodes
\((VD)\) and resistors: above — with several stages; below — with one stage.
Instantaneous operation is obtained by means of the rectified part of the voltage from the transformer being compared to the reference voltage — when the latter is exceeded an operating impulse is given to the tripping relay.

In later constructions of relays, the required time–current characteristics are formed with the help of a specialized microprocessor synthesizer. The time–current characteristics of such relays match exactly the characteristics of induction relays. This relay of the IC91 type, produced by ABB, can serve as a good example of such a relay (Figure 10.96).

FIGURE 10.95
An electronic relay of the RXIDE-4 type, with a dependent time–current characteristic. External view and block-diagram. 1 — Input transformer; 2 — current setting; 3 — RC-filter; 4 — rectifier; 5 — stabilizing circuit; 6 — time setting; 7 — level detector; 8 — time circuit; 9 — level detector; 10 — amplifier; 11 — tripping relay; 12 — instantaneous setting; 13 — level detector; 14 — amplifier; 15 — starting relay. (ABB Buyer's Guide 1990.)

Instantaneous operation is obtained by means of the rectified part of the voltage from the transformer being compared to the reference voltage — when the latter is exceeded an operating impulse is given to the tripping relay.

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FIGURE 10.96
(a) Block-diagram of a microprocessor current relay of the IC91 type with a dependent characteristic.

(Continues)
10.6 Harmonic and Voltage Restraint Relays

When a power transformer is energized, current is supplied to the primary, which establishes the required flux in the core. This current is called a “magnetizing inrush” and it flows only through CTs in the primary winding. This causes an unbalanced current to flow in the coil of the current relay, which would cause faulty operation if means were not provided to prevent it.

Power system fault currents are of a nearly pure sine waveform, plus a transient DC-component. The sine waveform results from sinusoidal voltage generation and nearly constant circuit impedance. The DC-component depends on the time in the voltage cycle at which the fault occurs, and upon the circuit impedance magnitude and angle.

Transformer magnetizing inrush currents vary according to the extremely variable exciting impedance resulting from core saturation. In modern transformers, larger than approximately 10 MVA and with orientated sheet-metal, the amplitude of the inrush current can be five to ten times of the rated current when it is connected to the high voltage side, and 10 to 20 times the rated current when it is connected to the low voltage side. The amplitude and duration of the inrush current (up to some few seconds) is dependent on the design of the transformer, its connection, and its neutral earth point, as well as the short-circuiting effects of the network.

These currents have a very distorted waveform made up of sharply peaked half-cycle loops of current on one side of the zero axis, and practically no current during the opposite half cycles. These two current waves are illustrated in Figure 10.97. Any current of distorted, nonsinusoidal waveform may be considered as being composed of a direct-current component plus a number of sine-wave components of different frequencies: one belonging to the fundamental system frequency, and the others, called “harmonics,” having frequencies which are 2, 3, 4, 5, etc., times of the fundamental frequency. The relative magnitudes and phase positions of the harmonics, with reference to the fundamental, determine the waveform. When analyzed in this manner the typical fault
current wave is found to contain only a very small percentage of harmonics, while the typical magnetizing inrush current wave contains a considerable amount (Table 10.2).

The high percentage of harmonic currents in the magnetizing inrush current wave affords an excellent means of distinguishing it electrically from the fault current wave. In special current relays the harmonic components are separated from the fundamental component by suitable electric filters.

The simplest type of relay with a harmonic restraint characteristic is the PT-40/F-type relay, differing from the PT-40-type relay considered above by a filter formed by inductance of the transformer \( T \) and the value of the capacitor \( C \) (Figure 10.98).

Currents of the highest harmonics are closed through the capacitor \( C \) and not applied to the winding of the relay. The parameters of the elements are chosen in such a way that the pick-up current of the relay at a frequency of 150 Hz is no less greater than eight times that of the pick-up current of the relay at a frequency of 50 Hz. In this way different sensitivities of relays to short-circuit currents (50 Hz) and current rushes of magnetization of the transformer (over 100 Hz) are provided.

Another widespread principle of construction of relays with harmonic restraint is to use a quickly saturated transformer (QST) cut in between the standard current relay and the current source (Figure 10.99). Such a QST is usually made on a triple core (Figure 10.99b), and contains two short-circuited windings \( w_3 \) and \( w_4 \) in addition to the working winding \( w_1 \) and the secondary winding \( w_2 \).

In the normal mode of operation, when the current \( I_1 \) is sinusoidal, the magnetic flux in the left rod of the transformer equals the sum of magnetic fluxes \( F_1 \) and \( F_2 \) created by the primary winding \( w_1 \) and the short-circuited winding \( w_4 \). At the nominal current value \( I_1 \) these fluxes create current \( I_2 \) in the secondary winding \( w_2 \), enough for pick-up of the

---

**TABLE 10.2**

Harmonic Analysis of a Typical Transformer Magnetizing Inrush Current Wave

<table>
<thead>
<tr>
<th>Wave Component</th>
<th>Ratio of Amplitude of Harmonic Component to Amplitude of Fundamental (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental</td>
<td>100</td>
</tr>
<tr>
<td>Direct current</td>
<td>57.7</td>
</tr>
<tr>
<td>Second harmonic</td>
<td>63.0</td>
</tr>
<tr>
<td>Third harmonic</td>
<td>26.8</td>
</tr>
<tr>
<td>Fourth harmonic</td>
<td>5.1</td>
</tr>
<tr>
<td>Fifth harmonic</td>
<td>4.1</td>
</tr>
<tr>
<td>Sixth harmonic</td>
<td>3.7</td>
</tr>
<tr>
<td>Seventh harmonic</td>
<td>2.4</td>
</tr>
</tbody>
</table>

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relay. When the nonsinusoidal magnetizing inrush current starts flowing in the primary winding of the QST, its core is quickly saturated, since this current is unidirectional. As a result, the current transformation to the secondary winding $w_2$ is especially reduced due to a decrease of the constituent of this current, obtained from the short-circuited winding. The current $I_2$ remains very small (not enough for a pick-up of the relay) even at a high amplitude of the input nonsinusoidal current. The principle of offset from rushes of

![Circuit and frequency characteristic of the simplest PT-40/F-type relay with a harmonic restraint characteristic.](image)

**FIGURE 10.98**
Circuit and frequency characteristic of the simplest PT-40/F-type relay with a harmonic restraint characteristic.

![Current relay of the PHT-565 type (Russia) with harmonic restraint characteristic produced on the basis of a QST.](image)

**FIGURE 10.99**
(a) Current relay of the PHT-565 type (Russia) with harmonic restraint characteristic produced on the basis of a QST. 1 — Heel piece; 2 — case; 3 and 4 — adjusting resistances; 5 — integrated. PT-40 relay (see above); 6 — QST. (b) A simplified circuit of an RNT-565 current relay with a QST.
magnetization current with the help of a filter is also used in electronic current relays (Figure 10.100).

The restraining method used in the RAISA relay is based upon the fact that the second harmonic (100 Hz) is relatively much larger in the switching surge than in the short-circuit current. The restraining voltage $U_S$ is obtained via transformers $T_3$ and $T_2$. The inductance of the transformers and the capacitance of the capacitors $C_1$ and $C_2$ are tuned for resonance at the second (100 Hz) and the fifth (250 Hz) harmonic components. The second harmonic component is used to restrain the relay from the magnetizing inrush current. The fifth harmonic component is incorporated to attain the desired insensitivity for higher harmonics. The transformers supply the rectifier bridge VD2, which provides the countering voltage $U_S$ for restraining. Voltages $U_f$ and $U_S$ are summed in accordance with their signs to a resultant voltage $U$, which is supplied to the measuring circuit.

Voltage restraint overcurrent relays are relays, the current pick-up of which changes because of voltage level, not harmonics as the in cases considered above. It is constructed as a standard current relay of the induction type with a rotating disk, but it is also equipped with an additional voltage coil which creates voltage restraint (Figure 10.101 and Figure 10.102). Why are such relays needed?

The voltage restraint overcurrent relay was designed for the purpose of providing external-fault back-up protection for the generator. System fault back-up protection should be provided at the source of faulty currents, the generator. Such protection should protect against the generator continuing to supply short-circuit current to faults in the adjacent system element, because the fault may not have been removed by other protective equipment. The current source for the voltage restraint relay should be a CT at the neutral end of the generator windings, or at the line-side CT. Phase-to-phase voltage should be obtained from the generator potential transformers. Loss of potential to the voltage restraint relay will cause the relay to trip if the generator load current, expressed in relay secondary amperes, is greater than the zero voltage pick-up current of the relay.

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10.7 Pulse Current Relays

The so-called pulse current relay is energized by very short current pulses with duration of just a few microseconds of input. Such relays must have a very small TD, sufficient to pick-ups when partial breakdown of isolation in high-voltage vacuum tube is occurred, or to operations with arresters, when current carry in lightning rods (when lightning strikes), etc., and also must have a long output signal, compatible with ordinary electro-mechanical devices.

In micro-electronic devices, especially high-frequency ones, electric signals of small duration are frequently used; therefore electronic circuits for pulse stretch are very widely used in these devices. An example of such a circuit is the RC-integrator (Figure 10.103).
For the same purpose the so-called “monostable multivibrator” (or “waiting multivibrator,” “one-shot multivibrator” or “univibrator”) is frequently used (Figure 10.104). Many companies produce special microchips that carry out functions of a monostable multivibrator. In powerful impulse devices in the electric power industry such high-sensitivity devices do not always work well, as they tend to pick-up under the external electromagnetic influences, and not from the input signals. In addition, such elements are not yet relays and additional circuits required: power supply, amplifying circuits, input and output devices. As far as is known to the author, there are still no universal pulse relays for high currents suitable for every such application available today in the market, therefore in each concrete case designers must invent, design, and develop such a relay in order to solve each specific problem.

The author solved one such problem when he developed a variant of the pulse relay for high currents (Figure 10.105). As a result, this very reliable relay, with a very low input resistance (that is, not sensitive to electromagnetic influences) was developed. This relay,
fixed on a thick copper conductor is capable of pick-ups from short pulses of current of only 5 to 10 μsec duration, with amplitudes from several tens of amperes up to several tens of thousands of amperes.

In tests, the high-voltage pulse generator of this relay made single current pulses with amplitudes ranging from 200 up to 20,000 A and standard pulse shape with $T_1/T_2 = 8/20$ (Figure 10.106). The exact threshold of the pick-up of this relay is adjusted by an internal trimmer. The duration of the output pulse depends on the capacity of capacitor $C_2$ and can change from tens of milliseconds within a few seconds.

Three independent identical units were used in the specific design of the relay developed by the author, adjusted on three different thresholds of pick-ups: 300, 1000, and 10,000 A (Figure 10.107). Each unit contains a thyristor VS1, which will be actuated by input pulse with level, exceeded of preset (by trimmer $R_2$) value and switched ON during few microseconds. Capacitor $C_2$ start charging across the open thyristor. Thyristor remains in open state during capacitor charging time and turned OFF after capacitor $C_2$ will be fully charged. In other words, weight of output pulse (up to 150 V, 0.1 A) is equivalent

---

**FIGURE 10.105**
External view (a) and circuit diagram (b) of the pulse relay for high currents.

**FIGURE 10.106**
Input pulse shape applied to relay during test and signal on relay output ($T_1/T_2 = 8/20$ μsec).
to the capacitor time charging. Relay returns to its initial state after capacitor C2 will discharge across resistor R4.

If the printed circuit board and input coil are placed in a high-voltage insulating case (like that are used in high-voltage reed relays of the RG-series, described above) and filled with epoxy resin, the result will be a fine high-speed protective relay with high-voltage isolation.

FIGURE 10.107
Printed circuit board (a) and input coils unit (b) of the multistage pulse current relay, developed by author.
11

Power and Power Directional Relays

Very often even in technical literature “power relays” and “power directional relays” are mixed up. Some books do not distinguish between these two notions, claiming that power relays respond only to the direction (sign) of the power applied to their clips, and not to the power value, which can vary within wide ranges. In other books, one can find claims that power relays respond both to the value and to the direction of power.

In fact, neither of these claims is exactly so. There are power relays controlling both the value and the direction of the power applied to them, and there are also power relays responding only to the direction of power flux. These are two different types of relays with different constructions and different characteristics.

11.1 Induction-Type Relays

The operating element of the power relay is of the watt-metric type, similar to that used in the standard watt-hour meter. It is provided with one current and one voltage coil on a common magnetic core. Interaction of the two fluxes developed by the coils produces a torque in the aluminum disk, causing the disk to rotate. An Alnico magnet provides effective damping of the disk so that the characteristics are accurate throughout the timing range. When the power flow equals or exceeds the power setting of the relay and is in the proper direction for tripping, the disk begins to turn. The contacts are geared to the operating shaft and close at the end of disk travel, at the zero time-level position. The time required to close the contacts is dependent on the magnitude of power and the time-level setting. The relay is, in effect, a contact-making wattmeter.

Power relays are commonly used (as over-power relays) for protection against excess power flow in a predetermined direction. Such a need arises, for example, in the case of a small generating station which has its own local load and a normally closed emergency tie to a large power source. The small station has enough capacity to supply its own load but cannot supply an appreciable amount of power into the large system. In such a case, a power relay can be used to trip the emergency tiebreaker if power in excess of a predetermined amount is fed into the large system for longer than the given length of time.

The ICW-type relay, produced by General Electric (Figure 11.1), is a typical example of such a power relay. Power direction relays are used in protective systems as units that determine the direction of power passing through a protected line, where damage has occurred to the protected line or to other outgoing lines adjoined to the same substation (Figure 11.2).
If a short circuit occurs, for example, at point A (Figure 11.2), the power ($S_A$) will pass from the source ($G_1$) to the closing point (A), through the installation place of the relay. If the short circuit occurs at point B, the power ($S_B$), in the opposite direction, will pass through the installation place of the relay — that is from the source ($G_2$) to the point of the short circuit (B).

To determine the direction of power, the exact values of power are not important. They can vary widely and are needed only for the estimation of the minimal power required for relay pick-up. This power is called as the pick-up power of the relay. *Power direction is determined by the angle between current and voltage.*

The power direction relay is based on an induction magnetic system with a rotating rotor (considered above) in the form of an aluminum cup (Figure 11.3), as such relays must be fast-acting and as has already been mentioned the rotating disk does not provide the required speed of operation. In addition to relays having a single-phase magnetic system with four poles, there are also three-phase power direction relays with eight poles (Figure 11.4).

---

**FIGURE 11.1**
(a) ICW51 type power relay (General Electric), based on an induction system with a rotating disk. 1 — Contact (silver); 2 — seal-in contacts; 3 — target; 4 — tap block for power setting; 5 — time dial; 6 — control spring; 7 — aluminum disk; 8 — Alnico magnet; 9 — relay drawout contacts. (b) Time–watt curves of ICW51 relay. (General Electric Type ICW Overpower Relays GEA-3417D.)

**FIGURE 11.2**
Connection of the power direction relay and its application for determination of damages in the line.
11.2 Characteristics of Power Direction Relays

As it has been considered above, perpendicular sinusoidal magnetic fluxes, $F_I$ and $F_U$ (created by current and voltage coils), induce eddy currents, $i_I$ and $i_U$, respectively, in the rotor body. These currents interact with the magnetic fluxes $F_I$ and $F_U$, inducing them to create a constant rotating torque ($M$) on the rotor:

$$M = kF_IF_U \sin \phi$$

where $\phi$ is the angle between the fluxes $F_I$ and $F_U$ and therefore between the currents in the current ($i_I$) and voltage ($i_U$) windings.
As the maximum value, \( \sin f \) takes place when \( f = 90^\circ \), one can say that the maximal torque (corresponding to the maximal sensitivity) will be developed in the relay when \( f = 90^\circ \). This is the angle between the current on the current coil (\( I \)) and the current in the voltage coil (\( IU \)), and not between the input current and input voltage (Figure 11.5).

In the formula shown above, if the magnetic fluxes \( F_I \) and \( F_U \) are replaced with the current \( I \) and voltage \( U \) (proportional to them), and the angle \( f \) with angle \( g \) — \( \phi \) equaling it, one obtains a general formula for the torque on the rotor, expressed through the input current and input voltage:

\[
M = kIU \sin \left( \frac{\phi}{w} \right) = kS
\]

where \( S \) is the full power on the relay input.

The interior angle of the relay \( \gamma \) is determined by the constructive parameters of the relay and may vary synthetically. If the voltage winding is made in such a way that its pure resistance is less than its reactance (\( R \ll X \)), the current in the voltage winding (\( IU \)) will be behind the applied voltage (\( U \)) by an angle approximating \( 90^\circ \) (that is \( \gamma = 90^\circ \)), and one will obtain the following formula for the torque:

\[
M = kIU \sin (90^\circ - \phi)
\]

or taking into account that \( \sin(90^\circ - \phi) = \cos \phi \):

\[
M = kIU \cos \phi = kP
\]

where \( P \) is the active power.

Relays reacting to active power are called active power relays or cosine relays. And vice versa, if pure resistance of the voltage winding is much higher than the reactance (\( R \gg X \)), the current in this winding (\( IU \)) will practically coincide in phase with the voltage (\( U \)), the angle between them will equal \( 0^\circ \) (that is \( \gamma = 0^\circ \)), and the torque (\( M \)) will be:

\[
M = kIU \sin (0 - \phi)
\]

or taking into account that \( \sin (0 - \phi) = -\sin \phi \):

\[
M = -kIU \sin \phi
\]

To obtain positive torque, outlets of the voltage circuit of this type of relay are made with opposite polarity. In this case:

\[
M = kIU \sin \phi = kQ
\]

where \( Q \) is reactive power.
Relays responding to reactive power are called reactive power relays or sine relays. At intermediate values of the interior angle (γ), the relay responds to both power constituents and is called as a mixed type relay. These relays are most widely used in the power industry. Characteristic of the power direction relay looks rather unusual in comparison with the characteristics of the other relays considered above (Figure 11.6). How such a characteristic is obtained?

First, one lays off the vectors of the actual current (I) and voltage (U) applied to the relay inputs, taking into account the actual angle (φ) between them. The vector of the voltage is the basis for counting. Then, through changing of the current phase (by turning vector I), the maximal sensitivity of the relay is achieved.

The angle between current and voltage at which the sensitivity of the relay is maximal is called the angle of maximal relay sensitivity (φ_M), and the line drawn at this angle through the beginning of the vector of the voltage (M–M) is called the line of maximal torques. In contrast to that, an additional line drawn at a right angle to the line of maximal torques is called the line of zero torques. As it can be seen from the characteristic, this is a very important line separating the working area of the relay from the dead zone (which is sometimes called the zone of dead band of the relay) and in which the relay will not work. What happens to the relay if the current vector crosses the line 0–0? Nothing terrible. The torque affecting the rotor (and the contacts through it) will change its polarity to the opposite one, that is, it will become negative. If the torque is directed to closing of contacts in the working area in the dead zone, it will be directed to repulsion of contacts. There are so-called double-acting relays in which the movable contact can move to both sides from an initial neutral position, closing the left-hand or the right-hand contact corresponding to direct or reverse direction of the power flux. Such relays are applied in double-side supply electric power systems.

When the power flowing through the installation point of the relay changes its direction, the angle between the current and voltage also changes. This allows use of the relay sensitive to this angle as a device responding to the direction of the power flux.

Another important characteristic of power direction relays is their volt–ampere characteristic (Figure 11.7). We have already mentioned that the power direction relay reacts to the direction of the power flux, and not to the power value; however, for normal relay operation a certain minimal power needed for rotor rotation, not equaling zero, must obviously be applied to the relay inputs. When there is a short circuit, voltage may considerably decrease in the circuit, which is why when one chooses a relay for a particular electric circuit, one must be sure that the proportion of voltage and current...
will provide the minimum required power for relay operation in every emergency mode. This proportion is described by the volt–ampere characteristic (Figure 11.7). For reliable relay operation, its working area must be higher than its volt–ampere characteristic.

As the pick-up power of the relay ($S_{\text{trip}}$) is measured within some limits depending on the angle between the current and voltage, the corresponding dependence for every particular relay can be plotted (Figure 11.8a), though it is not of that great importance and is needed just for understanding the principle of operation of the relay.

11.3 Electro-Dynamic-Type Relays

A whole series of relays including RP-1-, RP-2-, RPA-, and RPF type devices, produced by ASEA in the 1950–60's, had a peculiar (at least rear) construction. These were power electro-dynamic relays (Figure 11.9 and Figure 11.10).

These relays, which work on the electro-dynamic principle, are provided with an iron core (1), see Figure 11.9a, which is excited by the current in the coils $A_1$–$A_3$ and $A_2$–$A_4$. In the air gap flux of the iron core, the voltage coil (2) moves, this coil is being fixed to one end of the balance arm (5). The latter also supports the moving member (4) of the contact and a soft iron pin (6), which under the action of a small permanent magnet (7) provides the arm with the torque that determines the operating value of the relay, and retains the
arm in a defined initial position before operation. A damping device consisting of a metal vane (9), which moves in a dashpot (8) containing oil, prevents vibrations and hunting. When the two systems are supplied with current and voltage that have such a magnitude and phase angle that sufficient torque is obtained, the contacts (K1–K2 or K2–K3) close, depending on the direction of the power. The torque is largest when currents in the current coil and the voltage coil are in phase. If a phase shifting element is introduced into any of the circuits, it is possible to obtain the desired value of the angle between the voltage circuit voltage and the current of the current circuit at which maximum torque is obtained.

Because the RP-1 is not provided with any phase shifting element, the torque is proportional to the cosine of the angle between the currents in the two circuits. Due to this, the characteristic angle is 0° with a series resistance in the voltage circuit.

The mode of operation described above is most suitable for any directional-power relay in which the moving system is not influenced by any other mechanical forces than those the permanent magnet produces. On the other hand, when the type RPF relay is utilized as an over-, under- or regulating-power relay, it is provided with a spring and a graduated scale with a pointer by which the electro-dynamic forces can be balanced at a set power value.
The series resistors for the RP-1 and RPF relays are separately mounted. When the current coils are connected in parallel, these values are doubled. When the electrodynamic relay RP-1 is used and the protection is based on the active component of the fault current, for example, in compensated power networks, the voltage coil of the relay is connected in series with a resistor. In the case of networks having a free neutral, where the protection is based on the capacitive grounding current, the voltage coil of the relay is connected, on the other hand, in series with an inductance.

Also available is a two-phase electro-dynamic power direction relay (RPA type, Figure 11.10), which consists of two single-phase systems with a common shaft and contact. It is connected in accordance with the two-wattmeter method, and can consequently be used in asymmetrically loaded networks without a neutral.

11.4 Electronic Analogs of Power Direction Relays

As for all other types of relays, there are also electronic analogs of power direction relays. In any such a relay, the input current and input voltage are first converted to two low-level voltages, which are then applied to the circuit, determining the coincidence (or noncoincidence) of these voltages in phase. Such circuit is called a phase comparator (Figure 11.11).

FIGURE 11.10
A two-phase electro-dynamic power direction relay of the RPA type, with cover removed. (ASEA (ABB) 1968 Power Relays Types Catalog RK 51-1E.)

FIGURE 11.11
Block diagram of an electronic analog of a power direction relay.
In the simplest case, the circuit containing the two rectifying bridges and a threshold element cut in on the difference in voltage of these bridges can serve as this phase comparator (Figure 11.12). Let us remind ourselves that the voltage at the input and output of the rectifying bridge looks like in Figure 11.13.

The difference of voltages applied to the threshold element can be zero (other conditions being equal) only when the rectified voltages are in phase or in opposite phase, and maximal difference in these voltages occurs when the phases are displaced by $90^\circ$ between them (Figure 11.14). As a threshold element, one uses special highly sensitive electromagnetic relays with filters, providing leveling of the current in the winding or electronic switches. In a ring phase-sensitive circuit (Figure 11.15), diodes play the role of the switching elements, which are either in the open or closed position, that is, they either let current pass or not, depending on the polarity of the applied voltage.

Power direction relays with diode phase comparators were produced in the 1970s in many countries and were very popular due to their simplicity. This simplicity can be seen in the RXPE-4-type relay, produced by ASEA (Figure 11.16), which serves as a good example.

Phase comparators may be based not only on diodes, but also on transistors (Figure 11.17). The current through transistors VT1 and VT2 (Figure 11.17) is initially balanced by the potentiometer ($R_B$) bridging their emitters, so that zero potential exists across VT3. An input voltage which raises the potential of $A$ relative to $B$ ($A$ positive relative to $B$) causes VT2 to conduct more than VT1, which draws current through the base-emitter junction of VT3, which is then turned ON. In consequence, VT4 turns ON and produces an output voltage. When $A$ is negative relative to $B$, the output is zero.

Lately, electronic devices of phase comparison have become very popular. They are based on the measurement of coincidence time by the signs of the two voltages, one of which is proportional to the current, and the other to the voltage (Figure 11.18). This time is fully dependent on the angle of phase bias between the current and voltage, which is why it is a parameter applicable in power direction relays.

In the circuit in Figure 11.18a, both transistors (VT1 and VT2) are fully enabled since there are no input signals, and are shunting the capacitor $C$. When input voltages $E_1$ or $E_2$...
are applied, the corresponding transistor will be switched OFF. The voltage on the capacitor will always equal zero, if one of the transistors is constantly enabled, but if at any moment both transistors happen to be in state OFF, the capacitor C will begin charging during the period of time that they are in this state. The average voltage to which it can charge will be proportional to the time of coincidence of voltages $E_1$ and $E_2$, or to the angle of phase bias between the current and voltage. In fact this circuit is a transistor analog of the logical element "OR" with a capacitor at the output.

In Figure 11.18b, there are circuit transistors VT1 and VT2, connected in series, which will be open (that is, the part of the circuit between points 1 and 2 is shunted) only when both transistors are opened, and vice versa, voltage between points 1 and 2 occurs only when both transistors are disabled (closed). This is nothing else but the logical scheme “AND.” As is apparent, the breadth (duration) of the output pulse will be inversely proportional to the time of coincidence of the open state of transistors. The circuit shown in Figure 11.18c works similarly.

The same principle is applied to power direction relays based on a thyristor (Figure 11.19), patented by the author of this book in 1977. The principle of operation of such a relay is based on the fact that in order to open (switch ON) the thyristor on DC, two voltages must be applied to it: one between the anode and the cathode, and the other one between the cathode and the gate. The polarity of these voltages must be strictly defined; otherwise the thyristor will not be opened. In AC circuit, when these two voltages fully coincide in phases, the thyristor will be energized with a minimal angle of lag and will provide maximal average voltage in the load (for example, in the output relay winding). If there is a phase bias between these voltages, the thyristor will be switched ON with a certain delay with regard to the phase of the voltage applied to it, and as a result, the average voltage in the load will decrease proportionally to the phase bias. At angles approximating $170^\circ$, the thyristor will not be opened at all. Use of two thyristors connected inverse-parallel and of two output relays (their windings are marked as R1 and R2) allows us to obtain a double-acting relay for operation in double-side-supply power.
Power and Power Directional Relays

FIGURE 11.16
RXPE-4-type power direction relay, based on a diode phase comparator. VD — diode bridges; SC — smoothing circuit.

FIGURE 11.17
Phase comparator based on transistors.
networks. Capacitors in this circuit smooth voltage pulses in the load (the relay windings).

Generally, one can suggest a lot of variants of electronic circuits reacting to the phase difference between current and voltage. For instance, it is quite easy to implement the circuit measuring the time interval, when the sinusoids of voltages $E_1$ and $E_2$ pass through zero. Practically this can be implemented with the help of an electronic timer on a chip, which is energized when the sinusoid $E_1$ passes through zero, and stops when the sinusoid $E_2$ passes through zero. The phase bias between current and voltage will be determined by this very period of time.

Some industrial models of power direction relays are also based on the principle of the measurement of time of sign (polarity) coincidence of the input voltages, as in

![Diagram](image)

**FIGURE 11.18**
Electronic circuits determining the time of coincidence of (polarity) signs of input signals proportional to current ($E_1$) and voltage ($E_2$). SC — smoothing circuit.

![Diagram](image)

**FIGURE 11.19**
Figure 11.20, for example, an RM-11-type relay produced in Russia. In this device input, units 1 and 2 convert input current and input voltage to low-level voltages \( E_1 \) and \( E_2 \) proportional to them, which are applied to the phase comparator (3). Values with positive signs go to measuring unit 4 and those with negative signs to measuring unit 5. In these units, the coincidence times of the positive and negative values of the voltages \( E_1 \) and \( E_2 \)
are separately determined. Output voltages of units 4 and 5, limited by level with the help of a limiter (6), are summed up in a summation unit (7) and are applied to the threshold element (8) with an output electromagnetic relay (9) at the output. The full circuit scheme of the relay is shown in Figure 1.20c.

Coincidence time of positive values $E_1E_2$ and negative values $E_1E_2$ is measured by a sophisticated method based on alternating enabling and disabling of transistors VT1 and VT2 if instantaneous values (when signs) of both input voltages coincide. When the corresponding transistor is turned ON, there is a current pulse the breadth (duration) of which will be proportional to the duration of coincidence of the voltage polarities. These pulses are used to charge the capacitors $C_5$ and $C_6$, the voltage on which will be proportional to the time of coincidence of the signs of the input voltages. At that point, these voltages are summed up and the value is compared with the prescribed level; if it is exceeded, then the relay picks up.
12

Differential Relays

12.1 Principles of Differential Protection

The term “differential” itself signals that the chapter will be concerned with relays responding to differences of actuating quantities; and that is true. Differential protection compares two (or more) currents to locate a fault; which actually makes current protection. In comparison with other types of protection, differential current protection possesses an absolute selectivity in the sense that it operates smartly only in those cases where the fault is within the protected zone, and does not operate at all if the fault is out of its zone. The zone of the differential relay is limited by a part of the electric circuit between the current transformers (CTs), to which the relay is connected. Due to such high selectivity of protection, there is no need to activate a delay for the relay pick-up, which is why all differential relays are high speed. That being so, extraordinarily high selectivity and high speed of operation are the distinguishing features of differential protection.

Differential current protection is applied for sections of power lines and some important elements of the power-supply system such as generators, transformers, reactors, and power electric motors. In addition to the protection from current overloading, differential protection is also used for localization of insulation damages in high-voltage equipment (generators, for instance).

Differential protection of power lines is divided into longitudinal protection and transverse protection. The former refers to protection of longitudinal sections of single lines (which is of course why it is called “longitudinal”), and the latter to the protection of parallel lines (comparing currents in these parallel lines).

Longitudinal differential protection operates on the principle of comparison of magnitude and phase of the currents entering and leaving the protected circuit section or element. To accomplish differential protection, two CTs (CT1 and CT2), having identical ratios of transformation, are interposed in the circuit at both ends of the protected circuit element. These CTs have their secondaries interconnected by the connecting leads as shown for one phase in Figure 12.1. The differential relay Rel is arranged in parallel with the CT interconnection leads.

This scheme, based on the circulation of currents, was first established at the end of 19th centuries by Merz and Price and called the “Merz–Price differential scheme.” This fundamental principle has formed the basis of many highly developed protective arrangements.

If the secondary currents of CTs CT1 and CT2 are denoted, respectively, by $I_1$ and $I_2$, and the positive direction of the current in the relay is taken to be that of current $I_1$, during normal operating conditions on line AB (here and hereinafter vector values):
The relation is valid by virtue of the fact that the impedance of the winding of relay Rel (usually a current relay) is considerably less than that of the current-transformer secondary windings, and it can hence be considered that the secondary currents flow through interconnection leads and complete their circuits through the relay winding.

In the ideal case, during normal operating conditions and in the event of external short circuits (outside the zone of protection), the secondary currents of CTs CTl and CT2 will be equal in magnitude and opposite in direction. Because of this, no current will flow in the differential relay circuit or:

\[ I_{REL} = I_1 - I_2 = 0 \]

In the actual circuit, a current of unbalance will flow in the relay circuit because of the unequal magnitude of the CTs’ currents at one and the same primary current. This problem will be studied in greater detail below.

When a short circuit occurs within the zone of protection and the power supply comes from one end (Figure 12.1b), the relay circuit carries a current:

\[ I_{REL} = I_1 - 0 = I_1 \]

The relay then operates to transmit an impulse to trip the circuit breaker at the supply end.

When a short circuit occurs within the zone of protection and power is supplied from both ends (Figure 12.1c), the sum of the secondary currents will flow through the relay, or:

\[ I_{REL} = I_1 + I_2 \]

FIGURE 12.1
Circulating-current longitudinal protection performance during fault outside (a) and within zone of protection (b, c) (b) case of single-end supply; (c) case of two-end supply.
(these currents, in general, being different in magnitude). The relay in this case operates to transmit impulses to trip the circuit breakers at both ends of the faulted line.

The differential scheme studied here is called a "circulating-current circuit" due to the fact that the current continuously circulates in the interconnecting leads of this circuit. If two identical power lines are run in parallel from one substation to another and are connected to the buses by a common circuit breaker, a common protection is installed for both lines and will trip out the circuit breaker when a short circuit occurs on any one of the lines. For protecting two parallel high-voltage lines of wide applications, transverse differential current protection is implemented, based on a comparison of the magnitude

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**FIGURE 12.2**
Single-phase circuit diagram of transverse differential protection for two parallel lines with single-end supply.

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**FIGURE 12.3**
Three-phase version of the scheme of differential protection of the generator's stator with high-impedance differential relays. (a) Phase and earth fault protection; (b) restricted earth fault protection.
and phase of the currents in the parallel lines (Figure 12.2). As already mentioned above, the differential protection is applied not only for protection of segments of lines, but also for protection of such important system components as transformers, reactors, generators, switchgears, power motors, etc. (Figure 12.3).

12.2 High-Impedance Differential Relays

The most simple design of this type is the so-called “high-impedance differential relays,” used for protection of concentrated objects such as switchgear, bus bars, generators, reactors, and power motors. The following limitations on CTs are required for applying these relays:

1. All CTs in the differential circuit must have the same ratio.
2. All CTs should be operated on their full winding (i.e., tap connections must be given special consideration).
3. Inlet and outlet current levels of protection object must be equivalent.
4. No other equipment, including no other types of protection devices, can be connected to the CT used for high-impedance differential relays.

As already mentioned above, under external fault conditions if the CT has no error, the current in the secondary of the CT in the faulted line is equal and opposite to the vectorial sum of the currents in the secondaries of the remaining CT in the same phase. No current flows in the relay and the voltage that appears across the paralleling points is zero. Unfortunately during fault conditions, CTs do not always perform ideally, since core saturation may cause a breakdown of ratio. Such core saturation usually is the result of a DC transient in the primary fault current, and may be aggravated by residual flux left in the core by a previous fault.

The worst condition of unbalanced secondary currents is realized when the CT in the faulted circuit is completely saturated and none of the other CTs suffer a reduction in ratio. Under this condition the saturated transformer secondary winding presents an impedance which is practically equal to its DC resistance, since the leakage reactance of the full winding of the toroidally wound CT can be neglected and a secondary current will be forced through the saturated CT equal to the sum of the secondary currents in the remaining paralleled CTs, less the current through the high-impedance relay which is negligible. The maximum voltage across the relay under external fault conditions therefore, will be the resistance drop of the theoretical secondary current which flows through the leads and secondary winding of the saturated CT in the faulted line.

It is obvious that under external fault conditions, no higher voltage than this can exist, since either a reduction in ratio of any of the other CTs or a diversion of current through the relay will reduce the current through the saturated transformer secondary. Whatever secondary voltage is generated by the core flux of the saturated CT will also reduce the voltage across the paralleling points.

Therefore, in order to prevent incorrect operation under extreme values of external faults, it is only necessary to set the pick-up of the relay above this maximum through-fault voltage, which can readily be calculated from the resistance of the CT leads and
secondary winding, and the maximum short-circuit current. A factor of safety of 2:1 can be used in making this setting while still retaining good sensitivity for internal faults.

When an internal fault occurs, the secondary current from the source CT is limited by the impedance of the idle CTs and the voltage relay, which are all connected in parallel and are all high-impedance elements. Under this condition, the voltage that appears across the paralleling points approaches the open-circuit voltage of the CT secondaries. This voltage is reduced by the shunting effect of the exciting current for the idle CTs and whatever current flows through the relay.

When these shunting effects are taken into account in typical applications, it is found that the net voltage applied to the relay due to a comparatively low internal fault is greatly in excess of the pick-up value that is established for the maximum external fault condition. Since the source CTs are practically open circuited during an internal fault, it is necessary to limit the secondary voltage under this condition to relieve insulation stresses (Figure 12.4). For this purpose a special precision nonlinear resistor is connected in parallel with the relay.

General Electric Co. used nonlinear resistor, called Thyrite® (developed by GE in 1918) (Figure 12.5). Other companies used nonlinear resistor, called Metrosil®, or Ceramsil® (Figure 12.6 and Figure 12.7). These resistors are proportioned to shunt negligible current

![FIGURE 12.4](image_url)

Secondary voltage on open circuit CT during an internal fault in the protected zone, without over-voltage limiting.

![FIGURE 12.5](image_url)

Volt–ampere characteristic of nonlinear resistors Thyrite. 1 — For one four-disk Thyrite stack; 2 — for two four-disk Thyrite stack.
around the relay at voltages near the pick-up value, and to prevent a rise in voltage above a predetermined level by permitting a high current to flow on severe internal faults. These are not just simple nonlinear resistances of the varistor type, but are precision elements with precise volt–ampere characteristics, used when the pick-up parameters of the relay are calculated. Unlike standard varistors, these resistors have considerably more quiet characteristics, and can operate on the nonlinear sections, thus causing greater power releases on them. Usually these resistors withstand not more than 70 to 100 ms in this mode, which is enough for the relay pick-up. On one hand, these resistances effectively limit voltage in secondary circuits of the CT when a high-impedance differential relay (Figure 12.8) is used, and on the other hand they provide pick-up of the relay shunted by this resistance at a certain voltage level.

The working element of such a high-impedance differential relay is a voltage relay. Many companies produce such relays both of electromagnetic and electronic types. For

![Figure 12.6](image)

(a) A nonlinear resistor Metrosil: one three-disk stack (ALSTOM). (b) Volt–ampere characteristics of nonlinear resistor Metrosil (ALSTOM). 1 — For relay setting range 25 to 175 V; 2 — setting range 25 to 325 V; 3 — for setting range 100 to 400 V.

**FIGURE 12.6**

(a) A nonlinear resistor Metrosil: one three-disk stack (ALSTOM). (b) Volt–ampere characteristics of nonlinear resistor Metrosil (ALSTOM). 1 — For relay setting range 25 to 175 V; 2 — setting range 25 to 325 V; 3 — for setting range 100 to 400 V.

![Diagram](image)
example, earlier relays produced by General Electric were of a plunger type with a retractable core (Figure 12.9). As shown in Figure 12.9, the PVD11 relay consists of two plunger-type operating units: a “low-set” voltage unit (called as “device 87L”) and a “high-set” current unit (“device 87H”).

Device 87L is an instantaneous voltage unit with a high-impedance operating coil. To cancel the effect in the secondary of the DC component of an offset wave, which may be exaggerated by cumulative residual magnetism from previous faults, a circuit that is tuned for resonance at system frequency is used in series with the coil. In order to permit adjustment of the relay without affecting the tuning, a rectifier is interposed between the tuned circuit and the relay coil (Figure 12.10).
Device 87H is an instantaneous over-current unit with a low-impedance coil, which is connected in series with Thyrite resistor disks. The Type PVD II C relay has a stack of four Thyrite disks in its voltage-limiting circuit, and is intended for use with CTs having a 5-A secondary. The 87H unit, when set with the proper pick-up, may be used to supplement the voltage unit, 87L, and/or implement breaker failure protection when a suitable timing relay and other auxiliary devices are provided by the user. The required setting of the 87H unit is related to the actual setting of the 87L unit.

During an internal fault, current will flow in the Thyrite stack, causing energy to be dissipated. To protect the Thyrite from thermal damage, a contact of the lockout relay

**FIGURE 12.8**
Secondary voltage on open-circuit CT during an internal fault with over-voltage limiting by a Metrosil (ALS-TOM).

**FIGURE 12.9**
(a) and (b) High-impedance differential relay PVD-11 with plunger-type operating units. 1 — Seal-in coil with tap; 2 — seal-in contacts; 3 — low-set unit; 4 — operating coil; 5 — calibrated plunger rod; 6 — target; 7 — high-set unit; 8 — self-aligning contacts; 9 — marking strips; 10 — steel cradle; 11 — rectifier bridge (assembly); 12 — latches; 13 — reactor; 14 — Thyrite assembly. (General Electric Type PDV Instruction GEA-5449A.)
FIGURE 12.10
Circuit diagram of PVD11 relay. (General Electric Type PDV Instruction GEA-5449A.)

FIGURE 12.11
(a) Modern high-impedance MFAC34 type (ALSTOM) differential relays have a different construction of the case, but in all other respects they are similar to earlier PVD11 relays produced by GE. (b) Connection diagram for high-impedance differential relay MFAC34 type (ALSTOM).
(outside auxiliary relay) must be connected to short out the Thyrite during an internal fault; however, the 87H unit is not shorted so that the relay can continue to operate as an over-current function, remaining is picked up until the fault is cleared. The 87H unit may be used to implement breaker failure protection. The thermal limits of the Thyrite will not be exceeded if relay time plus lockout relay time is less than four cycles.

Later high-impedance differential relays produced by General Electric (PVD21) were based on attracted armature units, simple and robust. Similar relays were and are still produced by many companies at present. Thus the ALSTOM company (France) which has already been mentioned, produces high-impedance differential relays of the MFAC type (Figure 12.11), CAG34, based on the same principles as the relays described above.

The Australian company “Relay Monitoring Systems Pty Ltd” (RMS) produced high-impedance differential relays of the 2V73 type for one phase (Figure 12.12), and the 2V47K6 type for three phases. These relays are intended for various items of power system plants including generators, bus bars, and motors. The 2V73 is also suitable for restricted earth fault applications. The relay-measuring element is basically an attracted armature unit of simple and rugged construction powered from a bridge rectifier. Each phase of the relay can be set from 25 to 325 V AC in 50 V steps by using the front panel mounted selector switches. A capacitor is connected in series with the operating coil to make the relay insensitive to the DC component of fault current. The setting can thus be calculated in terms of RMS AC quantities without regard for the degree of offsets produced by the point on wave at which the fault occurs. An inductor connected in series with the capacitor forms a resonant circuit tuned to the relays-rated frequency. As an alternative to the simple high-impedance relays, biased systems can be used. Usage of such systems is particularly relevant for protection of power transformers.

12.3 Biased Differential Relays

In modern power systems, transformers with ratings of more than about 1000 kV A are protected against internal short-circuits by differential protection. The heart of this form of protection is the differential relay in which the currents on the primary and secondary
sides of the transformer to be protected are compared with respect to magnitude and phase relationship.

In normal operation, the ratio between the primary and secondary currents is constant at any instant, apart from the magnetizing current which appears on one side but which only amounts to a few percent of the rated current of the transformer, depending on the transformation ratio of the transformer. The phase relationship between the two currents is fixed by the vector group of the transformer. On occurrence of a fault inside the protected zone, restricted by the location of the CTs necessary for connecting the differential protection on the high- and low-voltage sides of the transformer, this ratio of the currents, and in some circumstances their phase relationship, is disturbed. The unbalanced current can be evaluated directly as a criterion of the fault. The differential relay responds to this current by closing its tripping contacts, causing the circuit breakers on the high- and low-voltage sides of the transformer to open.

Even under normal working conditions unbalanced currents (spill currents) appear, their magnitude depending on the individual ratio and phase-angle errors of the CTs employed. They generally increase as the load on the transformer increases. They attain particularly high values when through faults outside the protected zone, the CTs tend to saturate; and also in the case of tap-changing transformers, when (as is usual) the CTs are not adjusted when the ratio of power transformation is changed.

To compensate for these influences, the differential relay is stabilized, that is, the relay is given a characteristic basically similar to that in Figure 12.13. This shows the unbalance (differential) current \( I_d \) necessary to operate the differential relay in relation to the circulating current \( I_D \). Differently, the increase of a circulating current results in a desensitization of the relay to a differential current.

At low values of the circulating current the curve does not rise more steeply than is necessary with a view to the spill currents, and changes its slope only when the circulating currents are such that the CTs are approaching saturation.

Figure 12.14 is a schematic diagram of a differential protective system stabilized in this way. The measuring circuit of the differential relay contains a bias system (H) and an operating system (A), which work in opposition. The CTs in the same phase on the high- and low-voltage sides of the transformer are connected in series through the bias system.
(H) of the relay, and the operating system (A) is connected across the bridge. As will be seen in Figure 12.14, the vector sum of the two current-transformer currents:

$$|I_1 + I_2| = |2I_D + I_d|$$

acts on the bias system in a restraining sense, and the vector difference on the operating system in the tripping sense:

$$|I_1 - I_2| = I_d$$

The secondary currents of the CTs:

$$I_1 = |I_D + I_d| \quad \text{and} \quad I_2 = I_D$$

are so matched, if necessary, by the inclusion of intermediate CTs to compensate for differing current-transformer secondary currents, and in some cases, dissimilar phase angles if the protected transformer is of a vector group causing a phase difference. That is so because in normal working, a spill current flowing through the operating system is not sufficient to operate the differential relay. The desired relationship between the unbalanced current and the circulating current is obtained by suitable design of the bias and operating systems.

In early electromagnetic differential relays (e.g., the QS4, produced by AEG) the comparison of the vector sum:

$$|I_1 + I_2|$$

and the vector difference:

$$|I_1 - I_2|$$

FIGURE 12.14
Schematic diagram of transformer biased differential protection. $I_d$ — unbalance (differential) current; A — operating winding; $I_D$ — circulating current; H — bias winding. (AEG Transformer Differential Relay RQ4 1959.)

FIGURE 12.15
Schematic diagram of an early electromagnetic percentage differential relay of the QS4 type.
was effected by means of a mechanical balanced beam system as represented in Figure 12.15, in which the bias and operating system, in the form of electromagnets, act in opposite senses on a pivoted beam.

One of the disadvantages of the arrangements of this kind is that a separate beam system is necessary for each of the three conductors and the power consumption is relatively high.

12.4 Electromagnetic Percentage Differential Relay

In later designs (for example, the RQ4 relay, produced by AEG in the 1950–60’s, Figure 12.16) of transformer differential relays, the currents from the bias transformer \( T_b \) and the operating transformer \( T_d \) are rectified, the DC outputs being compared in a bridge circuit across which is a sensitive moving-coil relay \( \text{Rel} \) (Figure 12.17).

The advantages of this arrangement are firstly that the characteristic (unbalance current in relation to circulating current) can be largely matched to the requirements of the transformer differential protection by means of simple elements, and secondly that the power consumption is considerably less, with much shorter operating times.

When the power transformer is energized, current is supplied to the primary, establishing the required flux in the core. This current is called the ‘magnetizing inrush’ (which may reach a value several times the rated current of the transformer) and it flows only through the CTs in the primary winding. This causes an unbalance current to flow in the coil of the differential relay, which would cause false operation (trip) if means were not provided to prevent it.

The inrush current differs from the other currents due to internal faults in the transformer in that it has a considerably higher harmonic content. This property can be utilized...
to stabilize the differential protection against the undesired effect of the inrush current by means of a suitable blocking element, so that it is possible to dispense with the time-lag arrangements formerly employed.

In the RQ4 transformer differential relay a measuring element for determining the magnitude of the unbalance current \( I_d \) and a blocking element are combined in a single case. The measuring and blocking elements are in the form of moving-coil relays. The contacts of each relays (NO-contact of the measurement relay and NC-contact of the blocking relay) are connected in series and only permitting tripping when the unbalance current \( I_d \) is of a certain value and has not too high a harmonic content. Each of the two relays is provided with an instantaneously-acting contact-pressure reinforcing device, which ensures complete absence of bounce and acts as a safe and robust auxiliary relay.

When the transformer is switched ON, the inrush current causes the moving-coil relay of the blocking element to operate so rapidly as to open the tripping circuit (NC-contact) before tripping is effected by closing of the NO-contact of the measuring element. The contact of the blocking element does not reclose until the relay of the measuring element has returned to the off position after the inrush current has died away. On the occurrence of genuine faults within the protected zone of the differential protection, however, the contact of the blocking element remains closed because of the preponderance of the fundamental over the harmonics in the short-circuit current, so that instantaneous tripping is initiated.

Start relay operating times are thus obtained even with small unbalanced currents. With three-pole faults and \( I_D/I_d \) greater than 80%, they are less than 100 ms and with two-pole faults only slightly more.

The blocking element incorporated in the relay is the supplementary blocking relay, which has already proved highly satisfactory in service; this has been used as a separate supplementary relay both in conjunction with the well-known quotient differential relay QS4 and also with other modern relays. For these purposes, it is still used as a separate relay.

Figure 12.18 is a schematic diagram of the blocking element, the function of which is to prevent tripping by inrush current and to permit tripping only on the occurrence of genuine faults. The two three-winding CTs T1 and T2 in the unbalance current circuit feed an Ohmic shunt \( R_l \) and a reactive shunt \( L_2 \), respectively, which are connected through a nonlinear resistor \( R_{l2} \) and a high-pass filter \( F \) to a DC bridge, across which is the moving-coil relay Rel. The current which flows in the left arm of the bridge through

\[
l = | I_D + I_d |
\]

FIGURE 12.17
Schematic diagram of a later designed electromagnetic percentage differential relay of the RQ4 type. (AEG Transformer Differential Relay RQ4 1959.)
the rectifier VD1 tends to keep the contact of the moving-coil relay closed, while the current which is passed through the rectifier VD2 tries to open the contact. The high-pass filter is so designed that in the right arm of the bridge, all harmonics are effective and by the provision of suitable damping, the effect of the second and third harmonics is increased. Thus the second harmonics, which is particularly pronounced in the inrush current of transformer (about 30 to 70% of the fundamental), is amplified for the purpose of blocking the differential relay against the effects of inrush currents. As in the left arm of the bridge, unlike the right, no accentuation of the harmonics is effected. They add little to the fundamental harmonic fed into the bridge by the rectifier VD1, so that the moving-coil relay Rel connected across the bridge responds essentially to the ratio of all the harmonics to the fundamental.

On the occurrence of a short-circuit across the terminals on the primary side of the transformer, when the fault current is limited only by the impedance of the supply network, the main CTs may become saturated so that they also produce harmonics. To ensure that the blocking element shall also be effective in case of such very high fault currents, the nonlinear element R12 is included in the left arm of the bridge of the blocking element. It consists of a suitably dimensioned resistor shunted by rectifier cells in antiparallel.

Specialized differential relays for protection of power transformers with a sensitive element based on standard electromagnetic relays (or moving-coil relay, as in the case described above) are quite popular and were produced not only by AEG in 1960s to 1990s but also by many others, such as ASEA (ABB), Siemens, etc. These relays had similar circuits and principles of operation (Figure 12.19). As it can be seen from the circuit of connecting the relay to the power transformer, there is an additional transformer between one of the windings (“star”) and a 1-4-7 outlet of the relay. This transformer has the same transformation ratio as the power transformer and is necessary for leveling of currents applied to the inputs of the relay from the same CTs installed from both sides of the power transformer. This is a standard method widely used in all types of differential relays for the protection of transformers.
FIGURE 12.19
(a) Relay of the RT22b type for differential protection of power transformers (Siemens). External design. (b) Circuit diagram. (Siemens 1989 Protective Devices catalog NS 1-89.)
12.5 Induction-Type Differential Relays

Along with the principle of construction of differential relays for the protection of power transformers based on electromagnetic relays, described above, another approach was developed, based on application of an induction magnetic system with a rotating disk. It should be noted that induction-type biased relays are not more modern than the relays described above, they were developed parallel to and have been produced since the 1920–30’s by the Westinghouse Company (Figure 12.20). Induction-type biased relays contain two electromagnets similar to those described above, operating on a single disc assembly and arranged to develop opposed torques. The operation magnet will be supplied with the differential current while the other will be energized by the biasing quantity. The windings will be proportioned to provide the desired bias ratio.

According to such principle, many types of differential relays were designed and produced during the past 50 to 70 years, for example, this percentage-differential relay of the IJD53 type (General Electric Co.) (Figure 12.21). The IJD53 relays contain two shaded-pole U-magnet driving elements acting on opposite sides of a single disk. One of these (the operating element) drives the disk in the contact-closing direction, and the other (the restraining element) drives the disk in the contact-opening direction. Since it is not always possible to provide CTs that supply equal secondary currents, the relays have tapped coils to permit balancing these currents.

---

**FIGURE 12.20**
Induction-type biased relay, produced by Westinghouse since the 1920s to 1930s.

**FIGURE 12.21**
Single-phase percentage-differential relay IJD53C type (General Electric Co.). 1 — Seal-in coil; 2 — target; 3 — seal-in contacts; 4 — induction disk; 5 — taps in operating and restraining elements; 6 — contacts; 7 — slotted collar; 8 — spiral control spring. (General Electric Instruction GEA 3236B.)
Percentage-differential protection of a two-winding power transformer is shown in Figure 12.22. While this scheme balances the incoming current against the outgoing current, as is done in the protection of AC rotating machines, the CTs are in leads from different windings. Because of this, protection is provided for turn-to-turn faults as well as for faults to ground and for faults between phases or windings. Protection is also provided to the leads between the CT location and the power transformer.

The IJD53C relays will close contacts on a minimum operating current, with no restraint, of 0.4 times tap rating. This value, in conjunction with the short time delay provided by the relay, is usually not sufficient to prevent incorrect operation on magnetizing inrush currents that occur when the transformer is connected to the line or bus bar. It is probable that the current setting will not be high enough to take care of the magnetizing inrush, and therefore, it is recommended that auxiliary desensitizing equipment be added.

In high-speed differential relays, the induction magnet system with a rotated cup (rotor) is widely used also, for example, in CFD type relays, produced by the General Electric Co. (Figure 12.23). The CFD relays are of the induction cylinder construction. The unit consists of a multi-pole stator, a stationary central core, and a cup-like induction rotor. The cup rotates about a vertical axis in the air gap between the stator and core. The lightweight aluminum cylinder offers a high ratio of torque to inertia and results in a fast operate time. The axis of the cylinder is supported at the lower end by a steel pivot, which rotates against a selected sapphire jewel. The jewel is spring mounted to protect it from shocks. The upper end of the shaft is held in place by a polished steel pivot, which projects down through a bronze guide bearing mounted in the end of the shaft.

The stator of the induction unit is of the eight-pole construction, but uses only six of the poles in two sets of three. One set carries the current from the CTs in one phase on each side of the generator winding. The other set carries the difference current between the two CTs.
**Type CFD differential protective relays function on a product restraint principle.** The restraining torque is proportional to the product of the current entering one side of the protected equipment and the current leaving the other side. The operating torque is proportional to the square of the difference between the two currents. The operating and restraining torques balance when the differential current is 10% lesser than the other two, up to approximately normal current. This 10% “slope,” as it is called, allows small differences to exist due primarily to CT errors. Above normal current, the differential current circuit will saturate before enough operating torque is produced to close the contacts on a 10% slope basis.

The CFD type relay is a cup-type induction unit. This type of construction results in a fast-operating protective device, even at currents only slightly in excess of the pick-up value.

**12.6 Harmonic Restraint Differential Relays**

The high percentages of harmonic currents in the magnetizing inrush current wave afford an excellent means of distinguishing it electrically from the fault current wave.

In the BDD type relays (Figure 12.24), the harmonic components are separated from the fundamental components by suitable electric filters. The harmonic current components are passed through the restraining coil of the relay, while the fundamental components pass through the operating coil. The direct current component present in both the magnetizing inrush and offset fault current waves is largely blocked by the auxiliary differential CT inside the relay, and produces only a slight momentary restraining effect.
Relay operation occurs on differential current waves in which the ratio of harmonics to fundamental is lower than a given predetermined value for which the relay is set (e.g., an internal fault current wave) and is restrained on differential current waves in which the ratio exceeds this value (e.g., a magnetizing inrush current wave).

In the BDD15B type relay, the through CT has two primary windings, one for each line CT circuit. Winding No. 1 terminates at stud 6 and winding No. 2 terminates at stud 4 through current restraint transformer. The output is fed to a tapped resistor through the percent slope tap plate at the front of the relay. By means of the three taps a 15, 25, or 40% slope adjustment may be selected. Resistor taps are adjustable and preset for the given slopes. The right tap corresponds to the 40% slope setting. The output is rectified and applied to the restraint coil of the polarized unit. The differential CT secondary output supplies the instantaneous unit directly, the operating coils of the polarized unit through...
a series tuned circuit, and the harmonic restraint circuit through a parallel resonant trap. The operating and restraint currents are each passed through a full wave bridge rectifier before passing through the polarized unit coils. The series resonant circuit is made up of a 5 \( \mu \text{F} \) capacitor (C1) and a reactor (L1) which are tuned to pass currents of the fundamental system frequency and to offer high impedance to currents of other frequencies. Resistor R1 is connected in parallel on the DC side of the operate rectifier and can be adjusted to give the desired amount of operate current. The output of the rectifier is applied to the operating coil (2 to 3) of the polarized electromagnetic relay. The parallel resonant trap is made up of a 15 \( \mu \text{F} \) capacitor (C2) and a reactor (L2) which are tuned to block fundamental frequency currents while allowing currents of harmonic frequencies to pass with relatively little impedance. Resistor R2 is connected in parallel on the AC side of the

**FIGURE 12.24 (Continued)**

(a) Transformer differential relay with percentage and harmonic restraint of the BDD type (General Electric Co.).

(b) Internal connection. In circle — high sensitive two-winding polarized electromagnetic relay. (General Electric Instruction manual GEH-2057A.)
FIGURE 12.25
(a) Transformer differential relays of the STD15 type with percentage and harmonic restraint and electronic amplifier, instead of polarized relay. (b) Circuit diagram of electronic amplifier. (General Electric Instruction manual GEH-2057A.)
harmonic restraint rectifier and can be adjusted to give the desired amount of harmonic restraint. The output of the rectifier is paralleled with the through current restraint currents and applied to the restraint coil (1–8) of the polarized relay.

It is evident that if the differential current applied to the BDD type relay is of a sinusoidal wave form and system frequency, it will flow mostly in the operating coil circuit and will cause the relay to operate. If on the other hand the differential current contains more than a certain percentage of harmonics, the relay will be restrained from operating by the harmonic currents flowing in the restraint coil.

A Thyrite resistor connected across the secondary of the differential CT, limits any momentary high-voltage peaks which may occur, thus protecting the rectifiers and capacitors from damage without materially affecting the characteristics of the relay.

The instantaneous unit is a hinged armature relay with a self-contained target indicator. On extremely heavy internal fault currents, this unit will pick up and complete the trip circuit. The instantaneous unit target will be exposed to indicate that tripping was through the instantaneous unit.

Because of the saturation of the CTs and relay transformers at high fault currents, it is possible that less operating current will be provided from the differential-CT than the percentage slope tap would imply, and more harmonic restraint will be provided than the actual harmonic content of the fault current would supply. As a result, under conditions of a high internal fault current, the main unit may be falsely restrained.

Tripping is assured, however, by the over-current unit operation. Pickup is set above the level of differential current produced by the maximum magnetizing inrush current. The main operating unit of the BDD type relay is a sensitive polarized relay with components as shown within the large circle on internal connection diagrams (Figure 12.24c). The unit has one operating and one restraining coil. The relay is a high-speed low energy device, and its contacts are provided with an auxiliary unit whose contacts are brought out to studs for connection in an external circuit.

Precisely the same as the BDD relay, the electrical circuit and characteristics has a differential relay of the STD type (Figure 12.25). The difference consists only in replacement of the polarized relay assembly by an electronic amplifier, thus the STD type relay becomes an intermediate version, between electromechanical and electronic differential relays.

Transformer differential relays of the RADSB type (ASEA) with an electronic measuring element are based on a similar principle of operation, which differs from the relay considered above by its original construction, typical of the ASEA firm with its COMBIFLEX modular principle (Figure 12.26). As we have seen from the above
examples, relays for differential protection of power transformers have specific characteristics and peculiarities that provide effective protection of transformers from emergency modes.

12.7 Pilot-Wire Relays

Relays with specific characteristics are required not only for the protection of power transformers. For the protection of power lines, applications of simplified circuits such as that shown in Figure 12.1 are not practical or reasonable when one takes into account that the length of the protected section of line may constitute tens of kilometers. In such cases instead of one relay as it is shown on Figure 12.1, two relays (Figure 12.27) are used, each affecting a power circuit breaker which is the nearest to it.

Pilot wires between the relays have high resistance exceeding by tenfold acceptable bounds for the load of even the most powerful CTs. For example, for a length of 10 km resistance of a pilot copper wire with a section of 1.5 mm$^2$ is 130 $\Omega$, while the permissible load for CTs is 1 to 2 $\Omega$. This difficulty can be overcome with the help of auxiliary CTs CT1–1 and CT2–1 (Figure 12.28). Use of the second relay connected parallel (according to circuits 12.27 to 12.28) causes considerable changes in the conditions of operation of the

![Figure 12.27](image1)

**FIGURE 12.27**
A Scheme of longitudinal differential protection with two relays, installed on both ends of the line.

![Figure 12.28](image2)

**FIGURE 12.28**
Application of auxiliary CTs (CT1–1 and CT2–1) for reduction of the load of the main CTs (CT1 and CT2).
Differential Relays

Current applied from each of the CTs to each of the relays is distributed in inverse proportion to the resistance of their circuits. The circuit of the “farther” relay (for CT1, the “farther” relay is Rel2 and for CT2 — Rel1) includes pilot wires with high resistance, which is why current received to the “farther” relay is less than current received to the “nearer” relay. As a result, the currents applied to the relay will be unbalanced even if perfect (without errors) CTs are used.

Every protection of this kind, depending on its sensitivity, has a maximal allowable impedance value of pilot wires. If that impedance is exceeded, the protection will not operate properly, however, even if the impedance of the pilot wires equals zero (an absolutely hypothetical case), each of the parallel connected relays will receive only half of the current, which is why the sensitivity of such a protection decreases. Since there were many difficulties in implementing circuits based on the Merz–Price principle (see above) for longitudinal protection of lengthy power lines, another principle, based on a balanced-voltage system instead of a balanced-current system suggested in the Merz–Price circuit was used (Figure 12.29).

In the circuit with the balanced-current system, the secondary windings of the CT are connected to each other in phase and the main windings of the relay connected in parallel to these windings (Figure 12.28), while in the circuit with the balanced-voltage system (Figure 12.29), the secondary windings of the CT are linked with each other in a crisscross manner and the main winding of the relay connected to the windings of the CT in series.

In normal conditions in the circuit with the balanced-voltage system total impedance of the series circuit turns out to be very high, and voltages initiated in the secondary windings of the CT are mutually compensated, which is why there is no current in this series circuit (or in the windings of the relay, of course). This absence of current in the circuit and also in the pilot wires in the normal mode is a great advantage of the balanced-voltage system in comparison with the balanced-current system, as it reduces requirements for pilot wires and eliminates limitations on the size of the protected area. However, owing to the fact that a demagnetizing flux does not exist in the CT, and the entire current-transformer primary current is a magnetizing current, standard CTs are not suitable for such operating conditions, as they will then be operated close to an open-circuited secondary condition. For these cases incorporated in the scheme are auxiliary CTs that have their primaries connected in the main current-transformer secondary circuit (providing normal operating conditions for the main CTs). These auxiliary CTs are designed for continuous open circuited secondary operation.

In the circuit shown on Figure 12.29, and all following circuits in single-line modification, two pilot wires are shown. How can we deal with three-phase circuits? Can one use six such wires? Here is what the 41–658 “Type HCB Pilot-Wire Relaying and Pilot-Wire Supervision” directory, published in 1942 by Westinghouse says:
The advantages of pilot wire relay protective schemes for transmission lines have been recognized for many years. Before the advent of the HCB relay, pilot wire schemes were complicated by the objectionable necessity of using multiple wire circuits, batteries, and several relays per line terminal. The type HCB relay equipment was designed to overcome these objections (Figure 12.30). This equipment gives complete high speed one cycle protection for phase and ground faults, yet uses only two pilot wires, does not apply battery voltage to the pilot wires, and has only a single moving element at each end of the line section.

This scheme can be applied to either two or three terminal lines, and to lines containing a power transformer. The same pair of pilot wires can also be used to transmit a remote...
Differential Relays

tripping signal from one end of the line section to the other for special applications where this may be desired. Such special applications usually involve a power transformer in the protected section. The HCB scheme also leaves wide latitude with respect to the quality of CT with which it is used, since it does not require close matching of CT characteristics at opposite ends of the line section. The scheme can also be applied to systems having a ratio of 10 to 1 between minimum phase fault current and minimum ground fault current; that is, the zero sequence current can be one-thirtieth of the positive sequence current. The HCB scheme can also be used on privately owned pilot wires or on leased telephone wires. The HCB relay is normally supplied with a milliamperemeter and a test button to periodically check the condition of the pilot wires. Supervisory relays are available for continuous supervision of the pilot wires and for the remote tripping of circuit breakers over the pilot wire circuit.

So as the Westinghouse Company affirms, it was the first which managed to reduce the number of pilot wires to two ones in a three-phase circuit of longitudinal differential protection.

In modern circuits, a so-called “summation transformer” is used (Figure 12.31). This transformer has low-resistance primary windings (I–III), a high-resistance secondary winding (IV), and also a core with an air gap providing a linear characteristic. Such a transformer with an air gap is also called a “transactor” (a combination of the words “transformer” and “reactor”). The number of turns of the primary windings is taken in the following proportion:

\[ I : II : III = 1 : 1 : 3 \]

If the number of turns between the outlets of phases R–S and S–T is the same, the number of turns between the outlets of phases R–T will be doubled. This causes unequal sensitivity of protection to different combinations of damaged phases when a short-circuit occurs.

In some cases, this type of summation transformer is made as a part of the magnetic system of the relay (Figure 12.32). “Translay” is the trade name initially given to a biased, electromechanical balanced-voltage system introduced nearly 100 years ago, which is still providing useful service on distribution systems even though it remains fundamentally unchanged.

This electromechanical design derives its balancing voltages from the transactors incorporated in the measuring relay at each line end. The latter are based on an induction-type meter electromagnet as shown in Figure 12.32. The upper magnet carries a summation winding to receive the output of the CTs, and also a secondary winding which delivers the reference electromagnetic force. The secondary windings of the conjugate relays are interconnected, as a balanced-voltage system over the pilot channel, the lower electromagnets of both relays being included in this circuit.
Through current in the power circuit produces a state of balance in the pilot circuit and zero current in the lower electromagnet coils. In this condition, no operating torque is produced. An in-zone fault causing an inflow of current from each end of the line produces a circulation of current in the pilot circuit and energization of the lower electromagnets, which co-operate with the flux of the upper electromagnets to produce an operating torque in the discs of both relays. An in-feed from one end only will cause relay operation at the feeding end but there is no operation at the other end because of the absence of upper magnet flux.

Bias torque is produced by a copper-shading loop fitted to the pole of the upper magnet, thereby establishing a Ferraris motor (see above) action that gives a reverse or restraining torque proportional to the square of the upper magnet flux value. A permanent magnet is fitted for damping, providing further improvement of both mechanical and transient stability.

**FIGURE 12.32**
Circuit of the three-phase induction relay of HO4 type for the balanced-voltage longitudinal differential protection system (GEC Measurements, now ALSTOM). 1 — Summation winding; 2 — secondary winding; 3 — bias loop; 4 — pilot wires.

**FIGURE 12.33**
Pilot-Wire Supervision Relays (Westinghouse, 1942).
Damage of pilot wires (breakage, short-circuit) may cause incorrect operation of protection, which is why in order to increase its reliability it is equipped with special devices controlling the state of these wires. As the producer assured, already in the first Westinghouse differential relay with two pilot wires-special measures for control of these wires were taken. These measures consisted of the use of special relays, so called “Pilot-Wire Supervision Relays,” providing constant control of these wires (Figure 12.33). The principle of operation of such devices was that the source of direct current was switched to these wires. This direct current did not affect operation of the differential relay, but it allowed control of the state of the wires. This principle is still used today (Figure 12.34).

This scheme, shown in Figure 12.34, is in the higher speed class. It is also of the balanced-voltage type, but differs in its derivation of the reference voltage. An auxiliary summation transformer is loaded with a resistive shunt to provide voltage that is balanced over the pilot circuit, with a corresponding quantity at the other end of the zone. The measuring relay is a double-wound moving coil element of the axial motion type, the coils being energized through bridge rectifiers. One coil, connected in series with the pilots, observes any unbalance component. The other coil is connected in series with an adjustable resistance across the reference voltage, to provide restraint.

This scheme is suitable for use with pilots of up to 1000 Ω. The pilot loop, not including the relays, is made up to this value by padding rheostats, and the bias rheostat is also adjusted to give the correct degree of restraint, according to the length and capacitance of the pilot.

The pilots are compensated where necessary by shunt reactors at each end. Pilot isolating transformers used in high-induced voltage are expected and pilot supervision can be applied. This scheme will trip both ends of the circuit even if fault current is fed from one end only.

In cases where there are no power transformers (and therefore no problems with inrush currents) on the protected section of the line, it is more reasonable to apply simplified (and cheaper) differential relays containing no restraint coils. The RYDHL type relay, produced by the ASEA Company (ABB), known for decades, may serve as an example (Figure 12.35). This is really the simplest type of differential relay, containing very few...
elements: an electromagnetic clapper type relay, two Zener back-to-back diodes for protection from overvoltages, a trimming resistor, and a pick-up indicator with hand reset. The summation transformer is a separate unit without any cover, which can be placed in a suitable position in the relay cubicle. Similar relays were also produced by many other companies (Figure 12.36).

The pilot links between relays have been treated as an auxiliary wire circuit that interconnects relays at the boundaries of the protected zone. In many circumstances, such as the protection of long transmission lines or where the route involves installation
difficulties, it is too expensive to provide an auxiliary cable circuit for this purpose, and other means are sought.

It was offered to use the main line conductors as the interconnecting conductors of a longitudinal differential protection. The need for special interconnecting conductors (cables) then disappears and it hence becomes possible to set up a longitudinal differential protection on lines of any length. This is the basis of what are called “carrier-current protections.” To make the transmission of commercial-frequency load current possible, and at the same time use the main line wires as the interconnecting conductors of the differential protection, it is necessary to use a current of higher frequency in order to be able to transmit current impulses from one end of the line to the other. For this purpose, it is usual to employ auxiliary current having a frequency 50 to 150 kHz, generated by a special high-frequency transmitter and received at the other line end by a high-frequency receiver. The protected power line must then be accordingly equipped to handle the high-frequency current within its confines, this equipment comprising high-frequency traps (HFT) interposed in the line conductors at both ends of the protected line and coupling filter (capacitors) (Figure 12.37a).

The HFT (filter) is an LC-circuit tuned to resonance at high frequency. It hence presents high reactance to the high-frequency carrier current, but relatively low reactance to the power-frequency current. The high-voltage coupling capacitor connects the high-frequency receiver–transmitter to one of the line conductors and simultaneously serves to isolate the receiver–transmitter from the high power-line voltage. It presents a relatively low reactance to the high frequency and a high reactance to the power-frequency.

The carrier channel is used in this type of protection to convey both the phase and magnitude of the current at one relaying point to another for comparison with the phase and magnitude of the current at that point using FM modulation or analog-digital converters and digital transmission.

One another type of protection (phase-differential) uses carrier techniques for the communication between relays is phase comparison protection, when the carrier channel is used to convey only the phase angle of the current at one relaying point to another for
FIGURE 12.37
(a) Schematic diagram of carrier-current differential line protection; (b) Principles of phase comparison differential protection.
comparison with the phase angle of the current at that point. In this type of protection the
carrier channel transfers a logic or on/off signal that switches at the zero crossing points
of the power frequency waveform. Comparison of a local logic signal with the corre-
sponding signal from the remote end provides the basis for the measurement of phase
shift between power system currents at the two ends and hence discrimination between
internal and through faults. If the phase relationship of through-fault currents is taken as
a reference condition, internal faults cause a phase shift of approximately 180° with
respect to the reference condition. Phase comparison schemes respond to any phase
shift from the reference conditions, but tripping is usually permitted only when the
phase shift exceeds an angle of typically 30 to 90°, determined by the time delay setting
of the measurement circuit, and this angle is usually referred to as the stability angle.
13

Distance Relays

13.1 Principles and Basic Characteristics of Distance Protection

A number of cases in electric circuits of complex configuration with several power sources, neither maximal current protections nor directional protections (power direction relays), can provide selectivity of tripping a short circuit (SC). Why? Let us consider a simple example of a ring circuit with a two-way supply (Figure 13.1), provided with directional current protection (with each set of relays Rel containing current relays and power direction relays). The direction of the relay action and the directions of the power flows in the circuit when an SC occurs, are indicated by the arrows. As it can be seen in Figure 13.1a, an SC (SC1) creates conditions for picking up of sets of relays (Rel1, Rel2 and Rel3). Rel4 does not pick up because the direction of the power flow at that point of its installation does not agree with the standard installation of the power direction relay (from the bus bar to the line).

For selective deenergization of only Line 1, on which the SC occurs, relays Rel2 and Rel1 must pick up before relay Rel3 does. That is: \( t_2 < t_3 \). But if an SC (SC2) occurs on the other line (Line 2), for selective deenergization, the relays Rel3 and Rel4 must pick up before relay Rel2, that is, \( t_2 > t_3 \). Therefore, we can see that it is impossible to meet such opposing requirement with the help of current and directional protections. In such cases, so-called “distance protection” is used. Distance protection is that in which the time delay varies according to the distance to the point at which the SC has occurred (Figure 13.2).

If each of the relays installed along the line have time delays depending on impedance (distance), the relay which picks up first will always be the one that is nearest to the point of short circuiting. This is the main purpose of distance protection. In circuits with two-way supply, distance protection is directional (that is it responds only to one direction of the power flow).

An example of a distance protection scheme having coordinated characteristics of circuit breaker protection on a system with two-end power supply is seen in Figure 13.3. The time-delay characteristics of the odd-numbered relays 1, 3, and 5, operating on the fault-power flow in the left-to-right direction (denoted by the arrows at the circuit breakers) are represented on the top side of the axis, with those of the even-numbered protections below the axis. In the diagram, the shaded portions represent the tripping times of the distance protections on the corresponding lines. Thus, for example, when a fault appears on line BC (at point SC), relays 3 and 4 operate with the minimum time delay \( t_1 \). If for one or another reason, these protections fail to operate, circuit breakers 1 and 6 of the preceding circuit sections from the power supply are tripped, with the time delay \( t_2 \) and \( t_3 \). This is how back-up of the protection on the adjoining circuits is achieved.
FIGURE 13.1
Looped power system with two sources of power supply. SC — short circuit points, \( t \) — time delays of relays.

FIGURE 13.2
Principle of distance protection. Protective zones are shown for first (Rel1) relay. Each of the relays (Rel1–Rel3) has a same three-stage characteristic \( \Delta t = f(Z) \).

FIGURE 13.3
Principle of construction of directional distance protection with a time grading in power system with two-way supply.
Distance is determined in such protection by measuring impedance of the line up to the point of short circuiting. As impedance is a value determined by the proportion of voltage and current \( Z = \frac{U}{I} \), distance relays have measuring elements of voltage and current, and also a mechanism (or an electronic circuit) responding to the ratio of the voltage to the current, that is to some fictitious impedance seen at their terminals. This impedance may take the form of a full impedance \( Z \), a reactance \( X \), or a resistance \( R \). Distance relays may, hence, be subdivided into three types.

The impedance relay, which responds to the fictitious impedance:

\[
Z = \frac{U}{I}
\]

The operating characteristics of distance relays, as generally accepted, are plotted on the complex-quantity plane on which the resistance \( R \) is laid off on the real axis and the reactance \( X \) is laid off on the imaginary axis. The operating characteristic of an impedance relay on the complex-quantity plane is represented by a circle of radius \( Z_{\text{oper}} \) (Figure 13.4).

In 1937, M.J.H. Neher presented the first paper on distance-relay characteristics plotted on an impedance diagram (Neher J.H.A., Comprehensive method of determining the performance of distance relays, AIEE Transactions, vol. 56, 1937, pp. 833–844). Physically such characteristic means that the relay picks up as impedance decreases to a certain value (the radius of a circle) and does not depend on the angle \( \phi \) between \( X \) and \( R \) (that is between the current and the voltage), in other words the sensitivity of the relay is the same for any angle \( \phi \). The circle is the working area of the relay. The relay picks up at the entering (of vector \( A \)) at any angle in this circle from the outside. If this type of relay is used for distance protection of the line, it must be equipped with a separate power direction relay. Then the total characteristic of this relay set will look like as in Figure 13.5. The relay picks up at the entering (of vector \( A \)) at angle interval 180° (in a half circle) only in the first quadrant and partly (depending on angle \( \phi \)) in the second and fourth.

The characteristic of the directional impedance relay in Figure 13.6 has a form of a circle passing through the origin of the coordinates. As can be seen from the Figure 13.6, the length of the vector from the starting point (0) to the circle bound, is different for different angles. This means that the maximum sensitivity of the relay is achieved at a certain angle \( \phi \). This angle is called the angle of maximum sensitivity (or the angle of maximum torque) (Figure 13.7). The relay will not operate in the third quadrant. This means that it cannot operate if the power flow is directed from the line to the substation.

As the impedance relay picks up when impedance decreases to a certain threshold level, relays capable of picking up earlier, that is at greater impedance, are more sensitive, which is why the maximum radius shown in Figure 13.6 corresponds to the maximum
sensitivity of the relay. This means that at the initial point, the sensitivity (pick-up) of the relay to the impedance will be minimal.

Usually for all other types of relays, the following dependence is considered to be correct: the less the inlet actuating quantity (current, voltage, power, etc.) at which the relay picks up is, the higher will be the sensitivity of this relay. The directional impedance relay, as we see, operates like “vice versa”: picks up when input value — impedance — decreases. To emphasize this peculiarity of the relay, it was called “MHO,” that is OHM (the unit of measurement of resistance) in the reverse order. Of course, this expression belongs to slang but it is widely used in technical literature and specifications.

The MHO relay may have a characteristic displaced by $0 - S$ with regard to zero (Figure 13.8), which is why this relay operates not only on the protected line, but also covers the buses supplying the line and some parts of other outgoing lines. Theoretically the characteristic of the MHO relay can be biased in any direction, but in practice only a two-directional offset is used (Figure 13.9).

In addition to the impedance relay, there are also reactance relays and resistance relays (Figure 13.10). The reactance distance relay, which responds to the reactive component of the fictitious impedance, or:

$$X' = \frac{U}{I} \sin \phi$$

The operating characteristic of a reactance relay, as represented on the complex-quantity plane, has the form of a straight line, parallel to the $R$-axis (Figure 13.10a). In this figure, the area that has been shaded is the zone of operation of a reactance relay of the under-type. It is clear that the reactance relay responds to $X'$, irrespective of the value of angle $\phi$. 

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The resistance distance relay which responds to the active component of the fictitious impedance, or:

\[ R_0 = \frac{U}{I \cos \phi} \]

The operating characteristic of a resistance relay as represented on the complex-quantity plane is given in Figure 13.10b.

Resistance distance relays have not found application, due to the fact that they are the most complicated in construction and may be replaced with full success by simpler impedance distance relays. It is important to note that the reactance (OHM) relays will operate for faults that plot anywhere below its characteristic line on the \( R-X \) diagram. Thus, the relay is not directional in itself, and therefore is always used in conjunction with a (directional) MHO relay (Figure 13.11). Its horizontal characteristic makes this relay insensitive to resistance, and therefore it measures only the reactive portion of the impedance from the relay location to the fault. It operates to trip if this reactance is less than the relay setting. The measurement of this unit is unaffected by arc resistance in the fault and it is eminently suited for application on lines where arc resistance can be appreciable compared to the protected line impedance. This is generally true for short lines. The first zones of these relays are set to reach about 80 to 90% of the distance to the far end of the line. The second zone is set to reach beyond the end of the line and the third zone may be set beyond that.

The other type of this class of relay is a three-zone single-phase directional distance relay. It is composed of three cup-type MHO units, one per zone, which are combined as shown in the \( R-X \) diagram of Figure 13.12 to provide three-zone protection for all multiphase faults.
FIGURE 13.9
Building of MHO characteristics with offset. (a) Offset along maximum torque angle; (b) offset along X-axis; C — original center; C' — offset center.

FIGURE 13.10
Reactance (a) and resistance (b) relay characteristics.

FIGURE 13.11
Typical characteristics of three-zone single-phase directional distance relays, which compose three reactance (OHM) units (straight lines) and one impedance (MHO) unit (circle).

FIGURE 13.12
Typical characteristics of three-zone single-phase directional distance relays, which compose three MHO units (one per zone).
Because the characteristics of the MHO units pass through the origin of the $R-X$ diagram, they are inherently directional and provide their maximum reach in the general direction along the impedance angle of the protected line. Because of this, the relays have minimum exposure to system swings and are particularly well suited for applications on longer lines. The first zone unit may be set to reach as far as 80 to 90% of the distance to the remote terminal. The second zone is set to reach beyond the remote terminal and the third zone may be set beyond that.

13.2 System Swing

What is a “system swing” (or “power swing”)?

In 1937 C.R. Mason presented for the first time an AIEE paper in which he analyzed relay performance during swing conditions (Mason C.R., Relay operation during system oscillations, *AIEE Transactions*, vol. 56, 1937, pp. 823–832). The results of this analysis were summarized in plots of relay torque as a function of the separation angle between the two generators of his equivalent system.

What is actually meant is a mode dealing with operating irregularity of synchronous operation of generators working for the common network (the so-called “asynchronous running”). This mode is accompanied by periodical flows of great current through the line and considerable voltage drops (that is “swings” or “system swings”) — signs typical of SCs causing distance protections to respond. The impedance relay in itself is incapable of distinguishing between system swings and SCs without special blocking devices. To detect system swings the blocking unit is activated in different cases. One such case is the occurrence of dissymmetry in the circuit. An SC never occurs simultaneously between all three phases (three-phase SC). First, a single-phase ground SC or a short between two phases occurs, and then it may become a three-phase one. Even the contacts of a three-phase high-voltage circuit breaker, as it picks up, are not separated absolutely symmetrically. Unlike in cases of the SC mode, the network mode changes entirely symmetrically when a system swing occurs. This distinction is used in many types of distance relays produced in Russia as method of swing detection.

Detection of swing mode as rate of raise of power flow is quite popular in the West now: at an SC the power flow increases stepwise by the closure point, whereas at a system swing it varies slowly (low slip frequency) (Figure 13.13). As soon as a slow increase of the power flow is detected, an element blocking the relay operation is energized.

There is another method of detection of this mode, which is also quite widespread in practice. During a power swing, the change of impedance is slower than during a fault on the power system. The RXZD-4 relay is based upon this principle. The impedance measuring elements of the relay have an operating characteristic in the form of two concentric ovals in the $R-X$ plane (Figure 13.14). When a power swing occurs, the RXZD-4 measures the time difference between the impedance operating characteristic $ZP_2$ and $ZP_1$. If the time is longer than 50 ms, the power-swing-blocking relay operates and the output signal is maintained for approximately 2 sec. The power-swing-blocking relay has an 80° characteristic. The ratio between the major axis and the minor axis is 2/1. The set operate value corresponds to the outer oval $ZP_2$. The inner oval $ZP_1$ is fixed at 0.8 times of the set value of $ZP_2$.

How can one obtain relay characteristics in the form of circles, or is that just an abstraction which has nothing to do with reality?
Let us consider this.

Let us take an impedance relay with MHO and OHM elements — the GCX-17 type relay for instance (see a description of the construction below) and apply to its inlets (terminals 5, 7, 8, 10, 17, and 18) currents and voltages according to the scheme of testing of this relay given in the Instruction Manual (Figure 13.15).

Let us then choose some points (enough to build a relay characteristic), say five points. As can be seen from typical characteristics of the MHO relay, the points are placed in the quadrants I and II, that is within 0 to 180°. Dividing 180° into six equal parts we will have 30°. Let us draw five rays: a, b, c, d, and e, through each 30°, starting from 0 on the vector plane X–R (Figure 13.16).

Let us then apply currents and voltages according to the scheme considered above to the relay. We set a certain constant current value, 10 A, for instance, and we will continuously vary voltage with the help of a variac and record pick-up voltage for selected values of the angle φ.

As a result, we will obtain five values of pick-up voltage for the following important angles: 0, 30, 60, 90, and 120°. Then by Ohm’s law we will calculate impedance for the current and voltages for each angle value:

\[ Z = \frac{U}{2I} \] (doubled current value is used)

![FIGURE 13.13](image)

Power swing in a network with low slip frequency.

![FIGURE 13.14](image)

Operating characteristics of a power-swing-blocking relay of the RXZD-4 type.
because of series connecting of current windings in this experiment). We lay off the values as segments a, b, c, d, e on the rays corresponding to the angles. If we draw a smooth curve through these dots, we will have a circle.

In the GCX-17 type relay only one element of reactance measurement (OHM unit) for all three zones is used. For work in one of the zones only the settings of this element need to be switched with the help of an additional electromagnetic relay. The OHM unit is tested at constant voltage, changing only the angle. As a result one obtains similar values of pick-up current regardless of the angle (this proves that the characteristic of the OHM unit is a straight line). Having calculated the reactance value by Ohm’s law and laid off
the obtained value on the X-axis, we will have point 1. The line \( X_1 \) passing through this
dot will be the first stage of the OHM unit. In order to obtain the second-stage characteristic,
we close and fix the contacts of an additional electromagnetic relay and repeat the
experiment. As a result, one obtains a second value independent of the angle, and a
second line \( X_{II} \) corresponding to the second zone.

13.3 Principles of Distance Relay Construction

How are these relays, capable of measuring resistance, constructed?

The principle of operation of the distance relay is very much like that of the current
restraint relay in which the restraining is carried out by voltage (Figure 13.17). In such a
relay, the greater the current and the lower the voltage, the greater torque the final control
element of the relay will have, but current increase and voltage decrease in the circuit,
according to Ohm’s law, lead to a decrease of resistance of the circuit. It turns out that
such a relay picks up as the resistance of the controlled circuit decreases to a certain
threshold. This is what is actually called a resistance relay. In fact the resistance relay is
the one that responds to the ratio of one input quantity (voltage) to the other one (current);
that is it compares voltage and current.

These so-called “balanced-beam relays” of the simplest type (shown in Figure 13.17)
provided comparison of voltages and currents only by value and did not take into account
the angle between them, which was an essential disadvantage of this type of relay. A
more complex construction (Figure 13.18) allowed a comparison of current and voltage
not only by value, but also by phase.

Nevertheless, impedance relays of the induction type turned out to be the most
widespread (Figure 13.19) and relays of this type were produced by many companies
1920–30’s on (Figure 13.20). The first of these were relays with a rotating disk, and then
more modern cup-induction relays were introduced (Figure 13.21).

Let us return to the characteristics of relays considered above. What is the construction
difference between a reactance unit (OHM unit) and a directional impedance unit (MHO
unit)?

On closer examination (Figure 13.21), it turns out that there are not so many differences
in fact. What strikes the eye is that in the reactance unit the current winding is arranged

![Figure 13.17](image)

**FIGURE 13.17**
Principle of impedance relay construction with a balanced beam (balanced beam type relay) (a) Combined relay (induction disk and an electromagnet); (b) electromagnetic relay.
on three poles and the voltage winding is fully placed on one pole, while in the MHO unit, vice versa.

One relay may contain both an OHM unit and a MHO unit at the same time, as in the GCX type relay for instance (Figure 13.22), or three MHO units, as in the GCY type relay.

The MHO unit of the relay is the four-pole induction cylinder (cup) construction. The two side poles, energized with phase-to-phase voltage, produce the polarizing flux. The flux in the front pole, energized with a percentage of the same phase-to-phase voltage, interacts with the polarizing flux to produce restraint torque. The flux in the rear pole, energized with the two line currents, associated with the same phase-to-phase voltage, interacts with the polarizing flux to produce the operating torque.

The primary purpose of the MHO unit in the relay is to provide the directional discrimination that is necessary since the OHM unit is inherently nondirectional. The MHO unit directional characteristic is such that it will operate correctly for either forward or reverse faults at voltages down to 1% of the rated voltage over a current range of 5 to 60 A. A secondary purpose of the MHO unit is to measure fault impedance for the third zone of protection.

The OHM unit is also the four-pole induction cylinder (cup) construction. The front and back poles, energized with delta current, produce the polarizing flux. The side poles are energized with a voltage equal to the difference between the operating quantity ($IZ_T$) and the restraint voltage ($E$), where $I$ is the delta current and $Z_T$ is the transfer impedance of

**FIGURE 13.18**
Balanced-beam relay operated as an amplitude and phase comparator.

**FIGURE 13.19**
Principle of construction of an impedance relay of the induction type (principle of Ferraris motor, see above).
the transactor. The OHM unit reactance characteristic, when represented on the $R-X$ diagram, is a straight line parallel to the $R$-axis. The unit will operate for fault impedances lying below its characteristic and hence is nondirectional.

During normal conditions when load is being transmitted over the protected line, the voltage and current supplied to the tile unit present impedance that lies close to the $R$-axis, since the load will be very near unity power factor, in contrast with the reactive power that flows during fault conditions. Impedance near the $R$ axis will be below the OHM unit characteristic and hence the OHM unit contact will be closed. This will cause no trouble, however, since the directional MHO unit contact will not be closed for this condition.

The Ohmic reach can be extended by setting the restraint tap leads on the lower percentage position on the tap block. The setting of the two tap leads marked No. 1 determines the reach of the instantaneous or first zone, and the setting of the two tap leads marked No. 2 determines the reach of the intermediate or second zone.

The OHM unit transfer auxiliary is a simple type relay. The unit that is mounted at the top of the relay end is used to change the setting of the OHM unit to provide a second step of transmission-line protection. Its operation is controlled by a SAM type timing relay (see above). The normally-closed contacts of the transfer auxiliary provide the circuit with instantaneous tripping used for faults in the first step of line protection. If the fault is beyond the first zone of protection the transfer auxiliary changes the setting of the OHM unit by switching to the No. 2 taps on the autotransformer, from which a smaller potential is supplied to the unit potential restraint windings. This extends the ohmic reach of the

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**FIGURE 13.20**

Construction diagrams of impedance relays of the induction type with a rotating disk, produced in the 1920–30’s of the last century. (a) Relay produced by Siemens; (b) relay produced by Reyrolle; (c) relay produced by Oerlikon.
FIGURE 13.21
Simplified construction diagrams of modern cup-induction relay (a) for a basic directional impedance unit (MHO unit) and (b) for basic reactance unit (OHM unit).
OHM unit and enables it to operate for faults in the second zone of transmission-line protection.

The KPC (KPC-111, KPC-112, KPC-121, KPC-131, KPC-132, KPC-142, KPC-143) type impedance relays produced for many years in the former U.S.S.R. were also based on the induction cup-rotor magnetic system (Figure 13.23). In this relay, a magnetic flux $\Phi_i$ passes through the pole tips I–I, created by winding I which connected across the voltage:

$$U_i = U + E_i$$
where $U$ is the voltage applied to the relay from the bus voltage transformer through the auxiliary autotransformer and $E_i$ is the e.m.f. proportional to current in the protected line ($E_i = kI$).

The magnetic flux $\Phi_{II}$ which passes through pole tips II–II is created by an operating coil to which the voltage is applied:

$$U_2 = U - E_i$$

Connected in series with the operating winding are capacitor $C$ and active resistance $R$. Due to the existence of core air gaps in the auxiliary transformer-reactors (transactors), the e.m.f. $E_i$, fed into the circuit of operating and restraint windings, is directly proportional to the current $I$.

Under the action of voltages $U_1$ and $U_2$, the currents flow through the operating and restraint windings:

$$I_r = (U + E_i)/Z_r$$
$$I_o = (U - E_i)/Z_o,$$

where $Z_r$ and $Z_o$ are the impedances, respectively, of restraint and operating windings.

The fluxes $\Phi_1$ and $\Phi_{II}$ due to currents $I_r$ and $I_o$ are shifted in space by $90^\circ$ and also differ in phase by some angle. This angle between fluxes $\Phi_1$ and $\Phi_{II}$ and, consequently, the sense or sign of the operating torque, is a function of the angle between the voltages $U_1$ and $U_2$.

The value of this latter angle depends upon the preselected parameters of the relay (for example, the characteristics of windings, capacitor $C$), and likewise, on the relation of $U$ to $E_i$.

KPC-131 and KPC-132 type relays are cut into current difference of two phases and the linear voltage between them, and respond to a decrease below the fixed threshold value of impedance at the inputs of the relays as two or three-phase SCs occur.
13.4 Why do Distance Relays Need “Memory?”

If there are three-phase SCs close to the place of installation of the relay, all voltages turn to zero and all currents change the phase step-wise. There is no polarizing voltage vector with regard to which one could fix this change of the current phase. This is the so-called “dead zone” of the relay, within which it cannot operate. To reduce the dead zone at three-phase SCs one uses a slight displacement of the MHO characteristic of the relay with regard to the origin of coordinates along the maximum sensitivity axis towards the quadrant III (Figure 13.9a) (unfortunately, this causes deterioration of other characteristics of the relay).

A more cardinal solution is to use a “memory” device, which memorizes the voltage phase at the point of installation of the relay up to the moment of short circuiting, and applies this voltage to the polarizing winding of the relay during of a SC. The simplest “memory” device is made in the form of an RCL-circuit (Figure 13.24), capable of reserving energy and then returning it back to the circuit in the form of damped oscillations. Parameters of this circuit are chosen in such a way that the discharge current of capacitor \(C\) is of oscillatory character with a frequency of 50 Hz. At close SCs, when \(U \approx 0\), the energy stored in the “memory” circuit is enough for the relay pick-up. It is worth mentioning that the level of voltage received from the “memory” element is much lower than the normal one and that is why this voltage cannot be used for a precise determination of the resistance value up to the fault location. The “memory” element is used to obtain information only about the voltage phase preceding the moment of short circuiting. In such emergency mode the impedance relay actually turns to the power direction relay, allowing it to coordinate the protection operation correctly.

Such “memory” elements are used in the KPC-131 and KPC-132 type relays and also in some other types of distance protection relays. Aharon Bresler (1889–1951), a Russian engineer and inventor, suggested a relay (known as a “Bresler’s relay”) without a dead circuit of measuring currents, and voltage transformers that provide a two-stage distance protection.

The relay has windings \(w1\) and \(w2\) which are supplied by voltages \(U_1\) and \(U_2\) correspondingly. Each of these voltages is a difference of the linear voltage at the point of installation of the relay and the compensation voltage, which equals the voltage drop caused by the SC current in the given resistance of the protected line, that is:

\[
U_{\text{mem}} = U_{\text{inp}} - U_{\text{comp}}
\]

FIGURE 13.24
Construction of the “memory” of the simplest type and the form of its output voltage. \(U_{\text{inp}}\) — input voltage applied to the circuit in prefault conditions; \(U_{\text{mem}}\) — output voltage of the “memory” reproduced by the circuit after \(U_{\text{inp}}\) disappears at a SC; \(t_s\) — SC moment.
Due to the fact that the linear voltage is applied to the relay windings between the damaged and undamaged phases, in a two-phase SC the relay has no "dead zone." The relay also does not respond to symmetrical changes of currents in phases of power network and that is why no special blocking of the system swing is required. Another important peculiarity of this relay is that it does not respond to the load, which is why such a relay can operate in distance protection independently, without a starting element.

The relay designed by A. Bresler in the 1940s was produced by the Cheboksar Electrical Equipment Plant in the former U.S.S.R. for many decades (including in the 1970s and 1980s) under the brand KPC-121. In the book "Protection Relays," published in 1976 by the leading experts of this plant, Bresler's name is unfortunately not mentioned when his relay is described.

In many distance protection relays, only one element of impedance measurement for all zones is used in order to make them cheaper. In such relays the impedance element is constantly switched ON with the setting for the first zone. If a SC occurs outside the first zone, the starting relay automatically switches (with a time delay) the setting of the impedance element for the operation in the second, third, and even fourth zone. Current relays and impedance relays are mostly used as starting relays of distance protection. The main disadvantage of current starting relays is that they respond equally both to SCs and to swings and great load currents. Their advantages: simplicity and low cost. Such starting elements are applied in short lines with voltage not higher than 30 to 40 kV. In all other cases, the impedance relay is used as a starting element.

Nondirectional impedance relays with a circular characteristic are simpler than directional ones but respond to system swing, to currents and loads practically like current relays do. In contrast to the latter, though, they are more sensitive to SCs because they respond not only to the increase of current but also to voltage decreases during the SC.

\[ U_1 = kU_{R-S} - Z (I_R - I_S); \quad U_2 = kU_{S-T} - Z (I_S - I_T) \]
The area of application of such starting relays is restricted to circuits with a voltage of 30 to 40 kV and to short lines 110 to 160 kV with small loads. Directional impedance relays (MHO relays) are more sensitive to SCs than to the load. This is caused by dependence of the pick-up threshold of the relay from the angle between current and voltage. During SCs in the line this angle of the input terminals equals the so called “angle of line resistance” and usually is 65 to 80°, which is quite close to the angle of maximum sensitivity of the MHO relay.

At great loads of line caused by flowing of high active power through it, the angle of resistance is less than during an SC, and is usually 10 to 40½. At such angles, the sensitivity of the relay decreases by 20 to 50%, thus allowing the relay to distinguish SCs from a great load. The MHO relay is less prone to malfunctions caused by the system swing then the nondirectional relay, because it can pick up only when the impedance vector is in the first quadrant. At any other positions of the impedance vector, the relay simply cannot pick-up.

13.5 Distance Relays with Higher Performance

Relays with an elliptic characteristic instead of a circular one have an even better offset from great currents. The disadvantage of relays with characteristics in the form of ellipses or a lenses is that they are greatly affected by increased transient resistances at the site of short circuiting. This can lead to incorrect measurement of the distance to the fault point (and therefore to the wrong choice of the relay operation zone) which is why producers of relays try to make the performance of relays higher with the help of different sophisticated constructions (Figure 13.26). One can also offset the starting impedance relay from great load currents in distance protection by using an additional blocking relay with a so-called “blinder characteristic” (Figure 13.27).

The term “blinders” as it applies to phase distance relays has the same significance as when it is applied to a horse. In the case of the horse, blinders limit his vision to a narrow beam in the direction in which he is facing. In the case of a distance relay, blinders limit the operation of the distance relays to a narrow beam that parallels and encompasses the protected line. In general, relay blinders are required with MHO units only where long lines are involved and the resulting MHO unit settings are large enough to pick up on maximum full load currents or minor system swings.

The blinder and MHO unit contacts are interlocked in the trip circuit in such a way that tripping can only occur in the fault impedance plots inside the MHO characteristics and between blinders A and B. Actually the blinders are nothing more than reactance units similar to those of Figure 13.27 that have been rotated by modifying the power factor angle of the restraint circuit of the units. The A blinder operates for faults that plot to its right. The B blinder operates for faults that plot to its left. The overall effect of the blinders is to restrict the operating zone to an area on the R–X diagram that parallels the protected line and thus makes the combination relatively insensitive to system swings and immune to operation on full load.

One pair of blinders is required per phase, thus three pairs are needed per terminal on a three-phase system. Due to such a characteristic, the probability of malfunctioning of the relay because of system swings and great load currents is minimal, as all these exposures are out of the working zone of the relay.
As the blocking relays ("blinders") power direction relates with angles of internal displacement, 60 and 30° can be used. There are special relays with such a characteristic, such as the CEX-57 type relay for instance (Figure 13.28). CEX57 type relays are high-speed induction cup-type devices with OHM unit characteristics that can be set parallel to
the impedance of a transmission line. These relays are designed for use with other protective devices in "blinder" applications to restrict the tripping area of the tripping units used in a protective relay scheme.

CEX-57 type relays each contain two cup-type units (upper and lower), similar to the cup-type unit shown in Figure 13.28. The CEX-57F relay also contains an auxiliary telephone-type unit.

Either three CEX-57D or three CEX-57F relays are required. Basically, tripping will be permitted only when the fault impedance plots within the reach of the MHO tripping function AND both of the OHM units. Since the right hand OHM unit will operate only for faults to the left of it, both units can operate simultaneously only for faults that plot between them. The tripping function (MHO) will provide correct directional action, and limit the reach in the forward direction.

The units in the CEX-57 Type relay are four-pole induction cylinder (cup) units with schematic connections, as shown in Figure 13.29. These units measure impedance at an angle. The two front coils and the two back coils are energized with delta currents to produce polarizing flux. The same delta current flows through the operating coil to produce an operating flux. The phase-to-phase voltage is applied to the restraint coil to produce a restraint flux.

The angle-impedance unit characteristic is a straight line when plotted on $R-X$ diagram (Figure 13.30). The shorted distance from the characteristic to the origin ($Z_M$) is the minimum relay reach, which is determined by a set of relay taps. The angle of maximum torque ($\phi$) is the angle that the reach $Z_M$ leads the $R$-axis. This angle is adjustable in CEX-57 from 5 to 35° lead. The reach of the angle-impedance unit at any angle is given by the following equation:
\[ Z = \frac{Z_M}{\cos(\theta - \phi)} \] for upper unit

and

\[ Z = \frac{Z_M}{\cos(\theta - \phi + 180^\circ)} \] for lower unit

where \( \theta \) is the angle \( I_{AB} \) leads \( U_{AB} \) (see Figure 13.29).

The lower unit is identical to the upper unit, except that it is polarized to have maximum torque 180° from the upper unit. In fact, the characteristic of the relay can be
constructed by the fixed values $Z_M$ and $\phi$. One draws a ray advancing the axis $R$ by the angle $\phi$ through the zero point, then lays off sections with the value $Z_M$ on this ray to both sides of the zero point, and then draws straight lines perpendicularly to these sections and through their ends so that they form “blinders” on the characteristic of the relay. Theoretically this is the characteristic which proper relay functioning must have. One can obtain this characteristic experimentally if the relay is connected according to the scheme suggested by the producer (Figure 13.31).

A constant voltage of 120 V is applied to it and one measures the current while trying to make the relay pick up at certain fixed angles between the current and voltage. Impedance is calculated by the formula:

$$Z = \frac{U}{2I}$$

The values we have obtained are laid off on the rays corresponding to the given angle, forming sections. Straight lines drawn through the ends of these sections are called “blinders.”

A relay with a polygonal (quadrilateral) characteristic (see Figure 13.32) is even more effective. Usually microprocessor relays have characteristics of this type. Such characteristic is provided with forward reach and impedance reach settings that are independently adjustable. It therefore provides better resistive coverage than any MHO-type characteristic for short lines. This is especially true for earth fault impedance measurement, where the arc and fault resistance to earth contribute to the highest values of fault resistance. To avoid excessive errors in the zone reach accuracy, it is common to impose a maximum resistive reach in terms of the zone impedance reach. Recommendations in this respect can usually be found in the appropriate relay manuals.

Quadrilateral elements with plain reactance reach lines can introduce reach error problems for resistive earth faults where the angle of total fault current differs from the angle of the current measured by the relay. This will be the case where the local and
remote source voltage vectors are phase shifted with respect to each other due to prefault power flow. This can be overcome by selecting an alternative to use of a phase current for polarization of the reactance reach line. Polygonal impedance characteristics are highly flexible in terms of fault impedance coverage for both phase and earth faults. For this reason, most digital and numerical distance relays now offer this form of characteristic. Such characteristic provides the required sensitivity of the relay, and at the same time has the best offset from exposure of the load resistance and the system swing.

From the above explanations it is clear that the function of three-stage distance protection is carried out not by one, but by a group of relays, among which there should be starting relays for each phase, relays for measuring of impedance, several timers (each responsible for a certain zone), and auxiliary relays. Because of the complexity, distance protection devices based on electromechanical relays are usually occupies a whole separate cabinet.

In the 1970’s the Brown Bowery Co. came up with a unique design to cope with the complexity of electromechanical-relay-based distance protection devices, the LZ31 type relay, which unites in one design all of the necessary elements for three-stage distance protection, (Figure 13.13). In this device a pick-up of one of the starting elements (2) is achieved when the impedance of a line drops below a certain threshold value. The starting relay (Figure 13.13b) energizes a cam-timer (4) and the first contact (through the auxiliary relay) connects the first tap of the transformer (5) to the measurement-relay of impedance (1). If the voltage on the winding is not enough for operation of the relay (1), a cam-timer (4) continues a time-count and connects the second tap of the transformer (5) to the measuring relay (1). If this is still not enough, the cam-timer (4) continues to operate until it reaches its final position and energizes the output trip relay. Thus the time delay

**FIGURE 13.32**
Quadrilateral characteristic of distance relays.
FIGURE 13.33

(a) Distance relay LZ31 (BBC), dimensions: 778x484x206 mm, weigh 44 kg. 1 – measuring relay; 2 – phases and ground impedance starting relays; 3 – auxiliary relays; 4 – cam-timer with independent adjustable time for each step; 5 – multi coil transformer. (b) External view and connection diagram for impedance relay unit of LZ31 protection device (starting and measuring relays have same construction). CT and VT-auxiliary current and voltage transformers; VD1 and VD2 – rectifier bridges; Rel1-moving-coil relay; RC-spark suppression RC-circuit; Rel2 – output relay; TB-test button; R4 – potentiometer for setting pick-up value.
that corresponds to the most distant third zone will be the greatest. If at the very first connection of the transformer (5) to the relay (1) the voltage level appears to be sufficient for a pick-up of the relay (1), the output trip relay will be enabled and the process will stop. This corresponds to the first zone (the closest distance to the short circuit point) and the smallest time delay. The output voltage of the transformer (5) depends on the tap number and the voltage in the high-voltage line at the moment of short circuit (that is, proportionally to the impedance of that section of line, up to the short circuit point).

13.6 Electronic Analogs of Impedance Relays

As in all the other cases considered above, there are electronic analogs of electromechanical impedance relays. The simplest device of this type is a so-called relay with a detector circuit for comparison of current and voltage by absolute values. In fact, this is a direct electronic analog of the “balanced-beam relays” considered above (Figure 13.34). In the circuit of current balance, the output relay Rel is connected in parallel with the rectifier to the difference of rectified currents.

The current in the output relay $I_{\text{REL}} = |I_2| - |I_1|

In circuits based on voltage balance, the relay will operate only when $|U_2| > |U_1|$ Such impedance relays are nondirectional and have a characteristic in the form of a circle with its center at the origin of the coordinates. These relays are used as a starting element, switching ON the measuring unit of the distance protection.

Russian starting relays of distance protection of the DZ-1 type, produced in the 1960–80’s, were based on the balance of currents (Figure 13.35). The output relay is constructed on the basis of a highly sensitive polarized relay with moving coil (see below) or in the form of a standard electromagnetic relay with an electronic amplifier, working at only one polarity of the applied voltage (current). That is, the outlet relay will work if $|I_2| > |I_1|$ and will not pick up if $|I_2| < |I_1|$.

The RAZOG type distance protection (ASEA), widely produced in the years 1970–90’s, can serve as an example of relays based on the balance of voltages (Figure 13.36). This

![Figure 13.34](image_url)

**FIGURE 13.34**
Principle of construction of a nondirectional impedance relay with a detector circuit for comparison current and voltage by absolute values. (a) By balance of currents; (b) balance of voltages; TR — transactor; C — capacitor leveling voltage pulses (ripple).
distance protection contained a great number of separate relays connected with each other, so as to form a block diagram of the protection (Figure 13.36b). A nondirectional electronic impedance relay of the RXZE type (Figure 13.37), based on the balance of voltages mentioned above, is used as a starting element in this device.

The current quantity ($I$) (Figure 13.37) is transformed via transactor $Tr_1$, through the diode bridge ($VD_1$), after which an unsmoothed DC voltage is obtained across $R_1$, directly proportional to the supplied current. The voltage quantity ($U$) is transformed via transformer $Tr_2$ to two circuits where one of the circuits produces a smoothed and the other circuit an unsmoothed direct current.

The smoothed DC is produced by a six-pulse connection, which consists of an RC circuit plus six diodes. These are denoted as $R_5$, $C_1$, and the diode circuit $VD_3$ (Figure 13.37c). The capacitor ($C_2$) is used for smoothing the six-pulse voltage, which in turn gives a smoothed current through $R_2$ and $R_3$.

The unsmoothed direct current is produced by the diode bridge ($VD_2$). The capacitor $C_3$ is used to phase-shift the current about $30^\circ$, which is obtained by comparison with resistor $R_4$. This current produces an unsmoothed voltage across $R_2$. This phase-shift of the current quantity will cause the major axis of the characteristic to lie at about $60^\circ$ in the first quadrant of the $R$–$X$ plane. Other angles for the characteristic are, as such, obtained by altering the phase-shift of the unsmoothed direct current.

The above-mentioned currents are summed at point 6 (Figure 13.37c) and produce a summation voltage across $R_2$ proportional to the supplied voltage. The characteristic, with this circuit, becomes an oval, which lies symmetrically around the origin in the impedance plane.

If the unsmoothed direct current (unit III, Figure 13.37b) is eliminated, that is, not allowed to be summed at point 6, the voltage at that point will become a smoothed DC voltage and the characteristic will then become a circle, having its center at the origin in the impedance plane. By means of simple reconnection, circular, or oval characteristics are obtained, as shown in Figure 13.37d.
The Rel, the null-detector that is connected to points 2 and 6, senses the voltage difference between these two points. The detector gives an output signal when the instantaneous voltage at point 2 exceeds the instantaneous voltage at point 6. An auxiliary relay can be used as an output relay. The detector requires a separate auxiliary DC voltage.

As a rule this detector is constructed on the basis of a very sensitive relay — of a magneto-electric type (with moving coil), or a standard electromagnetic relay with an electronic amplifier. The RXZF is a single-phase relay. In three-phase circuits one applies a set including three such relays, three intermediate relays and a time relay (Figure 13.38).

**FIGURE 13.36**
(a) The board of the RAZOG type distance protection. (b) Block diagram for a RAZOG type distance relay. 1 — Starting elements; 2 — relays for phase-switching; 3 — compensating circuits and setting unit; 4 — measuring element; 5 — tripping relays; 6 — time-lag relays; 7 — indicators; 8 — auxiliary power supply. (ASEA (ABB) 1975 Distance Relay Type RAZOG.)
Directional impedance relays were also constructed on the basis of the balance of voltages (Figure 13.39). In this relay the required angle of maximum sensitivity is obtained due to displacement of the input current phase with the help of a TR1 transreactor by the angle equaling the angle of resistance.

This angle in a real construction can be adjusted within some limits due to variable resistors switched to the secondary windings of the transreactor TR1 (not shown on the scheme). The additional transreactor (TR2), tuned to resonance to the circuit frequency (50 or 60 Hz) is switched to an additional source of voltage biased by 90° with regard to the voltage \( U \), and works as a “memory” element (mentioned above) during three-phase SCs.

As it has already been mentioned above, in detector circuits of impedance relays either a special highly sensitive magneto-electric relay or an electronic relay (usually an electronic amplifier based on transistors or operational amplifiers). It is quite interesting to learn that such famous and prospective (from the point of view of new technologies) companies such as Siemens, produced impedance relays with an amplifier based on vacuum tubes in the middle of the 1970s (Figure 13.40). Such a relay was dependent on a time characteristic.
(based on charging–discharging of the RC-circuit) and did not require the use of a separate time relay as in distance protections of other types. The high and stable input resistance of an amplifier based on a vacuum tube allowed a dependence on time characteristics similar to those of induction relays.

As has already been mentioned above, the distance protection of power networks is carried out by a whole set of different relays in which the impedance relay is only one of many other components, although the main one. In the 1950–60’s, a set of electromechanical relays providing distance protection of power lines would occupy a whole cabinet. In the 1970–80’s, these became more compact, the constructions being based both on electromechanical (Figure 13.41) and electronic relays (Figure 13.42).
FIGURE 13.38
This three-phase impedance-measuring protective RAKZA type relay (ASEA), included three RXZF relays, three auxiliary RXMA1 relays, and a time-delay relay of the RXKB type. (ASEA (ABB) 1977 Catalog RK 65-52E.)

FIGURE 13.39
Circuit diagram of a directional impedance relay based on the balance of voltages (DZ-2, Russia).

FIGURE 13.40
RIZ80 type impedance relay on vacuum tubes (Siemens, 1972). (a) External design.
Distance Relays

FIGURE 13.40 (Continued)
(b) Fragments of the electronic circuits. (Siemens, 1972 protective devices catalog.)

FIGURE 13.41
Electromechanical relay of distance line protection of the LZ-31 type (Brown Bowery Co.).
Testing and adjustment of such relays are rather difficult. For testing of stability of the relay to transients, real transitive process in a real network is writing into fault recorder as a special file. This file by means of a computer is loading into special power simulator which converts the file into currents and voltages, applied to relay, which are fully complying with real transient (Figure 13.44).
Distance Relays

Lately practically all new types of distance protections are made on the basis of microprocessors (Figure 13.43), however, microprocessor relays and microprocessor distance relays in particular can hardly be called “relays,” but will be discussed in Chapter 15.
14
Frequency Relay

14.1 Why is it Necessary to Control Frequency in Electric Networks?

Voltage frequency is the most important figure in a power network. First of all, the speed of rotation of electric motors, and therefore the performance of the machines and mechanisms, depends directly on frequency.

Second, generators in power stations are designed for work at fixed frequencies. Deviations from these fixed frequencies, in either direction, by 5 to 10% can lead to a sharp intensification of vibration in a large-tonnage rotor (Figure 14.1), to premature failure of the generator, to sharp productivity slowdowns in the following: powerful pumps that deliver water to the boiler, fans of the air injection systems, cooling systems pumps and many other important systems of power plants.

Third, if there are several generators in the power network, their work must be synchronized by frequency with a high degree of accuracy.

Fourth, any decrease of voltage frequency caused by an overload of generators is inadmissible in itself. Even a slight excess of power consumption over generator power can lead to a significant voltage frequency drop in the power system (Figure 14.2). When there is such a frequency drop below a certain critical level, usually some of the customers, or even a line and whole subsystem, is automatically disabled in order to maintain serviceability of the generators and the network.

Frequency decreases because of power system overload, while a frequency increase is evidence of a power excess. Power excess occurs in the system when one or several hard loaded lines are suddenly disabled. Surplus power is directed to other lines, causing dangerous power flows that can lead to a power system breakdown. Such an accident, followed by a frequency excess of up to 63 Hz, took place on August 14, 2003 during the biggest power system breakdown in the U.S.A. That is why it is so important to control voltage frequency.

Like all other parameters of electric circuits, frequency too is controlled by special relays.

14.2 Charles Steinmetz — Inventor of the Frequency Relay

The basic principle of a frequency relay circuit was patented by Charles Steinmetz in 1900 (Figure 14.3).
Charles Proteus Steinmetz was a giant of a pioneer in the field of electrical engineering. Charles Steinmetz (originally named Karl August Rudolf Steinmetz) was born in Breslau, Prussia (now the city Wroclaw, Poland) on April 9, 1865. He studied in Breslau, Zurich, and Berlin. Shortly after receiving his Ph.D. in 1888, Steinmetz was forced to flee Germany after writing a paper criticizing the German government. Charles Steinmetz was an active socialist and held strong antiracist beliefs.

Thomas Edison founded the General Electric Company in 1886 and wanted to hire Steinmetz. In 1893 the newly formed General Electric Company purchased Eickemeyer’s company, primarily for his patents, but Steinmetz was considered one of its major assets. In 1894 Steinmetz was transferred to the main General Electric plant at Schenectady, New York. After studying alternating current for a number of years, Charles Steinmetz patented “A system of distribution by alternating current (AC power),” on January 29, 1895. Steinmetz retired as an engineer from General Electric to teach electrical engineering at that city’s Union College in 1902. General Electric later called him back as a consultant.

Charles Steinmetz died on October 26, 1923 and at the time of his death, held over 200 patents.

Frequency relays of the slow-speed (induction disk) type were commercially available in 1921, and the high-speed (induction-cup) type was put into use in 1948.
14.3 Induction Frequency Relays

Discrimination between normal frequency and abnormal frequency in the induction disk type relay (Figure 14.4) is accomplished by the opposite variation in impedance with the frequencies of two circuits, one circuit containing the coil of one U-magnet connected directly to the voltage supply and designated as the inductive circuit, the other circuit containing the coil of the remaining U-magnet in series with an external capacitor connected to the same supply voltage and designated as the capacitive circuit (since the capacitive reactance predominates at normal frequency).

In the under-frequency relay, the coil of the operating U-magnet composes the inductive circuit, and the coil of the restraining U-magnet in series with the capacitor composes the capacitive circuit. At normal frequency the torque produced by the current through the capacitive circuit (restraining U-magnet) is greater than the torque produced by the current (operating U-magnet). A decrease in the frequency of the supply voltage is accompanied by a decrease in the impedance of the inductive circuit permitting an increase of the operating current, while the impedance of the capacitive circuit increases, thereby reducing the restraining current. Thus as the supply frequency is decreased the operating U-magnet overcomes the restraining U-magnet and the relay operates.

The over-frequency relay differs from the under-frequency relay in that the operating U-magnet coil is in the capacitive circuit and the restraining U-magnet coil forms the inductive circuit. Consequently, the torque of the inductive element is adjusted to preponderate at normal frequency.

The electromagnet has potential windings on both the upper and lower poles. The under-frequency relay is so designed that at normal frequency (60 or 50) cycles the upper pole current leads the lower pole current and two out of phase fluxes thus produced act to give contact opening torque on the disk. When the frequency drops, the phase angle of the
lower pole circuit becomes more leading, until at the frequency setting of the relay the lower pole current begins to lead the upper pole current, and the relay torque is reversed to the tripping direction. The lower the frequency, the greater the phase angle displacement and hence the faster the relay trips. The relay has inverse time characteristics (Figure 14.5). An adjustable resistor in the upper pole circuit is provided to set the frequency at which the relay trips.

FIGURE 14.4
(a) Type CF-1 induction frequency relay for under- or over- frequency protection without case (Westinghouse, 1963). 1 — Frequency setting rheostat; 2 — time dial; 3 — moving contact; 4 — stationary contact; 5 — indicating contactor switch. (b) Circuit diagram of frequency relay CF-1 type.
The CF-1 type relay is available in two forms — either as an under-frequency relay or an over-frequency relay. The disk rotation of the under-frequency and the over-frequency relays is in the same direction. Where operation on both under-frequency and over-frequency is desired, two relays are required, one of each form.

Frequency relays with a rotating disk produced by some other firms in the 1950-70's, unlike the CF-1 type relay, do not contain an integrated capacitor. For over-frequency relay (IJF51A) the lower coil is the operating coil and upper coil is the restraint coil. For under-frequency relay (IJF51B) the lower coil is the restraint coil and upper coil is the operating coil. The IJF52A type relay is an over-frequency and under-frequency relay having double throw contacts. The left contacts close on under-frequency and the right contacts close on over-frequency.

High-speed frequency relays of induction-cup type were put into use in 1948. One of the first relays of this type was a CFF type relay (Figure 14.7). The CFF type under-frequency relay is a high-speed, induction-cup type. Its basic principle of operation is the use of two separate coil circuits (Figure 14.8) which provide increasing phase displacement of fluxes as the frequency decreases, thereby causing torque to be developed in the cup unit to close the tripping contacts. The quantity of torque produced is proportional to the sine of the angle between these two fluxes.

As the frequency decays the angular displacement increases, thereby increasing the torque produced. If the frequency decays rapidly the torque will increase rapidly and cause the relay to close its contacts in less time.

Due to application of a high-speed induction-cup rotor instead of a disk the speed of response of this type of the relay has been considerably increased (Figure 14.9). The relay operating time is an important factor, since the under-frequency condition will develop as a rate-of-change of frequency (ROCOF). While a constant ROCOF on a power system is
FIGURE 14.6
The IJF type induction disk type frequency relay (General Electric Co.). (a) Circuit diagram and external connection. (b) Front (1) and rear (2) views. 1 — Moving contact; 2 — target; 3 — seal-in unit; 4 — seal-in unit tap selector; 5 — stationary brush and contact assembly; 6 — control spring and adjusting ring; 7 — shaft; 8 — drag magnet; 9 — disk; 10 — lower coil; 11 — adjustable resistor; 12 — upper coil. (c) Type IJF51B (left) and IJF51A (right) time-frequency characteristics.
seldom experienced, it is believed that these time curves offer a more realistic way of analyzing the problem.

A serious under-frequency condition on a system is likely to be accompanied by low voltage. The voltage response of a frequency relay is therefore important. The relays considered above had quite considerable dependence of pick-up frequency on the applied voltage, which was an essential disadvantage of this type of relays. In contrast to them the CFF relays are remarkable for their increased stability of parameters. The CFF relay setting is continuously adjustable over a range of 56 to 59.5 Hz. Relay models are provided with compensation for voltage variation and self-heating; repeatability of set points is held within 0.25 Hz over the normal temperature range from −20 to +55°C, and AC input voltage variations from 50 to 110% of rating (Figure 14.10).
Induction frequency relays produced by many firms have similar constructions and principles of operation, for example Russian relays of the BBU-011 and BBU-3 type, and RFA type relays produced by ASEA, etc.

**FIGURE 14.9**
Time–frequency characteristics of high-speed induction-cup relays of the CFF type. (General Electric. Under-Frequency Relay Type SFF13A.)

So-called resonance frequency relays have a much simpler construction (Figure 14.11). Such relays contain three elements: a simple electromagnetic relay (Rel), a capacitor (C), a resistor (R), and a reactor. A transformer (Tr) is used to choose the level of supply voltage.

**FIGURE 14.10**
Variation in frequency relay pickup with applied voltage for CFF12 type relay. (General Electric. Under-Frequency Relay Type SFF13A.)

### 14.4 Resonance Relays

So-called resonance frequency relays have a much simpler construction (Figure 14.11). Such relays contain three elements: a simple electromagnetic relay (Rel), a capacitor (C), a resistor (R), and a reactor. A transformer (Tr) is used to choose the level of supply voltage.
The basic principle of this very simple relay is an application of a RLC-circuit tuned to resonance to the required frequency. If the input voltage deviates from resonance frequency, current jumps in the circuit and the relay picks up. The transformer inductance must be also taken into consideration when the circuit is adjusted. Moreover, one can adjust the form of the frequency characteristic by switching the outlets of the transformer ("a" and "b"). Apparently such a relay is simpler, cheaper and perhaps more reliable than an inductance one.

Parameters such as sensitivity and precision of operation of this relay depend much on the properties of the reactor and the individual characteristics of the electromagnetic relay Rel. If the quality of construction is high enough this relay may be quite competitive in its parameters with many more complex and expensive induction relays.

14.5 Electronic Frequency Relays

It is only natural that as in all other types of protective relays, frequency relays also have electronic analogues produced by all of the major (and not only) producers of protective relays. Semiconductor frequency relays are more precise than inductive ones, have less temperature dependence, and are less sensitive to sharp voltage variations at input. In the former U.S.S.R. electronic under-frequency (РЧ-1) and over-frequency (РЧ-2) relays were already produced in 1971. A bit earlier many Western companies started producing such relays, sometimes simultaneously with production of nonelectronic frequency relays.

In such a relay (Figure 14.12), the voltage of the circuit U is applied through the isolating transformer (1) and the filter suppressing high harmonics, to a phase shifter containing two frequency-dependent measuring elements (3), (4) with similar construction but with different adjustment parameters and a resistance divider (5).
Measuring elements transform change of frequency into change of the phase angle. They are made in the form of a series of resonance circuits with a resistance divider (Figure 14.13).

The voltage $U_1$ on the resistor $R_3$ is proportional to the current flowing through the reactor $L$ and capacitors $C_1$ and $C_2$. It is in phase with this current. The voltage $U_2$ on resistor $R_2$ is proportional to the voltage applied to the LC-circuit and is in phase with it. Voltage on the inductance $L$ leads the current in the circuit by an angle of $90^\circ$ and the voltage on the value $C$ lags from this current by the same angle. Parameters $L$ and $C$ can be chosen in such a way ($2\pi fL = 1/2\pi f/C$, where $f$ is frequency of supply voltage) that at a certain frequency of the supply voltage ($U_{inp} = 50$ or $60$ Hz) the leads angle equals the angle of lag. In this case the LC-circuit works as a standard resistor with very low

![Figure 14.13](image)

**Figure 14.13**

Simplified construction diagram of the measuring unit of a frequency relay.
resistance. This operation mode is called resonance, but as soon as the frequency of supply voltage deviates from the resonance frequency to which the relay is adjusted, the LC-circuit begins to reveal its properties. When frequency decreases, capacitive reactance increases and dominates in the circuit (that is, phase displacement between voltages $U_1$ and $U_2$ occurs) and when frequency increases, the inductive one does as well (the phase displacement has the opposite angle).

The resistance divider (5) is used for creation of reference voltage ($u_2$) with regard to which angles of phase displacement of voltages $U_1$ and $U_2$ are measured (in the block diagram these voltages are marked by $u_1$). The outlet voltage of the frequency-dependent measuring element (3) and the outlet voltage of the reference element (5) are applied to the inputs of the pulse shapers (7 and 8) in which alternating sinusoidal voltage is transformed to rectangular pulses ($u_3$ and $u_4$) respective to duration close to the duration of a sinusoid half-period of alternating voltage. The positions of the pulses formed by the reference voltage and the pulses formed by the output voltage of the frequency-dependent element in time are determined by the ratio of frequency of this reference voltage to the frequency of the voltage of the circuit. One must determine the moment when these pulses do not concur. This will mean that the frequency of the voltage in the circuit differs from the natural frequency to which the relay is adjusted. Concurrency or nonconcurrency of pulses in time (synchronization) is controlled by the logical element (10). At that point the output pulse is stretched, amplified, and is applied to the output electromagnetic relay. With the help of an additional external contact the second frequency-dependent measuring element (4), used for the return of the relay to the initial position at a certain circuit frequency, can be started.

RXFE-4 type relays have a similar construction and principle of operation (Figure 14.14). The RXFE-4 is a static, instantaneous frequency relay module available in both under-frequency (99.8%) and over-frequency (100.2%) models. Power to the static circuits is supplied from the measured voltage, thus a separate auxiliary supply is not required. A blocking circuit prevents unwanted operation when the measured voltage is switched ON or OFF.

The RXFE-4 operates on the principle of comparing the phase angle of the current in a tuned LC-circuit with the current in a purely resistive circuit, both circuits being supplied by the measured voltage after it has undergone transformation and filtering.

The resonant frequency of the LC-circuit and thus the operating value of the relay are continuously adjustable within a range of approximately 12% of rated frequency. The setting knob, located at the lower left of the relay module front plate, can be reached by inserting a small screwdriver through a normally plugged hole in the clear plastic cover.

A feedback circuit, which modifies the resetting level after operation of the output relay, provides a stable operating band of 40 to 70 Hz, depending on the measured voltage magnitude. A red target becomes visible upon operation of the output relay and is hand-reset by a knob on the front.

Digitalization of information has allowed considerable improvement of the parameters of the frequency relay, although their construction has become, of course, much more complex. The FCX103 type relay can be given as a good example of this (Figure 14.15). This relay is made of big discrete electronic components and has a modular construction typical of the 1970s. Its main features: one to four independent tripping levels; highly accurate frequency measurement ($\pm 0.03$ Hz); a wide setting range (39.1 to 65 Hz in 0.1 Hz increments); dimensions: $270 \times 210 \times 269$ mm.

The FCX103 type frequency relay can be delivered with one to four output stages and its tripping values and delay times can be individually selected for under- and over-frequency protection. The auxiliary supply for the electronic circuits is derived from the measured quantity. A matrix plug-board (see Figure 14.15b) is provided for setting
A high degree of accuracy is attained by using a crystal oscillator as a reference and employing digital techniques to compare the unknown period with the reference period. The number of oscillations of the quartz reference during each period of the system frequency is counted. At the end of the period, the relay decides whether the frequency of the system is greater or lesser than the relay setting. This decision is stored for at least 150 msec and tripping if during this time the measurements of all subsequent periods indicate the same result. The stable 100 kHz sinusoidal signal from the quartz oscillator (1) is counted by the binary counter (3). A square-wave signal is also derived from the

**FIGURE 14.14**
RXFE-4 type static frequency relay (ABB, 1990). 1 — Transformer for measured voltage and auxiliary voltage; 2 — low pass filter; 3 — LC-circuit with facilities for setting the operating value; 4 — R-circuit; 5 — auxiliary circuit; 6 and 7 — level detectors; 8, 9, 13, and 14 — inverting circuits; 10 and 11 — JK-triggers; 12 — “NO-AND” logical circuit; 15 — amplifier; 16 — output relay. (ASEA (ABB), 1982.)
system voltage via the shaper (4). Each positive flank of this signal causes the monostable multi-vibrator (5) to produce an impulse of 10 μsec which upon being applied to the counter resets it to zero.

The count reached by the counter immediately prior to being reset is proportional to the period of the system frequency. A decoder (7) is set by means of a plug-board (6) (Figure 14.15b) to detect the desired under- or over-frequency.

The binary setting (corresponding to the period of the pick-up frequency) depends on which combination of direct and inverted outputs from the counter are applied to the decoder (7), for example, for a period of 20 msec (50 Hz) the direct and inverse
counter outputs must be decoded such that at a count of 2000 (2000 periods of the 10 μsec long 100 kHz quartz signal are equal to 20 msec) a digital “1” is produced at the output of the “AND” gate. At frequencies above the setting (shorter period), the counter will be reset before it reaches the decoder count and no output will be generated by the “AND” gate. At lower frequencies, however, a 10 μsec impulse is produced by the “AND” gate once every period (upon reaching the decoder count, an impulse of this duration is applied to all the inputs of the “AND” gate). The short-duration impulses, produced when the frequency being supervised falls below the setting, are lengthened by the monostable flip-flop (8) and transformed into a continuous signal by the pulse stretcher (9). This signal controls the timer (11) either directly or via the inverter stage (10). With the inverter connected in series, the relay registers an over-frequency condition. Under-frequency is registered when the pulse stretcher is connected directly to the timer.

Each FCX103 can be fitted with from one to four tripping or output stages. The basic measuring unit includes the tripping stage “D” as standard, the plug-in additional stages “A,” “B,” and “C” being inserted as required.

In 1977 a modification of this relay (FCX103B) appeared. Instead of one of the blocks (YAT 111) it contained a special plug-in part YAT 115 based on integrated circuits which allowed this relay to measure the rate of change of frequency (df/dt).

Fundamentally the manufacturer is against the use of so-called df/dt ancillary units which measure frequency deviation because such relays are very sensitive to switching
operations and sudden changes in system voltage caused by such operations can also cause it to pick up, however, the $\frac{df}{dt}$ measurement can be used as an additional feature when the frequency decreases considerably, that is, when there is a large energy deficit not only can the load corresponding to the first shedding stage (10 to 20%) be shed, but also that of the second or third stages. This combination accelerates the action of the relay in the event of sudden overloading of the network.

Setting range pick-up value for frequency deviation of new YAT 115 integral circuit based unit, is 0.1 to 9.9 Hz/sec, accuracy $\pm 0.05$ Hz/s. Relays of this type have been in use for more than 15 to 20 years and still meet all the requirements.

Modern technical integrated circuits of high integration levels allow production of relatively simple and compact electronic frequency relays (Figure 14.16), not only by the leading relay producers but also by small companies. The most modern static under-frequency relay (Figure 14.17) employs digital counting techniques to measure system frequency. Basically this relay consists of a highly stable, crystal-controlled oscillator, which continuously supplies 2 MHz (5 MHz in some relay types) pulses to a binary counter. The counter, in conjunction with other logic circuitry, determines system frequency by counting the number of 2 MHz pulses that occur during a full cycle (one period) of power system voltage. For any preset frequency a specific number of pulses should occur during a one-cycle period. If the number of pulses is less than this specific number, this indicates that the system frequency is above the setting. Conversely if the number of pulses is greater than this specific number, it indicates that the system frequency is less than the setting.

For reasons of safety, an under-frequency indication must occur for a minimum of three consecutive cycles before the relay produces an output. This minimum time can be extended to 80 cycles by means of an adjustable auxiliary timer. If the system frequency recovers for even one cycle during the timing period, the timing circuits will be reset and the relay will immediately start monitoring system frequency again. The relay operating time is independent of the rate of change of the system frequency. The static under-frequency relay is an extremely accurate and stable device. It can be adjusted to a frequency range of 40 to 70.9 Hz in increments of 0.01 Hz, and its setting is accurate within $\pm 0.005$ Hz of the desired set point. This accuracy is maintained over an ambient temperature range of $-20$ to $+60^\circ$C and is independent of voltage over the range of 30 to 120% of rating. Some models are provided with an under-voltage detector, which blocks operation of the relay when the applied voltage falls below the set level of the detector.

The static relay has a minimum operating time of three cycles, as described previously, when the output is a thyristor. Most models provide electromechanical contact outputs and in these models the minimum operating time is increased to four cycles simply because of the operating time of the output telephone relay. A compromise solution is to use reed switch output relays (as in the SFF type relays).

Microprocessor frequency relays produced by the General Electric Company, Basler, have a similar construction and external design. Heavy steel cases of similar size and with similar attached elements to their electromechanical analogues, simplified applications of the new equipment and allowed replacement of some electromechanical relays with microprocessor ones in functioning power stations and substations. Such ideology was typical of the initial stage of development of microprocessor relay protection. More lately, relay producers have diverged from this ideology and now are producing microprocessor relays in cases of any shape and size (Figure 14.18).
FIGURE 14.16
This is how modern small-size frequency relays based on integrated circuits (produced by many firms) look.

FIGURE 14.17
Static digital frequency relay of the SFF204 type (GE) in a standard steel case (without front cover) with pull-out printed circuit boards.
Why it was necessary to replace cheap and reliable nonmicroprocessor semiconductor frequency relays providing accuracies of \( \pm 0.03 \) to \( 0.05 \) Hz with large and expensive microprocessor relays with an accuracy of \( \pm 0.005 \) Hz, and if such accuracy is really required in practice when do we have to apply frequency relays in electric circuits, are quite different questions. The author still fails to find a satisfactory answer to those two questions.

**FIGURE 14.18**

Microprocessor based frequency relays of the MIV (a) and DFF (b) type, produced lately by the General Electric Co. (General Electric 2004 online catalog) and the SPAF type (c), produced by ABB. (ABB Relay Units and Components Buyers Guide 1990.)

Why it was necessary to replace cheap and reliable nonmicroprocessor semiconductor frequency relays providing accuracies of \( \pm 0.03 \) to \( 0.05 \) Hz with large and expensive microprocessor relays with an accuracy of \( \pm 0.005 \) Hz, and if such accuracy is really required in practice when do we have to apply frequency relays in electric circuits, are quite different questions. The author still fails to find a satisfactory answer to those two questions.
15

Microprocessor-Based Relays: Prospects and Challenges

15.1. Is It a Relay at All?

Microprocessor systems are similar to simple digital computer systems (Figure 15.1), in which the microprocessor performs the timing and control of the system and carries out all arithmetic and logical operations. The system memory may be Read Only Memory (ROM) for dedicated applications or Random Access Memory (RAM) for the storage of data and programs, or a combination of both. System memory stores the program to be executed and the data relevant to the specific task.

The microprocessor communicates with the system memory by means of a bus system. The same bus system permits communication of the microprocessor with the interface adaptor, or input and output (I/O) unit, which makes possible the transfer of data and control signals to and from the system.

As it can be seen from Figure 15.1, the microprocessor is quite a complex device with specific terminology and principles of operation that have nothing in common with the protective relays considered above. The question arises if the “microprocessor-based relay” is a “relay” in the full sense of the word. On closer examination, it turns out that the “microprocessor-based relay” is a small computer in which the output circuits and voltage transformers, with a program stored in memory, allowing processing of input signals in such a way that operation of this or that type of protective relays can be modeled. With the help of a basic universal microprocessor one can create any relay by just making certain changes in the program, at least that is how it used to be at the initial stage of development of microprocessor-based equipment. For example, when the first universal programmable microcomputer (Elektronika-60) appeared at the end of the 1970s in the former U.S.S.R., a whole series of different protective relays was designed for the power industry, but input circuits of other types could also be installed and other programs set up on the same device (for example, a program directing a telescope to the sky in such a “relay”), making it not a “relay” in the full sense of the word.

So it turns out that the microprocessor becomes a “relay” only when it is based on a program of a “relay.” This sounds quite strange. Our computer does not turn to a canvas or a palette, only because we run PhotoShop® or CorelDraw® and start drawing a picture, although the computer does allocate us a zone for drawing (a virtual canvas) and a tool for color selection (a virtual palette) and a whole set of different virtual brushes, so just as in this example, a “microprocessor-based” relay is really only a “virtual” relay.

Opinions are sometimes expressed that protective devices now available on the market are in fact only single-purpose devices designed for execution of a limited set of functions,
typical of relays of some particular type. Such devices have names corresponding to the
name of a relay of a particular type, like Frequency relays, for instance, and one can
communicate with such a device only with the help of a special program which specially
created for this particular device, taking into account all of its peculiarities. Actually the
relay is programmed by inputting certain pick-up thresholds, time intervals, and algo-
rithms of choosing of the proper type, among all possible types of working characteristics,
but in this case, limitations are set not for the microprocessor (for which it is all the same,
whatever signals to process), but for ROM containing the program of this microprocessor
and the number of I/O channels. If in devices performing the function of protective
relays one uses not ROM, but Erasable Programmable Read-Only Memory (EPROM) or
Electrically Erasable Programmable Read-Only Memory (EEPROM) and a pocket
programmer that allows recording to ROM of any algorithm of a microprocessor
operation, one will obtain a universal protective relay instead of a frequency relay. It
will not differ practically from modern universal Programmable Logic Controllers with
digital and analog inputs such as Modicon\textsuperscript{\textregistered} family (Gould Modicon) or SIMATIC\textsuperscript{\textregistered}
family (Siemens) and many others. Each such device may contain tens of input modules
for transformation of signals to Boolean or hexadecimal code, tens of virtual timers of
different types, comparators, counters of different configurations, different types
of triggers, univibrators, a great number of memory registers used for recording of

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure15_1.png}
\caption{A structure of a typical microprocessor system.}
\end{figure}
intermediate results, powerful output modules, etc. Using this set of virtual elements in a computer program running in Windows®, one can draw very complex automation systems (much like in graphics editors) which are then loaded to the controller. Having chosen the option “simulation,” one can see on the display how this automation system works in real-time operation modes, or in emergency modes modeled purposely. Today a special computer program is used for work with each type of such controllers; however, scientists are trying to create a universal program allowing work with controllers of different types.

Of course there are devices with much lower performance capabilities, based on quite “simple” controllers and miniature EEPROM (Figure 15.3). But actually “low” performance capabilities are in fact not as low as it might seem. The EEPROM 24LC256 is capable of both random and sequential reads up to a 256 kb boundary. Functional address lines allow erase/write cycles ¼ 1,000,000; data retention > 200 years; a standard 8 up to 8 devices on the same bus for up to 2 Mb address space; pin DIP package. The PIC16C73B microcontrollers have high performance RISC CPU; 35 single instructions to learn; up to 20 MHz operating speed; 56 kb words of program memory; 192 × 8 bytes of data memory (RAM); 3 timers, 5 analog or digital channels; 11 interrupt sources; a 28-pin DIP package.

The “simplicity” of these devices is as relative as their “low” performance capabilities. For example, the Data Sheet for microchip PIC16C73B type, containing only brief descriptions and specifications of the device, has 189 pages!

Apparently the internal architecture and principles of operation of microprocessor-based devices have little in common with devices called “electric relays.” To illustrate this fact one can mention a well-known complex universal microprocessor-based relay of the REL-316 type (ABB), designed for distance protection of power lines and for differential protection. This relay appears to be used quite often as a substation controller and not as a protective relay, since it is based on a powerful universal microprocessor 486 series supplied with a great number of logical inputs and relay outputs.
As follows from the facts considered above, in the author’s opinion, construction and principles of operation of microprocessor-based devices, including protective relays, should be considered not in a book devoted to electrical relays, but in technical computer literature, however, since these virtual microprocessor-based relays are widely used as protective relays, it is still worthwhile to consider some important aspects of practical use of these devices.

First, we will consider those numerous advantages of microprocessor-based “relays” which are usually indicated in advertisements.

15.2 Advantages of Microprocessor-Based “Relays”

1. Many microprocessor-based relays allow us to record and then replay modes preceding or functioning during breakdowns, for the analysis of emergency situations.

Well, were power-engineering specialists really deprived of this possibility before? Are not there a great number of various loggers of emergency modes and of relay pick-ups? The ABB, Siemens, NxtPhase, Areva, RiS, Dewetron GmbH Company alone offers tens of variants of loggers and analyzers of various different emergency modes (Figure 15.4).

2. Microprocessor-based relays allow us to change pick-up settings with the help of a computer and to turn from one characteristic to the other using only software tools.

This is really more convenient than to adjust the relay with the help of potentiometers and a screwdriver, but how often does one have to adjust setting modes of the relay during 20 to 25 years? Two times? Three times?
3. Microprocessor-based relays allow us to provide all the information regarding their state to remote dispatching centers through special communication channels.

Had not remote multi-channel systems of data transmission (SCADA, for instance), transmitting information about the pick-up of every electromechanical relay to the dispatching desk, been used before microprocessor-based relays appeared?

4. Microprocessor-based relays allow us to change configuration of the relay protection set: to switch some functions ON or OFF (that is to switch ON or switch OFF some relays) by software means with the help of an external computer.

This is really much more convenient than to install separate relays and remake the assemblage in relay protection boards, but again the same question arises: How often does one actually need to resort to such operations? Once (or twice under the most adverse conditions) for the whole service term of the relay (20 to 25 years)?

5. Microprocessor relays are less prone to dust, increased humidity, aggressive gas and vapors than electromechanical relays.

The author wonders if the author of this thesis has ever been to modern halls (or rooms) of relay protection in power stations or substations. It seems that he has not, otherwise he would have been aware that, first, electromechanical protective relays have been produced for decades in heavy hermetic cases of metal and glass that are well protected from dust and other negative environmental factors. Second, modern halls of relay protection are separate clean enclosed spaces equipped with air-conditioners maintaining stable conditions regardless of conditions outside. Microprocessor-based relays are installed in similar halls.