Generator Protective Relaying

ASEA's protective relays for generators consist mainly of plug-in units which provide:

- Optimum protection requiring a minimum of space.
- Great flexibility in mounting and wiring.
- Easy installation, modification or extension.
- Simplicity of testing and maintenance.
- Reduction of spare parts.
Generator Protection

This pamphlet gives a general outline and description of the protective relay systems normally installed for a.c. generators. A brief account is given of mechanically actuated monitoring devices.

The recommendations listed herein are generally also applicable to synchronous condensers and large synchronous motors. However, the protective systems for such machines are not discussed in this pamphlet.
1 Introduction

Generators are designed to run at a high load factor for a large number of years and to permit certain incidences of abnormal working conditions. These, however, are required to be kept down to a minimum.

Normal service conditions are therefore supervised by sensitive direct-acting temperature detectors in order to prevent unnecessarily high working temperatures, which would result in early ageing of the insulating materials. In addition, mechanically actuated devices are installed to detect vibration, low pressure of lubricating oil or failure of cooling media, etc. Further, incoming transient voltages, or voltage surges, are limited by lightning arresters and surge capacitors. The maintenance of the machine, its prime mover and auxiliaries, are carried out at scheduled intervals. In short, all possible means are employed to safeguard the continuity of supply and to improve on the expected lifetime of the generating unit.

Abnormal conditions, with internal or external faults, are dealt with by the protective relays which are installed to provide high speed primary protection, and delayed, selective, back-up protection.

The requirements with regard to the inclusion of various types of protective relays are not laid down in any internationally agreed standard specification. The so-called common standard practice may, therefore, vary on certain points between different countries and also between power companies within the same country. This often depends on past experience and different ways in which fault statistics may be interpreted. It is commonly agreed, however, that "over-protecting" a machine to give 100% security should not be pursued, since the instillation of additional apparatus also increases the risk of possible failures.

By properly designing the protective systems, the danger to personnel, the damage at the point of fault and the time taken to return a machine to service will be reduced to a minimum. The cost of the relays and the relay panels with all the internal wiring completed is indeed negligible compared with the overall cost of the installation.

1.1 Principles of generator neutral earthing

The method of generator neutral earthing varies widely from one country to another, depending on past practice, earth-fault relaying and electricity board regulations. In the case of small generating sets (10—30 MVA) directly connected to a distribution system, the current rating of the neutral-point resistor and the earth-fault current may be found to vary from 10 A to more than 1000 A.

On the other hand, large generators which require step-up transformers are, in the majority of cases, equipped with a neutral point resistor which provides an earth-fault current of only 5—15 A. The reason for this apparent contradiction can be explained by referring to the various ways of arranging the earth-fault relaying. Basically, the stator earth-fault current should be limited to about 5—15 A in order to minimize burning of the core laminations. With such a low current, an earth fault can be permitted (although this is not recommended) to remain for some minutes without causing extensive damage that necessitates costly repairs, such as restaking of core laminations.

The neutral of the generator, or the system, should not be isolated from earth, because this may give rise to excessive transient over-voltages during intermittent earth faults (arching grounds). These transient voltages, however, remain within acceptable limits if the generator, or the system neutral, is earthed through a resistor that will pass the same magnitude of current as the total sound phase capacitive current. If relatively more current is passed through the resistor, only a slight reduction of the over-voltages is obtained.
In accordance with the basic theory of arcing grounds, the neutral resistor should be purely resistive, with a minimum of inductance. Our standard resistors are therefore made for direct connection to the neutral point, without using a special distribution transformer (see Fig. 1). Since the generator earth-fault protection normally initiates tripping of the machine within 1 second, the neutral earthing resistors can be made with a standard short-time rating of 10 seconds.

In the case of generator-transformer units, stray voltages will appear at the generator neutral during an earth fault in the HV network. This is due to the capacitive coupling between the HV and LV windings of the step-up transformer. The magnitude of these stray voltages depends on: (a) the method of neutral earthing of the HV network, i.e., effectively earthed or resistance earthed (Petersen-coil), and (b) the step-up transformer interwinding capacitance, and (c) the ohmic value of the generator neutral earthing resistor.

When the HV system is directly earthed, the voltage across the generator earthing resistor, during an HV earth fault, will be small and can normally be disregarded. However, if the HV network is Petersen-coil earthed, the neutral displacement voltage of the generator can reach the normal setting of the earth-fault protection. This problem must therefore be investigated for each particular installation, and can be solved by either increasing the earth-fault relay setting or reducing the ohmic value of the generator earthing resistor.

![Fault duration secs.](image-url)

**Fig. 1** Air-cooled, short-time rated neutral earthing resistor for direct connection to generator neutral (150 kV, 5 A, 10 sec).

![Test results showing effects of arc burning on stator core laminations during earth faults.](image-url)

**Fig. 2** Test results showing effects of arc burning on stator core laminations during earth faults.

arresters used on the HV side and also on the actual configuration of the HV busbar.

To protect generators from severe voltage surges, lightning arresters and surge capacitors are often used. In the case of smaller machines directly connected to a distribution network comprising overhead lines, such protective devices are of prime importance.

**Switching surges.** Switching operations may cause relatively high transient over-voltages if restriking occurs across the contacts of the circuit-breakers. These transients are similar to those obtained during intermittent earth faults (arcing grounds) and may be limited by using modern circuit-breakers. Lightning arresters installed between the generator circuit-breaker and the generator may also assist in reducing some of the highest switching surges.

**Intermittent earth faults (arcing grounds).** The amplitude of the transient voltages during arcing grounds may theoretically, under the most unfavourable conditions of arc-restricking, reach a value of 5 times normal line-to-neutral peak voltage. By means of the above-mentioned resistance earthing of the generator neutral these over-voltages will be reduced to a maximum value of about 2.5 times the rated peak voltage.

### 2. Origin of disturbances and failures

#### 2.1 Over-voltages

Atmospheric surge-voltages are obtained by direct lightning strokes to the aerial lines in the HV system. Induced, or capacitively transferred voltage surges can however reach the generator via the step-down transformer (see pamphlet 7632 EA). The amplitude and the duration of the surge on the LV side depends on the type of lightning

#### 2.2 Over-currents

**External faults.** During external faults with large short-circuit currents severe mechanical stresses will be imposed on the stator windings. If any mechanical defects already exist in the winding, these may be further aggravated. The temperature rise is, however, relatively slow and a dangerous temperature level may be obtained after about 10 seconds. With asymmetrical faults, severe vibrations and overheating of the rotor may occur.
Thermal overloading. Continued overloading may increase the winding temperature to such an extent that the insulation will be damaged and its useful life reduced.

Unbalanced loading. Continued unbalanced loads, equal to or more than 10 per cent of the rated current, cause dangerous heating of the cylindrical rotor in turbo-generators. Salient pole rotors in hydro-generators often include camper windings and are therefore much less affected by unbalanced loading (negative phase-sequence currents).

2.3 Winding faults

Faults in the stator windings may occur owing to insulation breakdown between conductor and iron core, between conductors of different phases or between turns of the same phase. Also in some cases (older machines) a rupture or open circuit may occur at soldered joints.

2.3.1 Stator Winding

Earth faults. These faults normally occur in the armature slots. The damage at the point of fault is directly related to the selected current rating of the neutral earthing resistor. With fault currents less than 20 A negligible burning of the iron core will result if the machine is tripped within some seconds (see Fig. 2). The repair work then amounts to exchanging the damaged coil without restacking of core laminations.

If, however, the earthing resistor is selected to pass a much larger earth-fault current (>200 A) severe burning of the stator core will take place, necessitating restacking of laminations. Even when a high speed earth-fault differential protection is used, severe damage may be caused owing to the large time constant of the field-circuit and the relatively long time required to completely suppress the field flux. In the case of high earth-fault currents it is therefore normal practice to install a circuit-breaker in the neutral of the generator in order to reduce the total fault-clearance time.

Short-circuits between the stator windings very rarely occur, because the insulation in a slot between coils of different phases is at least twice as large as the insulation between one coil and the iron core. If a phase-to-phase fault should occur, this is most likely to be located at the end-connections of the armature windings, i.e., in the overhanging parts outside the slots. A fault of this nature causes severe arcing with high temperatures, melting of copper and risk of fire if the insulation is not made of fire-resistant, non-inflammable material, such as Mikespar®. Since the short-circuit current in this case does not pass via the stator core, the laminations will not be particularly damaged. The repair work may therefore be limited to exchanging the affected coils and mechanical parts of the end-structure.

Interruption faults or short circuits between the turns of one coil may occur if the stator winding is made up of multi-turn coils. Such faults may develop owing to incoming current surges with a steep wave-front, which may cause a high voltage (L.B.U.) across the turns at the entrance of the stator winding.

Ir, however, the stator winding is made up of single-turn coils, with only one coil per slot, if is of course, impossible to have an interturn fault. If there are two coils per slot the insulation between the coils is of such dimensions that an interturn fault is not likely to occur.

For large machines (>50 MVA), it is the normal practice of ASEA to use single-turn coils, whereas in the U.S.A. and Canada multi-turn coils are used. In the latter countries, therefore, the interturn, or split-phase, protection has become very popular.

2.3.2 Field Winding

Insulation failure. A single earth fault in the field winding and its associated circuits gives rise to negligible fault current and therefore does not represent any immediate danger. If, however, a second earth fault should occur, heavy fault current and severe mechanical unbalance may quickly arise and lead to serious damage. It is essential, therefore, that an alarm is obtained upon the initial occurrence of insulation failure and that the machine is taken out of service as soon as possible.

Reduced excitation may be obtained owing to a short circuit or an open circuit in the field and exciter circuits, or a fault in the AVR (automatic voltage regulator). If an open circuit is caused by inadvertent opening of the field-switch, a fully loaded machine will quickly fall out of synchronism (less than one second), and run as an induction generator above synchronous speed, drawing reactive power from the system. To prevent this from causing system instability, it is our practice to include an intertripping scheme via auxiliary contacts so that opening of the field-switch causes tripping of the generator circuit-breaker.

2.4 Miscellaneous faults (mechanical)

In addition to the above-mentioned electrical faults, the running of a machine can be endangered by relatively minor mechanical defects in any of the auxiliary apparatus associated with the prime mover. In the following, some of the more important types of protective device are mentioned.

Over speeding may occur as a result of a fault in the turbine governor or its associated equipment. If the main generator circuit-breaker is tripped while full electrical power is being delivered to the network, dangerous overspeeding is prevented by the normal actions of the governor. It is essential, therefore, that the normal working of the governor be supervised by some additional protective device.

Vibrations may occur owing to unbalanced loads or certain types of mechanical faults. Vibration detectors are usually mounted on the generator bearing pedestal.

Excessive bearing temperature may arise owing to mechanical faults, impurities in the lubricating oil or defects in the oil circulation system. These faults may be detected by means of a temperature device embedded in the bearing.
Bearing current. An induced emf of some volts may be developed in the shaft of a generator owing to certain magnetic dissimilarities in the armature field. If the bearing pedestals at each side of the generator are earthed, the induced emf will be impressed across the thin oilfilms of the bearings. A breakdown of the oilfilm insulation in the two bearings can give rise to heavy bearing currents owing to the very small resistance of the shaft and the external circuit thus developed.

Consequently, the bearing pedestal furthest from the prime mover is usually insulated from earth and the insulation supervised by a suitable relay. Further, to prevent the rotor and the shaft from being electrostatically charged, the shaft is usually earthed via a slipping and a 200 ohm resistor. This resistor also contributes by taking the injected a.c. leakage current of the field circuit earth-fault protective scheme.

Motorizing of a generator will occur if the driving torque of the prime mover is reduced below the total losses of the turbo-generator unit. Active power will then be drawn from the network in order to maintain synchronous running, and the generator will work as a synchronous motor. If this is allowed to persist (>20 seconds), serious overheating of the steam turbine blades may occur, dependent on the type of turbine and the design limits imposed by the manufacturer.

3 Protective systems

3.1 List of protective relays

<table>
<thead>
<tr>
<th>Device Number Description</th>
<th>Relay Type</th>
<th>Literature Ref. No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection for external faults (back-up protection)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>59 Instantaneous over-voltage</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
</tr>
<tr>
<td>+ definite time-lag</td>
<td>+ RFK 31-2 E</td>
<td></td>
</tr>
<tr>
<td>51 Instantaneous over-current</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
</tr>
<tr>
<td>+ definite time-lag</td>
<td>+ RFK 31-2 E</td>
<td></td>
</tr>
<tr>
<td>51 DMTL over-current</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
</tr>
<tr>
<td>51 DMTL over-current</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
</tr>
<tr>
<td>21 Impedance (O/C)</td>
<td>RLE 50-303 E</td>
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<tr>
<td>49 Thermal overload</td>
<td>RLYA 48-1 E</td>
<td></td>
</tr>
<tr>
<td>49 Temperature monitoring</td>
<td>RLYA 48-1 E</td>
<td></td>
</tr>
<tr>
<td>46 Negative phase-sequence</td>
<td>RLYA 48-1 E</td>
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Stator winding protection (internal faults, primary protection)

<table>
<thead>
<tr>
<th>Device Number Description</th>
<th>Relay Type</th>
<th>Literature Ref. No</th>
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<tr>
<td>59 N Neutral voltage</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
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<tr>
<td>+ definite time-lag</td>
<td>+ RFK 31-2 E</td>
<td></td>
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<tr>
<td>51 N Neutral current</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
</tr>
<tr>
<td>+ definite time-lag</td>
<td>+ RFK 31-2 E</td>
<td></td>
</tr>
<tr>
<td>87 Q Generator differential</td>
<td>RLYA 48-1 E</td>
<td></td>
</tr>
<tr>
<td>87 T Overall differential</td>
<td>RLYA 48-1 E</td>
<td></td>
</tr>
<tr>
<td>90 Voltage balance, interturn faults</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
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Field excitation protection (field failure)

<table>
<thead>
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<th>Device Number Description</th>
<th>Relay Type</th>
<th>Literature Ref. No</th>
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<tr>
<td>64 Field earth fault</td>
<td>RREL 22</td>
<td>RK 41-2 E</td>
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<tr>
<td>40 Loss-of-excitation</td>
<td>RLYA 48-1 E</td>
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Miscellaneous protection

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<th>Relay Type</th>
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<tr>
<td>12—14 Speed monitoring</td>
<td>OSHA 20-300 E</td>
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<tr>
<td>12—14 Speed monitoring</td>
<td>—</td>
</tr>
<tr>
<td>36 Vibration protection</td>
<td>RLYA 48-1 E</td>
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<tr>
<td>36 Shaft current</td>
<td>RLYA 48-1 E</td>
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<tr>
<td>36 (bearing insulation)</td>
<td>RLYA 48-1 E</td>
</tr>
<tr>
<td>32 Reverse power</td>
<td>RLYA 48-1 E</td>
</tr>
<tr>
<td>32 —</td>
<td>—</td>
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</table>

3.2 Protection for external faults (back-up protection)

3.2.1 Over-voltage protection

During the starting up of a generator, prior to synchronization, the correct terminal voltage is obtained by the proper working of the AVR (automatic voltage regulator). After synchronization, the terminal voltage of the machine will be dictated by its own AVR and also by the voltage level of the system and the AVRs of nearby machines. Generally, the rating of one machine is very small in comparison with an interconnected system, it is therefore not possible for one machine to cause any appreciable rise in the terminal voltage as long as it is connected to the system. Increasing the field excitation, for example, by a fault in the AVR, merely increases the reactive MVAR output, which may ultimately lead to tripping of the machine by the over-current protection. In some cases, e.g. with process generators and synchronous condensers, which are often called upon to work at their maximum capability, a maximum excitation limiter is often installed. This prevents the rotor field current and the reactive output power from exceeding the design limits.

If the generator circuit-breaker is tripped while the machine is running at full load and rated power factor, the subsequent increase in terminal voltage will be limited by a quick acting AVR. However, if the AVR is faulty, or at this particular time switched for manual control of the voltage level, severe over-voltages will occur. This voltage rise will be further increased if simultaneous overheating should occur owing to a slow acting turbine governor. In the case of hydro-electric generators, a voltage rise of 50—100 percent can be possible during the most unfavourable conditions.

Modern step-up transformers with high magnetic qualities have a relatively sharp and well defined saturation level, with a knee-point voltage between 1.2 and 1.25 times $U_{n}$ (rated voltage). A suitable setting of the over-voltage relay is therefore between 1.15 and 1.2 times $U_{n}$ and with a definite delay of 1—6 seconds.

Previously, when oil-insulated VT’s (voltage transformers) were used, it was normal practice to insert M.V. fuses on the primary side of the VT’s in order to provide some protection for internal winding (inturn) faults in the VT’s. The inadvertent rupturing of a fuse would, however, be seen by the AVR as a serious voltage drop in the system and full field excitation would be obtained. If the over-voltage relay was connected to the same open-circuited VT, the subsequent increase in terminal voltage could not be detected. In a small system this could lead to sustained and dangerous over-voltages. Therefore, two sets of individually fused VT’s were used, permitting separate feeding of the AVR and the over-voltage relay.
With the new and modern cast-resin insulated VT's, the primary fuse is in fact more liable to failure than the VT's and has therefore been omitted altogether. In new installations, therefore, only one 3-phase set of VT's may be used, with a midget circuit-breaker (m.c.b.) inserted in each of the more important secondary circuits. These m.c.b.'s are equipped with auxiliary contacts, which can be used for interlocking (switching the AVR from automatic to manual control) and for signalling in the event of a faulty circuit.

Over-voltage protection (device no. 59) normally comprises one static over-voltage relay type RREG 25, with a high resetting ratio and one definite time-lag relay type RRKH 24 with a scale range of 1–6 seconds.

A current setting of about 1.5 times $I_n$ (rated current) is usually selected. This, however, depends on the magnitude of the available sustained short-circuit current, which is directly related to the type and the overload capacity of the AVR system.

In the case of a purely static excitation system, which receives its magnetizing power directly from the generator terminal, via a 3-phase step-down distribution transformer and high-current thyristor SCR (silicon controlled rectifiers), the magnitude of the sustained 3-phase short-circuit current depends on the generator terminal voltage. With nearly 3-phase faults, the generator terminal voltage will be small and the fault current may therefore fall below the setting of the over-current relay within a few seconds.

3.2.2 Over-current protection

As a back-up protection for sustained external faults, the simplest inverse or definite minimum time-lag over-current protection has for a long time been used. If the over-current relay is fed from CT's (current transformers) on the neutral side of the generator it will also act as a back-up protection in the event of internal faults when the generator is disconnected from the system. If the CT's are located on the generator line side, or on the HV side of the step-up transformer, back-up protection in the event of internal faults can only be obtained when the short-circuit current is supplied by the system.

Back-up over-current relays are always delayed, with a time setting of 1–6 seconds. A definite time-lag, or an inverse time characteristic may be used. The actual time setting and the choice of time characteristic is determined by the over-current relays in the external network, for which selective tripping is required.

In order to provide a back-up protection which is independent of the overload characteristics afforded by the AVR, an impedance (voltage restraint over-current) relay type RZE is available. At rated generator voltage, the RZE will work as a definite time-lag over-current relay. However, at reduced voltages the current required for operation will be similarly reduced, i.e., the relay will operate when the actual fault impedance ($Z=U/I$) drops below the pick-up value.

At zero voltage, operation of the RZE is obtained with a current of only 10 percent of rated current. The a.c. supply circuit must therefore be equipped with a midget circuit-breaker that has an auxiliary contact, which interrupts the trip supply in the event of a fault in the VT secondary wiring.
Back-up over-current protection may comprise one of the following items:

a) Definite time-lag O/C (device No. 51)
   3-Type BRL 24, instantaneous over-current relay
   t-Type RFLK-24, time-lag relay, scale 1–5 seconds.

b) Inverse time-lag O/C (device No. 51)
   3-Type RIDL, electro-mechanical over-current relay
   with IDMTL characteristic according D.S. 142: 1966.

c) Inverse time-lag O/C (device No. 51)
   1-Type RRIE, static 3-phase O/C relay with inverse
   (or very inverse) time characteristic.

d) Impedance or voltage restrained O/C (device No. 21)
   1-Type RZE 320, static 3-phase impedance relay,
   including definite time-lag relay, scale 1–5 seconds.

3.2.3 Thermal overload protection

Overloads between 1–1.5 times the rated current are not normally detected by the over-current protection. Sustained overloads within this range are therefore usually supervised by temperature monitors (resistance elements) embedded at various points in the stator slots. The ASEA temperature monitoring system type QSTC can be used to provide an alarm at low temperatures and tripping at high temperatures.

3.2.4 Negative phase-sequence (NPS) protection

Unbalanced loading may be obtained owing to a ruptured conductor or the failure to close of one pole in a 3-phase circuit-breaker. This causes negative-sequence currents (I1) to flow in the stator windings, giving rise to an armature field which rotates in the opposite direction of the rotor. Double frequency eddy currents, of an appreciable magnitude, may then be produced in the surface of a cylindrical rotor causing severe temperature rise at certain points, such as the slot wedges and the retaining rings at the rotor ends.

Negative-sequence currents are also produced during earth faults, and phase-to-phase faults, but the magnitude of the fault current is then usually much larger than the rated current and is therefore more easily handled by the standard protective relays. In practice, when a generator becomes damaged from unbalanced loading, the negative-sequence current is usually less than the rated current and the time duration normally more than 30 seconds.

The approximate heating effect on the rotor of a synchronous machine for various unbalanced fault conditions is determined by the product \( I_1^2 T \), where \( I_1 \) is the average negative-sequence current expressed in per unit (p.u.) stator current, \( T \) the duration in seconds and \( K \) a constant depending on the heating characteristic of the machine, i.e., the type of machine and the method of cooling adopted.

Typical turbo-generators and salient pole machines will not become seriously overheated by unbalanced loading if the product \( I_1^2 T \) is less than 30 and 40, respectively. In some special cases a value as low as 7 may apply for certain turbo-generators. This implies that in the case of \( I_1 = 1.0 \text{ p.u.} \), the duration of unbalanced loading should preferably be limited to less than 30 or 7 seconds respectively, in order to avoid a serious temperature rise. See Fig. 3. It should also be noted that, in the case when \( I_1 = 1.0 \text{ p.u.} \), is obtained owing to a phase-to-phase fault at the generator terminals, the actual time current can be shown to be 1.73 p.u. This normally causes tripping of the machine by the standard over-current relays within 1–5 seconds. The maximum permissible continuous value of \( I_1 \) is normally between 0.05–0.12 p.u. for turbo-generators and between 0.2–0.3 p.u. for salient pole machines.

The NPS protection type RYRIO comprises a negative-sequence current filter type RRTBD, which feeds a solid-state measuring unit. This provides an operating time characteristic \( I_1^2 T = K \) where \( K \) is continually variable between 0–30 (Fig. 3). The minimum pick-up value of \( I_1 \) is continuously variable between 0.15–0.6 p.u. An instantaneous alarm feature is also included, with a minimum pick-up value of \( I_1 \) continuously variable between 0.05–0.20 p.u.
As an alternative to the above, a definite time-lag MFS protection can be provided by arranging the RRTSB filter feeding two over-current relays, types RRL and RRIG. The value of $I_f$ required for tripping and alarm is then variable between 0.15–0.28 and 0.05–0.16 p.u., respectively. For hydro-electric generators, a higher setting of 0.24–0.47 p.u. is normally selected. The required relay is obtained by using type RRMH definite time-lag relays in both the alarm and tripping circuits. By including a sensitive and specially graduated indicating meter in series with the over-current relays, the actual percentage values of $I_f$ can be indicated, for example in the control room.

3.3 Stator winding protection (internal faults, primary protection)

The generator earth-fault protective relay is dependent on the system layout, i.e. whether the generator is directly connected to the busbars of a distribution system or via an intermediate step-up transformer to an HV system. In the latter case, the generator-transformer arrangement is called a unit system, i.e., the magnitude of the earth-fault current on each side of the step-up transformer differs completely and is dependent only on the method adopted for earthing within each (unit) system.

3.3.1 Earth-fault protection

Generators directly connected to distribution busbars.

The generator earth-fault protection must be capable of discriminating between internal and external faults. The neutral displacement relay, fed from a neutral point VT (voltage transformer) or from residually connected (broken delta) VT’s can therefore not be used on its own, because such a relay would operate for both internal and external faults.

A selective earth-fault protection must therefore be based on the information that can be obtained from the earth-fault currents. The design of this protection therefore depends on the earthing arrangement at the generator neutral and the neutral points in the external network.

If the earth-fault current is large, 10–20 per cent of the generator rated current $I_n$, the standard differential protection type RYICHA will also operate for earth faults, because its primary fault setting is about 2 per cent of $I_n$. As discussed in sections 1.2, however, it is our recommen...
mandation that the generator earth-fault current be limited to a maximum of 15 A. The earth-fault protective relays of the generator and also of the external feeders should then have a primary fault setting of 5 A or less. Such protective schemes have been used successfully by ASEA for several decades.

When two or more generators are to be paralleled to a common busbar it is our practice to keep the generator neutrals ungrounded (free), and to connect a small (15 A) zig-zag earthing transformer $Z_t$ to the busbars. This scheme involves a number of advantages, i.e., the economic factor, the ease of earth-fault relaying and the fact that no 3rd harmonic current can circulate between the parallel-connected generators.

With a free generator neutral, earth-fault relaying can be carried out as a simple residual connected scheme, as indicated in Fig. 4.

The C.T.s on the generator line side are paralleled, feeding a sensitive low-burden static over-current relay type RRKH 23. A primary fault setting between 1-3 A (about 0.001 $I_n$) is then normally obtained.

During heavy external short circuits, the RRKH 23 will, however, pick-up owing to dissimilarities in the C.T. characteristics and it is therefore necessary to include a delay, which is obtained by using a time-lag relay type RRKH 23 with a scale 0.3-2 sec. As an additional check feature, the normally closed contact (3) of the over-current protection, and the neutral displacement relay (2) type RREL are also included.

The minimum setting of the RRIG 28 is in some cases dictated by the line-to-earth leakage capacitance of the generator and its associated outgoing cables, surge capacitors, etc. With an external earth fault, the leakage capacitance takes a small zero-sequence current which will actuate the RRIG 28 if its setting is too low. If each of the generators that are connected to a common busbar have their own high-resistance neutral earthing resistor (as indicated by a broken line in Fig. 4), a sensitive earth-fault differential scheme is required in order to obtain selective tripping. The current transformer (5) must then be included.

Since the earthing resistor (Rg) is of the high-resistance type, the 3rd harmonic current which may circulate between paralleled generators is of the order of only a few amperes. The loss of energy and the heating effect of 3rd harmonic currents are therefore negligible. If, however, the harmonic value of the earthing resistors in the generator neutrals and also in the neutral points of the external network, has to be reduced for some reason, great care must be exercised, and the effects of increasing the 3rd harmonic currents must be fully investigated.

Earth-fault protection of generator-transformer units

It is common practice in most countries to use a neutral displacement relay for earth-fault protection of generator-transformer units. This relay may be fed either from a neutral VT or from the broken delta winding of the 3-phase VT's on the generator line side (see Fig. 5). The relay will operate for faults within the generator system and not for faults in the HV network (see also section 4.1).

In this case the earth-fault protection is therefore independent of the magnitude of the earth-fault current. The earthing resistor may then be selected mainly with the view of reducing arc burning of stator core laminations and limiting transient over-voltages during earth faults (arcing grounds). In the majority of cases a standard 5 A, 10-second resistor directly connected to the generator neutral will be more than adequate.

The primary fault setting of the neutral displacement relay type RREL 22 is normally between 5-10 per cent of rated line-to-neutral voltage. The required definite time-lag is obtained by using type RRKH 23, with a scale 0.3-2 seconds. With this protection, about 55 per cent of the stator winding can be covered, i.e., in the event of a fault 5 per cent or more from the generator neutral the RREL 22 will operate.

During certain load conditions synchronous generators may produce a 3rd harmonic line-to-neutral voltage between 5-10 per cent of rated voltage. The RREL 22 therefore includes a 3rd harmonic restraining feature with a damping factor of 7.
A 100 per cent earth-fault protection which covers the complete stator winding is in some cases considered an advantage. Such a scheme can be provided by making use of the 3rd harmonic voltage normally produced by the generator. Fig. 56 shows the de-energized position of a simple scheme which sounds an alarm for faults at or near the neutral point of the generator.

At no-load, or light load, it is assumed that the 3rd harmonic voltage \( U_{3h} \) and the secondary voltage \( U_{i_n} \) fed to the filter (1) and relay (2) are relatively small. The relay (2) therefore remains de-energized and its contact (b) is closed. However, with a load current \( I_L \) within the range 0.2–1.0 p.u. it is assumed that \( U_{i_n} \) causes relay (2) to operate, keeping its contact (b) open. Within the same range of load current relay (3) will be arranged to pick up and keep its contact (a) closed.

If, during this condition, an earth fault occurs at or near the generator neutral the secondary voltage \( U_{i_n} \) becomes zero, or negligibly small. Relay (2) therefore drops out, contact (b) closes and a delayed alarm is obtained via the time-lag relay (4).

This 100 per cent earth-fault scheme is suitable for generators with a 3rd harmonic voltage of about 1 per cent or more, within the load current range 0.2–1.0.

### 3.3.2 Differential protection

It is our recommendation that a differential protection be installed for all important machines of 2 MVA rating or more. This affords selective and high-speed tripping on all types of internal short circuits, i.e., phase-phase and 2-phase faults.

---

**Fig. 55** Earth-fault protection of generator-transformer unit, covering 95 per cent of stator winding.

- \( R_g \) Earth-fault resistor, normally 5 A, 15 seconds
- 1 Neutral displacement relay, type RREL 22 with 3rd harmonic restraint
- 2 Delinte time-lag relay, type RRKH 23 with a time scale 0.5–5 seconds

**Fig. 56** Basic details of 100 per cent earth fault alarm scheme.

1. Tuned filter, 250 Hz \( >450 \) Hz
2. Low-burden 3rd harmonic relay, type RFD
3. Under-current relay, type RRE 19
4. Delicate time-lag relay, type RRB 24
5. \( U_3 \) 3rd harmonic line-to-neutral voltage of generator, where \( U_3 = U_{G3} + U_{A3} \)
6. \( C_g \) Leakage capacitance to earth

**High-impedance differential protection, type RYDHA.**

This may be used for the generator and its associated outgoing leads provided the CT's on the line and the neutral sides all have the same turns-ratio. Owing to the high-impedance feature full stability will be obtained on through faults even when one of the CT's saturates as a result of differences in CT characteristics and the inclusion of a large d.c. component.

The outstanding features of the RYDHA are:
- High speed of operation, about 15 ms (excluding auxiliary relays)
- Low primary fault setting, about 2 per cent of CT rating
- Full stability on external faults
- Standard line CT's may be used
Overall generator-transformer differential protection, type RYDSA 20.

This is normally fed from CT's on the generator neutral side and on the HV side of the step-up transformer, if the HV leads to the station busbars are relatively long (1–2 km), these may be included within the protection by installing the HV CT's close to the busbars (see Figs. 10 and 11). Also, if a step-down station service transformer is connected to the generator terminals, this may be included within the overall protection by using CT's on the LV side.

The overall differential protection must have a restraining feature which can prevent misoperation during magnetizing inrush surges. Such a condition will occur when a nearby fault occurs on an adjacent feeder. During the time of the fault, the terminal voltage of the main transformer is practically zero and at the instant of fault clearance, i.e. when the circuit-breaker of the faulty feeder opens, the transformer terminal voltage quickly rises. This may cause severe magnetizing inrush currents.

When an overall differential protection is installed, the generator differential protection type RYDHA may be omitted.

The RYDSA 20 provides:

- **Three individual restraining circuits, to cope with:**
  - Through faults (over-current restraint)
  - Magnetizing inrush currents (2nd harmonic restraint)
  - Excessive excitation due to an abnormally high system voltage (5th harmonic restraint)
- **High speed of operation, about 23 ms at 3 times the setting,**
- **Low primary fault setting, about 20 per cent of CT rating,**
- **Low burden, allowing CT's with moderate characteristics to be used**.

### 3.3.3 Interturn fault protection

As mentioned in section 2.3, an interturn (or split-phase) protection may be installed if the stator winding comprises multi-turn coils.

In Fig. 6a, a simple but effective form of interturn fault protection is shown for a typical turbo-generator (a), and for a contra-rotating STAL-LAVAL steam turbine (b). During normal service the line-to-neutral voltages are perfectly balanced and no zero-sequence voltage will be obtained from the open delta winding (1), or from the VT (2) between the neutrals of the two identical STAL-generators.

If, however, some turns within one phase should become short circuited the line-to-neutral voltages will no longer balance and the resulting zero-sequence voltage will actuate the over-voltage relay (3). This relay, together with a series connected reactor (5), provides a restraint against 3rd harmonic voltages with a damping factor of about 14.

The 3rd harmonic voltages normally produced by a generator therefore cannot affect the protection.

The primary fault setting of the protection for turbo-generators is usually made with such sensitivity that tripping occurs when one turn becomes short circuited. The trip circuit of scheme (a) normally includes an over-current checking feature (4) and a 50 ms definite time-lag relay type FRKN (5). In scheme (b) where the two STAL-machines are made with identical characteristics instantaneous tripping is normally employed.

If the generators, scheme (a) and (b), are low-impedance earthed (>15 A earth-fault current) and directly connected to a distribution network, a large zero-sequence current may pass the generators during external earth faults. A zero-sequence voltage will then be imposed on the relay (3). If this voltage is too large a blocking feature from the neutral displacement relay is also included.
3.3.4 Fire extinguisher (CO₂)

Modern machines are normally equipped with cast-resin, Micapac or similar non inflammable insulating materials. The use of CO₂ fire fighting equipment is therefore no longer required. In older machines, with inflammable insulating material, the CO₂ equipment and the tripping of the machine were initiated by special flame detectors, installed at certain points around the armature winding overhang.

3.4 Field excitation protection (field failure)

The field excitation system of a synchronous machine may be considered to include the automatic voltage regulator (AVR), the main field winding, the d.c. exciter or the static d.c. power supply system. Protective relays are usually installed to operate in the event of field earth faults, loss-of-excitation or when the excitation is reduced to such an extent that the thermal design limits are exceeded.

3.4.1 Field earth-fault protection

As mentioned in section 2, it is of great importance that a field earth-fault protection is installed. This should be capable of detecting an insulation failure anywhere in the field winding, i.e., it should operate without any “blind spots”.

![Fig. 7 Field earth-fault protection](image)

Fig. 7 Field earth-fault protection

(a) For small machines with limited leakage capacitance to earth.
(b) For large machines.

1. Over-current relay, type RFL 23
2. Power directional relay, type RPAE
3. Capacitor
5. Resistor
6. Shaft earthing brush

Fig 7a shows a suitable protection based on the a.c. injection principle. During normal service the injection transformer (4) imposes 46 volts a.c. between the field winding and earth, via the capacitor (5) and the RFL 23 over-current relay (1).

Owing to the leakage capacitance to earth of the field circuit, a small a.c. leakage current of a few milliamperes will normally flow through the shaft earthing brush (6) to ground and in the RFL 23 relay circuit (1). The RFL 23 relay has a scale range 10–20 mA and is normally set to operate at 10 mA, or at a value which is twice the capacitive leakage current. This scheme can then detect a field earth fault when the normal insulation resistance of some megohms has dropped to about 3000 ohms or less.

If the total leakage capacitance to earth of the field circuit and its d.c. source exceeds 0.5 μF, the normal a.c. leakage current may exceed 10 mA and the scheme (a) is then unsuitable.

By using the scheme shown in Fig 7b the effects of the field circuit leakage capacitance to earth can be ignored. This because the relay (2) is of the power directional type which is set to operate only for the resistive (active) component of the injected current. The sensivity is basically the same as in schema (a).

If the d.c. source of the field excitation system comprises thyristors (silicon controlled rectifiers) an appreciable amount of harmonics may be imposed on the relay circuit. In the case of scheme (a), the harmonic currents through relay (1) may cause inadvertent operation. However, in the case of scheme (b), harmonics in the current coil of relay (2), must be accompanied by similar harmonics in the voltage coil in order to cause relay operation. Since no such harmonics will appear in the mains a.c. supply voltage, maloperation of relay (2) cannot occur.

The use of scheme (a) is therefore limited to smaller machines (for turbo-generators normally less than 40 MVA) and when the d.c. source for the field excitation does not give rise to harmonics. In all other cases, or when any doubt exists, scheme (b) should be used.

Since the shaft of a turbo-generator is earthed via a slipping and a carbon brush, the injected relay currents cannot damage the bearings. In the case of hydro-electric generators the shaft is normally effectively earthed through its direct water contact.

The primary voltage to the injection transformer is normally obtained from the common control- and relay-board a.c. supply, which includes a loss-of-voltage alarm feature.

In attended stations the field earth-fault relay is normally arranged to initiate a delayed alarm. In unattended stations delayed tripping may be used, depending on the requirements of the customer.

3.4.2 Loss-of-excitation protection

A complete loss-of-excitation may be obtained as a result of a fault within the AVR equipment, an open circuit or a short circuit of the main field.

Reduced excitation, causing excessive heating at the end region of the stator core, may be obtained during normal system conditions when there is a continuous tendency towards an increasing system voltage (dropping of reactive loads). In that case the normal AVR action will be to reduce the field excitation. Reducing the field too much will ultimately cause a loaded generator to fall out of synchronism.
An exact mathematical treatment of the loss-of-excitation problem is not possible owing to a large number of variables, including turbine governor and AVR actions. However, from special computer programs developed by ASEA, extensive studies show that the type RYGPA protection will be suitable in the majority of systems.

The normal working characteristic of a typical turbo-generator is indicated in Fig. 8a. The boundaries represented by the curves AB, BC and CD are called capability curves, beyond which the machine is not normally allowed to work. The curve DF shows the stability limit for the case when the AVR is in service and the external impedance $X_a$ to the infinitely large system is 0.2 p.u.

The apparent power vector $S_a$ represents rated power, at rated power factor ($P/F=0.8$). If the system voltage should start to increase steadily, the field excitation will be reduced correspondingly the normal working of the AVR. The point of vector $S_a$ then moves along the vertical line BH.

Continuous operation below the line DC causes severe localized heating of the stator end structure owing to an end leakage flux, which enters and leaves the stator core perpendicular to the laminations. In exceptional cases this may cause bluing of iron parts of the end structure, or charring of the armature winding insulation.

The type RYGPA protection comprises a directional current relay type RRIPE, with an operating characteristic which is basically independent of the magnitude of the polarizing voltage. This relay characteristic is arranged to coincide with the line CD, i.e., it will operate if excessive heating occurs as a result of prolonged under-excited operation.

With a properly working AVR, reduced excitation cannot occur simultaneously with a reduced generator terminal voltage. The RYGPA protection therefore includes an under-voltage relay type RREG, which is normally set to drop out when the generator terminal voltage is reduced below 0.85 p.u. (or 0.9×the minimum AVR setting).

The trip circuit of the protection is shown in Fig. 8b. Operation of only the directional relay RRIPE initiates an under-excitation alarm. If, however, simultaneous operation of the under-voltage relay RREG occurs, this indicates a fault within the excitation system and tripping of the machine is therefore effected.

The RRIPE directional relay has an inverse time characteristic according to Fig. 8c. This prevents the relay from maloperation during certain system power swing conditions, and also during asynchronous running with a fully intact field excitation system.

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Fig. 8 Loss-of-excitation protection type RYGPA comprising a directional relay type RRIPE and under-voltage relay type RREG.
(a) Capability curves for typical turbo-generator.
(b) Basic tripping circuit.
(c) Operating time curve (RRIPE).
Owing to the relatively long time constant of the machine circuit, a fully loaded generator, which loses excitation, will in most practical cases come 180° out-of-phase in respect of the system within 4–6 seconds. Operation of the protection then takes place within approximately 3–6 seconds, i.e., prior to the first pole slipping.

3.5 Miscellaneous forms of protection

3.5.1 Overload protection

The prime movers are normally equipped with a mechanical over-speed device of the centrifugal type. This may be supplemented with an electrical over-frequency relay. The type QSHA speed monitoring equipment can be arranged to indicate the speed at 3 different levels, varying between 10–200 per cent of nominal speed. This equipment may be operated from a PMG (permanent magnet generator) fitted on the main shaft, or alternatively from a much simpler electromagnetic device comprising a toothed collar mounted around the shaft.

3.5.2 Vibration protection

A vibration detector type SINUS may be mounted on one of the bearing pedestals in the case of a horizontal-shaft machine, or on the upper guide-bearing of a vertical-shaft machine. It may be set to trip the machine or to initiate an alarm when the radial deflections of a certain duration exceed a preselected value.

3.5.3 Bearing protection

The lubrication oil for the bearings is usually supervised with respect to pressure, rate of flow and the temperature at various points in the closed loop-circuit comprising the oil-cooler. Within the actual bearing monitors are embedded to check the temperature of the main metal parts. See section 3.2.3 for temperature monitoring system type CSTC. The shaft current protection type RYRIQ is installed to prevent the bearings being damaged by heavy currents in the event of insulation failure around the bearing pedestal. The equipment comprises a special "shaft current-transformer" mounted around the shaft, which thereby assumes the function of the primary conductor. The secondary winding of this C.T. feeds a static measuring relay, which can be set to operate for a shaft current as low as 1 or 1.5 A r.m.s. Tripping is effected via a definite time-lag relay RRRK, with a scale range 1–10 s. An instantaneous alarm, initiated by the measuring unit, is normally provided with a view to give some indication of a partly damaged insulation, in which case erratic current pulses of varying time duration may be obtained.

3.5.4 Reverse power protection

A reverse power relay is installed in order to prevent motoring of the generator, when the driving torque of the prime mover is reduced below the total losses of the unit. The damage which may be caused during such conditions is related to the prime mover rather than to the generator or the electrical system.

In the case of steam turbines, a reduction of the steam flow reduces the cooling effect on the turbine blades and overheating may occur. In the case of diesel engines, severe mechanical stresses are imposed on the shaft when synchronous running is enforced against the high internal pressure of the engine cylinders. The total losses, as a percentage of rated power of a prime-mover-generator unit running at rated speed is approximately:

- Steam turbine 3 per cent
- Diesel engine 25...
- Hydraulic turbine 3...
- Gas turbine 5...

These values apply to the case when the power input to the prime mover is completely cut off. Thus, in the case when the total losses of a unit are covered partly by the prime mover and partly by electrical power from the system, the actual power drawn by a generator during certain motoring conditions may be much less than the above percentage values.

By using the power directional relay type RRPE, motoring can be detected at a reverse power of 1 per cent or less. Tripping of the machine circuit-breaker is usually effected via a definite time-lag relay RRKH 26 with a scale range 3–20 seconds, set at about 10 seconds or in accordance with the requirements of the turbine manufacturer.

For diesel engines the reverse power is relatively large and a fault setting between 4–6 per cent is considered adequate. In this case RRPE relay with an inverse time characteristic will be most suitable.
4 Examples of protective relay applications

4.1 General

The number and types of relays to be included within a certain installation depend on its layout, size and importance. The protective arrangements dealt with in the following should only be regarded as our general recommendations. When required, the various schemes will be modified or new schemes added in order to comply with the standard practice of the customer.

For the contra-rotating STAT-turbines, Fig. 10, some simple but effective relays, devices No. 60 N and 60 F, can be included owing to the special connections of the two identical generators. For a complete description see informations Rk 60-310 E and Rk 60-311 E.

In the case of diesel-generators for marine or industrial applications the type RYGA protection constitutes a complete protective system. RYGGA comprises static elements of plug-in type, mounted in a standard relay case RYGA 30 and provides overload, over-current, reverse power and under-voltage protection. The trip circuit is arranged to provide two-stage load shedding at separate time-settings, instantaneous high-set and inverse time-lag over-current protection. For further information see Int. Rk 60-320 E.

4.2 Schematic diagrams

In the single-line schematic diagrams Figs. 8, 10 and 11, the main protective features are indicated by the device numbers referred to on page 10. The trip circuit is shown for a turbo-generator, in which case the emergency stop valves should be initiated only in the event of a serious internal fault. If the stop valves should be tripped owing to a minor external fault, e.g. first-stage over-current or unbalanced loading, an appreciable time may pass until the machine can be brought back to normal service.

For hydro-electric machines the problem of starting up after initiating a stopping impulse is entirely different and the main circuit-breaker, the field switch and the stop-valve are therefore in this case often tripped simultaneously.

A number of different trip-circuit arrangements may be used to avoid unnecessary overspeeding of turbo-generators as a result of sudden loss of load. In Fig. 9, a typical arrangement is shown where the back-up over-voltage protection (56) and the loss-of-excitation protection (40) initiate only the stop valve. When this closes, the limit switch LS also closes and effects tripping of the main circuit-breaker (M.C.E.) and the field switch (F).

In some cases a separate reverse power relay may be used instead of the limit switch LS. This ensures that disconnecting the machine from the network takes place only when the steam input to the turbine has been completely cut off.
### 4.3 List of symbols

<table>
<thead>
<tr>
<th>Device Number</th>
<th>Type of protection</th>
<th>Ref. page</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Impedance (over-current)</td>
<td>6</td>
</tr>
<tr>
<td>32</td>
<td>Reverse power</td>
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</tr>
<tr>
<td>35</td>
<td>Bearing (shaft) current</td>
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<td>40</td>
<td>Loss-of-excitation</td>
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<td>Negative phase-sequence</td>
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<td>49</td>
<td>Thermal overload</td>
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<td>Time-lag over-current</td>
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<td>Over-voltage</td>
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<td>60</td>
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</tr>
<tr>
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<td>Field earth-fault</td>
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<tr>
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<tr>
<td>11</td>
<td>Second time stage</td>
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<tr>
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<tr>
<td>Stop</td>
<td>Emergency stop valve</td>
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</tr>
<tr>
<td>LS</td>
<td>Limit switch on stop valve</td>
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<tr>
<td>Z3 n</td>
<td>Three-phase zig-zag earthing transformer</td>
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</tr>
<tr>
<td>Rg</td>
<td>Earthing (grounding) resistor</td>
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<td>Main circuit-breaker</td>
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</tr>
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<td>m.c.b</td>
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<td>Field switch</td>
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<tr>
<td>SCR</td>
<td>Silicon controlled rectifier</td>
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*) Acc. to B.S. and NEMA Standards*