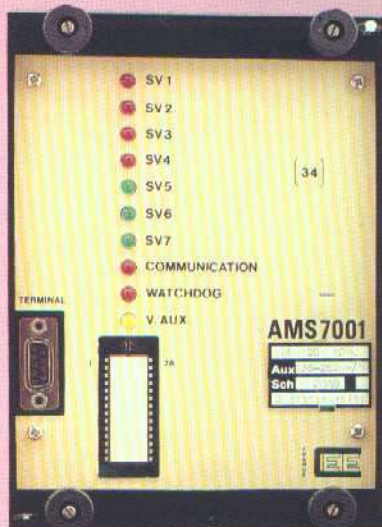


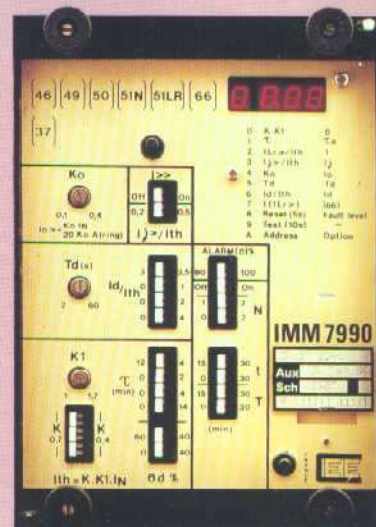




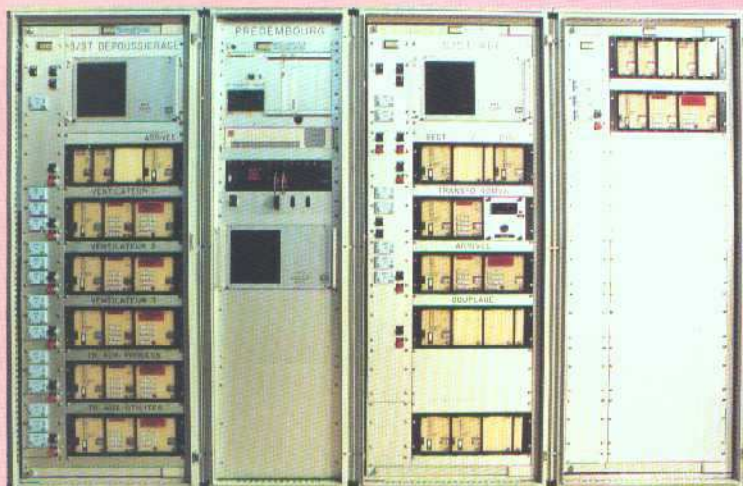
2 phase directional protection



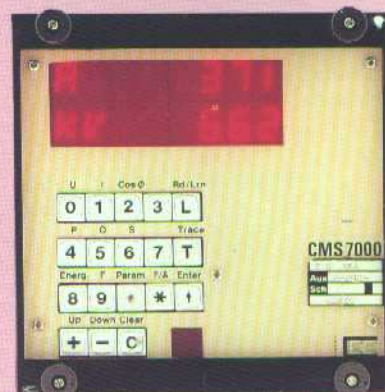
PLC for electrical cubicle



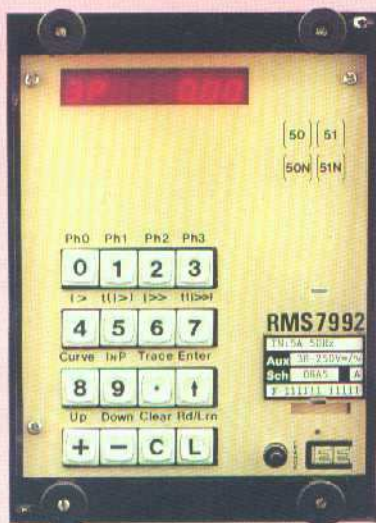
Motor protection



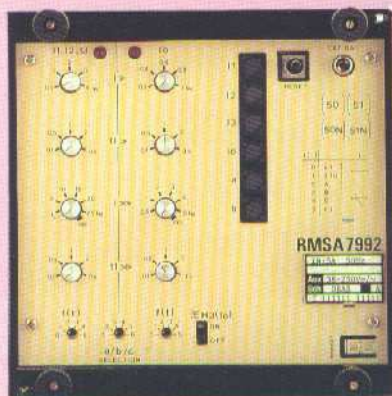
Protections integrated within a PS 2000 system



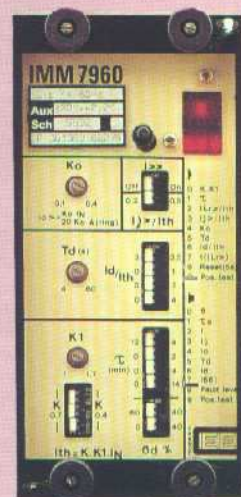
Instrumentation device



Overcurrent protection  
(3 phases + earth)



Overcurrent protection independent of auxiliary supply  
(3 phases + earth)



Motor protection

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## 1. **INTRODUCTION**

Protective Relays are the brain of the electrical apparatus. In this respect, their choice is a critical step in the Power System's Design and Development.

The selection of protective devices is based on:

- The safety of personnel and equipment (sensitivity of detection and response time).
- The quality and continuity of the electrical supply (fault determination, special directional protection, automatic transfer and fast clearing times to improve/ensure system stability).

The optimisation of the power system's reliability and safety dictates the use of independent stand-alone relays located close to the power circuit breakers that they control. In some cases, improvements in the overall protection performance are possible by transmitting the relay status to a remote location (known as "acceleration") or to an automation unit. It is, however, important to ensure that these additional functions do not jeopardise the inherent integrity of the local relays' performance.

In recent years, technological progress has led to the use of microprocessors in protective relay manufacture. This has led to:

- A significant increase in the amount of information that is processed by the relays.
- Easy calculation of electrical quantities such as harmonics.
- Secure and reliable exchange of digital information with remote locations.
- Continuous monitoring of protection relay integrity by self-supervision and auto-diagnostics.

CEE have developed the PROCOM range of digital protection relays, which benefits from the above advantages without sacrificing the stand-alone capability of the classical solid state relays such as the ITG and TTG series.

In addition to the PROCOM protection relays such as the RMS, RMSD, RMSR, IMM, GMS and DMS relays, the PROCOM range also includes the CMS digital instrumentation units, AMS local PLCs and PMG disturbance recorders. All are designed to the high standards required for CEE's protection relays.

It is therefore possible, by selecting the appropriate combination of units, to define a complete circuit breaker local management system including *Protection*, *Automation* and *Instrumentation*.

Nowadays, the difficult economic environment within the industry is imposing increasing demands on efficiency by reducing operating and maintenance costs. At the same time, improvements are required in the continuity and quality of supply, together with personnel and equipment safety.

With these trends in mind, CEE has recently developed the PROSATIN range of equipment, which combines the capabilities of the PROCOM range with that of the MicroSATIN range to provide the complete Integrated Protection, Supervision and Remote Control of Electrical Power Networks.

The PROSATIN systems therefore provide full SCADA function for Electrical Power Networks, combining the following functions:

- Protection
- Supervision (Measurements, Alarms, Data Logging and Mimic Diagrams)
- Control (Local or remote by VDU)



PROSATIN reduces costs and improves continuity of supply by:

- Reducing the time to check and analyse the power system operational status of parameters,
- Increasing preventative maintenance by automatic and continuous supervision including auto-diagnosis,
- Optimisation of energy costs, and
- Improvements in operational procedures and maintenance leading to reduced downtimes.

In order to be adaptable to varying degrees of user needs, PROSATIN is available in the following sub-systems:

- **PS1000:** Simple supervisory systems based on desktop PCs intended for use in relatively small electrical networks.
- **PS2000:** SCADA system with time logging for industrial plants and distribution networks.
- **PS4000:** Complete high-speed SCADA system for industrial plants.

The selection of protection relays therefore depends upon the answer to two basic questions:

- a) What are the local protective functions necessary to give the best conditions for the Power System Safety and fault discrimination?
- b) Will the power system be supervised or controlled in the future?

The answer to the second question determines the type of protective relay design – whether one should choose the classical solid state protection, or the more modern microprocessor controlled digital relays.

The answer to the first question determines the selection of protective relay types and their setting ranges. This, together with the power system behaviour (under both steady state and transient conditions) is the subject of this guide.

Note that the PROSATIN modular architecture enables a gradual step-by-step implementation of a full supervisory system. The PROCOM protection range can be easily integrated into an existing installation while the measuring units, the local PLCs and the data loggers are installed in stages, taking into account the existing system.

## **2. HIGH VOLTAGE INDUSTRIAL & DISTRIBUTION NETWORKS**

Protective relays play an important role in the operation of industrial networks. If they are correctly applied they provide protection of both equipment and personnel together and ensure the best possible quality of electrical power supply.

The object of this guide is to define the protective relays that are the most suited to the layout of the electrical power system network (parallel operation of production units or step-down substations, ring-main or radial distribution, type of network earthing, etc.).

Reference is made to various types of overcurrent relays: **ITG**, **RMS** and **RMSA** series.

- **ITG** relays are classical solid state overcurrent and earth fault relays.
- **RMS** and **RMSA** relays are microprocessor based relays which use an original method of analysing input current signals; the Fast Fourier Transformation. Using this feature a large number of harmonics are taken into account to build currents with a true RMS value. This permits relays to be desensitised to certain harmonics for special applications. Furthermore relays of the **RMSA** series are autonomous in that they can operate without an auxiliary supply by deriving their power from the CTs.

### **2.1 *PROTECTION AGAINST PHASE TO PHASE FAULTS***

Overcurrent protection is the basic protection used in electrical power networks. They must be both sensitive and rapid in order to minimise the stress imposed on the equipment during the fault period (electrodynamic and thermal stresses).

It is also essential that they should be selective, that is capable of eliminating only the faulty element whilst maintaining the supply to healthy parts of the network.

#### **2.1.1 Choice of the time/current characteristic [50,51]**

Overcurrent protection relays are mainly characterised by their time/current characteristic. Several types are available:

- Independent or definite time relays (whose operating time is independent of current level)
- Dependent or inverse time relays (whose operating time depends on the current level).

This last type of relay may be sub-divided into three categories according to the IEC standard 255-4:

- |  |  |
|--|--|
| - Inverse time relays                          | - <b>ITG7200</b> series  |
| - Very inverse time relays                     | - <b>ITG7300</b> series  |
| - Extremely inverse time relays                | - <b>ITG7400</b> series  |
| - Digital multi-curve overcurrent relay series | - <b>RMS700</b> , <b>RMS7000</b> , <b>RMST7000</b> and <b>RMSA7000</b> |

No particular criterion exists for the systematic choice of one or other type of relay. However, dependent time relaying is preferable in the following cases where:

- The operation of the network includes high-level short-time overloads,
- Magnetising inrush currents at switch-on may be considerable for several tenths of a second,
- Relay operation must be co-ordinated with a large number of fuses.

On the other hand, independent time relays are preferable when the short-circuit level is very high, or when it is likely to vary widely at a given point (for example when a network is supplied from small generators whose short-circuit decrement curve falls off rapidly).

As a basic rule, however, there is a general tendency to use independent time relays in Continental Europe and dependent time in Anglo-Saxon countries.

Time-delayed overcurrent relays lend themselves to chronological selectivity. This however is not without a certain inconvenience, in that fault clearance time increases closest to the source, where short-circuit levels are the highest. It is thus necessary to minimise the grading interval<sup>1</sup>.

The grading interval normally used for electronic protection relays is 400 ms, which is obtained by summing the following:

- Breaker fault clearance time,
- Summation of the time errors of the two relays,
- Overshoot of the upstream relay,
- Safety margin of approximately 100 ms.

When transformer feeder protection is being considered it is advisable to use relays having an instantaneous high-set unit. This is set above the secondary short-circuit level and transformer in-rush current, which then allows the operating time of upstream relays to be reduced thereby reducing the cable short-circuit withstand requirements.

The grading interval may be reduced if required, for times less than about 1 sec, to 250 ms, using relays with high-stability timer circuits (which is the case with **ITG 7000** or **RMS 700/7000** relays).

### 2.1.2 Accelerated selective protection [50,51]

In cases where the number of grading steps at one voltage level would lead to fault clearance times which are either too long for the withstand of the equipment in the network, or incompatible with the time allowed by the power distribution authority, it is possible to use an accelerated system.

This consists of reducing the relay time-delay to a pre-determined minimum value when the fault is on the section immediately downstream. The information required to achieve this is transmitted from the downstream relay to the upstream relay via wiring. The fault clearance time is thus independent of its location, the relay minimum operating time being a function only of the speed with which the downstream information can be transmitted (the operating time of the “instantaneous” unit of the downstream relay).

Relay types **ITG 7172** and **ITG 7173** (and **RMSR** relays) with a two-level definite time characteristic for phase faults and a single level for earth faults operate in accordance with this principle. The phase fault high-set unit and the earth-fault unit are associated with the acceleration logic incorporated inside the relay, the low-set unit being used to protect against overloads and is totally independent of the logic. In order to maintain a high degree of security, selective (or graded) back-up time-delays are incorporated, which trip under fault conditions even in the event of a fault occurring within the wiring connecting the relays.

---

<sup>1</sup>The difference in operating time between two relays in cascade on a radial network.

### 2.1.3 Differential protection [87]

This type of protection operates on the principle of current comparison in the same phase but at the two extremities of the protected equipment, (cable: **SOLKOR-RF**, transformer: **DMS7002**, **DTT7031**, rotating machines: **DMS 7001**, **DTM 7033**, **IAG 7034** or bus bars: **IAG 7034**) and has two main advantages:

- It may be instantaneous, because it only reacts to faults inside the protected zone,
- It will operate for the transfer of energy in either direction, which is particularly important in the event of multiple sources.

It may also allow a grading step to be eliminated, thus reducing the tripping time for faults on the upstream network. To counterbalance these advantages however, it requires pilot links (**SOLKOR-RF**) and matched class X current transformers are generally recommended with stabilising resistors for the differential protection of transformers, rotating machines and busbars.

The differential relays for cable protection, type **SOLKOR-RF**, operate on a special principle

- They do not compare individually the currents in each phase, but rather a combination of the three currents  $K1.I1 + K2.I2 + K3.I3$ .
- The advantage of this system is that only one pair of pilot wires is required, but the operating levels are different for faults on different phases.

### 2.1.4 Directional protection [67]

When a substation is supplied by two cables or two transformers in parallel, the protection on these two feeders (in the upstream substation) would operate simultaneously for a fault affecting one of them. To obtain selective protection it is necessary to use either differential or directional relays. In the latter case phase directional overcurrent relays type **RMSD7921** or **ITD7111** should be installed on each incomer.

The directional element of these relays checks the phase angle between the current and voltage of one phase, and allows the overcurrent unit to operate if this phase angle indicates current in the reverse direction.

**RMSD 7000** relays, with the FFT input signal treatment, check the phase angle between the fundamental of current and voltage. As a result they remain stable and selective even in networks containing high levels of harmonics.

The time delay of the directional relay is chosen to be selective with the upstream relays, and thus the loop is first opened (by tripping the correct LV breaker), followed by the upstream protection isolating the faulty feeder. Alternatively, the upstream breaker may be opened by sending an intertrip signal from the LV directional relay to accelerate fault elimination.

## 2.2 PROTECTION AGAINST EARTH FAULTS

An industrial network may have three distinct types of neutral connection, and it is necessary to examine each of the possibilities separately. The three distinct types are isolated (or un-earthed) neutral, impedance earthed neutral, and solidly (or low-impedance) earthed neutral.

### 2.2.1 Network with isolated neutral [50N,51N]

In isolated-neutral networks the earth-fault current amplitude is limited to the total capacitive current of the different elements in the network.

An insulation supervision device should be employed so that, after detection of a fault, it may be eliminated as quickly as possible, in order to avoid the risk of a second fault occurring before clearance of the first.



This function is provided by a neutral displacement relay type **TMS714** or **TTG7134** supplied from three VTs. If there is an accessible neutral point or if the three VTs are connected in open delta then the use of the **TMS714** or the **TTG7114** is recommended to fulfil this function.

In certain cases it is possible to provide automatic selective elimination of a fault immediately after it appears using sensitive zero sequence relays type **ITH7111** supplied from a ring (or core balance) CT around the three phases of the cables.

The setting of these relays should be approximately 1.5 times the capacitive current of the protected feeder. This is due to the fact that when a fault occurs on a nearby feeder, the capacitive current “returns” up the healthy feeder and flows into the fault, thus causing a risk of tripping the healthy feeder if the relay setting is too low.

On the other hand, in order to achieve a satisfactory sensitivity for resistive fault situations, the setting of earth-fault relays must be less than or equal to 20% of the maximum capacitive current of the entire network.

If these two conditions cannot be satisfied due to the presence of a feeder which is too long, it is possible to use a directional zero sequence relay type **RMSD7912** or **ITD7112**, whose current setting may be below the feeder’s capacitive current without causing a spurious trip whilst remaining sensitive to resistive earth-faults.

It must, however, be noted that this type of protection can only operate satisfactorily if the number of feeders in service (thus the phase to earth capacitance) remains relatively constant. It is also very difficult to obtain a selective detection when closed loops are possible in the network.

It is sometimes necessary to resort to other solutions, such as temporarily earthing the neutral via an impedance (for approximately 2 seconds) using the zero sequence voltage (or neutral displacement) relays **TMS714**, **TTG7114** or **TTG7134**.

This allows the zero sequence overcurrent relays to be more effective detecting earth fault on the installation and thereby ensuring clearance.

## **2.2.2 Network with impedance earthed neutral [50N, 51N, 67N]**

In these networks the earth fault current is limited to a value in the range approximately 10 to 1000 Amps. The different feeders must be equipped with earth-fault protection (**RMS711<sup>2</sup>**, **ITG7X05<sup>2</sup>**), fed either from a ring (or core-balance) CT or from the residual connection of the 3 line CTs. In the latter case, the operating level should not be set below 6% of the CT nominal current. This is due to the fact that in the event of an inter-phase short-circuit, the current transformers may start to saturate in a non-symmetrical manner, and this could cause spurious operation of a relay whose operating level is set too low.

If a relay supplied from a ring CT is used, the pick-up may be set at 1.5 times the zero sequence capacitive current of the feeder in question (of the order of 3 Amps/km for high voltage cables).

When several points in the same network are earthed, it is necessary to use directional earth-fault relays type **RMSD7912** or **ITD7112** in order to selectively clear one of the sources of zero sequence current in the event of fault occurring in this source.

In the case of a network having one or more generators feeding directly on to the main bus-bars the network may be earthed either on a generator neutral point or at the bus-bars. Earthing at busbars can be achieved using an artificial neutral point, such as a zig-zag transformer or a star/open delta transformer with the primary directly earthed and the open delta loaded by resistance.

---

<sup>2</sup> Or the zero sequence unit of a three phase and earth-fault relays such as **RMS791**, **RMS7992**, **RMST7992**, **RMSA7992**, **ITG7X96**.

The first method is not generally recommended because the earth-fault relay on the neutral point is required to have incompatible characteristics:

- Low pick-up level and rapid operation to protect the alternator effectively,
- Pick-up and time-delayed grading with the other zero sequence protective relays in the network.

On the other hand, the second method leads to a rapid and sensitive protection against generator earth faults as the generator incomers can in fact be treated as outgoing feeders as far as zero sequence currents are concerned.

### **2.2.3 Network solidly (or low-impedance) earthed [50N, 51N]**

The network is generally earthed on the neutral of an incoming delta/star transformer. When this neutral is not accessible, the network is earthed either through a zig-zag transformer or through a star/delta transformer connected to the main bus-bars.

The earth-fault current is thus limited only by the zero impedance reactance of the transformer (or earthing means) and its maximum value is of the same order of magnitude as the three-phase short circuit current.

It is therefore possible to achieve good sensitivity using relays supplied from the residual connection of the 3 line CTs (**RMS 711 / ITG 7X05**)<sup>2</sup>.

## **2.3 OTHER PROTECTION AND AUTOMATIC TRANSFER [37,81]**

In the event of loss of supply on the main distribution incomers, providing that these also supply other users, power relays type **WTG7100** may be used to separate an industrial network containing its own power generation from the distribution system, thus leaving it to operate in an island mode.

Frequency relays are also used for isolating various sections of a network or for load shedding of non-priority loads (over and under-frequency type **HDG7020**).

When the panel supply consists of two transformers, each supplying separately their own half of a bus, automatic load transfer from one incomer to the other may be used, should one transformer be damaged by a fault. To achieve this, the following relay functions are required:

- Transfer initiation by undervoltage relay (**TMS711** or **TTG7113**),
- Check that the supposedly healthy incomer has not been subject to disturbance during the few seconds prior to the transfer initiation (**TMS711** or **TTG7013/TTT7112**).
- Check that the voltage drop is not due to a downstream fault (**RMS791, RMS761, RMS7992, RMST7992, ITG7X96** or **ITG7X66**). A transfer under such conditions would cause the loss of the entire substation supply.
- Check the residual voltage on the busbar that is to be transferred whenever this feeds motors (**TTG7013**).
- Shedding of certain rotating machines on voltage dips (**TMS761, TTG7123** or **TTGd7112**).

Automatic transfer logic and various voltage measurements can be provided by the Local Switchgear PLC type **AMS 7000**.

## **2.4 MEASUREMENT, METERING AND SUPERVISION IN AN ELECTRICAL NETWORK [11M]**

In an electrical network main incomers and feeders can be fitted with the **CMS7000** measurement unit. This device provides a large amount of measured data, including energy metering, two 4-20mA programmable outputs (I,U,P,Q,S,pf,f) and can give an alarm in the event of over or reverse active power or overcurrent.

The **CMS 7000** is similar to other equipment of the **PROCOM** range (**RMS**, **DMS**, **GMS** etc.) and can be connected to a local sub-station PC (**PROCOM** or **PS1000** systems) or to a complete SCADA system (**PS2000** or **PS4000** systems).

## **2.5    *EXAMPLES OF PROTECTION FOR AN INDUSTRIAL NETWORK***

### **2.5.1    Example One (Figures A1 and A2)**

Figure A2 represents part of an industrial network having two high-voltage levels, each having an impedance-earthed neutral.

The earth fault current under bolted (or solid) fault conditions is limited to 30A on the 11kV network by an artificial neutral point on the main busbars, and to 100A on the 5.5kV network.

The 11kV busbar is supplied from two sources in parallel; a 20MVA generator with a transient reactance ( $X'd$ ) of 20% and a 10MVA transformer with a short-circuit impedance of 10% connected to the 90kV local distribution network.

The unit substation is supplied by two 11kV cables in parallel and each half of the 5.5kV bus-bar is normally used separately, but an automatic transfer scheme is employed in the event of one busbar being tripped out.

The overcurrent relays are of the independent (or definite) time variety, and are shown on the single-line diagram (Figure A1).

The corresponding protection co-ordination curves for the system are shown in Figure A2.

### **2.5.2    Example Two (Figures A3 and A4)**

Two 10MVA transformers operating in parallel supply the network as shown in Figure A3.

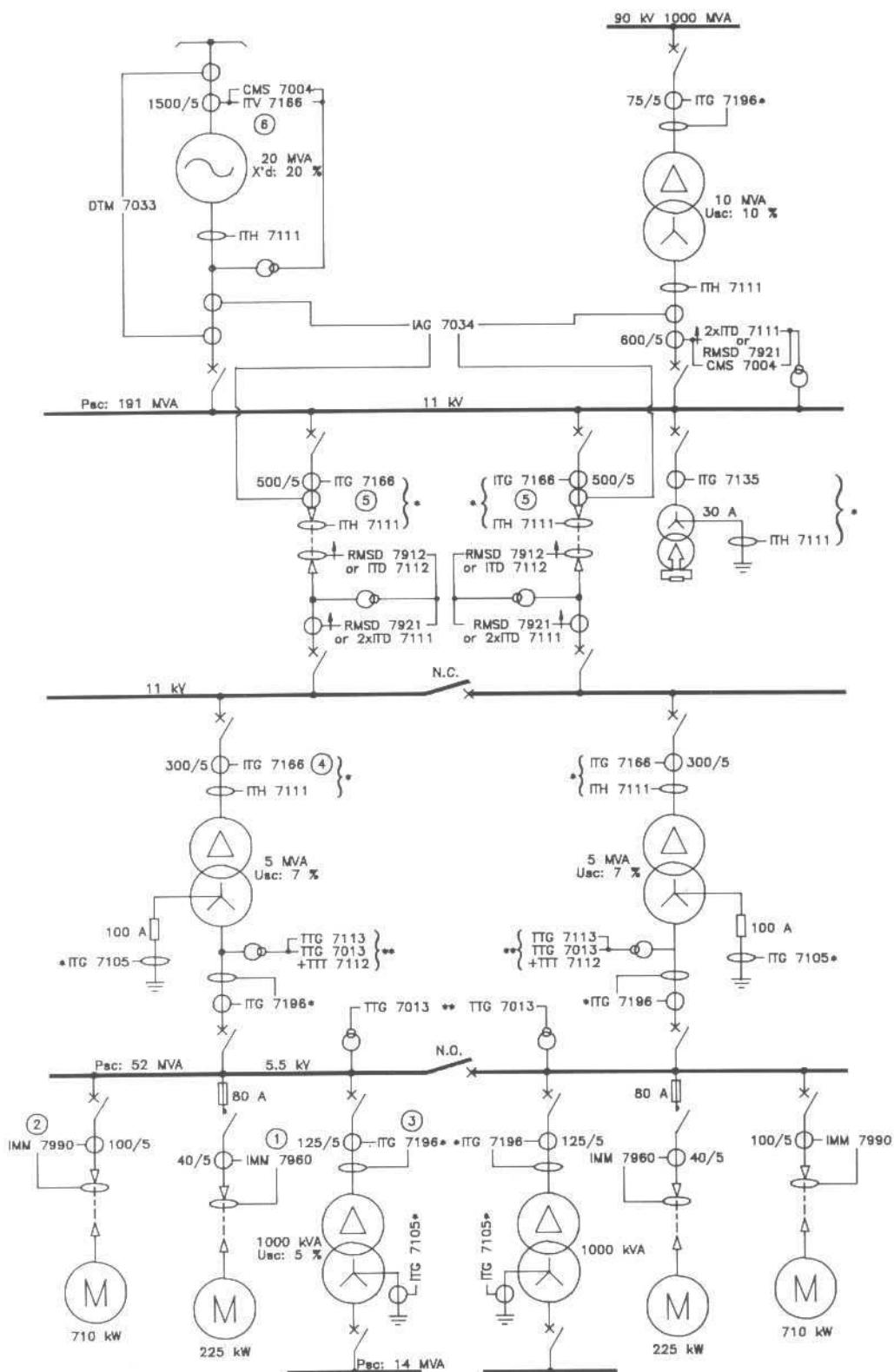
On the primary side, they are connected to the REC's 60kV distribution system.

The neutral earthing of the 6kV network is via a neutral earthing resistor (NER) on the neutral on the secondary of one of the transformers. This limits the earth fault current to a maximum of 1000A.

The protection consists of differential relays and dependent (or inverse) time overcurrent relays. As before, the relays are shown in Figure A3 and their corresponding curves shown in Figure A4.



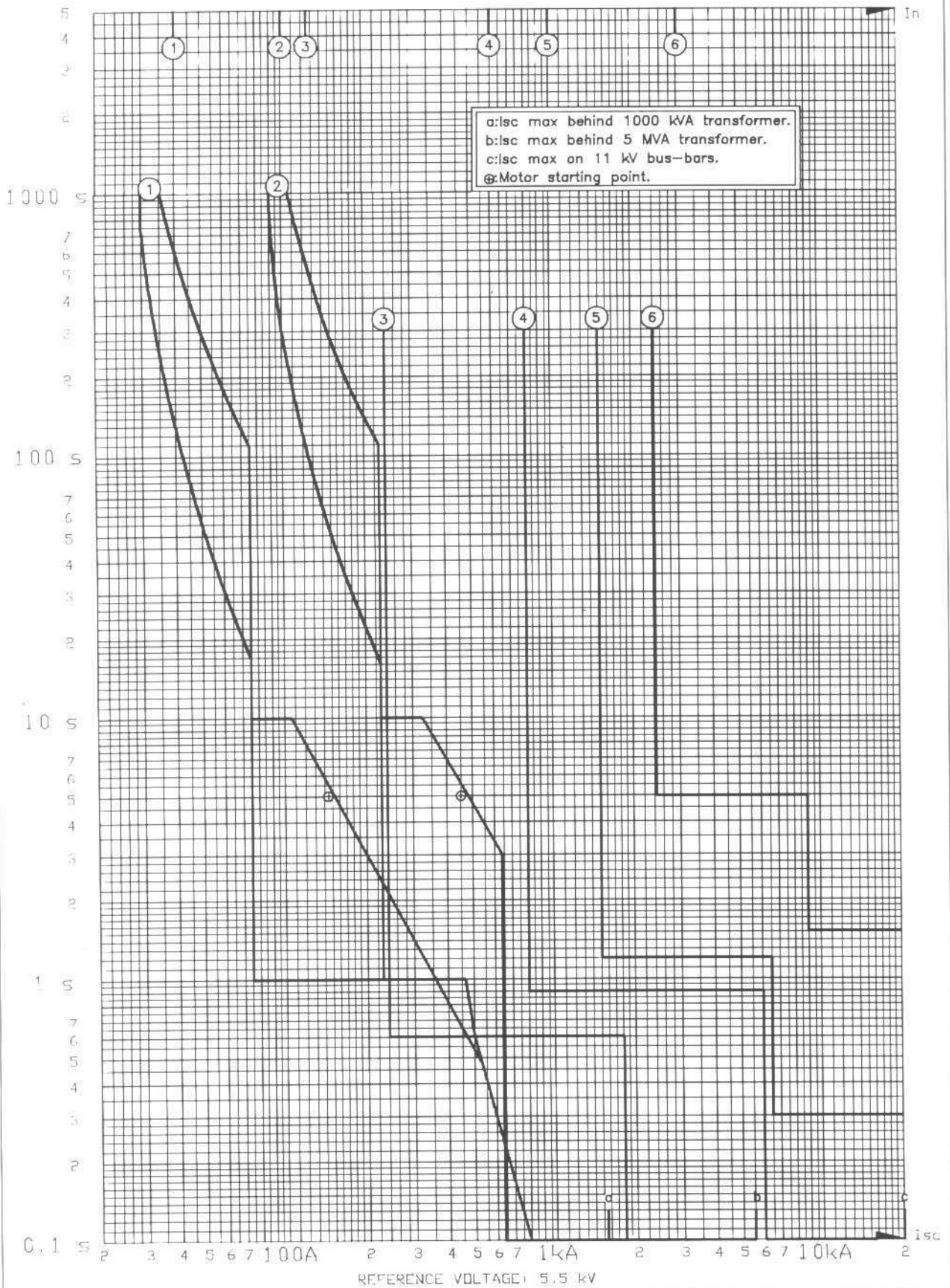
# A1 : NETWORK WITH HIGH IMPEDANCE NEUTRAL EARTHING



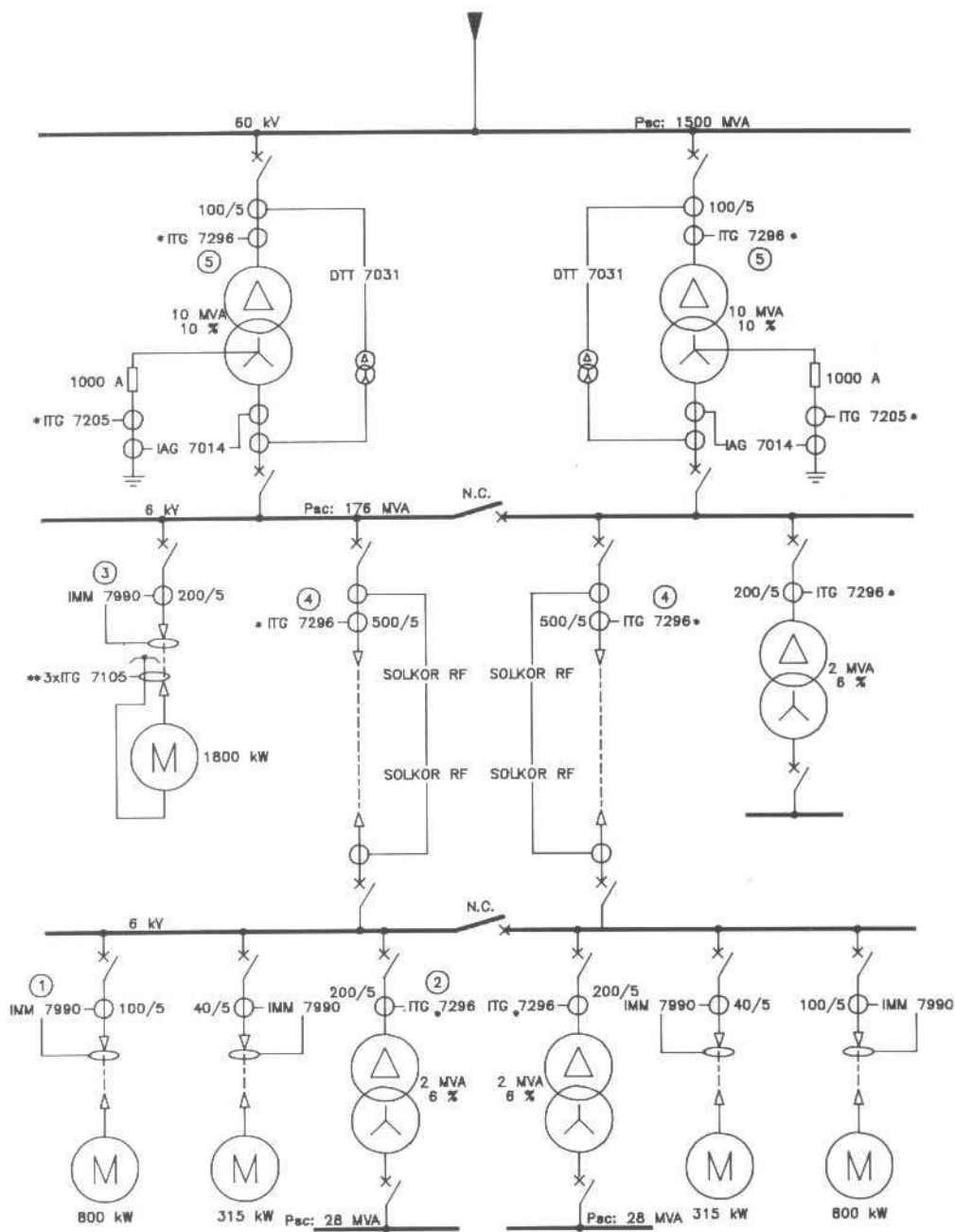
\* or multifunctions relay with communication capability RMS 7992 or RMST 7992.

\*\* or local P.L.C. AMS 7001.

## A2 : RELAY COORDINATION CURVES



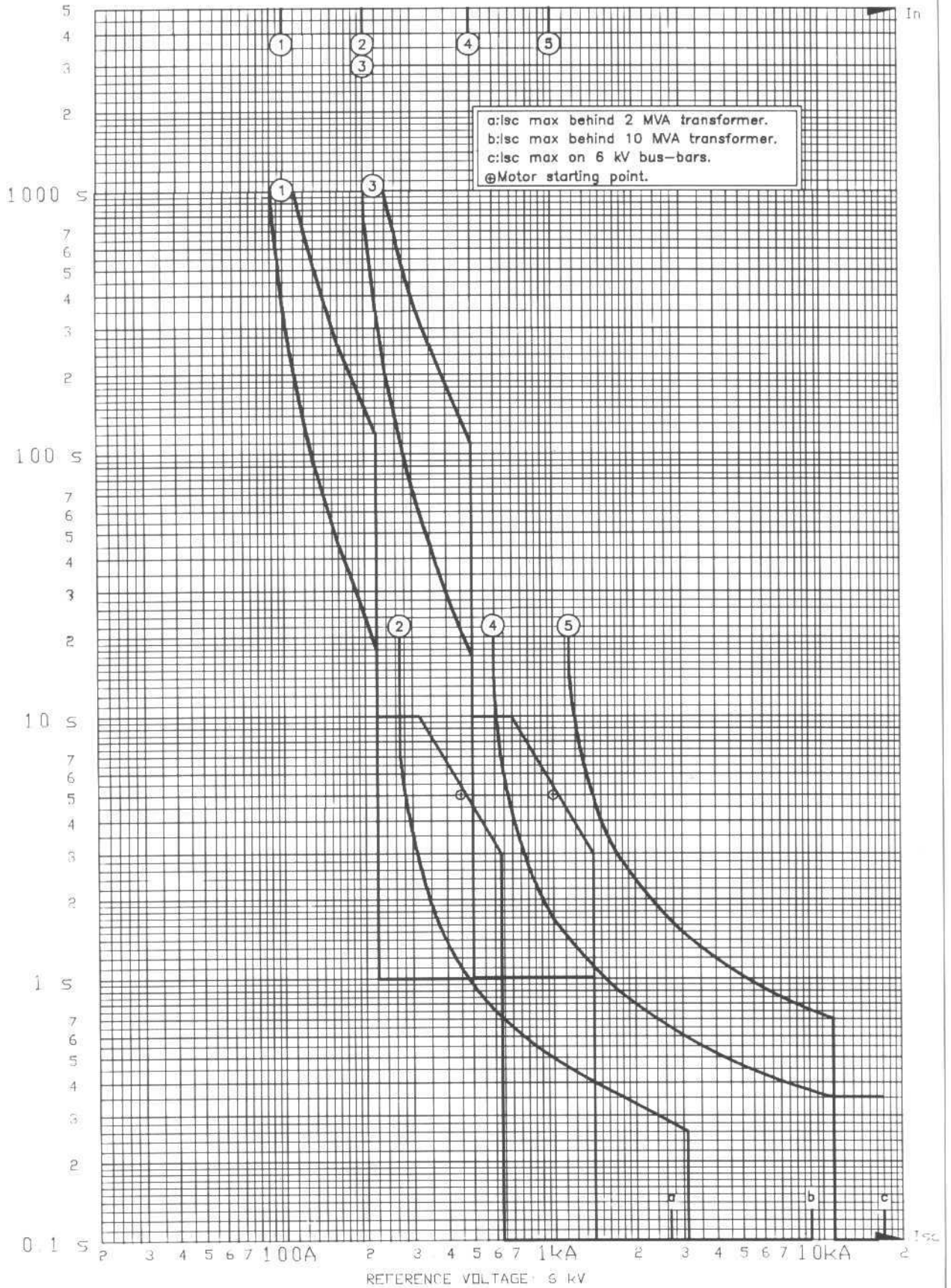
## A3 : NETWORK WITH LOW IMPEDANCE NEUTRAL EARTHING



\* or multifunctions relay with communication capability RMS 7992 or RMST 7992.  
 \*\* or other differential schemes, see chapter D.



# A4 : RELAY COORDINATION CURVES



### 3. **POWER TRANSFORMERS**

HV/HV or HV/LV power transformers may be damaged by internal faults or by external faults such as overloads or short-circuits, which cause overheating and excessive electrodynamic stresses in the windings.

Internal faults consist of inter-turn faults (short circuits between windings) or between one winding and the core or tank and their effect varies according to their location.

Detection and elimination of these different faults requires several types of protective relays, the functions of which are described below.

Other faults affecting the magnetic circuit itself (local overheating due to induced currents) cannot be detected by electrical protection. These are detected by mechanical devices actuated by the gas accumulation or surge caused by the fault (for example in liquid-cooled transformers). These devices are commonly called "Buchholz trip".

#### 3.1 ***OVERLOAD PROTECTION [49, 51]***

Where the installed power on the secondary of a transformer can result in overloads, in certain system configurations, it is necessary to provide protection against low-level but long duration overloads.

This overload protection can consist of a single-phase definite time overcurrent relay, time delayed between 20 and 30 seconds (type **RMS711** or **ITG7105**) used on alarm, or preferably by a thermal image relay (types **RMST7992** or **ITT7610**). The **RMST7992** has the advantage that it also provides overcurrent and earth protection as well as the thermal image protection.

The digital multi-function relay type **RMST7992** has a thermal time-constant adjustable from 4 to 180 minutes and provides a complete overload protection for all types of transformers. Furthermore a thermal alarm unit included in this relay can initiate load-shedding logic on downstream transformer feeders.

On large units having temperature sensors located at the hottest points in the windings, the best solution is to use temperature supervision relays. The **STEP7040** and **STEP7060** relays can permanently supervise 4 and 6 channels respectively.

#### 3.2 ***OVERCURRENT PROTECTION FOR PHASE FAULTS [50,51]***

On the primary side of transformers, an overcurrent relay having a time-delayed low-set unit and an instantaneous high-set unit is recommended. The low-set level is set to be selective ("graded") with the downstream protection, in order to provide back up and to eliminate internal faults of relatively low amplitude.

The choice of the time/current characteristic of this relay (independent time, inverse, very inverse, or extremely inverse) can be taken from the **RMS761**, **RMS791**, **RMS7992**, **RMST7992**, **ITG7X66** and **ITG7X96**.

The use of an inverse-time relay is sometimes preferable under the following circumstances

- The outgoing feeders on the transformer secondary side are protected by either fuses or another inverse time relay.
- The system operation gives the possibility of relatively high overloads of several seconds duration (for example motor re-accelerations).
- The magnetising currents during transformer energisation are of high amplitude and decrease slowly.

The high-set instantaneous unit is set slightly above the symmetrical three-phase short-circuit current on the secondary side (approximately + 20%) and also above the transformer inrush current. Set in this manner it remains insensitive to faults on the low-voltage side, ensuring that there is no possibility of a spurious instantaneous trip for a downstream fault.

However, this unit will operate very rapidly in the event of a heavy fault within the transformer, or a fault affecting the primary side feeder. Therefore the use of a relay with a high-set instantaneous unit for transformer protection enables a considerable reduction in the operating times of upstream protection for heavy fault levels which are the most damaging. Due to this, it is also possible to reduce the short-circuit withstand requirements for the transformer supply cables.

### **3.3 EARTH FAULT PROTECTION**

Except in the case of certain transformer configurations (star-star transformers or auto-transformers), earth-fault (zero sequence) currents cannot pass between the primary and secondary of a transformer.

It is therefore necessary to provide individual protection for primary and secondary sides for single phase to earth faults on either inside the transformer, or in its feeder cables.

#### **3.3.1 Single phase to earth fault on the primary side [50N, 51N]**

On the primary side, the residual current measurement is often performed using the three feeder CTs (this is the case for a single-phase relay or the zero sequence unit of overcurrent and earth fault relays). Either relay must, in this event, fulfil the two conditions below:

- Be slightly time-delayed to avoid spurious trips caused by circulation of a false zero sequence current following a brief period of saturation in the current transformers (magnetising current, switching surge, or down-stream fault). An operating level of approximately 6% minimum may be achieved in this case.
- Or be instantaneous, but the operating level must not in this event be less than 15 to 20% of the CT nominal.

Often, this limitation leads to too high a setting compared to the maximum available earth fault current, and consequently to a loss of sensitivity.

This difficulty can be largely overcome by using a ring or core-balance CT around the three phases in order to achieve zero-sequence current measurement. In this case the earth-fault relays **RMS711**, **ITH7111**, **ITG7105** or the zero-sequence units of the **RMS791**, **RMS7992**, **RMST7992** can simultaneously provide both rapid and sensitive earth fault protection.

#### **3.3.2 Single phase to earth faults on the secondary [50N, 51N]**

When the secondary windings of a transformer are connected in star configuration (referred to as “wye” in America) and the neutral-point is connected to earth, a single-phase overcurrent relay is installed on the neutral to earth connection. This relay must be set to be selective with the zero-sequence protection on the downstream network and is commonly known as a standby earth fault (SBEF) relay.

This relay may be type **ITG7X05** (or **RMS711** or **ITG7114** if a third harmonic filter is considered necessary).

It is also possible to add high-impedance Restricted Earth Fault (REF) protection using the **IAG7014** relay. This compares the current circulating in the neutral-to-earth connection with the sum of the three secondary phase currents (obtained from the residual connection of the 3 line CTs).

#### **3.3.3 Tank protection [51N]**

A very rapid protection, which detects internal transformer faults, can be provided by a relay on the tank-to earth connection.



If, as is often the case, the tank of the transformer is itself badly insulated from earth (with the earthing strap open), the protective relay should not be set below 10% of the maximum earth-fault current. This is in order to avoid operation on spurious zero sequence currents (for example, the earth-fault current of a neighbouring feeder flowing in the circuit formed by the tank and its earthing strap).

In practice it is generally advisable to time-delay this protection slightly (relay type **RMS711** or **ITG 7105**).

The transformer tank protection, together with the gas pressure relay (Buchholz and Qualitrol), high-set instantaneous unit, zero sequence units and restricted earth fault protection, provide secure detection and rapid clearance of faults affecting the transformer.

### **3.4 DIFFERENTIAL PROTECTION [87]**

This type of protection is suitable for higher power rating transformers and limits the extent of the damage caused by an internal fault by instantaneously clearing faults between turns or between windings on the same phase or on different phases.

It is preferable to retain the three-phase overcurrent protection as back up, and an earth-fault protection should also be provided (a zero-sequence relay on the primary) when the primary network neutral is earthed via an impedance.

In order to remain insensitive to the transformer magnetising inrush current, which occurs at switch-on and whose amplitude may be well above nominal current, the three-phase differential relays types **DMS7002** and **DTT7031** incorporate a second harmonic restraining feature (magnetising inrush currents are predominantly second harmonic).

In addition, in order to ensure the stability of the relays during external short circuit conditions, the operating level is increased in a manner proportional to the through current, when the through current is above nominal (through-load biasing).

When using the **DTT7031** auxiliary interposing CTs are required for the following reasons:

- To compensate for the amplitude and phase differences (in the case of Delta-Star connection) between the nominal currents on the secondaries of the CTs installed on each side of the transformer.
- To eliminate the zero sequence currents appearing on one side only of the transformer when its neutral point is earthed, during an earth-fault on the network.

When using the **DMS7002** auxiliary interposing CTs are not required because the above functions are performed within the relay itself.

Transformers are generally equipped with tap-changers, so the operating level of transformer differential relays is not normally set below 15 - 20%  $I_n$ .

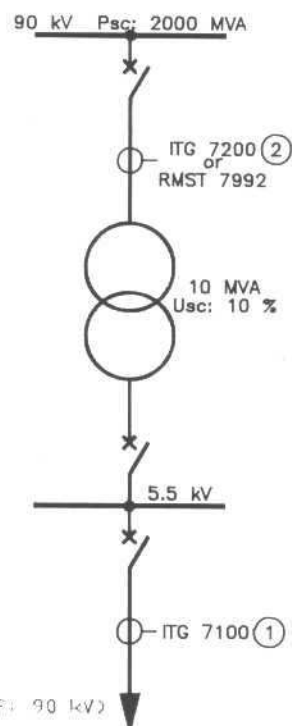
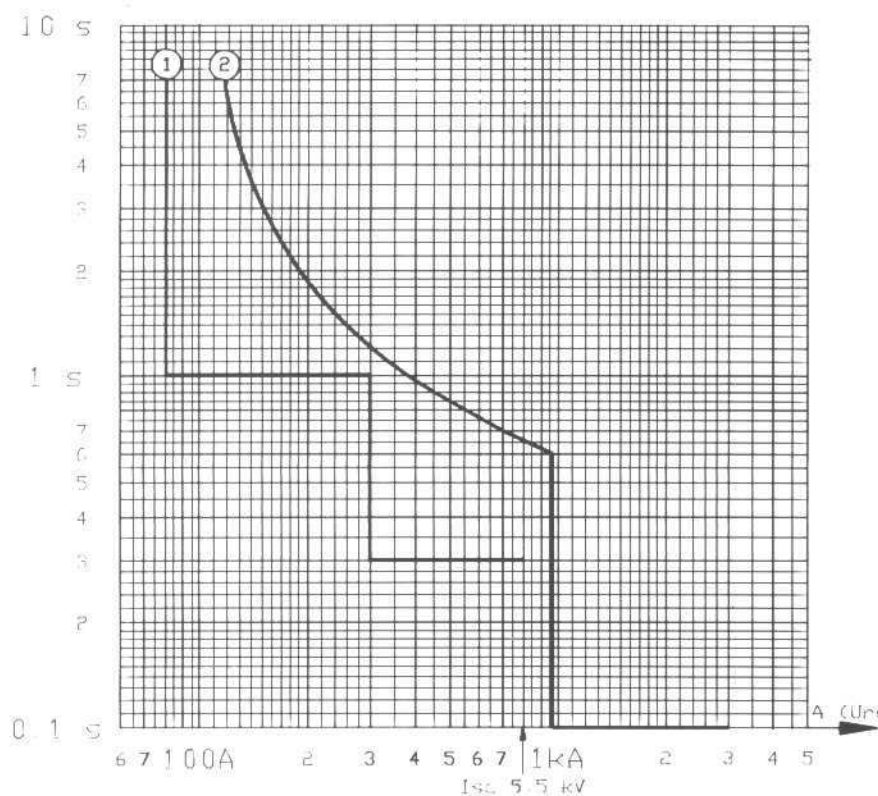
### **3.5 DIRECTIONAL PROTECTION [67, 67N]**

When a transformer not equipped with differential protection is in parallel with another source of energy, it is necessary to use a protection capable of initially separating the network following which selective clearance of the faulty equipment can be achieved.

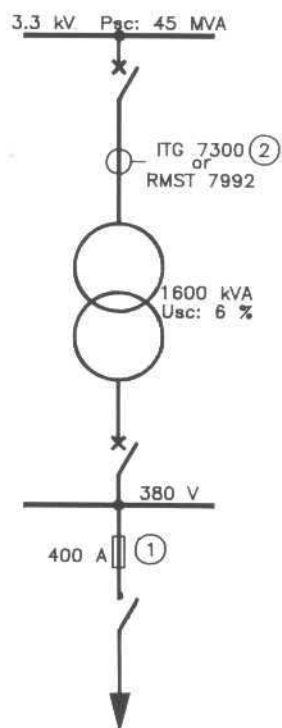
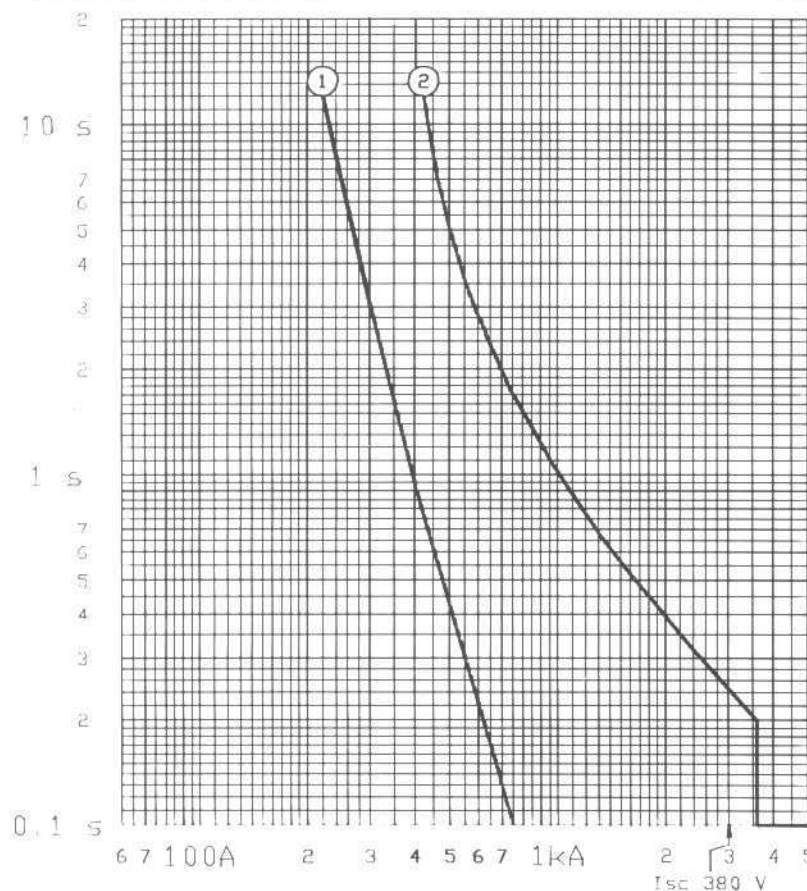
To perform this function, an **RMSD7921** or **ITD7111** directional relay can be used on the secondary side of the transformer to separate the network at this point in the event of a fault within the transformer itself or on the primary side network. It should be noted that the reverse power relay type **WTGA7131** can't fulfil this function correctly, because its operation cannot be ensured when the voltage under the fault condition is low.

A directional earth-fault (or zero sequence) relay types **RMSD7912** or **ITD7112** must also be used if the secondary network has at least two points earthed, one of which being the neutral of the transformer in question.

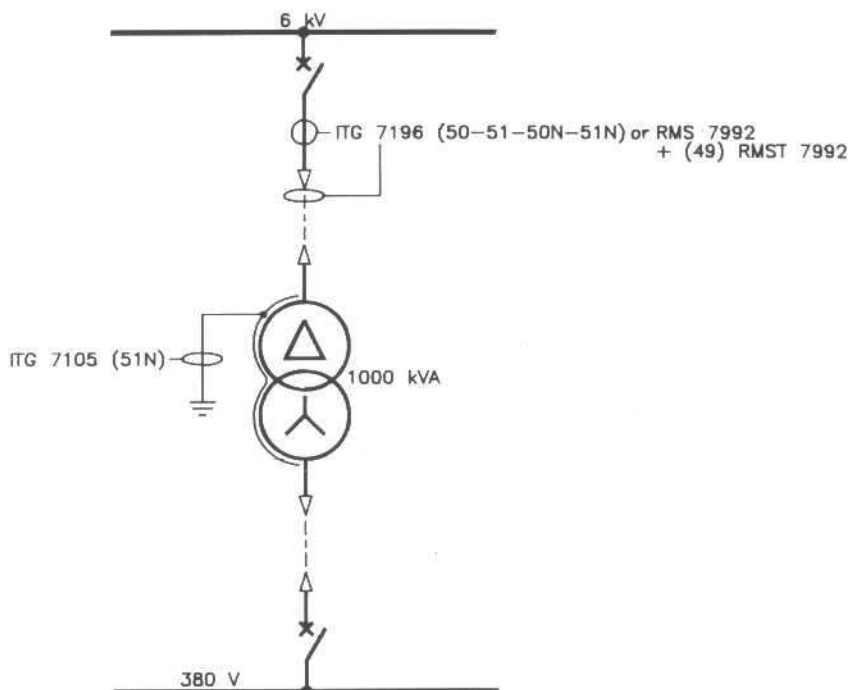
## B1 : COORDINATION BETWEEN INVERSE TIME AND INDEPENDENT TIME RELAYS



## B2 : COORDINATION BETWEEN FUSES AND VERY INVERSE TIME RELAYS

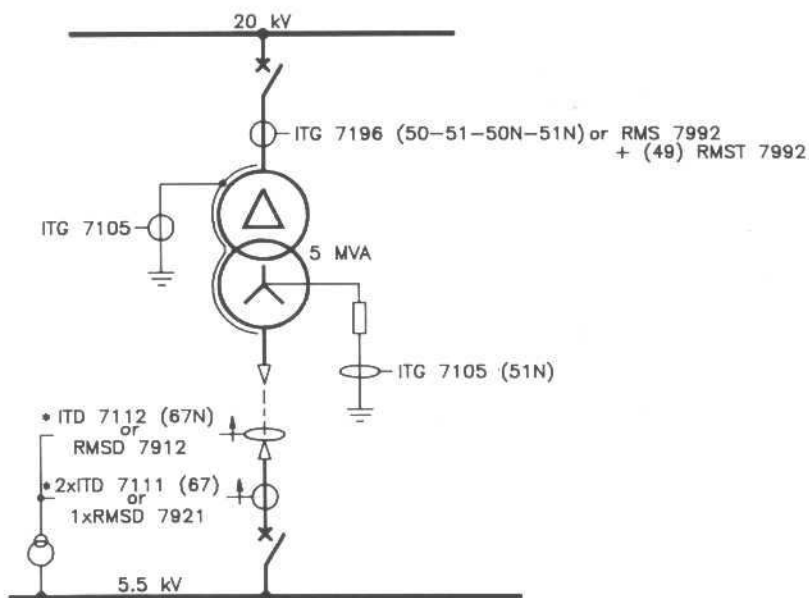


### B3 : PROTECTION EXAMPLE : MV/LV TRANSFORMER

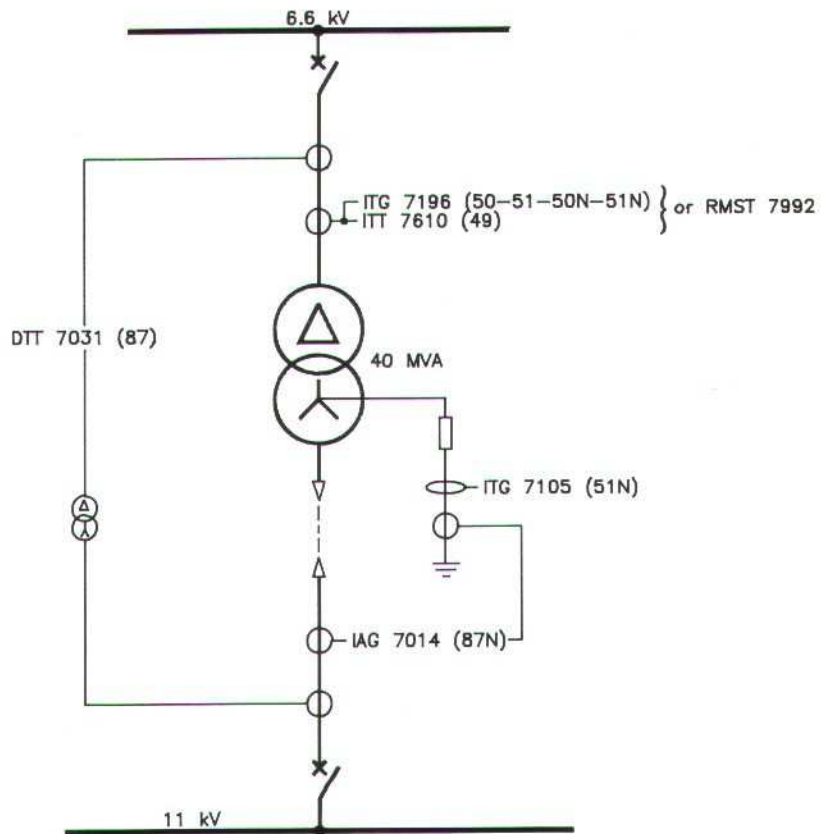


### B4 : PROTECTION EXAMPLE : MV/MV TRANSFORMER

\* IN CASE OF PARALLEL OPERATION.



## B5 : PROTECTION EXAMPLE : HV/MV TRANSFORMER



## 4. **GENERATORS**

The operation of a generator may be as easily affected by faults within the machine itself as by external disturbances occurring on the network to which it is connected. The generator protection must therefore be designed to react efficiently in both conditions.

The number and type of the protective relays, or functions, installed will be a function of the machine characteristics such as:

- Power rating,
- Prime mover,
- Steady state short-circuit current,
- Transient characteristics,
- Network short-circuit current,
- Type of neutral earthing,
- Position of earthing points,
- Operation alone or in parallel.

and also of economic factors, such as the cost of the protection in relationship to the cost of the machine, and the consequences resulting from out-of service periods.

For this reason, these notes present the different anomalies which can affect a generator and the type of relay, or function, to be used in each case (distinctions have been made based on the machine power where necessary). Reference is then made to two specific cases often encountered in industrial networks

- A Diesel generator in the hundreds of kVA,
- And a turbo-generator in the tens of MVA.

All the various generator protection functions shown in this section can be provided by the discreet relays mentioned in the text. However, a much more cost-effective method is to use a multi-function protection relay, which performs all the functions in one relay. The **GMS7001** performs all the protection functions discussed in the following sections, and is described in Section 4.13 below.

### **4.1 PROTECTION AGAINST EXTERNAL FAULTS [51V]**

When a fault occurs on the terminals of a cylindrical rotor alternator the short circuit current can, as an approximation, be described as follows:

- Initially, the stator currents are only limited by the sub-transient reactance ( $X''_d$ ), the duration being determined by the sub-transient time-constant  $T''_d$  (which is largely dependent on the damper windings).
- A few cycles after the fault initiation, a stable point is reached in the damper windings, and the current is limited by the transient reactance  $X'_d$ , diminishing in a way governed by the transient time-constant  $T'_d$ . Following this the fault current eventually stabilises at a magnitude determined by the internal electromotive force (EMF)  $E$  and the direct axis synchronous reactance  $X_d$ .

Thus, although initially the short-circuit current is in the region of ten times nominal, the amplitude decreases and eventually stabilises at a value generally below nominal, due to the high value of the synchronous reactance  $X_d$ . In some cases operation of voltage regulators (AVRs) can allow the fault current to be maintained above nominal current.



This type of fault can be detected by an impedance relay, or a voltage restrained overcurrent relay which is capable of operation in spite of the fall-off of the current, whilst having, under normal operating conditions, a pick-up above the nominal current. These relays also include a time-delay to facilitate co-ordination with downstream protection.

The **ITV7X66** series relays fulfil these requirements by reducing the current pick-up levels as the voltage drops on the machine terminals. These relays can be provided either with independent time, inverse, very inverse or extremely inverse timing characteristics. Furthermore, to provide an ultimate back-up protection in the event of a short circuit on the generator terminals with manual or shunt excitation, an undervoltage unit is also included.

In those particular cases where the stable short-circuit current of the generator remains at a value well above nominal current a standard overcurrent relay (**RMS761** or **ITG7X66**) can be used.

## **4.2 PROTECTION AGAINST OVERLOADS [49, 51]**

Overloads causing abnormal heating of the stator windings must be eliminated before a temperature dangerous for the machine is reached.

Depending on the power of the machine, the overload protection may be provided by an overcurrent relay, a thermal image relay or temperature sensors.

For generators in the range of the hundreds of kVA, the **ITV7X66** (or the **RMS761** or **ITG7X66**) can provide both overload protection and protection against external phase-phase faults. Overload protection is provided by its low-set element, set, for example, at  $1.15I_n$  and time-delayed by several seconds (to accept brief transients that can happen under normal operating conditions). Protection against external phase-to-phase faults, or heavy overloads, is provided by its high-set element, set, for example, at  $2I_n$  and time delayed by a few tenths of a second.

For turbo-generators of a higher power rating, a thermal image relay type **IMM7990** or **GMSx7001** can be used. These multi-function relays also provide protection against unbalance.

For these large generators, the indirect thermal protection is always backed-up by temperature sensors embedded in the stator winding and connected to a **STEP7000** relay. In this case, the **STEP7060** can provide a permanent check on the temperature at 6 locations (or, connected to 3 sensors, an alarm level and a trip level for each). When the machine is also fitted with sensors in the bearings, a **STEP7040** may be added.

## **4.3 PROTECTION AGAINST UNBALANCED LOADS [46]**

Generators designed for the supply of balanced loads can support only a small percentage of unbalanced load permanently. As a result they must be disconnected from the network if unbalance becomes excessive.

Protection against unbalanced loads is provided, for the small power range of generators, by the **IMM7990** or the **GMSx7001** using a negative sequence overcurrent element with an inverse time characteristic.

For the high-powered generators, it is necessary to use a negative sequence overcurrent relay type **ITI7521** with a time/current characteristic approximating the form:

$$I_2^2 t = K \text{ (constant)}$$

The pick-up setting (down to 8% of  $I_n$ ) and the characteristic curve provide the ideal matching between the protection and the generator negative sequence withstand, as defined in present standards.

This relay also has an alarm level, adjustable from 50 to 100% of the setting of the inverse-time curve.

#### **4.4 PROTECTION AGAINST REVERSE POWER CONDITIONS [32]**

As a general rule, generators operating in parallel with other sources should, according to the conditions stated by the manufacturer, be protected against motoring conditions by a reverse power (active power) relay.

The power necessary to cause a generator to operate as a motor varies from a few percent of nominal power for those driven by steam turbines up to around 25% for Diesel generators.

For this reason, a very sensitive relay type **WTGA7131** is used in the first case, and a less sensitive relay, the **PTG7111**, in the second. The reverse power setting range on the **GMSx7001** multi-function relay is suitable for all types of generator.

The action of these relays is generally time-delayed by a few seconds to avoid spurious trips due to transient phenomena during synchronising or after the clearing of a fault on the network.

#### **4.5 PROTECTION AGAINST FREQUENCY VARIATIONS [81]**

Particularly in the case of high-powered generators, it is necessary to detect machine overspeed following severe loss of load because this may be dangerous from the point of view of the mechanical stresses applied to the rotor. An over-frequency relay type **HDG7020** is generally used for this protection.

This relay also includes an under-frequency operating level, which may be used, for example, to start a load-shedding sequence to prevent the entire system being lost due to a generator overload.

#### **4.6 PROTECTION AGAINST UNDER AND OVERVOLTAGES [27, 59]**

When classic overcurrent relays are applied and also in cases where induction motors are being used, single, two or three phase undervoltage relays types **TTG7113**, **TTG7123** or **TTG7133** may be used.

In the event of tripping all, or part of the load, the generator terminal voltage increases suddenly to a value approaching the internal emf. The voltage regulator will normally modify the excitation in order to reduce this voltage rise. It is usual to apply a slightly time delayed overvoltage relay such as the **TTG7111** to detect this condition.

Alternatively multi-function over/undervoltage relays such as the **TMS711**, **TMS761**, **TMS7003** or **TMS7004** can be used, which have the additional benefit of programmable timing curves and other voltage measuring functions.

#### **4.7 PROTECTION AGAINST INTERNAL PHASE-FAULTS [51, 51V, 87]**

Supplied from CTs at the neutral end of each phase winding, the two-level overcurrent relay types **ITV7X66**, **ITG7X66** or **RMS761** protect against faults occurring in that part of the winding which is closest to the network, that is faults that cause currents of the same order as an external fault.

The **ITV7X66** relays, whose operating levels are reduced under low-voltage conditions, protect a higher proportion of the winding than the **ITG7X66** or **RMS761** relays.

In order to ensure a more rapid trip and to protect virtually all the winding, it is essential to use a differential protection.

Differential protection will instantaneously detect phase faults in the machine windings of very low current levels, which would otherwise remain undetected by the other protection. It also, of course, instantaneously detects phase faults of much higher magnitude.

Various possibilities of fitting current transformers lead to a choice between the following solutions:

- A classic biased differential relay type **DTM7033**, or digital type **DMS7001**, supplied from two sets of 3 CTs, one set at each end of the generator windings.
- A high impedance differential relay type **IAG7034** also supplied from two sets of 3 CTs, one set at each end of the generator windings.
- Three instantaneous overcurrent relays type **ITG7105** each supplied from a ring (or core balance) CT through which the single phase conductor and the cable on the neutral end of the same phase of the machine pass. The relay is thus supplied with the differential current, obtained directly on the ring CT secondary winding.

(Note one **ITG7135** relay may be used if phase identification is not required).

This latter type of protection leads to both high sensitivity and good stability in the event of external faults, provided that each ring CT is not affected by neighbouring phases. Interference may be avoided by having a sufficient clearance between the CTs.

- In cases where a generator / transformer is used, relay types **DTT7031** or **DMS7002** are the best suited for differential protection. In this case the CTs are located in the neutral end of the generator and on the remote side of the transformer.

#### **4.8 STATOR EARTH FAULT PROTECTION [59G, 51G, 64, 87]**

When the generator is galvanically isolated from the network, that is in the event of coupling through a delta-star transformer, there is total freedom of choice for adapting the position and type of earthing to that which best suits the machine protection. In this case two methods of earthing are employed, which are:

- Isolated neutral, where earth fault detection is by the use of a voltage relay type **TMS714** or **TTG7114** including a third harmonic filter supplied from a voltage transformer connected between the generator neutral point and earth.
- High resistance earthed neutral, where earth fault detection is by the use of a current relay supplied from a ring CT in the neutral connection to earth. The **ITH7111** relay set at 1 Amp gives 90% coverage of the windings in the event of an earth fault limited to 10 Amps.

When the alternator is directly connected to the network, the position and type of earthing is sometimes imposed by the network itself.

- In the case of an isolated neutral network, where the generator is the only source of power, a **TMS714** or **TTG7114** relay energised from a neutral VT is all that is required. Where there are several sources in parallel, and if the network is sufficiently extensive, then it may be possible to obtain selective protection using sensitive zero sequence relays like types **RMS711** or **ITH7111** operating on the capacitive current of the network. The **TMS714** or **TTG7114** would in this case be supplied from VTs on the busbars.

In the more usual case where earthing is used, from a protection point of view it is generally recommended that the earthing be done on the busbars, and not on the machine itself.

- In this case rapid elimination of internal faults can be achieved using a simple overcurrent relay of type **RMS711**, **ITH7111** or **ITG7105** whether several sources are in parallel or not.
- If this solution is not employed, and the earthing is performed at the generator, again a simple overcurrent relay of type **RMS711**, **ITH7111** or **ITG7105** can be used supplied from a ring CT on the earthing connection. This solution is acceptable provided that this is the only earthing point in the network, and that the earth fault current is limited to a value sufficiently low for the machine to withstand during the relay's time-delay (this time-delay is necessary to co-ordinate with other protection in the network).
- In the event of several machines operating in parallel, or when the network contains several earthing points, either it is necessary to provide a means of automatically switching in and out the different earthing points in order to leave only one in service. If this is not possible, one can use sensitive directional earth-fault relays such as the digital **RMSD7912** or the **ITD7112**. These relays are generally supplied from a ring (or core-balance) CT in order to achieve maximum sensitivity.

In those cases where the earth-fault current is not limited to a value below the nominal current of the machine, a fast-acting differential protection should be used. This is the case where the machine is low impedance or solidly earthed.

Operation of this protection should immediately trip the generator main breaker, the earth connection and the field, causing the field-shortening breaker to close.

Again there are three types of 3 phase differential relays that can be used. These are the **DMS7001**, **DTM7003** or the **IAG7034**. Alternatively if full differential is not justified a restricted earth-fault relay type **IAG7014** connected across the line CTs on the output of the machine and a CT in the machine neutral can be used.

The clearance of earth-faults outside the machine must also be as rapid as possible. Even if differential protection is employed a standby earth fault relay connected in the machine neutral is still used. This can be **RMS711**, **ITG7114**, **ITH7111** or **ITG7105** providing backup to the other protection. If desensitisation to 3<sup>rd</sup> harmonics is required then the former two relays are preferred.

#### **4.9 PROTECTION AGAINST LOSS OF FIELD [40]**

This protection is provided using an impedance relay type **YTM7111** with an offset circular characteristic (type "offset mho") on the R-X diagram.

- The centre of the circle is situated on the negative X axis,
- The diameter of the circle is set to a value equal to the machine direct axis synchronous reactance  $X_d$ ,
- The offset from the origin is set at half of the direct axis transient reactance  $X'_d$ .

Set in this manner, and due to its timer unit, the **YTM7111** relay is not affected by power swings (that is oscillations of apparent impedance), which can occur following the clearance of heavy faults on the network connected to the machine. It will, however, detect the reactive power absorbed under the asynchronous operating condition almost invariably associated with a loss of field.

It is possible to provide the same function using a reverse VARs power relay type **WTGR7132**, which should be time-delayed sufficiently to obtain stability under conditions of reactive power oscillation.

When a direct measurement of field current is possible using a shunt, a relay type **TTB7025** may be used, giving over - and under-current protection. If required an external timer type **TTT7121** may be added.

#### 4.10 ROTOR EARTH-FAULT PROTECTION [61F]

The rotor insulation resistance may be checked using either a **TTE7015** (which applies a DC voltage between the rotor circuit and earth) or the **TTE7017** (which applies a low frequency voltage). These two relays both detect earth-faults independent of their location.

#### 4.11 CHECK SYNCHRONISING [25]

To ensure that operators or automatic synchronising devices have correctly performed their function, the **STS7041** check synchronising relay may be used. Where the generator may in fact be the first source of supply, “dead-bus” relays type **TTG7013** are also required.

#### 4.12 FUSE FAILURE [60]

Particularly when using voltage restrained overcurrent relays the protection may become too sensitive in the event of failure or rupture of the fuses on the voltage transformer. The **TTGB7031** relay can compare the outputs of 2 VTs on the same electrical point in the network (for example protection VT and measurement VT) and give an alarm or transfer in the event of fuse failure.

#### 4.13 MULTI-FUNCTION GENERATOR PROTECTION RELAYS

As with all forms of protection, a microprocessor based relay is available which performs a large number of protection functions in one relay case. The GMSx7001 range includes the following functions:

Functions	ANSI code	GMS7001	GMSH7001	GMSV7001
Thermal Image Overload	49	x	x	x
Negative phase sequence over current	46	x	x	x
Field failure (loss of excitation)	40	x	x	x
Under impedance	21	x	x	x
Overcurrent	51	x	x	x
Overvoltage	59	x	x	x
Over fluxing (v/f)	24	x	x	x
Undervoltage	27	x	x	x
Under and over frequency	81	x	x	x
Reverse power	32-1	x	x	x
Under and over power	32-2	x	x	x
Neutral displacement over voltage	59G	x		x
Earth fault	64		x	

Combining the above functions into the one case leads to large savings in both panel space and installation wiring. This offers a large reduction in installation cost.

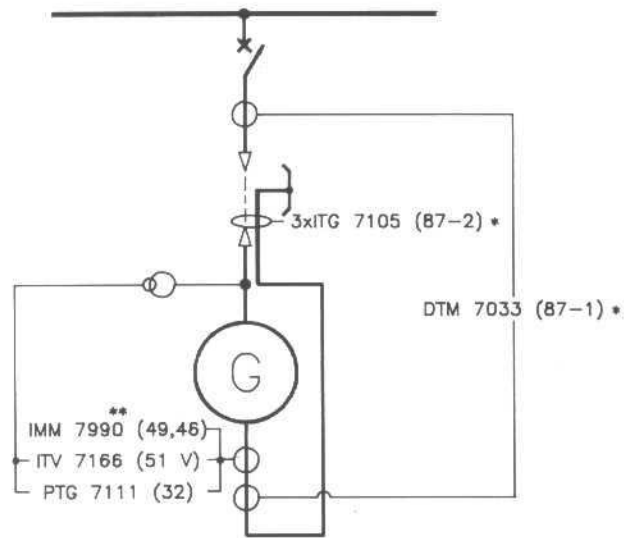
The GMSx7001 range of protection relays also offers the facility to be connected to either a local PC or a remote communication system. This enables the user to set-up the relay using a PC rather than the relay's keypad.

The relay can also be interrogated remotely, allowing the control room to analyse the disturbance that caused the relay to operate. This allows faster and easier fault location/prevention.

As with ALL forms of protection, multi-function relays should not be relied upon exclusively to clear a fault - there should ALWAYS be at least two independent protection relays protecting one part of a system.

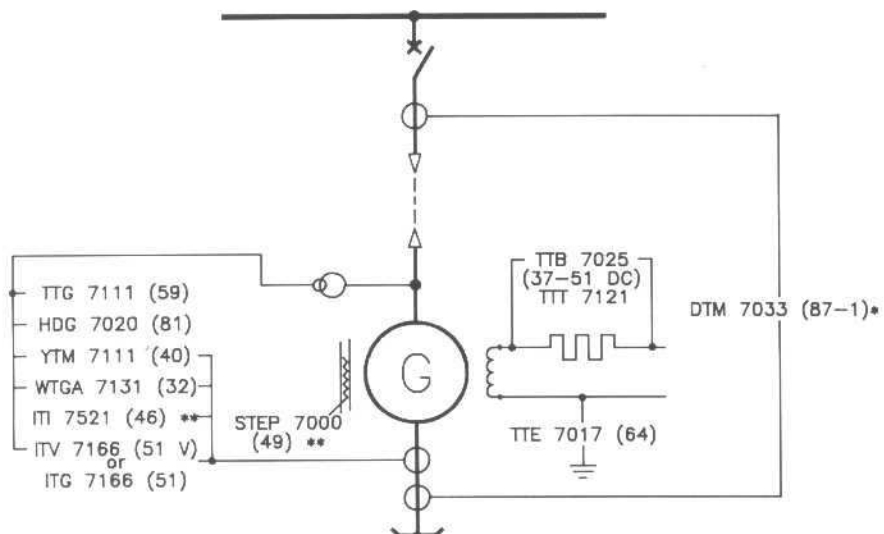


## C1 : DIESEL GENERATOR



- \* SEE TEXT § C VII AND DIFFERENTIAL SCHEME SECTION D.
- \*\* SEE TEXT § C II

## C2 : TURBO - ALTERNATOR



- \* SEE TEXT § C VII AND DIFFERENTIAL SCHEME SECTION D.
- \*\* SEE TEXT § C II ET C III

### C3 : STATOR EARTH - FAULT PROTECTION

FIGURE C3-1: GENERATOR / TRANSFORMER UNIT

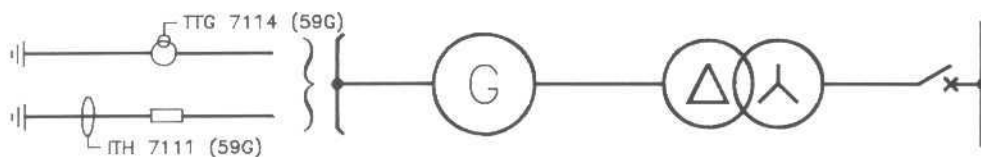


FIGURE C3-2: HV GENERATOR WITH ISOLATED NEUTRAL NETWORK

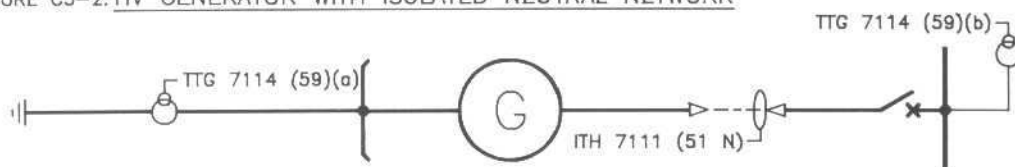


FIGURE C3-3: HV GENERATOR WITH IMPEDANCE EARTHED NETWORK

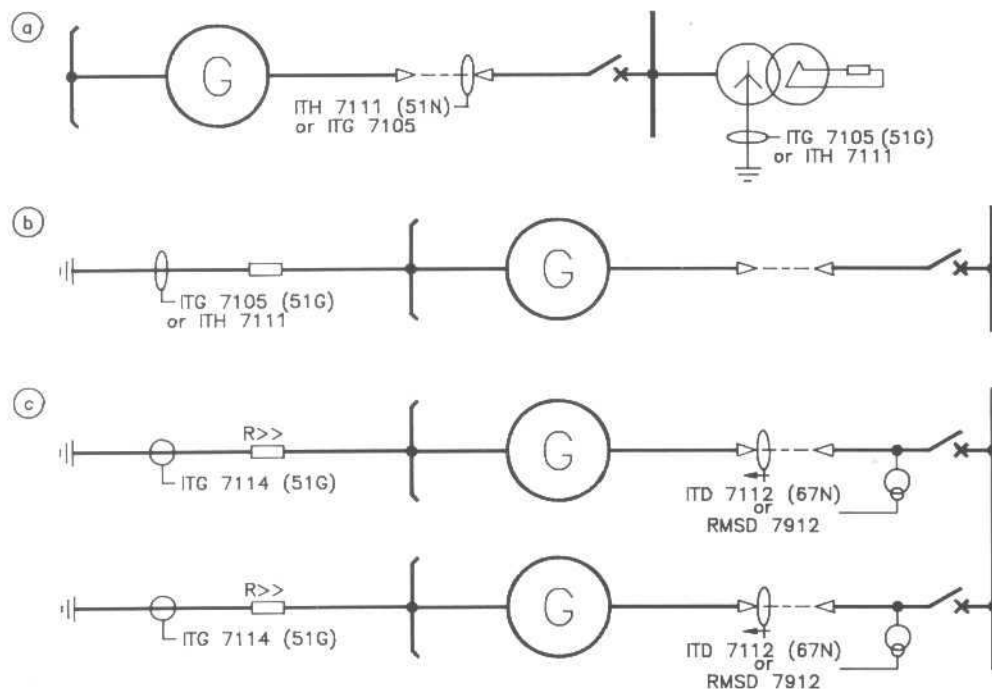
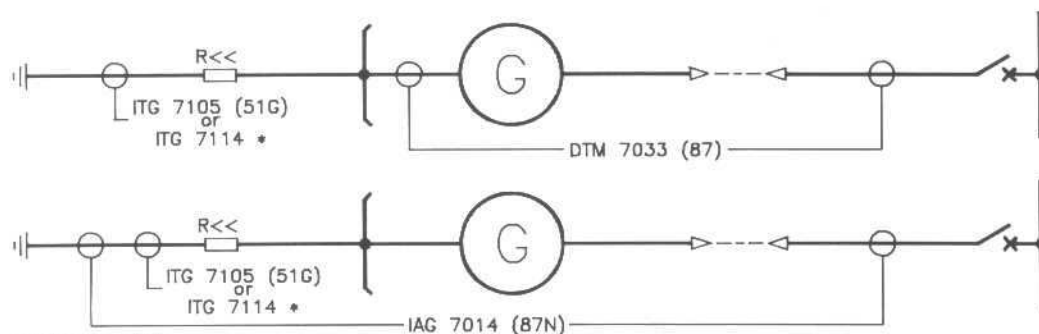


FIGURE C3-4: HV GENERATOR WITH LOW IMPEDANCE EARTHED NETWORK  
( $I_{sc} \text{ EARTH - FAULT} > I_n \text{ GENERATOR}$ )



\* SEE § C.VIII

## **5. HIGH VOLTAGE AND LOW VOLTAGE MOTORS ABOVE 75 KW**

### **5.1 INTRODUCTION**

We recommend for the protection of all types of motor, the use of digital multi-function relays including the following features:

- A sophisticated thermal image.
- A unit sensitive to the negative sequence component of current.
- A unit that provides rapid elimination of all heavy multi-phase faults.
- A zero sequence overcurrent unit supplied either from toroidal (ring-type or core-balance) CT or from the residual connection of line CTs.

The **IMM7990** and **IMM7960** relays meet these basic functions and provide others, which are described below.

The final choice multi-function relay, or a combination of this and additional protection, can only be made after a detailed study of the installation requirements, including the starting condition and the time constant of the motor in question. Also the power may not be taken as the only criteria for choice, as one or other of the types of protection may successfully be used in a wide range of motor applications.

The standard schemes at the end of this chapter explain the protection schemes for induction and synchronous industrial motors. These examples are given just for information assuming that the definite choice of motor protection schemes is also limited by economic considerations notably the cost of protection including the required current transformers, compared to the cost of the machine itself. Also the importance of the motor in the industrial process and the consequences of its out of service periods are to be taken into account for each particular case.

### **5.2 *BALANCED AND UNBALANCED THERMAL OVERLOAD [49]***

The steady state overload on a motor is generally the result of an increase of the load torque or a decrease in the motor torque due to the busbar voltage dipping or, on synchronous motors, due to a decrease in the DC field current.

If an overload is not rapidly cleared, the high current drawn by the motor will increase its temperature and this will lead at least to a reduction of the machine life expectancy due to premature ageing of the insulation.

A bad distribution of single-phase consumers or a small network unbalance creates negative sequence currents that also warm up the machine rotor.

The thermal image unit of **IMM7990** and **IMM7960** relays, will record all types of overload, whether balanced or not and its thermal time constant is adjustable in order to suit all types of motors.

The **IMM7990** relay is also fitted with a thermal pre-alarm unit. This unit can inform the user of motor overload before the final tripping signal is given. This provides the opportunity to avoid disruption to the industrial process.

In order to take into account all the different motors' cooling systems, the **IMM7990** relay is also fitted with a cooling time constant (when the motor is no longer supplied with current).

For high power motors where platinum temperature sensitive elements are built into the stator for supervision of hot spots, relays of the **STEP7000** series can be used. If the thermal detector elements are of the CTP type then the **TTS7024** relay should be used. These relays, with their direct temperature measurement, take ambient temperature and cooling system effects into account.

The long response time of the temperature sensitive elements and their reliability require the use of both **STEP** or **TTS** relays and **IMM** relays on high power machines.

The thermal unit of the **IMM7990** and **IMM7960** relays records all types of overload, whether balanced or not, and in the latter case, it also takes into account rotor overheating. The negative sequence component of the stator currents will in fact set up an electromagnetic field in the airgap, turning at synchronous speed in the opposite direction to that of the rotor. Because of this, currents at a frequency close to 100 Hz are set up in the rotor. These, due to "skin effect", are concentrated close to the surface of the rotor, creating high losses, and therefore cause overheating. In order to take these losses into account, the current passing through the thermal image is taken as a combination of positive and negative sequence current which are derived from the actual phase currents using a sequence filter. This results in a reduction in the response time of the thermal element when a considerable quantity of negative sequence component is present in the motor supply system.

### 5.3 **UNBALANCE [46]**

Operation of an induction motor on an unbalanced network can be the consequence of a fuse blown in one phase, a disconnect switch blade malfunction on one phase or inadequate transpositions of high voltage transmission lines supplying the motor installation.

The **IMM7990** and **IMM7960** relays include a negative sequence overcurrent unit of the dependent (or inverse) time type. This unit ensures detection and elimination of single-phase operation and phase to phase resistive faults. Set at 20%, this unit can detect the loss of one phase, even when the motor is not loaded or only lightly loaded. Also, the time-dependent characteristic of this unit helps to stabilise these relays either in the event of a heavy unbalanced fault upstream or during the starting period. During a heavy unbalanced upstream fault, motors will temporarily behave as negative sequence current generators. During the starting period, when the amplitude of the three-phase current can cause unequal saturation of the CTs, thus producing an artificial unbalance.

The output unit in this function has a minimum time of 0.5 seconds in order to allow the fuses to eliminate heavy unbalanced faults before causing a contactor trip. However the contactor must have a rupturing capacity at least corresponding to the current which would cause fuse operation in 0.5 second, since at this instant the fuses and the contactor will break the fault current simultaneously. As a consequence, the higher the fuse rating, the higher the rupturing capacity of the contactor needed.

Negative sequence currents circulating in transformer-motor units retain their amplitude across the transformer (taking account of the transformer ratio). Only their relative phase angle is affected, being rotated by a multiple of 30° depending upon the transformer connection. As a result of this, a relay on the primary side will detect the same amplitude of negative sequence component as that which would be measured if it were connected directly at the motor terminals.

With high power synchronous motors, it is necessary to detect a very small percentage of negative sequence component in the line current (down to 6%  $I_n$ ) so in this case it is preferable to use the **ITI7521** negative sequence protection relay. This relay incorporates a negative sequence element with two operating levels. The first one, generally used as an alarm, is of the independent-time type, the second one, used for the tripping signal, is of the dependent-time type.

### 5.4 **SHORT-CIRCUITS [51]**

A phase-to-phase short-circuit in the winding, at the motor terminals or between cables can destroy the machine due to overheating and electrodynamic forces created by the high currents involved.

The **IMM7990** and **IMM7960** relays are fitted with a high-speed positive sequence unit. The adjustment of this unit is derived automatically from the setting used for the starting characteristics. This function may be put out of service whenever the motor is controlled by a fuse-contactor.

For all machines, the short-circuit unit must be set above the starting current, thus for high power machines, such a setting makes this protection insensitive to an internal short-circuit close to the neutral point and leads to the choice of additional differential protection.

The **DMS7001**, **IAG7034** or **DTM7033** differential relays can be used in this case, the choice of one or other of these solutions is dictated by the CT mounting possibilities. An alternative is to use 3 **ITG7105** relays. This is described in more detail in Section 4.7 on page 22.

## 5.5 EARTH-FAULTS [50N, 51N]

An earth-fault is the most frequent fault occurring on rotating machines. These result from machine insulation damage, which allows a fault current to flow from the windings to earth via the stator laminations. The magnitude of this earth fault current depends on the network earthing arrangement. As in the case of phase-phase faults, a fast fault clearing time is required in order to reduce damage and repair cost.

Whatever neutral earthing arrangement is used, the zero sequence unit built into **IMM7990** and **IMM7960** relays, will provide adequate earth-fault protection. This unit may be connected either to a core-balance CT or used in the residual connection of the three line CTs. Its operating time is automatically increased when the positive sequence component is put out of service, which makes it compatible with fuse-contactor control.

To provide earth-fault protection, we recommend the core-balance CT solution whatever type of network earthing is used. This method allows for the detection of small resistive values of earth-fault current. Early detection of resistive earth-fault current limits fault damage and reduces repair costs (motor rewind instead of replacement).

Furthermore, an earth-fault unit supplied from the residual connection of three line CTs carries the risk of maloperation during starting. In order to obtain stability the pick-up must not be set below 0.15 to 0.2In of the CTs, which is often too high compared to the maximum earth-fault current.

However, there is a lower limit for the setting of the zero-sequence unit. This is imposed by the zero sequence capacitive current of the protected feeder itself. When supplying current towards a fault on a neighbouring feeder, the zero sequence unit could maloperate if set too low. As an indication, the zero sequence capacitive current per kilometre of cable is generally, for networks of 5 to 6 kV, about 2 to 3 A. The minimum operating level of **IMM7000** relays should be chosen at approximately 1.5 times the capacitive current of the feeder in question. In most cases, this setting will not be above 8 Amps.

In the case of networks with an isolated neutral, the **IMM** relay zero sequence unit can ensure selective elimination of an earth fault if the total zero sequence capacitive current is above 5 times the current of each of the feeders taken separately. If this ratio is not respected, a directional earth-fault relay type **ITD7112** or **RMSD7912** should be used. In any event, a general earth-fault alarm should be given using a zero sequence voltage relay type **TMS714**, **TTG7114** (open delta connection) or **TTG7134**.

Even if a single phase to earth fault cannot be detected by the zero sequence unit of the **IMM** relay, its use is justified by the fact that it remains the most sensitive detector in the event of a double earth fault at two widely separated points on the same network.

## 5.6 START-UP PROTECTION

### 5.6.1 Too Long Start (T.L.S.) Protection [51LR]

A too long start causes fast overheating due to the high starting current drawn by the machine during this critical period where the cooling system does not operate at its best efficiency (fan located on the shaft). This thermal overload is too fast to be cleared by the thermal unit and faster protection must be provided during the starting period.



The **IMM7990** and **IMM7960** relays incorporate an extremely inverse time unit ensuring efficient protection of the motor against abnormally long starting periods, which is independent of the network voltage. This unit is automatically set just above the motor start-up characteristics: starting current  $I_d$  and starting time  $T_d$ .

If the motor starting time  $T_d$  is longer than the locked rotor withstand time, then the above mentioned unit cannot be used; in this case an additional protection **TTB7025** connected to tachogenerator terminals will provide a direct shaft speed signal.

### 5.6.2 Number of Starts Supervision[66]

The **IMM7990** relay uses a counter to control the number of starts (N) in a certain time. A chosen number of starts (N) is permitted during a chosen reference period (t). If this number of starts is attained, any new start is prevented for a further period (T).

The **IMM7990** and **IMM7960** relays are fitted with a start authorisation unit taking into account the machine thermal state. Its contact is inserted into the closing coil chain. Thus it prevents the closing signal as long as the thermal state of the motor is above a limit which allows a successful starting sequence.

Note: Via their display the **IMM7990** and **IMM7960** relays give the operator the value "Ta". This "Ta" is the thermal time constant advised by the relay, taking into account of the starting time  $T_d$ , the starting current  $I_d$  and the thermal restart state. This feature can be very useful during the commissioning period (If the "Ta" is higher than that chosen it can be considered before problems occur during hot restarts).

## 5.7 RUNNING STALL PROTECTION [51LR]

From a protection point of view, stalling whilst running has to be considered more especially for an induction motor driving a crusher, kneading-machine etc.

On the **IMM7990** and **IMM7960** relays an independent time overcurrent unit provides protection against a locked rotor or stalling situation. This function is out of service during the starting period (Replaced by the TLS protection).

## 5.8 UNDERCURRENT PROTECTION (PUMP UN-PRIMING) [37]

The **IMM7990** is fitted with an optional undercurrent unit that comes into operation when the motor current stabilises close to the unloaded motor current for more than 3 seconds. This is the pump "un-priming" characteristic or belt/chain breaking.

If the multi-function **IMM7990** relay settings are too restrictive ( $0.151n < I < 0.41n$ ), then an additional independent time undercurrent protection type **ITG7118** may be used.

Sometimes, the current criteria may not be sufficient to detect pump un-priming. In these cases the use of an under - power (active) relay **PTG7113** or **WTGA7133** is suggested.

## 5.9 UNDERVOLTAGE [27]

Undervoltage relays type **TMS761**, **TTG7113** or **TTG7123** are generally set at about 0.7  $V_n$  to trip the induction motors which are at their operating limit. Sometimes, they may be replaced by a positive sequence undervoltage relay **TTGd7112**, which also prevents start-up with phase-sequence voltage errors on the upstream network.

The use of the above relays (**TTG7113** or **TTG7123**) are not required if a local PLC type **AMS7001** is already being used for restart supervision or automatic transfer. Effectively the **AMS7001** with its two voltage measurement inputs having 8 over or undervoltage thresholds and 16 timers, is a complete system for busbar voltage supervision.

## **5.10 SPECIAL PROTECTION FOR SYNCHRONOUS MOTORS**

Synchronous motor protection schemes tend to use most of the above relays, nevertheless some additional protection must be considered:

### **5.10.1 Loss of Field [40]**

Loss of field control and detection can be carried out by a DC undervoltage relay **TTB7025** delayed with a **TTT7121** timer. DC voltage is measured at the terminals of a shunt located in the field circuit. This **TTB7025** relay is also fitted with an overvoltage unit, which can be used to supervise AVR operation. In fact an AVR failure can destroy the rotor winding if the field current is too high.

The introduction of modern brushless systems on synchronous machines tends to limit the above mentioned protection scheme to the stator field circuit of modern exciters. Now, loss of field protection, may be ensured by an impedance (MHO) relay **YTM7111** supplied by line CTs and VTs as the complete protection or as an additional protection to those mentioned above. The **WTGR7132** relay can also be used for this purpose.

### **5.10.2 Loss of Synchronism [55]**

With a synchronous motor, shaft mechanical power is proportional to busbar phase-phase voltage, motor internal emf and the mechanical angle between rotor and stator fields. If the load increases, the busbar voltage decreases (short-circuit) or if the field current decreases, then the motor torque decreases and this tends to brake and pull the machine out of synchronism. If this happens then damage can occur on the dampers and rotor winding.

The **GTM7111** relay is sensitive to reactive power exchanges. It integrates slip over an adjustable period in order to give the motor a chance to recover synchronism if the initial network fault is rapidly cleared. If out of synchronism operation continues then the **GTM7111** will trip the motor. In addition this relay has the advantage of detecting loss of synchronism caused by loss of field.

Note: On synchronous motors with an asynchronous starting method, operation of **YTM7111** or **WTGR7132** and **GTM7111** must be blocked until field voltage is applied.

### **5.10.3 Rotor Earth Fault Protection [64F]**

When an earth fault occurs in the field circuit of a synchronous machine, it may only cause an alarm. As a matter of fact there is no immediate consequence due to the earthing of the field circuit. On the other hand, a second earth-fault will produce field circuit overload with shaft mechanical unbalance due to the unequal distribution of the rotor magnetic field.

The rotor circuit is supervised by an insulation control relay type **TTE7017**. This relay applies to the rotor DC voltage an additional low frequency voltage. The detection of a low frequency current is the relay operating criteria.

## **5.11 GMS7002 MOTOR PROTECTION RELAYS**

The GMSx7002 range of relays performs a number of the functions for protection of synchronous motors as described above. The full functions of the relays are described in the previous sections and are listed below. The GMS7000 range of relays (which include generator protection relays) can be connected to a PC as described in Section 4.13 above.

The protection functions provided by the GMSx7002 range are as follows:

Functions	ANSI code	GMS7002	GMSH7002	GMSV7002
Thermal Image Overload	49	x	x	x
Negative phase sequence over current	46	x	x	x
Loss of synchronism/pull out	55	x	x	x
Overcurrent	50	x	x	x
Too long start/locked rotor	51LR	x	x	x
Overvoltage	59	x	x	x
Over fluxing (v/f)	24	x	x	x
Undervoltage	27	x	x	x
Under and over frequency	81	x	x	x
Under and over power	32-2	x	x	x
Neutral displacement over voltage	59G	x		x
Earth fault	64		x	

More information on the GMS7000 range of relays is contained in our publication, which is available on request.

### **5.12 LOGIC DEVOTED TO MOTOR OPERATION [34]**

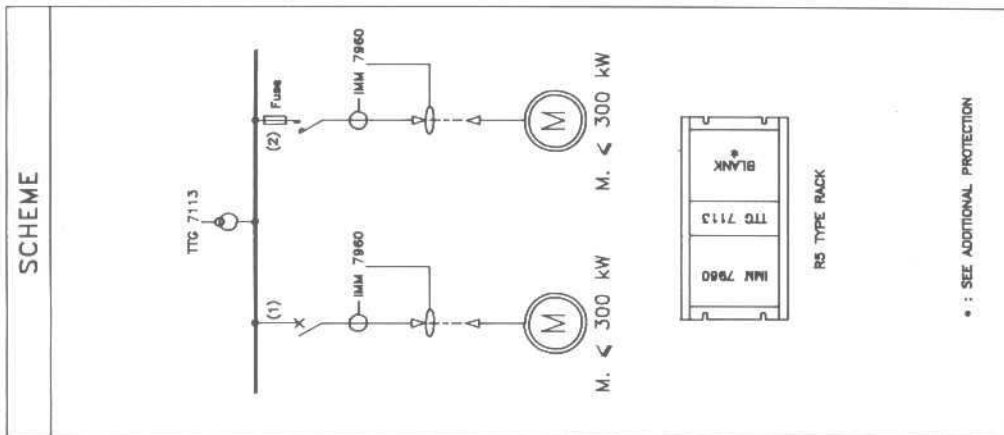
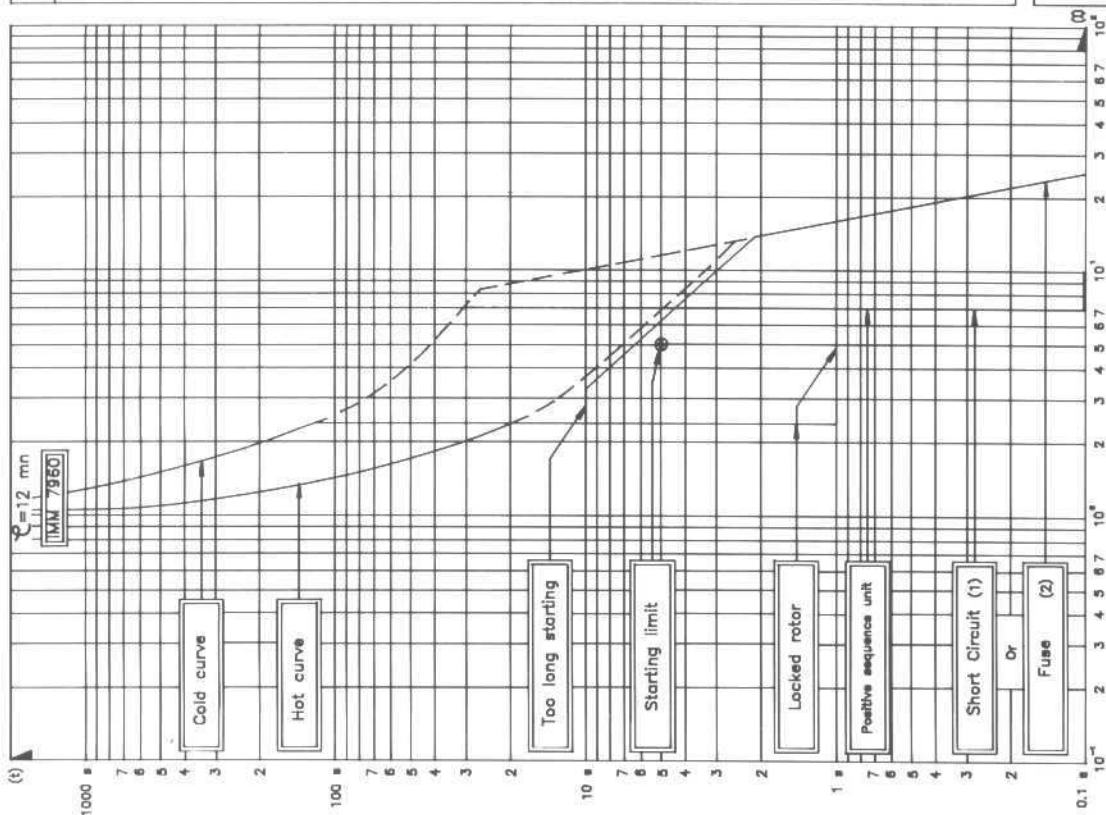
After an automatic transfer it is necessary to restart a certain number of motors. Due to the supply transformer limits it may be necessary to open the circuit breakers of the certain motors using an under-voltage level detector and then provide a time delayed reclosing procedure based on the busbar voltage.

The different voltage measurements, the various associated timers and automatic transfer or motor restart programs can be provided by the local Programmable Logic Controller **AMS 7001**

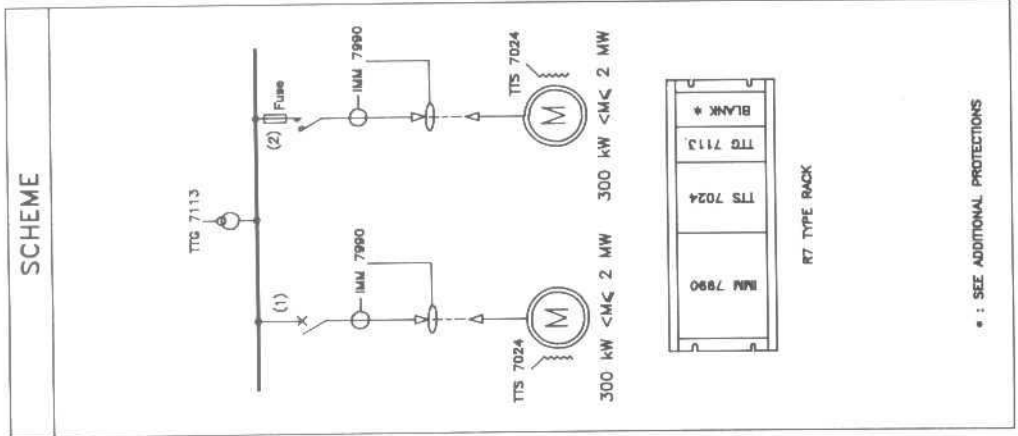
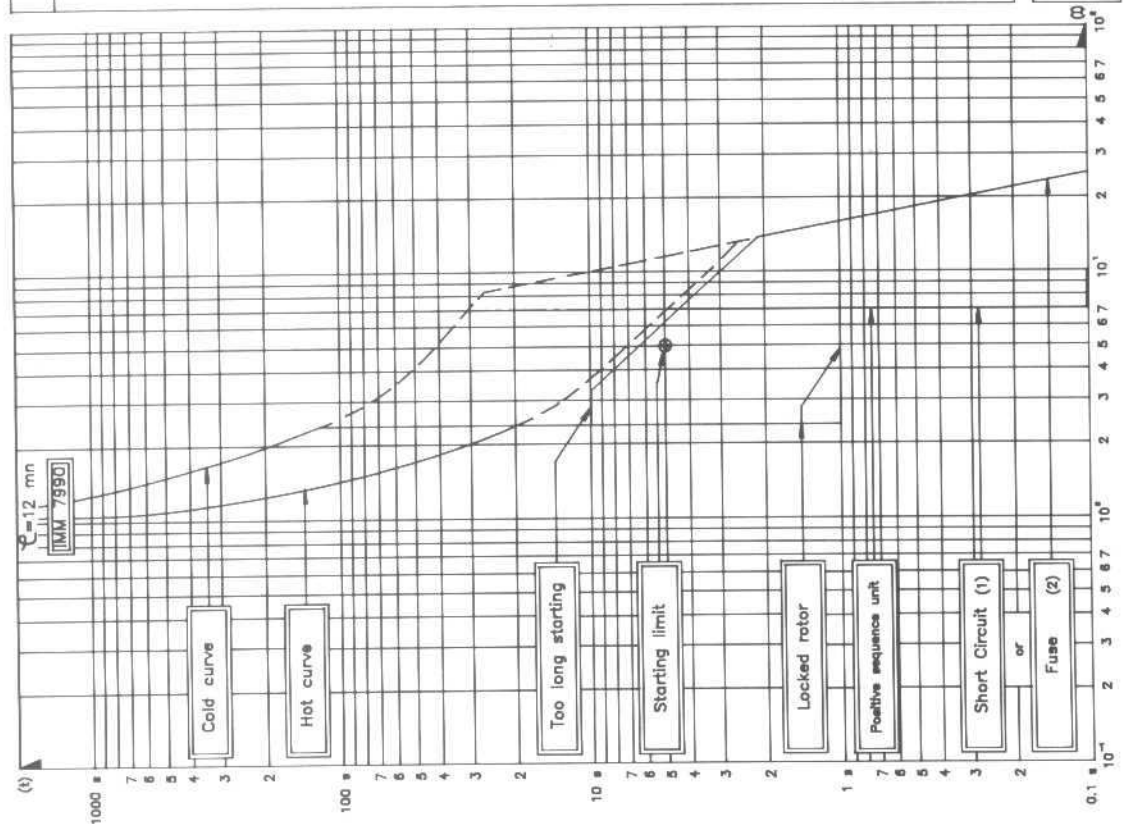
### **5.13 DATA MANAGEMENT [34, 11M]**

The motor protection relay **IMM7990**, together with the local PLC **AMS7001** and the measurement unit **CMS7004**, are elements of the “**PROCOM**” product range. A major characteristic of these products is their ability to communicate with the outside world. They can in fact exchange information, both locally (display) and to a remote location, using MODBUS/J-BUS protocol.

**PROCOM** products can then be integrated into a complete “**PROSATIN**” Integrated Protection, Supervision and Control System.

[illegible]

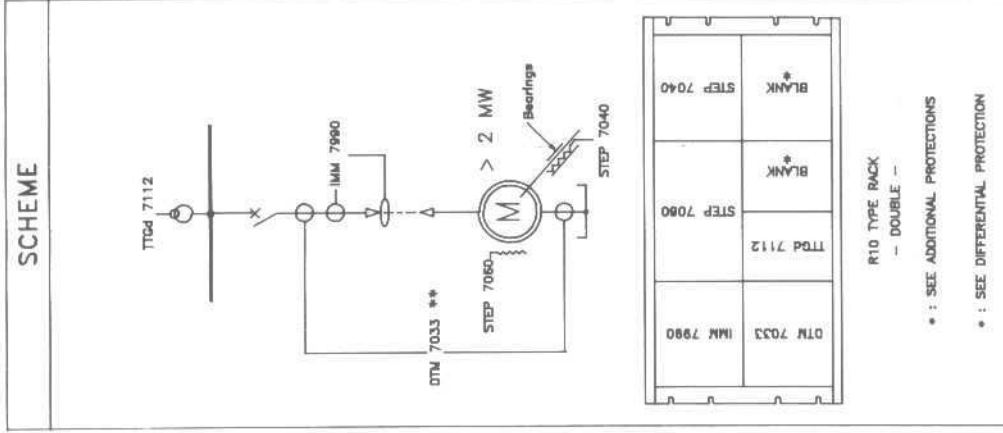
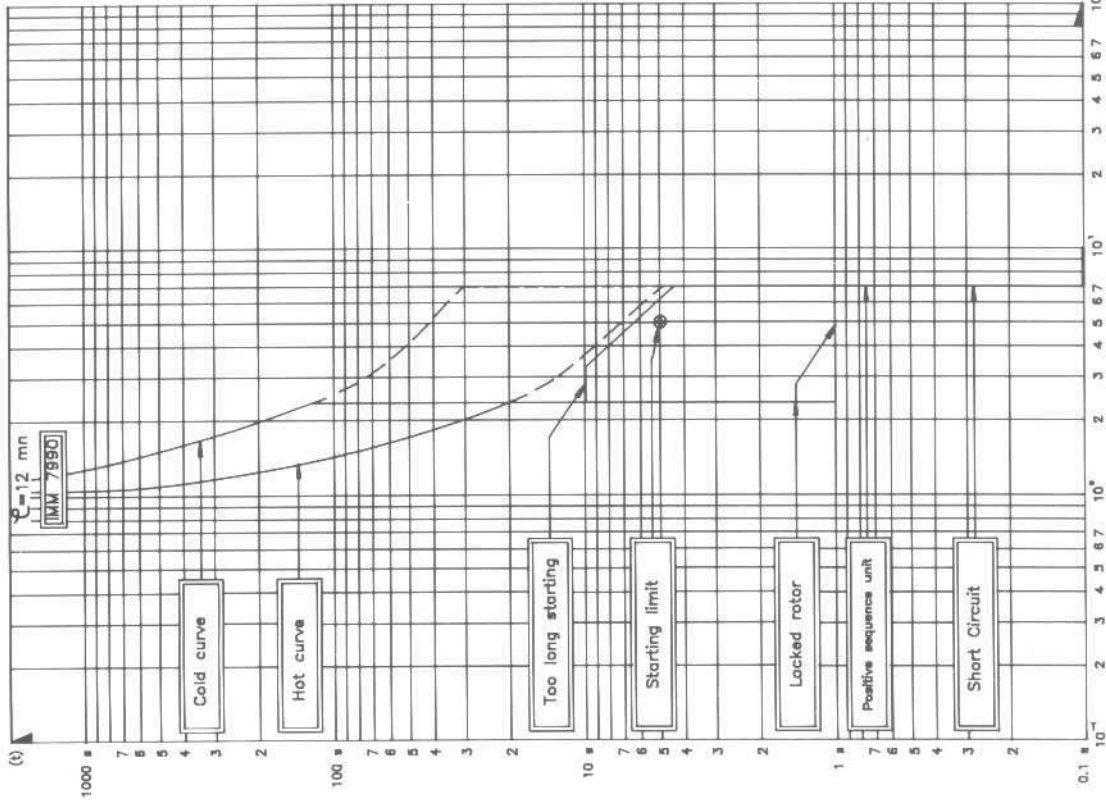
INDUCTION MACHINE PROTECTION :  $P_n < 300 \text{ kW}$



RELAYS	NOMENCLATURE	FUNCTION
IMM 7990	[49]	MULTI-FUNCTION MOTOR PROTECTION
		THERMAL OVERLOAD.
		THERMAL PRE-ALARM.
		LOCKED ROTOR
[51LR]		SHORT-CIRCUIT
[50]		UNBALANCE - SINGLE PHASING.
[48]		EARTH-GROUND FAULT
[31G]		START AUTHORISATION
		LIMITATION OF NUMBER OF STARTS.
[66]		TOO LONG STARTING.
[37]		UNDERCURRENT UNIT.
TTG 7113		UNDERVOLTAGE RELAY
[27]		DEFINITE TIME SINGLE PHASE.
TTS 7024		TEMPERATURE SUPERVISION-2 ELEM
[49]		RTD PROBES

INDUCTION MACHINE PROTECTION : 300 kW  $< P_n \leq$  2 MW

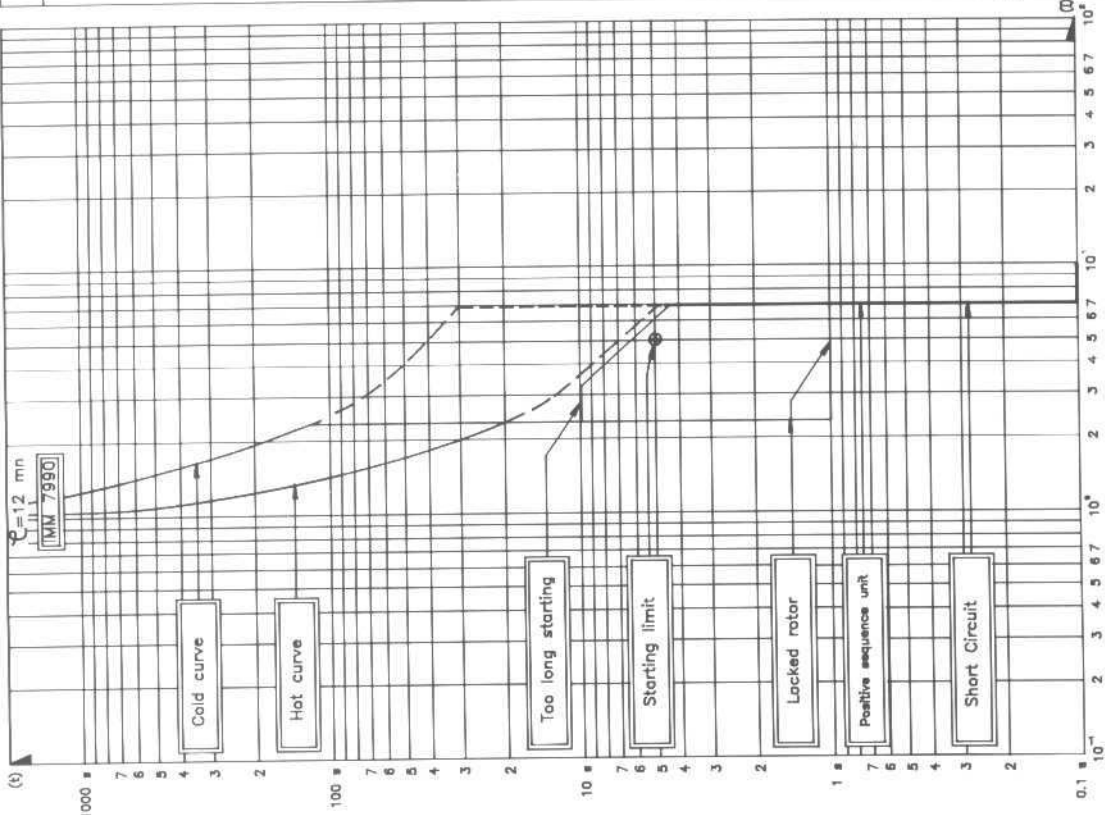




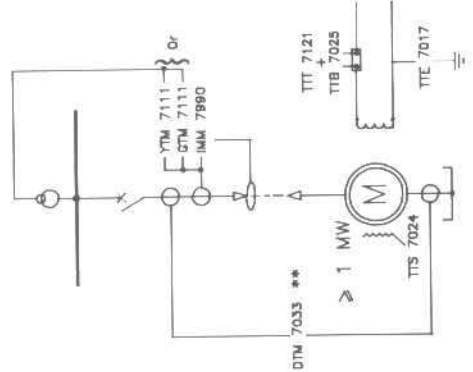
**NOMENCLATURE**

RELAYS	FUNCTION
IMM 7990 [49]	MULTI-FUNCTION MOTOR PROTECTION THERMAL OVERLOAD.
[51R]	THERMAL PRE-ALARM.
[80]	LOCKED ROTOR
[46]	SHORT-CIRCUIT
[51C]	UNBALANCE - SINGLE PHASING. EARTH-GROUND FAULT
[66]	START AUTHORISATION.
[37]	LIMITATION OF NUMBER OF STARTS TOO LONG STARTING. UNDERCURRENT UNIT.
DTM 7033 [87]	BIASED DIFFERENTIAL.
STEP 7040 [49]	TEMPERATURE SUPERVISION-4 ELEM. (PLATINUM PROBES PT100)
STEP 7060 [49]	TEMPERATURE SUPERVISION-6 ELEM. (PLATINUM PROBES PT100)
TTGD 7112 [27-47]	DEFINITE TIME POSITIVE SEQUENCE UNDERVOLTAGE RELAY.

INDUCTION MACHINE PROTECTION : Pn. > 2 MW



### SCHEME



IMM 7990	DTM 7033	YTM 7111 or GTM 7111	TTS 7024
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R10 TYPE RACK  
- DOUBLE -

\* : SEE ADDITIONAL PROTECTION  
\* : SEE DIFFERENTIAL PROTECTION

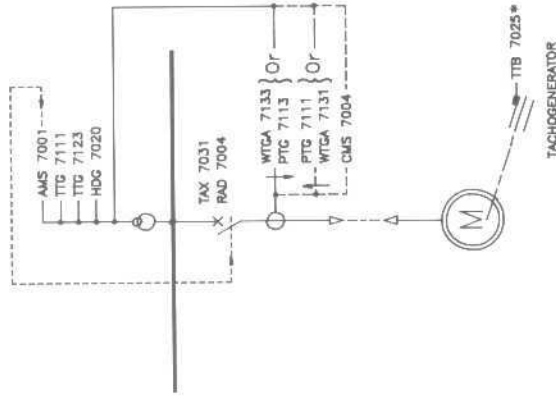
SYNCHRONOUS MACHINE PROTECTION : 5 MW  $\geq P_n \geq$  1 MW

### NOMENCLATURE

RELAYS	FUNCTION
IMM 7990 [49]	MULTI-FUNCTION MOTOR PROTECTION THERMAL OVERLOAD. THERMAL PRE-ALARM.
[51R]	LOCKED ROTOR
[50]	SHORT-CIRCUIT
[48]	UNBALANCE - SINGLE PHASING.
[51G]	EARTH-GROUND FAULT
[66]	START AUTHORISATION. LIMITATION OF NUMBER OF STARTS. TOO LONG STARTING.
DTM 7033 [87]	BIASED DIFFERENTIAL
TTS 7024 [49]	TEMPERATURE SUPERVISION-2 ELEM. (RTD PROBES)
TTE 7017 [64-1]	ROTOR EARTH FAULT DETECTOR.
TTB 7025 [27-590C]	OVER AND UNDER EXCITATION.
TTT 7121 [62]	TIME DELAY (2 TIMERS)
GTM 7111 [55]	OUT-OF-STEP.
YTM 7111 [40]	LOSS OF FIELD



## SCHEME



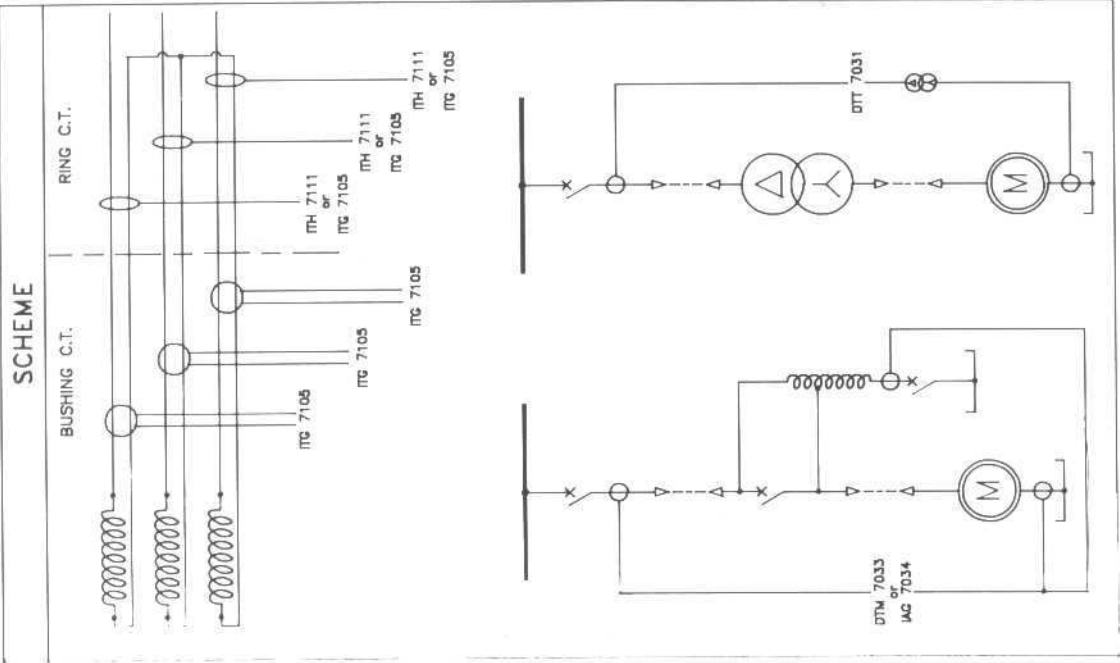
• LOCKED ROTOR PROTECTION IF STALLED MOTOR WITHSTAND TIME  
& STARTING TIME

## NOMENCLATURE

RELAYS	A.N.S.I	FUNCTION	COMMENTS
HDG 7020	[81]	INSTANTANEOUS UNDER AND/OR OVER FREQUENCY RELAY.	
TTG 7111	[59]	DEFINITE TIME SINGLE PHASE OVERVOLTAGE RELAY.	
TTG 7123	[27]	DEFINITE TIME TWO PHASE UNDERVOLTAGE RELAY.	
WTGA 7133 PTG 7113	[32]	DEFINITE TIME MINIMUM ACTIVE POWER RELAY.	
AMS 7001	[83][79]	CUBICLE DIGITAL MONITORING UNIT.	
	[27][62]	COMMUNICATION INTERFACE	
	[59]	P.L.C. RESTART UNIT.	
PTG 7111 WTGA 7131	[32]	REVERSE POWER RELAY	
CMS 7004		MEASUREMENT UNIT	
TTB 7025	[14]	LOCKED ROTOR PROTECTION	
TAX 7031	[74]	TRIP CIRCUIT SUPERVISION.	
RAD 7004	[86]	TRIP RELAY - HAND RESET.	

THESE PROTECTIONS ARE INTENDED TO PROTECT THE ROTATING MACHINERY AGAINST PERMANENT OR TEMPORARY LOSS OF SUPPLY VOLTAGE (e.g. DISCONNECTION BEFORE RESTART OR DURING A FAST RECLOSE CYCLE). THE EXACT TYPE AND NUMBER OF PROTECTIVE RELAYS TO BE USED DEPENDS UPON THE APPLICATION.

## ADDITIONAL PROTECTIONS

[illegible]

## SPECIAL DIFFERENTIAL PROTECTION SCHEMES

## **6. Busbar Protection Schemes**

### **6.1 *OVERCURRENT/EARTH FAULT PROTECTION [50, 51, 68]***

On lower voltage ( $\leq 11\text{kV}$ ), it is common to rely on relays such as the **RMS791/ITG7135** to clear a busbar fault. As described in previous sections, the relays on the incomers have to grade with those upstream (for example on the primary side of the feeding transformer) and those on the outgoing feeders.

If the two incomers are separated by a bus-section switch, then the relays on both incomers will both see a busbar fault, no matter which section of bar is actually faulty. In these circumstances, it is usual for the relays to trip (using an inverse time curve) the bus-section switch first, and start an auxiliary timer (such as the **TTT7111**). When the bus-section switch is opened, only one of the relays will continue to see the fault.

The timer on the feeder will continue to time (the time delay should be set to be greater than the breaker operating time) and the timer relay should trip the breaker on the feeder feeding the faulty section of bar. If this fails to clear the fault, then a second timer will send an inter-trip signal to the breaker on the primary side of the transformer to clear the fault. This inter-trip signal would trip the HV breaker faster than relying on the overcurrent protection tripping for a fault on the LV side of the transformer.

Tripping the bus-section switch before the incoming breaker adds to the fault clearance time, and therefore adds to the damage caused to the faulty busbar. The advantage of tripping the bus-section switch first is that it minimises the number of circuits lost due to the faulty bar.

If the relays on the outgoing feeders are able to send a “blocking signal” to the relays on the incoming feeders, busbar faults can be cleared more quickly. This is explained in more detail in Section 2.1.2 above. Using this method reduces the tripping time (excluding breaker operating time) from around 2-3 seconds with inverse time protection to around 300ms.

### **6.2 *UNIT PROTECTION [87]***

Busbars can also be protected using the Mertz-Price method of protection using, for example, the **IAG7034**. One **IAG7034** relay is needed for each section of bar (if one relay is used for more than one section of bar, then more circuits will be lost in the event of a busbar fault on one section of bar). In this application, the current flowing “into” the busbar from the incomers is compared with the current flowing “out of” the busbars through the feeders. If the difference between what is flowing in and what is flowing out is greater than a certain value, then the busbar is isolated.

Using this method of busbar protection, the tripping time is reduced further to around 30ms. This compares well with the overcurrent protection described above, but can still lead to considerable busbar damage in the event of a fault.

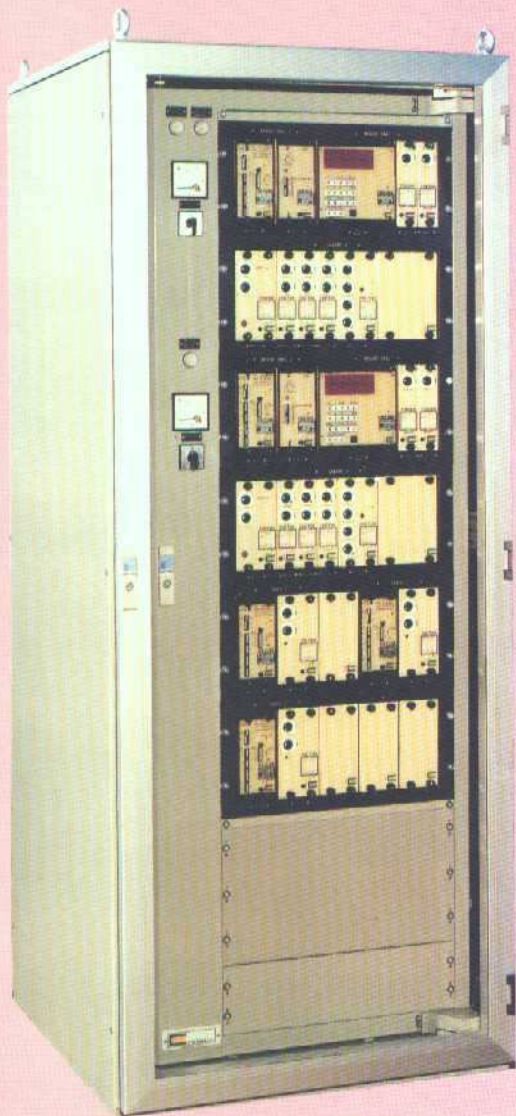
### **6.3 *ARC DETECTION***

A third, more recent, method of protecting against busbar faults is to mount light sensors inside the busbar chambers and switchgear itself. As soon as an arc begins to form, it is detected by the light sensors. Depending on where the arc begins to form, the arc-detection system can isolate the faulty section of bar by tripping the associated breakers. A current check can be added to prevent spurious tripping. This method results in a tripping time of less than 1ms - significantly reducing the damage caused by busbar faults

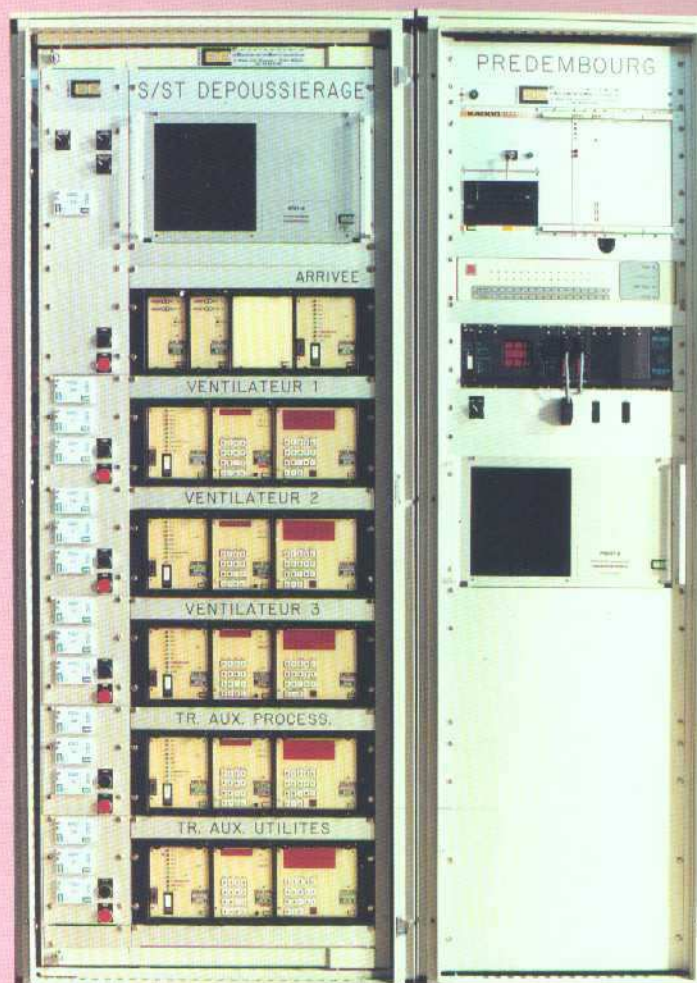


## 7. Index of CEE Protection Relays - including ANSI Codes

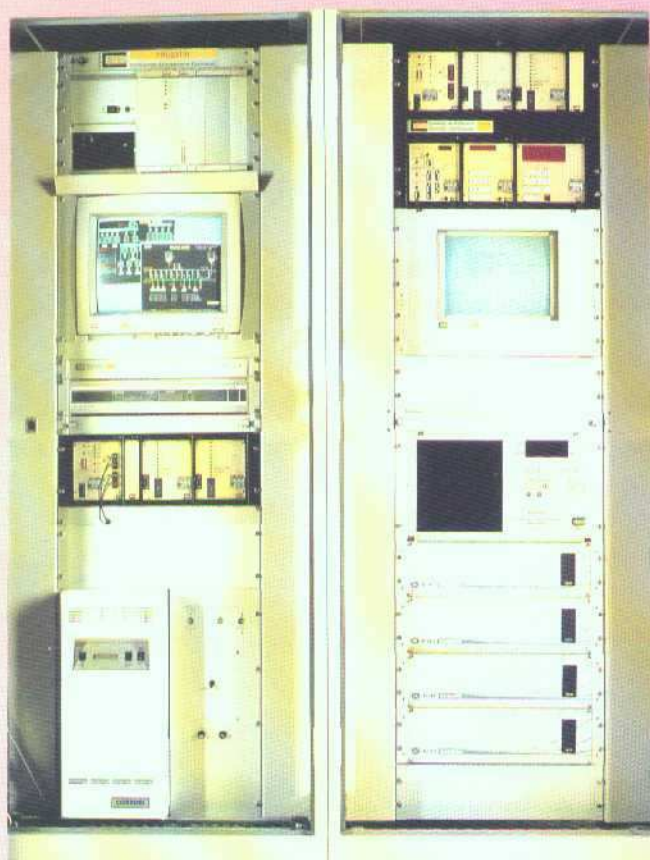
RELAYS	FUNCTION	ANSI CODE	TYPE
AMS7000	Local switchgear PLC	34	PROCOM
BAI7001	Amplification and interface device		PROCOM
BAT7001	Auxiliary supply for circuit breakers and relays		Solid state
CMS7000	Multi-function	11M	PROCOM
DTM7033	Rotating machine differential	87G	Solid state
DTT7031	Transformer differential	87T	Solid state
GMSx7001	Multi-function digital generator protection	49/46/40/21/51/59/24/27/81/32-1/32-2/(59N)/(64)	PROCOM
GMSx7002	Multi-function digital motor protection	49/46/55/50/51LR/59/24/27/81/32-2/(59G)/(64)	PROCOM
GTM7111	Out of step	55	Solid state
HDG7020	Over/under frequency	81	Solid state
IAG7014	Restricted earth fault - high impedance	87	Solid state
IAG7034	3 phase differential - high impedance	87	Solid state
IMM7960	Multi-function motor protection	49/46/51/51LR/64/37	Digital
IMM7990	Multi-function motor protection	49/46/51/51LR/64/37/66	PROCOM
ITD7111	Directional overcurrent - 1phase	67	Solid state
ITD7112	Directional earth fault	67N	Solid state
ITG71x6	Independant time series	51/50/51N/50N	Solid state
ITG72x6	Inverse time series	51/50/51N/50N	Solid state
ITG73x6	Very inverse time series	51/50/51N/50N	Solid state
ITG74x6	Extremely Inverse time series	51/50/51N/50N	Solid state
ITH7111	Sensitive Earth Fault	64	Solid state
ITI7521	Unbalance (negative sequence)	46	Solid state
ITT7610	Thermal image	49	Solid state
ITV7x66	Voltage restrained overcurrent series	51V	Solid state
PMG70xx	Disturbance recorder		PROCOM
PTG711x	Reverse or under power	32 or 37	Solid state
RMS700	Multi-curve over/under current series	51/51N/50/50N	PROCOM
RMS7992	Multi-curve overcurrent (3phase & e/f)	51/51N/50/50N	PROCOM
RMSA7992	RMS7992 independant of auxiliary supply	51/51N/50/50N	Digital
RMSD7912	Directional earth fault	67N	PROCOM
RMSD7921	Directional 2 phase overcurrent	67	PROCOM
RMSR7900	Multi-curve overcurrent and earth fault protection with autoreclose	51/51N/50/50N	PROCOM
RMST7992	RMS7992 with thermal image protection	51/51N/50/50N/49	PROCOM
SOLKOR RF	Pilot wire differential	87P	Solid state
STEP70x0	Thermal protection - PT100 Probes	49	Solid state
STS7041	Check synchronising	25	Solid state
TMS700	Multi-curve over/under voltage series	27/27N/59/59N	PROCOM
TMS7000	Multi-curve under/over voltage series	27/27N/59/59N	PROCOM
TTB7025	DC Over/under V or I	59DC/27DC	Solid state
TTB7027	DC Over V or I	59DC/27DC	Solid state
TTE7015	Rotor Earth Fault - DC injection	64F	Solid state
TTE7017	Rotor Earth Fault - AC injection	64F	Solid state
TTG7000	Over/undervoltage series	27, 59 or 59N	Solid state
TTGB7031	VT supervision	60	Solid state
TTGd7112	Time delayed +ve seq. undervoltage	27	Solid state
TTT7000	Timer	2	Solid state
WTGx7131	Reverse power (active or reactive)	32 or 32R	Solid state
WTGx7132	Over power (active or reactive)	40/32 or 40R/32R	Solid state
WTGx7133	Underpower (active or reactive)	37 or 37R	Solid state
YTM7111	Loss of field	40	Solid state



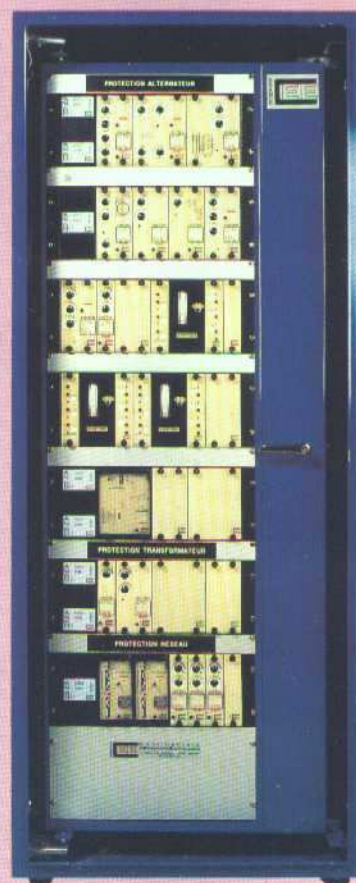
Power network protections



PS 2000 system



PS 4000 system



Block generator-transformer





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