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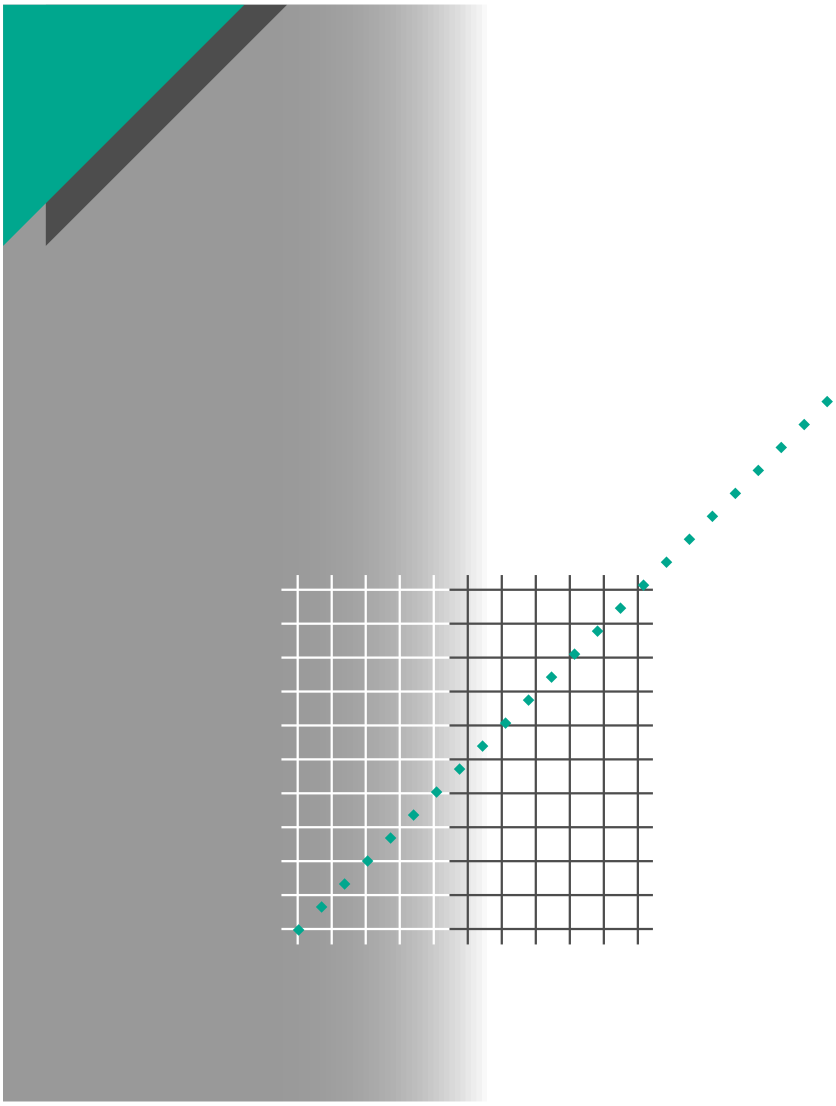
Protection of MV/LV substation transformers



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n° 192

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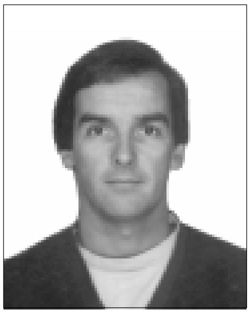

Didier FULCHIRON

Graduating as an engineer from the “Ecole Supérieure d'Electricité” in 1980, he joined the technical department in Merlin Gerin in 1981 at the high power testing station. Now in the Medium Voltage Division, he uses his knowledge of public distribution applications to work on expert assessments, specifications and standards.

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Lexicon

Chopped wave: part of an overvoltage wave, generally lightning generated, which continues propagating beyond arcing in an air gap (spark gap or insulator breakdown). The high gradient of the downward slope generated by arcing is very severe for certain equipment.

GRPT: device useable on hermetically sealed immersed type transformers with integral filling combining monitoring features for gas release, pressure and temperature.

Overlaying: technical and/or time-based differences in the users of a network that enables a maximum power rating to be used that is much less than the sum of the individual maximum powers.

Take-over current: value of current corresponding to the intersection of the time-current characteristics of two overcurrent protection devices (VEI 441-17-16).

Transfer current: value of the symmetrical three-phase current at which the fuses and the switch exchange the breaking function (in a combined fuse-switch) (IEC 420).

Protection of MV/LV substation transformers

The choices involved in the protection of MV/LV transformers can appear to be simple since they are often the result of usual practices of electrical network designers, or even of policy dictated by technical and economic considerations. In fact, the choices must be made as a function of the transformer technology, the type of loads that they are supplying, and above all the external environment that they are subjected to.

This “Cahier Technique” discusses the stresses to which the transformers are subjected during operation and the consequences of these stresses and goes on to present the various protection devices that can be used. It is necessarily simple, due to the large number of criteria and solutions that exist. Electrical engineers should however find this document provides the main information needed to make the right choices.

Contents

1 Introduction

1.1 MV/LV transformers and protection policy

Why transformers exist

Transformers are included in distribution networks in order to:

- minimize energy losses due to the Joule effect; increasing voltage by a factor of 10 reduces these losses by a factor of 100 (Losses = R $(P_{consumed} / U)^2$),
- minimize voltage drops, both resistive (R) and reactive (X) at the given transmitted power (U I cosϕ) ($\Delta U \approx R I \cos\phi + X I \sin\phi$),
- and possibly ensure electrical separation between networks of the same voltage (boundary limits, changes in the neutral arrangement, etc.).

Even though it is rare to voluntarily interrupt power distribution, transformers nevertheless have to be “switched” under normal operating conditions, e.g.:

- for network reconfiguration,
- for reasons of maintenance and security,
- to meet a consumption peak,
- to start or stop a process.

These operations are carried out on the transformer either under load or with no load which has a notable influence on the operating conditions and the resulting transitory electrical phenomena. Distribution transformers are very reliable passive devices with a life expectancy of several dozens of years. A Norwegian utility has cited an annual failure rate of 0.09 % (9 for 10,000), all reasons included, for an equipment base of 5,000 transformers monitored over four years. For underground networks, the observed failure rate still remains less than 0.2 %: It can increase to 0.5 % on certain overhead networks. It is often obsolescence - the evolution of the power or voltage levels - which leads to their replacement. Faults in service are very rare, but the need to provide safety of property and people as well as continuity of service nevertheless leads to the use of protection devices.

Stresses suffered by transformers

Transformers are subjected to many external electrical stresses from both upstream and downstream. The consequences of any failure can be very great in terms of damage as well as in terms of operating losses. Transformers must therefore be protected against attacks of external origin on one hand, and isolated from the network in case of internal failure on the other hand. The term “transformer protection” is very often associated with the action of disconnecting from the network, even though the transformer is already failing, and the amalgam is made between preventative measures (overvoltages, downstream faults, overloads, temperature) and corrective measures to isolate the failed transformer.

Protection policy

It is the electrical network designer's responsibility to define the measures to be implemented for each transformer as a function of criteria such as continuity and quality of service, cost of investment and operation and safety of property and people as well as the acceptable level of risk. The solutions chosen are always a compromise between the various criteria and it is important that the strengths and weaknesses of the chosen compromise are clearly identified. E.g., an operator and a utility can choose very different solutions for urban and rural network sections since the criteria of unit power, of cost and the consequences of an incident, are not the same.

The high reliability level of transformers is a decisive factor in the choices made by utilities, faced with the unit cost of the protection devices which can be associated with them. For example, it means that rather than looking to protect the transformer, in order to save the equipment, we seek to limit the consequences of a failure.

This situation can be illustrated using certain commonly encountered, although by no means systematic, choices such as:

- “protection” exclusively targeted to “prevent the risk of explosion and safeguard the MV network” for transformers connected to the public distribution network,
- temperature monitoring for industrial or tertiary sector installation transformers in which load shedding arrangements can be implemented,
- non-monitoring of overloads for public distribution transformers; customer overlaying making overloading relatively unlikely and, moreover, load shedding only being possible to consider in the case of an incident. If the transformer supplies a uniform group of customers, a need arises for overload protection since there is no longer any overlaying.

Since these various choices are always the result of a technical-economic compromise together with policy considerations, it is impossible to offer a solution providing satisfaction in every case. Therefore, after briefly reviewing transformers and their characteristics, we will go on to examine the stresses to which transformers can be subjected and the various means of protection. The chosen solution remains the network designer's responsibility, on a case by case basis.

1.2 A review of transformer technology and uses

Liquid filled or dry-type transformer technology has an influence on certain characteristics, on the protections to be implemented and on the possible installation locations.
It is necessary to know transformers' electrical and thermal characteristics in order to understand their behaviour and their resistance to stresses in operation or fault situations.

Technologies

- In general, liquid filled transformers are hermetically sealed with integral filling.

  These transformers are particularly suited to:
  - unsupervised substations (zero maintenance),
  - severe environments if the tank is suitably protected (active parts protected),
  - cyclic consumption applications (with good thermal inertia).

  On the other hand, the liquid dielectric has some inherent risks:
  - ground water pollution (in case of leaks of the dielectric), from which results the obligation, in certain cases, to provide for a back-up retention tank,
  - fire (see **fig. 1**) which is why they are prohibited in certain buildings.

  These risks are taken into account in the various regulatory texts and standards concerning the conditions of installation and limits of use.

- "Dry"-type transformers are more appropriate for:
  - locations with controlled environments: dust - humidity - temperature, etc. and must be periodically cleaned and dusted,
  - buildings, in particular high-rise buildings; since they can have good fire behaviour (e.g. class F1 according to NF C 52-726) and meet non-toxicity of fumes criteria.

Characteristics

The various rated values are defined by IEC 76 (power transformers). Certain electrical characteristics are required in order to be able to know how the transformer withstands stresses in operation and in fault situations; they are also decisive factors in the choice and setting of protection devices:

- Rated primary voltage (U_r)
  Applying IEC standard 71 (insulation co-ordination) enables the insulating voltage and the lightning impulse withstand to be selected (see **fig. 2**).

- Short-circuit voltage (U_{sc})
  This enables calculation of the current absorbed by the primary in case of short-circuit across the secondary's terminals:

$$I_{sc} = \frac{100\ I_n}{U_{sc}\ \%},$$

if the source impedance is disregarded. It also gives the transformer impedance, required to calculate the short-circuit current when this occurs in the LV distribution system:

$$Z = \frac{U_{sc}\ \%\ U_r}{100\ I_r}.$$

Short-circuit voltages are standardized and are a function of transformer power: 4 to 6% for MV/LV transformers (see **fig. 3**).

- Retention tanks
- Distances or screens to prevent propagation of fire
- Device to achieve spontaneous extinction
- Automatic de-energizing device on gas release
- Automatic de-energizing device on temperature rise
- Automatic de-energizing and extinction device on fire detection
- Automatic closing of fire doors

Fig. 1: fire protection devices when using liquid dielectric transformers.

Insulation level according to IEC 71	**17.5**	**24**	**36**
Highest voltage for the equipment	17.5	24	36
Industrial frequency withstand, 1 min.	38	50	70
Lightning impulse withstand	75 or 95	95, 125 or 145	145 or 170
Network operating voltage	12 to 17.5	17.5 to 24	24 to 36

N.B.: switching impulse withstand is not specified below 245 kV

Fig. 2: standard insulation levels (kV).

Rated power S_n in kVA	**U_{sc} according to**	
	CEI 76	**H426.S1 (Europe)**
$S_n < 50$	4 %	unspecified
$50 < S_n < 630$	4 %	4 %
$630 < S_n < 1250$	5 %	6 %
$1250 < S_n < 2500$	6.25 %	6 %

Fig. 3: standard short-circuit voltages for distribution transformers.

- Switching current
  In particularly unfavorable conditions (transformer under no load, large residual flux and zero voltage tripping with an initial half-wave flux of the same polarity as the residual flux), the magnetic core becomes very saturated, with the winding taking in up to three times its rated flux.
  Due to this saturation, the apparent inductance of the coil significantly drops, approaching the

behaviour of an air coil (increasing the leakage flux): the resulting current in the winding may therefore reach very high peak values, up to a dozen times the peak rated current, with an extremely distorted current wave form due to saturation phenomena (see **fig. 4**).

These switching phenomena damp down with a time constant that is dependent on the transformer, related to its magnetic characteristics and leakage flux. The time constant is of the order of a few hundreds of milliseconds for distribution transformers (a table of numerical values is given further on in the document).

Knowing the switching current is necessary to determine the choice and/or the settings of short-circuit protection devices located on the transformer's primary.

- Thermal inertia of the transformer

This varies according to transformer type (dry or liquid filled) and power. Knowing it is useful in determining the overload protection to be used.

Readers wishing to gain a more in-depth knowledge of transformers (technology, characteristics, and use) are invited to read the corresponding “Cahier technique”.

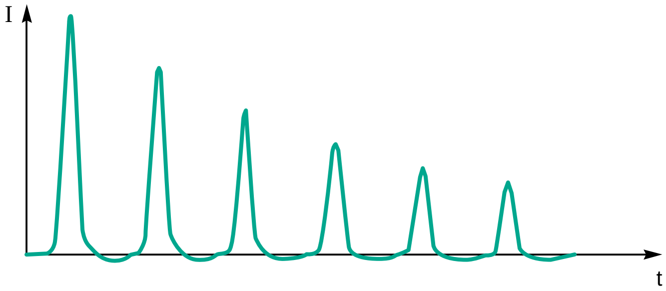


***Fig. 4**: profile of making currents with asymmetrical saturation.*

2 Operating stresses and failure modes

2.1 Energizing and de-energizing

Distribution transformer “operation” is limited to energizing and de-energizing. In public distribution, these operations are exceptional and do not really correspond to the operational use. Nevertheless, the transformers are energized and de-energized during network circuit-breaker operation, including during reclosing cycles. Rapid reclosing can cause energizing with a strong residual flux, which in turn generates particularly high switching currents.

In industrial or tertiary sector processes, the same switching operations can be performed systematically e.g. for process start-up/shut-down or site opening/closing, etc. When the load connected to the transformer is controlled, energizing can take place under load or under no-load conditions.

Since the damping of switching currents is related to the transformer's magnetic characteristics (mainly its hysteresis losses), the presence of a load has little effect on behaviour.

Energizing generally occurs with the loads connected. If these themselves have transitory phenomena, it is the overall behaviour which must be taken into consideration. E.g., in the case of motors units, the transformer's transitory current is superposed on the motor's start-up current, but the duration is significantly different and the transformer's impedance is dimensioned to limit current demand during the start-up phase. Such well-identified cases must be the subject of special study. They do not correspond to “distribution” type applications.

Switching currents require monitoring devices (associated current relays and sensors, fuses, etc.) to integrate the idea of time delay in order not to generate spurious actions. This aspect is dealt with further in the corresponding paragraphs.

2.2 External overvoltages

Origin and severity

Distribution transformers are subjected to transient overvoltages resulting from the networks to which they are connected. These overvoltages are either the result of direct or induced lightning strikes on the MV or LV networks (see “Cahier Technique” n°168: Lightning and MV electrical installations), or of transmission at MV level of switching over-voltages generated on the upstream network.

During de-energizing by switchgear situated immediately upstream, overvoltages can be generated by the combined transformer- supply circuit switchgear set leading to a dielectric stress on the transformer. This stress causes premature ageing, or even an insulation fault between turns or to earth. The most critical conditions are obtained during the de-energizing of transformers under no load, or by switching mechanisms capable of breaking high frequency currents such as vacuum circuit-breakers. The use of such switchgear as a means of operational switching should therefore be considered with caution.

The criteria determining the severity of the overvoltage for transformers are the peak value, naturally, as well as the voltage rising rate (increase gradient, or decrease gradient in case of near - by flash-over - “chopped wave”) which leads to the uneven distribution of stresses within the windings and therefore results in exceeding the inter-turns withstand limits even if the peak value across the primary winding terminals does not exceed the accepted values (see **fig. 5**).

Risks of exposure

The risks of exposure to overvoltages for a given transformer are related to its environment, with criteria such as:

- MV supplied by an overhead or underground network,
- the eventual presence, sizing and installation conditions of overvoltage limiting devices (lightning arrestors or spark gap protectors),
- the length and the type of connections between the network and the transformer,
- the switchgear type and the conditions of operation,
- the quality of earthing connections and of the design of the earthing network at the substation level,
- overhead or underground LV network,
- the earthing of the LV network and its possible coupling with the substation's earthing system.

The standard definitions relating to ideas of insulation level do not fully cover all stresses that transformers can be subjected to since certain network phenomena are poorly taken into consideration i.e. very steep-gradient transient voltages.

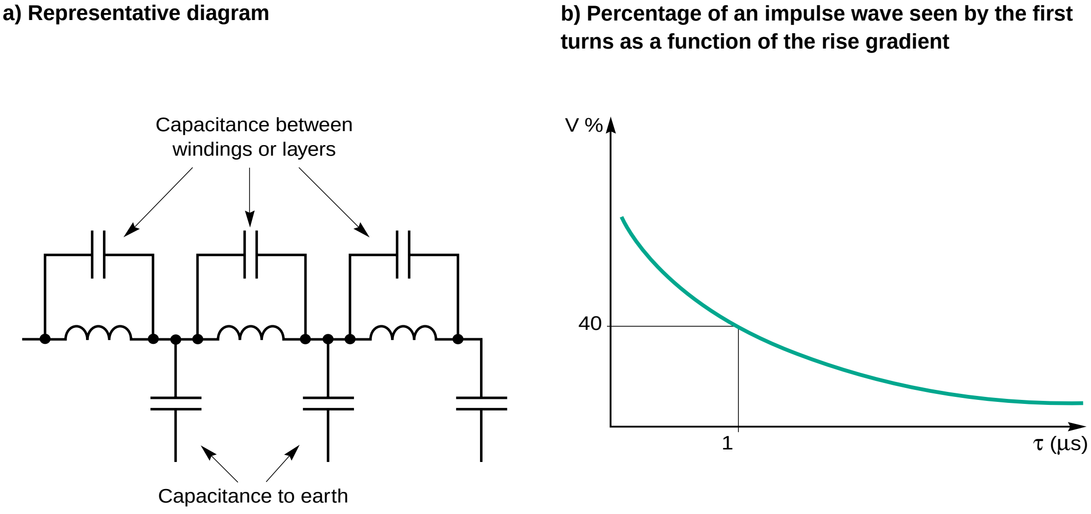
In practice, assessing the risks of overvoltage remains very global, since the stakes represented by an MV/LV transformer do not justify an in-depth insulation coordination study. Furthermore, it is wise for the network designer to avoid specifying characteristics which may require custom manufacturing. We therefore limit ourselves to a choice between standardized insulation levels (see **fig. 2**).

Insulation failures

- Internal failures caused by overvoltages can be observed in the following forms:
  - ☐ insulation faults between the turns in the same winding (the most frequent case),
  - ☐ insulation faults between windings,
  - ☐ insulation faults between the involved winding and a neighboring conductor (other winding, core or tank).

The behaviour associated with these two failure categories is further detailed in the following pages.

- External insulation of immersed transformers is over-dimensioned and cases of dielectric failure on these transformers are rarely observed, except for in certain cases of overhead network transformers in particularly polluted regions. As previously mentioned, dry-type transformers can be subject to external dielectric failures where there is pollution of the insulating surfaces.


a) Representative diagram

b) Percentage of an impulse wave seen by the first turns as a function of the rise gradient

Fig. 5: distributed capacitance and stresses along a winding.

2.3 Overloads

General

The acceptable temperature rises in the various parts of the transformer, taking account of the temperature rise threshold values provided by the standards, based on a life-expectancy related to the aging of the insulation material, are defined for continuous operation. A higher current value than the rated value corresponds to operation under overload conditions. Maintaining an overload situation leads to exceeding the temperature rise calculated at certain points on the transformer (according to how it is built) and, in the instance of a high ambient temperature, to the exceeding of acceptable temperatures.

The distinction between temperature rises and temperatures is important because it enables the criticality of certain overload conditions to be assessed differently. E.g. an overload related to electrical heating during the winter in a cold climate does not have the same consequences that an overload of the same level due to air conditioners in a hot climate during the summer.

Nevertheless, under abnormal or exceptional operating conditions it is acceptable to exceed the thresholds, possibly to the detriment of the life-expectancy. This may be preferable to interrupting service due to a momentary power peak.
The acceptable overload criteria, such as ambient temperature, operating with cyclic loads, etc. are discussed in the “Cahier Technique” on distribution transformers.

Overloads are often transitory and thermal equilibrium is not affected; the transformers thermal inertia, essential for “oil filled” technology transformers, enables these high values to be sustained, according to a law that is “inversely proportional to time” (see **fig. 6**).

Acceptable overload currents vary according to whether or not we are interested in steady-state operation; simply monitoring a current threshold in each phase can be unnecessarily penalizing.

Public distribution

In public distribution, overloads do not generally lead to transformer disconnection, continuity of service having been given short-term priority. Moreover, low voltage circuits are always over-dimensioned and a transformer overload never corresponds with an LV conductor overload. If overload situations are repeated too frequently, the utilities company is led to replace the transformer by a more powerful model. Certain utilities use current maxi-meters in order to be able to monitor the progression of the peak power demand on each transformer.

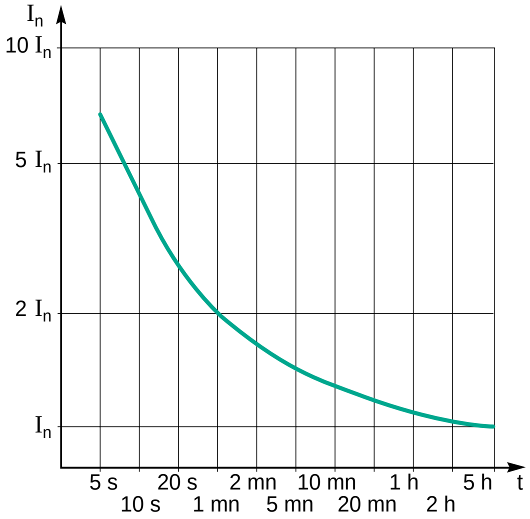


Fig. 6*: order of magnitude of the overload capacity of an oil filled transformer.*

Industrial distribution

In an industrial installation, an overload situation can be of a short duration, e.g. related to a machine start-up phase, or likely to be prolonged in the case of poor load overlaying. In these installations, the general low voltage switchboard immediately downstream of the transformer is equipped with circuit-breakers which protect against a prolonged overload situation.
Management is therefore performed on the LV side, either by load shedding procedures for complex installations, or by a general tripping if no other downstream tripping occurs beforehand.

Tertiary sector distribution

In “large tertiary” sector installations, such as office buildings, shopping malls, etc. the continuity of service criteria is important. There are no periodic loads with start-up arrangements or similar behaviour. Load shedding is essential in the case of transformer overload and can be executed at the expense of non-priority applications, e.g. air conditioning or heating systems.
The “load shedding” function is increasingly integrated in Technical Building Management systems.

2.4 Short-circuits on the LV network

In case of a fault downstream of the transformer, the impedance of low voltage circuits quickly becomes preponderant in short-circuit current calculations (see “Cahier Technique” n°158: Calculating short-circuit currents), and the only faults representing a significant stress for the transformer are those located within its immediate proximity. These faults are either managed by the LV protection concerned (fuses or circuit-breakers), or by the MV protection upstream from the transformer in the case of a fault upstream of the LV protections.

Remember that a transformer having a short-circuit voltage of 5 % has a short-circuit current of 20 I_n, with an infinite power source and a low voltage short-circuit impedance of zero. The hypothesis of an infinite power source is often realistic in public distribution, where the unit power of distribution transformers is low in comparison with the short-circuit power of the MV network. This is not generally the case in industrial and large tertiary sectors, and disregarding source impedance imposes unnecessarily elevated stresses for the design of the low voltage part of the network and its associated protection devices.

For transformers, a low voltage fault near to the terminals is translated into thermal stresses, according to the value and the duration of the fault, and mechanical stresses, due to the electrodynamic effect especially when the fault first appears. Transformers are generally designed to be able to withstand a short-circuit across their terminals (infinite source and bolted short-circuit), corresponding to a situation more severe than any foreseeable situations during operation. Nevertheless, repeated faults can have a cumulative effect, e.g. coil displacement, and contribute to premature ageing. In any case, the duration of the fault must be limited by a protection device otherwise it risks leading to destruction by thermal effects.

2.5 Progression of internal faults

Faults between turns

Faults between medium voltage winding turns are the most frequent failure mode as well as being the most difficult to detect.

They result from the localized deterioration of conductor insulation, due to thermal or dielectric stresses. The initial effect is limited to a slight increase in the primary current, due to the modification of the transformation ratio on the one hand and the appearance of a short-circuited turn phenomena on the winding concerned.

This faulty turn behaves as a secondary winding and is the seat of a current limited solely by its own impedance and the resistance at the point of fault (see **fig. 7**).

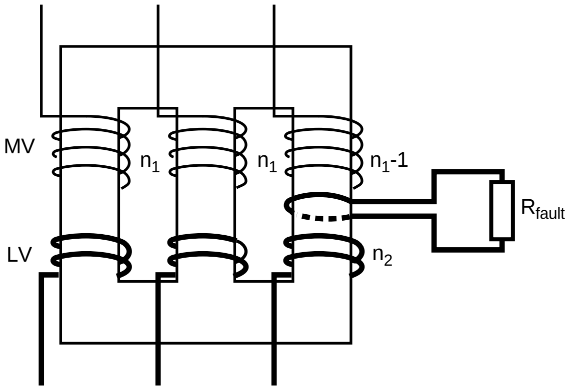


Fig. 7: functioning of a transformer with a short-circuited turn in the primary.

According to the current that passes through this turn, the progression of the fault will be more or less rapid. In the case of high currents, the local temperature rise will lead to the deterioration of the neighboring turns and the fault will quickly spread. The order of magnitude corresponds to approximately one hundred times the rated current or around 1 kA for the primary winding of a transformer of 400 kVA under 20 kV (CIRED 1991/1.14). In any case, the presence of local arcing will lead to a gaseous release, whether or not the transformer is of oil filled or dry type. This release can lead to a large increase in pressure, until part of the structure ruptures (tank or solid insulation).

If the fault causes a low primary current, the phenomena can be slow and difficult to detect through monitoring of the supply current. Laboratory tests on oil filled transformers have shown current of between 1 and 6 times the rated current, accompanied by large gaseous release, for faults involving up to 8 % of the primary turns (CIRED 1991/1.14). This is why monitoring of gaseous emissions or pressure can be used in a complementary manner to protection devices based on current measurement.

Faults between windings

- MV windings

Faults between MV windings are rare but can cause high fault currents, up to the network short-circuit current in the case of a fault at the terminals, with significant effects. Certain locations in particular, such as a fault between windings neighboring neutral point connections of a star coupling, are similar to a fault between turns since the points coming into contact are not at greatly differing voltages.

- LV windings

Faults between LV windings are exceptional since these windings are placed closest to the magnetic core and are surrounded by the MV windings. In the case of multiple LV windings on the same magnetic core column (e.g. zig-zag coupling), the possibility of a fault exists. In any case, the fault current remains less than that of a short-circuit across the secondary terminals, but progression can be quick due to the presence of an arc of significant intensity.

- MV/LV

A fault between windings can also lead to a contact between the primary and secondary, with the appearance of a dangerous potential on the low voltage network (see “Cahier Technique” n°172: Earthing systems in LV). The risk to equipment and people depends on the neutral arrangement of the two networks (see **fig. 8**). In certain applications, for enhanced safety of the lowest voltage winding, the use of a shield connected to earth, positioned between the primary and secondary windings enables this fault hypothesis to be eliminated by favoring phase-earth faults. In this case, earthing connections of the transformer frame and of the LV neutral are different, thus avoiding increased LV network potential relative to earth.

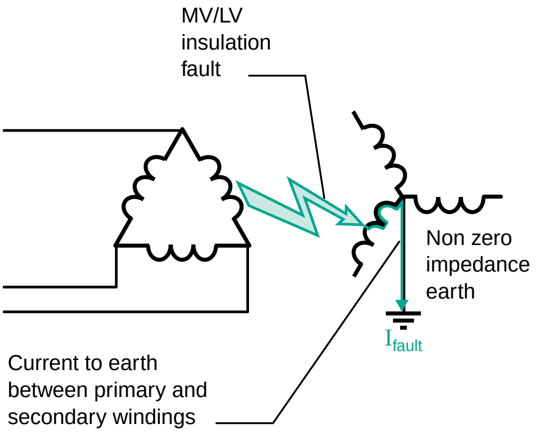


Fig. 8: example of a fault between primary and secondary windings.

Faults to earth and the influence of the neutral earthing arrangement

Faults between MV windings and earth most frequently originate from a break in insulation following an overvoltage. Nevertheless they can also be the result of mechanical type faults or the progression of an electrical fault as previously seen. The characteristics of an earthing fault, as well as the capacity to detect it, depend on the supply network earthing arrangement and on the location of the fault in the transformer (see **fig. 9**).

- In the case of a non-distributed medium voltage neutral, connected to earth by an impedance of some sort, the fault will cause a current to earth to appear varying as a function of the neutral impedance and the position of the fault on the winding. In the case of a very low fault current, there is a risk of a slow increase in pressure similar to that for faults between the turns. Arbitrarily fine detection of the current to earth would be an effective means of protection; nevertheless, such protection is not always technically and/or economically achievable.
- In the case of a tuned neutral network (earthed by a Petersen coil), an insulation fault in an oil filled transformer will be of recurring self-extinguishing type. The low value of the fault current enables its spontaneous extinction in the oil and progressive reappearance of the voltage, characteristic of a tuned neutral network, leading to another breakdown several hundreds of milliseconds later. The frequency of the phenomena will increase if there is progressive deterioration by successive breakdowns leading to a lowering of the dielectric withstand.
- In the case of a neutral network directly connected to the earth and distributed (4 wires network, of North American type), the presence of neutral current is normal, due to the existence of single-phase loads, and the appearance of a fault will increase this current (as a function of the impedance of the winding section not in short-circuit). The situation is therefore analogous with the short-circuited autotransformer. The fault current will always be significant and require quick response or otherwise risk resulting in an explosion. It risks, however, not being seen by the network's protection devices which are set to allow a large neutral current (up to 40 % of the line's rated current). It is therefore the transformer's protection which must be able to act.

A significant proportion of faults concern the transformer's frame, then the ground Protection against earth faults is therefore useful. The current to earth being zero under normal conditions (except in networks with an earthed and distributed neutral arrangement), such protection can be set with a low threshold, e.g. 10 % of the rated current with a time delay of 100 ms, in cases with current transformers and a few amperes in cases using a residual current sensor.

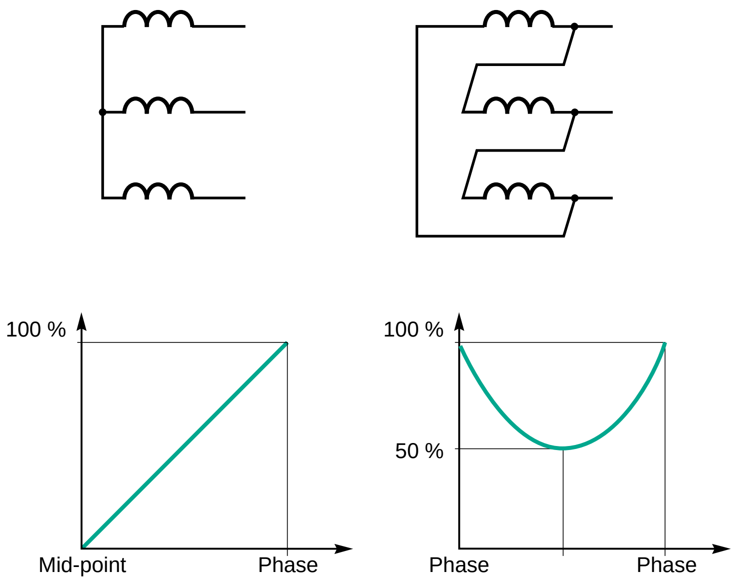


Fig. 9: fault current to earth as a function of MV coupling and the fault position.

2.6 Faults related to technology types

Internal transformer faults are primarily the consequence of external stresses (overvoltages, overintensities). We have previously seen the various failure modes and the manner in which the situation can progress.
Nevertheless, other failure modes are foreseeable according to the type of transformer technology.

■ Oil filled-type transformers

□ A dielectric leak not detected in time results in an electrical fault through the loss of insulation above the coils. Such a leak can be caused for example by corrosion of the tank or by an impact.

□ Pollution of the dielectric though the presence of particles from the tank itself, the core or the insulation, or water penetration, can also cause a situation of dielectric breakdown. Such pollution is not usually monitored in distribution transformers.

■ Solid insulation transformers

□ Abnormal mechanical stresses (impacts, efforts to tighten connections, etc.) can crack the insulation, causing arcing between turns or to neighboring earthing.

□ Insulation cracking can also be the result of abnormal thermal ageing related to wrong transformer use.

□ Molding imperfections in solid insulation can create partial discharge phenomena, if bubbles are present in the insulation in areas with a high electrical field. This phenomena causes internal breakdown of insulation material and can lead to a major failure.

□ The presence of external pollutants (dust) on such transformers disturbs the distribution of surface dielectric stresses and can cause insulation faults.

□ The presence of metallic earthing at a distance of less than that recommended by the manufacturer can cause excessive local stress on the insulation.

A summary of stresses in operation and their consequences is presented in **figure 10** .

Stress	**Possible cause**	**Most probable failure**	**Initial signs**
Overvoltages	Nearby lightning strike Network switching	Breakdown between MV turns Breakdown between winding and earth	Gas or smoke release Slight increase in phase current Current to earth
Slight overcurrent	Overload Impedent fault on the LV network	Destruction of windings at hot spots with short circuiting of turns	Gas or smoke release Slight increase in phase current
Violent overcurrent	Nearby LV fault	Destruction of windings at hot spots with short-circuiting of turns and shifting of windings	Quick and random progression towards a fault between windings
Ageing	Cumulative effect of past faults	Breakdown between MV turns Possible progress towards the earth	Gas or smoke release Slight increase in phase current Current to earth

N.B.: all failure modes, if not remedied in their initial stages, will develop to become generalized in the various windings and violent consequences such as rupturing of the tank and/or explosion of the windings possibly followed by a fire.

***Fig. 10**: summary of operating stresses and their consequences.*

3 Overvoltage protection

3.1 General

A single feeder supplied transformer, or one positioned at the opening point of a ring, represents a very high impedance at high frequency compared with the cable or supply line's wave impedance. Because of this, during wave propagation phenomena, the transformer represents a point of almost total reflection and the stress that it is subjected to can reach approximately twice the maximum voltage of the incident wave. It is essential that limiting devices are positioned in the immediate vicinity of the transformer in order to be effective. The corresponding order of magnitude is of around a dozen meters. Installation conditions, in particular the length of the connections and the earthing impedance values, have a large influence on protection device performance levels
(see “Cahier Technique” n°151: Overvoltages and insulation co-ordination HV and MV, and “Cahier Technique” n°168: Lightning and HV electrical installations).

3.2 Lightning arrestors and spark gap protection

Two means of overvoltage protection are widely used: spark gap protection and lightning arrestors.
Spark gap protection devices are simplest and least expensive. They are exclusively used on overhead networks.
Lightning arrestors provide protection with greater performance, but at a noticeably higher cost.

Spark gap protection devices

Spark gap protection devices are simple mechanisms comprising two electrodes in air. Voltage limiting across its terminals is achieved by arcing in the air gap.
This has a certain number of disadvantages such as:

- High variations in flash-over level as a function of environmental conditions (humidity, dust, foreign bodies, etc.).
- Dependence of the level of protection in relation to the steepness of the overvoltage gradient.
In fact, air behaves with an “arcing delay” which means that a high overvoltage with very steep gradient does not lead to arcing until reaching a peak value noticeably greater than the desired protection level (see **fig. 11**).
- The appearance of an earth fault current after spark gap protection operation.
This “follow-up” current, whose intensity depends on the network's neutral earthing arrangement, cannot in general extinguish itself spontaneously and requires the intervention of an upstream protection device. Reclosing performed a few hundreds of milliseconds later enables service to be restored.
Devices such as the shunt circuit-breakers, for impedance earthed networks, extinguish the arc and suppress the fault without leading to an interruption in supply.

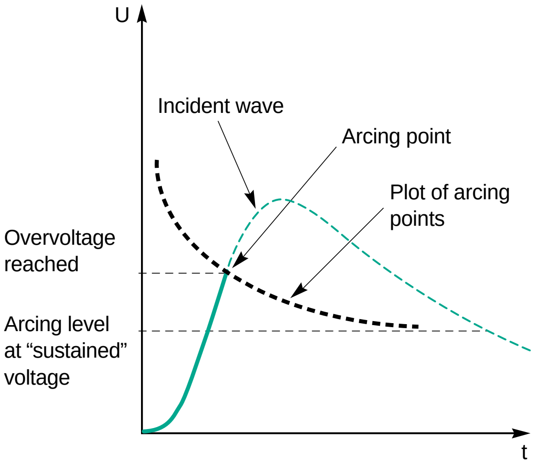


***Fig. 11**: behaviour of spark gap protection relative to a steep gradient; the more dV/dt increases, the higher the overvoltage.*

Lightning arrestors

Lightning arrestors enable this detrimental behaviour to be eliminated by having reversible behaviour. They are extremely non-linear resistors with a large decrease in internal resistance above a certain terminal voltage value (see **figure 12**). Operational reproducibility is much better than with spark gap protections and delay phenomena are non-existent.

The old silicon carbide (SiC) models are not able to withstand the operating voltage on a continuous basis since their residual current is too great and generates an unacceptable dissipated power. They are therefore associated with serial spark gap protection devices capable of interrupting the residual current and of maintaining the operating voltage.

The more recent zinc-oxide (ZnO) models have more accentuated non-linearity which enables them to have leakage currents less than 10m A at the operating voltage. Because of this, it is possible to permanently keep the active parts energised. Their extreme non-linearity also improves the efficiency of their protection against high currents (see **fig. 12**).

Zinc-oxide lightning arrestors, whose use is becoming widespread, are available in the references suited to use on overhead networks, in cubicles or in extension to the plug-in conection accessories. All installation possibilities can therefore be covered.

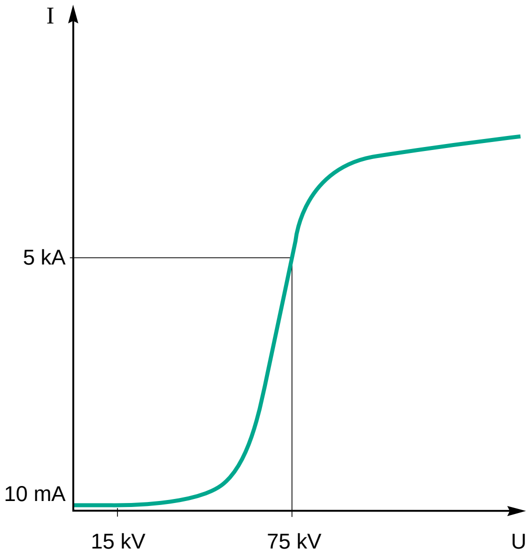


Fig. 12*: example of the characteristic curve of a zinc oxide (ZnO) lightning arrestor intended for 20 kV networks, insulated to 125 kV “impulse”.*

4 Overload protection

4.1 Current measurement protection

Protection against overloads must act at a threshold of between 110 and 150 % of the rated current and preferably operate in a time dependant manner. It can be placed on either the MV or LV side.

The lower the transformer power, the more the positioning of the protection on the low voltage side is suitable. As opposed to this, the higher the power, the more the choice of a protection on the MV side is wise.

MV side protection

Protection against overloads on the MV side is of interest for high power transformers with an MV circuit-breaker associated with auxiliary source protection devices. These protections can be constant time or time dependant. They also guarantee protection against high fault currents (i.e. MV fault). In any case, selectivity requirements with low voltage protection devices must be complied with.

LV side protection

LV side protection is easy to achieve with a main LV circuit-breaker. This type of device employs an inverse time curve (so-called thermal or long delay) which generally overprotects the transformer. In fact, the time constant and the inertia taken into consideration to define this curve are those of the low voltage ducting, which is lower than that of the transformer.

In order to protect the transformer, the circuit-breaker is not set as a function of the thermal withstand of the downstream conductors, as is often the case in low voltage networks, but as a function of the rated current of the transformer placed upstream which is generally lower than the rated current of the conductors. If the general circuit-breaker is time delayed, in order to ensure the time-based selectivity with the low voltage feeders, then selectivity (possibly with medium voltage protection) can become difficult. This subject is further developed in paragraphs discussing medium voltage protection.

Remember that in this type of low voltage protection scheme, we choose to protect the transformer against overloads and short-circuits on the low voltage network, without taking account of internal failure modes.

In public distribution networks, it is common practice to use fuses on low voltage feeders when the fault current throughout the network is sufficiently high. These fuses are rated to only operate during short-circuits between the public low voltage network conductors and are not intended to protect the overloaded transformer. The use of fuses, therefore, with quick response rates at high fault currents, makes coordination easy with any protection devices on the medium voltage side.

One case in particular in overhead public distribution is seen when the low voltage network has high impedance due to long distances and use of unshielded conductors. Faults can occur a long way from the transformer between phases or from phase to earth for which the current remains low, e.g. of the order of 2 or 3 I_n transfo.

Such a fault situation presents a public hazard at the fault location, as well as a risk for the transformer if it persists. These faults are not detected by the usual short-circuit protection devices such as fuses and can justify the adoption of a circuit-breaker “overload” protection capable of responding in this situation.

The release switches associated with such low-voltage circuit-breakers can be equipped with a “thermal imaging” function which tolerates single-phase overloads, if the other phases are hardly loaded and the resulting temperature within the transformer remains at an acceptable level. This operating mode is only valid for “oil filled” technology transformers in which the liquid dielectric favors heat exchange between its various components.

This solution is of particular interest in public distribution where the increase in loads connected to a low power transformer is difficult to optimize. It is used in circuit-breakers intended to for pole-mounted transformers and thereby helps eliminate unjustified customer power outages. The technology chosen involves recreating an interaction by heat exchange in the release between the three current measuring components - generally positive temperature coefficient resistors - as well as an overall thermal inertia which is representative of a protected transformer. For the same maximum hot spot temperature in the transformer, the tripping current in a permanently unsteady state can thereby be increased to values noticeably greater than those achieved by independent phase protection. Moreover, taking into account of thermal inertia enables a more efficient use to be made of the transformer during temporary overloads (see **fig.13**).

	Phase 1	**Phase 2**	**Phase 3**
Limit case	0	0	2.15
Frequent case	0.8	0.8	1.6
Without thermal imaging	1.2	1.2	1.2

Fig. 13*: thermal imaging protection - various cases of possible unbalanced operation.*

4.2 Temperature measurement protection

Temperature control of windings is the most relevant action since it is the temperature which ages the insulation.

Nevertheless, for temperature rises occurring in energized sections, the measurement cannot generally be taken directly on these points. The slow rate of temperature variation for the currents during overloading, due to the thermal inertia of the transformer, enables the measurement to be considered representative. A quick rise in winding temperature is normally managed by overcurrent detection.

For oil filled type transformers, it is generally the temperature of the oil that is taken as an indication. In fact, the liquid dielectric functions as a cooling fluid for the winding and tends to even out the internal temperature of the transformer. Temperature measurement can be achieved by a thermostat capable of independently supplying information to an output contact. Two thresholds may be used to define an alarm thresholds, e.g. leading to load shedding or assisted cooling, and a trip threshold. This function is included in devices such as the “GRPT” described below.

For cast resin transformers, it is not possible to only take one measurement since the temperatures can be very different from one winding to another in the case of imbalance. Moreover, their technology does not lend itself to the use of thermostats in which the active parts are fairly bulky. Manufacturers offer transformers equipped with platinum sensors, as on certain medium voltage motors. It is common practice to equip each winding with two sensors, in order to be able to closely monitor the spots known as being the hottest. These sensors are connected to electronic processing which can manage several thresholds used to cause either load shedding or general circuit-breaking.

5 Protection by MV fuses and fuse switches combinations

For operating requirements - switching, changing fuses, isolating - fuses are installed downstream of a switching device. Such switchgear often takes the form of fuse switches. In this case, the fuses are installed in the switchgear unit without there necessarily being a link between the melting of the fuses and the operation of the switch. When the fuse has a striker capable of opening the switch on melting, the device is then designated by the term “fuse switch combination”.

5.1 Characteristics of MV fuses

General

Fuses are a very widely used means of protecting distribution transformers, mainly due to their simplicity and the correspondingly reduced cost of the equipment.
Nevertheless, their technological limits lead to a certain number of disadvantages or imperfections which mean that fuse protection can be considered to be rather basic.

Fuses are characterized by their rated current, the highest current value that the fuse can accept on a continuous basis in an open-air installation, and by their current/time fusing characteristic.
The rated current depends on temperature rise criteria in steady state on the contact surfaces and on the insulating enclosures. It does not correspond to melting.
There is still a zone of current values between the rated current and the start of melting.
A current in this zone generates unacceptable temperature rises, deteriorating both the fuse and its environment to a greater or lesser extent.
Certain fuses integrate temperature sensitive mechanisms intended to trigger the switch in the case of a fuse switch combination.

Classification of MV fuses

There are two main families of fuses: expulsion fuses and limiting fuses.
Expulsion fuses are widely used in North-American type overhead distribution, in units which often provide an automatic disconnecting function.
Nevertheless, the fact that they are non-limiting, their limited breaking capacity and especially their external use means they tend to be less frequently used.
Because of this we will look in more detail at limiting fuses, such as those defined in the IEC 282.

- Of these fuses, the most common belong to the “back-up” (or “associated”) category of fuses. They provide a minimal breaking current (I_3 in the standards) greater than their minimum melting current.

- Fuses in the “general purpose” category are defined as having a minimal breaking current such that the corresponding melting time is greater than one hour.

- The fuses in the “full range” category guarantee clearing of all melting currents, up to the short-circuit breaking capacity.
These fuses are generally more expensive than those in the “back-up” category, which limits their use.
Moreover, they still enable overheating and do not provide a solution in all installations.

Looking at characteristic fuse curves we can observe that:

- the minimal fusing current is between 2 and 5 times the rated current, according to the types of fuses,

- the response time is extremely dependant on the current, and very variable (current tolerance of ± 10 %). The exact shape of the curve depends on the type of fuse, and its technology.
This time is very low for high currents (greater than 20 times the rated current) (see **fig. 14**).

Selection criteria

The ability of limiting fuses to respond within around a few milliseconds at high currents is their main advantage, excepting the cost.
This characteristic enables the fuses to provide a limiting effect on the current that is very useful on high short-circuit current installations.
In fact, the designer can dimension downstream circuit conductors and components taking account of this limiting effect and, therefore use fault current withstand values less than the network's short-circuit current.
This limiting also helps to reduce the destructive effects of a major fault.

The rules regarding the selection of fuses, given by the manufacturers and dependent upon the characteristics of each fuse type, cover the following criteria:

- the transformer's operating voltage,
- the switching currents,
- the generally accepted possibility of temporarily overloading a transformer,
- the need for a near-by low voltage fault (upstream of the LV protection devices) to be eliminated within a sufficiently short period of time,
- compliance with LV protection selectivity (see **fig. 15**).

These criteria are further covered in appendix 1.

Taking into account all of these criteria, as well as the MV short-circuit current, the installation conditions and the possible need for selectivity, makes the choice of fuses fairly complex.
Because of this, a number of installations operate with fuses that do not correctly ensure the protection for which they have been installed.
This can result, either in spurious melting during energizing or in non-protection due to the unsuitability of characteristics.

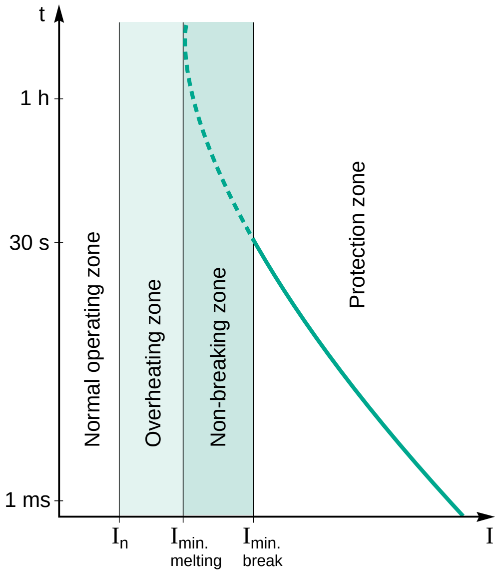


Fig. 14: characteristic curve typical of an “combined” fuse.

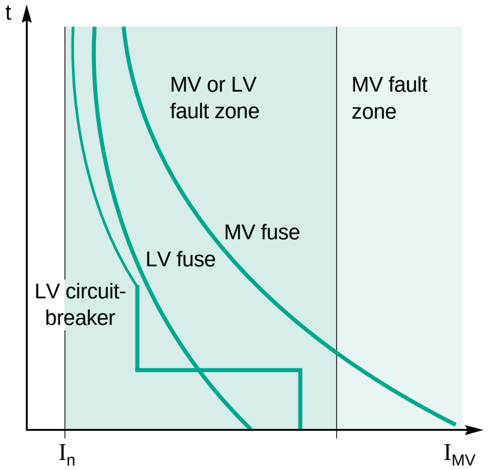


Fig. 15: selectivity between MV fuses and LV protection devices.

5.2 Limits of fuses

Handling precautions

Fuse technology - metal wires or ribbons parallel connected in sand - makes them mechanically fragile during handling or transport.
Deterioration is frequently observed due to the rupture of one or more conductors, in the absence of all electrical stresses.
The use of a damaged fuse is equivalent to using an abnormal low fuse rating and quickly leads to temperature rise phenomena. Such phenomena can have a disastrous effect on the switchgear and thereby on the whole installation.
In order to avoid this type of incident, operators can measure resistance just before installation, in order to ensure that the fuse's resistance is in conformity with its specifications and therefore the fuse does not have a broken conductor element.

Prohibited operating points

- The “prohibited” operating zone for “back-up” fuses extends from the rated current to the minimal breaking current. In this zone, two successive behaviours can be observed:
    - between the rated current and the minimal melting current, the excessive temperature rises can damage the fuse envelope and its environment within the switchgear;
    - between the minimal melting current and the minimal breaking current an arc appears that does not self-extinguish and which quickly leads to a major medium voltage fault if no other device intervenes.

Because of this, these fuses must be used with care, only in applications in which the occurrence of a current of value located in this critical zone is impossible. If these fault situations are possible, it is necessary to use the fuse switch combination. This solution is discussed below. The selection guide, IEC 787, regarding fuse protection of transformers reviews the various criteria.

- “Full range” fuses do not have a minimal breaking current. Their “prohibited” zone is therefore limited to the current values between the rated current and the minimal melting current, in order to comply with temperature rise limits. This is not a problematic zone except for semi-permanent phenomena which can lead to detrimental thermal effects. The order of magnitude of the time is one hour.

- In transformer protection applications, faults are often progressive, based on low currents. This type of fault can subject the protection device to a current that very gradually increases beyond the rated current. Such progression, in a circuit protected by fuses of whatever type can be considered as dangerous due to the fact that it will systematically take the fuse into the critical zone. A slowly progressing fault in the transformer, can result in failure of the device, through overheating or non-breaking of the fuse.

E.g: a 400 kVA transformer at 11 kV is protected by back-up fuses with a 40 A rated current, according to the fuse manufacturer's selection guide, while the rated current of the transformer is 21 A. The melting curve for such a fuse shows a minimal melting current of approximately 100 A with a minimal breaking current of approximately 130 A. In the case of a fault between the primary turns, there is a high probability that this fuse will be required to handle a dangerous level of current, the minimal breaking current being to the order of 6 times the transformer's rated current.

Single phase operation

Assuming only one fuse melts, the transformer is then supplied by the two remaining phases.

Depending on the transformer coupling, low voltage loads will observe a different situation.
In the case of a delta-star coupling, two low-voltage phases out of three will find themselves in a reduced voltage situation and the phase displacements no longer complied with.
This situation is mainly harmful to three-phase motors, as well as single phase motors connected to the phases with reduced voltage.
Other applications can also be affected by reduced voltage, e.g. relay beats or discharge lamps.
Separation on a single phase is therefore most often a situation to be avoided and can be considered as being worse than a complete outage bv.

Parallel connected transformers

In the case of using parallel connected transformers, it is essential to protect them using a common device.
This avoids the re-supply a transformer fault across the low voltage coupling (see **fig. 16**).

If we want to achieve such protection using fuses, the above mentioned dimensioning criteria are applied to select fuses using the current resulting from both transformers.
Because of this, the minimal melting and breaking currents are seen to increase by a factor of nearly 2, compared with fuses dedicated to a single transformer.
The protection given against internal faults in one of these two transformers is therefore notably reduced; There is therefore an increased risk of these fuses being subjected to critical over-heating situations or melting below I_3.
The use of fuse protection is therefore not recommended in such installations.

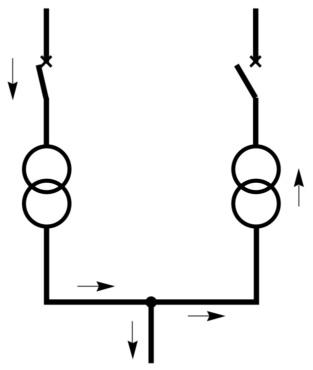


***Fig. 16**: current circulation after opening of an MV protection device during a primary fault.*

5.3 Using a fuse switch combination

Advantages

Spurious melting, caused by ageing or transitory phenomena are the main cause of situations in which one MV phase is missing.

Single phase separation is avoided by the use of a fuse switch combination, in which the fuses are equipped with a striker. In this type of device the first tripped fuse's striker activates the switch mechanism and causes it to open. The interruption of supply is therefore across all three phases whatever be the reason for the melting of the fuse.

This operating mode also enables the switch to clear low value fault currents situated in the fuse's prohibited zone (between the minimal melting current and I_3). The risk of the non-breaking of the fuse is thereby eliminated.

As opposed to this, since the combination's switch does not have a fault breaking capacity up to the short-circuit current, the selection of the switchgear-fuse pairing must comply with coordination rules. The objective of these rules is to guarantee that the switch will never be placed in a situation in which it will be incapable of breaking. The IEC publication 420 discusses these criteria.

In the fuse switch combination, we are therefore seeking to achieve separation of fault situations:

- high currents are eliminated by the fuses, using their breaking capacity and limiting effect,
- and lower currents are eliminated by the switch, by the striker or another external order.

Complexity

Among the parameters taken into consideration in deciding on a switchgear-fuse pairing is the ability of the switch to interrupt “transfer” currents. Transfer currents are defined as the value of the three phase current at which the fuses and the switch exchange the breaking function: immediately below this value, the current in the first pole that trips is cleared by the fuse, and the current in the two other poles by the switch; above this value, the current in all three phases is cleared by the fuses. The calculation of the transfer current is shown in appendix 2.

The calculations and the tests performed to cover this situation are all based on assuming constant fault impedance. This is not necessarily the case since the fault current is progressive and may have increased.

The positioning of the transfer current must also guarantee that fuses act in fault situations generating severe transient recovery voltages. E.g. for a fault across the transformer's low voltage terminals. Certain cases of low voltage faults between only two phases can, according to the transformer coupling, generate critical situations not covered by IEC 420.

Limits

The choice of fuse in a fuse-switch combination for a transformer protection application must satisfy a large number of criteria. Switchgear manufacturers supply the list of fuses that can be used in their combination (brand, types and ratings) for each type of application. In the case where these recommendations are not complied with, protection may be deteriorated, or safety compromised according to the faults occurring. The basic rules are further discussed in appendix 1 but alone they cannot guarantee coverage of all possible fault cases.

The overheating zone still exists, for virtually all fuses, and the use of a combined fuse-switch does not provide any means of protection against thermal damage if the current is maintained in this zone. This is why certain manufacturers offer fuses with an integrated temperature limiter which, in the case of abnormal temperature rises, trips the striker and thereby the combination.

Additional protection possibilities

The use of fuse-switch combination can be beneficial when adding an additional protection device such as earth fault protection or when taking account of pressure or temperature. The time delay must in all cases guarantee compliance with the combination's take-over current. The take-over current is defined as the current value at the intersection of the time-current characteristic curves of two maximum current protection devices (VEI 441-17-16), therefore being the current value at the intersection of the fuses' curves on one hand and the protection device on the other (IEC 420) (see appendix 2).

In conclusion, combined protection is relatively complex and involve risks. For this reason, the electrical installation designer may prefer circuit-breaker protection which he can more easily associate with high performance functions.

6 MV circuit breaker protection, associated tripping devices

The use of a circuit-breaker has the main advantages of not creating critical currents - the circuit-breaker is capable of breaking all currents lower that its breaking capacity - and of offering great flexibility in the choice of operating criteria. The technical solutions offered are frequently more costly with circuit-breakers than with fuses, fuse switches or fuse-switche combinations. Nevertheless, certain arrangements, particularly compact Ring Main Unit type devices, offer circuit-breaker solutions at a unit cost similar to fuse based solutions.

6.1 Trip-curve selection criteria

General

Maximum current protection devices operate when the current exceeds a set value for a set period of time.
So called “time dependant” protection devices, for which the trip time depends upon the value of the circulating current, are those most commonly used.
In fact, they make it possible to reconcile large time delays in low current zones (overload or “early” internal failure) with fast operation in case of major faults. The current-time curve of the relay also guarantees non-tripping during transitory phenomena such as inrush currents.
Several curves are provided in international standards (IEC 255) which have the advantage of offering selectivity between medium voltage circuit-breakers.
Other curves are provided by manufacturers, better suited to the protection of distribution transformers.

Selectivity

Selectivity involves only tripping the protection device closest to the fault, in order to minimize the portion of the installation or network taken out of service. In the specific application of protecting an MV/LV transformer, selectivity must be sought relative to the upstream MV circuit-breaker and, possibly, relative to downstream low voltage protection devices. In public distribution, the circuit-breaker immediately upstream of the transformer protection device is a feeder or branching circuit-breaker; its protection parameters are generally governed by much higher values and selectivity is achieved without any additional constraint.
Selectivity relative to downstream devices is only useful in cases where several low voltage protection devices are parallel connected. Even if there is only one LV protection device, a loss of selectivity does not change the fact that all the LV consumers are disconnected. One can therefore consider that the MV circuit-breaker and general LV protection device make up a single selectivity level. In fact, regulatory or contractual aspects between the utilities and the LV customers mean that operators rarely have access to both circuit-breakers. In private MV installations, and when the equipment used permits, the incorporating of logical selectivity between the MV circuit-breaker and general LV protection device provides considerable simplification (see “Cahier Technique” n°2: Protection of electrical distribution networks by the logic selectivity system).

Example

Figure 17 shows the fault current levels in an installation. One can observe that the low

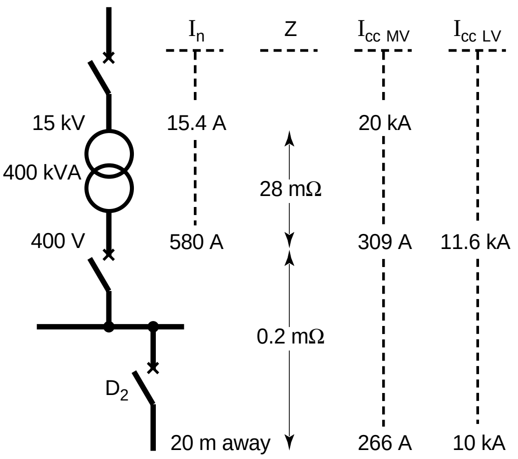


Fig. 17: impedances and fault currents – an example of an installation.

voltage short-circuit level varies quickly solely due to the impedance of the conductors.
If one considers that the D_2 circuit-breaker is not limiting and that it is set at 5 mohms from the transformer (15 to 30 meters of LV conductor), the fault current which can immediately be established across the downstream terminals is of around 16 times the transformer's rated current. It is therefore necessary to check that selectivity is achieved at this current value.
The quickest standardized curve (extremely inverse), set to obtain 20 ms at 20 I_n, therefore gives a tripping time equal to 31 ms.
Selectivity is obtained if the D_2 circuit-breaker eliminates the fault within 15 ms, to take into account the memory time of MV relays.
In the case of complex installations, in industrial distribution, it is possible that the D_2 circuit-breaker is itself time delayed at high fault values.
It is therefore necessary to use an operating mode on the MV relays which enables time based selectivity to be guaranteed up to this fault value of 16 I_n (see **fig.18**) or to use logical selectivity.
In the case of public distribution, one never finds cascading circuit-breakers without the impedance between them being fairly significant thus enabling current based selectivity.

Practical solutions

The thresholds available on relays only rarely correspond exactly with the rated current of the monitored transformer, which leads to a shift in the protection curve towards higher currents. This leads to increasing the selectivity margin. Manufacturers can therefore offer curves different from standardized curves, enabling operation to be better targeted towards the operational requirements of transformers.

A dedicated MV transformer protection device must meet the following criteria:

- always be quicker than the MV protection device immediately upstream,
- be as quick as possible for current values greater than the low voltage short-circuit current (20 to 25 I_n transfo depending on Z_{sc}),
- let inrush currents pass (see **fig. 19**),
- be able to guarantee monitoring of the overload zone, or the zone immediately above the overload threshold acceptable to the operator.

This is what justifies using a curve such as that illustrated in **figure 20** , used in certain Schneider group integrated protection devices. It can be noted that such a curve guarantees selectivity with any low voltage fuses, the latter

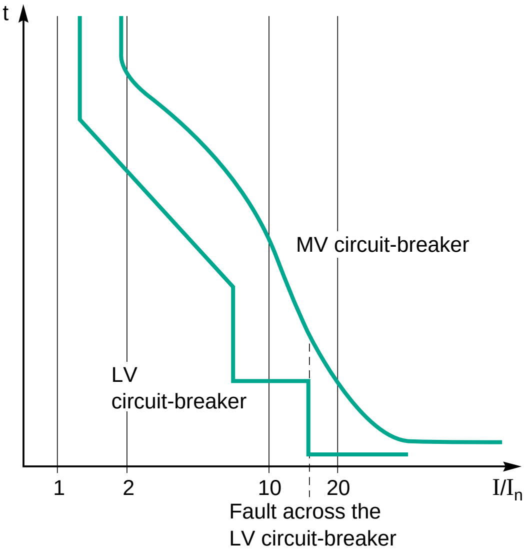


***Fig. 18**: co-ordination with a low voltage circuit-breaker by staggering time settings. Overloading is managed on the LV circuit. Internal faults are less well protected against.*

P (kVA)	I_{peak}/I_n	Time cnst (ms)
50	15	100
100	14	150
160	12	200
250	12	220
400	12	250
630	11	300
800	10	300
1000	10	350
1250	9	350
1600	9	400
2000	8	450

***Fig. 19**: making currents relative to the rated current (peak value) in oil filled transformers.*

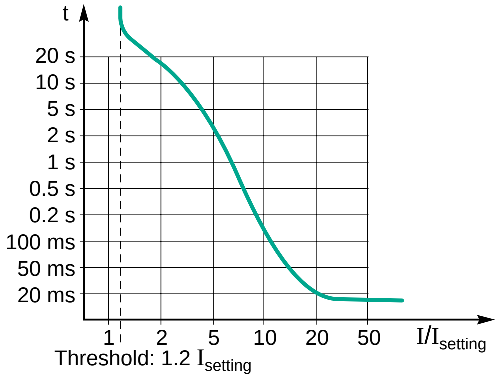


***Fig. 20**: trip curve for a relay dedicated to transformer protection.*

still achieving very rapid fault elimination (of the order of a few milliseconds) for fault currents near to the low voltage network's short-circuit capacity (see **fig.21**).

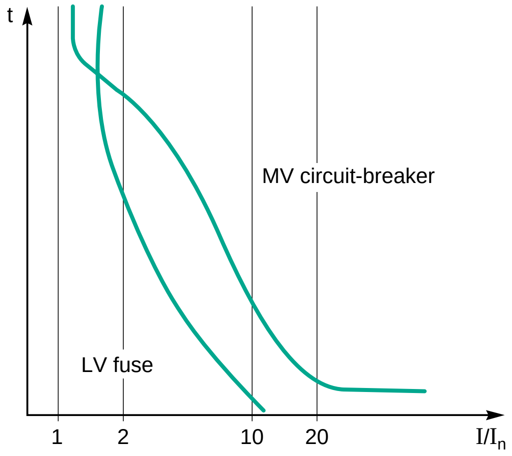


***Fig. 21**: operation relative to overload protection and internal faults by an MV circuit-breaker.*

6.2 Advantages of earthing protection

The behaviour observed during an internal ground fault depends on the MV network neutral earthing arrangement.
Residual current detection can cover all or part of these earth faults.
Furthermore, detection of residual current is also sensitive to the faults between primary and secondary windings, corresponding to earth faults detected by the upstream network.
Such protection is useful for a distribution transformer, apart from in earthed and distributed neutral networks.

Its operating threshold must be as low as possible; in fact there are certain limitations since:

- it must allow the “normal” residual currents to flow. In fact, in certain network operation situations, the imbalances of simple voltages - in relation to earth - can generate a residual current that is not zero across the transformer's stray capacitances and any connecting wires. Even outside of a fault situation, all parts of the network have a “natural” capacitive imbalance generating a residual current.
- it can be limited by the errors of instrument transformers in the case of a summation of three phase current measurements.

The technological limitations of the current transformers and protection devices require the use of threshold detection generally greater than 10 % of the rated current to avoid spurious tripping on the occurrence of transitory phenomena or in short-circuit.

In certain cases, “earthed tank” type detection, which implies being able to install the transformer insulated from the earth, can be considered.
Nevertheless, this type of protection poses difficulties in implementation related to the physical installation of the transformers and to the possible distance between these and the protection device. It is never used for distribution transformers.

6.3 Independent protection devices: Time Fuse Links (TFL) and relays

In many situations, particularly in public distribution and of course in small installations, it is not always conceivable to use an auxiliary power sypply to achieve protection. In fact, direct use of low voltage from the transformer does not enable a simple response to all fault hypotheses and the presence of an auxiliary source leads to a more expensive installation and unacceptable maintenance. Several types of protection devices without an auxiliary source exist, and fuses belong to this category.

Regarding the opening of a circuit-breaker, one finds three categories of mechanisms:

- Direct relays, in which the monitored current activates the release mechanisms by a thermal or magnetic effect, without current transformation.

This is the case of many low voltage circuit-breakers, but the direct relays are also suitable to medium voltage devices. They are tending nevertheless to disappear, basically due to their simple nature, their mediocre accuracy and their limited adjustment capacity.

- “Time Fuse Links” are mainly used by the British (see **fig.22**).
Under normal operating conditions, the coil is short-circuited by a low voltage fuse which is used to determine the protection parameters. In case of a fault, there is fusing and the current transformer's secondary current activates the coil. This basic principle is simple and efficient. Nevertheless, it implies having replacement fuses and it only offers a choice of limited characteristics related to the fuses' fusing curves.
Earthing protection can be achieved using a coil placed in the common conductor of current transformers. The current normally being zero in this section, there is no parallel connected fuse on this coil.

- Self powered electronic relays, in which the energy required for electronic and circuit-breaker tripping operation is taken from the sensors' secondary. These relays are combined with low energy release devices, generally with magnetic latching, which requires rearming by the circuit-breaking mechanism itself.
These relays are often combined with sensors, specially designed for this type of application, less voluminous and less costly than standardized current transformers.
The protection chain so formed can be integrated in a given switchgear, which enables a global solution to be offered with greater possibilities than the direct relay or TFL solutions.

The performance levels offered cover virtually all installation cases, using standardized curves or manufacturer's curves, and with very wide setting ranges.
The principle is nevertheless limited on low threshold values, due to the lack of available energy in the case of low MV current unless voluminous current sensors are used whose cost would be prohibitive.
Current limits (1998) for autonomous operation are approximately 10 amperes. Lower “ground fault” threshold values can be used, but will not be activated unless a load current - phase current - exists above the autonomous operating limit.

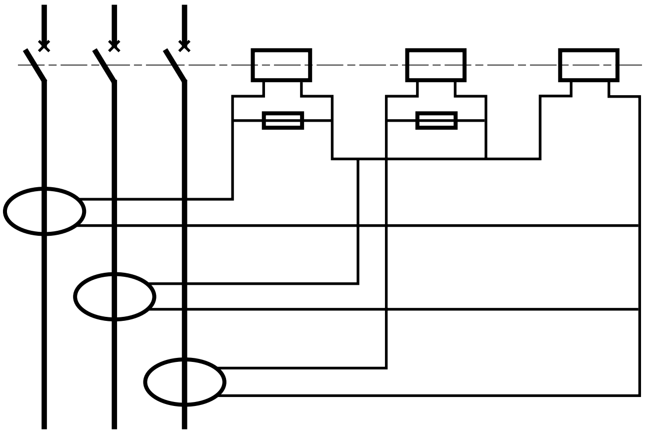


Fig. 22: wiring principle for a Time Fuse Links type protection device with two “phase” coils and one “earth” coil.

6.4 Protection devices with auxiliary power supply: GRPT, temperature sensors and relays

When an auxiliary source is decided upon to supply all or a part of the protection functions, it is possible to use other information than merely measurements of electrical values. The monitored transformer's low voltage can supply these functions if protection against the short-circuits is guaranteed by an independent mechanism.
Two widely used applications are dedicated to faults not yet causing a noticeable overcurrent and to overload situations: the GRPT and temperature sensors.

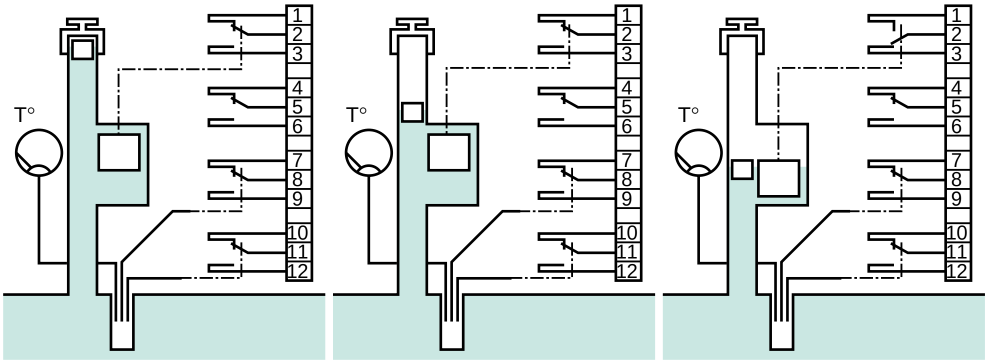
- The GRPT, standing for “Gaseous Release, Pressure, Temperature” is used for liquid filled and hermetically sealed transformers and is combined in one single auxiliary device monitoring these parameters. It therefore includes a pressostat function, a thermostat function, possibly with two thresholds, and a float mechanism which reacts to the abnormal presence of gas. It can be used for hermetically sealed immersed transformers. Several indication contacts are available for the various events which can take place (see **fig. 23**).

The function of monitoring gaseous release also acts in the case of accidental loss of liquid dielectric, in a preventative manner.

These functions are limited to slow phenomena. Quickly progressing faults requiring quick response, still require relaying in terms of analyzing electrical values.

- Temperature sensors, generally associated with dry transformers, supply accurate information on internal thermal stresses. They are combined with electronic processing which can manage various thresholds (overload alarm, load shedding, tripping). This information is used by the control system to manage the surrounding switchgear.

Moreover an auxiliary power supply provides access to low threshold protection values, to phase or to earth.
When a relay supplied by an auxiliary source achieves the basic protection functions (including protection against short-circuits), it is essential to have a back-up supply available. This guarantees the ability to manage all fault situations, whatever the LV voltage during the fault. The existence of a back-up source, as well as the monitoring and maintenance which must be associated, are a heavy constraint which limits the use of such devices to installations already with a back-up supply at their disposal for another reason. Such relays are therefore not found apart from in industrial or tertiary sector substations.


Normal Low drop in level Large drop in level

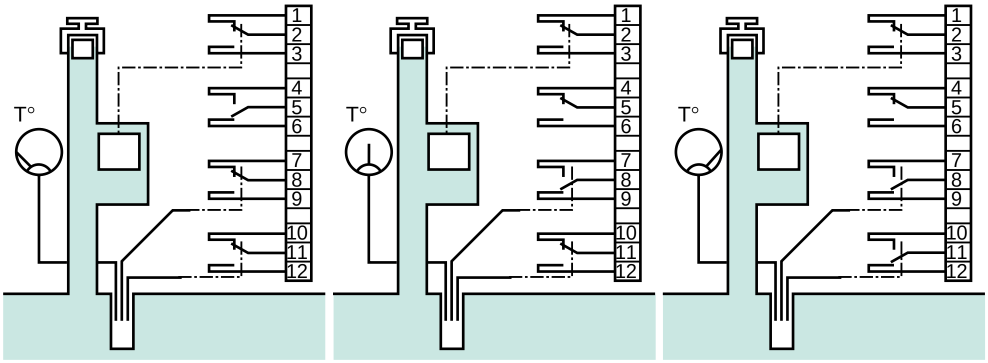

Internal overpressure Temperature rise (threshold 1) Temperature rise (threshold 2)

***Fig. 23**: operation of a GRPT device.*

7 Conclusion

The choice of distribution transformer protection (MV/LV) is a relatively complex matter since it must take account of a large number of parameters and several technical choices may be suitable and provide the same type of protection.

The transformer is generally specified initially. However, beyond criteria related to transformer functional requirements such as power or operating voltages or those related to installation conditions (presence of harmonics, risk of overload), the user should define his choice in terms of the operation and protection policy:

- the safety of people and installations or external effects in the case of a fault,
- continuity of service or life expectancy of the equipment,
- investment cost relative to the probability of fault.

Since the protection devices downstream of the transformer are directly dependent on the type of LV network and on the load characteristics, they are normally defined before the upstream protection devices.

The choice of protection devices used with the transformer is made at this moment; an iterative process is then required to ensure the consistency of the whole system: transformer, LV protection device and MV protection device (see **fig. 24**).

The various protection options are summarised in the logic diagram shown on the back cover. It shows the many different interrelations between the technical choices and also illustrates the

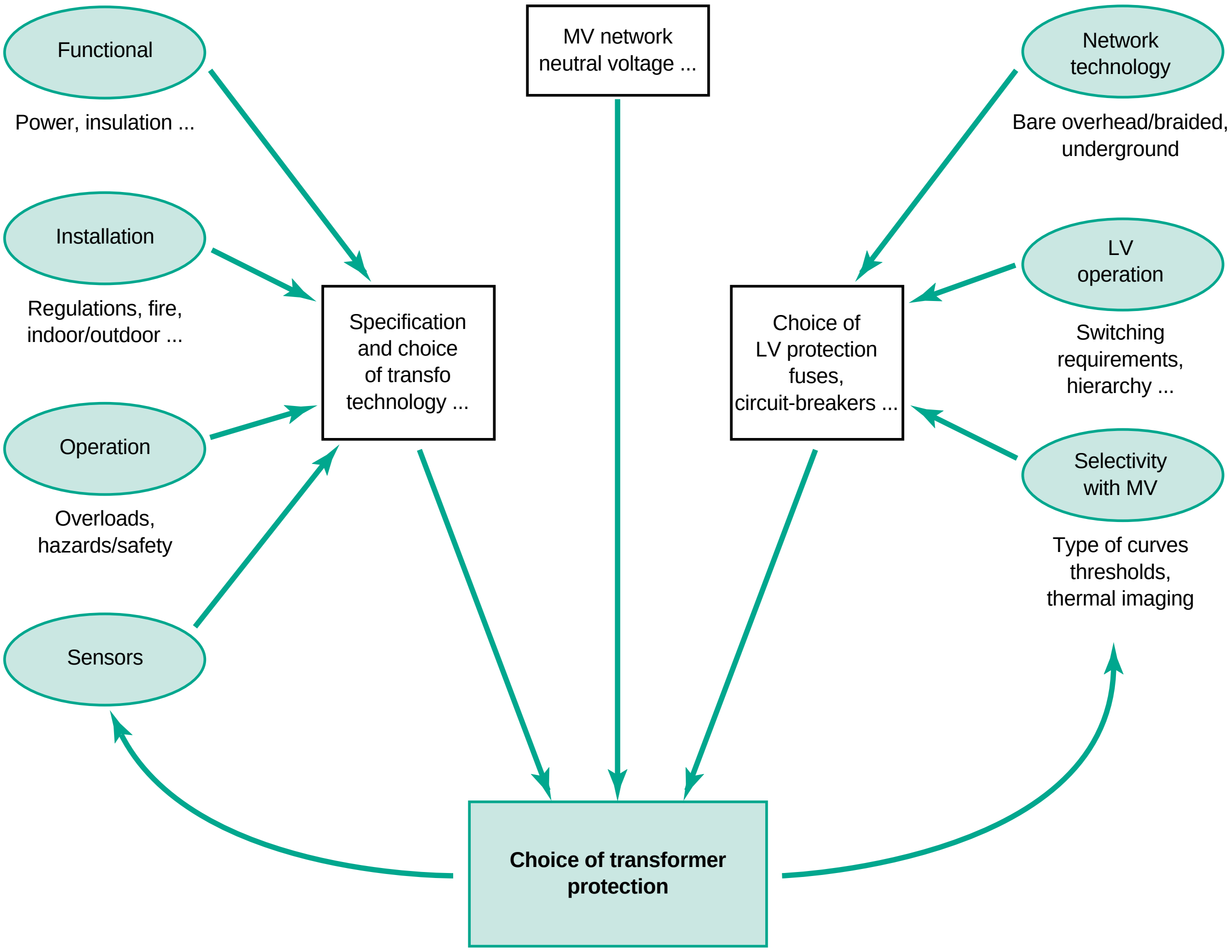


Fig. 24: processus itératif de choix d'une protection transformateur.

multi-criteria approach required to determine which protection device to use. The table in **figure 25** provides an overview of the possible technical criteria. It highlights the complexity of the interactions and the absence of an ideal and absolute solution.
In fact, MV protection devices are an integral part of the switchboards and the choice can be affected by others criteria. E.g. in choosing whether to use modular switchboards or compact switchboards, the choice is often made based on criteria not involved with protecting the transformer, such as the environment or the upgradability leading to a very different economic positioning for possible solutions. Indeed, the use of fuses in compact switchgear technology implies placing them in sealed enclosures which represents significant extra cost. With such technology a circuit-breaker solution becomes particularly competitive. In contrast, modular switchgear ranges offer fuse solutions which are more economical than the circuit-breaker solutions.

Result ⇒		Protection of a healthy transformer			Separation of damaged transformer		
	Situation ⇒	MV overvoltages	Overloads Far LV fault	Nearby LV fault	Internal fault 1	Internal fault 2	Major MV fault
Device ⇓	**Risk** ⇒	Internal type 1 or 2 fault	Temperature rise, reduction in life span	Thermal destruction (several seconds)	Progresses towards explosion	Progresses towards explosion	Explosion, fire
LV fuse				✡✡✡			
LV circuit-breaker			✡ (thermal imaging for immersed type)	✡✡✡			
Spark gap		✡					
Lightning arrestors	(znO)	✡✡✡					
MV fuse			💣	✡		💣	✡✡✡
Combined	IEC 420			✡	✡✡ (2)	✡✡ (3)	✡✡✡
MV circuit-breaker	Time dependent relay		✡	✡✡	✡✡	✡✡✡	✡✡
Temperature	With combination or circuit-breaker		✡✡		✡		
Pressure	With combination or circuit-breaker (only oil filled)				✡✡ (1)	✡✡	

Type 1 fault: fault to earth of a value less than the rated current
Type 2 fault: fault generating a current of a value between one and five times the rated current
Major MV fault: fault generating a current greater than 5 I_n
(1): overpressure detection can be used for faults generating a gas release, whatever the value of the current
(2): by combining with a earth fault relay
(3): as long as there is appropriate co-ordination
💣: risk of fuse failure in these situations

Fig. 25: table summarizing the various cases and possibilities of transformer protection.

Appendix 1: Rules governing selection of a fuse to protect a transformer

The selection guides offered by fuse and switchgear manufacturers take account of the following rules, for the part that concerns them, as well as any particularities of the switchgear in question (confining of fuses modifying their conditions of cooling for example) (see IEC 787).

I_{n_t}: rated current of the transformer.

$I_{sc\ LV}$: primary current in case of an LV short-circuit.

I_{n_f}: rated current of the fuse.

$I_f(t)$: current leading to melting in time t (the fuse's characteristic time-current curve).

I_3: minimal breaking current of the fuse.

Rules to avoid spurious melting

- Withstand operating current (and possible overloads)

$1.4\, I_{n_t} < I_{n_f}$.

- Withstand inrush currents

$12\, I_{n_t} < I_f\,(0.1\text{s})$.

Rule to eliminate a major LV fault

- Act before the destruction of the transformer

$I_f\,(2\text{s}) < I_{sc\ LV}$.

Rule for correct functioning of the fuse in the absence of a combination

- Do not operate the fuse in its critical zone. Manage situations with $I_{n_f} < I < I_3$ using a complementary means.

Rules for coordination to ensure the correct functioning of a fuse-switch combination

(see IEC 420)

t_s: minimal opening time of the combined switch caused by the striker.

t_d: opening time of the combined device under the action of the tripping device.

I_4: rated transfer current of the combination.

I_5: rated take-over current of the combination.

- Do not operate the switch beyond its performance levels: transfer current less than the rated value

$I_{transfer} < I_4$.

See appendix 2 for details of the calculation.

- Do not operate the switch beyond its performance levels: transfer current less than current in the instance of a fault across the low voltage terminals,

$I_{transfer} < I_{sc\ LV}$

(this rule does not cover all cases of faults only involving two phases on the low voltage side).

- Do not operate the switch above its performance levels: take-over current less than the rated value

$1.065\, I_f\,(t_d + 0.02\ \text{s}) < I_5$.

See appendix 2 for the details of this calculation.

Appendix 2: Calculating transfer and take-over currents of a fuse switch combination

Transfer current

To characterize the operating limits of a combined device, the search for the most severe conditions leads to considering the following operation (see **fig. 26**):

- when subjected to a fault current I_d, the first fuse to melt is on the minimal limit of the time-current curve,
- the two other fuses are on the maximal limit and are subjected, starting from the moment of clearing the first phase, to a current with a reduced value of 0.87 I_d.

IEC standard 420, which discusses these combined devices, provides a detailed calculation which leads to the following conclusion: the transfer current is the current corresponding to a melting time at the minimal characteristic equal to

$$t_{I_t} = 0.87^{\alpha}\, t_s \,/\, \left[(1.13)^{\alpha} - 1\right]$$

where t_s is the opening time of the combined device under the action of a striker, and a the slope of the fuse's characteristic time-current curve near the point under consideration (see **fig. 27**).

An iterative calculation, of a few steps, is generally necessary due to the variation of the slope along the characteristic curve. One can use the t_s value as an initial value of t_{I_t} for such an iteration (see **fig. 28**).

Manufacturer's settings for fuses can vary from one rating to another within the same range. E.g. within Merlin Gerin's FUSARC range, the

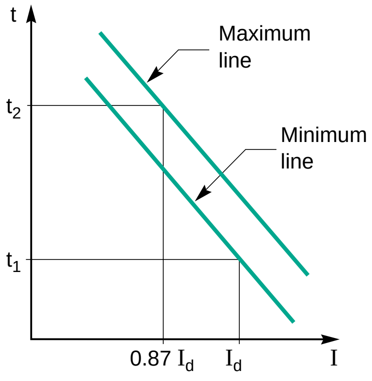


Fig. 26: determining the transfer current.

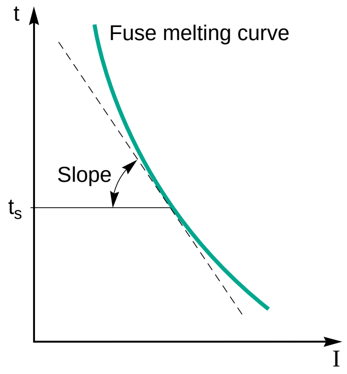


Fig. 27: determining the coefficient at the slope of the fuse melting curve.

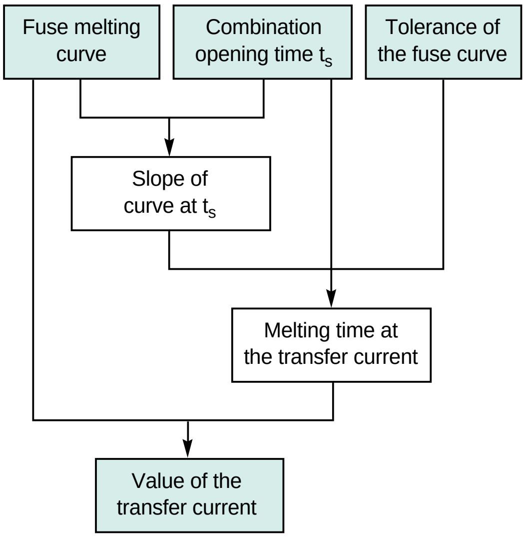


Fig. 28: principle for determining the transfer current.

coefficient α varies from 2.2 to 5.2; the transfer current for each fuse used in the combination must be less than the rated transfer current of the combination.

Numerical examples:

Considering a fuse-switch combination equipped with 80 A/24 kV fuses, where the time of opening after striker action is 60 ms (t_s).
If one chooses SIBA fuses, the slope obtained from the characteristic curve is α = 3.32; this gives a time from melting to transfer equal to:

$$t_{I_t} = 0.87^{3.32} \times 60 \,/\, \left(1.13^{3.32} - 1\right) = 75.5 \text{ ms}$$

or, according to the fusing curves, I_t = 850 A.
Choosing Merlin Gerin fuses, gives α = 3.34 which is similar. The transfer current is obtained from the melting curves, I_t = 800 A. Both fuses used in a combined RM6 device therefore provide equivalent operation.

Now let us consider the same combination equipped with 125 A/12 kV fuses. In the case of SIBA fuses, the curves provide us with a coefficient a equal to 3.1 giving a melting time of 85 ms. The transfer current is then 300 A. In the case of Merlin Gerin fuses, the curves give a equal to 2.65, or a melting time of 108 ms. The transfer current is therefore only 870 A. In this case the choice of fuse strongly influences the demands which can be placed on the switch of the combination, even if both these values can be acceptable.

Take-over current

The rated take-over current of a combination (designate by I_5) is the maximal take-over current acceptable. The switchgear manufacturer provides the opening time td of the switch under the action of the release device. All fuses used in the combination must guarantee compliance with the rated take-over current (see **fig. 29**).

In the most severe case for a given fuse, it is characterized as follows:

- "instantaneous" operation of the external relay; the standard proposes using a reaction time of 20 ms for such instantaneous operation. The resulting opening time is therefore the opening time of the combination under the action of the release device (t_d) increased by 20 ms;
- a fuse in a cold state and at the maximum of its tolerances (the standard considers that the tolerance for the melting curves is of ± 10 % of the current, enabling the use of a value of two standard deviations, or ± 6.5 %).

The take-over current is taken from the characteristic time-current curve under the above stated conditions, for the melting time of t_d + 20 ms.

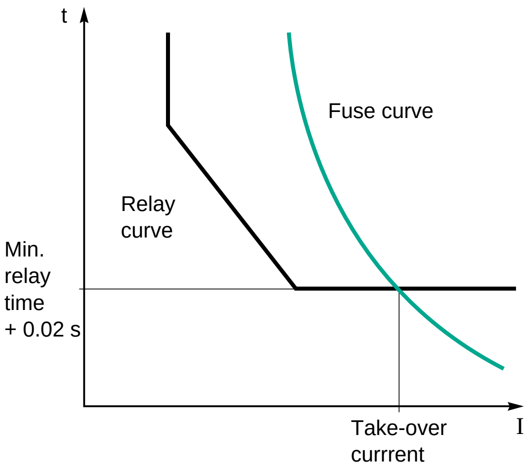


Fig. 29: determining the take-over.

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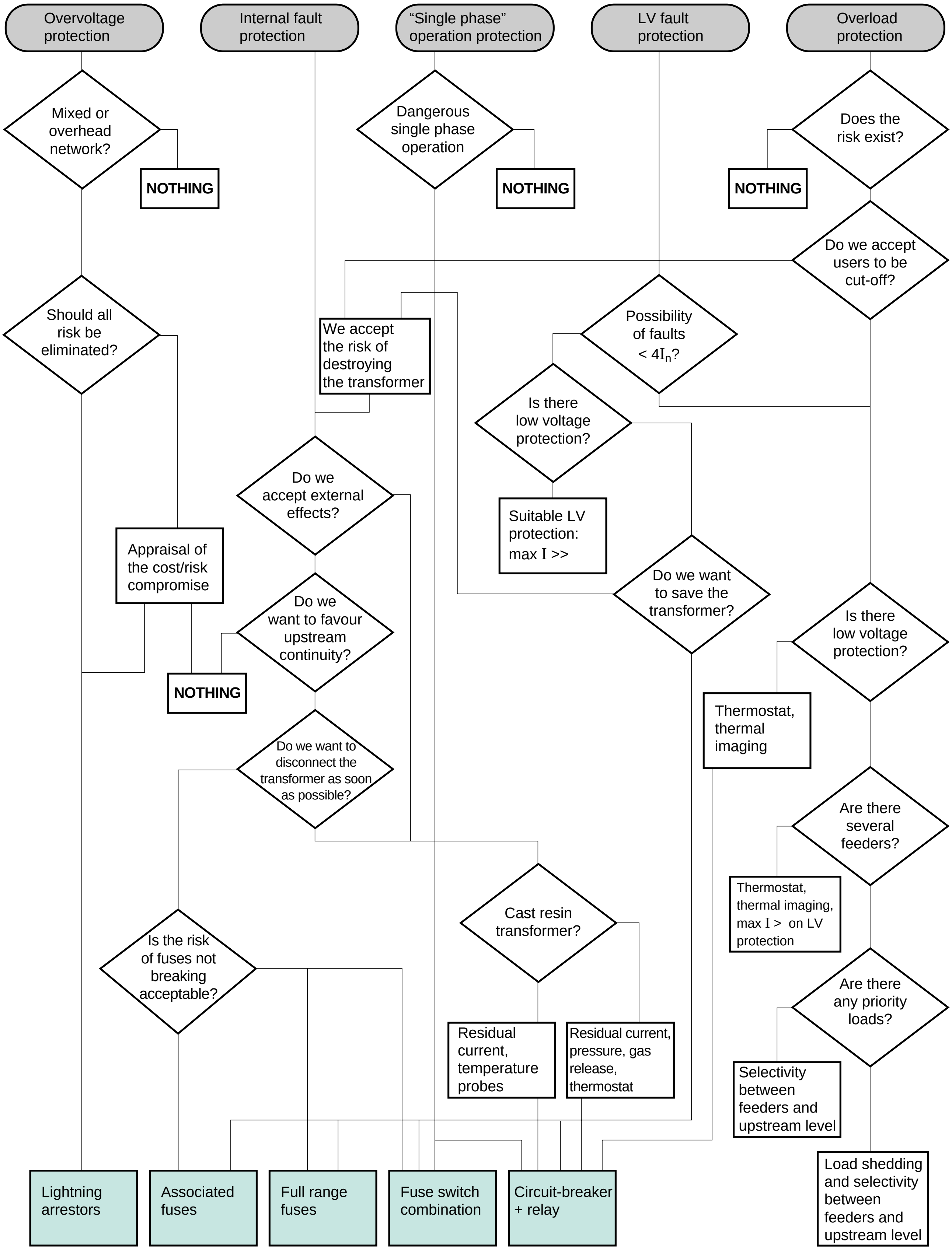

Fig. 30: logic diagram of situations, criteria and solutions.

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