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HIGH PRESSURE (HP) TRANSMISSION SYSTEMS

STANDARD FOR CABLE AND APPLICATION

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CHANGES LOG

REVISIONS LOG

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REFERENCE DOCUMENTS

ELOT EN 60034
[Rotating Electrical Machines]

IEC 60183
[Guide to the selection of high-voltage cables]

IEC 60287
[Electric cables - Calculation of the current rating]

IEC 60364-4-43
[Erection of low-voltage installations - Part 4-43: Protection for safety - Protection against overcurrent]

IEC 60364-5-52
[Erection of low voltage installations - Part 5: Selection and erection of electrical equipment - Chapter 52: Wiring systems]

IEC 60502
[Power cables with extruded insulation and their accessories for rated voltages from 1 kV (U_m = 1,2 kV) up to 30 kV (U_m = 36 kV)]

1.0 SCOPE

This specification specifies instructions to design engineers for the correct selection of power cable type and for optimum sizing with respect to the mode of installation for normal and abnormal operating conditions.

Particular attention is paid to thermal operating conditions.

The selection of cables with respect to external influences (corrosion, humidity, etc.) is not covered by this report.

The report refers particularly to the installations in industrial and power plants.

2.0 GENERAL

2.1 STRUCTURE OF THE REPORT

The report contains the following parts:

- part 1 - Typical installation methods

- part 2 - Cable sizing criteria

2.2 REFERENCES

The report makes reference to European practice for cable application in industry.

In the following particular references and sources of information will be indicated with / / (bibliography at the end).

2.3 EU LEGISLATION, EUROPEAN AND INTERNATIONAL STANDARDS

Basic reference is made to IEC standards and documents.

This report is to be read in conjunction with the **IEC 60287.**

The selection of cables with regard to system voltage is not covered in this report and reference is to be made to **IEC 60183.**

3.0 TYPICAL INSTALLATION METHODS

3.1 GENERAL

The usual installation methods used in industrial plants are considered.

3.2 UNDERGROUND INSTALLATION

Direct burial cables are the most important, because it corresponds two basic requirements:

a) protection against fire, mechanical and chemical damage;

b) minimum interference with other above - ground installations.

3.2.1 DIRECT BURIED CABLES

Cables are buried in the ground with a suitable bed and cover of sand; the sand is the most important element of soil thermal resistance, unless the surrounding material has worse thermal characteristics than the sand.

The depth of laying is generally dependent on the rated voltage of the cables, being usual values as follows:

h > 0,5 m. for U< 1 kV,

h = 0,6 m. to 0,8 m. for U 1 kv to < 30kv

h = 1,0 to 1,2m. for U>30kV.

Larger values are applicable to installation in public areas. For dangerous locations the depth of laying shall not be less than 0,6 m or according to applicable standards.

3.2.2 LAYING IN DUCTS

Laying in ducts encased in concrete banks may be restricted to road crossings of extended to entire process plots, where required by corrosion danger.

It must be noted that the air between cable and conduit constitutes an additional thermal resistance, which requires a derating of 0,7 to 0,8. The presence of the air in the concrete bank reduces the heat transfer capability of the concrete, so that for multicable banks the use of iron conduits is strongly recommended, instead of PVC conduits (see **para 5.3**).

3.2.3 LAYING IN PREFABRICATED TRENCHES - SAND FILLED

It is important that communication with lateral and bottom surrounding soil is permitted, to prevent drying - up of the sand bed of cables.

Masonry or concrete trenches without bottom and with lateral holes respond to this requirement.

3.2.4 LAYING IN PREFABRICATED TRENCHES. AIR FILLED

This laying method is restricted to non classified locations and is frequently used within electrical installations such as substations, switchyards and power stations.

3.3 ABOVE GROUND INSTALLATIONS

Two methods are used:

- installation in conduit, and
- installation on trays

Trays may be open or closed, giving origin to different cooling conditions. The installation of cables above ground gives the following advantages:

a) it permits the addition or replacement of cables after plant completion. This mode of installation is frequently adopted for chemical plants and generally where the fire risk is not very severe;

b) the installation in air requires, with respect to underground installation with the same amount of cables mutually interfering, lower cross section of conductors, being the effect of mutual heating not so detrimental on derating factors, mainly in the case of many cables per layer and multiple layer installation.

3.4 CABLE TUNNELS

This method of installation is not considered; it may be reconducted to the laying in ducts (without ventilation) or to the laying in open air (with forced ventilation).

4.0 GENERAL CRITERIA FOR CABLE SIZING

4.1 GENERAL

The selection of conductor cross sectional area is generally made with reference to the maximum allowable temperature of insulation at normal operating conditions.

PROTECTION AGAINST OVERLOADS: According to IEC 60364-4-43 protective devices shall be provided to break any overload current flowing in the circuit conductors before such a current could cause a temperature rise detrimental to insulation, joints or surrounding goods to the conductors. The operating characteristics of a device protecting a cable against overload shall satisfy the two following conditions:

$$I_B \leq I_n \leq I_z$$

$$I_2 \leq 1{,}45 \times I_z \qquad (1)$$

Note 2 of the mentioned standard calls the attention on the fact that the coefficient 1,45 (which represents the limit of possible overcurrent in the cable not securely interrupted by the protective device) may "not ensure complete protection in certain cases" (*).

The selected cross section of conductors is to be verified versus other operating conditions, which may be:

a) voltage drop limit at nominal operating conditions (or at different operating conditions, e.g. rated absorbed power of user);

b) voltage drop at starting conditions for motors ;

c) voltage drop at restarting (or reacceleration) conditions for group of motors (apply to group - feeders);

d) maximum conductor temperature at conditions b) and c);

e) maximum conductor temperature at "emergency conditions";

f) maximum conductor temperature at short circuit conditions;

g) economics (loss evaluation), mainly applicable for main feeders.

(*) Caution is required for cables in heavier dangerous zones (zone 1) and for safety services: in these areas the coefficient 1,45 should be 1,0.

4.2 OHM' S THERMAL LAW

The steady state thermal operating conditions of cables are represented by the following equation, which simplifies the more complex one given by **IEC 60287.**

$$\Delta t = tc - ta = R_{EQ} * I^2 * [\,T1 + n*(T3+T4)], \quad (2)$$

where:

- tc, ta = conductor, ambient temperature,
- R_{EQ} = equivalent conductor electrical resistance per unit length (this resistance includes the effect of the Joule loss in all metalic parts of the cable - see **para. 4.5**),
- n = number of cores of the cable,
- T1, T2, T3 = thermal resistance per unit length between one core and sheath, of the sheaths, between the sheaths and the external medium,
- I = the current in the cable (in each core).

The equation (2) may be simplified to the following:

$$\Delta t = R_{EQ} * I^2 * T = P_L * T, \quad (2)$$

Where: T represents the equivalent total thermal resistance and P_L the power dissipation (loss) in the cable.

It can be seen that the ampacity of a cable depends on two quantities:

- the maximum allowable temperature rise of conductors above ambient temperature,
- the thermal resistance which opposes to heat transfer (within the cable itself and the external ambient).

Any possible laying of operating condition of a cable, which differs from standard ones, may be reconducted to a variation of one or both of these two quantities.

The change of ampacity depending on variation of conductor and ambient temperature includes also the extremely important case of multicable canalizations, where cables are subject to mutual thermal affect, or, in other words, when they are operating with ambient higher temperature.

The thermal behavior of HV cables, having not negligible dielectric loss is to be considered separately.

To be noted that the method used in **para. 4.6** is based on loss separation and differs only formally and for some simplifications from the **IEC 60287** method, which is based on the reduction of available temperature rise on conductors.

4.3 TEMPERATURE LIMITS OF INSULATION MATERIALS

The limits of allowable temperatures for insulation materials are fixed by applicable standards or by manufacturers with reference to expected life duration of the product.

Temperature limits for short circuit conditions are generally considered only for insulation material, but also the limits allowable for external sheaths and for connectors, joints and terminations much be taken into consideration.

Maximum conductor temperatures are as shown on the following **TABLE 1** (which includes the information given from **IEC 60287** and **IEC 60502**).

TABLE 1

HIGHEST PERMISSIBLE TEMPERATURE FOR VARIOUS INSULATING COMPOUNDS.

Insulation	Maximum rated conductor temperature (°C)		
	Normal operation*	**Short circuit (5 s max. dur.)**	**Emergency operat. (.)**
Fluid oil impregnated paper	90 (+)	220 (*)	
Impregnated paper	50 to 80 (+) (++)	200 (+)	
Butyl rubber	85	220	
Polyvinyl chloride or the coplolymer of vynil chloride and vynil acetate (PVC)	70	160 (+++)	
Thermoplastic polyethylene (PE)	70 **	130 ***	100 (+)
Cross-linked polyethylene (XLPE)	90	250 (++++)	
Ethylene propylene rubber (ERP)	90	250 (++++)	130 (+)
Sylicon rubber	180	350	

TABLE 1 **Notes:**

(.) Values correspond to a loss of life of about 1% for each application lasting 5 hours.

(+) Values suggested by Pirelli, not yet recognized by IEC.

(+ +) Values depending on rated voltage and on type of impregnating compound.

(+ + +) For conductor cross sections larger than 240mm^2, consider 140°C.

(+ + + +) For conductor cross sections larger than 240 mm^2 and rated voltage not exceeding 1kV, consider 220°C, if the cable is PVC sheathed.

* It is essential that dielectric losses are taken into account when Do is equal to or greater than the values give in **IEC 60287.**

** 75°C for PE of density higher than 0.960 g/cm^3 at 23°C.

*** This temperature may be increased to 150°C by use of a suitable conductor screen construction.

4.4 DIELECTRIC LOSS (NO LOAD LOSS)

Generally cables up to 20kV rated voltage do not have remarkable dielectric loss (no load loss). (*)

The dielectric loss is to be considered, also if of a magnitude order of few watt/meter, when the derating factor is so low, that the total allowable heat loss becomes of the same magnitude order as the no load loss.

The influence of no load loss in the case of application of a derating factor is examined in the following **para 4.5.**

The dielectric loss (no load loss) is given by the equation:

$$P_{NL} = U^2 * \omega * C * \tan\delta \text{ (W/m)} \quad (3)$$

Voltage increase augments the dielectric loss (no load loss) result as per equation (2), Capacitance C and values of tanδ as per **IEC 60287.**

(*) **IEC 60287,** "Dielectric losses", reads as follows:

"The dielectric loss only becomes important when the voltage to earth exceeds 30 kV for paper - insulated of 6 kV for PVC - insulated cables where 3 - core screened or single core cables are used. The corresponding voltage for butyl rubber and polyethylene are under consideration".

4.5 LOAD LOSS

The load loss is due to conductor losses and to additional losses in metallic screens.

The **IEC 60287**, give the method to define the additional losses.

For a three core cable the load loss (Joule loss) is given by the equation:

$$P_L = 3 * R_{EQ} * I^2 \quad (W/m) \qquad (4)$$

The resistance R_{EQ} in the formula is a fictitious value, to include additional load loss, in metallic parts other than conductors, depending on load current.

4.6 IMPACT OF DIELECTRIC LOSS (NO LOAD LOSS) WHEN AN AMPACITY REDUCTION FACTOR IS APPLIED

Any ampacity reduction factor (derating factor) refers to total losses and not only to load loss. To visualize the impact of no load loss, consider the case of one 20 kV cable, with copper conductors, with cross sectional area of 120 mm^2, with two different insulation materials: PVC and EPR.

Ins.	Capac. (μF/km)	tanδ	Resistance		Amp. (A) (*)	Losses (W/m)		
			(ohm/km)	at (°C)		No. L	Load	Total
PVC	0,42	0,1	0,185	70	290	5,3	46,7	52,0
ERP	0,24	0,02	0,198	90	335	0,6	66,7	67,3

(*) Ampacities are referred to standard underground installation conditions.

The grouping factor be, e.g., equal to 0,5 that means that total losses must be reduced by $0,5^2 = 0,25$.

a) For the PVC cable:

$P^*_{TOT} = 52 * 0,5^2 = 13$ W/m,

$P_{LOAD} = P^*_{TOT} - P_{NL} = 13 - 5,3 = 7,7$ W/m.

The effective ampacity derating factor will be:

$K^* = 7,7 / 46,7 = 0,406$ instead of 0,5.

For a grouping factor equal 0,4 the effective ampacity derating factor would be 0,254. At the limit, where the grouping factor is:

$K_{LM} = (P_{NL} / P_L)^{1/2} = (5,3 / 52)^{1/2} = 0,32$

The load current must be zero.

b) For the EPR cable:

$P^*_{TOT} = 67,3 * 0,5^2 = 16,82$ W/m,

$P_{LOAD} = P^*_{TOT} - P_{NL} = 16,82 - 0,6 = 16,22$ W/m.

The effective ampacity derating factor doesn't practically differ from 0,5:

$K^* = 16,22 / 66,7 = 0,493$.

4.7 REFERENCE AMPACITY

The ampacity given by standards and by cable manufactures are generally referred to standard conditions (*).

Unless otherwise indicated in the catalogs of cable manufactures or specified in **IEC 60287,** for particular countries, the following conditions apply for the calculation of reference current carrying capacities.

(*) For reference sources see **para. 5.1.2.**

4.7.1 AMBIENT TEMPERATURES AT SEA LEVEL

TABLE 2

AMBIENT REFERENCE TEMPERATURE

Climate	Ambient air temperature		Ambient ground temperatures at a depth of 1m	
	Min.	Max.	Min.	Max.
	°C	°C	°C	°C
Tropical	25	55	25	40
Sub-tropical	10	40	15	30
Temperate	0	25	10	20

4.7.1 THERMAL SOIL RESISTIVITY

It is essential that current ratings should be valid for the maximum temperature given. The lower values are for winter ratings if required. The values correspond with the temperature limits of winter and summer, alternatively rainy and dry seasons. When no information about the depth of lying is given the standard depth is to be taken as 1 m.

TABLE 3

SOIL REFERENCE RESISTIVITY VALUES

Thermal resistivity °C cm/W	Soil conditions	Weather conditions
70	Very moist	Continuosuly moist
100	Moist	Regular rainfall
200	Dry	Seldom rains
300	Very dry	Little or no rain
100	Concrete (*)	

(*) Value not shown in **IEC 60287.**

To be noted that the correct values in the IS system are:

0,7, 1,0, 2,0, 3,0, °C m/W.

5.0 AMPACITY CORRECTION FACTORS

5.1 CALCULATION OF AMPACITY CORRECTION FACTORS

From equation (2) it is easy to calculated the correction factors correspondent to conditions different from standard (or reference) ones.

Generally cable manufacturers (catalogs) furnish correction factors corresponding to the variation of only one parameter at once.

When the installation conditions differ from the reference ones, ampacity correction factors shall be applied to account for different conditions.

It must be considered that the application of correction factors gives valid results only if the resulting factor is not very much deferent from the unity.

When the resulting factor is low (e.g. lower than 0,5) a better result will be obtained by the application of the general equation (2), **para. 4.2.**

The most important of the correction factors is the "grouping factor" which accounts for the effect of mutual heating of simultaneously loaded cables.

5.1.1 GROUPING FACTOR

The grouping factor KGR is valid only in the theoretical case of n equal cables, loaded with the same current.

Being in general not this the real situation, the application of grouping factors may result in an excessive oversizing of cables.

For underground cable installation it is recommended to use the **IEC 60287** methods, which, by considering the actual mutual heating effect permits to take advantage of cables oversized for any reason (short circuit, voltage drop, normalization of cross sectional areas, minimum size adopted).

The presence in the trench or tray of cables normally energized and of cables normally not energized (such as cables of spare items normally not energized, or cables of items energized only during plant shut - down, e.g. welding receptacles) results in a lower ambient temperature than expected. With the use of IEC method it is possible to take into account this situation and also the fact that the actual operating currents which give origin to the mutual heating from each individual cable are normally lower than user's rated currents.

It is possible to take account of the effect of normally not energized users by considering a fictitious larger distance between cables, than the actual one.

An other important case where the use of the **IEC 60287** method permits optimum cable sizing is the situation with numerous cables having different insulation, e.g. PVC and EPR. If the actual temperature situation determined by mutual heating is not known, it is practically necessary to consider for EPR cables a lower maximum temperature, in order not to exceed the allowable temperature rise on conductors of PVC cables.

Mutual heating from cables loaded less than rated current A simplified method to account for reduced mutual heating due to other cables, which are supposed to operate at a lower current than their rated value, is illustrated in the following.

The method permits to size individually each cable for its own rated current, but with reduced mutual heating effect.

Consider a situation where the grouping factor for equally loaded cables would result equal to 0,5 because of many cables in one layer (other installation conditions are standard). The grouping factor accounts for the effect of mutual heating which reduces the allowable conductor temperature rise over ambient.

For EPR insulation the allowable conductor temperature rise is:

tc - ta = 90 - 20 = 70 °C;

if the grouping factor K_{GR} = 0,5, the actual allowable conductor temperature rise is reduced to:

$\Delta tc = 0{,}5^2 * 70 = 17{,}5$ °C

and the fictitious ambient temperature results:

$ta^* = ta + \Delta tm = 20 + (1 - 0{,}5^2) * 70 = 20 + 52{,}5 = 72{,}5$ °C

If remaining users operate with a current, assume, equal to 0,8 rated value, the mutual heating effect would be reduced to:

$\Delta tm^* = 0{,}8^2 * 52{,}5 = 33{,}6$ °C

and the total temperature rise would be:

$\Delta tc + \Delta tm^* = 17{,}5 + 33{,}6 = 51{,}1$ °C

The possible multiplying factor of the grouping factor be a>1,0 and the "normal operating" factor relevant to other cables be β<1,0.

The available temperature rise would now be subdivided as follows:

$\Delta t^*cond = a^2 * K^2_{GR}$ (p.u.).

The mutual heating effect:

$\Delta t^* = a^2 * \beta^2 * (1 - K^2_{GR}) = 1{,}0$ (p.u)

The sum of the new values must be equal to 1,0:

$$a^2 * K^2_{GR} + a^2 * \beta^2 * (1 - K^2_{GR}) = 1{,}0 \quad (5)$$

$$a = (K^2_{GR} + \beta^2 - \beta^2 . K^2_{GR})^{-1/2}$$

the new grouping factor will be:

$K^*_{GR} = a * K_{GR}$

a) $K_{GR}=0{,}5$; $\beta=0{,}8$; $a=1{,}17$; $K^*_{GR}=0{,}585$;

b) $K_{GR}=0{,}4$; $\beta=0{,}75$; $a=1{,}257$; $K^*_{GR}=0{,}53$

5.1.2 MULTIPLE LAYER INSTALLATION

For hand calculations a conservative simplified approach to multilayer cable installation is to consider that the cables in each column dissipate the same power as permitted for one cable in a single multicable layer.

It means that the grouping factor valid for one layer has to be multiplied by reduction factor tabulated herebelow.

Multilayer reduction factor	Number of layers
0,71	2
0,58	3
0,5	4
1/n	n

Where to find ampacity factors and ampacity correction factors

In addition to the application of the **IEC 60287** methods for calculating the actual ampacity of buried cables the following sources may be utilized:

- **IEC 60364-5-52**
- National standards and manufacturer's catalogs.

5.2 CABLES IN METALLIC DUCTS

The resistance of the duct is negligible if it is metallic (the use of PVC or concrete pipes is not recommended). The incidence of conduit external diameter on soil thermal resistance may be disregarded (cautelative); the presence of air resistance may be taken into account with a reduction factor 0,7 to 0,8 (lower values for smaller cables), or better with the formal proposed by **IEC 60287,** (to be considered that due to mutual heating the air temperature may be very close to the maximum allowable for conductors).

For road crossing the presence of air may be disregarded if the conduit length is not larger than 8 to 10 times the depth. In case of wider road crossings, the filling of conduit with a good conduction material (such as Benthonite, see Appenix A) may be convenient, to prevent oversizing of an entire cable length because of only a limited critical situation.

IEC 60287, clause 9.10 indicates a method to calculate the correction term to be added to the thermal resistance external of the duct when the soil thermal resistivity is different from that of concrete.

5.3 SOIL HUMIDITY AND IMPROVEMENT OF SOIL THERMAL CHARACTERISTICS

In very critical situations (high soil temperature, high soil thermal resistance, high number of cables, more than one layer) it may be convenient to substitute the soil around the cable bank for a portion larger than usual excavation. It must be noted that a relevant part of the soil resistance is concentrated in the space just around the cable bank, so that a sensible reduction of ambient resistance may be obtained by extending the excavation by about 0,5m at the bottom and on both sides.

A soil composition which may comply with this requirement is ordinary raw material with gravel and sand, compressed by a soil compacting machine (hand compaction will not be enough).

The quality of a bedding material depends on the grain distribution in general and on a sufficiently large percentage of fine grain. This type of material has a thermal resistivity which does not practically depend on soil humidity.

Soils composed by mix materials such as slag, ash, industrial refuses, organic matter etc. thermal resistance as per **IEC 60287.**

Where the solar radiation is high and the drying - out effect of the soil may effect the thermal resistance, the cables should be placed deeper (note that soil thermal resistance does not sensibly depend on depth of laying).

Normal sand has a thermal resistivity of 100, if the humidity is 10%; it rises up to 400 °C cm/W, when the humidity lows down between 1 to 2%.

The critical temperatures at which the soil may dry-up are at 30 - 50 °C, i.e. very much lower than the soil temperatures which are present in a multicable (multilayer) trench.

In this case a very low grouping factor is applied, and the fictitious ambient temperature is very close to the maximum conductor temperature (for EPR 90 ^{0}C).

To consider this phenomenon a fictitious higher value of soil resistivity portion of soil with a diameter of about 0,3 to 0,4 m and with a thermal resistivity for dry conditions may be included in the calculation.

5.4 CABLES IN AIR

The ampacity in air depends on the type of installation, which determines the mode of heat transfer to surrounding ambient through the air movement.

The grouping factor to be applied for more than one cable may be interpreted:

a) as the result of a more difficult movement of air (improvement of external thermal resistance) and

b) of an increased ambient temperature, due to mutual heating.

It is important to refer to interpretation a) or b) when extrapolations on cable performance are needed and cautelative results are desired.

For calculation of additional temperature rise when a cable is overloaded (*), refer to interpretation a): it is as if the total allowable temperature rise is spent to win external thermal resistance.

Consider an EPR cable loaded with full current:

Δtcond = tcond - tamb = 90 – 30 = 60 °C.

If the current is increased up to 1,1 the new conductor temperature will rise up to (by disregarding the effect of conductor resistance variation):

t*cond = tamb + $1,1^2$ * Δtcond = 30 + 1 ,21 * 60 = 102,6 °C

(*) It may be the case of determining the conductor conditions when a current=I2 is circulating (refer to **para. 4.1**).

For calculations based on initial temperature (such as short circuit or motor starting), it is convenient to refer to interpretation b).

Consider the same cable as before, and compare the ampacity given for multicable installation and for one cable: the ratio of these two values may be interpreted as a grouping factor. Let be, e.g., K_{GR}=0,7; the fictitious ambient temperature would be:

t*amb = tamb + (tcond - tamb) (1 - K^2_{GR})= 30 + 60 (1 - 0,72) = 60,6°C.

If the actual current in the conductor is lower than the allowable current, a=0,9, the conductor temperature will be:

t*cond = t*amb + (tcond - tamb) * K^2_{GR} * a^2 = 60,6 + 60 * 0,72 * 0,92 = 84,41°C

This conductor temperature may be considered as initial for short circuit (the application of interpretation

a) would give t*cond = tamb + (tcond - tamb) * a^2 = 30 + 60*0,92 = 78,6 °C, a less conservative value.

5.5 VALUE OF DESIGN CURRENT

It is important to determine the value of the "current for which the circuit is designed: IB(refer to **para.4.1**).

In general this current is the rated current of the user or of the feeder, but a problem may exist when the load current is not constant (e.g. type of service different than S1 in **ELOT EN 60034**).

For voltage drop calculations the circuit highest current must be considered. For thermal sizing of cables it may be considered the equivalent thermal current:

$$I_{TH} = [1/T(I^2_1{*}T_1 + I^2_2{*}T_2 + \ldots + I^2_n{*}T_n)]^{1/2} \qquad (7)$$

Attention must be paid however to the thermal time constant of the cable. If the duration of the larger current in a cycle is larger than a specific time, the cable may reach the final temperature corresponding to the steady state conditions for this current, which is higher than that expected for the current I_{TH}.

Orders of magnitude of cable time constants are from some minutes up to one hour for cables in air, with cross sectional areas from 1 mm^2 to 240mm^2.

6.0 <u>VOLTAGE DROP CHECKING</u>

6.1 VOLTAGE DROP AT RATED CONDITIONS

It is normal practice to verify the voltage drop on the cable for the rated conditions at user's terminals (rated power and voltage).

This conditions corresponds to the usual situation, where the voltage upstream a final feeder (at switchgear busbars) is slightly higher than nominal to account feeder voltage drop.

Also for hand calculations (with the use of pocket calculators) it is possible to make an exact calculation with the Boucherot method.

$$P_{BUS} = P_{LOAD} + 3\, R_{CB} I^2,$$
$$Q_{BUS} = Q_{LOAD} + 3\, X_{CB} I^2,$$
$$A_{BUS} = \sqrt{P^2_{BUS} + Q^2_{BUS}},$$
$$\Delta U = \frac{A_{BUS}}{A_{LOAD}} - 1 \text{ (p.u.)} \qquad (8)$$
$$\text{where } I = \frac{P}{3 \,.\, U_n \,.\, n \,.\, \cos\varphi}$$

and R_{CB}, X_{CB} are the cable parameters (R calculated at conductor' s rated operating temperature).

6.2 VOLTAGE DROP AT MOTOR STARTING CONDITIONS

It is usual practice to verify the voltage drop on the cable for the worst condition that is rated voltage on the busbars (which is generally cautelative).

The starting motor is represented as a constant impendence Z_{ST}.

$$R_{ST} = Z_{ST} \,.\cos\varphi_{ST} = [\, (U^2_n \,.\, n \,.\, \cos\varphi) \,/\, (I_{ST} \,.\, P)\,] \,.\, \cos\varphi \qquad (9)$$

$X_{ST} = Z_{ST} \,.\, \sin\varphi_{ST}$,

where I_{ST} is the starting current multiplier (p.u.)

$$U_{ST} = Z_S \,/\, Z_{(ST+CB)} = \{\, (R^2_{ST} + X^2_{ST}) \,/\, [(R_{ST} + R_{CB})^2 + (X_{ST} + X_{CB})^2]\,\}^{1/2} \text{ (p.u.)} \qquad (10)$$

$\Delta U = 1 - U_{ST}$ (p.u.) ,

An important condition is the evaluation of the temperature to be considered. For the general cases, when the starting time does not exceed 10 sec, the adiabatic approach, as for short circuit, is acceptable.

For larger starting times, the same approach results in a conservative criterion.

The resistance R_{ST} may be assumed as correspondent to the final temperature allowable for starting conditions, or may better calculated with the actual final temperature reached at the end of starting, by applying the **IEC 60183**.

$$\rho_{tf} = \rho_{20} \,.\, (1/\alpha_0 + t_{fin}) \,/\, (1/\alpha_0 + 20)$$

where $1/\alpha_0$ is the reciprocal of temperature electrical resistance coefficient at 0°C.

Numerical values of $1/\alpha_0$ are given in the following **TABLE 5, para 7.3**.

7.0 SHORT CIRCUIT RATING

7.1 GENERAL

The thermal checking of cables for short circuit conditions is generally made considering the phenomenon as adiabatic (*).

This assumption is valid for short circuit durations up to about 5 s, depending on conductor's cross sectional area.

For very small cross sections the adiabatic method may result too conservative, being the thermal capacity of the insulation of the same magnitude order of that of conductor and being therefore not negligible the heat transfer from conductor to insulation.

7.2 CURRENT TO CONSIDER FOR SHORT CIRCUIT CABLE SIZING.

Upstream or downstream of feeder

The current to be considered for short circuit cable sizing depends on the type of protection device installed to protect the cable line.

a) If the protection device is of the independent time type, the maximum current at supply point (possibly reduced by consideration of protection device impedance) should generally be considered.

   Only if no danger exists in case of cable damage due to short circuit near the supply point, the reduced short circuit current for a fault along the cable line could be considered (by introducing in the current calculation also the cable line impedance).

b) If the protection device is of the limiting type (fuse), having a I^2_t = constant characteristic for the highest current values, the short circuit current to be considered is the down stream current, because to this current it will correspond a higher Joule integral than for upstream faults (the fuse characteristic deviates from the straight tone).

   For low voltage circuits also allowance for arc resistance should be considered (30 – 50 V).

(*) For short circuit duration exceeding 5 s, the adiabatic method gives excessively large cross sections;

7.3 CONSTANT SHORT CIRCUIT CURRENT

If the short circuit current may be considered as constant (line or transformer short circuit with constant impedance and with such duration that the effect of the d.c. component may be disregarded), the minimum conductor cross sectional area is given by the relation:

$$A = I_{SC} \,.\, t^{1/2} \,.\, (1/K) \qquad (11)$$

where:

A = conductor's cross sectional area (mm^2),

L_{SC} = short circuit current (r.m.s.) (A),

t = short circuit duration (s),

K = short circuit ampacity coefficient ($A.s^{1/2}.mm^2$)

The values of K for copper and aluminum conductors and for different initial and final temperatures are given in the following table 4. K may be calculated with the equation:

$$K = [\, Y_C \,(1/\alpha_0+20)/\rho_{20} \,.\, t_n.\ (1/\alpha_0 + t_{sch}) \,/\, (1/\alpha_0 + t_{in})\,]^{1/2} \qquad (12)$$

where:

Yc = average specific heat ($/w.s/^0C.cm^3$),

$1/\alpha_0$= reciprocal of temperature electrical resistance coefficient at 0 °C (°C),

t_{sch}, t_{in} = conductor's temperature at the end and at initial conditions of short circuit

ρ_{20} = conductor's electrical resistivity at 20°C ($ohm.mm^2/m$).

Values of coefficients are given in the following **TABLE 5**.

It must be noted that the application of the (11) may require a larger cross-sectional area than thermally required for the circuit design current, having as consequence a lower short circuit initial temperature, which could it turn require a lower short circuit sizing (trial and error method).

TABLE 4

VALUES OF SHORT CIRCUIT AMPACITY COEFFICIENT K FOR COPPER CONDUCTORS IN FUNCTION OF INITIAL AND FINAL SHORT CIRCUIT TEMPERATURE (°C).

Conductor temperature (C)						
initial	final					
	140	160	180	200	220	250
130	37	64	81	95	106	120
120	53	74	89	102	113	126
110	65	83	97	109	119	132
100	76	92	105	116	125	138
90	86	100	112	122	131	143
85	90	104	115	125	134	146
80	94	108	119	129	137	149
75	99	111	122	132	140	151
70	103	115	125	135	143	154
65	107	119	129	138	146	157
60	111	122	132	141	149	160
50	118	129	139	147	155	165
40	126	136	145	153	161	170
30	133	143	152	159	166	176
20	141	150	158	165	172	181

TABLE 4a

VALUES OF SHORT CIRCUIT AMPACITY COEFFICIENT K FOR ALUMINIUM CONDUCTORS IN FUNCTION OF INITIAL AND FINAL SHORT CIRCUIT TEMPERATURE

Conductor temperature (C)						
Initial	Final					
	140	160	180	200	220	250
130	24	41	52	61	68	78
120	34	48	58	66	73	81
110	42	54	63	70	77	85
100	49	59	67	75	81	89
90	55	64	72	79	85	92
85	58	67	74	81	86	94
80	61	69	77	83	88	96
75	64	72	79	85	90	98
70	66	74	81	87	92	99
65	69	76	83	89	94	101
60	72	79	85	91	96	103
50	77	83	90	95	100	105
40	81	88	94	99	104	110
30	86	92	98	103	107	114
20	91	97	102	107	111	117

TABLE 5

VALUES OF COEFFICIENTS APPEARING IN THE RELATION GIVING K

Conductor material	Yc	$1/\alpha_0$	ρ_{20}
Copper	3,47	243,5	0,01724
Aluminum	2,39	228	0,02828
Lead	1,42	230	0,2140
Steel	3,43	202	0,1380

7.4 DECREASING SHORT CIRCUIT CURRENT

When the influence of the d.c. component and of short circuit impedances of rotating machines (generators and motors) is not negligible, of when the interrupting time is within one cycle (e.g. short circuit limiting fuses), the relation (11) must be written in the form:

$$(KA)^2 = I^2 \cdot t = \int_0^t i_{SCH}^2 \, dt \qquad (13)$$

where the Joule integral is calculated with the actual current values during the time t.

7.5 DYNAMIC STRESSES

Cables sized for thermal stresses may generally withstand also dynamic stresses if the short circuit duration is not very much different from 1 s.

For armored cables the dynamic withstand is very high with respect to non armored cables: in general, if the short circuit duration is lower than about 0,1 s, a checking may be convenient.

To be noted that more critical conditions may exist for joints and termination accessories.

8.0 EMERGENCY CABLE RATING

8.1 GENERAL

As it appears from the graph of figure 1, the standard values of conductor limit temperature are fixed with respect to expected life duration of about 20 to 30 years.

For particular applications (e.g. field construction facilities) it may be accepted to reduce the expected life of cables and to adopt lower cross sectional areas.

For example for an expected life of 5 years the limit temperatures for PVC and EPR would be respectively:

PVC: 83°C; EPR: 106°C.

Similar consideration may be valid to a system with dual supply, where the expected operation time with the total load applied to one unique feeder may not exceed 10-20% of the operation time with partial load applied on each feeder.

A particular case is the starting of motors.

8.2 STARTING OF A MOTOR - THERMAL CHECKING

The starting of a motor is a normal operation and the repeated application of the starting current to the cable must not damage it.

The expected frequency of starting or the number of starlings in the life of the installation shall serve as a reference for checking the thermal conditions.

It has been used in the past to consider for the starting conditions the same final temperature as for short circuit; this practice is to be abandoned and it seems to be good practice to consider for the final temperature the so called "emergency temperatures" (**para 4.3** and **TABLE 1**):

100°C for PVC
130°C EPR

These temperatures correspond to a loss of life of the cable of the magnitude order of $1/10^5$ for each starting, with a duration of about 3 s. Should the number of startings be very high, so a lower temperature is lo be considered.

APPENDIX A

USE OF BENTONITE FOR ROAD CROSSINGS

A.1 GENERAL

To reduce the detrimental effect of the additional thermal resistance of air in the empty space between cable and conduit, it is possible to fill this space with a compound having a good thermal conductivity.

The compound here described is based on Bentonite and may be easily prepared and applied in field, using normal concrete mixers.

A.2 COMPOSITION OF THE COMPOUND

The composition of the compounds is as follows:

White of grey Bentonite	8%
Normal Portland / Cement	7%
Sand	15%
Water	70%

The compound assumes a gelatinous aspect and become hard as concrete after curing.

A.3 CHARACTERISTICS OF THE COMPOUND

A.3.1 THERMAL RESISTIVITY

Thermal resistivity is about 1 °C m/W, of the same magnitude order as good soils.

A.3.2 POSSIBILITY OF REMOVING THE COMPOUND

Should be necessary to pull out the cable form the conduit, the compound may be remove with a water injection under pressure (better using warm water), and becomes again the gelatinous aspect.

A.4 INJECTION OF THE COMPOUND IN THE PIPE

To avoid the presence of air within the conduit, it is important to inject the compound with a suitable mortar pumping machine. The pumping machine may be the same used for grouting in prestressed concrete.

After conduit filling the two ends must be sealed with bituminous mastic to prevent the entrance of underground water and evacuation of the compound.

The length of the conduit shall not exceed 15 m, to achieve good filling.