FEEDERS

Criteria for Sizing

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1 - PURPOSE

The purpose of this technical information is to define some criteria to assist in the sizing of feeders when the exact information of the manufacturers of the conductors and the installations is not available.

2 - REFERENCE DOCUMENTS

2.1 - Spreadsheets

PL.EL.SA.CA.06.R1 Feeders – Criteria for Sizing

3 - INTRODUCTION

When the conductors of an installation are dimensioned, the exact data of the cables that will be used and the final conditions of their assembly and operation are not known. However, in advance, these conductors must be defined for the development of projects and purchase of materials.

The sizing is usually done by experienced professionals who, without oversizing the conductors, can define them very closely. For this, the professionals involved must have knowledge of the loads, their operating conditions, locations, and types of installation.

As the real feeders' information are only available at the end of the assembly, it would be very expensive and laborious to replace conductors that are not sized correctly and/or installed as intended. Thus, what should be done is, based on the experience of the professionals and adopting the appropriate safety factors, to perform the dimensioning that will represent the future reality, that is, this dimensioning should ensure that it will not be necessary to change it.

During the development of the works there are changes in the loads and conditions of operation and/or installation, which imply in the revision or verification of the sizing of its circuits, still in time to make corrections. However, if there has been a failure in some dimensioning, what can be done, before condemning a circuit, is a detailed check, also applying the concepts defined here.

4 - CURRENT CONDUCTION CAPABILITY

The current conduction capacity of the cables depends mainly on the materials of the conductor and the insulation, type of installation, ambient temperature, grouping of the circuits and design factors. Current conduction capabilities, as well as correction factors, are defined in detail by the applicable standards. Due to the wide variety of alternatives, the current conduction capacity of the cables will not be discussed in this technical information.

The cost difference of the cables is not in the type of insulation, but in the material of the conductor, usually copper. Therefore, preference should be given to conductors insulated with EPR/XLPE, which have a current conduction capacity approximately 30% higher than PVC-insulated cables, withstand a higher temperature during a short circuit, 250ºC for EPR/XLPE against 160ºC for PVC, and practically at the same cost.

5 - REACTANCES AND RESITANCES

The values of the reactances and resistances of the conductors are informed by the manufacturers and are calculated according to the constructive characteristics of the cables. However, when doing a project, it is necessary to perform the sizing without having this information.

To establish some criterion to calculate the voltage drops, according to the other technical information, the values of the reactances and resistances of the cables can be defined quite closely, as it is intended to show below.

5.1 - Reactances

The value of the reactance of the drivers that can be adopted, with quite approximation, for any section at 50Hz is 0.080Ω/km. The reactance, which referred to at 60Hz will be:

$$X_{60Hz} = 0{,}080x\frac{60}{50} = 0{,}096\Omega/km$$

5.2 - Resistances

As the resistivity of copper at 20ºC (ρ_{20}) is 58 $\Omega mm^2/m$ and the resistivity at temperature θ is given by the equation:

$$\rho_\theta = \frac{1000}{\rho_{20}}[1 + 0{,}00393(\theta - 20)]$$

$$\rho_\theta = \frac{1000}{58}[1 + 0{,}00393(\theta - 20)]$$

$$\rho_\theta = 17{,}241[1 + 0{,}00393(\theta - 20)]$$

Where:

ρ_θ resistivity of copper at temperature θ (Ω/km)

For 70ºC $\rho_{70} = 20{,}629\Omega\text{mm}^2/\text{km}$

For 90ºC $\rho_{90} = 21{,}984\Omega\text{mm}^2/\text{km}$

The approximate value of the resistance of the cables will be given by the formula:

$$R_{S_\theta} = \frac{\rho_\theta}{S}$$

Where:

R_{S_θ} - Resistance of copper cable with S-section at temperature θ (Ω/km).

S - Nominal cable section (mm^2).

For PVC and EPR/XLPE insulated cables, the resistances and reactances in Ω/km are as shown in the following tables:

Cables Data		
S (mm^2)	R_{70}	X_{60Hz}
2,5	8,252	0,096
4	5,157	0,096
6	3,438	0,096
10	2,063	0,096
16	1,289	0,096
25	0,825	0,096
35	0,589	0,096
50	0,413	0,096
70	0,295	0,096
95	0,217	0,096
120	0,172	0,096
150	0,138	0,096
185	0,112	0,096
240	0,086	0,096

Cables Data		
S (mm^2)	R_{90}	X_{60Hz}
2,5	8,794	0,096
4	5,496	0,096
6	3,664	0,096
10	2,198	0,096
16	1,374	0,096
25	0,879	0,096
35	0,628	0,096
50	0,440	0,096
70	0,314	0,096
95	0,231	0,096
120	0,183	0,096
150	0,147	0,096
185	0,119	0,096
240	0,092	0,096

When the current circulating in the cable is less than the current permissible, the estimated operating temperature (θ) can be calculated by the formula:

$$\theta = \theta_0 + (\theta_{Max} - \theta_0).\frac{I}{I_{Max}}$$

Where:

θ_0 - Ambient temperature (of the no load conductor, normally 40ºC)

θ_{Max} - Maximum conductor temperature

I - Conductor's actual current (A)

I_{Max} - Maximum permissible current in the conductor at the maximum temperature (A);

For example, if an EPR/XLPE insulated cable of rated section 120mm², which supports a current of 279A when installed in a tray, is conducting a current of 190A, its estimated operating temperature will be:

$$\theta = 40 + (90 - 40).\frac{190}{279}$$

θ =74,1ºC

So

$$\rho_{74,1} = 17{,}241[1 + 0{,}00393(74{,}1 - 20)]$$

$$\rho_{74,1} = 20{,}907$$

$$R_{120_{74,1}} = \frac{20{,}907}{120} = 0{,}1742\Omega/km$$

These values can be used for the most accurate calculations of voltage drops.

6 - SHORT CIRCUIT

The choice of cables by the short-circuit criterion must meet the following condition:

$$I^2t \leq k^2.S^2$$

Where:

I Short circuit current (A)

t Duration of the defect (s)

k Constant that depends on cable material and insulation (A^2s/mm^2)

S Conductor section (mm^2)

The values of k for copper cables are:

k=143 For cables insulated in EPR/XLPE, with initial temperature of 90ºC and final temperature of 250ºC.

k=115 For cables with a section equal to or less than 300mm², insulated in PVC, with an initial temperature of 70ºC and a final temperature of 160ºC.

In case the feeder is formed by more than one cable per phase, and the defect is considered in a snippet of the path, the verification must be made only for one of the cables, that is, the total short current is not divided between the cables of the same phase, it circulates only in the defective cable.

The calculations of the cables, by the criterion of short circuit, can be made considering:

- That the current that will circulate through the cable is the same short circuit current from the source. This criterion ensures that, in case of defect, at any point of the circuit, the cable will not suffer damage if the defect current is interrupted in the time established in the calculation. This criterion should be applied in cases where the length of the feeders is too short or that, in case of defect, at any point of the feeder, the cable can be repaired.

- That the current that will circulate through the cable will be limited by its impedance. This criterion shall be applied whenever the length of the feeder is greater than the minimum length which guarantees that the short circuit current that will circulate through the cable will be less than the maximum current bearable by the cable if the effect current is interrupted in the defined time. If the cable defect occurs at a distance from the source, greater than the minimum length set, the cable can be repaired.

- That the defect interruption time will be less than a set time. This criterion can be applied to feeders, not very short, in which it is possible to limit and guarantee the time of action of the protection.

The above considerations are based on the same condition, i.e. $I^2t \leq k^2.S^2$. Only the focus of consideration is made to reduce costs by attending to the technique. For example, if we consider the short-circuit current of a panel, to size the conductors of the load feeders, all cables should have the same minimum section. However, if we consider that the short circuit currents will be limited by the impedance of the cable itself, or that the time of action of the protection will limit the time of the defect, the sections of the cables will be reduced considerably and checked on a case-by-case basis.

6.1 - Short Circuit of Source

This calculation criterion directly uses the formula:

$$I^2t \leq k^2.S^2$$

$$S^2 \geq \frac{I^2t}{k^2}$$

$$S \geq \frac{I_{CC}}{k_\theta}\sqrt{t}$$

Where:

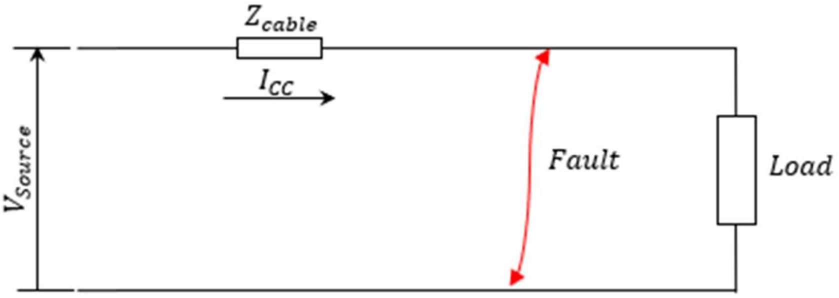
I_{CC} Short-circuit current from the source (A)

k_θ Cable material and constant of the insulation (A^2s/mm^2)

By this criterion, all feeders originating from the source under consideration will have the same minimum section, regardless of the length of the circuit and the current of the load.

6.2 - Minimum Cable Length

This criterion defines the minimum length of the cable that ensures that the short circuit current that will circulate through the cable is less than the maximum capacity that the cable supports. To define this minimum length, the circuit will be the one in the figure below:



Considering that the short-circuit power at the source is infinite, which will not significantly change the result, we have:

$$I_{CC} = \frac{V_{Source}}{Z_{cable}}$$

Where:

I_{CC} Current at the point of fault (A)

V_{Source} Source voltage (V)

Z_{cable} Impedance of the cable snippet (Ω)

The most conservative condition will be to consider the maximum voltage of the source, that is:

$$V_{Source} = V_{Max}$$
$$Z_{cable} = R_{cable} + jX_{cable}$$
$$Z_{cable} = l.(R_\theta + jX_{Hz})$$

Where:

l Cable length (km)

R_θ Cable resistance at temperature θ (Ω/km)

X_{Hz} Cable reactance at system frequency (Ω/km)

So:

$$\overrightarrow{I_{CC}} = \frac{\overrightarrow{V_{Max}}}{\overrightarrow{Z_{cable}}}$$

$$\left|\overrightarrow{I_{CC}}\right| = \left|\frac{\overrightarrow{V_{Max}}}{\overrightarrow{l.(R_\theta + jX_{Hz})}}\right|$$

$$I_{CC}{}^2 = \frac{V_{Max}{}^2}{l^2(R_\theta{}^2 + X_{Hz}{}^2)}$$

Substituting I in formula $I^2t \leq k^2.S^2$ have:

$$I_{CC}{}^2 t \leq k_\theta{}^2.S^2$$

$$\frac{V_{Max}{}^2}{l^2(R_\theta{}^2 + X_{Hz}{}^2)}.t \leq k_\theta{}^2.S^2$$

$$l^2 \geq \frac{V_{Max}{}^2.t}{k_\theta{}^2.S^2(R_\theta{}^2 + X_{Hz}{}^2)}$$

$$V_{Max} = \frac{V_n.f}{100\sqrt{3}}$$

Where:

V_n Rated system voltage (V)

f Maximum voltage factor (%)

$$\boldsymbol{l \geq \frac{V_n.f\sqrt{t}}{100\sqrt{3}k_\theta.S\sqrt{R_\theta{}^2 + X_{Hz}{}^2}}}$$

For cables with PVC insulation, rated system voltage 480V, voltage factor 110%, for short circuit duration times 0.05s, 0.1s 03s and 0.5s, the protected cable lengths are as indicated in the following table:

$$\boldsymbol{l \geq \frac{V_n.f\sqrt{t}}{100\sqrt{3}k_{70}.S\sqrt{R_{70}{}^2 + X_{60Hz}{}^2}}}$$

Using the spreadsheet, we have:

CABLES INSULATED WITH PVC						
System Nominal Voltage (Vn)				480	V	
Maximum Voltage Factor (f)				110	%	
Protected Cable Length (m)						
Cables Data			Fault Interruption Time (s)			
S (mm²)	R 70	X 60Hz	0,05	0,10	0,3	0,5
2,5	8,252	0,096	29	41	70	91
4	5,157	0,096	29	41	70	91
6	3,438	0,096	29	41	70	91
10	2,063	0,096	29	41	70	91
16	1,289	0,096	29	41	70	91
25	0,825	0,096	29	40	70	90
35	0,589	0,096	28	40	69	90
50	0,413	0,096	28	40	69	88
70	0,295	0,096	27	39	67	86
95	0,217	0,096	26	37	64	83
120	0,172	0,096	25	35	61	79
150	0,138	0,096	24	33	58	75
185	0,112	0,096	22	31	53	69
240	0,086	0,096	19	27	47	61

For example, if the maximum fault duration time is 0.3s, for a cable with a nominal section of 70mm² to be protected, the length of the feeder must be equal to or greater than 67m, or the fault in the cable must occur at a distance from the source greater than 67m, and the cable can be repaired at the place where the defect occurred.

For cables with EPR/XLPE insulation, rated system voltage 480V, voltage factor 110%, for short circuit duration times 0.05s, 0.1s 03s and 0.5s, the protected cable lengths are as indicated in the following table:

$$l \geq \frac{V_n . f\sqrt{t}}{100\sqrt{3}k_{90}. S\sqrt{{R_{90}}^2 + {X_{60Hz}}^2}}$$

Using the spreadsheet, we have:

CABLES INSULATED WITH EPR/XLPE						
System Nominal Voltage (Vn)				480	V	
Maximum Voltage Factor (f)				110	%	
Protected Cable Length (m)						
Cables Data			Fault Interruption Time (s)			
S (mm²)	R 90	X 60Hz	0,05	0,10	0,3	0,5
2,5	8,794	0,096	27	38	66	85
4	5,496	0,096	27	38	66	85
6	3,664	0,096	27	38	66	85
10	2,198	0,096	27	38	66	85
16	1,374	0,096	27	38	66	85
25	0,879	0,096	27	38	66	85
35	0,628	0,096	27	38	65	84
50	0,440	0,096	26	37	65	83
70	0,314	0,096	26	36	63	82
95	0,231	0,096	25	35	61	79
120	0,183	0,096	24	34	58	76
150	0,147	0,096	23	32	55	71
185	0,119	0,096	21	30	51	66
240	0,092	0,096	19	26	46	59

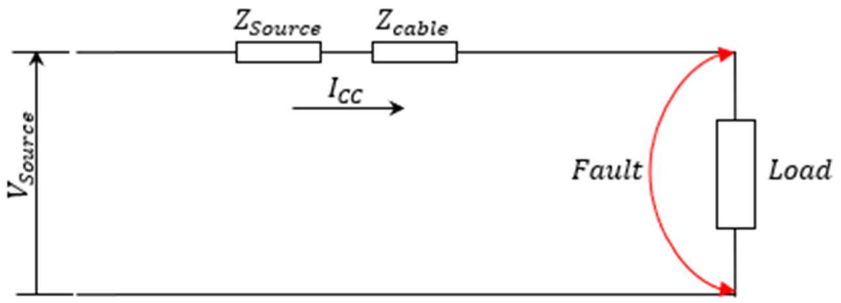
It was considered that at the time of 0.05 seconds, the direct current component of the short circuit current is very small and therefore the short circuit current is already equal to the symmetric short circuit current.

Note that the minimum length of protected cable almost does not vary much with the section, but with the time of action of the protection. For a protection actuation time of 0.1s, the protected cable length is 38m for all cables between 2.5 and 35mm^2. Therefore, if a cable does not support the short circuit current, for a certain time of action of the protection, the solution will not be to increase the section, but to reduce the time of action of the protection.

For lengths shorter than those defined, the protection guarantee must be made using cables with nominal sections calculated with the short circuit current of the source.

6.3 - Maximum Protection Operation Time

The recommended condition considers the fault at the end of the cable, that is, it considers that the cable will withstand the short circuit current without suffering damage and is represented by the following figure, where the impedance of the source was introduced:



To simplify the calculations, it will be considered that the impedance of the source will be the reactance, calculated based on the short circuit power of the source. Like this:

$Z_{cable} = R_{cable} + jX_{cable}$ e $Z_{cable} = l(R_\theta + jX_{cable})$

Where:

Z_{cable} Impedance of the cable snippet (Ω)

l Cable length (km)

R_θ Cable resistance at temperature θ (Ω/km)

X_{cable} Cable reactance at system frequency (Ω/km)

Whereas:

$$Z_{Source} = X_{Source} = \frac{{V_n}^2}{P_{CC_{Source}}}$$

Where:

V_n Rated system voltage (V)

$P_{CC_{Source}}$ Short circuit power of the source (VA)

The short circuit current will be:

$$I_{cc} = \frac{V_{Source}}{l(R_\theta + jX_{cable}) + jX_{Source}}$$

$$I_{cc} = \frac{V_{Source}}{l.R_\theta + jl.X_{cable} + jX_{Source}}$$

$$I_{cc} = \frac{V_{Source}}{l.R_{\theta} + j(l.X_{cable} + X_{Source})}$$

$$I_{cc} = \frac{V_{Source}}{\sqrt{(l.R_{\theta})^2 + (l.X_{cable} + X_{Source})^2}}$$

$$V_{Source} = \frac{V_n.f}{\sqrt{3}}$$

Where:

f Maximum voltage r factor (%)

Replacing V_{Fonte} and X_{Fonte} have:

$$\boldsymbol{I_{cc} = \frac{\frac{V_n.f}{\sqrt{3}}}{\sqrt{(l.R_{\theta})^2 + \left(l.X_{cable} + \frac{{V_n}^2}{P_{CC_{Source}}}\right)^2}}}$$

$${I_{cc}}^2 = \left(\frac{\frac{V_n.f}{\sqrt{3}}}{\sqrt{(l.R_{\theta})^2 + \left(l.X_{cabo} + \frac{{V_n}^2}{P_{CC_{Fonte}}}\right)^2}}\right)^2 = \frac{\frac{{V_n}^2 f^2}{3}}{(l.R_{\theta})^2 + \left(l.X_{cabo} + \frac{{V_n}^2}{P_{CC_{Fonte}}}\right)^2}$$

Replacing I in the formula $I^2 t \leq k^2.S^2$ have:

$${I_{cc}}^2 t \leq {k_{\theta}}^2.S^2$$

$$\boldsymbol{t \leq \frac{{k_{\theta}}^2.S^2}{{I_{cc}}^2}}$$

For PVC-insulated copper cables, rated system voltage 480V, voltage factor 110%, and frequency 60Hz, the maximum protection actuation times and short circuit currents for the defined cable lengths are calculated by considering:

$$\boldsymbol{I_{CC} = \frac{\frac{V_n.f}{\sqrt{3}}}{\sqrt{(l.R_{70})^2 + \left(l.X_{60Hz} + \frac{{V_n}^2}{P_{CC_{Source}}}\right)^2}}}$$

$$\boldsymbol{t \leq \frac{{k_{70}}^2.S^2}{{I_{cc}}^2}}$$

$$\boldsymbol{k_{70} = 115}$$

For EPR/XLPE insulated copper cables, rated system voltage 480V, voltage factor 110%, and frequency 60Hz, the maximum protection actuation times and short circuit currents for the defined cable lengths are calculated by considering:

$$\boldsymbol{I_{CC} = \frac{\frac{V_n.f}{\sqrt{3}}}{\sqrt{(l.R_{90})^2 + \left(l.X_{60Hz} + \frac{{V_n}^2}{P_{CC_{Fonte}}}\right)^2}}}$$

$$t \leq \frac{{k_{90}}^2 . S^2}{{I_{cc}}^2}$$

$$k_{90} = 143$$

To ensure that the cable is protected in case of defect, for each cable there will be a short circuit current and a maximum time of protection actuation. Using the spreadsheets below, for PVC and EPR/XLPE insulated cables we have, for example, for cables with a length of 50m, short circuit power at the source of 16.63MVA (20kA at 480V):

CABLES INSULATED WITH PVC					
Source Short Circuit Power (Pcc)				16,63	MVA
System Nominal Voltage (Vn)				480	V
Maximum Voltage Factor (f)				110	%
Feeder Length				50	m
Cables Data			Short Circuit Current (KA)	Maximum Time for Protection to Operate (s)	
S	R_{70}	X_{60Hz}			
2,5	8,252	0,096	0,74	0,15	
4	5,157	0,096	1,18	0,15	
6	3,438	0,096	1,76	0,15	
10	2,063	0,096	2,91	0,16	
16	1,289	0,096	4,54	0,16	
25	0,825	0,096	6,73	0,18	
35	0,589	0,096	8,74	0,21	
50	0,413	0,096	10,96	0,28	
70	0,295	0,096	12,82	0,39	
95	0,217	0,096	14,12	0,60	
120	0,172	0,096	14,84	0,86	
150	0,138	0,096	15,33	1,27	
185	0,112	0,096	15,66	1,85	
240	0,086	0,096	15,92	3,00	

CABLES INSULATED WITH EPR/XLPE					
Source Short Circuit Power (Pcc)				16,63	MVA
System Nominal Voltage (Vn)				480	V
Maximum Voltage Factor (f)				110	%
Feeder Length				10	m
Cables Data			Short Circuit Current (KA)	Maximum Time for Protection to Operate (s)	
S	R_{90}	X_{60Hz}			
2,5	8,794	0,096	3,42	0,01	
4	5,496	0,096	5,36	0,01	
6	3,664	0,096	7,71	0,01	
10	2,198	0,096	11,50	0,02	
16	1,374	0,096	15,09	0,02	
25	0,879	0,096	17,69	0,04	
35	0,628	0,096	18,94	0,07	
50	0,440	0,096	19,73	0,13	
70	0,314	0,096	20,13	0,25	
95	0,231	0,096	20,33	0,45	
120	0,183	0,096	20,42	0,71	
150	0,147	0,096	20,48	1,10	
185	0,119	0,096	20,51	1,66	
240	0,092	0,096	20,54	2,79	

For PVC and EPR/XLPE insulated cables we have, for cables with a length of 50m, short circuit power at the source of 8.35MVA (10kA at 480V):

CABLES INSULATED WITH PVC					
Source Short Circuit Power (Pcc)				8,31	MVA
System Nominal Voltage (Vn)				480	V
Maximum Voltage Factor (f)				110	%
Feeder Length				50	m
Cables Data			Short Circuit Current (KA)	Maximum Time for Protection to Operate (s)	
S	R_{70}	X_{60Hz}			
2,5	8,252	0,096	0,74	0,15	
4	5,157	0,096	1,17	0,15	
6	3,438	0,096	1,74	0,16	
10	2,063	0,096	2,82	0,17	
16	1,289	0,096	4,22	0,19	
25	0,825	0,096	5,80	0,25	
35	0,589	0,096	6,95	0,34	
50	0,413	0,096	7,91	0,53	
70	0,295	0,096	8,54	0,89	
95	0,217	0,096	8,89	1,51	
120	0,172	0,096	9,06	2,32	
150	0,138	0,096	9,17	3,54	
185	0,112	0,096	9,24	5,30	
240	0,086	0,096	9,29	8,82	

CABLES INSULATED WITH EPR/XLPE					
Source Short Circuit Power (Pcc)				8,31	MVA
System Nominal Voltage (Vn)				480	V
Maximum Voltage Factor (f)				110	%
Feeder Length				10	m
Cables Data			Short Circuit Current (KA)	Maximum Time for Protection to Operate (s)	
S	R_{90}	X_{60Hz}			
2,5	8,794	0,096	3,30	0,01	
4	5,496	0,096	4,92	0,01	
6	3,664	0,096	6,55	0,02	
10	2,198	0,096	8,43	0,03	
16	1,374	0,096	9,58	0,06	
25	0,879	0,096	10,16	0,12	
35	0,628	0,096	10,38	0,23	
50	0,440	0,096	10,50	0,46	
70	0,314	0,096	10,56	0,90	
95	0,231	0,096	10,59	1,64	
120	0,183	0,096	10,61	2,62	
150	0,147	0,096	10,61	4,08	
185	0,119	0,096	10,62	6,21	
240	0,092	0,096	10,62	10,44	

The maximum actuation times of the indicated protections, consider that the currents are the symmetrical short circuit currents, that is, without the direct current component. As it was considered that, in the time of 0.05s, the direct current component is very small, for values lower than this time, the asymmetry factor should be considered, which depends on the characteristics of the system.

For low voltage circuits the asymmetry factor can be 1.25 or another that the professional determines. For these cases, the maximum time of action of the protection must be recalculated with the use of the spreadsheets.

Short circuit currents and high times must be evaluated by the professional because the equipment of the installations (frames, load centers, transformers, etc.), support the short circuit currents for a limited time and the protections, for high short circuit currents, must act in times lower than those limited by the equipment. For example, transformers must withstand short-circuit currents at their terminals for a maximum of 2 seconds.

6.4 - Conclusions

Excluding the options of using the curves of the passing energy of the protection devices, which are not the subject of this information, the sizing criterion that is more convenient for the professional can be used, that is, in a feeder circuit can consider the maximum short circuit current of the source, in another of the minimum length of the cable that limits the short circuit current and in another, the time of operation of the protection, provided that everyone meets the condition:

$$I^2 t \leq k^2 . S^2$$