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Calculation of minimal short-circuit current in parallel arrangement of cables for a three phase short-circuit fault

Abstract. *In commonly used short-circuit current calculation methodology, the acceptance of a short-circuit site in the middle of their length leads not only to a significant overestimation of short-circuit currents, but also does not guarantee the selective coordination of electrical apparatus and its proper protection function against electrical shock. The paper presents new approach to the problem of calculation short-circuit current in parallel cables. It is proven that the worst case scenario is highly influenced by the number of cables connected in parallel.*

Streszczenie. *W powszechnie stosowanej metodologii obliczania prądu zwarciowego przyjmuje się, że miejsce zwarcia występuje w środku ich długości co prowadzi nie tylko do znacznego przeszacowania prądów zwarciowych, ale również nie gwarantuje selektywnej koordynacji aparatury elektrycznej i jej odpowiedniej ochrony przed porażeniem elektrycznym. W artykule przedstawiono nowe podejście do problemu obliczeniowego prądu zwarciowego w przewodach równoległych. Udowodniono, że w najgorszym przypadku duży wpływ ma liczba połączonych równolegle kabli.* ***(Obliczanie minimalnego prądu zwarciowego w układzie równoległym kabli dla trójfazowego zwarcia)***

Keywords: cables, short-circuit distance, short-circuit impedance, short-circuit currents
Słowa kluczowe: kable, odległość zwarcia, impedancja zwarcia, prądy zwarciowe

Introduction

Power increase: required by low-voltage switchgears, individual loads (most often powering the technological line), MV / LV transformers make the required cross-section of a single power cable often larger than the cross-section offered by manufactures. In this situation, the only solution is to use cables that are laid in parallel along the same route. Other reasons for the use of parallel cables are the permissible bending radius of a single conductor (this applies mainly to power cables), mass and cost of laying. The method of laying cables mainly affects the permissible long-term load capacity of conductors, including, among others, the asymmetry coefficient [2]. Cable resistance plays a positive role in evennes of the current distribution. When increasing the reactance proportions in the resultant cable impedance, the load on the individual cables increases asymmetry [4]. Non-symmetrization of loads in individual cables is problematic in terms of design and operation [3]. For shielded cables, the influence of the arrangement method affects the power losses generated in the screen [7]. It is suggested that in order to obtain the lowest asymmetry coefficient, the cables should be arranged in an equilateral triangle [6, 5]. If all of the above conditions are met the current will be evenly distributed in all of the cables (both in normal and fault conditions).

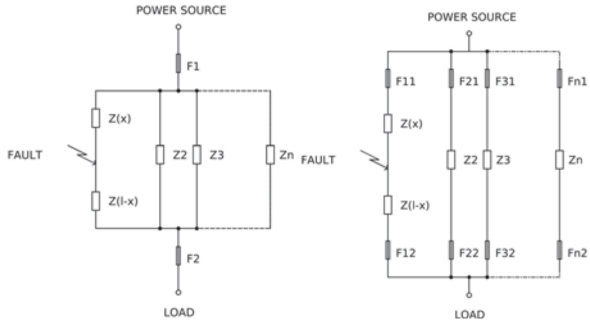
Cables operating in parallel system should have the same cross-sections and lengths, and working conductors and PEN and PE conductors should be made of the same material. The specified requirements are also listed in the IEC 60364-5-52 standard [1]. In the event of a short circuit with one of the cables of the parallel circuit, the same short-circuit current flows through the remaining parallel-connected cables. This applies both to the three-phase and single-phase short-circuits.

Therefore, in the analysis of three-phase short-circuit current described below, it was assumed that power lines connected in parallel are of the same type, have the same cross-section of the working wire and PEN or PE conductor, have the same length and the same unit impedance.

Protection apparatus in parallel cables

The parallel schematic diagram of cables connected in parallel, used for the analysis of short-circuit currents, is shown in Fig. 1. The parallel wires shown can be protected in two ways:

- one common overcurrent protection installed in the power supply system (Fig. 1a),



(a) (b)

Fig. 1: Scheme of a parallel connection of wires and two ways of installing overcurrent protections: a) common to all conductors, b) independently for each conductor

- two overcurrent protections installed at the beginning and end of each wire (Fig. 1b).

The use of common overcurrent protection does not allow any connectors to be installed in any of the conductors that may cause their continuity to be interrupted and forces the verification of short-circuit durability for each conductor. In the second case, correctly selected overcurrent protection device only turns off the voltage from the line in which the short-circuit occurred.

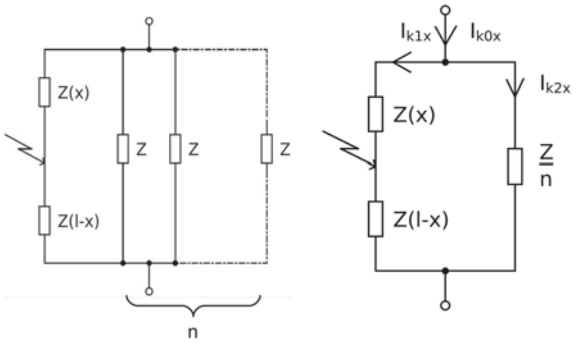
The adoption of one of the two given ways of installing overcurrent protection apparatus also has a significant impact on the reliability of the customer's power supply. In the first case, a short circuit in any parallel cable completely deprives the user of the possibility of its supply, in the latter case does not deprive the power supply.

The base for analysing the magnitude of short-circuit currents flowing in parallel connected (*n+1*) cables is the assumption that in the case of a short-circuit in any of the wires:

- short-circuit current also flows through the *n* of the other wires connected in parallel,
- the number of PE protective conductors connected in parallel or protective neutral PEN is the same as the number of live conductors,
- the value of short-circuit current depends not only on the type of short-circuit (three-phase symmetrical, single-phase), but also on the place of its occurrence.

The object of the analysis is to determine:

- the impact of fault location in one of the parallel



(a) (b)

Fig. 2: Location of short-circuit fault in one of the parallel connected cables, current distribution (a) and impedance circuit diagram of the short-circuit (b): *x* – the place of occurrence of a short circuit, *l* – length of the wire, I_{k0x} – short-circuit current in the power supply network, I_{k1x} – current flowing to the fault location directly from the power supply network, I_{k2x} – current flowing to the fault location from the other *n* parallel wires

connected wires on the value and short-circuit current flow,

- how the number of cables connected in parallel influences the value and distribution of short-circuit current,
- when and under what conditions the minimum short-circuit current in the fault circuit will occur.

The answer to the questions posed is of great importance for the correct selection of overcurrent protection apparatus installed at the beginning of each conductor in order for them to act selectively and evaluate the effectiveness of the protection against electrical shock performed with their help. Such analysis was carried out for three-phase circuit.

For the sake of simplicity, it was assumed that the *n+1* wires connected in parallel (where: *n* – is the number of parallel connected wires through which short-circuit current flows feeding the short-circuit in the *n+1* cable) are of the same type, the same cross-section of the working conductor and the PEN or PE conductor, have the same length (*l*) and the same unit impedance (Z_0).

Three-phase symmetric fault in parallel connection system

Assuming a three-phase, symmetrical short-circuit in one of the parallel connected cables occurring at a distance *x* from the connection point (Fig. 2a), the value of the initial short-circuit current flowing from the supply network to parallel connected wires can be determined from the formula 1.

$$I''_{k0x} = \frac{cU_N}{\sqrt{3}Z_{kx}} \quad (1)$$

where: Z_{kx} – short circuit impedance module, *c* – coefficient depending on the value of the supply voltage and the purpose of calculations, U_N - line voltage of the supply network in which the short-circuit occurs.

For a short circuit occurring in one of the wires at a distance *x* from the connection point to the supply network (Fig. 2b), the short circuit impedance Z_{kx} is the resultant of parallel impedance connection directly binding the shorted cable to the supply network ($Z(x)$) and serial connection of the impedance of the remaining part of the shorted conductor ($Z(l-x)$) with the resultant impedance of the parallel *n* wires (Z/n). For the simplification assumptions given above and after a series of transformations, the impedance of the short circuit circuit is described with equation 2.

Table 1: Impedance of the short circuit circuit Z_{kx}, depending on the place *x*, the occurrence of a short circuit in the wire and the number *n* of the remaining parallel connected wires

n	Z_{kx}	x_{max}
1	$Z_0x\,(2l-x)\,/2l$	1,0 l
2	$Z_0x\,(3l-x)\,/3l$	0,75 l
3	$Z_0x\,(4l-x)\,/4l$	0,67 l
4	$Z_0x\,(5l-x)\,/5l$	0,60 l
∞	$Z_0x\,(l-x)\,/l$	0,5 l

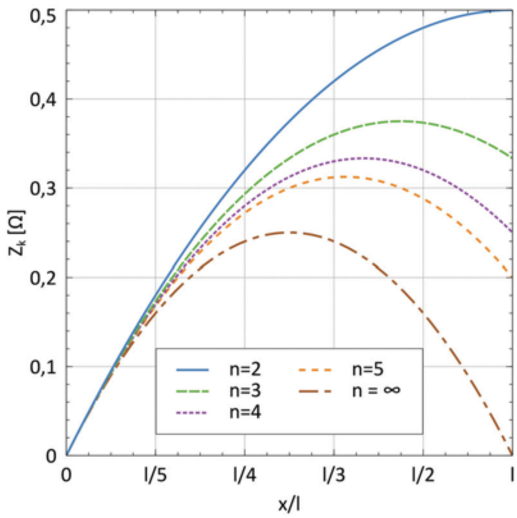


Fig. 3: The short-circuit impedance changes depending on the *x* location of the short-circuit in the *l* length cable for different numbers of *n* parallel connected cables. The calculations were made for $Z_0 = 1\Omega$

$$Z_{kx} = Z_0x\left(1 - \frac{n}{(n+1)}\frac{x}{l}\right) \quad (2)$$

where: Z_0 – unit impedance of cables, *x* – distance of fault location in the cable from the power supply network, *l* – length of parallel connected cables, *n* – the number of cables connected in parallel through which the current feeding the short-circuit in the *n+1* conductor flows.

The analysis of the equation 2 shows that the impedance of the short circuit circuit Z_{kx} and the value of fault currents I_{k0x}, I_{k1x} and I_{k2x} (Fig. 2b) depends on the location of the short circuit and the number *n* of parallel connected wires. Analytical dependencies describing the changes of short circuit impedance Z_{kx} depending on the number *n* of wires connected in parallel are given in Table 1. The impedance changes Z_{kx} depending on the place of fault is shown in Figure 3.

By differentiating and comparing to zero the equation 2, one can determine the distance x_{max} of the fault location in the line from the supply network, at which the maximum impedance value of the short circuit Z_{kmax} and the minimum short-circuit currents I_{k0x}, I_{k1x}, I_{k2x} will occur (Fig. 2b).

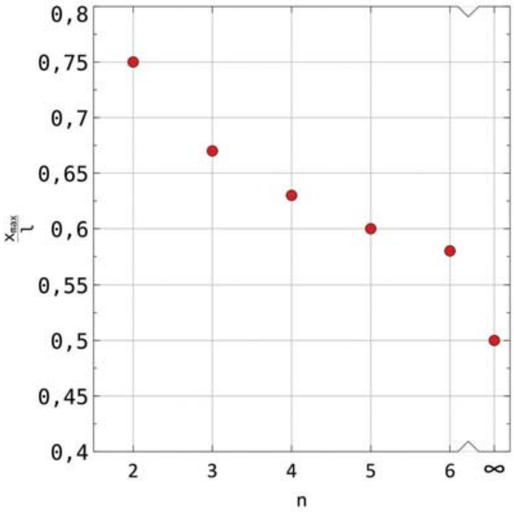


Fig. 4: The influence of the number *n* of wires connected in parallel to the place x_{max}, the occurrence of a short in the cable of length *l*, for which the impedance of the short circuit reaches the maximum value Z_{kmax}

The expression allowing to determine x_{max} is shown in equation 3.

$$x_{max} = \frac{l}{2}\left(1 + \frac{1}{n}\right) \tag{3}$$

Table 1 and Fig. 3 show, determined on the basis of the expression 3, the distance x_{max} of the short circuit in the cable, depending on the number *n* of the other wires connected in parallel. The analysis of the dependencies shown in Fig. 3 and Table 1 shows that a significant influence on the fault location for which the impedance of the short-circuit protection Z_{kmax} reaches the maximum value has the number *n* of the other wires connected in parallel. The specified distance x_{max} decreases with the number *n* of wires connected in parallel. In the extreme case, when the number of wires connected in parallel is infinitely large, the maximum value of the short-circuit fault impedance Z_{kmax} will occur for a short-circuit occurring in the middle of the shorted cable length. For such a short circuit, the values of short-circuit currents in parallel connected cables are considered, estimated and calculated. However, under operating conditions, the number of cables connected in parallel does not usually exceed 2 or 3. Therefore, short circuit impedance values used for calculation of short-circuit current are undervalued, and do not guarantee the correct selection of overcurrent protection apparatus (mainly fuses) installed as shown in Fig. 1b, their selective cooperation as well as proper protection against electric shock.

Knowing the impedance of the circuit in one of the parallel connected cables at the distance *x* from the place of its connection to the supply network described with the dependence 2, using the formula 1, the value of short-circuit currents I_{k0x}, I_{k1x} and I_{k2x} flowing from the supply network to the system of parallel (*n+1*) wires I_{k0x}, directly from the supply network to the fault location I_{k1x} and in the remaining *n* connected in parallel wires I_{k2x} to the fault location. The equations 4, 5 and 6 are describing the mentioned currents for a three-phase symmetric short-circuit.

Table 2: The minimum values of short-circuit currents in a parallel wiring arrangement

n	x_{max}	I''_{k0min}	I''_{k1min}	I''_{k2min}
1	1,00 l	2,00 A	1,00 A	1,00 A
2	0,75 l	2,67 A	1,33 A	1,33 A
3	0,67 l	3,20 A	1,50 A	1,50 A
4	0,60 l	3,33 A	1,67 A	1,67 A
∞	0,50 l	4,00 A	2,00 A	2,00 A

$$I''_{k0x} = \frac{cU_N}{\sqrt{3}Z_0 x}\frac{1}{\left(1 - \frac{nx}{l(n+1)}\right)} \tag{4}$$

$$I''_{k1x} = I''_{k0x} \cdot k_{1(x)} \tag{5}$$

$$I''_{k2x} = I''_{k0x} \cdot k_{2(l-x)} \tag{6}$$

In this equations:

- $k_{1(x)} = \left(1 - \frac{nx}{l(n+1)}\right)$ share coefficient of current flowing from the supply network directly to the fault location,
- $k_{2(l-x)} = \frac{nx}{l(n+1)}$ share coefficient of the current flowing through *n* wires connected in parallel to the fault location.

Using the formulas 4, 5 and 6 the minimum value of the short-circuit currents can be determined in the case of a short-circuit in a parallel circuit, described by equation 3, from its connection to the main line. After the transformations, the analytical relationships allowing to calculate the minimum values of short-circuit currents from Fig. 2b are shown in equations 7 and 8.

$$I''_{k0min} = \frac{cU_N}{\sqrt{3}Z_0}\frac{4n}{l(n+1)} \tag{7}$$

$$I''_{k1min} = I''_{k2min} = \frac{cU_N}{\sqrt{3}Z_0}\frac{2n}{l(n+1)} \tag{8}$$

The analysis of equations 7 and 8 shows that the minimum value of short-circuit currents depends not only on the parameters of the wires (Z_0), but also on the number *n* of the other wires connected in parallel. The minimum values of short-circuit currents I''_{k0min}, I''_{k1min}, I''_{k2min} for a short-circuit occurring in one of the wires at a distance x_{max} from the supply network for different numbers of *n* remaining wires are listed in Table 2, and the their changes are shown in Figure 5. Calculations were made with the assumption that $cU_N/\sqrt{3}Z_0$ part of equations 7 and 8 is equal to one.

In the case of a single-phase short circuit, the design is similar. The impedance of the circuit is twice as large, while the short-circuit currents described by the relations 7 and 8 are two times smaller.

In practice when determining the value of short-circuit currents in a parallel arrangement of cables with length *l*, it is recommended to take a short-circuit in the middle of the length of a shorted conductor. In such a case short circuit impedance and short-circuit currents, determined respectively from formulas 2 and 4, 5 and 6 for $x = l/2$, are described by dependences 9, 10 and 11.

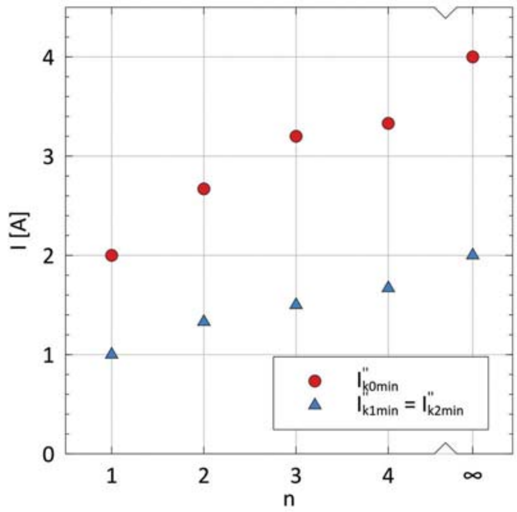


Fig. 5: Minimum values of short-circuit currents I''_{k0min}, I''_{k1min}, I''_{k2min} for a short-circuit occurring in one of the cables at a distance x_{max} from the supply network for different numbers of *n* remaining wires

$$Z_{kx} = Z_0 l \frac{(n+2)}{4(n+1)} \tag{9}$$

$$I''_{k0} = \frac{cU_N}{\sqrt{3}Z_0} \frac{4(n+1)}{l(n+2)} \tag{10}$$

$$I''_{k1} = \frac{cU_N}{\sqrt{3}Z_0} \frac{2}{l} \tag{11}$$

Comparing the relationships 7, 8 and 10, 11 to determine the short-circuit currents for a short-circuit occurring in one parallel circuit, respectively, at a distance of x_{max} from the supply network and half its length $x = l/2$, you can notice significant differences in them. These differences cause that short-circuit currents calculated on the basis of dependence 10 and 11 for a short-circuit occurring in the middle of the length of the conductor are much greater than the actual minimum short-circuit currents. These values are important in the selection of overcurrent protections for their selective coordination and the protection against electrical shock. For this reason, a comparative analysis of the values of short-circuit currents determined for the above mentioned fault locations was carried out. Table 3 and Fig. 6 shows the relative error when estimating short-circuit currents for a short-circuit occurring in the cable at a distance of x_{max} from the supply network and half its length $x = l/2$. As in previous case calculations were made with the assumption that $cU_N/\sqrt{3}Z_0$ part of equations 7, 8, 10, 11 is equal to one. From the analysis of Table 3 and Fig. 6, the greatest overvaluation of the short-circuit currents will occur, in the most-used system in operation, containing 2 or 3 cables connected in parallel. The error was calculated according to equations 12 and 13.

$$\delta I''_k = \frac{I''_{k0} - I''_{k0min}}{I''_{k0min}} \tag{12}$$

$$\delta I''_{k1}; \delta I''_{k2} = \frac{I''_{k2} - I''_{k2min}}{I''_{k2min}} \tag{13}$$

Table 3: Short-circuit currents in a parallel wiring arrangement, relative error of short-circuit currents for a short-circuit occurring at a distance of x_{max} from the supply network and half of the length *l* of a short-circuited conductor for different numbers of *n* connected in parallel cables

n	Fault location x_{max}		$x = \frac{l}{2}$		Relative error δ	
	I''_{k0min}	$I''_{k1min} = I''_{k2min}$	I''_{k0}	$I''_{k1} = I''_{k2}$	$\delta I''_k$	$\delta I''_{k1} = \delta I''_{k2}$
1	2,00 A	1,00 A	2,66 A	1,33 A	0,333	0,333
2	2,67 A	1,33 A	3,00 A	1,50 A	0,125	0,125
3	3,20 A	1,50 A	3,20 A	1,60 A	0,067	0,067
4	3,33 A	1,67 A	3,33 A	1,67 A	0,040	0,040
∞	4,00 A	2,00 A	4,00 A	2,00 A	0	0

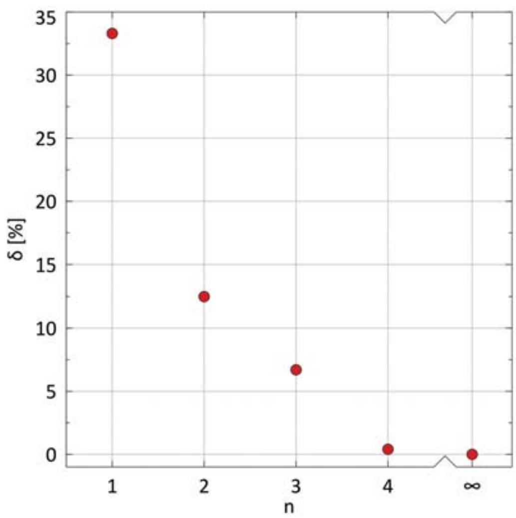


Fig. 6: Relative error of estimation of the three-phase short-circuit currents for a short-circuit occurring in the middle of the length *l* of the conductor and in the distance x_{max} from the supply network for various numbers *n* connected in parallel to the compact conductor

Conclusions

From the presented analysis of three-phase fault currents in a parallel arrangement of cables it follows that:

- in case of short-circuit in one of the cables, the value of short-circuit currents depends on the fault location and the number of other cables connected in parallel,
- for each number of cables connected in parallel, there is a strictly defined distance of the fault location in one of them from the supply network, at which short-circuit currents reach the minimum value,
- the distance of the fault location decreases with the number of cables connected in parallel; in the extreme case, when the number of cables connected in parallel is infinitely large, it will occur for a short-circuit occurring in the middle of the length of a shorted conductor,
- short-circuit currents determined for a short-circuit in the middle of the cable's length are much larger than those actually occurring,
- the largest overestimation of the expected values of short-circuit currents will occur in the most common system in operation, containing 2 or 3 cables connected in parallel; in the given case, the overestimation of short-circuit currents can reach even 33%,
- for each overcurrent protection (mainly fuses) installed in each conductor independently, the values of short-circuit currents determined for short-circuit faults in the middle of their length do not ensure their selective coordination and protection against electric shock.

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