1. Paweł ALBRECHTOWICZ[1], 2. Bartłomiej BIESAGA[2]

Politechnika Krakowska, Katedra Inżynierii Elektrycznej (1), Enetecs Engineering Technologies Sp. z o.o. (2)
ORCID: 1. 0000-0003-1607-6598

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The short-circuit analysis in multi-parallel single cable lines

Streszczenie. *Artykuł przedstawia metodologię analizy wartości prądów zwarciowych w układach zasilanych wielkokablowymi, jednożyłowymi liniami na fazę. W artykule opisano zależność pomiędzy zmianami impedancji w funkcji liczby i lokalizacji zwartych kabli. W artykule przedstawiono, że najgorszy przypadek występuje gdy tylko jeden kabel z całkowitej N-liczby jest zwarty (np. doziemienie). W rezultacie rzeczywista wartość impedancji pętli zwarcia wzrasta, co pozwala na kwestionowanie skuteczności zadziałania urządzeń zabezpieczających. (**Analiza zwarć w wielorównoległych liniach kablowych jednożyłowych**)*

Abstract. *This article presents the methodology of the short-circuit analysis when it occurs in the arrangement of multi-parallel cables per one phase. Therefore the relations between impedance changes as a function of the number of faulted cables and localization are described. As it is presented in this article, always the worst case is visible, when only one cable from total number N is faulted (e.g. ground fault). In this way the resultant real short-circuit impedance increase and proper work of the protection devices may be questioned.*

Słowa kluczowe: równoległe linie kablowe, zwarcia, wiązki kablowe.
Keywords: parallel cable lines, short-circuit, cable bundles.

Introduction

This article presents an analysis of possible short-circuits (SCs) occurring in power lines made as a few single-core cables (Fig 1). Due to the many possible SCs in such arrangements, a detailed theoretical verification has been carried out. The analysis of SCs in the designed installation/system is one of the basic conditions to be verified. Every designer of electrical installations must know the basics of calculating the minimum, maximum SC current and its effects. However, at the design stage of more advanced installations, with circuits made not as a single cable per phase, but as multiple single-core cables forming a single phase, detailed calculations of possible SC are not carried out. The usual approach is that the probability of SC is minimal in such a segment made as several cables, and the start or end of such a segment is used for the calculation (as the maximum or minimum SC current calculation respectively). SC e.g. in the middle of such a cable route segment is usually ignored.

The problem of calculating the minimum SC current in parallel cable systems is described in paper [1]. The authors analyze the possibility of a three-phase SC in parallel cable lines and its effect on the installation and protection apparatus. It is clear from their results that in some cases the SC current can be significantly lower than the tripping values of the protective apparatus. In the scientific literature it is possible to find articles that address the topic of multiple parallel cables in various aspects. Such considerations are made for low- and high-voltage cables made as underground or in building installations.

The finite element method (FEA) is used to verify the current distribution in parallel single-core cables [2]. Based on the results obtained from simulation tests of several formation cases, the main conclusion is that the triangular formation allows the best operating conditions (lowest mutual inductance and electromagnetic coupling in the immediate vicinity). Also, FEM methods have indicated that a single phase built with several cables in different formations, e.g. flat, does not allow the best power flow conditions due to skin and proximity effects [3]. Also the problem of magnetic fields with distorted currents in multi-cable systems was analyzed in [4]. As it turned out, the problem of laying a cable bundle with more than one cable per phase is also considered in aeronautical power systems [5]. The actual resistance for AC systems with cable bundles is calculated, simulated and measured. The results show that the relative errors are less than 11% for the assumed conditions.

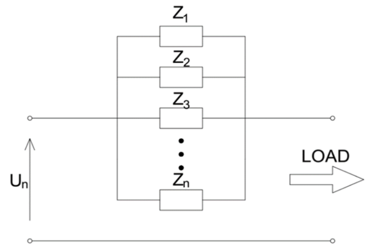

Fig. 1 An example of the multiple parallel connected single cables forming one phase.

Parallel cables per phase were studied in [6]. The authors considered what was the best arrangement to reduce the current circulation in the sheath of a section of high voltage (HV) cables. As a result of their work, they proposed a ‘symmetrical pin’ arrangement to reduce the effects of coupling between parallel cables. In [7], a methodology was proposed for calculating cable parameters in sheath grounding applications. Based on this research, an algorithm was developed to take full account of electromagnetic coupling phenomena.

The paper [8] developed a method for the best formation of parallel single cables. The authors extended the standard IEC method, allowing the most useful layout to be found also for three-phase systems with a neutral conductor (for a power load factor of 100%). For three-phase systems, multi-objective optimization using the Immune vector algorithm was applied [9]. On the basis of these studies, the authors drew conclusions allowing further analyses to find the best conditions, including unbalanced current and magnetic flux minimization, depending on the cable layout, the number of cables and their geometrical features. Building installations made on metal troughs with parallel connections of single cables are also studied in [10]. Mathematical models were developed and various cable layouts were verified, including the influence of mutual resistance and reactance for the systems considered.

Based on literature items, cable systems are extensively analyzed in many aspects. Low or high voltage problems related to the installation environment (buildings [11] or underground systems [12, 13]), steady-state and transient thermal analyses [14] as well as.

It is worth noting that not only cable lines but also overhead transmission lines made as a parallel connection are analyzed. In the paper [15], a four-parallel transmission line in China was analyzed to find SC. The proposed study combines sequence and phase components to obtain accurate fault location.

As can be seen from a brief review of the state of the art, many scientific aspects have been investigated by researchers, but the installation of many parallel cables has not been thoroughly verified. Furthermore, no basic theories covering the cases of parallel cables with short-circuit and overcurrent protection with modern electrical equipment can be found [16]. The world's leading manufacturers of protective equipment, such as fuses and residual current circuit breakers (MCBs), prepare manuals for engineers responsible for the design of electrical installations, but these publications cover the basic topics and principles without the cases presented in this article. Therefore, this publication aims to fill the research deficit, especially for low-voltage applications.

It is structured as follows: the next section describes the theory of SC, including typical and unusual cases. In the third section, the rules for parallel arrangements of single cables during a fault on a single cable are presented. This is followed by relevant analyses covering 1 to n-1 single cable faults. The final section concludes this article.

Short-circuit fundamentals

The basic principles of the SC current calculations are well-known and described in many publications. Also each electrical engineering course has subjects with this topic. The SC current I_k is defined as:

(1) $$I_k = \frac{c\, U_N}{\sqrt{3}\, Z_k}$$

where: c is the voltage value limits coefficient; U_n is the nominal phase-to-phase voltage, V; Z_k is the short-circuit impedance, Ω.

On the Eq. 1 basis, the SC current is set (among others) to select cable's size (cross-sectional area) and protection devices [17]. In this way the primary conditions of the installation project may be verified.

It should be noted that the basic approach for calculating SC parameters is prepared for grid supply. SC from local power sources, e.g. standby generators, may have different current waveforms, including generator transients [18, 19]. These phenomena are important in hybrid installations, where SC conditions can be markedly different for grid and local backup generator supply [20]. In this article, only grid supply is considered, and any other time-domain SC current dependencies are not included.

According to the statistical data, in the power systems the single-phase SC is the most common one. According to the [20], the single-phase SCs are more than 60% of all SCs types, while three-phases SCs are up to 5%. Therefore, this type will be analyzed, however the general approach is common for any SC case.

Each SC should be switched off within time given by the standards and the domestic laws in a given country [21]. For the parallel connected cables creating one phase in installation, two types of protection devices application can be distinguished basic. One cumulative circuit breaker/fuse or each single cable has two protections: one in the beginning and the second one in the end (Fig. 2).

The functions of each protective device (PDn1 and PDn2) in operation during SC is not considered. This issue is a separate topic and should be investigated in other publication. However, due to presented theory in further parts of this article, the working operation of these important elements of the installation should be precisely studied. In reference [22] some cases are studied how the SC current flows in a parallel system and how the PDs work. However, in this study the complex analysis is performed to present faster calculation methods.

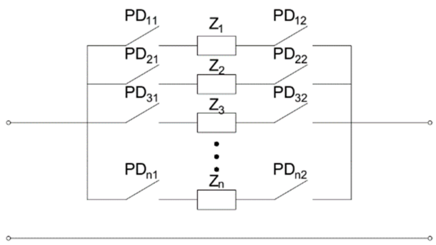

Fig. 2. The idea of installed protective devices (PDs) in both ends of every single cable.

Installations with multi-parallel single cables

The SC issue in multi-parallel single cable lines is analyzed in reference [1] and as a continuation in [23, 24]. Presented approach led to the following equation to calculate SC current flowing from the mains in the parallel cable connection with faulted one of N parallel cables.

(2) $$I_{kx} = \frac{c\, U_N}{\sqrt{3}\, Z_{kx}}$$

where: Z_{kx} is the SC impedance loop module, Ω. This value can be expressed as:

(3) $$Z_{kx} = Z_L x \left(1 - \frac{n}{(n+1)} \frac{x}{l}\right)$$

where: Z_L is impedance per one meter of the single cable, Ωm-1; n is the number of parallel single cables without fault, x is the fault location, m; l is the single cable length, m.

According to the Equation (3), the impedance variations may be plotted as it is depicted in Figure 3.

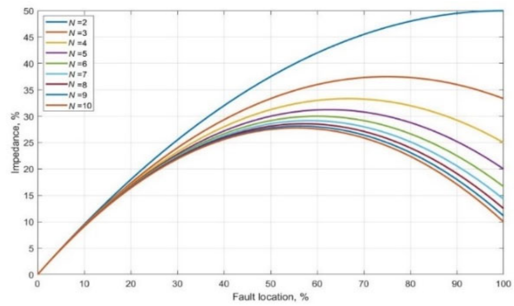

Fig. 3. Impedance changes for N parallel cables with faulted one in a distance x from 0 to 100 % of line length.

An increase in the number of parallel cables leads to changes in the resulting impedance value. For two single cables, the highest impedance is at the end of the cable, whereas for an increasing number of parallel cables (up to an infinite number of cables), the maximum impedance point would move to x=50 % of line length. The extrema of the impedance function can be found using the formula obtained by comparing the derivative dz_{kx}/dx to 0. Then the Eq. 4 is possible to calculate maximum of the function:

(4) $$x_{max} = \frac{l(n+1)}{2n}$$

Then the worst case, due to maximal loop impedance is possible to show for total number of N parallel cables.

Tab.1 The maximal impedances and their location for N-parallel cables

N	2	3	4	5	10	100	∞
Z_{max}, %	50	37.5	33.3	31.3	27.8	25.3	25
x_{max}, %	100	75	66.7	62.5	55.6	50.5	50

According to the loop impedance relationship shown, there can be serious consequences for the correct operation of the installation, including the operation of PDs and their coordination.

Short-circuits with parallel cables

The analysis of *N*-parallel cables with faulted n_f -cables has the same approach as it was described in the section III. The location of the SC and the number of faulted single cables have crucial impact on the resultant SC loop impedance and then on the SC current. To estimate the impedance, the calculation should be conducted including:
1) parallel connection of the faulted *n*-cables from the supply side,
2) parallel connection of the faulted *n*-cables from the load side,
3) parallel connection of the n_p-cables without fault,
4) series connection of cable parts from point 2) and 3).
5) parallel connection of cable parts from point 1) and 4).

Such approach allow to calculate the SC loop impedance necessary to set the SC currents. The mathematical formula for the final impedance is visible below:

$$Z_{nkx} = \frac{Z_L x\left(1 + \frac{n_p}{n_f} - \frac{x n_p}{n_f}\right)}{n_f + n_p} \qquad (5)$$

where: n_p is the number of parallel cables without fault, n_f is the number of faulted parallel cables. It is worth to note, that the sum of n_f and n_p is equal to *N*.

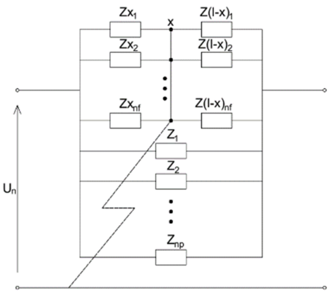

Fig. 4. The idea of the N – parallel cables with faulted nf – cables in location x, and np number of not faulted ones.

Similarly to previous consideration, for this case it is possible to find the maximum values of the function describing loop impedance Z_{nkx}. After equating to 0 the derivative dz_{nkx}/dx, the following expression can be written:

$$x_{nmax} = \frac{n_f + n_p}{2\, n_p} \qquad (6)$$

The Eq. (6) allows to find maximal value of the loop impedance, only if the condition (7) is fulfilled:

$$n_f < n_p \qquad (7)$$

If n_f is equal or greater than n_p, the $x_{n\_max} = l$.

Examples of the SC impedance loop changes are presented in Fig. 5

Tab. 2. The maximal impedance and their location for N-parallel cables

n_f	N	3	4	5	10	100
1	Z_{max}, %	37.5	33.33	31.25	27.78	25.25
	x_{max}, %	75	66.67	62.5	55.56	50.51
2	Z_{max}, %	33.33	25	20.83	15.63	12.76
	x_{max}, %	100	100	83.33	62.5	51.02
3	Z_{max}, %	-	25	20	11.90	8.59
	x_{max}, %	-	100	100	71.43	51.55
4	Z_{max}, %	-	-	20	10.42	6.51
	x_{max}, %	-	-	100	83.33	52.08
5	Z_{max}, %	-	-	-	10	5.26
	x_{max}, %	-	-	-	100	52.63
9	Z_{max}, %	-	-	-	10	3.05
	x_{max}, %	-	-	-	100	54.95
49	Z_{max}, %	-	-	-	-	1.0004
	x_{max}, %	-	-	-	-	98.04

One can notice, that two faulted single cables in each case has different Z_{nkx} values (Fig. 5). Also fault location x moves towards 50% (for maximal impedance value), while the total number of cables *N* increases. In Table 2 are presented chosen values of Z_{nkx} and x_{n_max}.

Table 2 intentionally introduced an example of *N*=100 to show how the maximal impedance and its localization vary when n_f is growing. The percentage values of the SC loop impedance Z_{max} is calculated in relation to the impedance of single cable. Figures 6 and 7 are prepared to visualize how the maximal impedance changes during considered SCs when the resultant loop impedance of a given arrangement is related to the base value ($Z_{base} = \frac{Z_L}{N}$).

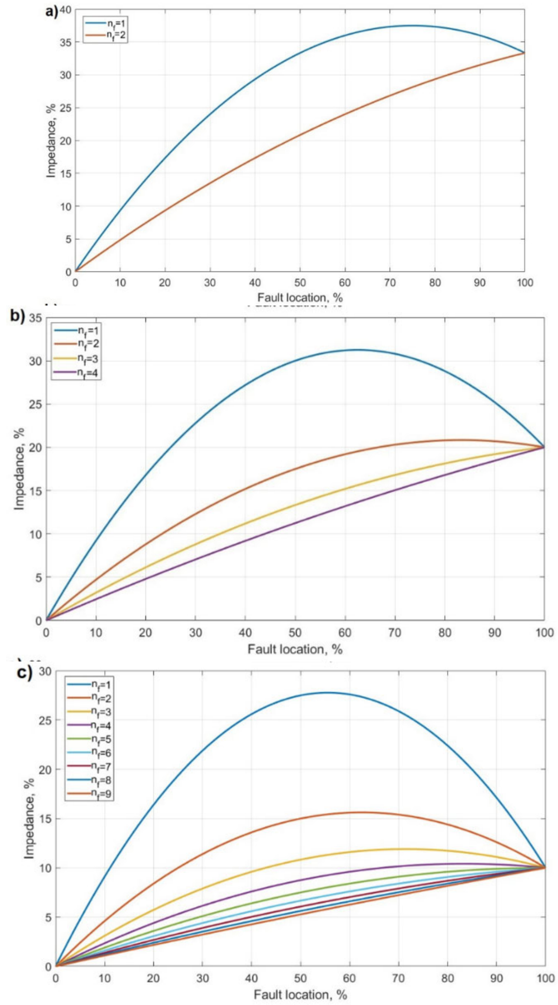

Fig. 5. The SC loop impedance changes for faulted n single cables as the distance x function in cases of: a) N=3, b) N=5, c) N=10.

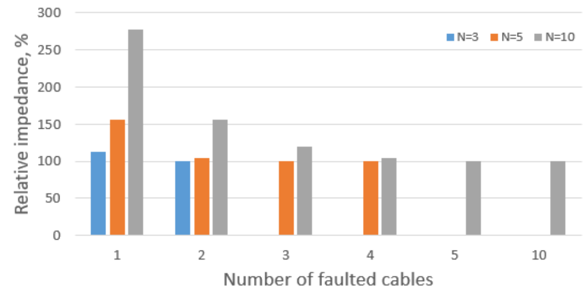

Fig. 6. The relative impedance values for N cables with n_f faulted ones.

Figures 6 and 7 show that the highest relative impedance is obtained for each *N*-case when only one cable is damaged. In addition, when the total number of *N* cables connected in parallel increases, the relative impedance also increases. According to equation (7), the maximum impedance is greater than the base impedance if the number of damaged cables n_f is less than half the total number of N cables.

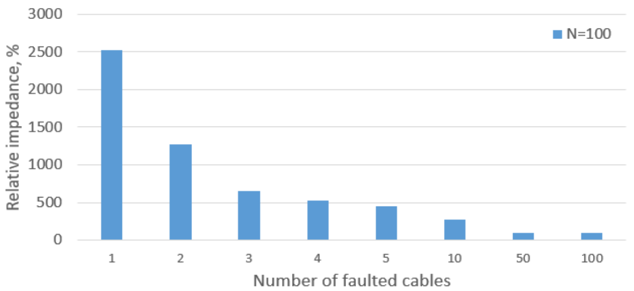

Fig. 7. The relative impedance for N =100.

This fact of impedance variation is important when analyzing the SC current and selecting protective devices (both for safe and rapid shutdown and for proper coordination between PDs). Due to the presented relations of the impedance changes, the SC current flow may change dependently on the protection devices working sequence.

To calculate currents flowing directly to the fault location through the parallel n_f cables, Equation (8) can be used:

$$I_{knf} = \alpha_{nf} I_{knx} \qquad (8)$$

where: I_{knx} is the SC current flowing from the grid, A; $\alpha_{nf} = \frac{n_f + \frac{n_p(1-x)}{l}}{n_f + n_p}$ is the coefficient specifying the SC current flowing directly from the grid through the faulted n_f cables.

The SC current supplying fault but flowing through parallel cables without fault can be described likewise Eq. (9):

$$I_{knp} = \alpha_{np} I_{knx} \qquad (9)$$

where: $\alpha_{np} = \frac{x\, n_p}{l(n_f + n_p)}$ is the coefficient specifying the SC current flowing from the grid through not faulted directly n_p cables.

The schematic division of the currents is presented in Fig. 8.

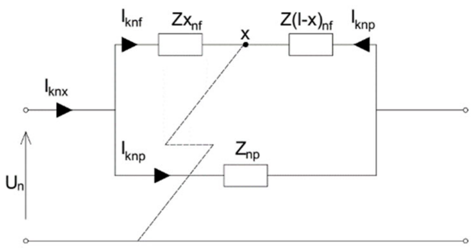

Fig. 8. The SC current paths.

The changes of the current due to different paths and number of faulted cables requires a deep analysis with consideration properties of the possible to install PDs. Also, in the arrangement with the PDs installed in both ends of each single cable, the SC conditions will change not only according to the number n_f and fault localization x, but also according to an order of protective apparatus acting. It means that to fault location x, in the SC beginning flows the whole current I_{knx}, but then this value may be only equal to I_{knf} or I_{knp}.

The coefficients of the SC current division α_{nf} and α_{np} are useful to determine the values of both currents and their impact on the PDs in the further stages of the fault duration. The variations of both α_{nf} and α_{np} are visualized in Fig. 9.

Based on the above presented relations, the SC currents in each path can be plotted, as they are presented in Figs. 10 – 12. The SC current flowing directly from the grid through the n_f faulted single cables is the same for each value of n_f, independently from total number of cables N (because this impedance is proportional to $\frac{x}{n_f}$). Therefore limited current (I_{knf} and I_{knp}) values to 3000 A are shown in Fig. 12. Figs. 10 and 11 present values of only I_{knp} to prove, that the values in this path changes dependently on the number N and faulted cables n_f.

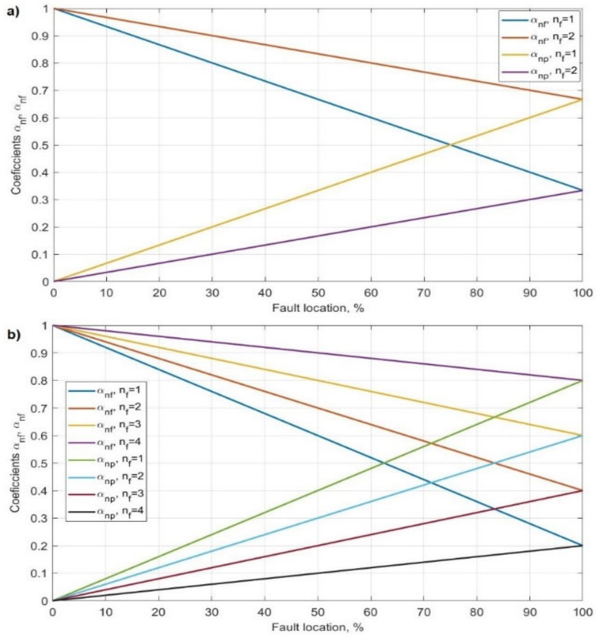

Fig. 9. The changes of coefficients α_{nf} and α_{np} for nf = (1,…, N-1) as a function of fault location x: a) N=3, b) N=5.

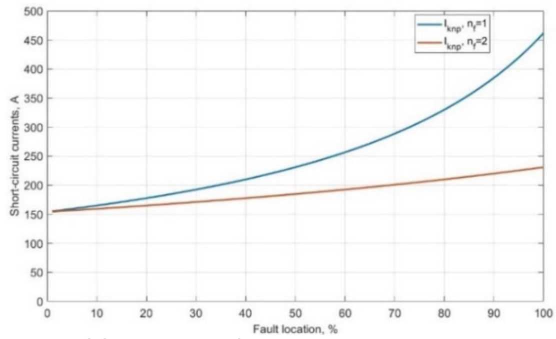

Fig. 10. The SC currents I_{knp} for N=3.

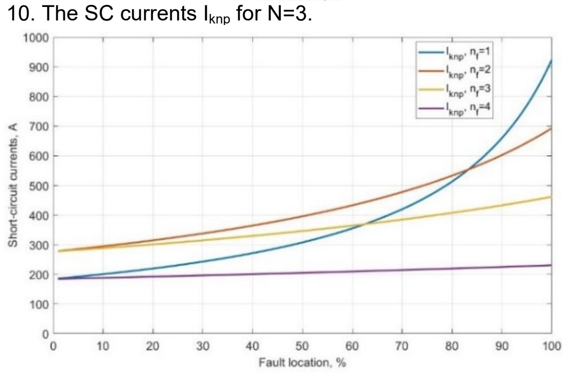

Fig. 11. The SC currents I_{knp} for N=5.

From above figures representing currents I_{knp} one can see that the values may vary depending on the fault location and number of faulted wires. However, for the SC path through the n_p cables (Fig. 12) the SC currents are greater if n_p is greater than n_f and the fault location is greater than 50%

(the greater n_f, the greater value x of the I_{knf} and I_{knp} equality). And in these cases the protective devices need to be especially analyzed when they are selected.

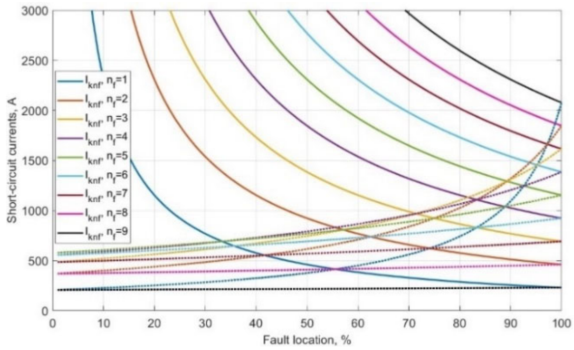

Fig. 12. The SC currents I_{knf} and I_{knp} for N = 10 (continuous line is I_{knf} and dotted one is I_{knp}).

Conclusions

This paper presents a theoretical analysis of the dependence of impedance and short-circuit current on the location of the fault and the number of faulty single cables forming one phase in multi-pair systems. The cases considered allow for a wide range of possible short-circuit effects (from a total of 3 to 100 parallel single cables per phase). Of course, it is difficult to find such systems with a dozen or more single cables connected in parallel, but this study was intended to demonstrate the principles of potential short circuit analysis.

It was proved that in each N-cables arrangement can be found location, when the impedance is maximal and greater than the single cable one.

The more individual cables that form a single phase, the greater the differences in short-circuit currents. In some cases, the values of the short-circuit currents of the two paths that occur during a fault can differ by up to more than 10 times. For this reason, these types of possible failures should also be analyzed during the design of the installation. In addition, engineers should also consider proper coordination between consecutive protective devices, as the wide range of possible currents makes it more difficult to adjust cascaded protective devices. It should be underlined, that in this article only an effect of a considered parallel cables is analyzed. The impact of cable lines impedance (and it's maximal value) depends on the total short-circuit impedance (for low voltage systems it means that system and transformer impedance should be taken into account).

Based on the presented relations, the investigation presented in this article can be efficiently applied to any case studies concerning the multiple parallel single cable arrangements.

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