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ASSESSMENT OF DYNAMIC EFFECTS IN DISTRIBUTION SUBSTATIONS WITH FLEXIBLE CONDUCTORS REGARDING SHORT-CIRCUIT DURATION VALUES

WARTOŚCI CZASU TRWANIA ZWARCIA A OCENA SKUTKÓW DYNAMICZNYCH W ROZDZIELNIACH Z PRZEWODAMI GIĘTKIMI*

The paper refers to the finding of the short-circuit duration when computing the dynamic effects in the EHV distribution substations with flexible conductors using statistical-probabilistic method. A dedicated simulation model comprising an important element i.e. a short-circuit duration model has been developed. Referring to the obtained results, the probabilistic analysis of values of short-circuit duration, short-circuit current and dynamic forces has been carried out for the substation's selected points. In computations, faults on bus and in the substation's bays, transformers and electric power lines have been taken into account. A risk criterion- based method of finding the short-circuit duration values needed in computations of dynamic forces in the power distribution substations has been presented.

Keywords: *dynamic effects, short-circuit duration, EHV distribution substations, simulation.*

Artykuł dotyczy zagadnienia określania wartości czasu trwania zwarcia podczas obliczania skutków dynamicznych w rozdzielniach najwyższych napięć z przewodami giętkimi metodą statystyczno-probabilistyczną. Do realizacji zadania opracowano model symulacyjny, którego ważnym elementem jest model czasu trwania zwarcia. Wyniki badań symulacyjnych pozwoliły na przeprowadzenie probabilistycznej analizy wartości czasu trwania zwarcia, prądu zwarciowego oraz sił dynamicznych dla wybranych punktów rozdzielni. W obliczeniach uwzględniono zwarcia na szynach i w polach rozdzielni, transformatorach oraz liniach elektroenergetycznych. Przedstawiono metodę określania wartości czasu trwania zwarcia dla potrzeb obliczeń dynamicznych sił w rozdzielniach elektroenergetycznych opartą na kryterium ryzyka.

Słowa kluczowe: *skutki dynamiczne, czas trwania zwarcia, rozdzielnie najwyższych napięć, symulacja.*

1. Introduction

Taking decisions related to the electric power system operation and maintenance shall be preceded by many analyses. Accepted data and assumptions as well as the developed models introduce different sources of uncertainty [2]. Decisions taken on the base of the determined magnitudes do not give any image of risk of making a too important mistake; one does not know if the assumed criterions result in the solutions which are either too reliable or too unreliable regarding the incurred costs. Such a problem appears when the short circuit capacity in the considered power distribution substation rises and the devices are to be adapted to the operation with higher short-circuit current values. One of the significant effects of the short-circuit current flow through the bus conductors are the dynamic forces on the supporting structures. The computation of dynamic effects in the substations with flexible conductors has been a question discussed by the Polish and foreign authors [1, 11, 12, 14, 15, 18, 19].

When designing the distribution substation's modernization, an assessment of dynamic effects of the short-circuit current flow requiring a proper definition of the short-circuit conditions is required. In addition, the short-circuit current's value and flow characteristics are to be considered. The computed dynamic force values in substations are significantly dependent on the assumed short-circuit duration T_k [16]; too high or too low assumed T_k value can result in the economic losses due to the erroneous decision leading to over-sizing, damage or even destruction of devices. For instance, the supporting structures can be left unchanged, reinforced or rebuilt throughout the substation. The problem is closely related to the power distribution substation's reliability. Few papers treating the statistical studies on the short-circuit duration in the HV grid provide a view on the type of distribution of this magnitude. However, due to the relatively low number of available samples, the credibility of obtained distributions of this random variable is low and does not allow to assess the short-circuit duration value T_k basing on the probability of its occurrence. The probabilistic analysis can be helpful when choosing the short-circuit duration values for finding risks caused by the fault disturbances. Application of the probabilistic approach to the choice of electric power devices has been a subject of many works worldwide [4, 10, 20] and in Poland [3, 6, 17]. The works on criterions of choice of the short-circuit duration when computing the dynamic effects in the substations with flexible conductors are missing in the available literature.

In the paper, the application of the Monte Carlo simulation method to the short-circuit duration analysis in the EHV grid regarding dynamic effects in the distribution substation with flexible conductors has been presented. A dedicated simulation model providing possibility of simulation of short-circuits on bus, in substation bays, transformers and electric power lines has been developed. Due to the simulation, the probabilistic analysis of values of short-circuit duration, short-circuit current and dynamic forces in chosen points of substation has been carried out. To determine the short-circuit duration values needed in the dynamic forces' analysis, a method based on the risk criterion (i.e. on the expected annual frequency of exceeding the force to be found) has been proposed. For illustration, an analysis for

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** the 220 kV substation and some selected configurations of the automatic power protections (EAZ) has been carried out and reported.

2. Simulation model for dynamic effects' analysis

One of the methods of the dynamic force computations is that given by the standard PN-EN 60865-1 [16]. Besides the force resulting from the mutual influence of the adjacent phase conductors F_t and that related to the force of the post-fault fall of conductors F_f the force due to the dynamic interaction of conductors within the bundle F_{pi} is also taken into account. To compute the dynamic effects, the data describing span geometry, conductor and supporting structures in the span as well as short-circuit parameters are required; the latter are of the random type.

It can be assumed that the short-circuit duration does not affect the force F_{pi} [6]. As the influence of the periodic component of short-circuit current on the forces due to the adjacent phase conductors' interaction F_t and F_f, is negligible [16], in the actual span, value of aperiodic component of short-circuit current in the bus conductors as well as the duration of its flow significantly affect the value of these forces.

General scheme of finding distributions of dynamic forces F_t and F_f in the actual span of the substation using Monte Carlo simulation is shown in Fig. 1. In computations, the faults in the substation alone and in its neighborhood have been considered.

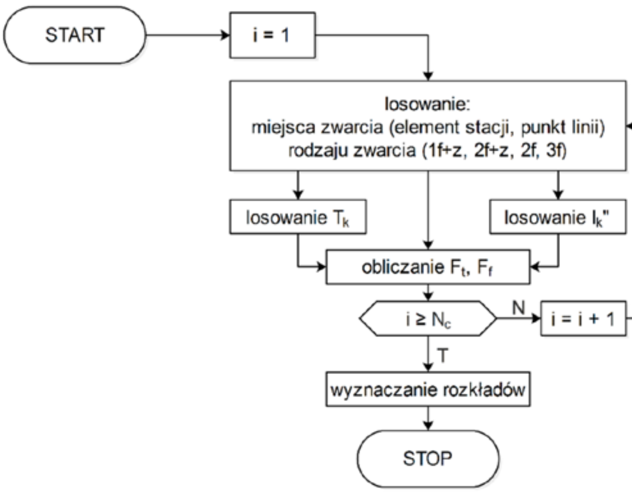

Fig. 1. Scheme of finding dynamic force distributions

In simulation, the fault's location and type are defined; then, the short-circuit current value in the bus conductors and the duration of its flow are computed. In next step, for an actual span of the substation, the dynamic force values are calculated. After having done an assumed number of simulations, the annual frequency of occurrence of theses forces is calculated. The dedicated computer program has been written in Delphi environment. In its development, the simulation model for short-circuit current analysis [6, 8] additionally equipped with the correlated model of the short-circuit duration and with the module computing the dynamic effects in substations has been applied

3. Short-circuit duration model

The short circuit duration time for finding the short-circuit effects is computed referring to the knowledge on the operation time of the EAZ system as well as the operation time of the circuit breakers clearing the fault disturbances in the substation. The following relationship has been applied to find the short circuit duration value:

$$T_k = t_{zab} + t_{wy} \tag{1}$$

where T_k - short circuit duration

t_{zab} - the protection's operation time measured between the moment the short circuit occurs and the moment the „switch off" pulse appears at the protection's output

t_{wyl} - the circuit-breaker operation time measured between the time the „switch off" pulse is received and the short-circuit current is broken off.

The general rule of finding the T_k value using the Monte Carlo simulation technique in the form of consecutive simulation steps is discussed in details in [9]. Detailed requirements concerning the protections installed in the HV and EHV substation's bays as well as the power automatic equipment are given by *Instruction of Transmission System Operation and Maintenance* [13].

The layout of the system section containing the considered 220 kV substation is shown in Fig. 2. Protections Z and circuit-breakers W are marked on the scheme.

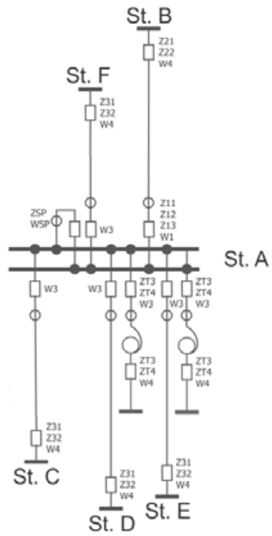

Fig. 2. Scheme of considered section of 220 kV grid

In the developed model of the short-circuit duration, the EAZ elements of substation's bus, connected lines and electric power transformers have been taken into account. The following EAZ equipment has been considered:

- Line bays are equipped with two distance protectons and overcurrent earth-fault protections; no unit protection,
- Duplicated operation of distance protections on individual lines (can be switched-on independently on any individual line),
- automatic reclosing equipment (SPZ) on lines (can be switched-on independently on any individual line),
- protection in bus coupler bay,
- bus bar protection,
- local circuit-breaker back-up (LRW)
- two differential protections on each transformer, distance protections in transformer bays and earth-fault protection.

For instance, when the disturbance appears in AB line, the action of protections in the tested substation in the line AB bay (Z11, Z12, Z13), in the bay at the opposite line end (Z21, Z22), on the opposite ends of line branches connected to the considered 220 kV substation (Z31, Z32 – in adjacent substations), in transformer bays (ZT3 i ZT4) and on the opposite side of transformer (ZT3) is taken into account.

The LRW failure frequency is not assumed whilst the failure frequency of circuit-breakers excited by this unit is assumed. ZT1 and ZT2 are the residual-current operated protections (RCDs) protecting the transformers with the lowest possible time delay. Regarding its operation principle, it is the fastest protection installed in the trans-

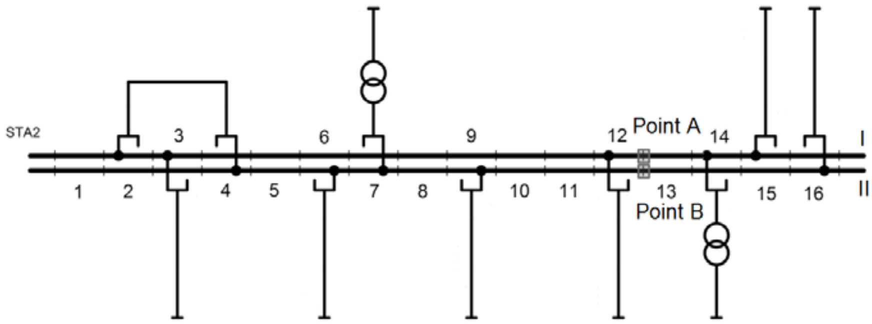

Fig. 4. Scheme of 220 kV substation under consideration; lookout points A and B are depicted as squares on the I and II bus systems between bays No. 12 and No. 13

former bay. Every transformer installed in the HV and EHV grids is protected by at least one RCD protection. Transformer can be equipped with a second set of such protections provided that the IRiESP requirements are met. The area protected by the RCDs falls between the current transformers installed in the bay and the bushings of the second side voltage transformer. When the RCD protection acts, the pulse is transmitted to the transformer's circuit-breakers on both sides.

ZT3 is the distance protection like those installed in the line bay; however, its settings are slightly different. The zone I reach is of 70% of protected transformer's impedance. Within the zone, the operation is delay-free. The zone II reach includes busbar on the opposite side of transformer, and the time setting is 1 s. The protection has „a backward zone" reaching of 60% impedance of the shortest line connected to the substation with time setting of 0.6 s. The backward zone provides protection against the near faults (i.e. will restrict the short-circuit current through the transfoirmer) when the bay protections, busbar protections or coupling bay's protection will not act.

When the protection ZT3 acts in the „forward" zone, the pulse is transmitted to both circuit-breakers (CBs) of the tranformer. When the fault is detected in the backward zone, the pulse is transmitted only on the CB in the auxiliary bay.

Moreover, the transformer is protected by the ZT4 earth-fault protection looking toward the grid (it has two current settings and corresponding time settings) and by the earth-fault protection in the transformer's star point (also two current settings). Time settings of these protections are high and are not taken into account in the algorithm.

Detailed values of reach of the protection zones considered in simulation calculations are described in [8].

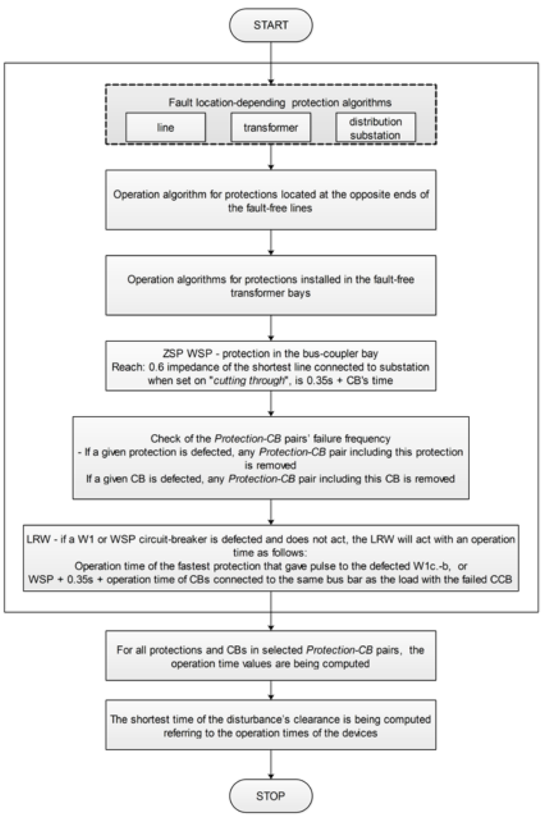

Fig. 3. General algorithm for simulation-based finding of the short-circuit duration

General algorithm of finding the short-circuit duration for substation is shown in Fig. 3. In the first step, depending on the fault location, the operation algorithm of protections detecting ad clearing the fault at its location is carried out (Fig. 3 dotted line). Detailed description of algorithms can be found in [9], and refers to the protections directly protecting lines, transformers and busbar systems.

The next simulation steps consider successively the operation of:

- protection on the opposite ends of line cooperating with the CB, which can switch-off the fault current flowing to the disturbance's location,
- protection in the transformer bay,
- protection disconnecting the couplers in the bay when the fault occurs within its reach of activity.

In the successive step, the „out-of-work" protections and CBs which are not able to take part in the disturbance clearance are indicated. If the CB is in failure, the operation of the LRW unit is additionally considered in the simulation.

In the final simulation step, according to the assumed distributions, the operation time of protections and CBs is being found. The shortest total operation time of the devices is treated as the disturbance's clearance time. According to the recognition, it has been assumed that the DLF circuit breakers are used in the tested 220 kV grid; therefore, the operation time distribution found for DLFs has been introduced. The operation time distributions for chosen protections obtained on the base of records of their operation times are presented in the work [7].

4. Distribution substation model and short-circuit current distribution

In Fig. 2, the scheme of substation is presented; the lookout points (A, B) of short-circuit conditions on the No. I and No. II bus systems between bays 12 and 13 are depicted. In the first case, the two bays to which the transformer (bay No. 14) and line (bay No. 15) are connected is situated on the one side of the lookout point whilst the other branches of the scheme are on its other side. In the second case (sys-

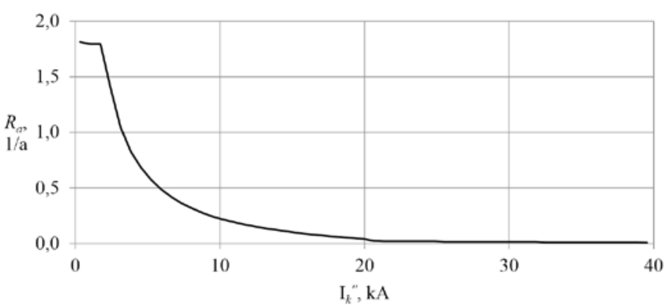

Fig. 5. Annual frequency of exceeding actual values of short-circuit current at the lookout point B

tem No. 2), only the line (bay No. 16) with a very low contribution to the bus short-circuit current is on the one side of the lookout point. To find the short-circuit currents' flow, a Plans-based grid model has been applied. For simulation computing needs, the short-circuit current values in the system have been over-scaled to obtain the maximum current on substation's bus equal to 40 kA.

In Fig. 5, annual frequency of exceeding actual values of short-circuit current at the lookout point B under short-circuit conditions within the considered section of the system has been plotted. As the contribution of the short-circuit current in the line connected in the bay 16 is negligible, maximum current values are of 40 kA (values of short-circuit currents on bus). It should be underlined that maximum short-circuit current value on the bus occurs under the single-phase fault conditions. Under a three-phase fault conditions on the bus of considered substation, the current value is slightly lower than 40 kA.

The plot of Annual frequency of exceeding actual values of short-circuit current at the lookout point A under the faults in the considered section of the system is shown in Fig. 6. Due to the short-circuit current flow through the substation's bus, a maximum value of the current expected at the lookout point is slightly higher than 25 kA. Total contribution of the line (bay 15) and transformer (bay 14) to the bus short-circuit current is near to 15 kA.

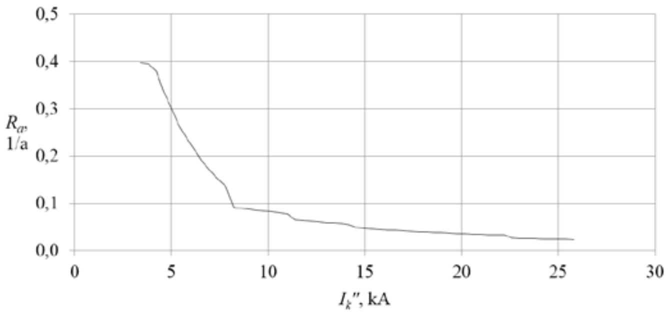

Fig. 6. Annual frequency of exceeding actual values of short-circuit current at the lookout point A

More detailed analysis of the short circuit currents' distributions in the EHV substations using statistical-probabilistic method is reported in [8].

5. Results of the short-circuit duration analysis

Annual frequency of exceeding the actual short-circuit duration values for four different configurations of the EAZ equipment in 220 kV substation has been discussed. The EAZ configurations are described in details in Table 1. In simulative computations, the system sections in which the faults-related flow of the significant short-circuit current values through the lookout points occurs, regarding the dynamic effects analysis, have only been taken into account.

Expected annual frequency of exceeding actual values of the short-circuit duration (short-circuit current flow duration) at the lookout point A is plotted in Fig. 7. The faults have been simulated on the part of the bus-bar system No. 1, in the line bay and line as well as in the transformer bay and transformer (part of the system located on the right of the lookout point).

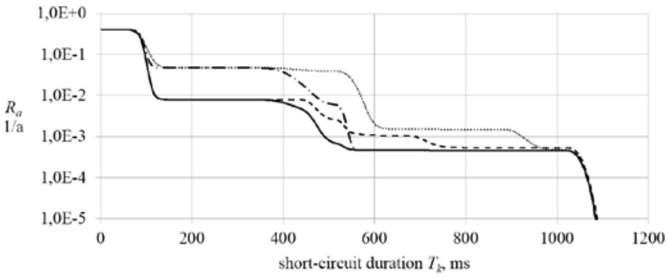

Fig. 7. Annual frequency of exceeding actual values of short-circuit duration at the lookout point A

Lower values of the frequency of exceeding for the most frequent short durations of the fault (up to 150 ms) occur for configurations No. 1 (full) and No. 3 (no disconnecting protection with the operation delay of 400 ms in the coupler bay).

Higher values of the frequency of exceedings correspond to the configurations No. 2 (free of the SPZ on the line and with no duplicated operation of protections) and No. 4 (no bus bar protection).

When frequency of exceeding is 10^{-2} 1/a and 10^{-3} 1/a, significant differences in the short-circuit duration values for different configurations can be seen. For frequencies 10^{-4} 1/a and lower, the influence of the EAZ configuration type is negligible.

Short-circuit duration values, found at the lookout point A for chosen levels of frequency of exceedings and four EAZ configurations are presented in Table 2.

Table 2. Short-circuit duration values, T_k, found at the lookout point A for chosen levels of frequency of exceedings and four EAZ configurations

R_a, 1/a	Conf. No. 1	Conf. No. 2	Conf. No. 3	Conf. No. 4
	T_k [ms]	T_k [ms]	T_k [ms]	T_k [ms]
10^{-1}	97.2	108.7	97.2	101.2
10^{-2}	119.6	569.8	119.8	469.3
10^{-3}	491.1	923.9	689.4	545.2
10^{-4}	1066.4	1067.6	1069.0	1065.8

Annual frequency of exceeding actual values of short-circuit duration at the lookout point B is plotted in Fig. 8. In calculations, the faults on the section of the busbar system No. II in the line bay No. 16 and on the line connected to this bay (on right side of the lookout point) have been taken into account.

When there is only one 220 kV line on the right to the lookout point, the investigated frequency of exceeding is mostly influenced by the SPZ devices and duplicated work of protections on this line. For frequency values of 10^{-1} 1/a and 10^{-2} 1/a, the lack of these devices results in an important increase in the found short-circuit duration values. The influence of automatic devices protecting the line on which the disturbances are simulated is higher than for the line considered at the lookout point in the system I. It results from the fact line connected in the bay 16 is almost 7 times longer than that in the bay 15. The runs of curves shown in Fig. 8 for configurations No. 1, No. 3 and No. 4 are similar. For frequency of exceeding 10^{-3} 1/a and lower, no impact of the EAZ configuration on the obtained results has been observed.

Table 1. Configurations of EAZ equipment in substations

Equipment	Conf. No. 1	Conf. No. 2	Conf. No. 3	Conf. No. 4
Automatic reclosing equipment and duplicated operation of protections	YES	NO	YES	YES
Circuit-breaker back-up system	YES	YES	YES	YES
Disconnecting protection in bus coupler bay	YES	YES	NO	YES
Busbur protection	YES	YES	YES	NO

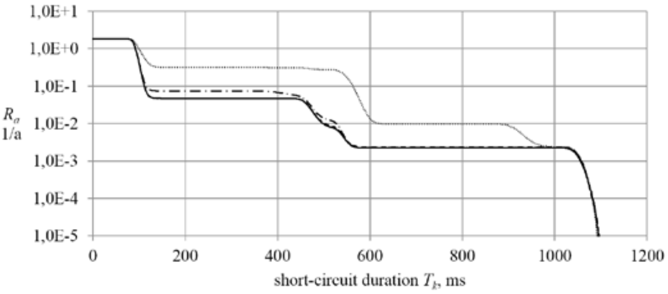

Fig. 8. Annual frequency of exceeding actual values of short-circuit duration at the lookout point B

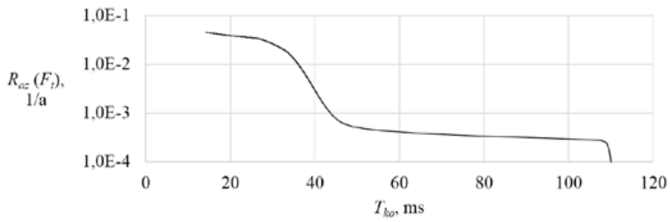

Fig. 11. Risk of exceeding force F_t versus T_{ko} for short-circuit conditions at point A for configuration No. 1

Short-circuit duration values for chosen levels of frequency of exceeding and for considered EAZ configurations found at lookout point B are presented in Table 3.

Table 3. Short-circuit duration values, T_k, found at lookout point B for chosen risk levels and four EAZ configurations

R_a, 1/a	Conf. No. 1	Conf. No. 2	Conf. No. 3	Conf. No. 4
	T_k [ms]	T_k [ms]	T_k [ms]	T_k [ms]
10^{-1}	111.5	562.9	111.5	115.1
10^{-2}	498.7	620.6	503.4	527.2
10^{-3}	1055.9	1058.7	1058.3	1057.2
10^{-4}	1081.9	1081.0	1081.2	1081.6

6. Assessment of dynamic forces and short-circuit duration for computation purposes

The analysis of the dynamic force values has been carried out using computer simulation in which the computation scheme shown in Fig. 1 has been used. A an example, computations for a defined 220 kV span, 56 m long, has been carried out.

In Fig. 9, expected annual frequency of exceeding the actual values of force F_t found for EAZ configuration No. 1 in the substation is presented. Referring to the found curve and the relationship between the force F_t and the short-circuit duration found for 40 kA (Fig. 10), the values of the short-circuit duration, T_{ko}, which are to be assumed when computing the F_t force in substation can be estimated, at the assumed risk value R_{az} (i.e. expected frequency of exceeding the found force). An example: the force F_{t1} of 23.1 kN corresponds to the frequency of exceeding of 10^{-3} 1/a (Fig. 9). Referring to the curve in Fig. 10 one can see that the time T_{ko1} = 43.9 ms corresponds to that value. In such a way, the short-circuit duration values assumed in calculations of dynamic effects in the substation of maximum short-circuit current 40 kA can be lied to the expected risk of exceeding a force value being found during the faults.

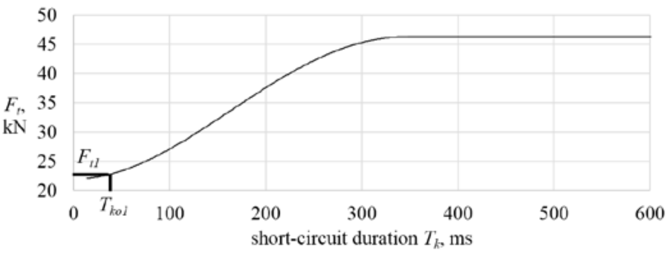

Fig. 9. Annual frequency of exceeding actual values of force F_t at the lookout point A and configuration No. 1

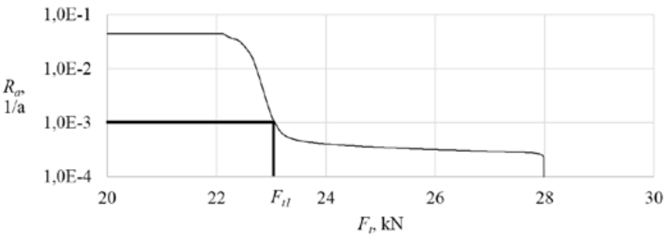

Fig. 10. Force F_t versus short-circuit duration for I_k'' = 40 kA

Using the method described above, the curve of risk of exceeding the force F_t being found from the value of time T_{ko} taken to calculate the value of this force, can be plotted. For the last example, such a relationship is given by the curve presented in Fig. 11.

Listing of the force F_t values and corresponding time T_{ko} values for four considered EAZ configurations at the chosen risk levels are reported in Table 4. The results refer to the short-circuit conditions at the lookout point A. The results of similar analysis carried out under the short-circuit conditions at the lookout point B are reported in Table 5.

Table 4. Values of force F_t and time T_{ko} for defined risk levels and different EAZ configurations under short-circuit conditions at the lookout point A

R_a, 1/a	Conf. No. 1		Conf. No 2		Conf. No 3		Conf. No 4	
	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms
10^{-1}	-	-	-	-	-	-	-	-
10^{-2}	22.7	36.2	22.8	37.6	22.7	36.2	23.0	41.5
10^{-3}	23.1	43.9	25.2	77.6	23.1	43.9	28.0	110.0
10^{-4}	28.0	110.0	28.0	110.0	28.0	110.0	28.0	110.0

The results reported in Table 4 indicate that the time T_{ko} is very low and rises up to 100 ms just for the risk of exceeding equal to 10^{-4} 1/a. It results from the fact the maximum short-circuit current value at point A is much below 40 kA. As there is no busbar protection, the time value being found increases. It is explicitly observed at the risk of 10^{-3} 1/a.

Under the short-circuit conditions at point B, the found values of time T_{ko} are explicitly higher and for the risk equal to 10^{-3} 1/a are of 100 ms (configurations No. 1 and No. 3). As there is no busbar protection, the time value being found significantly (3 times) increases. At the considered risk level, the effect of lack of both the SPZ devices and the duplicated work of protections is observed (T_{ko} is of 160 ms).

Similar analysis has been carried out for the force F_f. In Fig. 12, expected annual frequency of exceeding the actual values of force F_f found for the EAZ configuration No. 1 under the short-circuit conditions at point B has been presented. The relation between the force F_f and the short-circuit duration at the current 40 kA is shown in Fig. 13. For instance, the time T_{ko} value for calculation of the force F_f under the assumed risk of exceeding equal to 10^{-4} 1/a has been found. The force value read out from the curve in Fig. 12 is 61.5 kN whilst the corresponding value of the short-circuit duration read out from Fig. 13 is of 400 ms.

Table 5. Values of force F_t and time T_{ko} for defined risk levels and different EAZ configurations under short-circuit conditions at the lookout point B

R_a, 1/a	Conf. No. 1		Conf. No. 2		Conf. No. 3		Conf. No. 4	
	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms
10^{-1}	-	-	-	-	-	-	-	-
10^{-2}	25.0	74.2	25.6	82.0	25.0	74.2	25.8	84.8
10^{-3}	27.6	104.7	32.9	156.0	27.6	104.7	45.9	317.1
10^{-4}	45.9	317.1	45.9	317.1	45.9	317.1	45.9	317.1

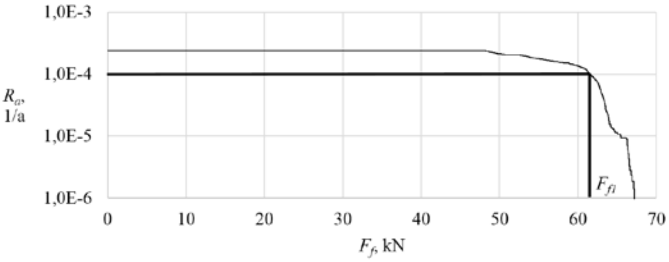

Fig. 12. Risk of exceeding force F_f at lookout point B for configuration No. 1

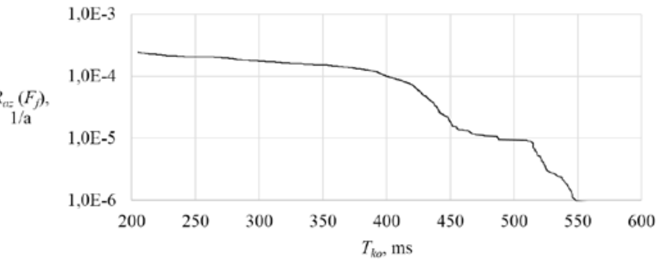

Fig. 14. Risk of exceeding force F_f versus T_{ko} under short circuit conditions at point B for configuration No. 1

Table 6. Force F_f and time T_{ko} values for defined risk levels and different EAZ configurations under the short-circuit conditions at point B

R_a, 1/a	Conf. No. 1		Conf. No. 2		Conf. No. 3		Conf. No. 4	
	F_f, kN	T_{ko}, ms	F_f, kN	T_{ko}, ms	F_f, kN	T_{ko}, ms	F_f, kN	T_{ko}, ms
10^{-2}	-	-	-	-	-	-	-	-
10^{-3}	-	-	53.8	280.3	-	-	63.2	433.1
10^{-4}	61.5	399.7	64.8	469.4	63.7	444.6	66.4	517.2
10^{-5}	65.4	486.8	66.8	531.9	66.7	528.3	66.7	529.9

A curve representing the relation between expected risk of exceeding the found force F_f and the time T_{ko} taken to calculate the force value is shown in Fig. 14.

Listing of the force F_f values and corresponding time values for four considered EAZ configurations and chosen risk levels is shown in Table 6. The results refer to the short-circuit conditions at point B. For the short-circuit conditions at point A, force F_f is missing completely. From the results listed in the Table 6, the conclusion can be drawn that there is no need to take into account the force F_f when analyzing the dynamic effects in the substation for EAZ configuration No. 1 and No. 3 at the assumed risk equal to 10^{-3} 1/a. For EAZ configurations No. 2 and No. 4, the short-circuit duration values of 280 ms and 433 ms should be assumed, respectively.

7. Final remarks

Finding of short-circuit duration values during computations of dynamic forces in the EHV substations can be based on the levels of risk assumed in analysis, i.e. on expected annual frequency of exceeding of the force being found in train of the substation's operation and maintenance (static operation conditions assumed). For a defined span of the substation, the values depend mostly on (1) the substation point for which the short-circuit conditions are being, (2) assumed risk level for which the computations are being carried out and (3) substation's EAZ equipment.

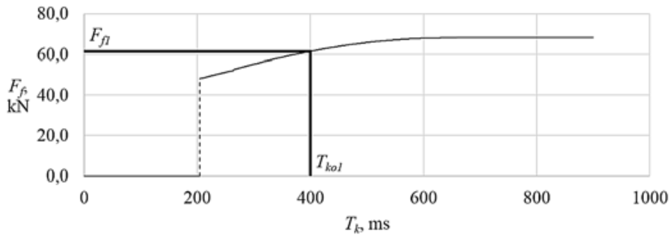

Fig. 13. Force F_f value versus short-circuit duration for $I_k'' = 40$ kA

In the EHV substations, due to the length of spans, the force F_f values are, in general, higher than those of the force F_t; however, the probability of its occurrence is low. The Authors of works treating the question of the allowable risk when choosing the devices regarding the fault conditions indicate the values 10^{-2} 1/a, 10^{-3} 1/a [6]. The time T_{ko} values found to calculate the force F_f under the risk 10^{-3} 1/a and lower are higher than those used to calculate the force F_t. In doubtful cases, the force F_f should be taken into account when the modernization version is chosen and the choice shall be proven by the economic analysis.

One has to be aware that the time T_{ko} values being found will also depend on parameters of the substation's span, applied static tension of conductors, short-circuit current flow within the substation (including reactance ratio x_0/x_1), accepted models and data. In the next step of studies, the authors plan to undertake work aiming to estimate the influence of the factors listed above.

Our assumptions, especially decision to omit the current flow within a single span and to take a constant temperature of conductors before the fault, lead to a significant increase in the expected risk value (i.e. introduce a safety margin).

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