Computer Applications in Electrical Engineering
Vol. 12 *2014*

Values of short-circuit duration and dynamic forces during short-circuits in the EHV substations: simulation-based investigations

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Presented question is the continuation of investigations concerning the short-circuit duration's estimation in the short-circuit effect calculations using the probabilistic method. In the paper, the developed simulation model of the short circuit duration under the disturbing conditions just in the distribution substation is presented. The model development was based on the analysis of operation of the automatic power protections EAZ and circuit-breakers in the EHV substations during short–circuits. The results of simulation investigations aiming to estimate the frequency of occurrence of the defined short-circuit duration are reported. The calculations have been carried out for different configurations of the EAZ system. For selected spans in the 220 kV substation, probabilistic analysis of dynamic forces accompanying the in-substation faults has been carried out. Also, the way of the short-circuit duration's estimation when calculating the dynamic effects of the fault current flow basing on an assumed risk value has been proposed.

KEYWORDS: short-circuit duration, EHV substations, simulation

1. Introduction

The fault conditions are defined basing on the knowledge on the short-circuit current's waveform and characteristic parameters. In general, the parameters are random [1]. For practical reasons, the short-circuit magnitudes are found using the deterministic techniques with a series of simplifications. One of the significant parameters affecting the thermal and dynamic effects in the electric power substations is the short-circuit duration. An incorrect short-circuit duration assumed in the practical calculations can result in the economic loss. In the paper, the simulation model developed to assess the short-circuit duration time in substations basing on probabilistic method is presented. Investigations has been carried out for faults in the substations, and some examples of the analysis have been presented for selected EAZ configurations.

2. Model of the short circuit duration under the disturbing conditions in substation

2.1. Concept of the 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 disturbances in the substation. The following relationship has been applied to find the short circuit duration value:

$$T_k = t_{zab} + t_{wyl} \qquad (1)$$

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 according to the formula (1) using the Monte Carlo simulation technique in the form of consecutive simulation steps (Fig. 1) is discussed in details in [2].

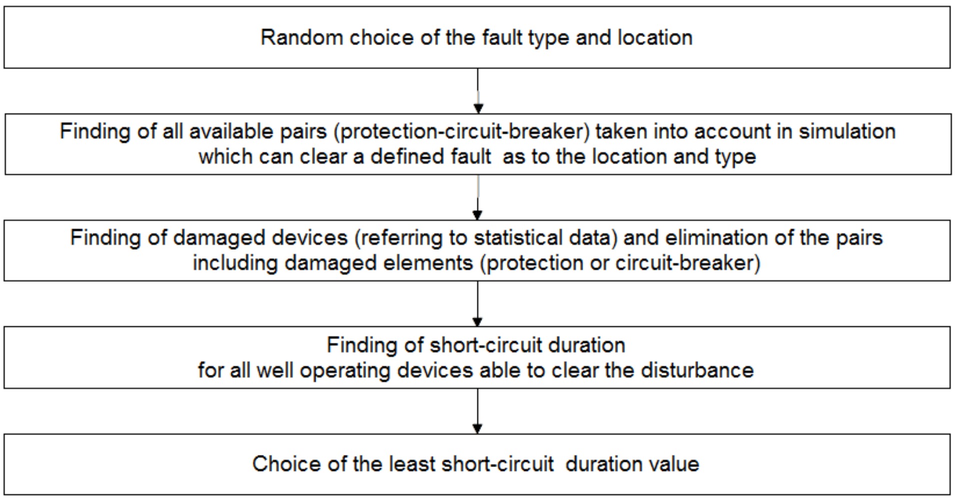

Fig. 1. Steps of finding the short-circuit duration time using simulation

Detailed requirements concerning the protections installed in the HV and LV substation's bays as well as the power automatic equipment are given by *Instrukcja Ruchu i Eksploatacji Sieci Przesyłowej (IRiESP)* [3].

2.2. Layout and implemented assumptions

The layout of the system section containing the considered 220 kV substation is shown in Fig. 2.

The protections and circuit-breakers involved into the clearance of faults in the substation (on bus bar and bays) as well as the examples of the reach of the time zones of the considered protections have been marked. Operation of protections during faults in lines as well as the concept of the software for finding the duration of such faults are described in details in [2].

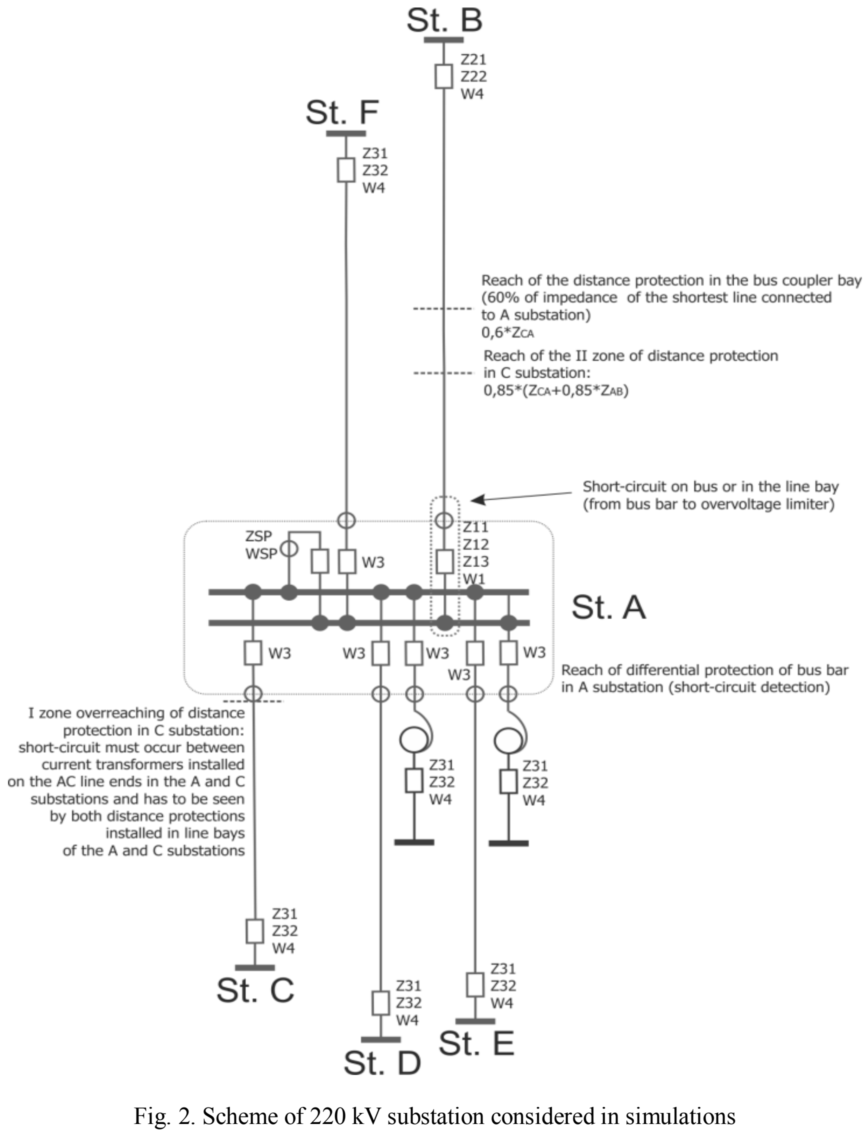

Fig. 2. Scheme of 220 kV substation considered in simulations

The operation of the following systems has been taken into account: bus bar differential protection ZSZ, earth-fault protections and unit protections as well as automatic reclosing equipment (SPZ) and local circuit-breaker back-up (LRW). Also, the correlated work of protections in the bay at the opposite ends of the line has been considered.

2.3. General algorithm for calculations and computer program

General algorithm for finding the duration of the short-circuit in the substation is shown in Fig. 3.

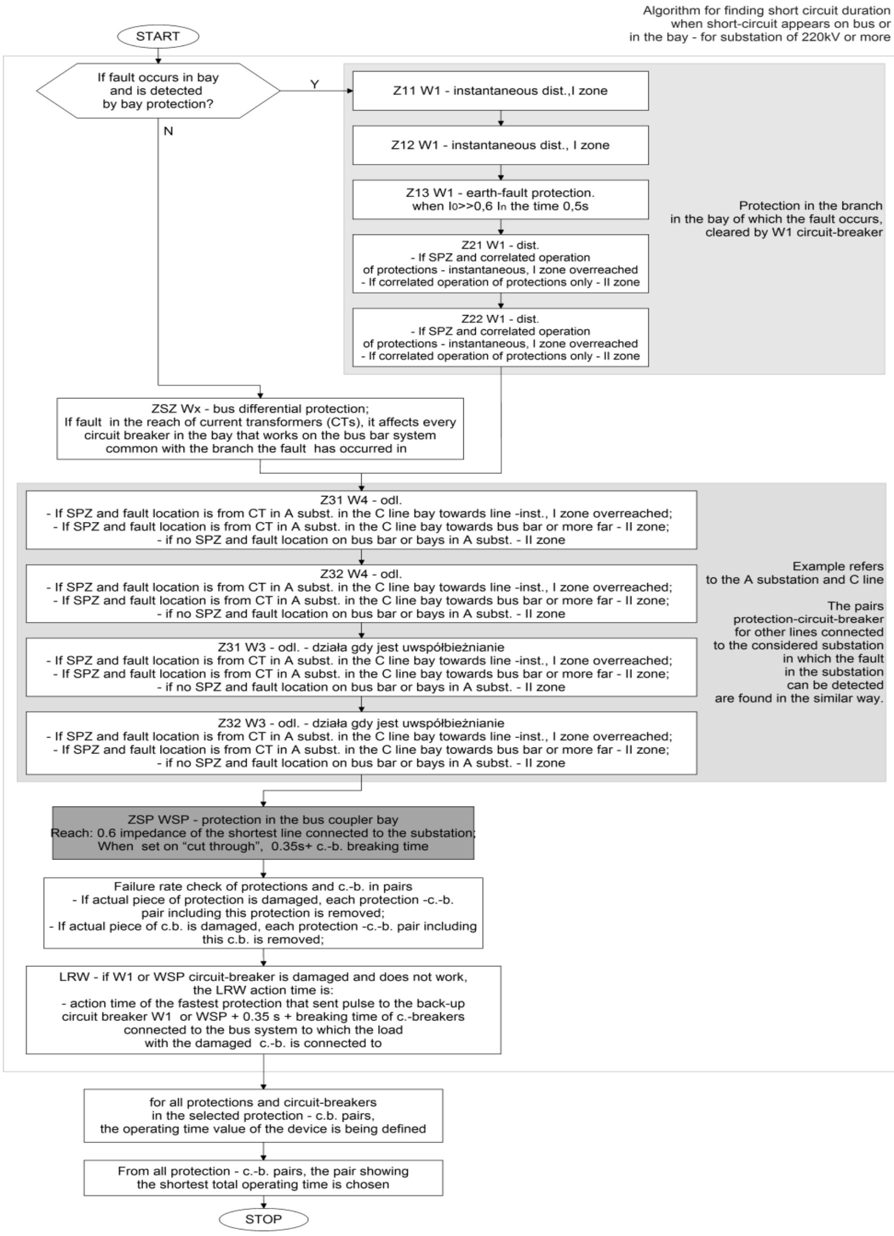

Fig. 3. Protections' operation algorithm for faults within substation

In the algorithm, two principal sections can be indicated. There are two principal paths in the algorithm, depending on the fact the short-circuit appears in the substation area covered by the current transformers in the substation's bays or not.

If the short-circuit appears in the substation area covered by the current transformers installed in the substation's bays, the instantaneously acting differential protection of the bus is significant. When the substation is not equipped with such a protection, the short-circuit is being detected by the protections located in adjacent substations and in the bus-coupler bay of the substation in which the disturbance occurred. When the fault appears behind the current transformer in the line bay, the algorithm is identical as that for the faults in the line [2].

When all the protection-circuit breaker pairs that can be involved into the clearance of the fault are found, the failure frequency of devices and, sometimes, the LRW system work is checked. The least sum of the operating times of the working *protection-circuit breaker* pairs is assumed to be the disturbance's duration value.

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2.4. Short-circuit duration analysis: examples of computation results

For example, the short-circuit duration analysis has been conducted for the 220 kV substation with layout as in Fig. 4 (view of the program window) with 16 bays and two bus bar systems. In the figure, between the bay 15 and bay 16 of the second bus bar system, the point at which the short-circuit current flow is inspected has been marked.

For calculations, the unreliability coefficient of all protections and circuit-breakers is assumed to be 0.03. Short circuit duration is calculated starting from the moment the short-circuit current value falls below 2/3 of its maximum value. The assumption is backed by the fact that only high values of the short-circuit current resulting in significant dynamic effects are interesting ones.

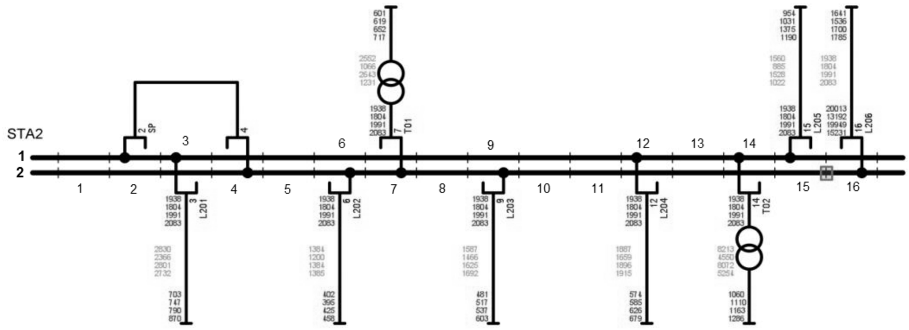

Fig. 4. Scheme of 220 kV substation under consideration; inspection point is marked (small square) on the second bus bar system between bay 15 and bay 16

In authors' opinion, the flow of short-circuit current lower than 2/3 of its maximum value does not pose a risk. In general, opening of the circuit-breaker in the bus coupler's bay results in the lowering of the short-circuit current value below the value indicated above. Also, when the fault is being cleared by circuit-breakers at the opposite ends of the line connected to the considered substation, the decrease in the short-circuit current equal 1/3 of its maximum is meant to indicate the moment the fault is finished. Analysis of short-circuit duration distribution has been carried out for four different configurations of the EAZ equipment applied in substation (Table 1).

Table 1. EAZ configuration in substation

	Conf 1	Conf 2	Conf 3	Conf 4
Circuit-breaker back-up system	Yes	Yes	Yes	Yes
Automatic reclosing equipment	Yes	no	Yes	Yes
Correlated (duplicated) operation of protections	Yes	no	Yes	Yes
Coupler	Yes	Yes	no	Yes
Bus bar protection	Yes	Yes	Yes	no

In successive tables (Tables 2, 3 and 4), the short-circuit duration values found for chosen exceeding risk levels (expected annual frequency of exceeding) are reported for the EAZ configurations under consideration. In the studies, all short-circuit types have been taken into account.

In Table 2, the results of analysis of the short-circuit duration during faults on the substation bus bar are presented. In such faults, the differential protection of the bus acts instantaneously, as the first. For configurations 1, 2 and 3, the short-circuit duration values are similar and, at the risk levels of 10^{-2} 1/a and10^{-3} 1/a, are definitely shorter than those for configuration 4 (no ZSZ) at which they exceed 450 ms. In configuration 4, there is no protection acting instantaneously. These values result either from the operating time of protection in the coupler bay (350 ms approx.) and circuit-breaker's breaking time (100 ms approx) or from the operating time of protections in adjacent substations, within the II time zone (the faults do not appear in the line i.e. are not seen by the distance protections installed at both ends of the protected line). However, for risk 10^{-4} 1/a, influence of the protection in the coupler bay operating under the substation's double-system operation can be seen. The short circuit duration found for that risk level at the configuration 3 of EAZ (no protection in coupler's bay) is 10 ms higher than that found at the EAZ configurations 1 and 2.

Table 2. Short-circuit duration values for faults on the bus bar in function of the substation's EAZ equipment

R_a [1/a]	Configuration			
	1	2	3	4
	T_k [ms]			
Fault location – bus bar system				
10^{-1}	-	-	-	-
10^{-2}	76.8	76.8	76.8	453.9
10^{-3}	100.9	101.3	100.1	541.9
10^{-4}	531.6	532.5	544.8	552.6
10^{-5}	547.3	548.5	554.6	560.0
10^{-6}	584.0	586.0	589.0	600.0

In Table 3, the results of similar analysis for faults within the substation bay are reported. In case of such disturbances, some faults are also cleared by the bus bar protection acting instantaneously. If such protection is missing (Configuration 4), short circuit duration significantly increases as compared to other EAZ configurations at the risk levels 10^{-2} 1/a and 10^{-3} 1/a; the same is observed for faults within the bus system. Some of the faults are cleared by line protections; therefore, the lack of both the automatic reclosing equipment and the correlated (duplicated) operation of protections results in higher duration times in configuration 2 than those in configurations 1 and 3 at the risk levels mentioned above.

For risk 10^{-4} 1/a, evident influence of the protection in the coupler bay operating under the substation's double-system operation (Configuration 3) can be seen. The short circuit duration found for that risk level is about 80 ms higher than that found at the configurations 1 and 2.

Table 3. Short-circuit duration values for faults in the L206 bay in function of the substation's EAZ equipment

R_a [1/a]	Configuration			
	1	2	3	4
	T_k [ms]			
Fault location – apparatus in the bay				
10^{-1}	-	-	-	-
10^{-2}	97.0	104.9	97.0	400.3
10^{-3}	116.2	397.9	116.4	494.8
10^{-4}	448.6	454.9	539.5	543.9
10^{-5}	534.5	536.6	551.7	553.8
10^{-6}	579.0	582.0	591.0	585.0

In turn, in Table 4, the results of analysis of the short-circuit duration during faults on the substation bus bar and in the bay of considered L206 line are presented. In some words, it is total result of the short-circuit simulation in both selected sections of the substation. Differences in the short-circuit duration values found for individual configurations of protections are observed at the risk levels equal to or exceeding 10^{-4} 1/a. For lower risk levels, the short-circuit duration values are at the stable level.

Table 4. Short-circuit duration values for faults on the bus bar and in the L206 bay in function of the substation's EAZ equipment

R_a [1/a]	Configuration			
	1	2	3	4
	T_k [ms]			
Fault location – bus bar system and apparatus in the bay				
10^{-1}	-	-	-	-
10^{-2}	100.4	110.3	100.4	454.0
10^{-3}	372.0	431.2	445.2	541.9
10^{-4}	530.8	532.9	545.2	553.0
10^{-5}	547.6	549.3	555.0	560.4
10^{-6}	582.0	584.0	598.0	596.0

The found short-circuit duration values are strongly affected by the bus bar differential protection (Configurations 1-3 at risk level 10^{-2} 1/a). At risk 10^{-3} 1/a, the influence of both the automatic reclosing equipment and the coupler's by protection can be seen (Configuration 1 compared to Configurations 2 and 3).

3. Dynamic force values under disturbing conditions in substation

3.1. Scheme of computations

General scheme of finding distributions of the dynamic forces F_t and F_f, computed regarding standard requirements [4] using simulation with Monte Carlo technique is shown in Fig. 5.

For the short-circuits simulated successively, the location and type of the short-circuit is found; then, the short circuit current value in the bus conductors as well as the short circuit duration are found. Then, for specified span of the substation the values of dynamic forces and annual frequency of their occurrence is computed.

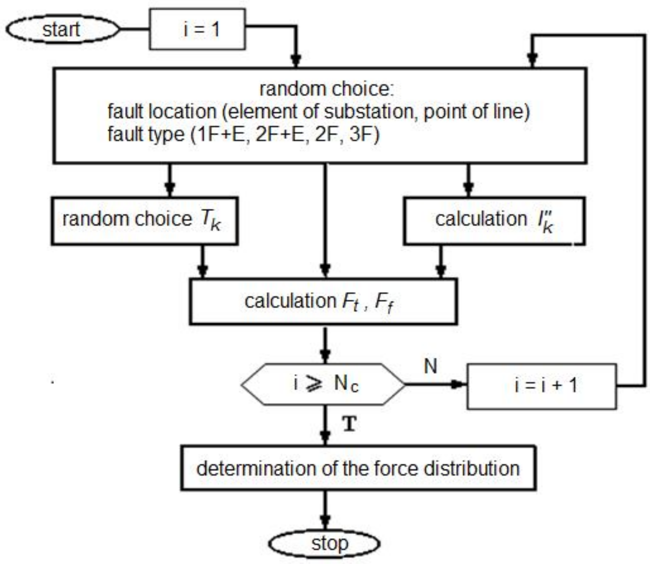

Fig. 5. Algorithm for finding distributions of dynamic forces

3.2. Some results of dynamic force computations

The dynamic forces have been analyzed with the assumption that the current during a 3-phase short-circuit on the substation bus is 40 kA, and the current is negligibly affected by the bay of line L206. Moreover, analysis has been carried out for four substation's EAZ equipment configurations studying how the latter affect the dynamic force's values as well as for two substation spans, P1 and P2, of significantly different length. Their length l, static tension F_{st} and additional mass m_d is reported in Table 5.

Table 5. Parameters of spans under consideration

Code	l, m	F_{st}, [kN/fazę]	m_d, [kg]
P1	56	20	40
P2	28	20	40

Plots of expected yearly frequency of exceeding (risk) R_a of the force F_t found for spans P1 and P2 for first EAZ configuration are shown in Fig. 6. Under identical short circuit conditions, maximum value of F_t for span P1 exceeds slightly 45 kN whilst, for the span two times shorter, is slightly higher than 30 kN.

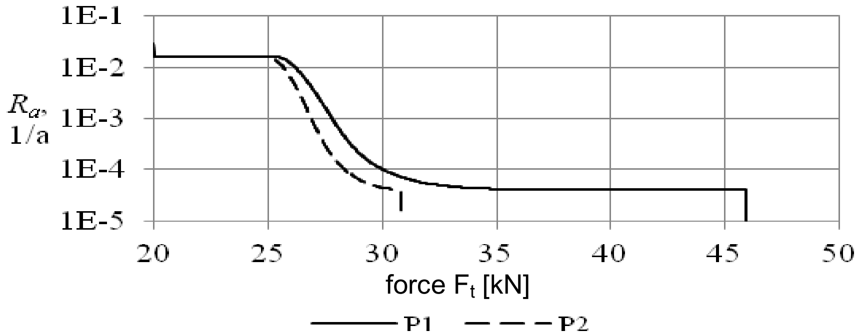

Fig. 6. Plot of risk of exceeding the F_t force for considered spans

Maximum value of F_f. is less than 70 kN for span P1, and is almost two times lower for the span P2. However, probability of occurrence of the force F_f is very low. The expected yearly frequency of its occurrence is below 10^{-4} 1/a. Plot of risk of exceeding the high value of F_f force are presented in Fig. 7.

Found values of forces F_t and F_f at chosen risk levels and for two spans under consideration are reported in Table 6.

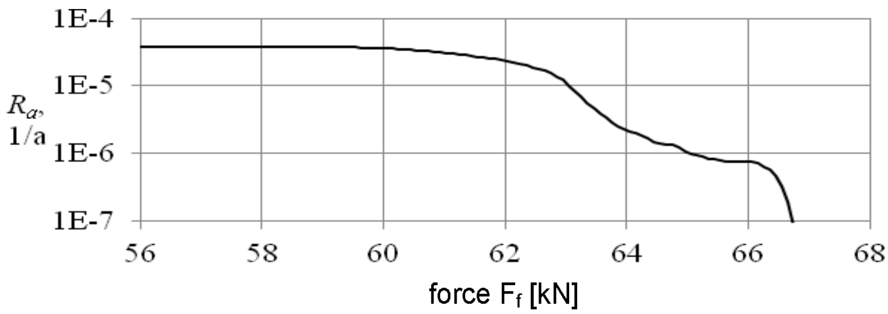

Fig. 7. Plot of risk of exceeding the F_f force for span P1

Table 6. Values of F_t and F_f at selected risk levels, for P1 and P2 spans

R_a, [1/a]	F_t, [kN]		F_f, [kN]	
	P1	P2	P1	P2
10^{-1}	-	-	-	-
10^{-2}	26,21	25,68	-	-
10^{-3}	27,82	26,92	-	-
10^{-4}	30,00	28,38	-	-
10^{-5}	45,90	30,80	63,02	-
0	46,31	30,98	68,21	34,42

In Fig. 8, plot of risk of exceeding the F_t force for four considered EAZ configurations are presented. For risk levels 10^{-2} 1/a and10^{-3} 1/a, F_t values are similar for all configurations.

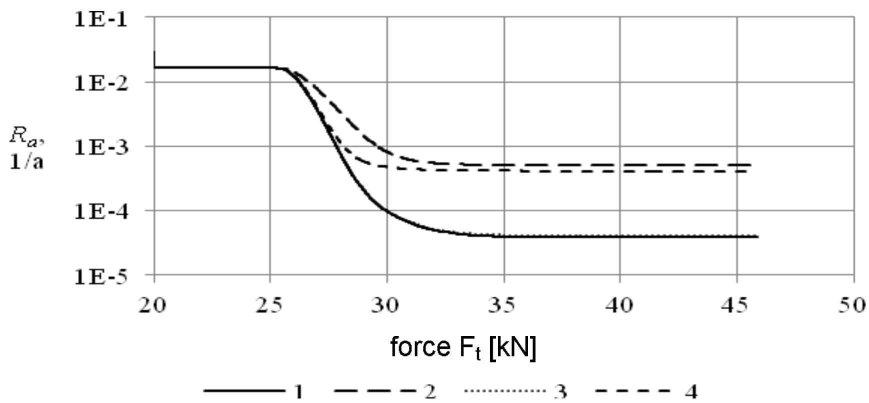

Fig. 8. Plot of risk of exceeding the F_t force for considered EAZ configurations

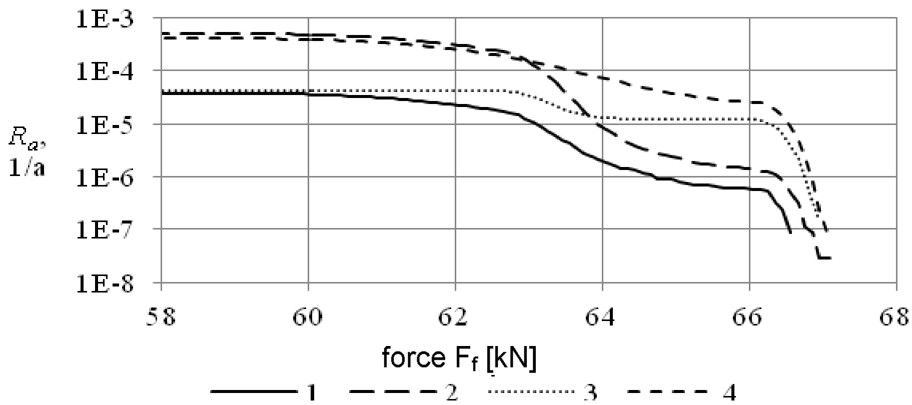

Fig. 9. Plot of risk of exceeding the F_f force for considered EAZ configurations

However, for risk 10^{-4}, the force value is evidently higher (by 16 kN) and equal almost 46 kN (for configurations 2 and 4 the influence of the automatic reclosing equipment and correlated (duplicated) operation as well as bus bar protection, respectively) For even lower risk levels, the F_t values are almost equal to each other for each EAZ configuration and are close to the maximum value.

Plots of risk of exceeding the F_t force for different EAZ configurations are compared in Fig. 9. It can be seen that, for configurations 1 and 3 at risk 10^{-4} 1/a, the force F_f is quite missing. Under assumed short-circuit conditions, the force F_f start to appear when the short–circuit duration exceeds 400 ms.

3.3. Procedure of finding short-circuit duration for the F_t and F_f forces' computation using probabilistic method

Relationship between the force F_t found for span P1 at maximum short circuit current value and the short circuit current duration is plotted in Fig.10a. In Fig. 10b, an expected yearly frequency of exceeding individual values of the force F_t found by simulation for first EAZ configuration is presented. The results can be used to determine the short circuit current duration values when calculating the F_t at the preset risk value. For example, the risk of exceeding the force F_{t1} of 27.82 kN is equal to 10^{-3} 1/a whilst a risk of exceeding the force F_{t2} of 30.00 kN is equal to 10^{-4} 1/a (Fig. 10b). Referring to the relationship shown in Fig.10a, the short circuit duration values corresponding to these forces can be read out; we obtain T_{ko1} = 107.5 ms and T_{ko2} = 128.9 ms, respectively.

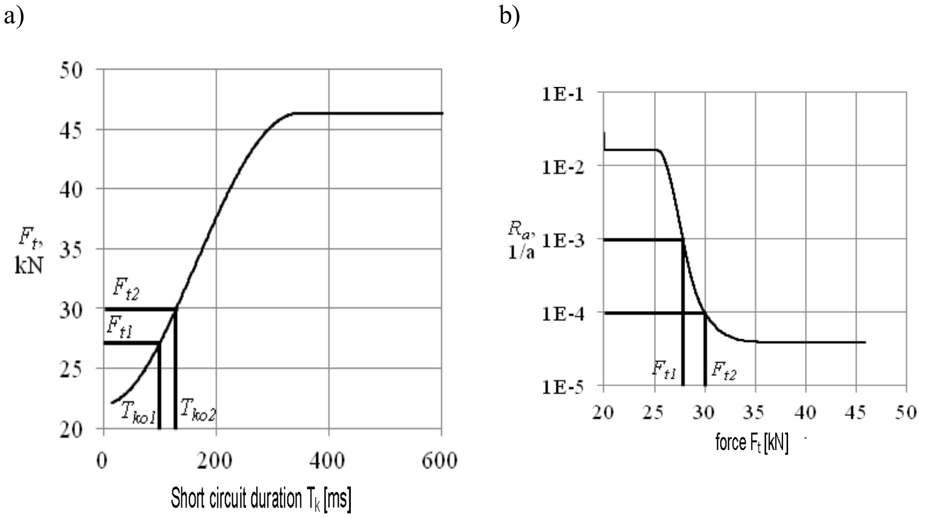

Fig. 10. (a) Force F_t versus fault duration; (b) yearly frequency of exceeding individual values of the force F_t, for span P1 of 220 kV substation

Thus, the short circuit duration values taken for the dynamic effects calculation can be linked to the values of expected risk of exceeding the calculated values of forces at the assumed maximum short circuit (40 kA in the example reported here). Higher duration values correspond to the lower risk values. Full table of the forces found that way as well as corresponding short circuit duration values, for selected risk values, are listed for the forces F_t and F_f in the tables 7 and 8, respectively. Also, four EAZ configurations under consideration have been taken into account.

Table 7. Values of forces F_t and short-circuit durations found at different risk levels

R_a, [1/a]	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	F_t, [kN]	T_k, [ms]	F_t, [kN]	T_k, [ms]	F_t, [kN]	T_k, [ms]	F_t, [kN]	T_k, [ms]
10^{-1}	-	-	-	-	-	-	-	-
10^{-2}	26.2	89.8	26.6	94.5	26.2	89.8	26.3	90.3
10^{-3}	27.8	107.5	29.6	125.1	27.8	107.5	28.1	110.6
10^{-4}	30.0	128.9	45.9	317.1	30.0	128.8	45.9	317.1
10^{-5}	45.9	317.1	45.9	317.1	45.9	317.1	45.9	317.1
0	46.3	>347.4	46.3	>347.4	46.3	>347.4	46.3	>347.4

Table 8. Values of forces F_f and short-circuit durations found at different risk levels

R_a, [1/a]	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	F_f, [kN]	T_k, [ms]	F_f, [kN]	T_k, [ms]	F_f, [kN]	T_k, [ms]	F_f, [kN]	T_k, [ms]
10^{-3}	-	-	-	-	-	-	-	-
10^{-4}	-	-	63.0	429.7	-	-	63.6	441.7
10^{-5}	63.0	429.6	63.9	449.1	66.2	511.5	66.4	517.7
0	68.2	>659.3	68.2	>659.3	68.2	>659.3	68.2	>659.3

4. Conclusions

The developed model of the short-circuit duration for the in-substation faults as well as the reported examples of simulation analysis carried out confirm usability of the model for probabilistic assessment of the short-circuit duration regarding EAZ configuration. Due to the developed model of the short-circuit duration and the reference to other random variables, the simulation-based probabilistic analysis of dynamic forces during the in-substation faults can be carried out. Basing on the results of such analysis, the short-circuit duration values that shall be taken when calculating the dynamic effects at the preset level of risk of exceeding the determined force values can be determines. In further works, the developed model of the short circuit duration in lines [3] and electric power substation elements is planned to be applied: (1) to assess the dynamical effects of the short-circuit current flow for different distribution substations, (2) to develop indications how to determine the short-circuit duration values during assessment of dynamic effects, using probabilistic approach.

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