Factors affecting the choice of fault duration in transmission lines for computation of dynamic effects in EHV distribution substations

Ryszard Frąckowiak, Piotr Piechocki
Poznań University of Technology
60-965 Poznań, ul. Piotrowo 3a, e-mal: Ryszard.Frackowiak@put.poznan.pl

In the paper, the method of assessment of the fault duration in transmission line regarding dynamic effects in the EHV distribution stations with flexible bus conductors is presented. Expected yearly frequency of exceeding the indicated dynamic forces has been assumed to be a criterion of choice of the short-circuit duration values. Results of simulations carried out using Monte Carlo technique have shown the influence of parameters of the distribution substation and devices installed in it (nominal voltage, short-circuit capacity, unreliability of circuit-breakers and protections, EAZ configurations) on suggested fault duration values in the engineer-type short-circuit computations.

KEYWORDS: substation, dynamic effect, short-circuit duration, probabilistic method

1. Introduction

Values of the dynamic tension of conductors in the distribution substations with flexible conductors depend not only on geometrical and mechanical parameters of the substation spans but also on the short-circuit currents waveform parameters including the short-circuit duration. Incorrect short-circuit duration value assumed in the engineer-type analyses can lead to the device over-dimensioning-related economic losses or even to the damage or destruction of devices. As relatively small number of the fault duration values recorded in the true grid is available, the credibility of distribution of this random variable is low and there is no opportunity to assess the T_k time basing on the probability of occurrence of such a value. The Monte Carlo-based simulation studies can aid, to some degree, the choice of the short-circuit duration for determining short-circuit related disturbances. In the paper, a method of assessment of the short-circuit duration in transmission line regarding its dynamic effects in the distribution substations with flexible conductors is presented. Simulation analysis results refer to 220 kV and 400 kV substations.

2. Simulation model for dynamic effects' analysis. Implemented assumptions

Calculation of the dynamic forces value are based on the method described in the PN-EN 60865-1 standard [1]. The program Flexible Conductor [2] for the force analysis purposes has been developed. To calculate the dynamic effects, the span geometry, specific data about conductors and pylons within the span as well as the short-circuit parameters are to be known. The latter are random. One can assume the short-circuit duration does not affect the forces resulting from the dynamic interaction of conductors within the bundle F_{pi} [3]. For an individual span, the short-circuit current value in bus conductors as well as the duration of its flow significantly affects the value of the force F_t resulting from the adjacent phase conductors‘ interaction and the force F_f, related to the fall of conductors after having the fault cleared. The direct current component's influence on values of these forces is negligible [1].

General algorithm for finding distributions of dynamic forces F_t and F_f using Monte Carlo method is shown in Fig. 1.

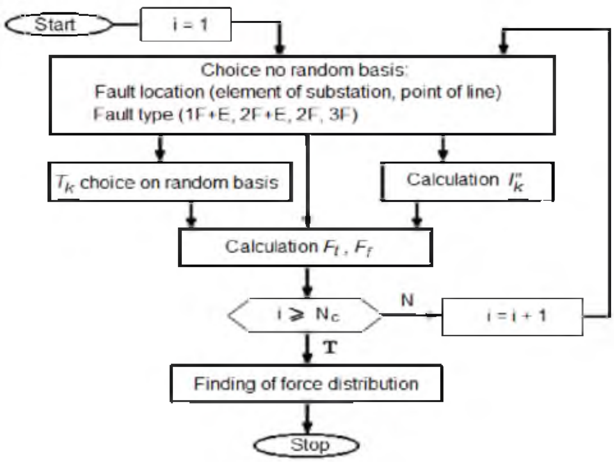

Fig. 1. Algorithm for finding distributions of dynamic forces

Short-circuits are simulated one by one, and for each of them the location and type is introduced; then, the short-circuit current value in bus conductors as weel as short-circuit duration are computed. Then, the values of dynamic forces and yearly frequency of its occurrence are computed for a defined span of substation. Suitable software called SOZ program has been developed in *Delphi* environment. The rule and algorithm of finding the short-circuit duration is described in [4]. Operating times of protecions for an indicated time setting are mapped wuth logarithmic-normal or normal distribution. In the algorithm, the opeartion of the self-reclosure (on short-circuit) devices, correlated (duplicated) operation of protections, operation of the bus-coupler - circuit-breaker pairs and operation of the circuit-breaker local reserve (LRW) are considered.

Analysis of the short-circuit duration distributions (the time of current flow from the substation side) during disturbances on the transmission line has been carried out for indicated protection types and for different EAZ configurations.

Considered configurations of the distribution substation's EAZ equipment are specified in Table 1. In addition, the substation bays are assumed to be equipped with DLF circuit-breakers and their unreliability coefficient q_w is 0,03.

Table 1. Considered configurations of the substation's EAZ equipment

Configurations	LRW system	Automatic Reclosing Equipment	Correlated operation of protections in line under consideration	Protection in coupling bay
Configuration 1	YES	YES	YES	YES
Configuration 2	NO	YES	YES	YES
Configuration 3	YES	NO	NO	YES
Configuration 4	NO	NO	NO	YES
Configuration 5	YES	YES	YES	NO
Configuration 6	NO	YES	YES	NO
Configuration 7	YES	NO	NO	NO
Configuration 8	NO	NO	NO	NO

For considered EAZ configurations, simulations have been carried out and a risk of exceeding the short-circuit duration T_k. has been plotted in Fig. 2. The most evident influence on the fault duration value comes from the correlated (duplicated) operation of protections along with automatic reclosing equipment (SPZ) due to which the protections act with their shortest reaction time (configurations 1, 2, 5 and 6) regardless the distance to the fault location. Results in Table 2 show that in EAZ configurations with correlated (duplicated) operation of protections and autoreclosing the probability of higher T_k. values is evidently reduced.

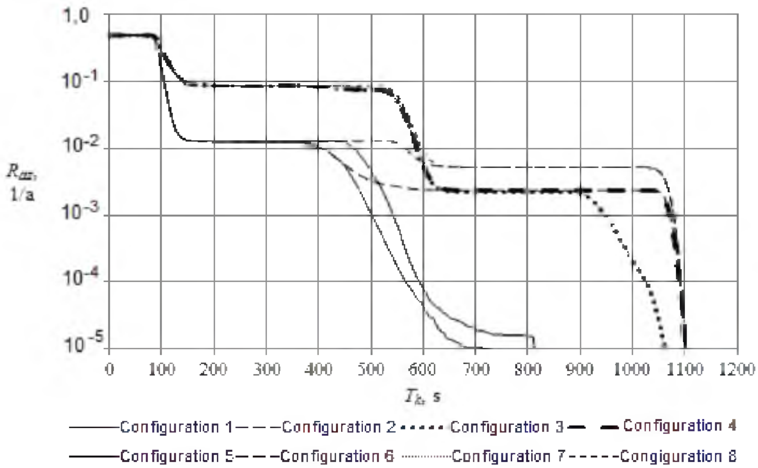

Fig. 2. Plots of risk of exceeding the short-circuit duration time for considered configurations of the substation's EAZ equipment

Table 2. Fault duration values for selected levels of risk of exceeding for considered EAZ configurations at the faults in 220 kV line of length 30 km

R_{az}, 1/a	T_k, s			
	Configuration 1	Configuration 2	Configuration 3	Configuration 4
10^{-1}	104	104	145	145
10^{-2}	407	407	587	587
10^{-3}	501	1071	947	1071
R_{az}, 1/a	T_k, s			
	Configuration 5	Configuration 6	Configuration 7	Configuration 8
10^{-1}	104	104	146	146
10^{-2}	461	566	587	597
10^{-3}	542	1077	947	1077

Protection in the coupler bay contributes also to the short-circuit duration; however, it will act only for the faults nearby the distribution station. Protection in the coupler bay (configurations 1, 2, 3 ind 4) does not clear the short-circuit current completely. Nevertheless, for the dynamic forces analysis purposes, the following assumption has been implemented: after having switched off the circuit breaker in the coupler bay, the short-circuit current is reduced to the level that does not affect the dynamic-force-related risk.

Operation of the LRW system significantly restricts the probability of occurence of higher values of the fault duration. For risk of 10^{-3} in configuration 1, 3 as well as 5 and 7, the fault duration values are much higher.

Comparing fault durations for selected risk levels for a shorter line (Table 2) to those for longer line (Table 3), one can see an evident increase in duration, especially for risk levels 10^{-1} and 10^{-2}. For longer line, relative length of the line section protected by the protection in the coupler bay and by the protections in adjacent substations is much smaller. In effect, the probability of occurrence of longer short-circuit duration values increases to some extent.

Table 3. Short-circuit duration values for selected levels of risk of exceeding for considered EAZ configurations at the faults in 220 kV line of length 110 km

R_{az}, 1/a	T_k, s			
	Configuration 1	Configuration 2	Configuration 3	Configuration 4
10^{-1}	119	119	567	567
10^{-2}	474	531	623	627
10^{-3}	537	1090	992	1090
R_{az}, 1/a	T_k, s			
	Configuration 5	Configuration 6	Configuration 7	Configuration 8
10^{-1}	119	119	568	571
10^{-2}	516	1072	624	1074
10^{-3}	559	1097	992	1097

Analysis of dynamic forces has been carried out for two substations: 220 kV and 400 kV. The maximum current during the three-phase short-circuit on substation bus in the planned grid configuration is assumed to be 40 kA. In addition, the point of issue was the short circuit current flowing in the considered line during the fault on bus is negligibly low, i.e. maximum value of the short-circuit current flowing from the bus during the fault on the considered line is about 40 kA. The current's flow layout nearby the substation was found assuming that short-circuit currents coming into the bus from the other bays rose proportionally to the value under the actual network. Also, the value of the short-circuit current was assumed to be constant along the full length of the bus span under consideration. The reduction in the short-circuit current value in the span due to its flow layout within the substation was not taken into account.

The goal of the assumptions described above was to choose the least convenient conditions regarding the calculation of the short-circuit's dynamic effects. Yearly frequency of exceeding individual values of short-circuit current flowing from the substation during the three-phase and two-phase faults on the lines under consideration are presented in Fig. 3 a, b.

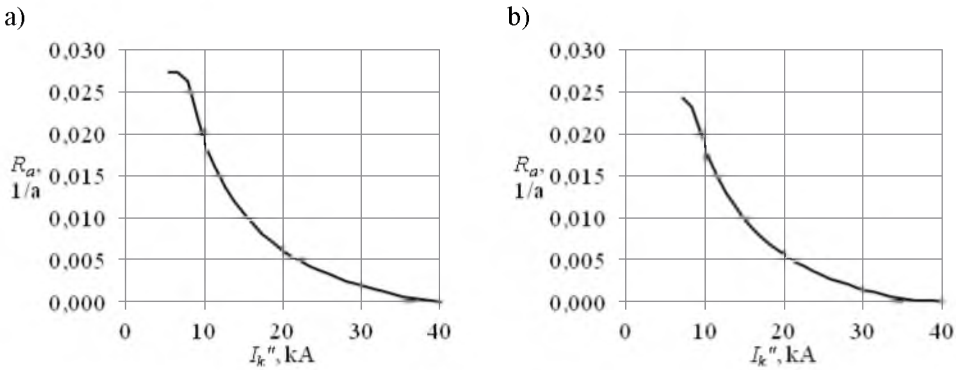

Fig. 3. Yearly frequency of exceeding individual values of short-circuit current during faults on the line under consideration a) 220 kV, b) 400 kV

3. Analysis of dynamic forces in substation

3.1. Computations for selected spans

Studies of dynamic F_t, and F_f have been carried out for the main span of the 220 kV substation (length l is 56 *m,* inter-phase distance 3,5 *m)* and 400 kV substation (length l is 72 *m,* inter-phase distance 6 *m).* In both spans, two conductors AFL-8-525 per phase with a distance of 200 mm were applied. The assumed value of the static force F_{st} was 20 kN per phase. In Fig. 4a, the relation between the analyzed force F_t and the short-circuit duration is plotted for span

220 kV whilst in Fig. 4b, the expected yearly frequency of exceeding individual values of the force found by simulation is presented.

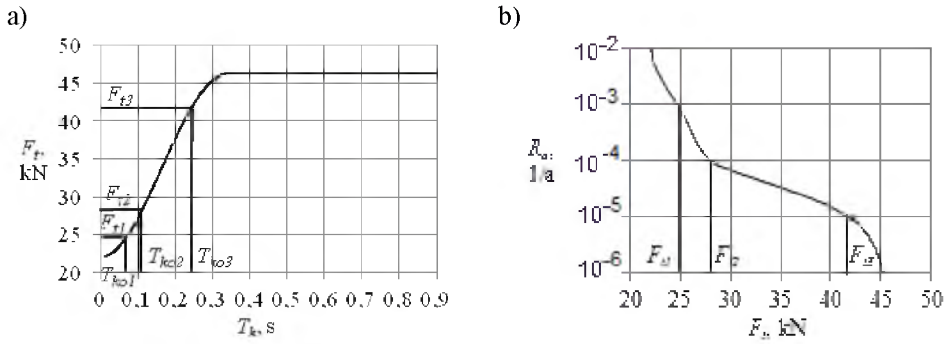

Fig. 4. (a) Force F_t versus short-circuit duration; (b) yearly frequency of exceeding individual values of the force F_t (b) for considered 220 kV span

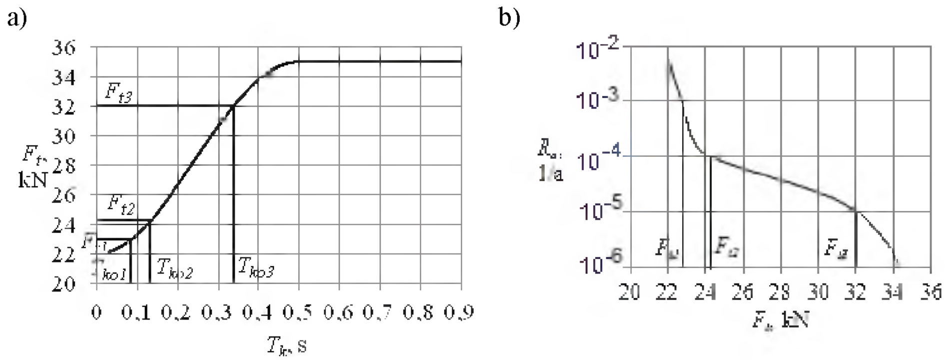

Fig. 5. (a) Force F_t versus fault duration; (b) yearly frequency of exceeding individual values of the force F_t (b) for considered 400 kV span

Similar analysis has been carried out for the 400 kV span. In Fig. 5a, the relation between the analyzed force F_t and the short-circuit duration is plotted whilst in Fig. 5b, the expected yearly frequency of exceeding individual values of the force found by simulation is presented.

Referring to the results obtained, the shirt-circuit duration values T_{ko} which should be applied when computing the F_t force under assumed value of risk R_{az} (expected frequency of exceeding the found value of F_t force) can be found. In figures 4b and 5b, the values of forces F_{t1}, F_{t2} and F_{t3} corresponding to the value of risk of exceeding: 10^{-3} 1/a, 10^{-4} 1/a and 10^{-5} 1/a, are indicated. In Fig. 4a and Fig. 5a, the short-circuit duration values T_{ko1}, T_{ko2} and T_{ko3} corresponding to these forces are shown. The duration values for calculation of the force F_t, found for considered 220 kV and 400 kV spans and for three risk values are listed in Table 4. In the Table 4, the maximum values of the force as well as the minimum time that elapses before the values appear are also indicated. The calculation results are affected by the following magnitudes: substation voltage level, parameters of the span under consideration and short-circuit current distribution.

More precise analysis shows also that, under identical short-circuit conditions, higher values of T_{ko} are to be assumed for longer spans with lower static tension and higher additional weight.

In Table 4, the results for 220 kV line 110 km long are also shown. Values of the dynamic force F_t and time T_{ko} are only slightly higher for the longer line than for the shorter one. Thus, the conclusion can be drawn that the line length affects the dynamic phenomena in a very small percent.

Table 4. Short-circuit duration values suggested for use when finding force F_t for considered spans of 220 kV and 400 kV distribution substations at defined risk values R_{az}

R_{az}, 1/a	220 kV – line length 30 km		220 kV – line length 110 km		400 kV	
	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms	F_t, kN	T_{ko}, ms
10^{-3}	24,70	71	24,80	72	22,73	74
10^{-4}	28,00	109	28,27	112	24,24	133
10^{-5}	41,87	246	41,89	246	31,95	335
0	46,31	>347	46,31	>347	34,98	>499

The force F_f appers when the values of the short-circuit currents as well as the duration of their flow through the span's conductors are high enough. The lower the short-circuit current values, the higher the values of duration of the short-circuit after which the force F_f appears. It is illustrated by curves found for 220 kV span (Fig. 6). When the current is lower than 26,5 kA, the force F_f will not appear at all. The relationship between force F_f and time T_k is affected by the value of F_{st}, additional weight and span length.

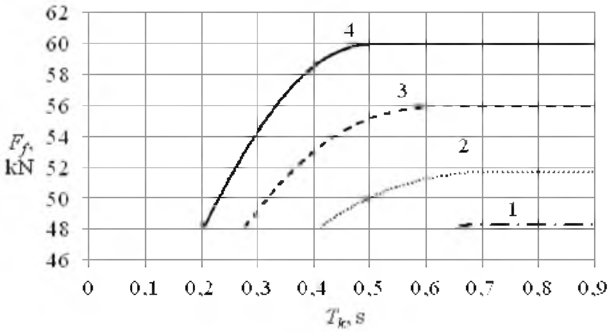

Fig. 6. Force F_f *versus* short-circuit duration for span 220 kV found for four fault current values: 1 – 26,5 kA, 2 – 30 kA, 3 – 35 kA, 4 – 40 kA

Even if the force F_f in the EHV distribution substations can reach high values, exceeding that of the force F_t, the probability of their occurrence is very low. The analysis shows that the frequency of occurring of the force F_f for span the 400 kV and 220 KV substations is lower than 10^{-5} 1/a and 10^{-4} 1/a, respectively. In face of such a small value of frequency of occurrence, the opportunity of its omission in the dynamic effects' calculation can be considered [5]. The short-circuit duration value that should be applied to found the force F_f in 220 kV span at the risk R_{az} = 10^{-5} 1/a is 380 milliseconds. The influence of span parameters on the time values applied to this force calculations is like that for the force F_t.

The fact that the highest F_t, appears for the temperature of –25°C has been taken into account. When calculating the force F_f, the higher value from those calculated for the –25°C and +80°C temperatures has been selected. In Fig. 7a, the force F_f *versus* short-circuit duration T_k is shown whilst in Fig. 7b the force F_f *versus* short circuit current value is plotted.

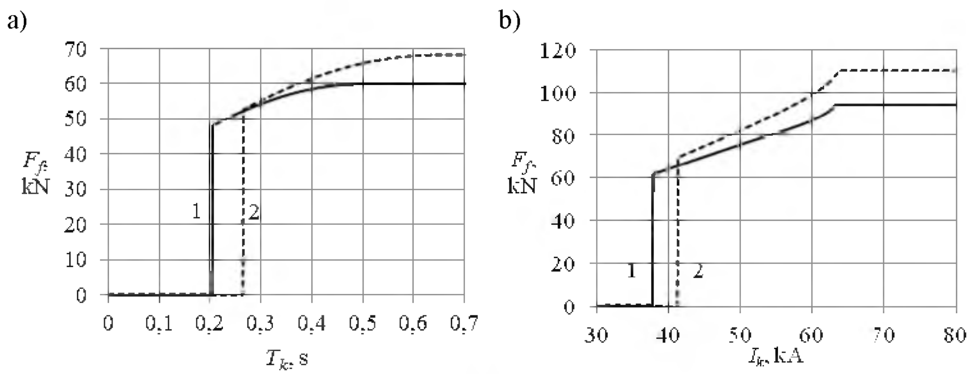

Fig. 7. (a) Force F_f *versus* fault duration (I_k'' =40 kA); (b) Force F_f *versus* short-circuit current (T_k = 0.6 s). Plots for span 220kV, computed for temperature –25°C (curve 1) and +80 °C (curve 2)

The plots as above indicates that, for longer short circuit duration values and higher short-circuit currents, higher force F_f value occurs at temperature of +80°C. For lower values of time and currents there are ranges of values in which the force F_f occurs at -25°C and does not occur at +80 °C.

3.2. Influence of EAZ configuration

The EAZ configuration evidently affects the choice of the short-circuit duration. Some calculations have been carried out for different EAZ configurations and results are listed in Tables 5 and 6.

For any of the risk levels under consideration, the lower short circuit durations appear when the SPZ is on and the protections in the consider line are correlated.

Probability of occurrence of the force F_f is very low; thus, for higher values of the risk, the force should not be taken into account at all (Table 6). For configurations 1, 2, 5, 6, this force is to be considered only if the assumed risk is 10^{-5} in the 220 kV substation. In the 400 kV substation, there is no need to consider it for any of the defined risk levels.

Table 5. Examples of short-circuit duration values (T_{ko}, ms) for finding force F_t, in selected EAZ configurations

R_{az}, 1/a	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV
10^{-3}	71	74	71	74	94	110	94	110
10^{-4}	109	133	111	133	232	327	232	327
10^{-5}	246	335	246	339	298	437	299	438
R_{az}, 1/a	Configuration 5		Configuration 6		Configuration 7		Configuration 8	
	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV
10^{-3}	71	74	71	74	94	110	94	110
10^{-4}	110	133	111	134	232	328	232	328
10^{-5}	246	345	246	349	298	439	299	438

Table 6. Examples of short-circuit duration values (T_{ko}, ms) for finding force F_f, in selected EAZ configurations

R_{az}, 1/a	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV
10^{-3}	-	-	-	-	-	-	-	-
10^{-4}	-	-	-	-	406	-	408	-
10^{-5}	367	-	385	-	521	571	522	564
R_{az}, 1/a	Configuration 5		Configuration 6		Configuration 7		Configuration 8	
	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV
10^{-3}	-	-	-	-	-	-	-	-
10^{-4}	-	-	-	-	420	-	426	-
10^{-5}	398	-	482	-	521	573	530	573

For any of the considered risk levels, the lowest short-circuit duration values appear when the SPZ is on and the protections in the line under consideration are correlated(duplicated

Probability of occurrence of the force F_f is very low; thus, for higher values of assumed risk, the force should not be taken into account at all (Table 6). For configurations 1, 2, 5, 6 in 220 kV substation, the force shall be taken into account only for assumed risk 10^{-5} 1/a. In the analyzed span of the 400kV substation, the probability of occurrence of the force F_f is even lower.

3.3. Influence of circuit-breaker unreliability

Relationships between T_{ko} values and circuit-breaker unreliability for 220 kV span are presented in Fig. 8. When the q_w value is lower than 0.05 we can observe the following: the lower value of assumed risk level, the stronger influence of the q_w coefficient on the T_{ko} value applied to calculate the F_t force. The higher unreliability factor, the lower its meaning when finding the T_{ko}.

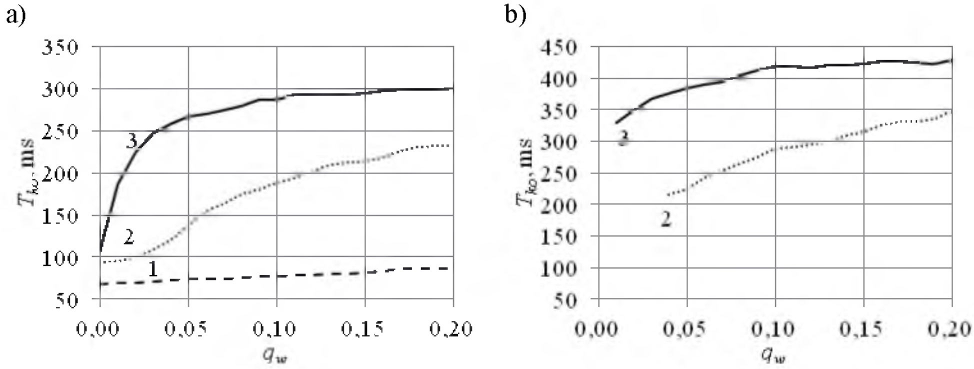

Fig. 8. Time T_{ko} for finding dynamic forces (a) – F_t, (b) – F_f) *versus* unreliability factor of circuit-breakers, for risk R_{az} in considered span 220 kV: 1 - 10^{-3} 1/a, 2 - 10^{-4} 1/a, 3 - 10^{-5} 1/a

Relationship between T_{ko} values and q_w factor for 400 kV span is like that for 220 kV span (Fig. 9). The force F_f in 400 kV span appears only at risk of 10^{-5} 1/a under very high failure rate of the circuit-breaker ($q_w > 0.1$); however, such a value does not appear in the true network.

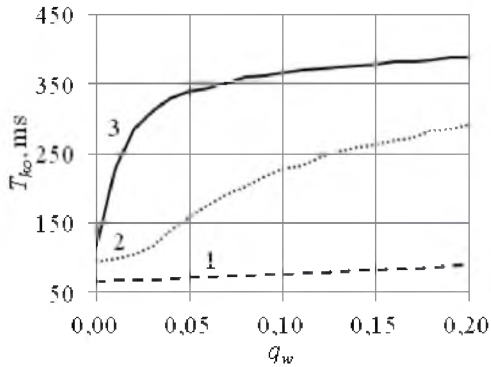

Fig. 9. Time T_{ko} for finding dynamic forces F_t *versus* unreliability factor of circuit-breakers, at risk R_{az} for considered span 400 kV: 1 - 10^{-3} 1/a, 2 - 10^{-4} 1/a, 3 - 10^{-5} 1/a

3.4. Influence of protection unreliability

Influence of applied value of protection unreliability q_z on T_{ko} value is negligible (see Fig. 10 and Fig. 11 for the 220 kV and 400 kV distribution substation, respectively). In the considered range of the failure rate of protections, the influence of the protection unreliability on T_{ko} value applied to calculate the F_t force is negligible.

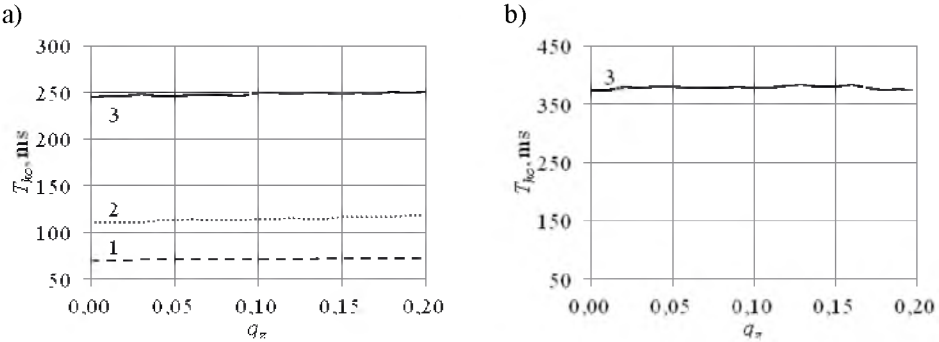

Fig. 10. Time T_{ko} for finding dynamic forces (a) – F_t, (b) – F_f) *versus* unreliability factor of protections, at risk R_{az} for considered span 220 kV: 1 - 10^{-3} 1/a, 2 - 10^{-4} 1/a, 3 - 10^{-5} 1/a

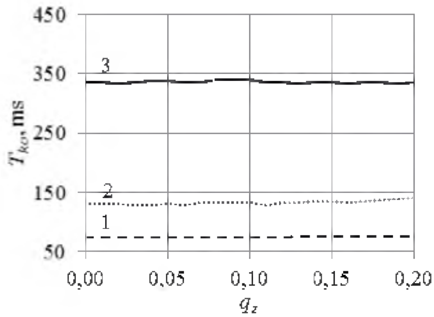

Fig. 11. Time T_{ko} for finding dynamic forces F_t *versus* unreliability factor of protections, at risk R_{az} for considered span 400 kV: 1 - 10^{-3} 1/a, 2 - 10^{-4} 1/a, 3 - 10^{-5} 1/a

Important influence of the q_z factor on the T_{ko} value appears when the q_z are higher, and it is not a true case (for the force F_t, at q_z greater than 0.3).

3.5. Influence of the distribution substation short-circuit capacity

There is an evident relation between T_{ko} value and the current value measured on the substation bus during the short-circuit. Also, the higher short-circuit current values, the higher dynamic force values. However, the time values applied to find the F_t force at an indicated risk level are lower for substations with higher short-circuit currents. The reason is: higher short-circuit current is attenuated by the line reactance. It is well illustrated in Fig. 12 in which the results of simulation carried out for 220 kV and 400 kV spans are presented.

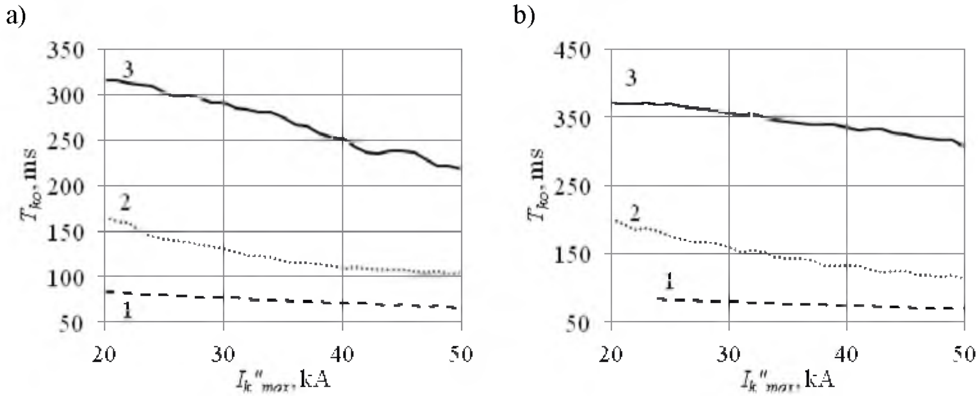

Fig. 12. Duration T_{ko} for finding the F_t force *versus* maximum short-circuit current on bus, risk R_{az}: 1 - 10^{-3} 1/a, 2 - 10^{-4} 1/a, 3 - 10^{-5} 1/a; for span: a – 220 kV, b – 400 kV

In turn. F_f force appear not but at high values of short-circuit current. At risk level 10^{-5} the force F_f for span 220 kV and 400 kV appears when the short circuit current exceeds 30 kA and 45 kA, respectively. For higher risk levels, the force F_f does not occur.

4. Final remarks

Simulation results can aid when the short-circuit duration is being chosen for engineer-type computations of the F_t and F_f forces. The suggested choice is based on the risk level assumed in analysis, i.e. on expected frequency of exceeding the indicated force during the substation operation and maintenance. The short-circuit duration values which are to be found depend mainly on the substation span parameters, applied static tension of conductors and the short-circuit capacity.

In general, in the EHV distribution substations with long spans, the force F_f is much higher than F_t; *however,* the probability of its occurrence is very low. Mainly, when the distribution substation is to be modernized, such influence is taken into account if economically proved. The results obtained for 400 kV distribution substation show that the expected frequency of occurrence of F_f forces is below 10^{-5} 1/a.

Due to implemented assumptions, mainly those keeping the short-circuit current flow within the substation out of consideration as well as those stating the constant temperature of conductors before the fault, the expected risk value is significantly higher.

The authors plan to apply the presented method to determine the time T_{ko} for the short-circuits within the distribution station as such.

References

[1] PN-EN 60865-1 Obliczanie skutków prądów zwarciowych – Część I: Definicje i metody obliczania (IEC 865-1. Short-circuit currents - Calculation of effects. Geneve 1993).

[2] Frąckowiak R., Piechocki P.: Model symulacyjny do oceny obciążeń dynamicznych w rozdzielniach z szynami giętkimi – koncepcja programu komputerowego, *Materiały XII Konferencji Naukowej – Zastosowanie Komputerów w Elektrotechnice, ZKwE'07*, Poznań 2007, ss. 179-180.

[3] Frąckowiak R., Mitkowski E., Paszylk R.: Application of Monte Carlo method to dynamic tension assessment in substations with flexible bus-bars, *Archives of Electrical Engineering,* vol. XLIX No 192 – 2/2000. pp. 243-261.

[4] Frąckowiak R., Piechocki P.: Wartości czasu trwania zwarcia w sieci elektroenergetycznej najwyższych napięć w świetle badań symulacyjnych. *Academic Journals Electrical Engineering,* 2012, nr 70, pp.75-82.

[5] Pscherer L., Stegemann G., Probabilistyczna ocena obciążeń zwarciowych wyłączników wysokiego napięcia (język niemiecki: Warrscheinlichkeitsorientierte Bewertung von Leistungsschalterbeanspruchungen durch Kurzschlusstrome). *Materiały III Międzynarodowe Sympozjum "Jakość zasilania z układów sieciowych*", Gliwice 1986, ss. 279 -292.