Computer Applications in Electrical Engineering
Vol. 13 *2015*

Short-circuit duration and dynamic forces in central section of substation

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

Presented topic is the continuation of investigations concerning the estimation of short-circuit duration when computing the short-circuit effects using probabilistic methods. In the paper, an expanded model of distribution substation for simulation-based analysis of the short-circuit conditions and dynamic effects in the central section of bus-bar is presented. In the model, the operation of protections in the transformer bay has also been considered. The results of simulations aiming to assess the frequency of occurrence of the defined values of short-circuit current, short-circuit duration and dynamic forces are reported. Also, the question: "How the transformer's protections involved in simulation affect the simulated short-circuit conditions?" has been answered. Computations have been carried out for four different EAZ system configurations.

KEYWORDS: EHV distribution substations, short-circuit dynamic effects, simulations

1. Introduction

Presented results of work refer to the probabilistic methods – based assessment of dynamic short-circuit effects in extra high voltage distribution substation with flexible bars. Previous research work of the paper's authors was focused on how the short-circuits affect the dynamic effects in the outmost span of the substation. Then, the assumption has been made that the short-circuit current flows practically from one side of the point in which the short-circuit conditions have been assessed. Consequently, the next stage of studies is focused on dynamic effects in the span located in the central part of the bus bar. Therefore, a simulation model has been extended: the flow of short-circuit currents within the substation as well as operation of the power EAZ protections and circuit breakers in the EHV substations during faults in the electric power system have been introduced. In the short-circuit duration model based on the analysis of operation of the power EAZ protections and on the circuit breakers in the EHV substations during faults, the operation of the residual current-operated protective devices (RCDs) of both the bus bar and the transformer, distance protections, earth-fault protections and unit protections as well as the automatic reclosing equipment (SPZ) and local circuit-breaker back-up (LRW) have been taken into account. Results of the testing experiments aiming to assess the frequency of occurrence of the defined values of short-circuit current, short-circuit duration and dynamic forces are reported. Computations have been carried out for different EAZ system configurations.

2. Simulation model – initial assumptions

2.1. 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 disturbances in the substation. General rule that governs the finding of T_k value using the Monte Carlo simulation in the form of successive steps is described in details in [1]. Detailed requirements as to the protections installed in the HV and EHV bays of the distribution station as well as the power automatic equipment can be found in *Instrukcja Ruchu i Eksploatacji Sieci Przesyłowej (IRiESP*) [2].

In the algorithm of the short-circuit duration, the transformer protections have been added. The completed short-circuit duration algorithm is shown in. Fig. 1.

Examples of reach of zones of the transformer's protections are presented in Fig. 2. The ZT1 and ZT2 are the RCDs protecting the transformers with the lowest possible delay. Regarding the operation princip, it is the fastest protrection installed in the transformer's bay. Each transformer installed in the HV an EHV network is protected by at least one of such a protections. Transformer can be equipped with a second set of such protection provided that meets requirements given by the *IRiESP.* A zone protected by the RCD protection is between the current transformers installed in the bay and the transformer's bushings on the opposite voltage side. If the differential protection became active, the pulse is sent to the transformer's circuit-breakers on both sides.

Protection ZT3 is a distant one similar to those installed in the line bay (but with a bit different settings). The the I zone's reach is of 70% of impedance of protected transformer. In that zone, the protection operates immediately. The II zone's reach includes the busbar on the opposite side of transformer and the time setting is 1 second; the protection has a reverse zone up to 60% of impedance of the shorted line connected to the substation with a time setting of 0.6 seconds. The zone provides protection against the faults appearing nearby in face of the lack of operation of bays' protections, bus bar protections or coupling bay protection to limit the short-circuit current flowing by the transformer.

When protection ZT3 acts in the zone „towards", the pulse is sent to both circuit-breakers of the transformer. If the fault is in the backword zone, the pulse is sent only to the circuit-breaker in its proper area.

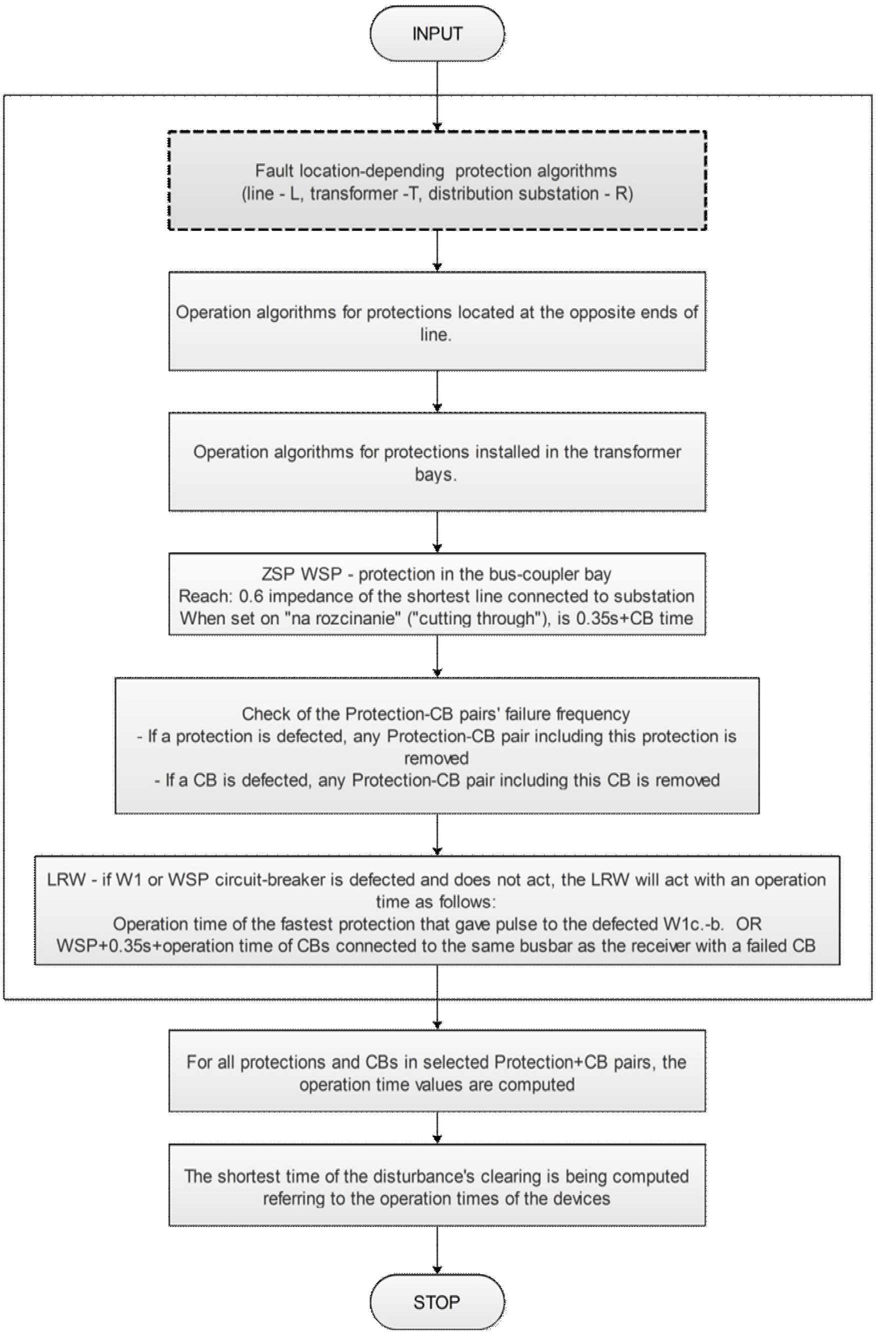


Fig. 1. General algorithm for finding short-circuit duration in distribution substation

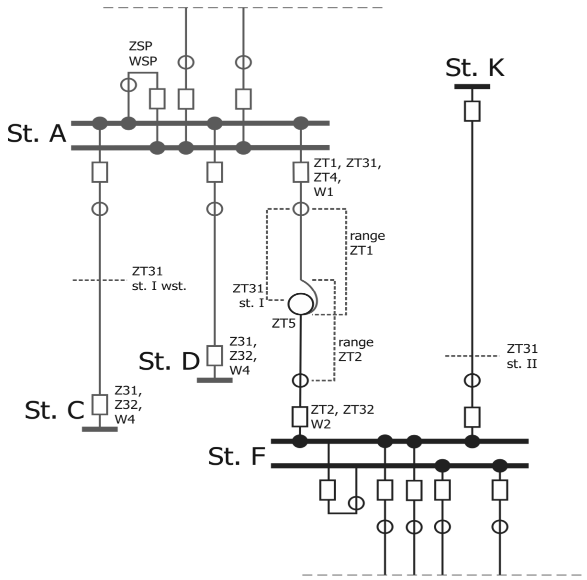
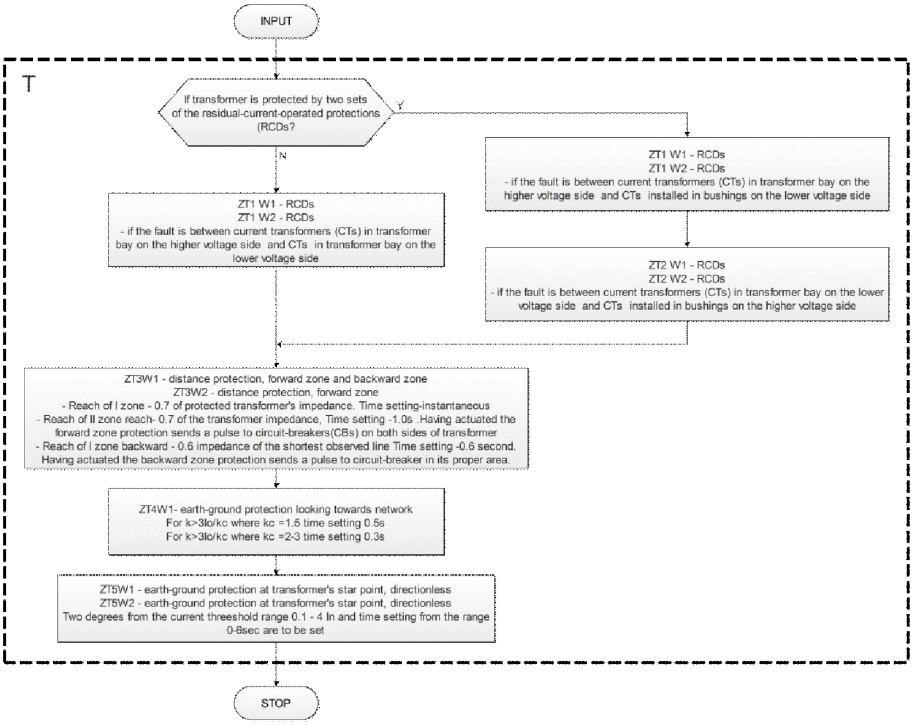


Fig. 2. Examples of the reach of protection zones protecting transformers



If transformer is protected by two sets
of the residual-current-operated protections
(RCDs?

ZT1 W1 - RCDs
ZT1 W2 - RCDs
- if the fault is between current transformers (CTs) in transformer bay on the higher voltage side and CTs installed in bushings on the lower voltage side

ZT2 W1 - RCDs
ZT2 W2 - RCDs
- if the fault is between current transformers (CTs) in transformer bay on the lower voltage side and CTs installed in bushings on the higher voltage side

ZT1 W1 - RCDs
ZT1 W2 - RCDs
- if the fault is between current transformers (CTs) in transformer bay on the higher voltage side and CTs in transformer bay on the lower voltage side

ZT3W1 - distance protection, forward zone and backward zone
ZT3W2 - distance protection, forward zone
- Reach of I zone - 0.7 of protected transformer's impedance. Time setting-instantaneous
- Reach of II zone reach- 0.7 of the transformer impedance, Time setting -1.0s .Having actuated the forward zone protection sends a pulse to circuit-breakers(CBs) on both sides of transformer
- Reach of I zone backward - 0.6 impedance of the shortest observed line Time setting -0.6 second. Having actuated the backward zone protection sends a pulse to circuit-breaker in its proper area.

ZT4W1- earth-ground protection looking towards network
For k>3Io/kc where kc =1.5 time setting 0.5s
For k>3Io/kc where kc =2-3 time setting 0.3s

ZT5W1 - earth-ground protection at transformer's star point, directionless
ZT5W2 - earth-ground protection at transformer's star point, directionless
Two degrees from the current threeshold range 0.1 - 4 In and time setting from the range 0-6sec are to be set

Fig. 3. Operation algorithm for protections in the transformer branch

In addition, the transformer is protected by the earth-fault protection towards the ZT4 network (with two current settings and corresponding time settings) and by the earth-fault protection in the ZT4 transformer's star point (also two current settings). The time settings of these protections are high and are not considered in the algorithm.

Detailed algorithm of finding the short-circuit duration in face of disturbances in the transformer branch are shown in Fig. 3. Operation of protections during faults on lines and within the distribution station as well as the development of the computer program for finding duration of such faults are discussed in details in [3, 4]. In new developed algorithms, the fact that the transformer protecting protections act also during disturbances appearing in lines or within distribution stations has been taken into account.

2.2. Distribution substation model

In Fig. 4, a scheme of distribution substation (computer program screen shot) is presented; the short-circuit conditions' observation point on the busbar system No.1 between bays 12 and 13 is marked. On one side of the observation point, two bays are found to which the transformer T02 and the line L205 are connected. On the opposite side, other branches considered in the scheme are found. To find the flow of the short-circuit currents, the network model in the *Plans* program has been applied. These values are indicated on the substation scheme shown in Fig. 4.

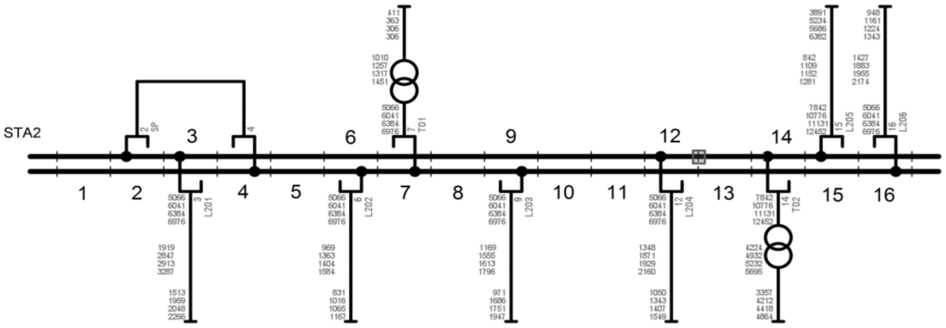
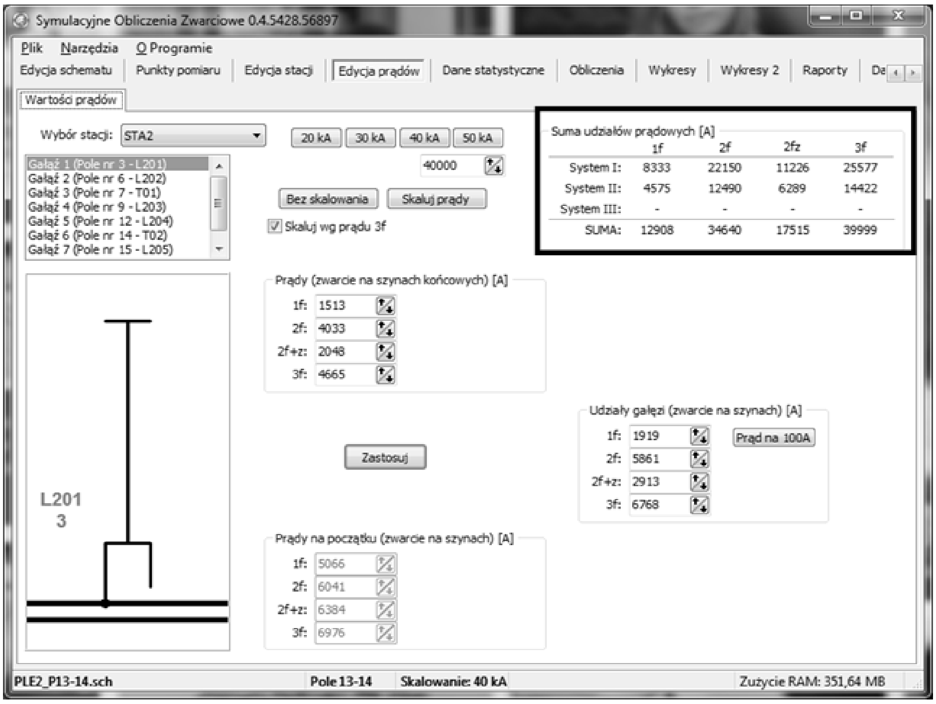


Fig. 4. Scheme of considered 220 kV distribution substation – observation point marked with a square on the No. 1 busbar system between bays No. 12 and 13

Simulation-based computations have been carried out basing on the assumption that maximum current at the three-phase fault on the substation's bus bar is 40 kA. For simulation-based analysis of dynamic forces, the currents were accordingly scaled. The program window enabling the edition of the short-circuit currents flowing through a selected point of the substation during disturbances at different sections of substation as well as at the ends do connected branches (lines and transformers) are presented in Fig. 5. In this window, the short-circuit currents can be scaled to a chosen maximum value for a three-phase short-circuit.



Wybór stacji: STA2

Gałąź 1 (Pole nr 3 - L201)
Gałąź 2 (Pole nr 6 - L202)
Gałąź 3 (Pole nr 7 - T01)
Gałąź 4 (Pole nr 9 - L203)
Gałąź 5 (Pole nr 12 - L204)
Gałąź 6 (Pole nr 14 - T02)
Gałąź 7 (Pole nr 15 - L205)

40000

☑ Skaluj wg prądu 3f

Suma udziałów prądowych [A]

	1f	2f	2fz	3f
System I:	8333	22150	11226	25577
System II:	4575	12490	6289	14422
System III:	-	-	-	-
SUMA:	12908	34640	17515	39999

Prądy (zwarcie na szynach końcowych) [A]
1f: 1513
2f: 4033
2f+z: 2048
3f: 4665

Udziały gałęzi (zwarcie na szynach) [A]
1f: 1919
2f: 5861
2f+z: 2913
3f: 6768

Prądy na początku (zwarcie na szynach) [A]
1f: 5066
2f: 6041
2f+z: 6384
3f: 6976

PLE2_P13-14.sch | Pole 13-14 | Skalowanie: 40 kA | Zużycie RAM: 351,64 MB

Fig. 5. Program window for edition of flow of short-circuit currents

3. Short-circuit currents and short-circuit duration: analysis results

To verify correctness of the developed model, a detailed analysis of distributions of the short circuit current in the chosen point of substation as well as of the short-circuit duration has been carried out. In Table 1, selected values describing the flow of these short-circuit currents in substation are reported.

Table 1. Short-circuit currents values

Short-circuit current	2-phase current [kA]	3-phase current [kA]
Short-circuit on substation's bus bar	34.64	40.00
Share of T02 transformer	10.15	11.76
Share of L205 line	2.28	2.64
Short-circuit on right side of observation point	22.21	25.6
Short-circuit on left side of observation point	12.43	14.4

In Fig. 6, a risk of exceeding the actual values of short-circuit currents appearing at the observation point during the faults on the bus bar system, in bays 14 and 15 as well as in line L205 and transformer T02 is reported.

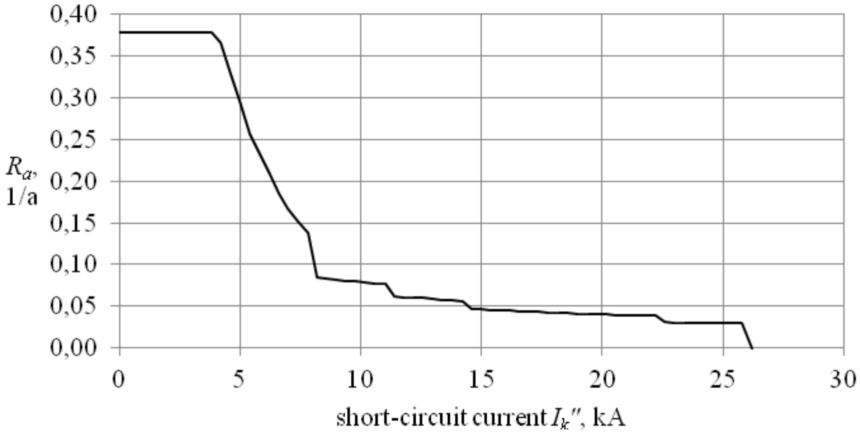


Fig. 6. Risk of exceeding the actual values of short-circuit current during the faults on the bus bar system, in bays 14 and 15 as well as in line L205 and transformer T02

Plot of risk (expected annual frequency) of exceeding the actual values of short-circuit duration for disturbances appearing in the considered grid section is shown in Fig. 7.

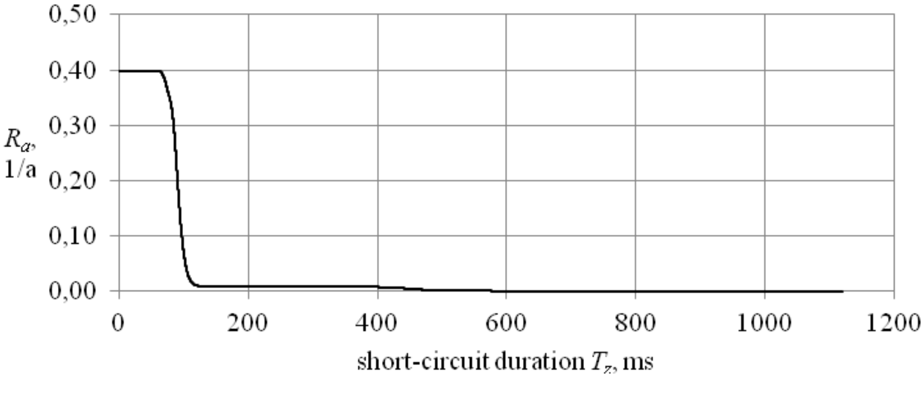


Fig. 7. Risk of exceeding the actual values of short-circuit duration during the faults on the bus bar system, in bays 14 and 15 as well as in line L205 and transformer T02

The analysis of short circuit duration's distributions has been continued assuming four different EAZ configurations listed in Table 2. Values of considered time for selected risk levels are reported in Table 3.

As the influence of the transformer protecting protections on the short-circuit duration values in the substation and on the lines has not been considered, the values of considered time are evidently overvalued especially for risk values higher than 10^{-4} 1/a; the results reported in Table 4 are a good illustration for it [5].

Table 2. EAZ configuration under consideration in substation

	Conf.1	Conf.2	Conf. 3	Conf. 4
Circuit-breaker back-up system (LRW)	Yes	Yes	Yes	Yes
Automatic reclosing equipment (SPZ)	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

Table 3. Short-circuit duration values at selected risk levels in function of the substation's EAZ equipment

R_a [1/a]	EAZ Configuration			
	1	2	3	4
	T_k [ms]			
Fault location – bus bar, devices in bays 14 and 15 as well as line L205 and transformer T02				
10^{-1}	97.5	109.9	97.5	103.2
10^{-2}	134.8	572.6	134.2	535.8
10^{-3}	549.7	924.3	696.1	558.3
10^{-4}	1065.3	1067.6	1067.8	1065.9
10^{-5}	1084.1	1087.0	1086.1	1083.9
10^{-6}	1120.0	1116.0	1123.0	1121.0

Table 4. Short-circuit duration values at selected risk levels in function of the substation 's EAZ equipment regardless transformer protecting protections

R_a [1/a]	Configuration			
	1	2	3	4
	T_k [ms]			
Fault location – bus bar, devices in bays 14 and 15 as well as line L205				
10^{-1}	102.5	372.1	102.5	110.2
10^{-2}	540.3	793.3	1058.6	554.2
10^{-3}	1061.6	1062.8	1074.1	1061.9
10^{-4}	1074.5	1076.1	1085.0	1074.6
10^{-5}	1084.5	1086.5	1094.9	1085.7
10^{-6}	1122.0	1122.0	1131.0	1122.0

4. Analysis of dynamic forces

The dynamic force analysis has been carried out using Monte Carlo simulation [4], regarding requirements of the standard [6]. A plot of risk of exceeding actual values of the force F_t for two considered span length values (56 m – P1, 28 m – P2) found under short-circuit conditions at selected point of the substation is presented in Fig. 8. The most significant are faults on the section 1 of the busbar, in bays 14 and 15, transformer T02 and line L205. Maximum force value for the shorter span, P2, is slightly below 24 kN whilst, for span P1, the value is of 28 kN. More detailed analysis indicates that the computation of the risk is in the lowest degree affected by the bus bar faults, a bit more affected by the short-circuits in the transformer , then in the line under consideration, and is in the highest degree affected by the short-circuits in the considered bays of substation. The low influence of the faults in line L205 on the computed risk comes from the fact the line is very short (about 15 km). The low influence of the transformer is due to the low frequency of occurrence of the short-circuits in the transformer units.

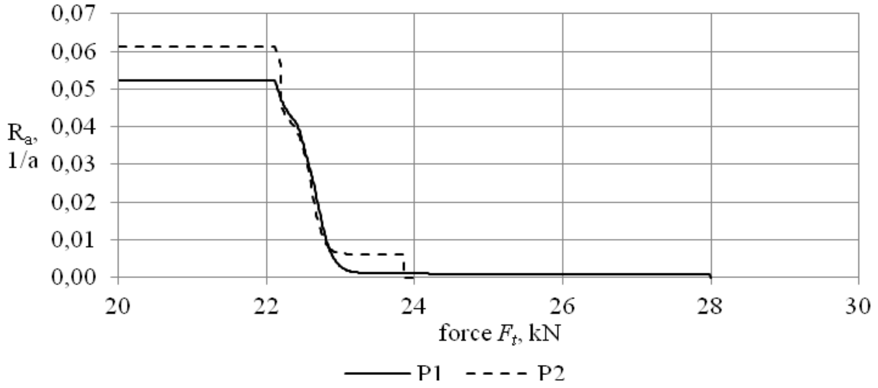


Fig. 8. Risk of exceeding actual values of force F_t for two considered span length values in the substation's section under consideration

The influence of the EAZ equipment configuration on the plot of risk of exceeding the force F_t has been found by simulations and is shown in Fig. 9.

As the influence of the transformer protections on the short-circuits in the substation (on busbar, bays and on the line) has not been introduced, the computed value of risk of exceeding the force value higher than 24 kN is overvalued by more than ten times.

As the plotted curves in Fig. 9 are located close to each other, the influence mentioned above seems to be relatively low. The highest increase in the computed frequency of exceeding is due to the lack of the busbar's RCD protection.

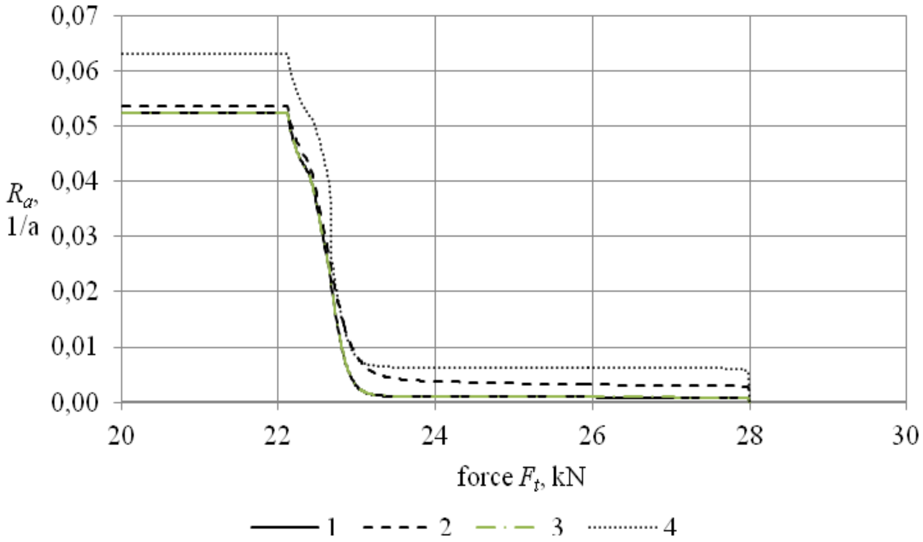


Fig. 9. Risk of exceeding actual values of force F_t found for span P1 for considered EAZ equipment configurations

Under short-circuit conditions existing at the assumed point of the substation, the force F_f is missing completely. In Fig. 10, F_f force values in function of short-circuit current found for different short-circuit durations are presented. The plots indicate that for the short-circuit duration values appearing in practice, the short-circuit currents values at the observation point are too low to “create” the force F_f.

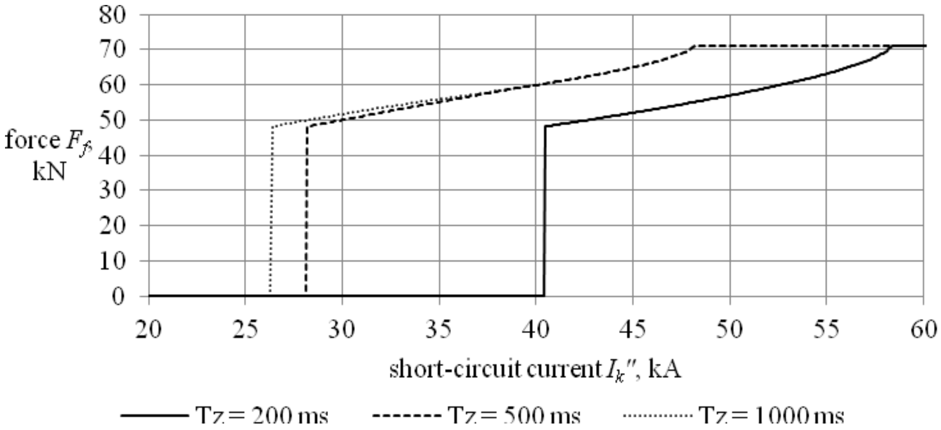


Fig. 10. F_f force values in function of short-circuit current found for different short-circuit durations

5. Conclusions

The developed model as well as examples of simulation-based computations carried out are a successive stage of work aiming to assess both the short-circuit duration accompanying disturbances in the EHV substations and the dynamic forces accompanying the short-circuit disturbances. In the presented model, the transformer and the precise model of its protections have been involved. When the influence of these protection on the short-circuit duration values in the tested section of the network is taken into account, both the short-circuit duration values and the dynamic force values computed at defined risk values become undervalued. Development of a model for simulation-based assessment of the short-circuit duration and dynamic effects of the short-circuit current flow is now in progress and its tests and studies are to be continued. It is expected that the analysis carried out with the model will provide helpful indications how to compute dynamic short-circuit forces.

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(Received: 7. 10. 2015, revised: 2. 12. 2015)