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Specifics of Switch-Gear Capacity Fault Analysis of Kosovo Power System Substations by Comparative Analytical and Numerical Software Methodology

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Abstract

This paper deals with short circuit fault analysis for checking out and determining the adequacy of the power switchgear capacity following changes in network configuration for a given power system substation facility under assumed worst case scenarios of fault occurrences. Namely, changes in the configuration of the power system alter both the short circuit levels and short circuit currents in the system. Hence when any major modifications to the power system are made, these computations must be repeated to determine the adequacy of the protective equipment [1] i.e. circuit breaker switchgear. The case study analyses a typical substation facility of the Kosovo Power System (KPS) with short circuit fault calculations for the analysed busbar have been carried out in order to establish whether fault currents exceed the earlier installed switchgear/circuit breaker capacity following more significant changes in network configuration. Functional performance of power circuit breakers have been checked out in view of this for an entire sequence of symmetrical and unsymmetrical short circuit fault in order to avoid equipment failure i.e. related dynamic or thermal equipment damage in a typical power system substation with two modes of operations.

The analysis is carried out by simulating the full range of short-circuit faults with emphasis on the three-phase and single-line-to-ground faults. The fault calculations for the analysed case study have been carried out with different fault methodologies i.e. by application of the power system software packages such PSS/E, the MATLAB as well as the classical analytical Thevenin method. The results obtained are used also for a establishing a practical applicative methodology of switchgear check-out thru an easier applicable preliminary fault analysis. A comprehensive assessment pertaining to the adequacy of the switchgear is then made based on a parallel and comprehensive fault analysis with different comparative methodologies and levels of calculation accuracy for determining accurately switchgear ratings as applied also in the KPS.

Keywords:	Adequacy of switchgear capacity; Circuit breaker; Comparative fault analysis; Short circuit fault current, Power system

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1. Introduction

The demand for electric power consumption continues to increase globally with no significant saturation trend in sight. In order to meet this demand appropriately a continuous increase in generation, transmission and distribution facility capacities are necessary. Therefore, every year many more power stations, substations and transmission lines are added to thus permanently expanding power systems. These changes in the configuration of the power system alter increase short circuit fault levels and short circuit fault currents in the system [1]. Hence the installation of appropriately dimensioned switchgear for protection and control of the network that can withstand possible major fault occurrences and power disruptions. It is therefore important to determine the values of system voltages and currents during faults short circuit conditions so that protective devices may be set to minimize the harmful effects of such contingencies [2]. The proper coordination of protective relays and the correct specification of circuit breaker rating are based on the result of such fault calculations and analysis [3].

The probability and gravity of major network faults and ensuing disruptions increases proportionally with network enlargement and complexity that result in increasing fault levels i.e. fault currents. Hence fault currents have to be kept in check with appropriately rated protective switchgear in order to minimize potentially serious permanent equipment and network damage.

Network faults can strike in various forms and gravities. The ones that are accompanied with manifold larger currents and fault levels than the near-nominal load ones are short circuit fault currents, the gravest being usually those of 3-phase faults and in certain cases also line-to-ground faults [4]. Fortunately 3-phase faults are the simplest ones for calculation, analytically and numerically, due to their inherent fault symmetry.

The line-to-ground (L -G) faults, which by the same token are the most frequent and most complex for calculation, statistically reach the highest incidence of occurrence of some 70% of the overall number of short circuit faults. The line-to-line (L-L) faults have an incidence of ca. 15%, line-to-line-to-ground (L-to-L-to-G) faults stand at ca. 10%, whilst the incidence of the 3-phase faults stands at some 5% of such fault occurrences [5].

The 3-phase short circuit occur rarely but it is the most severe type of fault involving largest fault currents and fault levels. For this reasons this symmetrical short circuit calculation is performed to determine the largest currents to determine the rating of circuit breaker switchgear [1] despite the fact that L-to-G faults sometimes reach somewhat higher values in certain circumstances i.e. when they occur in the vicinity of synchronous generators.

2. Case study

The case study for the analysis is taken to be the Kosovo Power System respectively its Substation Podujevo (SP) of rated capacity 2x40 MVA and 220/35/10 kV with the one-line diagram shown below in Figure 1.

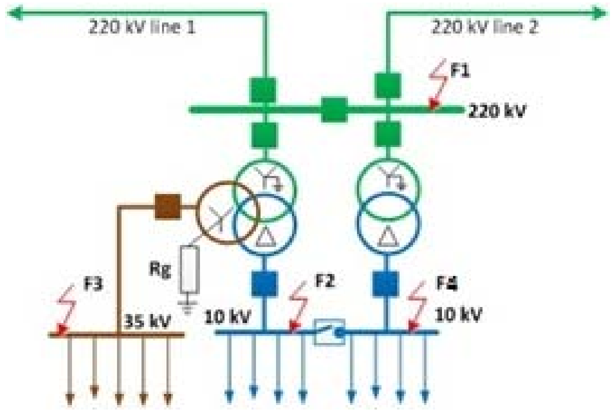

Figure 1. Single-line diagram of the faulted substation SP

Fault calculations provide information on currents and voltages of a power system during short circuit fault conditions. For the purpose of the comparative fault analysis a sequence of typical faults are applied on the mentioned substation busbars connecting its two parallel power transformers as shown in Fig.2. The sequence of faults applied consists of all the four standard types of short circuits mentioned above affecting all its 220/35/10 kV busbars. The fault points at all of its three-voltage levels are symbolically noted with F1, F2, F3 and F4 as shown in Figure 2.

The two parallel power transformers TR1 and TR2 of the analysed substation are: A three-winding transformer 220/35/10(20) kV with rated capacity 40 MVA, and a two-winding one 220/10 kV of the same rating. Their relevant data are given in Table 1 below. Note: u_k not available N/A for HV-LV level for TR2 – values taken from manufacturer's data.

Table 1: Transformer data[1]

ID	TR1	TR2
S_n [MVA]	40	40
V_p [kV]	220	220
V_s [kV]	36.75	10.5
V_t [kV]	10.5	
Regulation [%]	±12x1.25	±12x1.25
Connection group	YNyn0 d5	YNyn0 (d5)
u_k-HV-MV [%]	10.97	15.41
u_k-HV-LV [%]	15.29	NA
P_{cu}HV-MV [kW]	178	181
P_{cu} HV-LV [kW]	187	NA
P_{fe} [kW]	36	36
i_0 [%]	0.2	2

3. Fault analysis with PSS/E program package

The initial calculation of short circuit fault currents for the purpose of providing for the study case of the comparative analysis for the sequence of fault occurrence analysis for the SP substation was carried out with the highly accurate large scale industrial PSS/E program package. Upstream boundary conditions of the system are simulated with the actual fully accurately represented interconnected integrated real regional power system.

3.1. Fault calculation – Substation power transformers in non-parallel mode of operation

The three-winding transformer TR1 and the TR2 have been appropriately modelled as such in the PSS/E. The 10 kV windings of both transformers have both delta windings d5.

The obtained results from the same series of fault simulations consisting of Line-to-Ground fault (L-G), Line-to-Line (L-L), Line-to-Line-to-Ground (L-L-G) and 3-Phase (3-PH) faults are presented as given in Tables 2 and 3.

[1] Subscripts of data transformer table (n, p, s, t, k, Cu, Fe, o) pertain to nominal, primary, secondary, tertiary, short circuit voltage, copper and iron losses and transformer magnetizing current respectively.

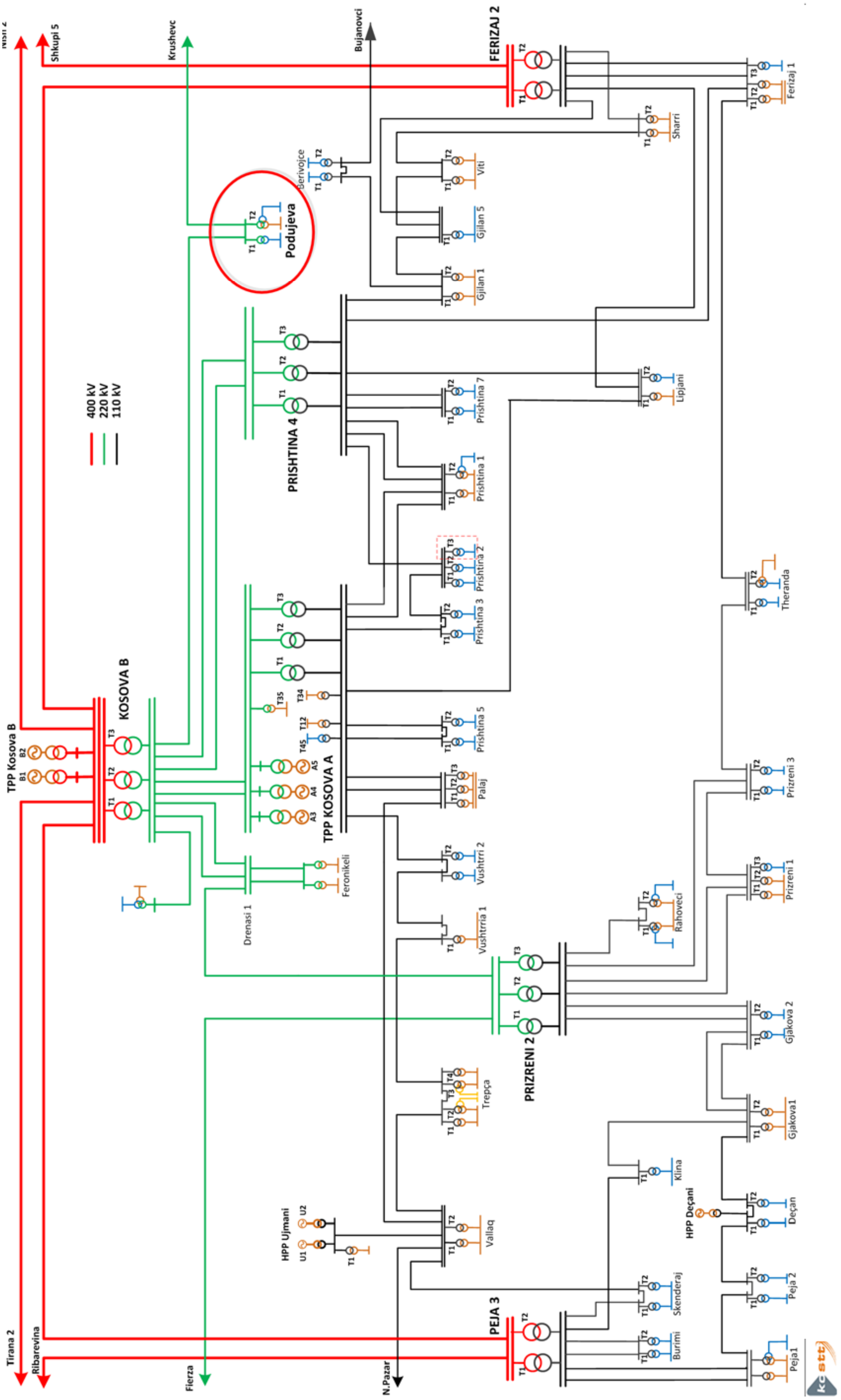

Figure 2. Single-line diagram of the Kosovo Power System

Table 2: Non-parallel mode of operation – fault currents

BUS	L-G [AMP]	L-L [AMP]	L-L-G [AMP]	3-PH [AMP]
220 kV (F1)	6005.8	7052.4	4769.7	8165.9
35 kV (F3)	303.9	3827.9	152.8	4421.1
10 kV-T1 (F2)	0.0	17676.8	0.0	20417.7
10 kV-T2 (F4)	0.0	15398.6	0.0	17785.6

Table 3: Non-parallel mode of operation – fault powers

BUS	L-G [MVA]	L-L [MVA]	L-L-G [MVA]	3-PH [MVA]
220 kV (F1)	2288.53	2687.32	1818.00	3111.64
35 kV (F3)	18.42	232.05	9.26	268.11
10 kV-T1 (F2)	0.00	306.17	0.00	353.64
10 kV-T2 (F4)	0.00	266.71	0.00	308.06

From the results obtained other indicators of fault currents can be observed such as the dynamic currents, which taken as peak values are: I_{dyn}[2] = I_{peak} = 11.8091 kA for the 3-phase faults and I_{dyn} = I_{peak} = 0.4384 kA for the single-phase faults. This peak current would be taken as meritory for the short circuit Making[3] Current of the circuit breaker as opposed to the short circuit Breaking Current for which meritory is the symmetric steady state short circuit current. Depending on the X/R ratio i.e. the DC component of the short circuit current the Making current can be up to 2.5 times the Breaking current despite its extremely short duration of half a cycle i.e. ca. 5 msec. Hence the dc component is also calculated for the entire series of the faults applied and stands at: I_{dc} = 1.7223 kA.

The related Breaking Current i.e. the Breaking Capacity of the switchgear is taking into account most frequently when fault calculations for circuit breaker capacity are determined for fault points in close electrical proximity to synchronous generators which would significantly increase the Breaking Capacity of the switchgear. As the duration of the peak dynamic short circuit i.e. asymmetric maximal momentary current is half a cycle i.e. 5 milliseconds that no protective relay can react within such an instantaneous time frame, no significant thermal effect can take place within the half cycle, especially as the substations not in electrical proximity of synchronous generators the Breaking capacity of the circuit breakers has been taken as meritory rather than the Making capacity.

Power switchgear capacity for the 220 kV voltage level stands at I_{k3}=40 kA, for the 35 kV one at I_{k3}=25 kA, while for the 10 kV stands at I_{k3}=25 kA. From the results obtained and the installed power switchgear capacity nominal ratings, it can be clearly seen that *for the non-parallel transformer mode of operation* of the Podujevo substation, which is a critical one in the KPS in this respect, fault currents pose no danger of exceeding switchgear power rating and hence no damage can result even in the worst case scenario. In other words the analysed installed switchgear provides a sufficient safety margin for their respective power ratings. This mode of operation is the standard mode applied in KPS substations [6].

3.2. Fault calculation – Substation power transformers in parallel mode of operation

The case of parallel mode of operation of the two power transformers of the substation, as the worst-case scenario i.e. mode of operation of the substation has also been subjected to the entire series of faults at F1, F2, F3 and F4 for the comparative analysis. The obtained results have been presented as given in Tables 4 and 5.

From the results obtained from the fault simulation at F2 for the case of the parallel mode of operation of the two substation transformers, it can be seen that the fault current I_{k3}= 34.573 kA clearly exceeds the rated maximal switchgear capacity, which for the 10 kV voltage level stands at 25 kA. Hence if such a fault occurs for the parallel mode of transformer operation the switchgear equipment would not have the required rating i.e. capacity to withstand this fault current and hence permanent equipment damage, thermal and/or mechanical and possibly even personnel damage would be caused as well as a power system disruption.

Such a surge increase of the fault current close to being coupled (precisely 70% increase i.e. from 20.4 kA to 34.5 kA) for the 3-phase fault at the fault point F2 of the 10 kV voltage level for the parallel mode of operation of the two substation transformers, as compared with the same fault current for the non-parallel mode of operation. This is obviously due to the approximate

[2] Subscripts of data transformer table (dyn, peak, dc, k3) pertain to dynamic, peak, direct and 3-phase short circuit currents respectively.

[3] The two ratings of the circuit breaker which require the calculations of the short- circuit currents are: Rated Momentary (Making) Current & Rated Symmetrical Interrupting (Breaking) Current. Symmetrical short-circuit current is obtained by using subtransient-reactance for synchronous machines, while Momentary (breaking) currents (RMS) is then calculated by multiplying the symmetrical current by a factor of 1.6 to account for DC offset component current [1].

Table 4: Parallel mode of operation – fault currents

BUS	L-G [AMP]	L-L [AMP]	L-L-G [AMP]	3-PH [AMP]
220 kV (F1)	6005.8	7052.3	4769.6	8165.8
35 kV (F3)	304.6	5618.7	152.9	6490.1
10 kV-T1 (F2)	0.0	29925.5	0.0	34573.0
10 kV-T2 (F4)	0.0	29925.5	0.0	34573.0

Table 5: Parallel mode of operation – fault currents

BUS	L-G [AMP]	L-L [AMP]	L-L-G [AMP]	3-PH [AMP]
220 kV (F1)	2288,52	2687.30	1817.48	3111,59
35 kV (F3)	18,46	340.61	9,27	393.44
10 kV-T1 (F2)	0.00	518.32	0.00	598.82
10 kV-T2 (F4)	0.00	518.32	0.00	598,82

halving of the equivalent substation reactance resulting from the parallel connection/operation of the two transformers (see Figure 1) can be technically implemented within a transient-transfer time frame of 60 sec. by SCADA-activated 10 kV bus-coupler switch.

Nevertheless the optional parallel connection of the two transformers thru the 10 kV as shown in Figure 1 for the given ratings of the installed switch gear of 25 kA is provided for as an N-1 criterion emergency operating option for the case of an outage of any of the two substation transformers. In such a case the transformer remaining in operation would be able to overtake and supply the consumers on both groups of 10 kV feeders irrespective of the outage of the parallel one as both transformers have the rating to cover the entire substation load separately and currently without even reaching full-load condition This substation full redundancy capacity that provides for the fulfilment of N-1 criterion is system code policy applied in all major KPS substations [6-7, 10].

Alternatively, should the two substation transformer been allowed to operate in parallel the circuit breaker switchgear rating would have needed to be enhanced from the 25 kA class rating to the 40 kA class rating to provide the respective breaking capacity for the 3-phase current of 34.5 kA, along with other downstream ones other facilities compromising the comparable cost-effectiveness of the solution.

4. Fault calculations with the MATLAB program package

The same series of fault analysis for the case study was carried out with the application of the MATLAB software. The respective equivalent schematic Mat/Lab block diagram of the KPS as presented in Figure 3.

The entire spectra of faults analysis mentioned before was carried out for both two modes of operation of the substation i.e. the non-parallel and the parallel mode of operation. In other words for the two substation transformers operating independently, whilst the other case being the two substation transformers operating in parallel mode thru the interconnecting power bus-coupler 10 kV closed (see Figure 2). The respective equivalent schematic MATLAB block diagram is presented in Figure 4. The two inter–connected 220 kV

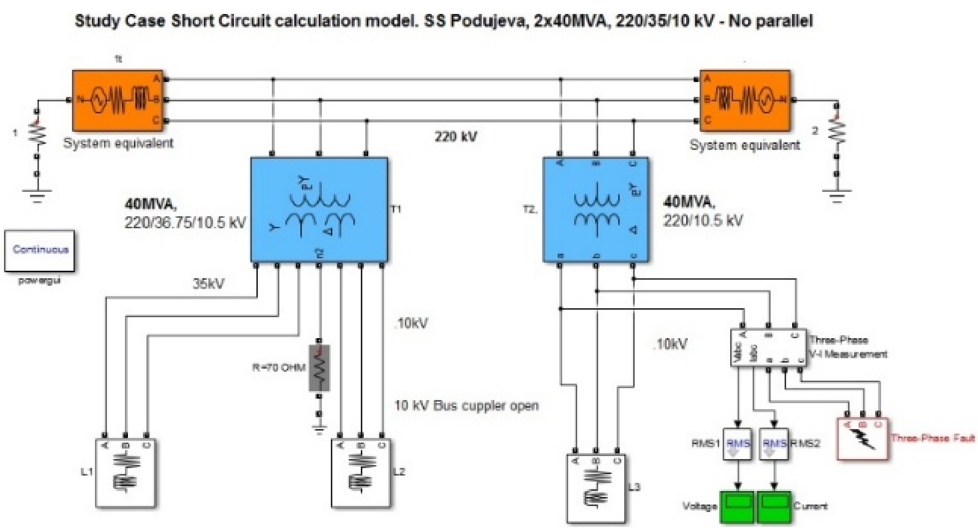

Figure 3. Schematic Matlab/Simulink block diagram for the fault analysis – case of non-parallel mode of operation – transformer inter-connecting power link switch open

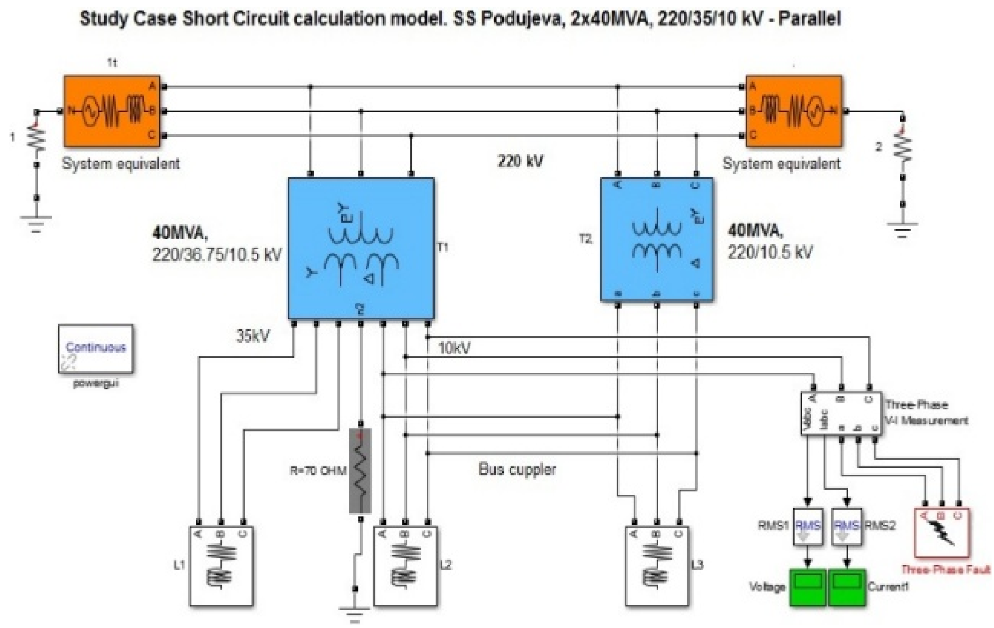

Figure 4. Schematic Matlab/Simulink block diagram for the fault analysis – case of parallel mode of operation – transformer inter-connecting power link switch closed

network systems have same fault levels (of 15.000 MVA) respectively finite bus external impedances $Xe_{1.2}$.

In order to calculate the sub-transient fault current or the initial symmetrical current for a 3-phase short circuit in a power system, the following assumptions are made for the simplicity of calculations:

- Transformers represented by their leakage reactances;
- Transmission lines represented by their equivalent series reactances;
- Synchronous machines are represented by constant voltage sources behind sub-transient reactances;
- Non-rotating (dynamic[4]) impedance load are neglected;
- Rotating (dynamic) loads are neglected or if of larger ratings then represented by constant voltage transient reactance.

In the case study analysed and for reasons of a solid base for a greater accuracy of the comparative short circuit fault analysis the two parallel substation transformers have been represented with "T" equivalent scheme meaning with the included shunt impedance. Dynamic loads have been neglected and after the power transformer data in per unit have been fed into respective schematic blocks including the 220 kV network parameters the simulations have been carried out for the faults occurring at 0.2+ sec. and being cleared at 0.4 sec, with simulation time extending to 0.5 sec. as in the previous analytical calculation.

The obtained results have been graphically presented for the case of the 3-phase fault occurring at F4 for the non-parallel mode of operation of the two substation transformers. As can be seen in the Figure 5 below, all the three fault regimes i.e. the sub-transient, transient and the stationary ones are clearly discernible. Relevant for our comparative analysis is however the stationary 3-phase fault current observed to stand at 17.1 kA rms as shown in Figure 5 in a time-current coordinate system below, while standing at 17.7856 kA rms when simulated by the PSS/E (see Table 2). Figure 6 below shows the 3-phase rms voltage curve in a time-voltage coordinate system before, during and after the fault occurrence is cleared.

Figure 7 below shows the stationary 3-phase fault occurring at F2 for the parallel mode of operation of substation transformers standing at 33.750 kA rms, as compared to 34.573 kA rms when simulated by the PSS/E (see Table 4).

In Table 6 and Table 7 rms values for fault currents have been presented for the line-to-ground fault, line-to-line one and for the 3-phase faults at F1, F2, F3 and F4 for the two case studies analysed.

[4] In the case analyzed the contribution of dynamic loads further downstream are neglected as there are hardly any of significant power rating downstream, nor are there any sizable motor-load industry facilities [8].

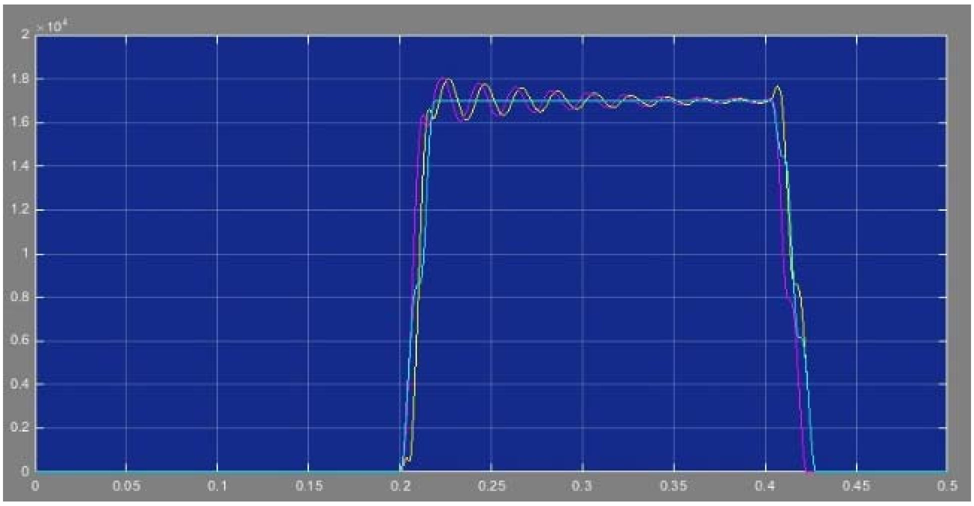

Figure 5. Fault current sec. for the 3-phase fault occurring at F4, case of non-parallel mode of transformer operation

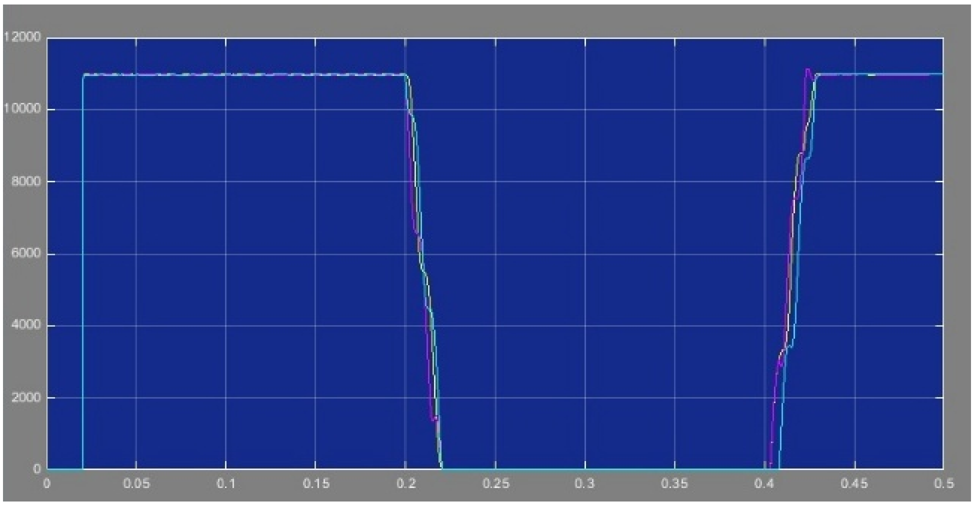

Figure 6. 3-phase fault rms voltage curve before, during and after the fault occurrence at F4 case of non-parallel mode of transformer operation

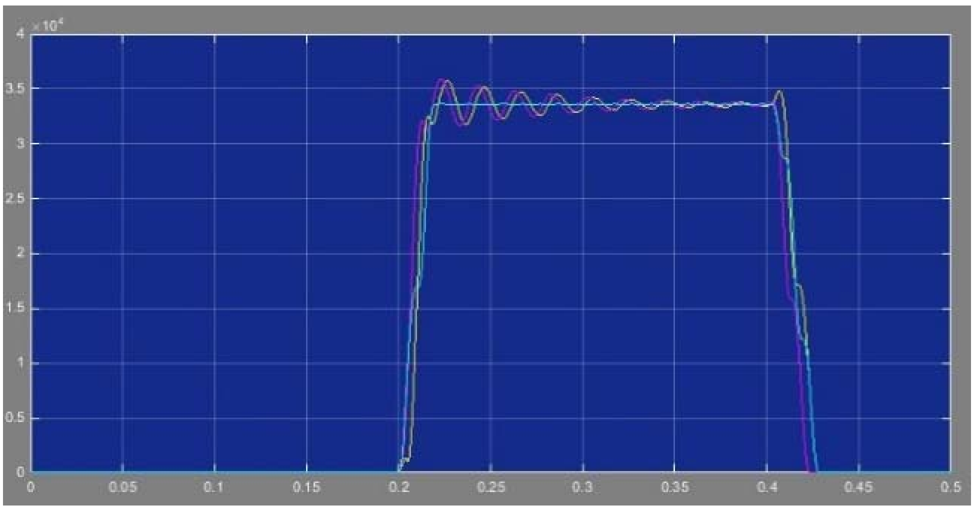

Figure 7. 3-Phase fault current at F2 for parallel mode of transformer operation

Table 6: Non-parallel mode of operation – fault currents

BUS		L-G [AMP]	L-L [AMP]	3-PH [AMP]
220 kV	**(F1)**	6750	7238	8360
35 kV	**(F3)**	313	3861	4440
10 kV-T1	**(F2)**	0.0189	17491	20080
10 kV-T2	**(F4)**	0.0189	14870	17100

Table 5: Parallel mode of operation – fault currents

BUS		L-G [AMP]	L-L [AMP]	3-PH [AMP]
220 kV	**(F1)**	6766,20	7215	8355
35 kV	**(F3)**	313.85	4494	5169
10 kV-T1	**(F2)**	0.0189	29010	33750
10 kV-T2	**(F4)**	0.0189	29010	33750

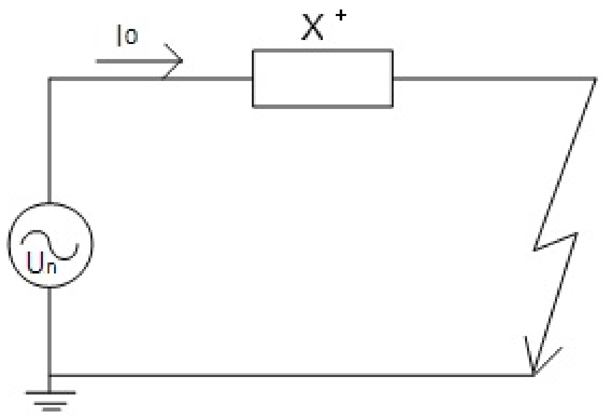

Figure 8. Equivalent Thevenin scheme

5. Analytical fault calculation

For the analytical i.e. the Thevenin method of fault calculations, the fault types analysed were taken to be the 3-phase fault and the single-phase one for the two modes of transformer operation the non-parallel and the parallel one. Most of the cases of short-circuit calculation is a simple E/X calculation (E being the circuit operating voltage and X the equivalent reactance) if X/R is 15 or less [9].

5.1. Phase fault calculation

The power system elements are represented with their equivalent reactances calculated as reduced at the faulted–busbar voltage level. The line resistances and admittances of the power network have been neglected for the simplicity and transparency of calculation. For the assumed 3-phase fault at F3 the same two inter-connected network reactances (X_{e1} and X_{e2}) have been calculated, whilst the TR1 and TR2 transformer reactances (XA, XB and XC) have been calculated as below and schematically presented as in Figure 8.

$$X_{e1} = X_{e2} = \frac{U_n^2}{S_{k3}} \cdot m = j1.0273\ [\Omega] \quad (1)$$

where m is transformer ratio.

$$X_{T2} = \frac{U_n^2}{S_n} \cdot u_K = j5.203\ [\Omega] \quad (2)$$

For TR1 the reactances are calculated as below:

$$X_A = \frac{1}{2} \cdot (x_{AB} + x_{AC} - x_{BC}) = j3.852\ [\Omega] \quad (3)$$

$$X_B = \frac{1}{2} \cdot (x_{BC} + x_{AB} - x_{AC}) = -j0.149[\Omega] \quad (4)$$

$$X_C = \frac{1}{2} \cdot (x_{AC} + x_{BC} - x_{AB}) = j1.3101\ [\Omega] \quad (5)$$

With the equivalent reactance being:

$$x_{de} = j4.21755\ [\Omega]$$

From Figure 8 the three-phase fault current can be calculated to be:

$$\underline{I}_{k3} = \underline{I}_0 = \frac{c \cdot U_n}{\underline{x}_{de}} = \frac{1.1\ 36.75 \cdot 10^3}{\sqrt{3} \cdot j \cdot 4.21755} = -\boldsymbol{j} \cdot \mathbf{5.53}[\boldsymbol{kA}] \quad (6)$$

The three-phase fault current F3 calculated by the PSS/E stands at 4.4211 kA rms and by MATLAB at 4.44 kA rms, thus resulting in less than 1% relative difference i.e. accuracy deviation between the two applied software methods. However the accuracy deviation between the PSSE/E method and the analytically calculated one by the Thevenin equivalent as presented above has resulted in an accuracy deviation of 25.2% and 22.5% respectively.

5.2. Line-to-Ground fault calculation

The L-G fault is assumed to have occurred at F3 on the 35 kV busbar of TR1. For the analytical calculation the approximation included taking into account only the grounding resistance Rg as the other reactances are significantly lower than the Rg, with c=1.1, where *c* represents the voltage security margin according to the IEC standard. The respective Thevenin equivalent schemes as established for the direct, inverse and zero sequences are presented as in Figure 9:

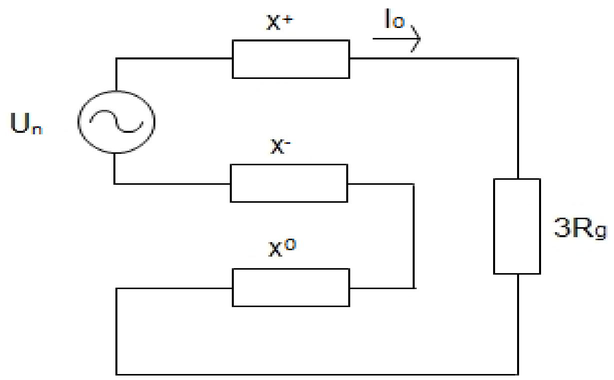

Figure 9. Network equivalent schemes for d, i, o sequences

Hence

$$I^{+} = I^{-} = I^{0} = \frac{c \cdot U_n}{x^{+} + x^{-} + x^{0} + 3 \cdot R_g} \tag{7}$$

In the expression above Rg represents the grounding resistance installed for limiting (asymmetric) fault currents. The grounding resistance Rg is very large compared to other components of the denominator of the expression which are therefore negligible.

Hence

$$I^{0} \cong \frac{c \cdot U_{Af}}{3 \cdot R_g} \tag{8}$$

than

$$I_{k1} = 3 \cdot I^{0} = \frac{1.1 \cdot 36{,}75}{\sqrt{3} \cdot 70} =$$

$$= 3 \cdot \frac{c \cdot U_{Af}}{3 \cdot R_g} = \frac{U_{Af}}{R_g} = \boldsymbol{-j333.42}\ [\boldsymbol{A}] \tag{9}$$

As the single-phase fault current F3 calculated by means of the PSS/E stood 303.9 A rms, while the one resulting from the MATLAB stood at 313 A rms, the relative difference i.e. accuracy deviation between them standing at only 2.99%. However the accuracy deviation between the PSS/E method and the analytically calculated one by the Thevenin equivalent as above has resulted in an accuracy deviation of 9.7% and 3.1% respectively.

6. Conclusion

This paper has carried out a comparative fault analysis of a crucial substation of the KPS for checking out the adequacy of the installed switchgear ratings applying the three short-circuit calculation methods most frequently used in power system fault calculations. Thus two numerical computer methods i.e. power system software packages have been applied along with the classic analytical Therein equivalent method and the results obtained have been subjected to a comparative analysis. Numerical software packages used were PSS/E and the MATLAB based on the IEC standards).

By comparing the fault power levels S_k of the KPS substation taken as case study subjected to a full sequence of possible short-circuit types with the rated power capacity of the installed switchgear, this paper concludes that the two power parallel transformers of the substation may not be allowed to operate in parallel mode at the 10 kV voltage due to the fault levels exceeding the rated installed switchgear capacity. The KPS transmission operator Electrical Equipment Code-based policy implemented in all of its major the substations is that its transformers operate independently and not in parallel. This due to severely increased potential fault currents in case of their parallel mode of operation as presented above and so that the fulfilment the N-1 criterion for all major substation as an emergency operating option i provide for. Namely that for the case of an outage of any of the two substation transformers, the remaining one in operation would be able to cover the entire substation load of both 10 kV feeder groups separately irrespective of the outage of the other one. This substation full redundancy capacity that provides for the fulfilment of N-1 criterion is system code policy applied in all major KPS substations. Along this line it can be concluded from the analysis that an occurrence of a severe fault in case of a parallel operation mode would put at risk all of the 10 kV feeder circuit breakers.

Alternatively, a parallel transformer mode of operation, if needed for the substation and the system, could be permitted only if all the installed 25 kA power circuit breakers would be replaced by a higher class of capacity ratings of 40 kA on practically all 10 kV feeders thus providing the required power capacity redundancy for such contingencies. Such an approach would clearly entail a significant costs increase for the respective system operator, as the next higher class of switchgear power capacity are significantly more expensive. There we arrive at the necessity of determining the compromise cross point between the economic and the functional technical aspect of the power system i.e. substation operation.

It is important to conclude also that the comparative fault calculation analysis presented in this paper clearly indicates that thorough fault analysis of power system are simply indispensable periodically as system expands and its configuration changes. Namely as the system expands and the fault levels increase this necessarily imposes respective periodic check-outs and verification of the adequacy of the installed switchgear ratings/

capacities. Therefore application of more practical and simpler fault calculation methods as the Thevenin classical method can be efficiently applied for preliminary purposes and assessments. Namely they can provide sufficient accuracy for the purpose rather than applying accurate but exhaustive power system software methods posing significant computational time and capacity requirements.

The comparative analysis carried out on the case study has concluded that a preliminary assessment of fault current levels with an acceptable accuracy range deviation of 10-25% can be achieved also with the simple classical Thevenin method and/or the MATLAB application as compared to the elaborate and sophisticated software packages such as the PSS/E. However this would be applied primarily for the purpose of a preliminary and educated assessment of fault levels and fault currents.

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