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Transients Caused by Sequential Circuit Breaker Tripping Issued by Busbar Protection

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SUMMARY

A study of transients in a high voltage substation 400/110 kV is presented in the paper. An analysis was carried out after a fault on the 110 kV busbar, which caused severe damage in the substation. Investigation was focused on a time frame of several sequential circuit breaker trippings. A first step of the study was collection of data from the primary and secondary system in the substation and the control centre. After numerous analyses of data an attempt was made to construct a precision model, which could be used in the computation. Appropriate models were developed for circuit breakers, voltage (potential) and current metering transformers, power transformers, surge arresters, overhead lines and an equivalent grid. The components of the power system can be modelled for the very particular purpose, which means that a different frequency model should be used and each element in this analysis has a specific frequency response. An attempt was made at very detailed modelling of a power transformer, air blast and SF_6 circuit breakers. Computed results of fault currents were compared with measurements captured by the disturbance recorders in the field, mainly in differential numerical relays. Different switching schemes and different tripping sequences of several 110 kV circuit breakers were analysed with a constructed model in the millisecond range. Models of circuit breaker with different types of media, air blast and SF_6 gas were used in the cases investigated. Modelling of the circuit breakers' electrical arc was an important item in all cases in order to take into account the interaction between electrical arc and circuit current during the process of current interruption. The Schwarz/Avdonin equation is applied to model the dynamic behaviour of an electric arc. The fault studied was accompanied by a large short circuit current. For this particular case two types of circuit breaker, air blast and SF $_6$ were modelled. An important conclusion from those analyses was that sequential tripping of several circuit breakers does not cause superposition of overvoltages, because interruption the current happens when it is passing through the zero. Even the record from the substation and the disturbances recorder proves that each particular circuit breaker was successfully opened. On that basis, focus was put only on the final opening of the breaker and its arc extinction. The conclusion can be drawn that such a substation fault should have no influence on excessive overvoltages that can threaten the insulation of components in the substation.

KEYWORDS

Switching - Overvoltage - Circuit Breaker Model - Disturbance Recorder - Arc - Extinction - Computation

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1. INTRODUCTION

The detailed analysis was carried out after one fault that happened on the 110 kV busbar, which caused tripping of several circuit breakers in a few tens of milliseconds. The consequence of the fault was damage on the 110 kV circuit breaker and the power transformer 300 MVA. An effort was undertaken to form a model, which can reconstruct the dynamic of the fault in order to get an insight into transient currents and voltages provoked by the fault. Special attention was dedicated to select and form suitable models for elements in the substation. Several models (Cassie, Mayres, Schwarz and Schwarz/Avdonin) were implemented in the detailed study of the interaction between electrical arc and circuit current during the process of current interruption. Current wave shapes during the switching off operation were recorded by transformer differential protection devices and those data were compared with results of short circuit currents that were computed with the help of the developed model.

2. MODELS FOR TRANSIENTS CALCULATION

The models were developed in the calculation of switching overvoltages for circuit breakers, voltage (potential) and current metering transformers, power transformers, surge arresters, overhead lines and equivalent high voltage network. Each element in the analysis has a specific frequency response, which means that a different frequency model should be used.

The model for overhead lines should take into account their frequency dependence.

Metering transformers in a transient state can be modelled in accordance with the standard IEC 60044 [1], [2] and [3].

A power transformer represents an important component in transient processes. A general model of the power transformer, when calculating switching overvoltages in the frequency range of 50 Hz – 20 kHz comprises, besides linear R, L, C elements, the nonlinear inductance of the core, whose influence should be taken into consideration when the eddy currents hinder the magnetic flux to pass through the core. This effect can already appear with frequencies of 3-5 kHz. The nonlinear inductance of the core is connected to the tertiary winding of the transformer model.

The fault studied was accompanied by a large short circuit current and modelling of the circuit breakers' electrical arc was an important item in all cases.

The current interruption requires that the interelectrode gap changes from conductive plasma into an insulating gas, [4] and [5]. This transition occurs around the current's passing through zero.

Black-box models give a mathematical description of the process and they are appropriate for digital simulation of transients, although most of these models actually have no real physical justification [6]. They describe the interaction of the switching arc and the corresponding electrical circuit during the interruption process. The models of Cassie, Mayer and Schwarz can be implemented in the detailed study of the interaction between electrical arc and circuit current during the process of current interruption.

The short circuit current flows through the hot arc until it crosses natural zero [7]. In this way current chopping is not possible when interrupting the short circuit current. The speed of current falling to zero depends on the type of circuit breaker and its corresponding heat and time constants. However the interaction between the electrical networks on the arc can be significant and in most cases it finishes with a relatively natural current drop to zero. A large heat constant influences the faster current drop to zero. Eventually the small post-arc current flows when the arc resistance takes values of a few thousand ohms.

The Schwarz/Avdonin equation is applied to model the dynamic behaviour of an electric arc:

$$\frac{1}{g}\cdot\frac{dg}{dt}=\frac{d\ln g}{dt}=\frac{1}{\tau_0 g^{\alpha}}\cdot\left[\frac{u\cdot i}{P_0 g^{\beta}}-1\right]$$

Where:

g - arc conductance;

u - arc voltage;
i - arc current;
P - removed power (by conduction, convection, radiation)
τ_0 - time constant
α, β - constants

Circuit breakers with different types of media, i.e. air blast and SF_6 gas, were investigated in order to study their influence on the transient's processes [8].
The model on an electric arc is validated with the experimental results obtained on the test circuit [9].

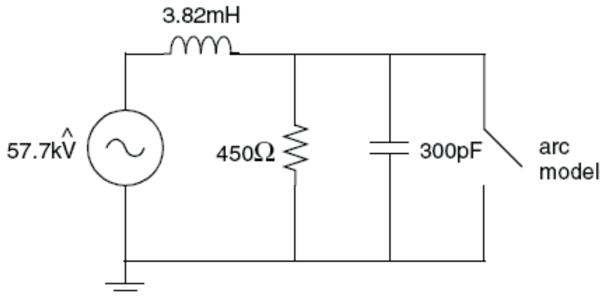

Fig. 1. Test circuit used for the validation of the applied model

The following constants were used for the SF_6 gas circuit breaker model:
$P_0 = 4$ MW, $\beta = 0.68$; arc time constant: $\tau = 1.5$ μs; $\alpha = 0.17$.
Constants for the air blast circuit breaker according to the reference [5] are:
$P_0 = 16$ MW, $\beta = 0.5$; $\tau = 6$ μs; $\alpha = 0.2$

The dynamic behaviour of the arc is studied on the simple test circuit in order to avoid undesirable influences. The time dependence of the arc voltages are calculated and depicted in Fig. 2. and Fig. 3.

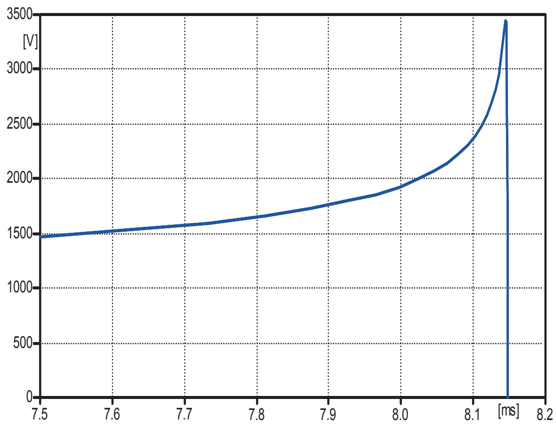

Fig. 2. Arc voltage in the SF_6 circuit breaker

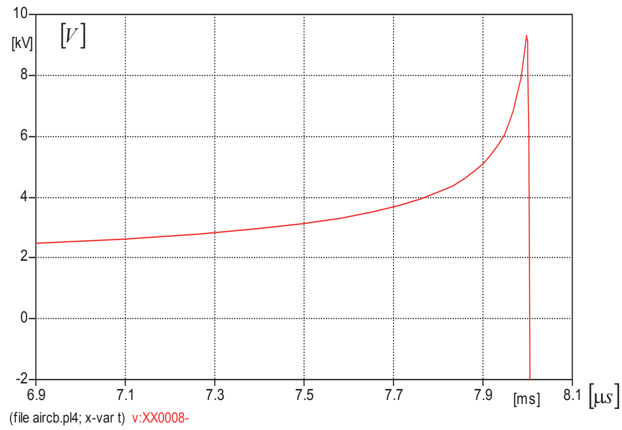

Fig. 3. Arc voltage in the air-blast circuit breaker

The peak values of the arc voltage of the SF_6 gas and air-blast circuit breaker were 3.4 kV and 9.3 kV respectively. The post-arc current of the air-blast was approximately 5.4 greater than the post-arc current of the SF_6 circuit breaker.

3. ANALISYS OF SWITCHING OPERATIONS

Transient's processes were studied in a substation during the switching off operation of several circuit breakers of different type in a time interval of some tens of milliseconds.
The fault which happened on the 110 kV busbar was initiated by a breaker fault in the zone of busbar relay protection. An air-bushing exploded on a 110 kV breaker of line 7. Operating status in that time was normal; two busbar systems were connected with the bay coupler breaker (Fig. 4.).
Busbar relay protection switched off the faulty busbar system. The transformer T3 was also switched off. In such conditions, both transformer circuit breakers (on 110 kV and 400 kV voltage side) were

switched off. Altogether, seven circuit breakers on 110 kV voltage level were switched off and one on 400 kV voltage level, red colour on Fig. 4.

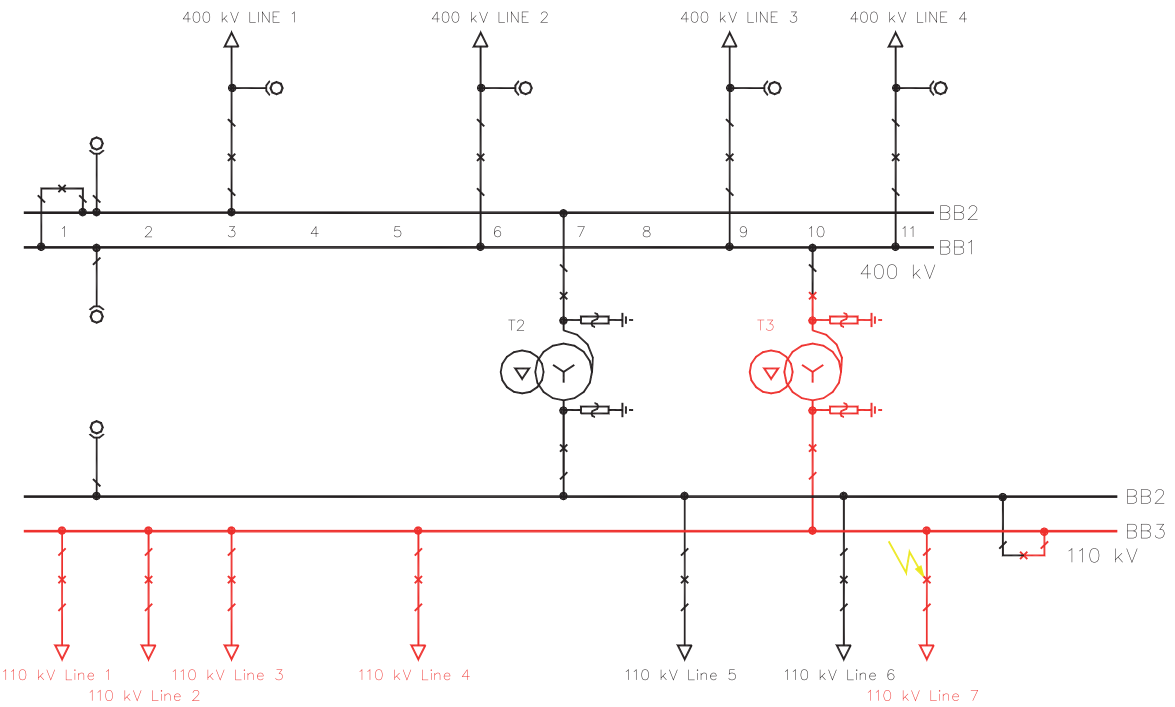

Fig. 4. Operating status of the 400/110 kV substation before fault [8]

3.1. SHORT CIRCUIT IN THE SWITCHYARD

Transformer differential relay protection was activated by the fault that happened in the substation and the currents captured by the disturbance recorder are shown in Fig. 5. The fault clearance times were short; the duration of the fault was less than 100 ms in the 110 kV switchyard as can be seen in Fig. 5., and the fault lasted a little longer in the 400 kV switchyard.

This dynamic sequence of events was simulated on the computational model with the aim of reconstructing the transients provoked by the fault. The main intention was an attempt to calculate voltages and currents in the switchyard and in the power transformer during transient's processes.

Fig. 5. presents currents captured by the disturbance recorder and Fig. 6. depicts currents resulting from computation.

Transformer 110 kV circuit breaker was opened after 4.5 periods of 50 Hz (Fig. 5.), and the same time was chosen in the computation (Fig. 6.). After 85 ms the current exceeded the zero value on the 110 kV side of the power transformer. The circuit breaker on the 400 kV side was slower and the tripping took place at 102 ms. The current I_{L3} does not fall to zero immediately as can be seen in Fig. 5., but in reality the circuit breaker had successfully opened the contact and it was estimated that this part of the current recording is false due to the saturations in the current transformer.

A big impact on the initial value of the short circuit current is caused by a DC component, which strongly depends on the time instant of the fault's initiation. The difference between the real and computed currents at the end of the fault remains less than 10% (peak values of the field and computed currents are 10500 A and 9500 A respectively).

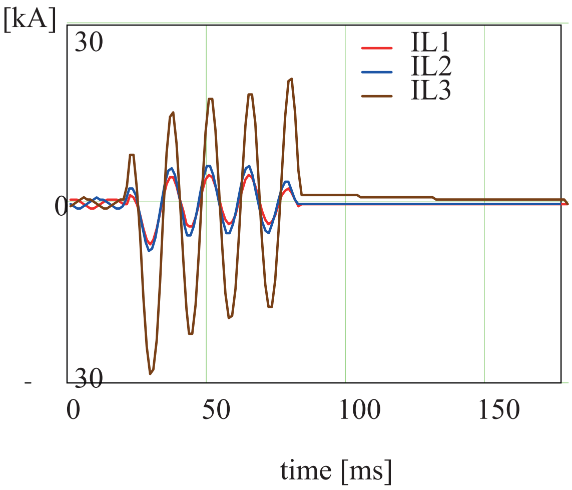

Fig. 5. Recorded currents

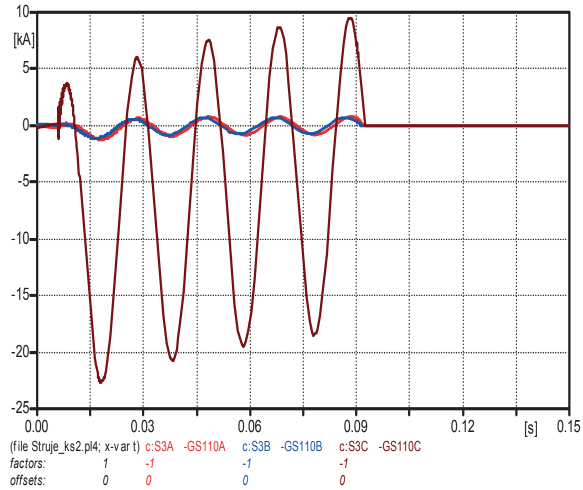

Fig. 6. Computed currents

3.2. SEQUENTIAL TRIPPINGS OF CIRCUIT BREAKERS

The simulation is conducted for the real case of tripping five 110 kV line circuit breakers (line1 ,line 2, ….line 5) and one bay coupler circuit breaker. The complete power transformer model (inrush nonlinear branch, surge arresters on tertiary winding, windings capacitance, and leakage capacitance) is used in computation for this purpose. In order to calculate the maximum overvoltages that can appear on both sides of the power transformer many possible occurrences that could happen in the switchyard were examined, simulated and analysed [8].

Focus was put on the sequential tripping of circuit breakers and in that circumstance the maximal computed overvoltage at 110 kV side reached a very moderate value of 148 kV (Fig. 7.), which was calculated in the simulation of opening the 110 kV circuit breaker. Fig. 8. depicts transient voltages on the 400 kV side for the same case, and no overvoltages could be noticed (Fig. 8.). After the relay had tripped on the 400 kV transformer side, all voltages were oscillatory falling to zero.

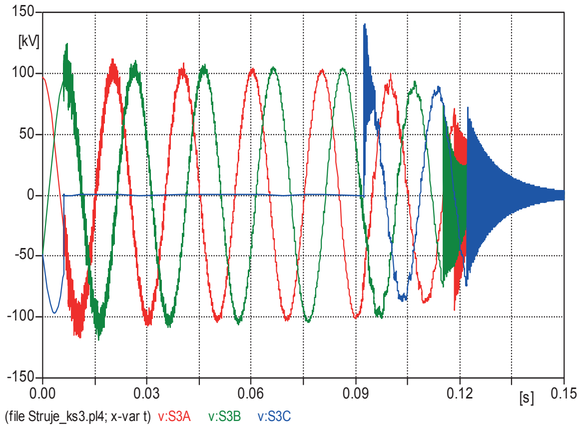

Fig. 7. Voltages on 110 kV side of transformer

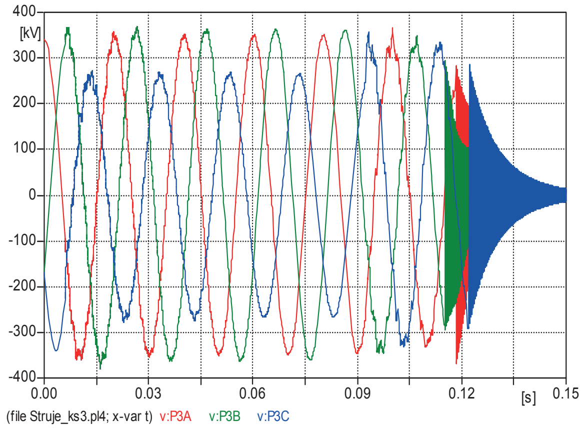

Fig. 8. Voltages on 400 kV side of transformer

Overvoltages were also observed on the tertiary transformer windings where the internal surge arresters were connected and the analysis of computational results did not show any excessive overvoltages caused by sequential trippings of circuit breakers.

The study [8] in which two types of the circuit breaker (air-blast and SF_6 gas) were compared has shown that the type of breaker has not very strong influence on the overvoltages in the switchyard and on the power transformer. Slightly higher overvoltages were noticed when the tripping was done with the air-blast circuit breaker.

4. CONCLUSION

The busbar fault in the switchyard was successfully captured by the differential relay disturbance recorder and on this occasion the busbar protection tripped seven 110 kV circuit breakers.

An attempt to reconstruct the whole fault was undertaken and the fault in the switchyard is analysed on the basis of the conducted computer simulations. For this purpose detailed models of all switchyard components, power transformers and overhead lines were built and very special attention was devoted to form the model of an air-blast and SF_6 circuit breaker.

The comparison between the recorded and computed fault currents showed relatively good correspondence.

On the basis of the list of events and disturbance recorder in the switchyard it was concluded that every breaker successfully opened its contacts. The analysis of the fault showed that sequential breaker tripping had not generated excessive overvoltages because the current in each breaker was interrupted when crossing zero. The opening stage of the final breaker is decisive for the transient overvoltages in the substation and its arc extinguishing was analysed for two breaker types. The current chopping and associated overvoltages are not possible when interrupting the short circuit current, while the short circuit current flows through the hot arc until it reaches natural zero crossing.

Calculated overvoltages on the power transformer bushing during the dynamic phenomena do not have values that can damage the transformer insulation.

The final conclusion is drawn that the circuit breakers of both types (air-blast and SF_6 gas) generate moderate overvoltages, when breaking short circuit currents, which normally should not threaten the insulation of the components in the switchyard.

BIBLIOGRAPHY

[1] IEC 60044-6 - Ed. 1.0: Instrument transformers - Part 6: Requirements for protective current transformers for transient performance, 1992-03.

[2] IEC 60044-2 - Consol. Ed. 1.2 (incl. am1+am2): Instrument transformers - Part 2: Inductive voltage transformers, 2003-02-13.

[3] IEC 60186: Voltage transformers, 01-Jan-1987.

[4] IEC 62271-100 - Consol. Ed. 1.1 (incl. am1): High-voltage switchgear and control gear - Part 100: High-voltage alternating current circuit-breakers, 2003-05-23.

[5] CIGRE, Working Group 13.01 of Study Committee 13: State of the Art of Circuit-Breaker Modelling, December 1998.

[6] V.I. Phaniraj, A.G. Phadke: Modeling of circuit breakers in the EMTP, IEEE Transactions on Power Systems, Vol. 3, No. 2, 799-805, May 1988.

[7] C.H Flurscheim, et Al: Power circuit breaker theory and design, IEE, 1982.

[8] I. Uglešić, S. Hutter, V. Milardić, I. Ivanković, M. Mandić, A. Tokić: Switching Overvoltages as Consequence of Sequential Switching off a Number of Circuit Breakers (in Croatian), Study, 2005.

[9] P. H. Schavemaker, L.Van Der Sluis: The Arc Model Blockset, Proceedings of the Second IASTED International Conference, POWER AND ENERGY SYSTEMS (EuroPES), June 25-28, 2002, Crete, Greece