INVESTIGATION ON CIRCUIT BREAKER INFLUENCE ON TRANSIENT RECOVERY VOLTAGE

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ABSTRACT

As Hammarlund stated in [1], Transient Recovery Voltage (TRV) investigation can never be finished completely, as the progress of circuit breaker construction and network design goes on. The most common approach to TRV investigation is concerning the so called *prospective* TRV, in which an assumption of neglecting interaction between circuit breaker itself and the inherent system recovery voltage is being made. However, it still seems to be worthy to investigate how circuit breaker affects TRV. In presented paper such an influence is being investigated in some detail, with use of black-box Habedank circuit breaker model [2], in exemplary MV large industrial network [3]. The influence of reactance of inductive fault current limiter as well as distance to fault in short line fault condition on rate of rise of recovery voltage has been investigated. The investigation has been made by means of simulation performed using Matlab/Simulink programme.

Keywords: transient recovery voltage, black-box circuit breaker modelling, short line fault, Matlab/Simulink.

1 MOTIVATION AND SCOPE OF THE PAPER

In MV industrial networks power is being consume mostly by high voltage motors supplied by short cable lines, at attendance of fault current limiters (FCL) – with up to 80% share in exemplary networks investigated in [4, 5]. Short line faults (SLF) are characterized by much higher frequency range than terminal faults, reaches 100 kHz as reported in [6] and even higher as reported in [3]. Also, natural frequencies of FCL are much higher than those produced by system or transformer [6]. This frequency components are determining one of the most important factor of TRV severity, namely rate of rise of recovery voltage (RRRV), defined as u_c/t_3, where u_c is peak value of TRV and t_3 is time parameter obtained from envelope of TRV as defined in [7] and depicted in Figure 1. This implies the importance of investigation on RRRV in SLF condition at attendance of FCL.

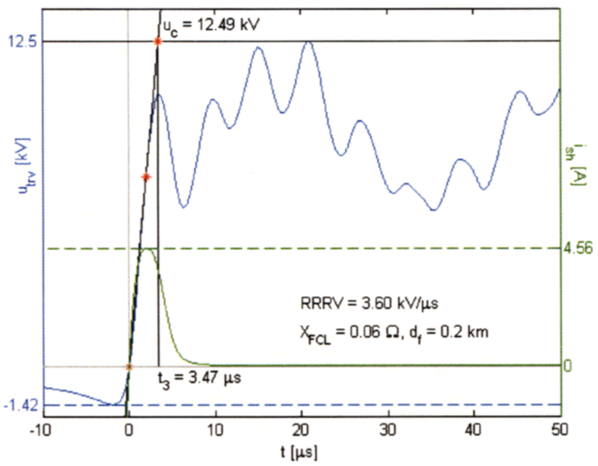

Figure 1 Exemplary TRV shape with envelope.

The scope of presented paper is to investigate how distance to fault in SLF condition and reactance of FCL influence RRRV, and how the model of circuit breaker that is used in simulation affects this influence. The simulation was performed with use of two models of circuit breaker: ideal and Habedank, as introduced in [2].

The second aim of presented paper is to extend the previous research group work, as the new research group has arisen in the field of TRV investigation in MV industrial networks at Warsaw University of Technology (WUT). For this reason, in section 2 the main papers of the previous group will be recall briefly on the background of TRV investigation methods.

2 TRV INVESTIGATION METHODS

Transient recovery voltage has a great history of investigation, beginning in the early years of XX century. Presumably the first author [1] who gave a clear mathematical description of the phenomena was Slepian, in 1923 [8]. He found out that circuit breaker interrupting capacity is greatly affected by the system voltage natural oscillations, when current is interrupted after the instant of current zero. This TRV stresses the circuit-breaker gap when the gap conducts from the state of being good conductor to its normal condition of a good insulator.

2.1 Possible methods of investigation

Since the Slepian work, plenty of methods have been developed to investigate TRV. In general, methods of investigations can be divided into two categories: measurement or calculation methods. The first ones are appropriate only in those networks which already exist, but they are the most accurate. This methods are subdivided into two further categories: direct or indirect methods, depending on how the measurements are being taken: directly, by breaking short-circuit current, or indirectly, by means of measuring some auxiliary phenomena and hence conclude TRV in question. Some of these methods require to operate on network whilst in service, either fully or partially supplied, other methods are intended to operate on dead network, either with or without breaker action.

The second branch of the methods – calculation methods – are more general than the measurement ones, however they require a good knowledge of models of network elements together with its parameters. In the subject of modelling network elements, great effort has already been done, hence there are plenty of known models as well as modelling techniques for use in TRV investigations. Some, but not obviously all of these models have been successfully implemented in commonly used numerical simulators, like ATP/EMTP or Matlab/Simulink.

Obtaining network parameters is a great challenge of calculation methods, and also – it brings the most share to the methods accuracy. As it is often in case, the knowledge of network parameters is greatly improved when calculation methods are combined together with measurement methods. In this category, an exemplary method of [9] is worthy to be recalled. In this method, network elements are being stimulated to their self oscillations with their natural frequencies, caused by application of the current-surge indicator. By connecting additional capacitance or inductance on terminals of the indicator during the measurements, the changes of frequencies and amplitudes of oscillations are to be observed, from which equivalent circuits together with their parameters can be deduced.

2.2 TRV investigation in Polish MV large industrial networks

Based on the later method mentioned above, the most comprehensive investigation on TRV in Polish MV large industrial networks has been made by Roguski in 1962 [10]. Further measurements performed by WUT research group was published by Ciok in 1982 [4], completed also by Ciok at al. in 1996 [3]. Since some results from the latter papers have been used in presented paper, it is worthy to mention that two of the papers just recalled, namely [4, 10], had been used in CIGRE report [11], concerning TRV in MV networks, which is still in use nowadays [12] with reference to TRV standardization. Presented paper extends the scope of investigations reported in [3].

3 METHODOLOGY

The research reported in presented paper involves yet another approach to TRV investigation, combining measurement and calculation methods. In this approach, not the TRV itself, but the influence of a certain network element (i.e. cable, fault current limiter and circuit breaker in that case) on a given prospective TRV is being investigated.

In this methodology the prospective TRV might be given either from measurements or standardization. In presented paper, the prospective TRV has been taken from measurements reported in paper [3] (see Figure 2).

The methodology consists of three steps. First, the appropriate model (as shown in Figure 4b), together with its parameters, has been identified thus it produced the desired prospective TRV shape (as shown in Figure 3). This has been delivered by some elementary algebraic transformations from well known equations describing double frequency equivalent circuits (see section 4.2). When the model has been identified, models of: circuit breaker, FCL and cable have been assumed (see sections 4.3, 4.4, 4.5). Finally, the interaction between these models has been investigated by means of computer programme (see section 4.6).

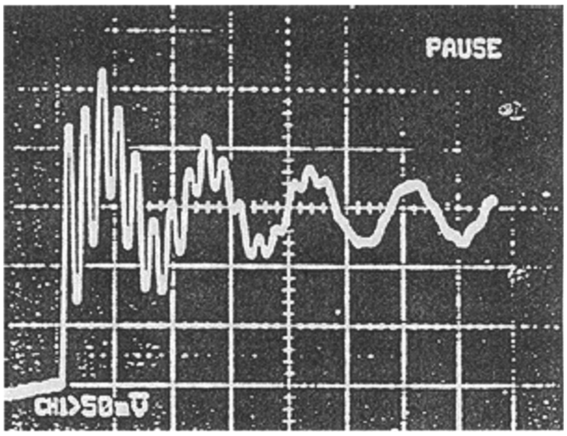

Figure 2 Prospective TRV, reported in [3].

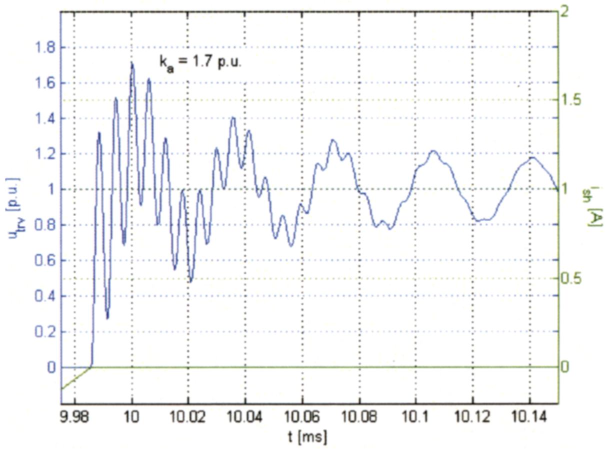

Figure 3 Prospective TRV, obtained in a model shown in Figure 4b.

As an example, the two papers involving such a methodology was reported in 2002 [13, 14], where the influence of FCL and cable length on one frequency

TRV shape based on standardization was investigated during SLF condition, with ideal breaker employed.

4 SET-UP OF SIMULATION

4.1 Introduction

High frequency models of network elements have not so far been implemented in commonly used simulator programmes, like ATP/EMTP or Matlab/Simulink [15-17]. Even the newest transformer model implemented recently [18] in ATP/EMTP is suitable up to a few kHz only, whereas transients observed in MV networks have frequencies in much higher range, as it was already mentioned.

Because of the lack of models which are ready to use in high frequency range, one is suggested to use some general purpose methods, based on identification basis, e.g. reported in [19], with reference to model individual network element. Another approach is to take advantage of Greenwood's remark, stated that apparently complicated circuits often have surprisingly simple transient response [20] (as Ciok stated in [4] – ime responses consisting more than two free frequencies are almost not observed in MV industrial networks). That makes it possible to make of use of some well known equivalent circuits, one or double frequency (e.g. those shown in Figure 4), with the assumption that parameters of such models should correspond to high frequencies rather than to power frequency [1].

Based on well known fact, that successful clearing of the first phase implies that the two last phases are also sure to clear [1], it is often in use to simplify the calculations further, by treating three phase circuit as one phase circuit with the assumption that the star point of network is grounded and three phase to ground fault is occurring, or with employ of the first-pole-to-clear factor (k_b) multiplying system rated voltage.

4.2 System and transformer modelling

In presented paper the latter method outlined above has been used to model system and transformer in MV industrial network described in [3]. As Ciok at al. reported in [3], the share of TRV shapes consisting of at least two free frequencies in network in investigation was 70%. For this reason, a double frequency equivalent circuit AB, as shown in Figure 4b, has been assumed.

To identify parameters of the model, RS circuit shown in Figure 4a has been taken into account initially. The total value of inductance, $L=L_R+L_S$, has been derived from source voltage and short circuit current: $\omega L = k_b \cdot Vr/\sqrt{3} \cdot I_{sh} = 1.5 \cdot 7.2kV/\sqrt{3} \cdot 26kA$, where k_b is first-pole-to-clear factor already mentioned, V_r is rated voltage of the network, I_{sh} is the short circuit current of circuit breaker, ω is network pulsation equals 100π. The values of L_R and L_S have been derived from ratio [1]: $L_S/L_R = a_R/a_S$, where a_R and a_S are amplitudes of the two free components of prospective TRV shown on oscillogram in Figure 2 and equals 1/2. Hence, the values of L_R and L_S have been delivered from: $L_S = L/(1+a_R/a_S)$ and $L_R = L_S \cdot a_R/a_S$. The values of capacitances, C_R, C_S, have been obtained from frequencies of the two free components of prospective TRV in Figure 2, which are given by expressions: $\omega_R^2 = 1/L_RC_R$, $\omega_S^2 = 1/L_SC_S$.

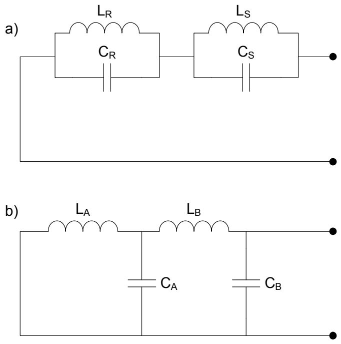

Figure 4 Double frequency circuits: a) AB circuit, b) RS circuit [1].

Knowing parameters of RS circuit (L_R, L_S, C_R, C_S), parameters of AB circuit have been obtained by means of equations:

$$L_A = \frac{\alpha}{\beta}, \qquad C_A = \frac{\beta^2}{(C_R + C_S)\alpha},$$
$$L_B = \frac{(C_R + C_S)^2 L_R L_S}{\beta}, \quad C_B = \frac{C_R C_S}{C_R + C_S}, \tag{1}$$
$$\alpha = (L_R C_R - L_S C_S)^2, \qquad \beta = L_R C_R^{\ 2} + L_S C_S^{\ 2}.$$

Equations (1) have been obtained by use of the statement [1] that two circuits have the same response if their impedances' poles and zeros are equal.

Once inductances and capacitances have been obtained, resistances R_A and R_B have been added in parallel with the capacitances C_A and C_B (see Figure 4b), having the values of 1 kΩ and 10kΩ respectively, that yield to TRV amplitude factor k_a equals 1.7, as it is shown in Figure 3.

Similarity between TRV shape recorded in modelled process (Figure 2) and obtained in the model of the process (Figure 3) can be easily noticed.

4.3 Circuit breaker modelling

There are two main approaches to modelling circuit breakers, involving: black-box models or physical models. While physical models are mainly applied in circuit breaker development research, black-box ones are useful to investigate the impact of circuit breaker on external circuit [21]. Therefore, black-box model has been chosen for the purpose of presented paper.

From very variety of black-box model types, the Habedank model [2] has been chosen for the reason that parameters of the model have been published by Pinto at. al in 2000 [22] for MV network rated at 11.5kV (with no first-pole-to-clear factor applied) and short circuit current equals 30 kA. Since values $\sqrt{;2/3}$ 11.5kV (in [22]) and $1.5 \cdot \sqrt{;2/3}$ 7.2kV (in presented paper) differs only in 6%, and short circuit currents differs in 15%, the values of arc parameters has been assumed to be appropriate for the network in consideration.

Habedank model [2] of circuit breaker is constituted by nonlinear, time varying conductance, described by Cassie and Mayr equations:

$$\begin{aligned} &\frac{1}{g_c}\frac{dg_c}{dt} = \frac{1}{\tau_c}\left(\frac{u^2}{U_c^{\,2}}\frac{g^2}{g_c^{\,2}} - 1\right), \\ &\frac{1}{g_m}\frac{dg_m}{dt} = \frac{1}{\tau_m}\left(\frac{u^2}{P_o}\frac{g^2}{g_m} - 1\right), \\ &\frac{1}{g} = \frac{1}{g_c} + \frac{1}{g_m}; \end{aligned} \tag{2}$$

where: g – the total conductance of the arc, g_c/g_m – the conductance of arc described by Cassie/Mayr equation, τ_c/τ_m – the Cassie/Mayr time constant, U_c – the Cassie constant arc voltage, P_0 – the Mayr constant steady-state power-loss of the arc.

The two serial conductances in the model plays significant role in different phases of current interrupting process. At high currents practically all the voltage drop takes place in the Cassie portion of the model [2]. In current zero crossing phase the voltage drop on Mayr portion increases while the Cassie portion goes to zero, which is consistent with Cassie and Mayr models assumptions.

The values of model parameters are as follows [22]:
U_c = 200 V, P_o = 70 kW, τ_c = 3 μs, τ_m = 1.1 μs.

For the purpose of model implementation, the approach presented by Schavemaker at al. in 2002 [23] has been applied (see section 4.6 and Figure 6).

For ideal circuit breaker model, a common ideal switch implemented in Matlab/Simulink has been used. The switch opens at first current-zero crossing after tripping signal is given, conducing its resistance from value of 10 mΩ to 1 MΩ.

4.4 Fault current limiter modelling

Fault current limiters can be modelled similarly to transformers [6, 20]. For the purpose of presented paper the model taken from [14] was a reference, with stray capacitance neglected and terminal capacitance divided at both terminals: C_{FCL} = 0.5 nF, as it is shown in Figure 5. Reactance of FCL (X_{FCL}) was variable in simulation, varying from value of 0.04 Ω to 1.04 Ω.

4.5 Cable modelling

As it is recommended in [6], a cable is to be consider as long if its travelling time is higher than about 30% of the time constant of the main voltage rise in network in consideration. This statement can be expressed as:

$$2\frac{l_{\min}}{v} = 0.3\frac{1}{2f} \Rightarrow l_{\min} = 0.3\frac{v}{4f}, \tag{3}$$

where: l_{min} [m] is a minimum length above which a cable should be consider as long, v [m/s] is propagation velocity of transients in a cable, f [Hz] is the highest TRV frequency in a process modelled.

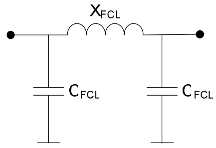

Figure 5 FCL model.

In presented paper the highest frequency was taken from oscillogram shown in Figure 2, as equals 170 kHz (actually, the exact value was obtained from private communication with the authors of paper [3], since it was not included in the paper). The value of velocity v has been assumed as 10^5 km/s, as it was assumed in exemplary cable recalled in [24]. For these values the minimum length of cable obtained from equation (3) is: l_{min} = 44.1 m.

In network in consideration, lengths of cables vary from few tens of meters to few hundreds of meters [3], which is more than the critical length estimated above. Thus, the model of distributed parameters line was involved. For that purpose the model based on Bergeron's travelling wave method, outlined e.g. in [25], has been chosen, since it is implemented in both popular simulators: ATP/EMTP and Matlab/Simulink [15-17].

The Bergeron's model is represented by: cable length, which in the context of presented paper is called distance to fault (d_f), velocity of transients propagation v and surge impedance Z_c. For surge impedance, the value of 35 Ω was assumed as it was used in paper [13] in application to MV network rated at 13.8 kV, which was assumed to be similar enough to the rated voltage 1.5·7.2 kV of network in consideration. Also, this value was classified as a typical one in [20]. Velocity v was taken as 10^5 km/s, as it was already mentioned. Distance to fault was variable in simulation, having values 0.2, 0.6 and 1.0 km. Cable was short-circuited at its end by resistor of value 1 mΩ.

4.6 Model implementation

For the purpose of investigation presented in section 5, over three hundred of simulations (326 exactly) have been performed (each of the simulation matches with the corresponding point depicted in Figures 7, 8, 9). Such amount of simulations implied the need for some extended management of data obtained. This management has been divided into three steps:

1. First, the procedure has been written to obtain and visually verify the zero crossing point of short circuit current and hence – the zero point of TRV.

2. Then the procedure has been written to obtain and visually verify TRV envelope, and its parameters such as RRRV, as it is shown in Figure 1.
3. Finally, all the data was stored in data base for the purpose of plotting selected results later on.

As Greenwood stated in [20], EMTP had become a kind of cult in the electric power industry. This situation seems to last nowadays, hence ATP/EMTP was chosen as a reference to justify the choice of Matlab/Simulink in presented paper.

In paper [26] same advantages and disadvantages of Matlab/Simulink versus ATP/EMTP has been discussed, from which two are worth to mention in the context of procedures listed above. The main advantage of Matlab/Simulink from this point of view is its open code structure – user is able to write almost any mathematical and logical procedure, even based on modern object oriented basis. This implies Matlab/Simulink is much more flexible in use than ATP/EMTP. The main advantage of ATP/EMTP in turn might be its nodal approach to network analysis contrary to the state-space approach involved in Matlab/Simulink. This implies ATP/EMTP is faster for large scale systems (see discussion in [26]).

Since model involved in presented paper has only up to ten state variables, whereas extended data management was needed as it was mentioned, Matlab/Simulink has been chosen as more suitable for the model implementation.

The implemented model is shown in Figure 6. In addition to the models of network elements already described, the two blocks have been used, which are specific to transient simulations performed with use of Matlab/Simulink. The so called *Hit crossing* block ensures that the simulation finds the current and voltage zero crossing point by adjusting step size of simulation, as it was implemented in [23]. *Transfer function* block allows to avoid algebraic loop arising when controlled current source is driven by signal taken from its own terminals. This is being done by a first-order transfer function, H(s) = 1/(1+Ts), introduced into the system, with a time constant so fast (T = 0.01 μs) that it does not significantly affect the result accuracy [17].

The model shown in Figure 6 involves Habedank model of circuit breaker as it was described in section 4.3. For ideal model of circuit breaker, the controlled current source has been replaced by a common ideal switch model implemented in Matlab/Simulink, that opens at first current-zero crossing after tripping signal is given.

To solve equations constituting the model, the *ode23tb* (TR-BDF2) variable-step stiff solver [27] has been used as it is recommended [17, 27] for a system containing nonlinear elements that leads to stiff differential equations.

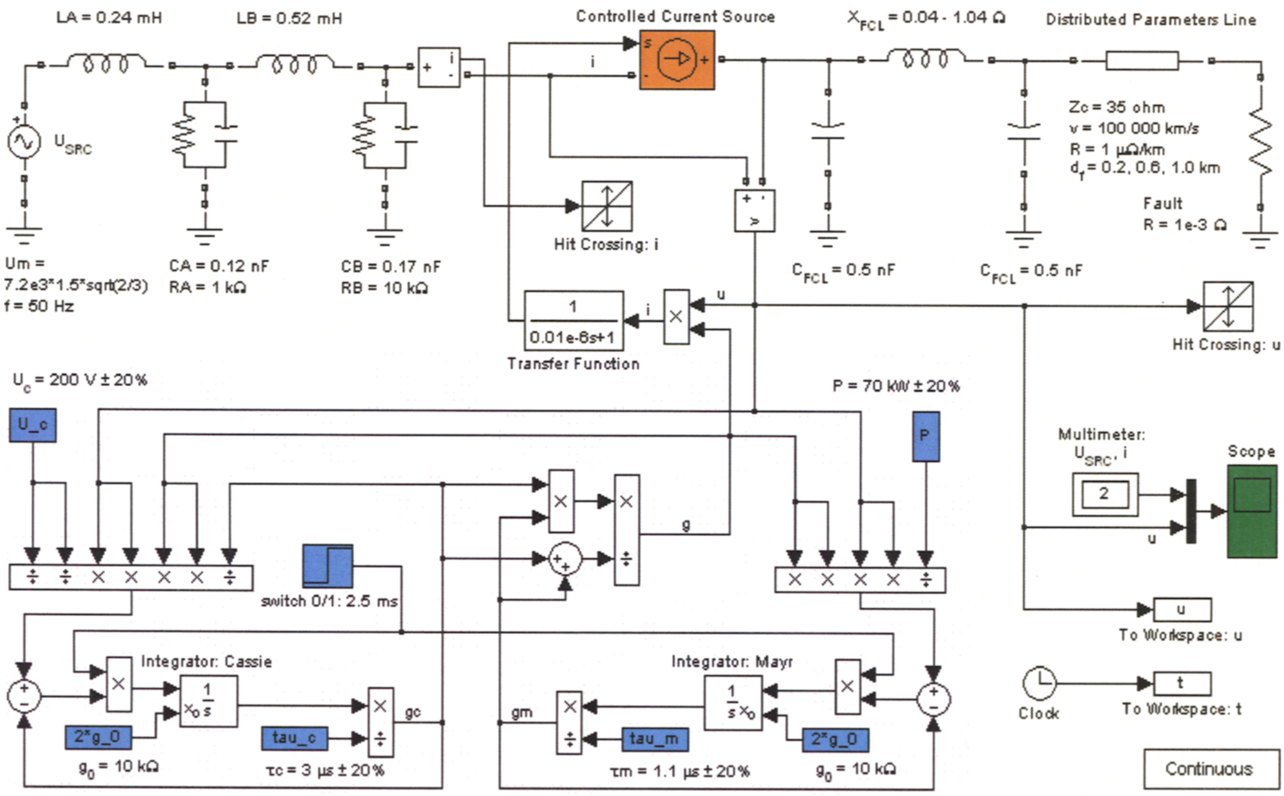

Figure 6 Model implemented in Matlab/Simulink, used for calculation.

5 RESULTS OF INVESTIGATION

Results of investigation are presented in Figures 7, 8, 9.

Figure 7 shows how RRRV depends on reactance of FCL (X_{FCL}) and distance to fault (d_f). Simulations were performed with use of both circuit breaker models: ideal (marked as Alpha) and Habedank, for three distances to fault. As it is shown in Figure 7, for ideal model RRRV initially increases and then decreases, while for Habedank model RRRV increases in whole range of X_{FCL}, reaches a plateau finally. For both models, the shorter distance to fault implies the higher RRRV.

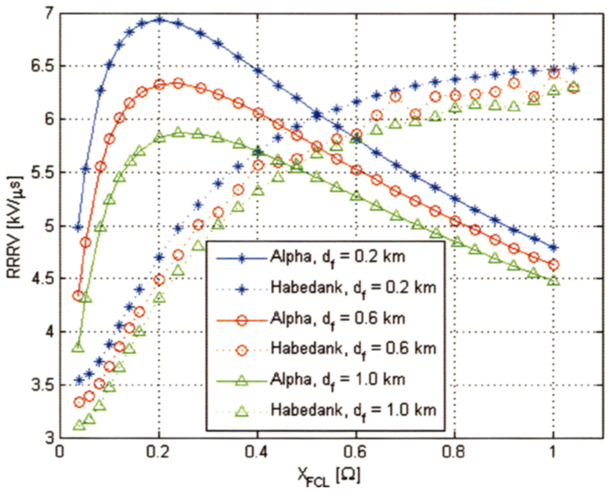

Figure 7 RRRV versus X_{FCL} for different distances to fault d_f and both: ideal (Alpha) and Habedank circuit breaker model.

The variation of RRRV with distance to fault can be explained by the saw tooth component of TRV related with cable [20]. Since its base frequency is given by expression: $f = v/4/d_f$, the shorter distance to fault is, the higher frequency is, hence the higher RRRV emerges.

The variation of RRRV with reactance of FCL (X_{FCL}) for ideal circuit breaker can be explained as follows. For small values of X_{FCL}, the frequency of FCL component of TRV, given by expression $f = 1/2/\pi/\sqrt{;X_{FCL}C_{FCL}/\omega}$, is much higher than those of AB circuit and cable components. At that time, the amplitude of the FCL component is neglected in comparison with AB and cable components, because of the small value of X_{FCL}. Hence RRRV results from AB and cable components only. When the value of X_{FCL} increases, frequency of related component decreases, but it is still much higher than those of the remaining components. As the amplitude of FCL component increases with X_{FCL} growth, it brings more and more share in resultant TRV, and hence RRRV increases, reaches its maximum value for a certain value of X_{FCL} (approximately 0.2 Ω in that case). For this value, the FCL component of TRV become such a dominant in comparison with remaining components, that it entirely determines the character of TRV. Now the rule of decreasing RRRV with decreasing frequency of FCL component is working, since practically only this component remains. In consequence, RRRV decreases with X_{FCL} growth.

Figure 8 shows how RRRV depends on individual parameters of Habedank circuit breaker model, for distance to fault (d_f) equals 0.2 km and reactance of FCL (X_{FCL}) equals 0.32 Ω. The values of parameters were deviated in the range of 20%. Because of great difference in significance between individual parameters, the values were plotted in two subplots.

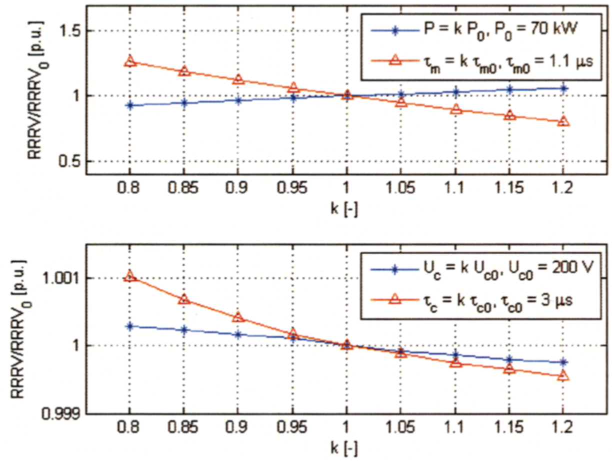

Figure 8 Contribution to influence of individual parameters of Habedank model on RRRV; P_0 = 70 kW, τ_{m0} = 1.1 µs, U_{c0} = 200 V, τ_{c0} = 3 µs, X_{FCL} = 0.32 Ω, d_f = 0.2 km, $RRRV_0$ = 5. 39 kV/µs.

Figure 9 shows how RRRV depends on reactance of FCL (X_{FCL}) when Habedank circuit breaker model was employed for different values of Mayr-part parameters of the model.

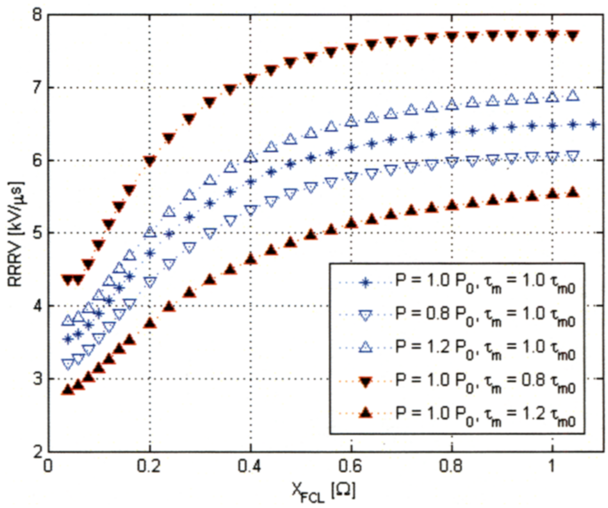

Figure 9 RRRV versus X_{FCL} for Mayr-part model parameters; d_f = 0.2 km, P_0 = 70 kW, t_{m0} = 1.1 µs.

6 CONCLUSIONS

The objective of presented paper was to investigate how circuit breaker model affects transient recovery voltage (TRV). As a parameter characterizing severity of TRV, rate of rise of recovery voltage (RRRV) has been chosen.

Secondary aim of the paper was to contribute continuation of research in Polish MV large industrial networks began by Roguski and Ciok at Warsaw University of Technology. For that purpose, the case of MV network described in [3] has been chosen to perform identification of parameters of network model.

While MV large industrial network has been taken under consideration, the problem of breaking short circuit current in short line fault (SLF) condition at presence of inductive fault current limiter (FCL) has been chosen to investigate.

Attention was pointed at the influence of distance to fault (d_f) and reactance of fault current limiter (X_{FCL}) on RRRV. The simulation was carried with use of two different circuit breaker models: ideal (marked as Alpha) and Habedank, implemented in Matlab/Simulink programme.

Results of simulations are shown in Figures 7, 8, 9. The following conclusions can be stated:

1. The shorter distance to fault is, the higher value of RRRV is, regardless of what circuit breaker model has been involved (Figure 7).
2. RRRV versus reactance of FCL increases and then decreases for ideal circuit breaker, while increases and then reaches a plateau for Habedank circuit breaker model (Figure 7). Thus it has been shown that application of circuit breaker model might significantly change character of correlation between RRRV and X_{FCL} when simulated by means of commonly used modelling techniques.
3. In Habedank model of circuit breaker four parameters exist, from which only those related with Mayr-part of the model have significant influence on RRRV, whereas those related with Cassie-part have negligible influence on RRRV in the case of interest (Figure 8). The current zero crossing phase is crucial in Habedank model in that case.
4. The most significant contribution to RRRV in Habedank circuit breaker model is brought by Mayr time constant τ_m (Figures 8, 9).

7 ACKNOWLEDGMENT

The authors acknowledge to *Polish State Committee for Scientific Research* the contribution of this work financed as granted research project No. N510 004 32/0358.

8 REFERENCES

1. Hammarlund, P., *Transient recovery voltage subsequent to short circuit interruption with special reference to Swedish power systems*. 1946, Stockholm: Ingeniörsvetenskapsakademiens Handlingar Nr. 189.
2. Habedank, U., *Application of a New Arc Model for the Evaluation of Short-circuit Breaking Tests*. IEEE Transactions on Power Delivery, 1993. **8**(4): p. 1921-1925.
3. Ciok, Z., et al. *Transient Recovery Voltages in Selected Medium Voltage Networks*. in CIGRE. 1996.
4. Ciok, Z., *Transient Recovery Voltages in Large Industrial Networks*. Acta Polytechnica (CVUT - Technical University of Prague) (in English), 1982. **20**: p. 75-82.
5. Ciok, Z. *Overvoltages in industrial networks*. in Athens Power Tech Conference "Planning Operation and Control of Today's Electric Power Systems", vol. 2, pp. 946-949. September 5-8, 1993.
6. CIGRE-WG33.02, *Guidelines for representation of network elements when calculating transients*. CIGRE Brochure 39, 1990.
7. Standard, IEC 62271-100. *High-voltage switchgear and controlgear – Part 100: Highvoltage alternating-current circuit breakers*. 2001, IEC. p. 340.
8. Slepian, J., *Extinction of an A-C Arc*. Transactions AIEE, 1928. **47**(4): p. 1398-1407.
9. Roguski, A., *Method of Determination of Restriking Voltages by Measuring the Local Restriking Voltages (in Polish)*. Archiwum Elektrotechniki, 1960. **9**(1): p. 157-202.
10. Roguski, A., *Investigations of Restriking Voltages in Polish Networks (in Polish)*. Prace Instytutu Elektrotechniki. Transactions of the Electrotechnical Institute., 1962. **30**: p. 1-46.
11. CIGRE-WG13.01, *Transient recovery voltage in medium voltage networks*. CIGRE Working Group 13-01 Technical Brochure 134, December 1989. **88**: p. 49-88.
12. CIGRE-A3.11, *Guide for Application of IEC 62271-100 and IEC 62271-1 304. Part 1 - General Subjects*. 2006. p. 107.
13. Dufournet, D. and G.F. Montillet, *Transient Recovery Voltages Requirements for System Source Fault Interrupting by Small Generator Circuit Breakers*. IEEE Transactions on Power Delivery, 2002. **17**(2): p. 474-478.
14. Calixte, E., et al., *Interrupting Condition Imposed on a Circuit Breaker Connected with Fault Limiter*. International Journal of Power & Energy Systems, 2002. **25**(2): p. 75-81.
15. Prikler, L. and H.K. Hoidalen, *ATPDraw User's Manual*. 2002: SINTEF Report, No. F5680.

16. Dommel, H.W., *Electromagnetic Transients Program (EMTP) Theory Book*. 1987, Portland, Oregon: Boneville Power Administration.
17. Mathworks, *SimPowerSystems for use with SIMULINK, Modeling, Simulation, Implementation - User's Guide, Version 4*. 2006: The Mathworks Inc., 24 Prime Park Way, Natick. MA 01760-1500. 1154.
18. Mork, B.A., et al., *Hybrid Transformer Model for Transient Simulation - Part I: Development and Parameters*. IEEE Transactions on Power Delivery, 2007. **22**(1): p. 248-255.
19. Morched, A., L. Marti, and J. Ottevangers, *A High Frequency Model Transformer for the EMTP*. IEEE Transactions on Power Delivery, 1993. **8**(3): p. 1615-1626.
20. Greenwood, A., *Electrical Transients in Power Systems*. 1991: John Wiley & Sons, Inc.
21. CIGRE-WG13.01, *Practical Application of Arc Physics in Circuit Breakers. Survey of Calculation Methods and Application Guide*. Electra, 1988. **118**: p. 66-79.
22. Pinto, L.C. and L.C.J. Zanetta, *Medium voltage SF6 circuit-breaker arc model application*. Electric Power Systems Research, 2000. **53**: p. 67-71.
23. Schavemaker, P.H. and L. Sluis. *The Arc Model Blockset*. in The Second IASTED International Conference: Power and Energy Systems (EuroPES). 2002. Crete, Greece.
24. Sluis, L., *Transients in Power Systems*. 2001: John Wiley & Sons, Inc.
25. Henschel, S., A.I. Ibrahim, and H.W. Dommel, *Transmission Line Model for Variable Step Size Simulation Algorithms*. Electrical Power and Energy Systems, 1999. **21**: p. 191-198.
26. Mahseredjian, J. and F. Alvarado, *Creating an Electromagnetic Transients Program in MATLAB: MatEMTP*. IEEE Transactions on Power Delivery, 1997. **12**(1): p. 380-388.
27. Hosea, M.E. and L.F. Shampine, *Analysis and implementation of TR-BDF2*. Applied Numerical Mathematics, 1996. **20**(1): p. 21-37.

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