NONLINEAR SECONDARY ARC MODEL USE
FOR EVALUATION OF SINGLE POLE AUTO-RECLOSING EFFECTIVENESS

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Abstract

Purpose – The paper discusses two evaluation methods of single pole auto-reclosing process effectiveness in HV transmission lines. Secondary arc current and recovery voltage results obtained by load flow calculation are compared to the results obtained by the time domain simulations. Moreover, a nonlinear secondary arc implementation is presented.

Design/methodology/approach – A computer simulation studies were performed using DIgSILENT PowerFactory® software to analyse phenomena during single phase to earth short circuit and during single pole circuit breaker opening. Possibilities of electric arc extinction for different earthing solutions of shunt reactors were examined.

Findings – The authors indicate, that precise representation of secondary electric arc in power system studies could lead to different conclusion than analysis carried out on simplified arc models. Recommendations for line construction (i.e. earthing reactor installation) and line operation (i.e. prolongation of dead time during auto-reclosing) based on time domain simulations are less restrictive than resulting from the traditional steady-state calculation approach.

Originality/value – An implementation of mathematical model of nonlinear secondary arc for DIgSILENT PowerFactory® software is presented. The model could be used during the process of design of HV transmission line, to assess its proper operation, to calculate dead time during single pole reclosing or to evaluate the necessity of installing additional earthing reactors.

Keywords –Recovery voltage, Secondary arc current, Single-phase auto-reclosing, Single phase short-circuit.
Paper type – Technical paper

I. INTRODUCTION

The single phase to earth short-circuits are the most common faults of high voltage overhead transmission lines. To enhance power system stability and reliability a single pole tripping and single phase auto-reclosing are often used. The course of events during this process is as follows. When a short-circuit occurs, line current increases which causes protective relays to pickup and to identify the faulted phase, then finally to trip the corresponding circuit-breaker pole. After the circuit-breaker opening the fault current is significantly reduced, but still exists because of capacitance and inductance couplings between phase switched off and the energized ones. Fig. 1 shows couplings that energizes arc in case of double circuit line. If the poles of both circuit-breakers (at both ends of the line) are opened in phase A of circuit 1, then the arc voltage V_{ARC} depends on mutual couplings between wires in circuit 1 (M_{1AB}, M_{1AC}) and capacitive couplings (C_{1AB}, C_{1AC}) in circuit 1. The second circuit influence the arc voltage and arc current too, by inter-circuit inductance couplings (M_{1A2A}, M_{1A2B}, M_{1A2C}) and capacitive couplings (C_{1A2A}, C_{1A2B} C_{1A2C}). The arc voltage V_{ARC} and nonlinear arc resistance R_{ARC} determines arc current value I_{ARC}. This current is called secondary arc current. The secondary arc current value depends on the mentioned couplings, thus depends on line parameters (line length, number of circuits, pylon geometry, transpositions) and operating conditions. Its typical values, for different power lines, according to numerous reports, are in the range from 10 to 70 A. For example in work (Esztergalyos *et al.*, 1992) authors indicate, that for 500 kV power line, without compensation, a typical secondary arc current is 12 A per 100 km.
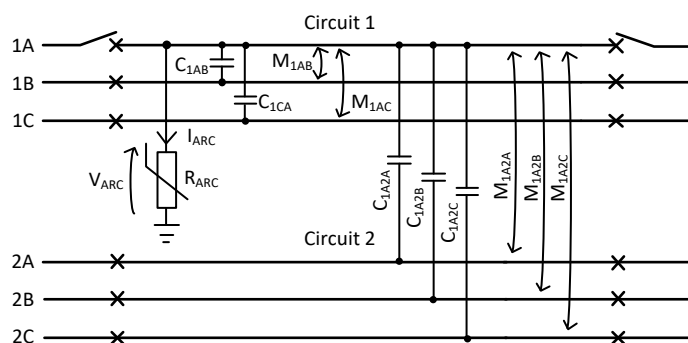

Fig. 1 Capacitive couplings and inductance couplings energising secondary arc in case of double circuit transmission line.

Recovery voltage is another quantity associated with single pole tripping and successful auto-reclosing. It is defined as a voltage across the fault path after the secondary arc extinction, but before the circuit breakers reclosing (Kimbark, 1976). In

other words the recovery voltage is equal to arc voltage V_{ARC} if the arc current is equal to zero ($R_{ARC}=\infty$). Typical value of recovery voltage varies from 10% to 25% of nominal power line voltage (Esztergalyos *et al.*, 1992).

Precise determination of the secondary arc current and recovery voltage values is critical for successful auto-reclosing. These quantities affect time of the secondary arc extinction, and ability to the arc re-ignition. Analysis of the secondary arc current and the recovery voltage which are carried out on the transmission line design stage allows to determine whether the conditions are sufficient to make the arc extinguished or some actions to reduce the arc current (i.e. auto-reclosing dead time prolongation, earthing reactor installation) have to be done.

The paper draws attention to some assumptions which are made during the secondary arc current and the recovery voltage calculation. The paper shows that calculations based on the steady state short-circuit calculation, or time domain simulations that assume constant arc resistance can lead to results quite different, than the one obtained for time domain simulation with use of nonlinear electric arc model.

II. SECONDARY ARC MODEL

Various models of electric arc are proposed in literature. They vary in complexity of the arc phenomena mathematical description, from comprehensive 3D models, i.e. (Daszkiewicz and Tarczyński, 2010) to simplified ones. The following propositions of secondary arc phenomena modeling are noteworthy. The first are 'black-box' models proposed by Cassie and Mayr. An arc model presented in EMTP software was established by Johns A. T. (Johns and Ritchie, 1984) and implemented by Goldberg S. (Goldberg *et al.*, 1989). Interesting voltage studies results of long arc in free air are presented by (Terzija *et al.*, 2004). Secondary arc was simulated with energy balance and Ohm's law by Evdokunin G. and his work was implemented by (Dudurych *et al.*, 2004). The secondary arc model was also developed in works of M. Kizilcay i.e. (Kizilcay *et. al.*, (2003). The model differs significantly from Johns' model by a method of determining the time of arc extinction.

Authors used mathematical model of the secondary arc developed by Johns because of its wide implementation in commercial software as well as many research papers i.e. (Ngamsanroaj *et al.*, 2008) or (Xiang *et al.*, 2009).

The model is based on following assumptions:

- The arc conduction characteristics is described as voltage across arc path dependency on arc current. The I-V characteristics is hysteretic and non-linear (Fig. 2).
- When arc is not conducting an air withstand voltage across arc path is calculated as function of: time from initiation of secondary arc, time from last arc extinction and arc current (Eq. 2).
- Restrike of arc occurs when the recovery voltage exceeds air withstand voltage.
- The length of arc is varied (it increases with time), thus it influences arc resistance and air withstand voltage (Eq. 3).

One of the most important aspects of arc modelling is its current-voltage characteristics. According to Johns the arc voltage could be approximated as shown in Fig. 2. The proposed shape results from series of experiments. For typical range of secondary arc currents, the arc voltage can be estimated by:

$$V_p \approx 7500 \cdot l \cdot I_p^{-0.4} \qquad (1)$$

where I_p is the peak value of secondary arc current assuming zero arc resistance (calculated from an initial steady-state study) and l is arc length.
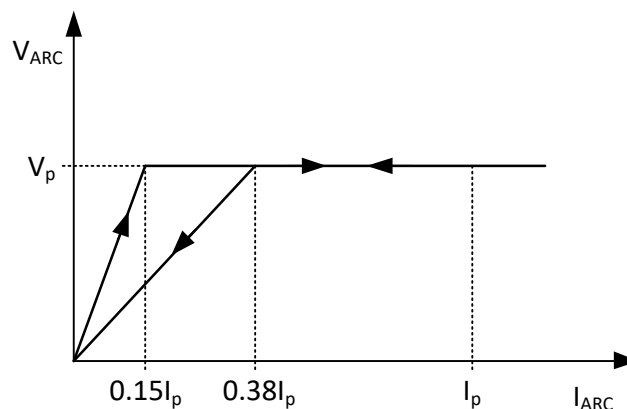

Fig. 2 I-V arc characteristics.

When arc is not conducting, the air withstanding voltage is calculated as follows:

$$V_{air}(t_r) = \left(5 + \frac{1620 \cdot T_e}{1.52 \cdot I_p}\right)(t_r - T_e)h(t_r)l(t_r) \qquad (2)$$

The length of the arc is given by:

$$l(t_r) = \begin{cases} l_0 & t_r < 0.1s \\ l_0 \cdot 10 \cdot t_r & t_r \geq 0.1s \end{cases} \qquad (3)$$

Where:

l_0 – initial arc length
T_e - time of any temporary or final extinction period measured from last arc ignition
t_r - time from initiation of secondary arc

$$h(t_r) = \begin{cases} 1 & t_r \geq T_e \\ 0 & t_r < T_e \end{cases} \qquad (4)$$

The arc model was implemented in DIgSILENT PowerFactory® software. The arc is represented by time-varying resistor and circuit-breaker connected in series. The arc resistance is calculated in every simulation step according to the above assumptions, from I-V characteristic. The circuit-breaker state (open/close) is determined by judgment of the recovery voltage and the air withstand voltage – if arc extinguishes the circuit-breaker opens, if arc restrikes the circuit-breaker closes again. The model is defined by two parameters: initial arc length (equal to typical length of insulator) and peak value of secondary arc current assuming zero arc resistance calculated from initial steady-state study.

III. TEST RESULTS

A. The study case

The paper considers the double circuit 400 kV transmission line of length 164 km, which is designed to connect the Western and Central European electricity network (ENTSO-E) with the Baltic States networks via back-to back converter station (Robak and Wasilewski, 2012). Each circuit is equipped with two shunt reactors SR_A and SR_B located on both line ends (substation A and substation B). The shunt reactors of rating 50 Mvar at substation A, and 72 Mvar at substation B are designed to provide line reactive power (charging power) compensation. Transmission line connection diagram is shown in Fig. 3.

All the calculations were done with use of DIgSILENT PowerFactory® software. The transmission line is modelled as three serially connected, π-sections. Each section, of length equal to 1/3 of the total line length, is represented by two three-phase, coupled circuits with overhead earth wires. The line is transposed to limit its asymmetry i.e. phase wire sequence changes for each section. The line model includes magnetic couplings as well as capacitive couplings between circuits. The line parameters are calculated directly from the transmission tower geometry and the conductors data sheets. The power losses due the corona effect are not included in DIgSILENT PowerFactory® built-in overhead line model, so they are represented in the simulations in a simplified way, by a constant resistance connected to the both ends of each section of the line.

The transmission system operator requires a single phase auto-reclosing on both line circuit. To ensure compliance with this requirement, a series of tests were made. This paper presents comparison of study case results obtained for simplified and detailed nonlinear arc modelling.
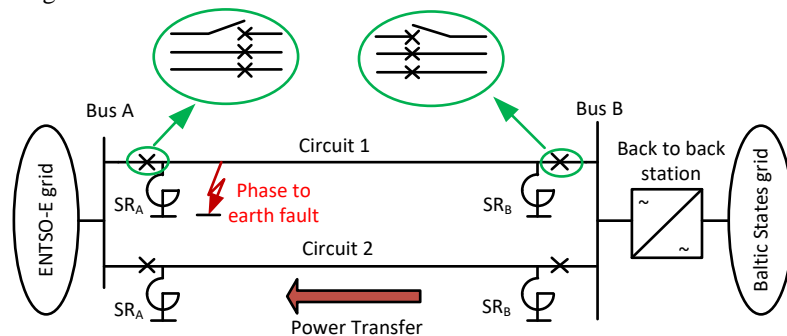

Fig. 3. Transmission line connection diagram in case of single phase to earth fault and circuit-breakers single pole opening.

B. Steady state recovery voltage and secondary arc current calculation

The star point of shunt reactors (SR_A, SR_B in Fig. 3) can be isolated, solidly earthed or connected to the additional earthing reactor (X_G) as shown in Fig. 4. The solution of shunt earthing influences mainly the secondary arc current and it has a little impact on initial short-circuit current in typical transmission network (which are usually solidly earthed).
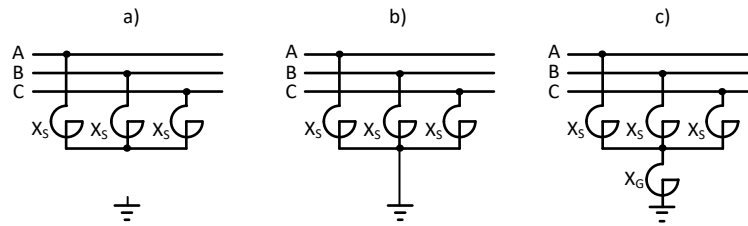
Fig. 4. Different solutions for star point of shunt reactor earthing. a) isolated, b) solidly earthed, c) earthed by additional reactance.

The steady state secondary current and the recovery voltage or the recovery voltage rate calculations are often used do decide which solution of star point earthing provides successful single phase auto-reclosing in desirable dead time. Figure 5 shows an dependence example for the considered transmission line of the secondary arc current and the recovery voltage in case of single phase to the earth fault for different reactance of earthing reactor (X_{GB}) in substation B. Star point of shunt reactor in substation A is assumed as solidly earthed.
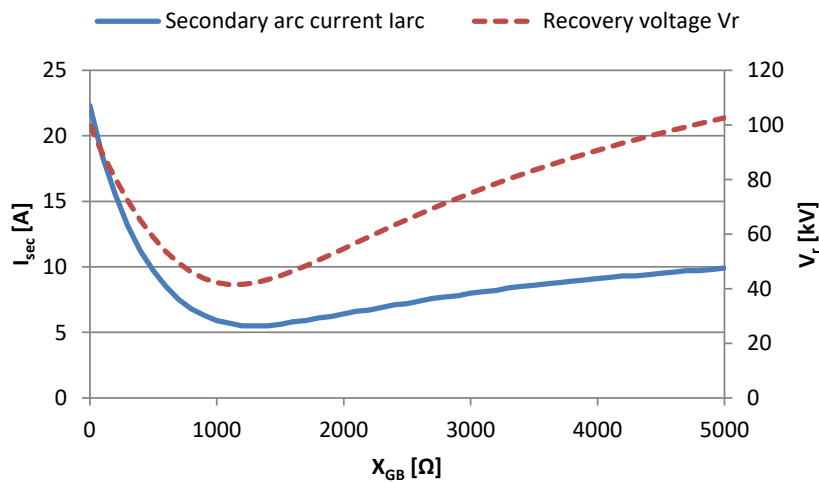

Fig. 5. Recovery voltage and secondary arc current as function of earthing reactance in substation B.

It can be seen, that minimum value of the recovery voltage is obtained for the certain earthing reactance, in this particular case equal to $X_{GB} = 1100\ \Omega$. According to works (Thomann *et al.*, 1993) or (Nayak *et al.*, 2006) successful arc extinction would apparently be expected after 0.5 s if the secondary arc current is less than 40 A and the rate of rise of recovery voltage does not exceed 10 kV/ms. Assuming sinusoidal (50 Hz) recovery voltage, the permissible voltage rate corresponds to rms value equal to 22.6 kV. It means that successful arc extinction in this case is not possible and other actions need to be taken to ensure successful auto-reclosing.

C. Recovery voltage and secondary arc current calculation with time domain simulation including nonlinear arc model

Below, there are presented examples of time domain simulation for different earthing reactances in substation B. Three cases are analysed: solidly earthed star point of shunts ($X_{GB} = 0$), star point of shunts earthed by optimal reactance – providing minimal recovery voltage ($X_{GB} = 1100\Omega$) and isolated star point of shunts ($X_{GB} = \infty$). Figures 6 to 11 present results of single phase to earth fault transient simulations using the proposed model of arc. A fault occurred at time t = 0.1 s, and after 100 ms it was cleared by single pole circuit-breaker opening. The initial arc length was assumed equal to 4 m.

Figures 6 and 7 show results of time domain simulation obtained for both shunt reactors solidly earthed, i.e. for conditions found from steady state calculation (Fig. 5 $X_{GB} = 0$) as unacceptable because of too high recovery voltage. Time domain simulations reveals, that arc can be extinguished after less than 0.25 s after circuit-breaker opening (t = 0.42 s in Fig. 6). It can be seen, that for time lower than 0.35 s (Fig. 7), every time the current value crosses zero the arc re-ignite almost immediately. However all the time the arc elongates, and the air withstand voltage increases. The longer time from circuit-breaker opening, the harder for the arc to re-ignite. Finally at time t = 0.42 s the arc extincts and the air withstand voltage increases rapidly, what is shown in Fig 7. The recovery voltage does not exceed the air withstand voltage and the arc does not restrike.

The obtained results lead to conclusion, that for this particular case additional earthing reactors are not needed, and typical dead time of 0.50 s allows for successful auto-reclosing.
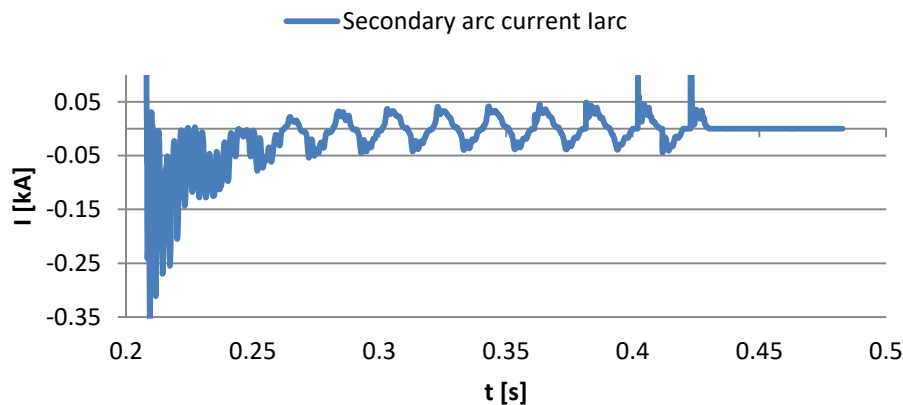
Fig. 6. Secondary arc current after single pole circuit-breaker opening, star point of the shunt reactor in substation B solidly earthed.
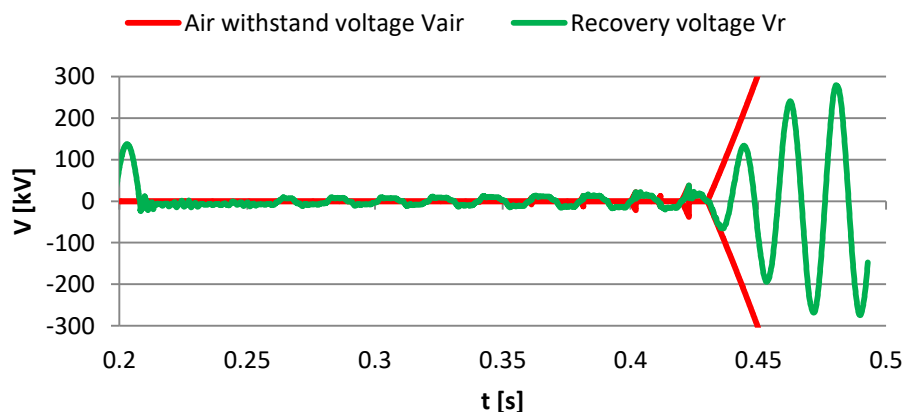

Fig. 7. Recovery voltage and air withstand voltage after single pole circuit-breaker opening, star point of the shunt reactor in substation B solidly earthed.

Figures 8 and 9 show results obtained for next analysed case i.e. one shunt reactor solidly earthed (in substation A) another (in substation B) earthed by additional reactance. These conditions are found from steady state calculation as most effective for arc extinction (Fig. 5 $X_{GB} = 1100\Omega$) because of the lowest recovery voltage and secondary arc current. Time domain simulation results confirm, that the arc can be extinguished much faster than in the previous case. Arc is finally interrupted 0.07 s after circuit-breaker opening ($t = 0.27$ s in Fig. 8). It can be seen high frequency oscillation for time lower than 0.24 s (Fig. 7), because of resonance phenomena between line capacitance and reactor reactance. When high frequency oscillations cease, the fundamental frequency (50 Hz) of current can be seen. Its magnitude is limited by additional earthing reactance, therefore arc extinction is very fast. It is worth noting, that simulation results confirms steady state calculations (Fig 5.) that additional earthing reactor decreases not only the current, but limits recovery voltage too. In the analysed case highest magnitude of transient recovery voltage is 100 kV, while for solidly earthed shunt reactor recovery voltage magnitude is 3 times higher (Fig. 7).
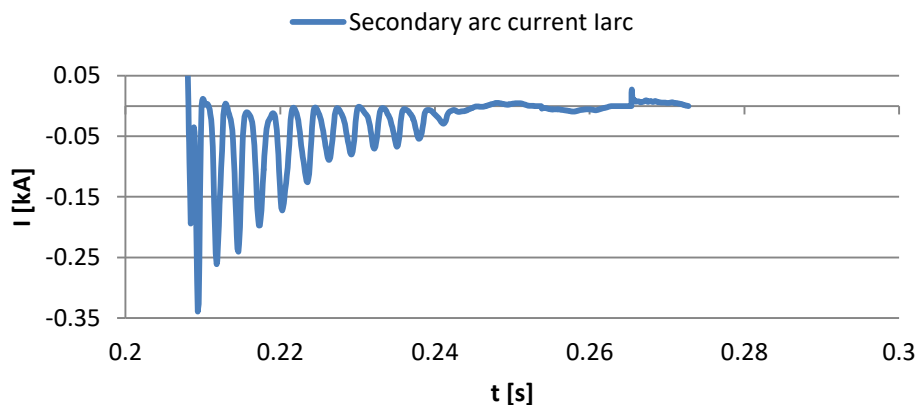

Fig. 8. Secondary arc current after single pole circuit-breaker opening, star point of the shunt reactor in substation B earthed by reactance $X_{GB} = 1100 \ \Omega$.
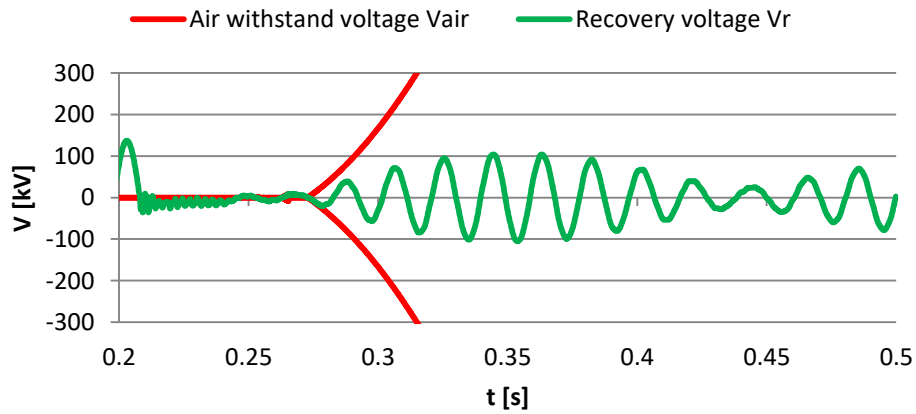
Fig. 9. Recovery voltage and air withstand voltage after single pole circuit-breaker opening, star point of the shunt reactor in substation B earthed by reactance $X_{GB} = 1100 \, \Omega$.

The isolated star point of the shunt reactor in substation B is the last discussed case. The results are presented in Figs. 10 and 11. In this case the secondary arc current is reduced in comparison to the solidly earthed shunt reactor, but recovery voltage is higher, which makes more difficult conditions for arc extinction. The arc is successfully extinguished 0.14 s after circuit-breaker opening (t = 0.34 s in Fig. 10).
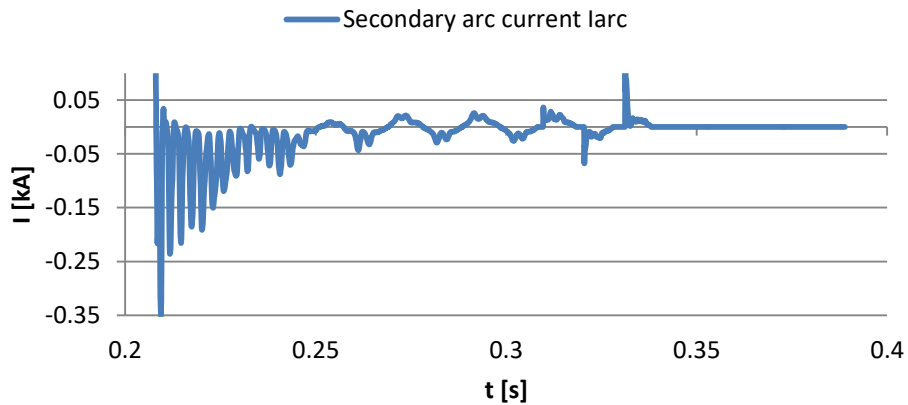

Fig. 10. Secondary arc current after single pole circuit-breaker opening, star point of the shunt reactor in substation B isolated.
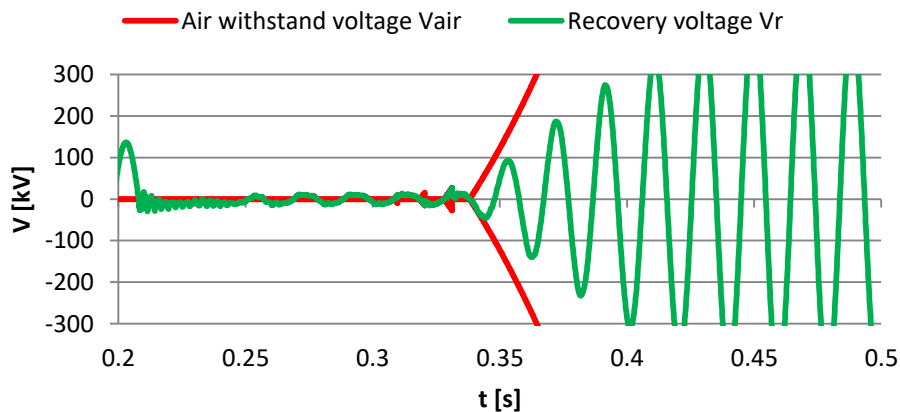

Fig. 11. Recovery voltage and withstand voltage after single pole circuit-breaker opening, star point of the shunt reactor in substation B isolated.

IV. CONCLUSION

In the paper two methods for the secondary arc current and recovery voltage calculation are compared. The time domain simulations with non-linear model of secondary arc reveal, that conclusions related to the arc extinguishing and successful single phase auto-reclosing could be completely different depending on calculation method used. A traditional approach based

on steady state recovery voltage and secondary arc current calculation leads to much more pessimistic assessment of the situation.

For the considered transmission line the steady state calculations reveal high value of recovery voltage, especially when earthing reactor is not used. Using this result for the power system substation design could lead to conclusion that a single pole auto-reclosing is not possible and only three phase auto-reclosing must be applied. Analysis of the same cases done by time domain simulations shows that the secondary arc is quickly (in time less than 0.25 s for the worst case) and efficiently extinguished. The estimated duration of the arc can be base for setting a dead-time in automatic reclosing devices. For the analyzed case, after taking into account a safety margin, the dead time should be set as not less than 0,5 s.

The considered examples show the earthing reactor is effective element of the power system which allows to reduce the secondary arc current and the recovery voltage and allows to keep reasonably short auto reclosing time (dead time). The considered system operation with star point of the shunt solidly earthed or isolated is also possible.

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