Method for Three-Phase Reclosing after Line-to-Ground Fault on Compensated Lines

P. Mestas, M. C. Tavares

***Abstract*-- The regular transmission line three-phase reclosing is performed after a pre-defined dead time. However, if the reclosing occurs before arc extinction or onto an existing fault, the system stability and reliability can be compromised. Besides, the service life of power system equipment can be reduced. To solve this problem, the present paper proposes a new control method that allows performing the reclosing after fault clearance and reduces overvoltages due to three-phase reclosing of shunt compensated transmission lines. The performance of the proposed scheme is verified by comparing with the conventional reclosing method. The transient analysis and power system modeling were carried out through simulations using PSCAD/EMTDC software.**

***Keywords*: Controlled switching, Shunt compensation, Three-phase reclosing, Transmission lines.**

I. Introduction

TRANSIENT and line-to-ground (LG) fault is the most frequent fault in EHV/UHV (Extra and Ultra High Voltage) systems [1]. This kind of fault can be effectively cleared by the implementation of single- or three-phase auto-reclosing. However, a large number of transmission lines are typically equipped with three-phase auto-reclosing devices that reenergize a line after a fixed dead-time. This technique could put the system stability and reliability at risk if reclosing occurs before arc extinction. Besides, if the reclosing is performed onto an existing fault, the service life of power system equipment is reduced and the system stability is negatively affected. Consequently, it is essential to detect the fault extinction before reclosing.

Long EHV/UHV transmission lines are often equipped with shunt reactors to compensate line capacitive reactive power and suppress power frequency overvoltage. Usually, a fourth small reactor is installed between the neutral point of phase reactors and the ground to compensate inter-phase coupling capacitance. This neutral reactor is important to reduce secondary arc current amplitude, which in turn will decrease the secondary arc extinction time during reclosing of transmission lines [2], [3]. Most of researches of this technique focuses on the single-phase adaptive reclosure, [4], [5], though, there is not much available information concerning the analysis of neutral reactors during three-phase reclosing.

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P. Mestas and M.C. Tavares are with the School of Electrical and Computer Engineering, University of Campinas (UNICAMP), 13083-250, Campinas, SP, Brazil.
(e-mail: pmestasv@dsce.fee.unicamp.br; ctavares@unicamp.br).

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Regarding the mitigation of overvoltages during the reclosing switching, it is worth mentioning the use of traditional circuit-breakers (CB) with pre-insertion resistors (PIR). This method is able to attenuate the overvoltages to the admissible levels; however, such devices may present a considerable number of operational failures, leading to an increase in the overall maintenance and replacement costs of components [6].

To eliminate the need of pre-insertion resistors arises the possibility of using controlled switching techniques, also named point-on-wave (POW) technique. This is referred to the devices capable of identifying favorable regions or instants for switching circuit-breaker contacts, providing transient reduction and improved power quality [7].

Although there are references related to the performance of approaches based on controlled switching for three-phase reclosing, it should be noted that such researches consider conditions without internal fault, i.e., when there is no unbalanced voltages [8], [9]. Therefore, it is worth mentioning that during short-circuit occurrence, the behavior of the oscillatory frequencies at the transmission line requires appropriate studies, because they will by large influence reclosing overvoltages.

In this context, a method for controlled reclosing after three-phase tripping due LG fault for shunt compensated transmission lines is proposed. For the proper operation of the method, previously aspects related to the neutral reactor optimization and its effect during three-phase reclosing are examined.

Next, a performance evaluation of proposed method is made through a comparison among three transient overvoltage reduction techniques. As a result, it is concluded that the proposed method allows three-phase reclosing for shunt compensated lines, assuring the fault has extinguished, while restoration of power system is performed with minimum overvoltages.

II. Test Power System

An actual 500 kV power system was used to the study, whose single-line diagram is shown in Fig 1.

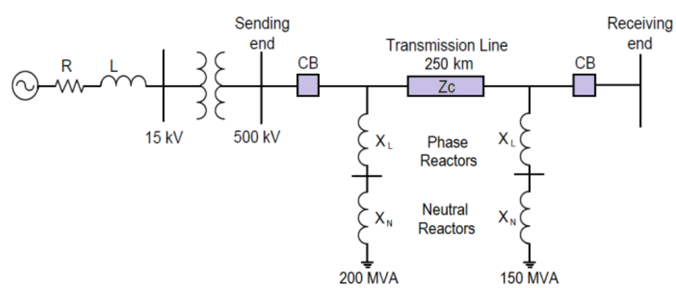


Fig. 1 Single-line diagram of studied system

The generation system consists of three units of 15 kV and 472.5 MVA. For each unit, the equivalent resistance is Rg = 0.00377 Ω and sub-transient reactance is X''g = 0.12952 Ω. Also, there are three power transformers of 15/500 kV Delta-Wye connection with primary and secondary leakage reactance of 31.338 Ω and 0.0846 Ω, respectively. The coil quality factor is taken as 100.

The 250 km transmission line has two shunt reactors of 200 and 150 MVA at each end of the line. The scheme of compensation is composed by banks of three single-phase reactors, with quality factor 400, grounded through a neutral reactor with quality factor of 40. The fault was modeled by a 20-Ω resistor that was removed when the fault current reached 5 A.

The proposed technique is analyzed through PSCAD/EMTDC digital simulations. The transmission line was represented using the frequency dependent phase-domain model whose parameters are presented in Table 1.

TABLE I
BASIC LINE UNITARY PARAMETERS – 60 HZ

SEQUENCE	LONGITUDINAL (Ω/km)	TRANSVERSAL (μS/km)
Positive/negative	0.0161 + j 0.2734	j 6.0458
Zero	0.4352 + j 1.4423	j 3.5237

III. Influence of Neutral Reactor on Three-Phase Reclosing

For single-phase reclosing, only the faulted phase is tripped and the fault arc path is maintained by the energized phases through the capacitive and inductive mutual couplings. Consequently, after the primary arc, a secondary arc continues to exist even if the faulty phase is opened. In the case of three-phase reclosing there is no power flowing through the healthy phases, therefore the secondary arc current will have lower magnitude [10], [11].

For long EHV/UHV transmission lines, shunt reactors are applied to compensate the excess of reactive power and often an additional single-phase reactor is connected between neutral point and the ground to neutralize the interphase capacitive current. This neutral reactor is dimensioned such that the inter-phase capacitance resonates with the equivalent inter-phase inductive branch. In ideal conditions, this parallel inductive and capacitive circuit provides infinite inter-phase impedance, thus avoiding healthy phases feeding the fault [3], [12].

An approach used to select a proper value for the neutral reactor depends on the ratio of positive and zero sequence capacitances of the shunt reactor bank. The ratio r_h is employed to choose the optimum neutral reactor value:

$$r_h = \frac{Z_h}{Z_d} = \frac{Z_f + 3Z_n}{Z_f} \quad (1)$$

where, Z_f and Z_n are, respectively, the phase reactors and neutral reactor impedances and Z_h and Z_d are, respectively, the zero and positive/negative sequences impedances of reactors.

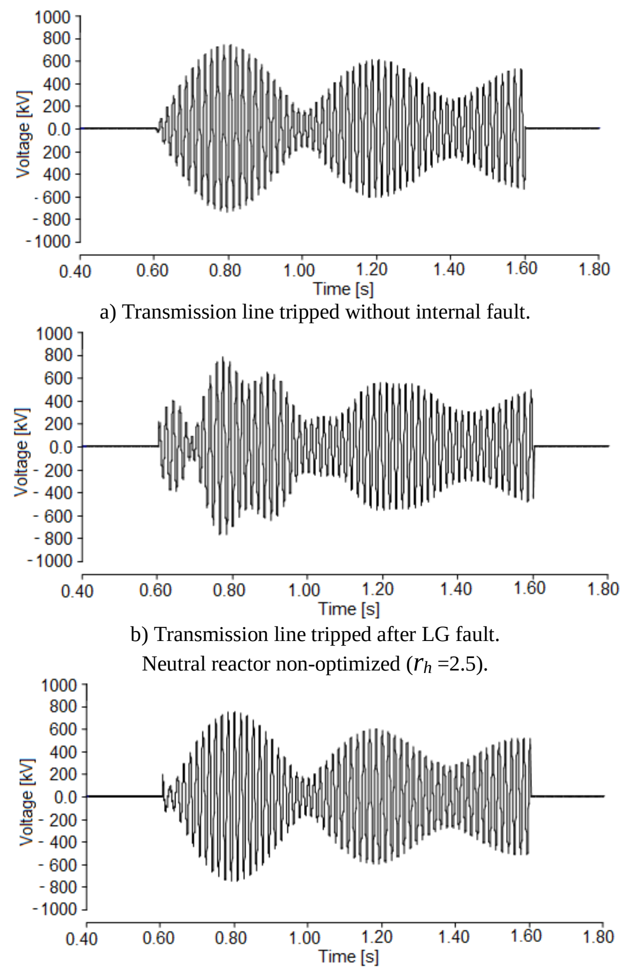
Most of studies of this practice are regarding the single-phase adaptive reclosing [4], [5], therefore there is not much available information regarding the application of neutral reactors during three-phase reclosing. However, the neutral reactor has an important role during the reclosing maneuver, especially on the wave-shape across circuit-breaker and the reduction of secondary arc extinction time.

A. *Waveshape across circuit-breaker*

For shunt compensated transmission lines, after both sides tripping, an oscillatory behavior characterizes the wave-shape of the voltage across circuit-breaker due to circuit involving the line capacitances and the inductance of the compensation reactors [9]. The voltage across circuit-breaker contains different frequency components, which are dependent on the line characteristics, its degree of compensation and the type of fault that produced its tripping.

If the three-phases are tripped without fault in any phases, i.e. for some causes different from an internal fault, the wave-shape of the beat is clearly defined and is the same for the three phases (Fig. 2-a)

On the other hand, when a LG fault occurs, and the three-phases are tripped, the phase with fault affects the wave-shape of the other two healthy phases, distorting the beat across circuit-breaker in each phase. In Fig. 2-b it is possible to observe one of healthy phases which is influenced by the phase under fault. It is important to mention that in this case the line is using a non-optimized neutral reactor (r_h=2.5).



a) Transmission line tripped without internal fault.

b) Transmission line tripped after LG fault.
Neutral reactor non-optimized (r_h =2.5).

c) Transmission line tripped after LG fault.
Optimized neutral reactor (r_h =1.7).

Fig. 2. Healthy phase voltage wave-shape across the CB: Transmission line with 90% of shunt compensation.

The Figure 2-c shows the significant influence of neutral reactor optimization (r_h=1.7) regarding to the well-defined voltage beat across the circuit-breaker. The two healthy phases show beats better defined and the periods of both phases are very similar.

Therefore, an important consequence of neutral reactor optimization during three-phase reclosing is the improvement of voltage beat across the circuit-breaker. The better defined beat will be important to the proposed method to reduce overvoltages.

B. Arc extinction time reduction

The neutral reactor contributes to coupling reduction and is important to reduce secondary arc current amplitude, which in turn will decrease the extinction time of secondary arc during single-phase reclosing of EHV/UHV transmission lines. Also, the neutral reactor optimization generates a significant extinction time reduction of secondary arc during three-phase reclosing.

As an example, for the line in study, Figure 3 summarizes the results of sensitivity analysis in function of the relation between zero and positive sequence impedances (r_h). An optimized neutral reactor with a value of r_h=1.7 generate around 70% of arc extinction time reduction (comparing to a non-optimized neutral reactor case). Thus, it is possible to assure that for a three-phase reclosing, a proper selection of neutral reactor will implicate in secondary arc extinguishing faster. However, specific analysis should be done for each system, considering particular characteristic of the line under study.

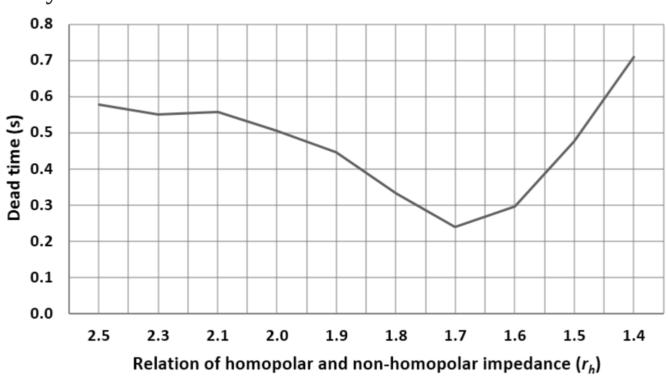


Fig. 3. Arc extinction time for different homopolar and non-homopolar impedances ratio (r_h).

IV. EXTINCTION FAULT IDENTIFICATION

In case of a transient LG fault, after the extinction of secondary arc, a resonant component or beat can be identified in the voltage of the faulted phase terminal. This phenomenon is produced by the resonant discharge of energy in shunt reactors with line capacitance. The amplitude of this beat depends on the voltage at open phase end and its frequency is lower than power frequency.

For a three-phase reclosing, Figure 4 represents the faulty phase voltage. The sequence of events includes LG fault occurrence at 0.5 s, three-phase line tripping to isolate the faulty section after 100 ms. Before line tripping the fault arc can be classified as primary arc. After this event, the interval from 0.6 to 0.9 s represents the behavior of secondary arc extinction. Finally at instant 0.9 s, a characteristic recovery voltage appears, which indicates the arc extinction. Consequently, the three-phase reclosing can be performed successfully. Otherwise, if no oscillatory voltage waveform is observed, this means that the fault is permanent [13]. The identification of arc extinction will be applied to properly determine the adaptive dead-time in order to perform a successful three-phase reclosing, with minimum switching overvoltages.

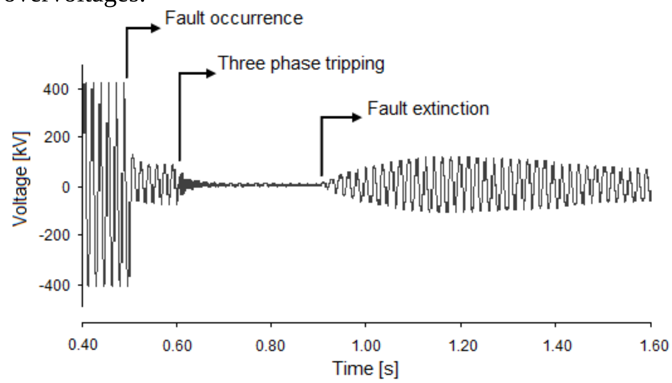


Fig. 4. Typical waveform of recovery voltage of faulty phase. Initial line side.

V. PROPOSED RECLOSING METHOD

The proposed method refers to three-phase reclosing optimization for shunt compensated transmission lines [13]. Thus, the technique consists of two stages. First, the check whether the arc extinguished in order to prevent reclosing onto fault. Next, the method detects the optimum region on the voltage across circuit-breaker and send the command for reclosing, reducing the amplitude of the overvoltages arising from the switching.

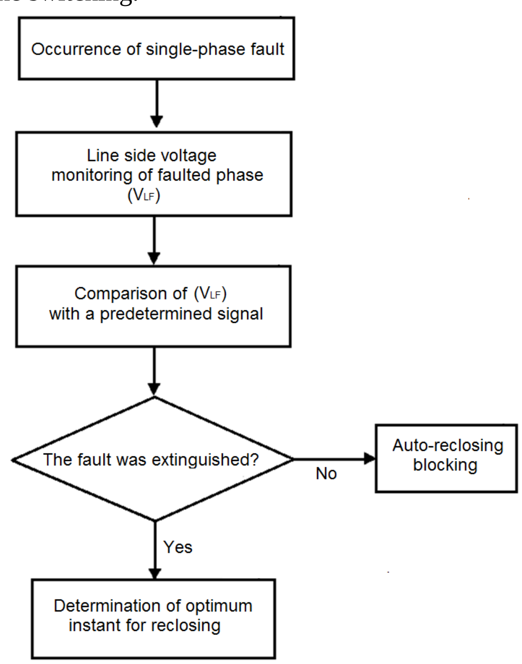


Fig. 5. Flow-chart of proposed scheme to determine fault extinction

Figure 5 shows the process flow-chart to identify the instant of fault extinction: When a LG fault occurs, the faulted phase is monitored through the line-side voltage (V_{LF}). This signal in turn is sampled and compared to a pre-determined signal, allowing to identify the instant when V_{LF} is different from zero. In that instant, the fault extinction is verified. If the fault does not disappear within the set dead-time, the automatic reclosing block is carried out. If the fault is extinguished, the optimum reclosing time is determined.

Next, as a second part of the method, the optimal instant for reclosing is determined through the algorithm detailed in the block diagram shown in Figure 6.

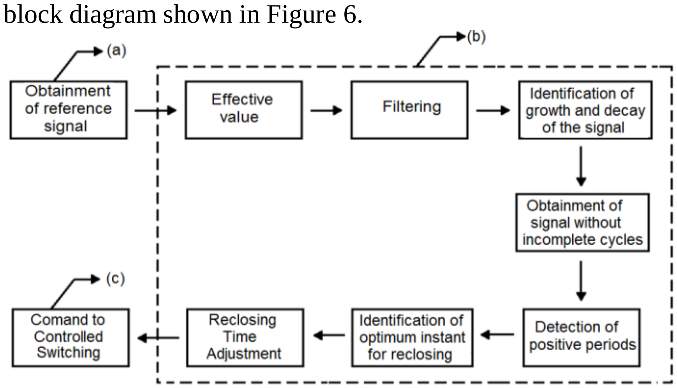


Fig. 6. Block diagram illustrating the controlled switching algorithm

The three-phase voltages are continually monitored by potential transformers (PTs). First, the voltage at the power system side and the voltage at the line side are measured to define the voltage waveform across CB. This is the reference signal. With signal processing, the rms value is determined and a low-pass filter is employed in order to attenuate high-frequency components.

Next, it is necessary to obtain a signal without incomplete inconvenient cycles. The instant when the fault extinguishes is random and could correspond to any point on the voltage across CB. Due to this fact, to identify the first half cycle after the fault extinction is very important. The beat half-period duration is identified by determining the point at which it achieves its first maximum (Fig.7). Hence, if the reclosing signal is to be given at the next minimum beat, the delay for closing from the instant is also half-period beat. This way the goal for closing in the next region of minimum beat is achieved.

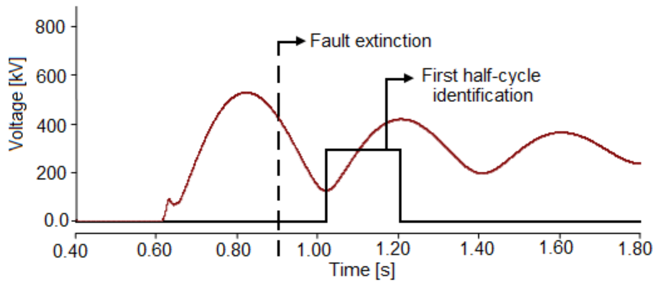


Fig. 7. Identification of first half cycle after fault extinction

VI. Evaluation of the Proposed Method

The transmission system analyzed is described in Fig. 1. Metal–oxide arresters rated at 420 kV were assumed to have been installed at either ends of transmission line.

A performance evaluation of proposed method is made for 90% shunt compensated line through a comparison among three transient overvoltage reduction techniques:

1) only surge arresters (SA);
2) surge arresters and pre-insertion resistors (PIR);
3) surge arresters and proposed controlled switching method.

Simulation case 1) is conducted for reclosing at a time 500 ms after CB opening fusing only surge arresters at both line ends.

Simulation case 2) uses pre-insertion resistor and surge arresters. Pre-insertion resistors are used in combination with circuit breakers to absorb switching transients and come into effect during the reclosing operation of the breaker. In this study, an existing 400 Ω resistor was simulated, with insertion duration of 8 ms, beginning at 500 ms ms after line opening (typical Brazilian value 500-kV transmission systems is in the range 500–1100 ms).

Simulation case 3) assumes reclosure using surge arresters and the proposed controlled switching method. Controlled switching is a technique that uses an electronic device to control the timing of closing/reclosing of independent pole breakers with respect to the phase angle of an electrical reference voltage signal. In this case, after the extinction fault identification, the circuit-breaker closes at optimum region that corresponds to the second minimum voltage beat across circuit-breaker.

Overvoltages occurs at the instant of reclosing. In this sense, different fault inception angles do not affect the effectiveness of the proposed approach to reduce overvoltages during three-phase reclosing. However, cases with fault insertion angle of 0°, 45° and 90° have been analyzed, confirming that this variation does not affect the overvoltages level.

Fig. 8 shows the three-phases´ voltages across circuit-breaker, as well as the voltage at the end of the transmission line (receiving end). In this figure, the reclosing occurs after a fixed dead-time (500 ms) and using only surge arrester to control the overvoltages. As the reclosing time is random, in this case it coincides with the maximum of the voltage beat across CB, consequently, higher overvoltages are generated.

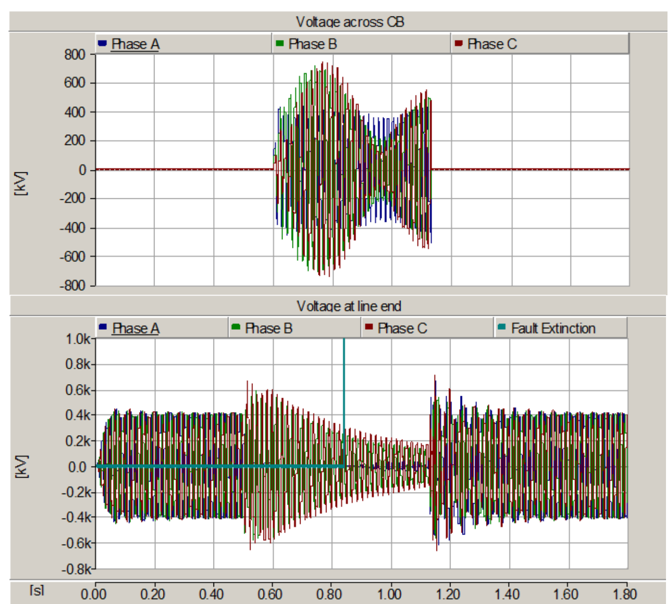


Fig. 8. Reclosing of the transmission line using only surge arresters.

In the same way, Fig. 9 shows the same maneuver, but this time, using in addition to the surge arresters, pre-insertion resistors. In this case, although the reclosing region is inconvenient, the resistor works well as a method to reduce overvoltages.

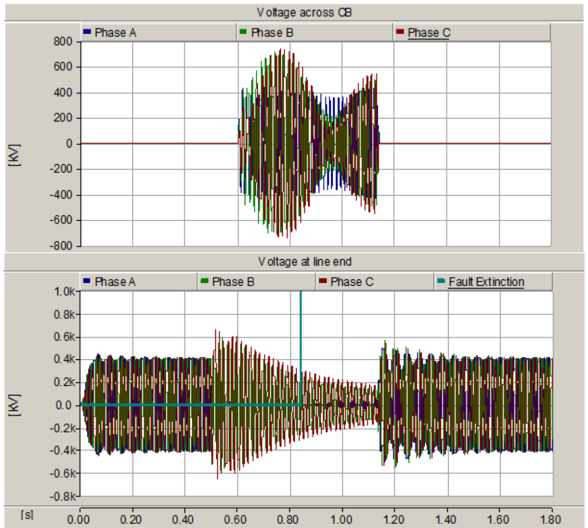


Fig. 9. Reclosing of the transmission line using surge arresters + PIR

Instead, in Fig. 10, it is possible to observe the proposed method performance. After fault extinction, the algorithm send the command to reclose in the second region of minimum beat, taking as reference the voltage signal across circuit breaker. As a result, the overvoltages are significantly reduced.

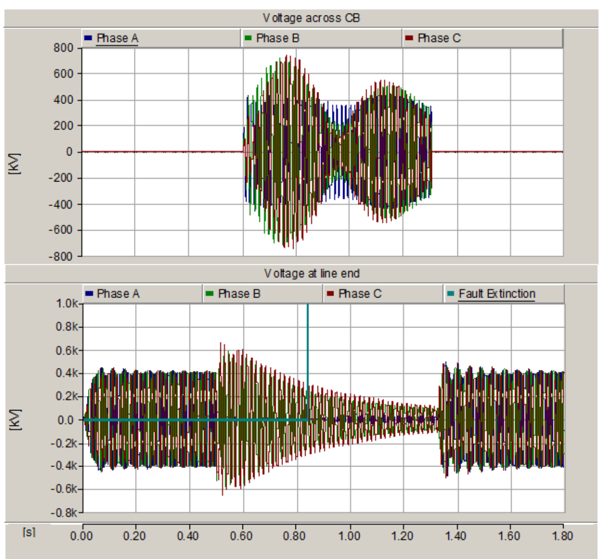


Fig. 10. Reclosing of the transmission line using SA + proposed method.

Based in [14], in order to ensure the statistical representation of the study, 200 simulations of the transmission line reclosing, each using a different set of circuit breaker closing times were performed. The range for the mean closing time has been distributed uniformly over 1 cycle of the fundamental frequency. For the three studied cases, an order to close the three phases at the same instant is sent, which means that the mean reclosing time is the same for the three phases, but the individual operating instants of each phase follow a Gaussian distribution with a standard deviation of 1 ms.

Table II summarizes the simulation results. The controlled switching proposed method provides the best performance for the line with 90% shunt compensation. It is possible to infer that the application of controlled switching allows that arresters suffer less stress and the energy absorbed is reduced accordingly.

On the other hand, the use of controlled switching method and the use of pre-insertion resistors are equally viable and effective to control overvoltages on long shunt compensated lines. Both methods, keep the energy absorption levels of arresters far below their capacity. For the worst case, only using surge arresters, the maximum surge arrester energy at line receiving terminal is 0.35 MJ. The pre-insertion resistor absorbed 2 MJ during the 8 ms insertion time.

TABLE II
OVERVOLTAGES ON THE RECEIVING END OF THE TRANSMISSION LINE

	Voltage at line end (pu)		
	Maximum	Mean	St. Deviation
Only Surge Arresters (SA)	1.81	1.77	0.05
Pre-insertion resistor + SA	1.52	1.42	0.06
Proposed method + SA	1.50	1.39	0.09

VII. CONCLUSIONS

A new method for the three-phase reclosing on long EHV/UHV shunt compensated transmission lines was proposed and its effective performance was confirmed comparing it with traditional methods.

The proposed method allows detecting the instant of fault extinction in order to ensure successful reclosing or aborting auto-reclosing. Additionally, the method identifies the optimal closing time, which is obtained several power frequency periods in advance, permitting additional adjustment, if necessary, to the poles spread and dielectric characteristics of circuit-breaker. The method adapts itself to any compensated transmission line where a line-to-ground fault occurs.

The comparison with traditional methods indicates that the use of the controlled switching proposed method and the use of pre-insertion resistors are similarly viable and effective to control switching transient overvoltages on shunt compensated transmission lines. The main advantages of proposed method are the implementation and maintenance costs reduction and the increase in the maneuver reliability, since the closing is performed after the fault extinction.

As result, it is concluded that neutral reactor optimization improves voltage beat across circuit-breaker. The better defined voltage beats are important to the appropriate performance of proposed method. Another advantage of neutral reactor optimization is the time reduction of fault extinction during three-phase reclosing. As the coupling between healthy phases and faulty phase if minimized, less energy is transferred to the ionized arc path, provoking faster arc extinction.

The results cannot be generalized. A correct estimation of line reclosing overvoltages requires specific simulations in which the line and network under study are modeled.

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