Neutral Reactor Optimization in order to Reduce Arc Extinction Time during Three-Phase Tripping

P. Mestas, M. C. Tavares

***Abstract.* — The optimization of the grounding neutral reactor is a common practice in order to have successful single-phase reclosing of shunt compensated transmission lines. This paper analyzes the optimization of neutral reactor to reduce arc extinction time with focus on three-phase reclosing. In addition, an analysis to improve the conditions of three-phase reclosing after single-fault is presented. The study is implemented in an actual 500 kV transmission line considering three different shunt compensation degrees. Digital simulations were performed using the PSCAD/EMTDC software.**

***Index Terms*-- Neutral reactor, Optimization, Three-phase reclosing, Shunt compensated transmission lines, Arc extinction.**

I. Introduction

Long transmission lines (TL) are subject to overvoltages at the line terminals during open circuit and light load conditions due to Ferranti effect (sustained overvoltages) and due to switching (transient overvoltage). In order to control these overvoltages, a reactive power compensation scheme is commonly employed. Basically, the compensation scheme is composed of three phase reactors and a fourth reactor, which is installed between the phase reactor neutral point and the ground. Current flows through neutral reactor only during the occurrence of an imbalance involving ground.

For Extra High Voltage (EHV) lines, up to 70-90% of the faults occurring are single line to ground, and most of these are non-permanent and originated due to lightning. In such case, to eliminate the fault, both types of maneuvers can be performed: single-phase and three-phase tripping and their subsequent reclosing. When single-phase reclosing is performed, only the faulted phase is opened in the presence of a single-phase fault and reclosed after controlled delay period. On the other hand, for three-phase reclosing, the three phases are opened after fault incidence, independent of the fault type and reclosed after a predefined period, following the initial tripping [1], [2].

For both cases, the maneuver will be successful if the fault is eliminated before reclosing. During single phase reclosing, the transient arc is maintained not only by the inter-phase capacitive and inductive coupling between faulted phase and energized phases of the same circuit, but also by the mutual coupling of the other healthy circuit in case of double circuit.

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The arc that exists before line or phase tripping is called primary arc and has current magnitude in the range of dozens of kA. After line or phase tripping this arc has its magnitude reduced to dozens up to 0.2 kA and is called secondary arc.

For shunt compensated lines, frequently, an additional single-phase reactor is connected between neutral and the ground. This reactor contributes to coupling reduction and is important reduce secondary arc current amplitude which in turn will decrease the secondary arc extinction time.

When three-phase reclosing is employed there is no power flowing through the healthy phases and the secondary arc current will have lower magnitude, which is maintained due to trapped charge in the healthy phases. The probability of successful reclosing is much higher than with single-phase reclosing, as the trapped charge is drained through the arc fault. However, for three-phase reclosing, the dead time can be much larger than for single-phase reclosing due to higher reclosing overvoltage, affecting the power system stability. The dead time is directly related to the secondary arc extinction of single-phase to ground fault.

In this context, this paper aims to analyze the optimization of neutral reactor in order to reduce arc extinction time with particular interest to three-phase reclosing of shunt compensated lines.

The analysis includes the variation of relation of the homopolar and non-homopolar reactor bank impedance and the influence of the reactor quality factor. Also, a study to mitigate three-phase reclosing overvoltages is presented.

II. System analyzed

The transmission system analyzed is showed in Fig. 1. The system is based on an actual transmission system of 500 kV and 1052 km. To consider the shunt compensation effects, the study was focused on the following lines sections:

1) final segment of the line that corresponds to a 252 km line section in between busses B4 and B5, including two shunt reactors with 50% and 40% compensation, respectively (90% total shunt compensation); in this case, the line was opened and closed using circuit breaker CB7;

2) the 320 km line segment between busses B2 and B3 with the two connected shunt reactors (70% total compensation); the line was opened and closed using breaker CB3;

3) the same final 252 km segment between B4 and B5 considered in 1), but this time with only one shunt reactor connected (50% shunt compensation), again opened or closed with CB7.

The shunt compensation scheme in field is composed of three single-phase reactors with quality factor of 400, grounded through a neutral reactor with quality factor of 40. The line parameters for the fundamental frequency (60 Hz) are shown in Table 1.

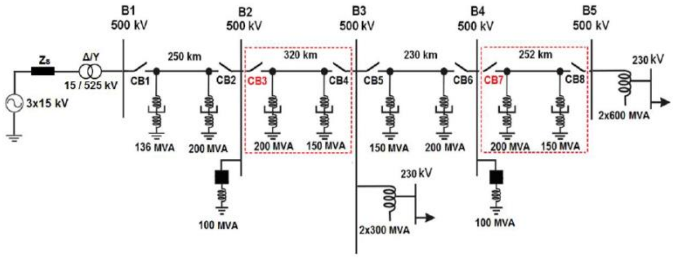


Fig. 1. 500 kV transmission system

TABLE I
BASIC LINE UNITARY PARAMETERS – 60 HZ

Components	Longitudinal (Ω/km)	Transversal (μS/km)
Non homopolar	0.0161 + j 0.2734	j 6.0458
Homopolar	0.4352 + j 1.4423	j 3.5237

Digital simulations were performed with PSCAD/EMTDC software. Transmission line was modeled using phase domain model.

III. RECLOSING OF TRANSMISSION LINES

When single-phase maneuver is applied to eliminate single-phase fault the faulty phase must be de-energized for a predefined time interval owing to the capacitive and inductive coupling between the faulty phase and the healthy phases. The higher the coupling the larger the arc current magnitude and its duration.

In the case of three-phase reclosing, the three phases are tripped, thereby reducing the line charge to just the trapped charge. This will result in faster arc extinction than for single-phase tripping. The secondary arc current waveform will vary for shunt compensated and non-compensated line. For shunt compensated lines the secondary arc becomes extinct and reignites repeatedly until the arc voltage is lower than the reigniting voltage. This oscillation is due to natural response between line transversal parameter and shunt compensation reactors. When the energy stored in faulty phase is too small the secondary arc will no longer reignite and the arc extinguishes. After fault extinction a voltage oscillation can be observed in the faulty phase due to voltage oscillation in healthy phases that will still have trapped charge. If the line was not reclosed this oscillation would last until the trapped charge is drained.

But if the fault is permanent there is no arc extinction and there is no oscillating voltage waveform in the faulty phase [3]. The trapped charge in the healthy phases will be drained faster through the permanent fault.

In summary, after a three-phase tripping, if the fault is transient and secondary arc extinguished, an oscillatory voltage signal in the faulty phase appears, which indicates the arc extinction, consequently the three-phase reclosing can be performed with success. Whereas, if the fault is permanent the faulted phase voltage becomes nil and a permanent fault can be promptly detected [4], [5]. No oscillatory voltage waveform is observed. This concept will be applied to determine the appropriate dead time in order to perform a successful three-phase reclosing.

Fig. 2 illustrates the voltage waveform at the line side of the faulted phase of 90 % shunt compensated line. The instant when the voltage beat appears, as an indicator of single-phase fault extinction, is clearly observed.

Normally, fixed time delays are employed after a fault to automatically reclose a transmission line. However, there are various drawbacks using fixed time delays for three-phase reclosing. First, if the delay is longer than the duration of the arc fault, stability of the power system may be adversely affected. Secondly, if the delay is shorter than the arc fault duration, reclosing will be unsuccessful. Further, a reclosing operation may be performed even in case of a permanent fault, there may threaten to power system stability and be a serious loss in power equipment. Thus, a procedure for reclosing faulted transmission lines immediately after the secondary arc self-extinguished was implemented.

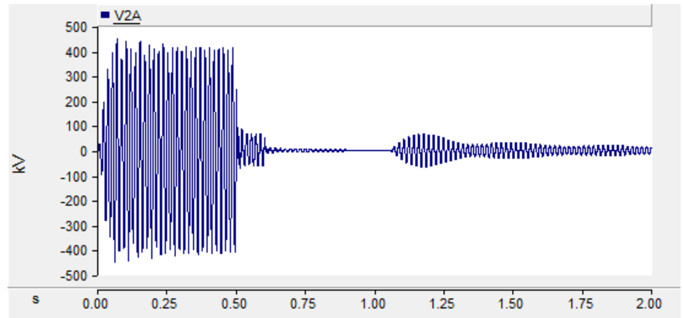


Fig. 2. Voltage at the line side of the faulty phase during three-phase tripping.

IV. OPTIMIZATION OF NEUTRAL GROUNDING REACTOR FOR THREE-PHASE RECLOSING

The compensation scheme is optimized, via properly sized neutral reactor, and as a result secondary arc magnitude is reduced and arc extinction will be also decreased [6]. This occurs because the optimized neutral reactor will minimize line mutual capacitance, what in turn will reduce the faulty phase charging by the healthy phases. This technique is commonly applied when single-phase reclosing is adopted. However, henceforth, in this paper this procedure will be analyzed with focus on three-phase reclosing.

The common, simplest and economical procedure for optimizing the neutral reactor is to dimension appropriately the ratio between the homopolar impedance and the non-homopolar impedance of the shunt reactor banks [6], [7]. The parameter chosen, to select the basic characteristics of the neutral reactor, is the ratio r_h:

$$r_h = \frac{Z_h}{Z_d} = \frac{Z_f + 3Z_n}{Z_f} \tag{1}$$

where, in complex notation, at 60 Hz, Z_f and Z_n are, respectively, the phase reactors and neutral reactor impedances and Z_h and Z_d are, respectively, the homopolar and non homopolar impedances (or zero sequence and positive sequence impedances) of the shunt reactor bank.

A. Variation of relation of homopolar and non-homopolar impedance

This section aims to analyze the variation of ratio r_h in order to size adequately the neutral reactor. Table II and Fig. 3 summarizes the results for three line compensation degrees, according to Section II.

The fault was modeled by a 20-Ω resistance that was removed when the fault current reached 5 A. No arc-model

TABLE II
RESULTS OF ANALYSIS OF r_h VARIATION

Compensation degree of TL (%)	r_h in field values	r_h optimized values	Arc extinction time reduction (%)
90	2.5	1.7	58.5
70	2.5	1.7	58.5
50	2.5	1.6	50.6

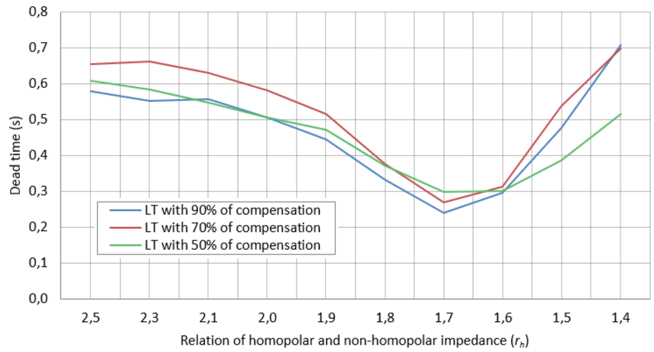


Fig. 3. Arc extinction time for different homopolar and non-homopolar impedances r_h ratio – Different compensation levels.

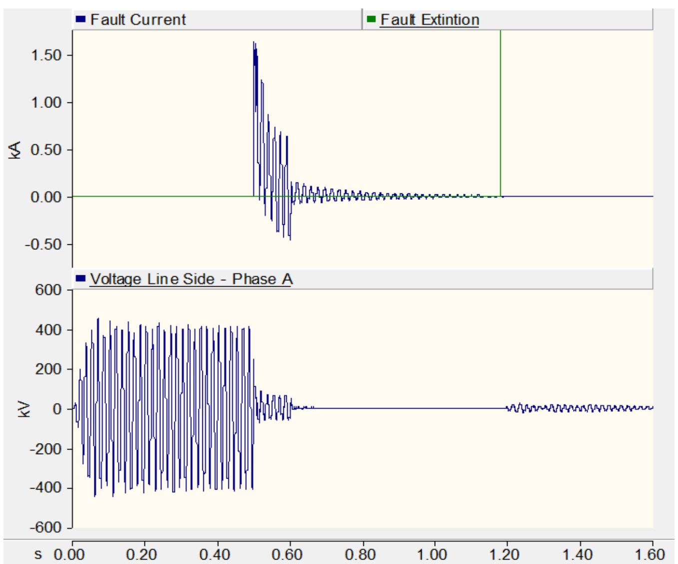


Fig. 4. Fault current and voltage at faulty phase of line side for 2.5 r_h ratio. - 90% shunt compensated transmission line.

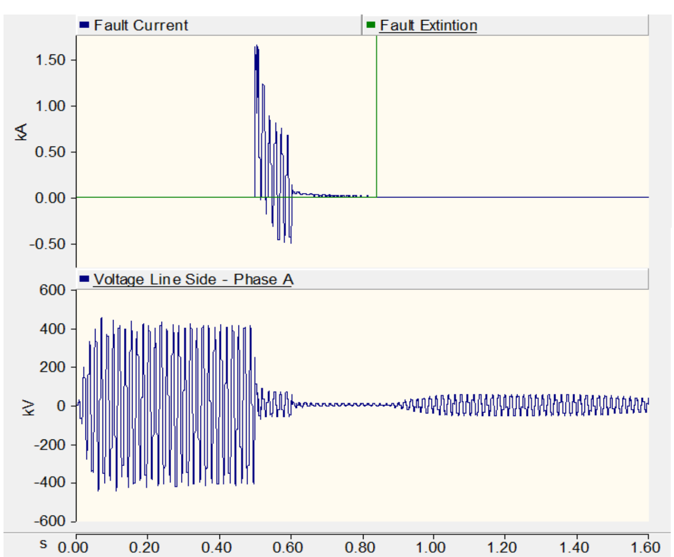


Fig. 5. Fault current and voltage at faulty phase of line side for 1.7 r_h ratio. - 90% shunt compensated transmission line.

was used as the arc parameters could interfere in the analysis, while the time the arc current takes to reach 5 A is not influenced by the resistor. The three-phase tripping occurs 100 ms after fault occurrence. In Fig. 4 and 5 for the r_h ratios 2.5 and 1.7 respectively, it can be observed the fault current and oscillatory voltage waveform at faulty phase of line side indicating the fault extinction. Both the fault current magnitude and the fault duration varied as expected.

Based on the results, it can be concluded that the neutral reactor optimization generates a significant arc extinction time reduction for the three compensation degrees. Moreover, for an optimized r_h ratio, the voltage beat at faulty phase appears more clearly when the fault is extinguished.

B. *Influence of the neutral reactor quality-factor*

The quality factor (X/R) of a reactor is the ratio of its inductive reactance to its resistance at fundamental frequency, and is a measure of its efficiency. The higher the reactor quality factor, the closer it approaches the behavior of an ideal lossless inductor. A regular neutral reactor quality factor is around 40.

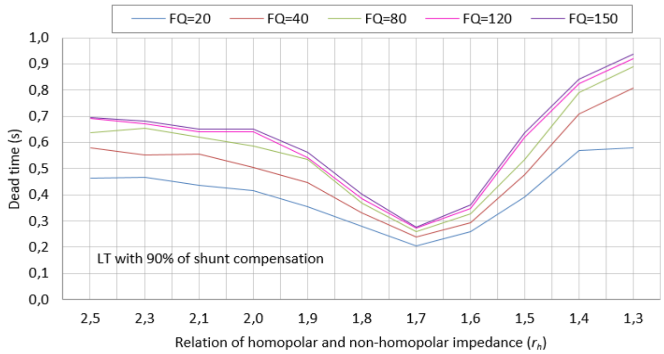
In this section, the influence of the neutral reactor quality-factor on fault duration is analyzed. The study was performed for 90 %, 70 % and 50 % shunt compensated lines. As a result, the Fig. 6 shows that the quality factor variation does not affect the r_h optimization, as this is related to the reactance.

The neutral reactor does not need to have a high quality factor, as it will only operate during unbalance and a high resistance will help damping transients. Also, it can be observed that increasing the neutral reactor quality factor increases the fault duration, which would imply in increasing dead-time to ensure a successful reclosing. This result is coherent as the lower the quality factor the higher the neutral reactor resistance, which will contribute to extinguish the secondary arc. This increase tends to be higher for transmission lines with lower shunt compensation levels.

V. ANALYSIS TO IMPROVE THE CONDITIONS OF THREE-PHASE RECLOSING

From the above analysis it has been determined that the neutral reactor optimization reduces the fault duration during three-phase reclosing. However, it is known that the random switching of circuit breakers during three-phase transmission lines reclosing generates high magnitudes of voltage and current transients, which may produce negative impacts for power systems.

In the case of shunt-compensated lines, the degree of compensation has important role on the voltage waveform across the circuit breaker poles. Due to the oscillatory circuit formed by the transmission line transversal parameter and the shunt compensator's inductance, the voltage across the circuit breaker poles after tripping is characterized by a beat. When the line tripping occurs without fault in any of the phases, i.e. when the three phases are opened for some reason but not due to an internal fault at the line, the voltage across the circuit breaker shows a clear beat and the wave shape is similar for the three phases (Fig. 7). In this case, the optimal region for reclosing should be the minimum voltage beat across the circuit breaker, considering the dead time for protection actuation, according to compensation degree [8].



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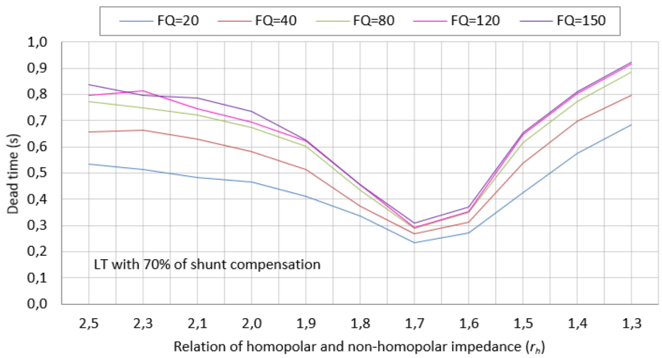

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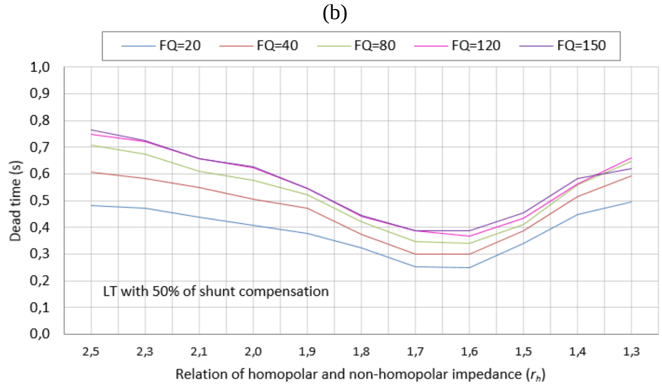


(c)

Fig. 6. Influence of the neutral reactor quality-factor for three levels of shunt compensation. (a) 90% shunt compensation. (b) 70% shunt compensation. (c) 50% shunt compensation.

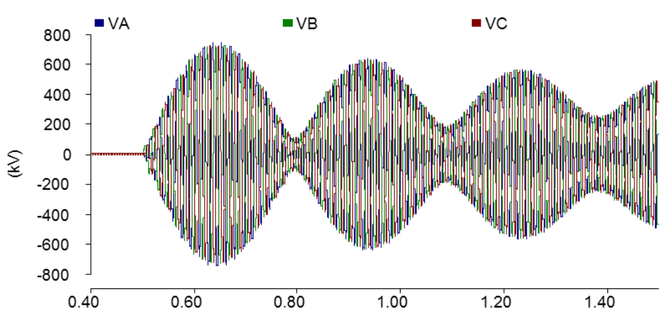


Fig. 7. Voltage waveshape across the CB: transmission line with 90% of shunt compensation – tripped without fault occurrence.

In contrast, when a single-line-to-ground fault occurs and a transmission line experiences a three-phase tripping, the phase under fault influences the waveform of the other two healthy phases, consequently the signals obtained are very complex and the expected beat is distorted. For this reason, the three-phase reclosing scheme should be performed considering the time necessary for the fault extinction.

For 90% shunt compensated line, Fig. 8 shows the sequence of events for reclosing operations due to single-line-fault, which includes fault occurrence, three-phase line tripping by circuit breaker to isolate the section under fault, fault extinction, and finally breaker reclosing to reenergize the line.

In Fig. 8(a)–(c), waveforms are shown for the voltage across the circuit breaker and voltage at line end for phase A, phase B and phase C. In the case of voltage across the circuit breaker of phase A under fault, it can be observed that after arc extinction, the phase voltage begins to oscillate. The time for fault extinction takes 678 ms after fault occurrence.

From the figure of the voltage across the circuit breaker of healthy phases B and C it is possible to observe that beats loses its definition and its periods are out of phase. Another important aspect to be taken into account is that the reclosing occurs after arc extinction, which corresponds to the maximum of the beat. As a result, higher overvoltages are generated when the circuit breaker is reclosed.

The same procedure for reclosing is presented in Fig. 9(a)–(c), but this time the neutral reactor is optimized and the circuit breaker reclosure occurs in the first minimum voltage region of the beat, after the fault extinction has been detected. As can be seen from the Fig. 9(a), the result of the optimization of the neutral reactor is an important reduction of the fault extinction time. The voltage beat in faulty phase appears 340 ms after fault occurrence, as a sign of arc extinction. Another important consequence of neutral reactor optimization is the definition improvement of the voltage beat across the circuit breaker. In addition, for this case, the voltage beats periods of the phase B and C are very similar.

The three-phase reclosing was performed at the minimum of the voltage beat in order to minimize the reclosing impact. Comparing the voltage waveforms at receiving end of Figs. 8 and 9, it can be seen that not only the overvoltage is reduced with the reclosing at the minimum beat, but the waveform also has a lower harmonic content.

VI. Conclusions.

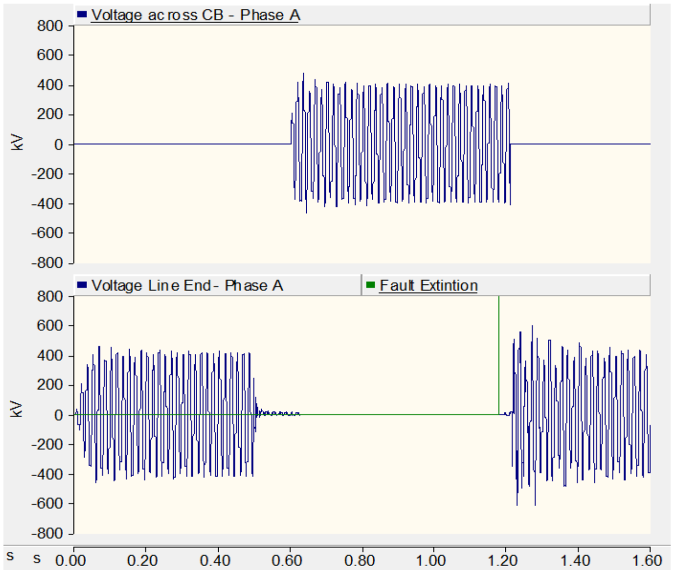
An analysis of neutral reactor optimization in order to reduce arc extinction time after three-phase tripping was performed.

Based on the results, it can be concluded that the neutral reactor optimization causes an important fault duration reduction for three-phase tripping. Consequently, it is possible to ensure reclosure at the earliest possible time, thereby reducing the power energy interruption.

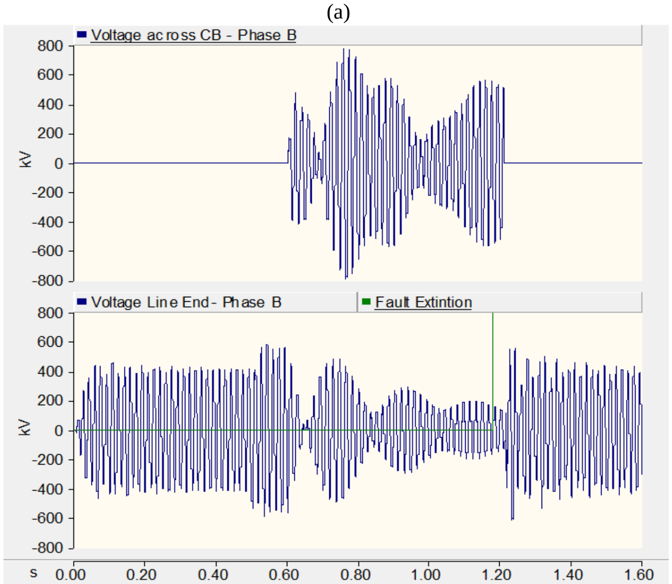
The neutral reactor quality factor does not affect the determination of the optimized rates of r_h, which are the same for all values of quality factor analyzed. However, the lower the neutral reactor quality factor the lower the fault duration time, which also will permit a lower dead time.

For the line with optimized neutral reactor, the reclosing at the minimum beat of the voltage across the circuit breaker will mitigate reclosing overvoltages and produce voltage waveforms at line end with lower harmonic content.

In summary, if optimized neutral reactor is designed controlled reclosing switching can be implemented to mitigate overvoltages for three-phase tripping due to single-phase line fault.



(a)



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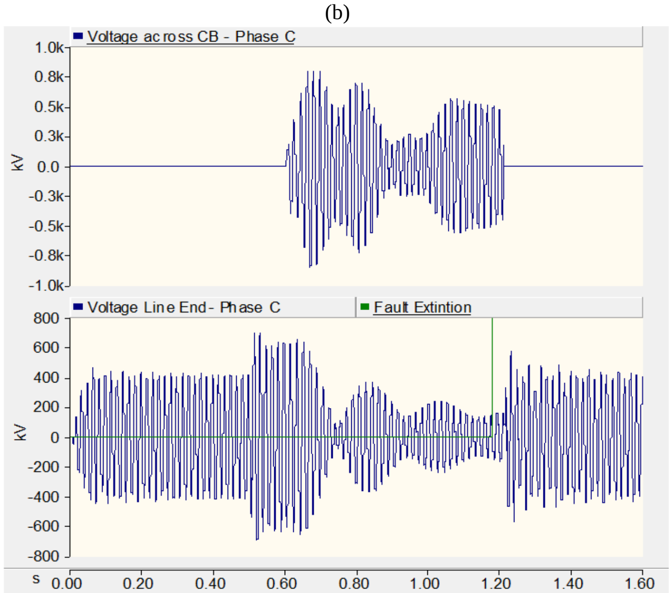
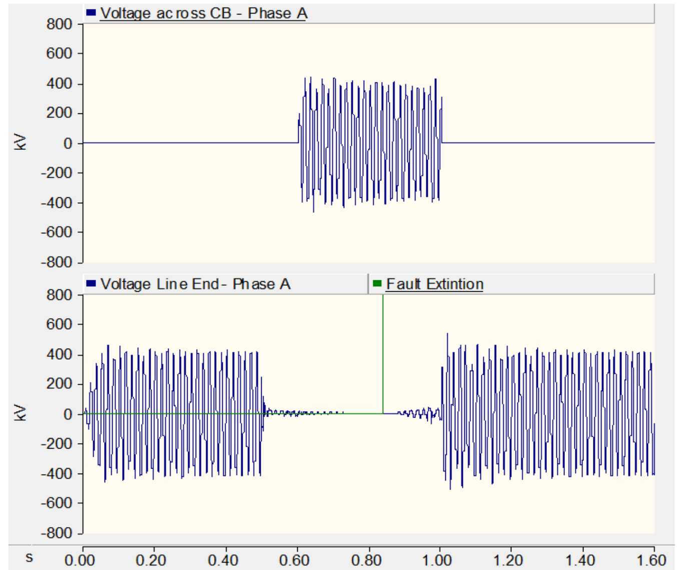


(c)

Fig. 8. Reclosing without neutral reactor optimization (2.5 r_h ratio). (a) Voltage across CB and voltage at line end - Phase A. (b) Voltage across CB and voltage at line end - Phase B. (c) Voltage across CB and voltage at line end - Phase C



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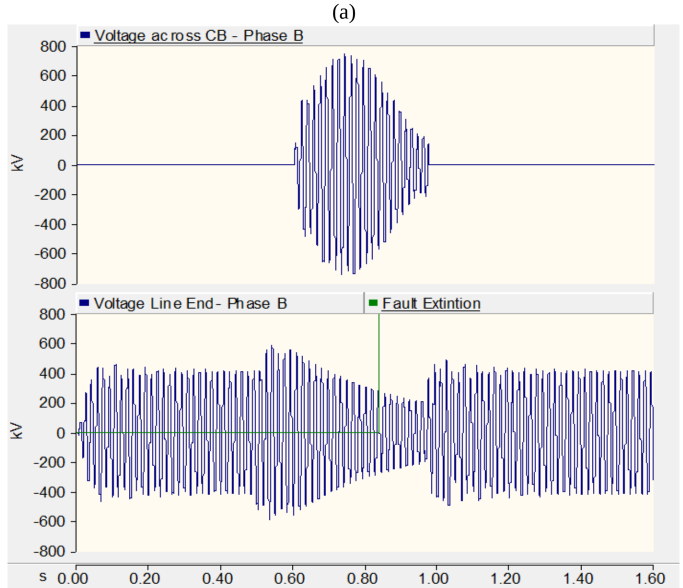

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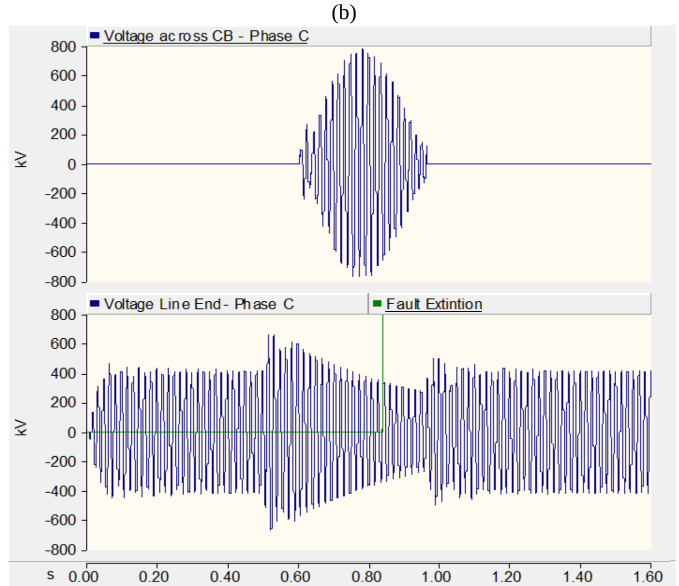

(c)

Fig. 9 Reclosing with neutral reactor optimization(1.7 r_h ratio).. (a) Voltage across CB and voltage at line end - Phase A. (b) Voltage across CB and voltage at line end - Phase B. (c) Voltage across CB and voltage at line end - Phase C

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