A Suitable Method for Line Controlled Switching

K. M. C. Dantas, W. L. A. Neves, D. Fernandes Jr. and L. C. Fonseca

Abstract— **An approach for controlled reclosing of transmission lines with shunt reactive compensation, is presented. Karrenbauer's transformation is used as a matrix operator to perform the analysis of the voltage signals required to control switching operations of transmission lines with actual transposition schemes. The procedure safely determines the arc extinction time for single and double-phase to ground faults. The approach is evaluated through ATP simulations using actual parameters from the Brazilian Power System Grid. The results attest the efficiency of the applied method.**

Index Terms— **Controlled Switching; Switching Overvoltages; Transmission Lines.**

I. INTRODUCTION

AMONG the alternatives used to mitigate switching surges in power systems, controlled switching of circuit-breakers (CB) has gained a great emphasis in the last years [1]–[5]. Some approaches has been reported in literature regarding the application of this method for transmission lines closing and reclosing [6]–[10]. Although the main reason for a line reclosing is the clearance of a fault in the line and the need to restore the system as quickly as possible, these approaches do not consider the line side voltage characteristics under fault conditions or the possibility of a permanent fault [11], [12], which could lead to an unsuccessful reclosing. This work attempts to overcome these drawbacks.

An approach for controlled switching of line circuit-breakers has been proposed and evaluated by the authors [13], [14]. Here, a step forward is made for the controlled reclosing of transmission lines with shunt reactive compensation. The suitable making instants for line reclosing are determined from the analysis of the line side voltage characteristics by applying modal transformation. By using this procedure, the arc extinction time of single and double-phase to ground faults are determined and reclosing onto fault is avoided.

Data from the Brazilian Power System Grid were used to produce some case studies using EMTP (Electromagnetic Transients Program) and the results attest the efficiency of the proposed approach to determine the arc extinction time as well as to mitigate the switchings surges, regardless of the parameters evaluated, such as the line compensation degree, fault resistance and fault location.

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II. TRANMISSION LINE CONTROLLED SWITCHING FUNDAMENTALS

The closing command for the circuit-breaker is normally issued randomly at some instant $t_{command}$ with respect to the phase angle of the voltage across the circuit-breaker contacts, which is the reference signal for the controlled closing. Furthermore, the contacts making instant occurs after a period of time commonly called the operating time of the circuit-breaker ($T_{operating}$). The timing sequence for controlled closing is shown in Fig. 1, in which the optimal making instant is the zero crossing of the reference signal. The method consists on controlling the instant $t_{command}$ delaying it for a time interval T_{delay} in order that $t_{optimal}$, previously predicted, occurs at the instant $T_{delay} + T_{operating}$ after $t_{command}$.

A. Transmission Line Closing

During this operation, there is no trapped charge on the line and the optimal making instant for each transmission line phase is the zero crossing of the source side voltage, which is the reference signal.

B. Shunt Compensated Transmission Line Reclosing

This operation is normally performed with trapped charge in the line. After the line opening, the line side voltage presents an oscillating characteristic and the reference signal is the voltage across the circuit-breaker contacts. The optimal making instants for one of the phases of a non-faulted 80% shunt compensated line, which occur at the zero crossing and at the minimum beat of the reference signal, are indicated in Fig. 2. This is the situation considered by the existing methods. The reference signal for a sound phase of this line under a single-phase to ground fault is shown in Fig. 3, in which the fault effect over the reference signal waveform is evident when comparing to Fig. 2.

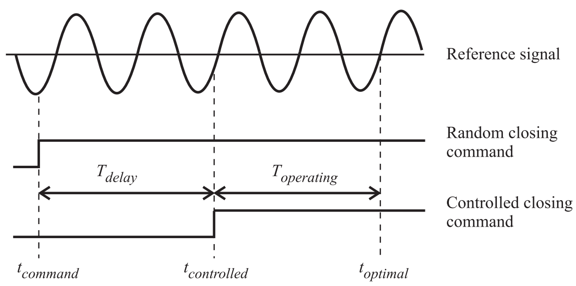

Fig. 1. Schematic controlled closing sequence.

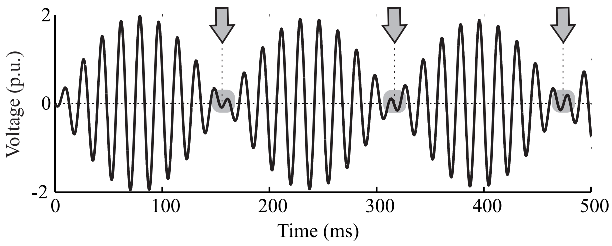

Fig. 2. Voltage across the circuit-breaker contacts for 80% shunt compensated lines.

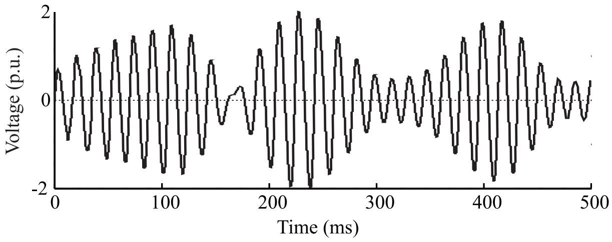

Fig. 3. Voltage across the circuit-breaker contacts for 80% shunt compensated lines under a single-phase to ground fault.

III. Line Side Voltage Analysis

For a better understanding of the line side voltage oscillating behavior, consider the opening of a three-phase fully transposed line with shunt compensation and no fault condition. Due to the electromagnetic coupling between the line phases and the three-phase shunt-reactors, the line-reactor circuit has two natural oscillating frequencies: f_1 and f_0, which correspond to modes 1 and 0, respectively. These frequencies can be determined ignoring the line series reactance, since it is very small compared to the reactor reactance:

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{1}$$

and

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_0}}\ , \tag{2}$$

where

L_0, L_1	-	shunt reactor inductances for modes 0 and 1, respectively.
C_0, C_1	-	line capacitances for modes 0 and 1, respectively.

Under fault condition, the oscillating frequencies of the line side voltage can be obtained by means of fault analysis using modal transformations. In this paper, the Karrenbauer matrix was used as an operator, due to its simplicity, and the relation between the line side voltages in phase domain (v_a, v_b and v_c) and in modal domain (v_0, v_1 and v_2) can be expressed as follows:

$$\begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} . \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} . \tag{3}$$

For single-phase to ground faults, it can be shown that after line opening, the modal circuits are connected in series as in Fig. 4. The following equations for the modal voltages are obtained:

$$v_0(t) = v_0(0)\cos\left(\sqrt{\frac{2L_1 + L_0}{L_1 L_0 (C_1 + 2C_0)}}\ t\right)\ , \tag{4}$$

$$v_2(t) = -\frac{v_0(t)}{2} + \left[\frac{v_2(0) - v_1(0)}{2}\right] . \cos\left(\sqrt{\frac{1}{L_1 C_1}}\ t\right) \tag{5}$$

and

$$v_1(t) = -\frac{v_0(t)}{2} - \left[\frac{v_2(0) - v_1(0)}{2}\right] . \cos\left(\sqrt{\frac{1}{L_1 C_1}}\ t\right)\ . \tag{6}$$

The oscillating frequencies of the line side voltage are determined by the arguments of the cosine functions in (4), (5) and (6). At the instant in which the fault is extinguished, the modal circuits are decoupled and then the oscillating frequencies of the line side voltage are then determined by (1) and (2). As an example, a typical oscillogram for a single-phase to ground fault in a 80% shunt compensated line is shown in Fig. 5. The fault occurs at $t = 100$ ms and after the line opening at $t = 200$ ms, the trapped charges at the sound phases assume an oscillating characteristic determined by the frequency contents of voltage modes 1 and 0, which are obtained using (3) and are shown in Fig. 6.

For double-phase to ground faults it can be shown that, due to the modal circuits connection, there is only one oscillating frequency at the sound phase, which is given by (7). This can be seen in Fig. 7, in which a double-phase to ground fault, involving phases A and B, for a 80% shunt compensated line is shown. After the arc extinction at phase B, the line side voltage will behave as in the case of a single-phase to ground fault.

$$\frac{1}{2\pi}\sqrt{\frac{L_1 + 2L_0}{L_1 L_0 (C_0 + 2C_1)}}\ Hz. \tag{7}$$

In the case of phase-to-phase faults, it can be shown that there are two oscillating frequencies in the line side voltage, which are given by (1) and (2). These frequencies are also observed after the fault extinction, as discussed previously. For three-phase faults, there may be trapped charges in the line. However, these charges are quickly damped out and after the dead time, the line side voltage is negligible.

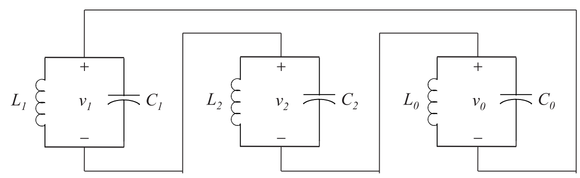

Fig. 4. Connections of the Karrenbauer modal circuits for an opened line under single-phase to ground fault.

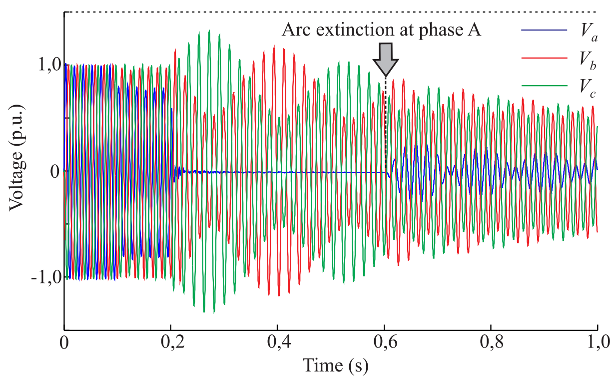

Fig. 5. Line side voltage for a line opening due to a single-phase to ground fault.

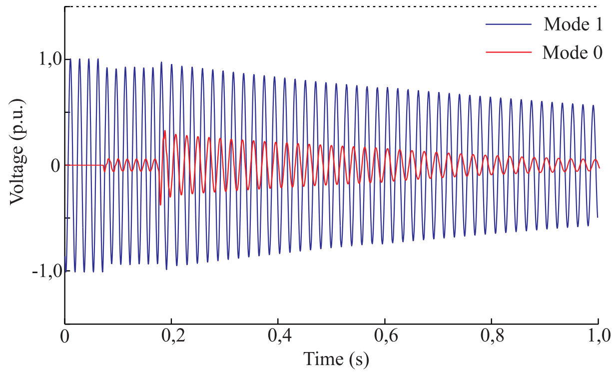

Fig. 6. Modal components 1 and 0 for the line side voltage at the sound phase of Fig. 5.

IV. Proposed Procedure

A new procedure for controlled reclosing of shunt compensated lines is proposed here. This is an improvement of the approach proposed in [9] and it is based on a simple zero-crossing algorithm and modal transformations to analyze the line side voltage after the line opening. The frequency components contained in these voltage signals are obtained according to Section III by using (3). Since each component assumes a sinusoidal waveform, the periods of the signals are determined by means of two consecutive zero crossings and their magnitudes are determined finding the highest absolute value between two consecutive zeroes.

Then, the reference signals (voltage across the CB) are estimated ahead in time in order to predict the suitable making instants for line reclosing. A making instant is determined when the slope (derivative) of both line side and source side voltage have the same direction at the time these signals cross, which means a zero crossing of the reference signal at its minimum beat.

When the line is opened to clear a fault, it is necessary to check whether the arc is extinguished during the line dead time (t_{dead}) in order to prevent reclosing onto fault. The proposed approach determines the arc extinction time of single and double-phase to ground faults.

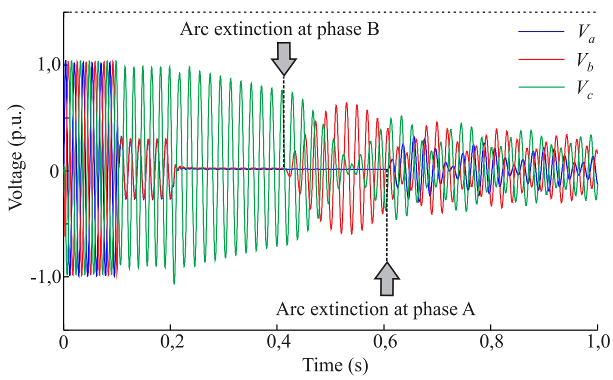

Fig. 7. Line side voltage for a line opening due to a double-phase to ground fault.

A. Extinction of Single-Phase to Ground Faults (SPG)

If $v_1 + v_2 = -v_0$, the fault remains in the line, that is, the signals $-v_0$ and $v_1 + v_2$ are equal and have a sinusoidal waveform whose frequency is determined by the argument of the cosine function in (4). Once the fault is extinguished, v_0 oscillates at a frequency determined by (2) while $v_1 + v_2$ oscillates at a frequency determined by (1). Consequently, it is possible to determine the extinction of SPG based on the following statement: while $v_1 + v_2 = -v_0$, the fault remains.

The statement above is valid only for the ideal situation in which the fault impedance and the line series reactance are neglected. In practice, the sum of the modal voltages ($v_0+v_1+v_2$) depends on the fault impedance. Then, instead of checking the equality $v_1 + v_2 = -v_0$ point by point, it is checked whether the signals are close enough to each other over a given time interval and techniques employed in evaluating the quality of curve fitting are used. A statistical parameter suitable for this purpose is the coefficient of determination R^2. This adimensional coefficient, quantifies the quality of the fit between zero and one, where values closer to one indicate a better fit. The definition for R^2 is given as follows:

$$R^2 = 1 - \frac{SSE}{SST} \ , \tag{8}$$

where SSE is the sum of the squared differences between $v_1 + v_2$ and $-v_0$, in a range with N samples of each signal:

$$SSE = \sum_{k=1}^{N} \{[v_1(k) + v_2(k)] - [-v_0(k)]\}^2 \tag{9}$$

and SST is the sum of the squared differences between the samples of $-v_0$ and its mean value ($\overline{v_0}$) in a range with N samples:

$$SST = \sum_{k=1}^{N} \{[-v_0(k)] - \overline{v_0}\}^2. \tag{10}$$

Considering a range corresponding to one cycle of the fundamental frequency and a typical sampling rate of 16 samples per cycle, R^2 is calculated for $N = 16$ samples. With each new sample, a new value for R^2 is calculated based on the latest 16 samples. After the line opening, R^2 must be close to one, since the signals $v_1 + v_2$ and $-v_0$ must be close to each other. When the fault is extinguished, these signals become far apart from each other and a zero value for R^2 is expected. Thus, based on the value of R^2, it is possible to determine the extinction of SPG, as illustrated in Fig. 8(a) for the SPG shown in Fig. 5. The modal voltages $v_1 + v_2$ and $-v_0$, which are similar only during the fault, are shown in Fig. 8(b).

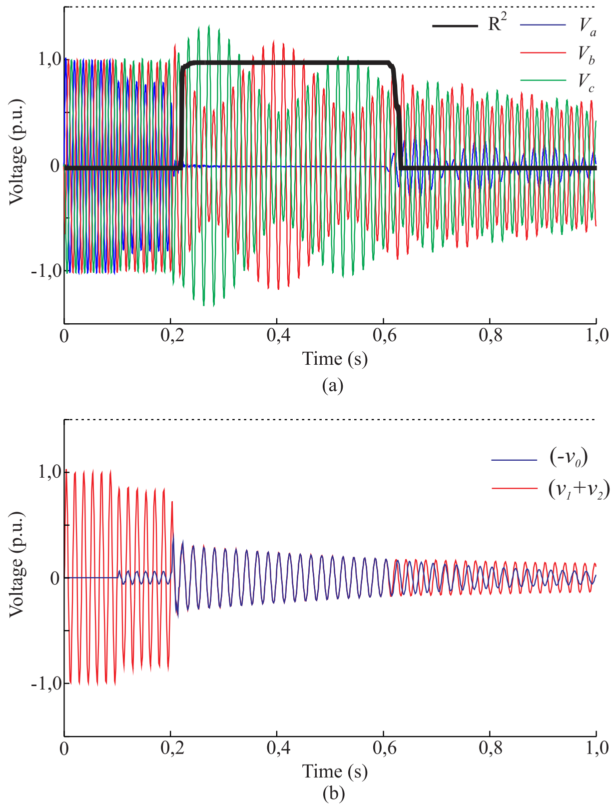

Fig. 8. Determination of SPG extinction using R^2: (a) Line side voltages and R^2; (b) Modal voltages $-v_0$ e $v_1 + v_2$.

B. Extinction of Double-Phase to Ground Faults (DPG)

Considering that the phases involved in the fault (e.g, phases A and B) have zero voltage values, it can be shown from (3) that the equality in (11) is satisfied. That is, the condition set to a DPG involving phases A and B ($v_1 + v_2 = -v_0$) is the same for a SPG involving phase A. Similar analysis can be performed for a SPG involving phase B. So, the extinction of a DPG can be determined similarly to the case of SPG, though the two phases involved in the fault must be analyzed.

$$v_1 + v_2 = -v_0 = \frac{1}{3}(-v_c). \qquad (11)$$

With the proposed approach, it is possible to reclose the line at the first suitable making instants following the arc extinction and minimize the line dead time in which it is out of service. Moreover, in the case of line opening due to external faults, the reduction of the line dead time is possible since the analysis of the line side voltage starts right after the line opening.

V. Proposed Procedure Evaluation

The proposed procedure is evaluated through digital simulations using the ATP (Alternative Transients Program) [15]. Data from the 500 kV Brazilian Power System Grid reported by [9] were used to produce some case studies. Its single-line diagram is shown in Fig. 9 and the focus is on the 400 km shunt compensated line between Milagres and S. J. do Piaui. 420 kV class metal oxide arresters (MOA) are connected at both ends of the line. The MOA have a protection level of 830 kV at 2 kA. The line is modeled using distributed constant-parameters whose data are shown in Table I. The following operating conditions were considered, in which the ratios X_0/X_1 for the shunt reactors include the neutral reactors:

- Shunt reactors with $X_0/X_1 = 1.73$ connected at both line ends (58% compensation);
- Shunt reactors with $X_0/X_1 = 1.73$ connected only at Milagres (29% compensation);
- Hypothetical situation for a 80% shunt compensated line and reactors with $X_0/X_1 = 2.90$.

A. Fault Extinction Analysis

Single-phase and double-phase to ground faults were simulated considering different parameters: line compensation degree (29, 58 and 80%), fault resistance (0.1, 10 and 100 Ω) and fault location along the line. The faults occur at $t = 100$ ms and at $t = 200$ ms the line is opened. Around $t = 600$ ms the fault is extinguished. Some results regarding the proposed procedure performance are shown in Fig. 10. The performance for SPG at Milagres (monitoring point) and S. J. do Piaui (remote end) for 58 and 29% shunt compensation, with fault resistances (r_{fault}) of 0.1 and 100 Ω, respectively, are shown in Fig. 10(a) and 10(b). The performance for DPG, with $r_{fault} = 10$ Ω, at mid span of a 80% shunt compensated line is shown in Figs. 10(c). For all case studies, the proposed approach was able to identify the fault extinction.

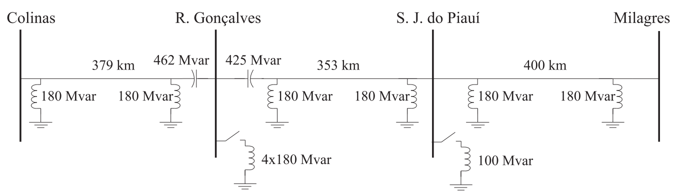

Fig. 9. Single line diagram from part of the Brazilian Power System Grid.

TABLE I
SEQUENCE PARAMETERS FOR THE LINE MILAGRES - S. J. DO PIAUI.

Sequence	R (Ω/km)	X (Ω/km)	ωC (μ℧/km)
Zero	0.4930	1.339	2.890
Positive	0.0186	0.267	6.124

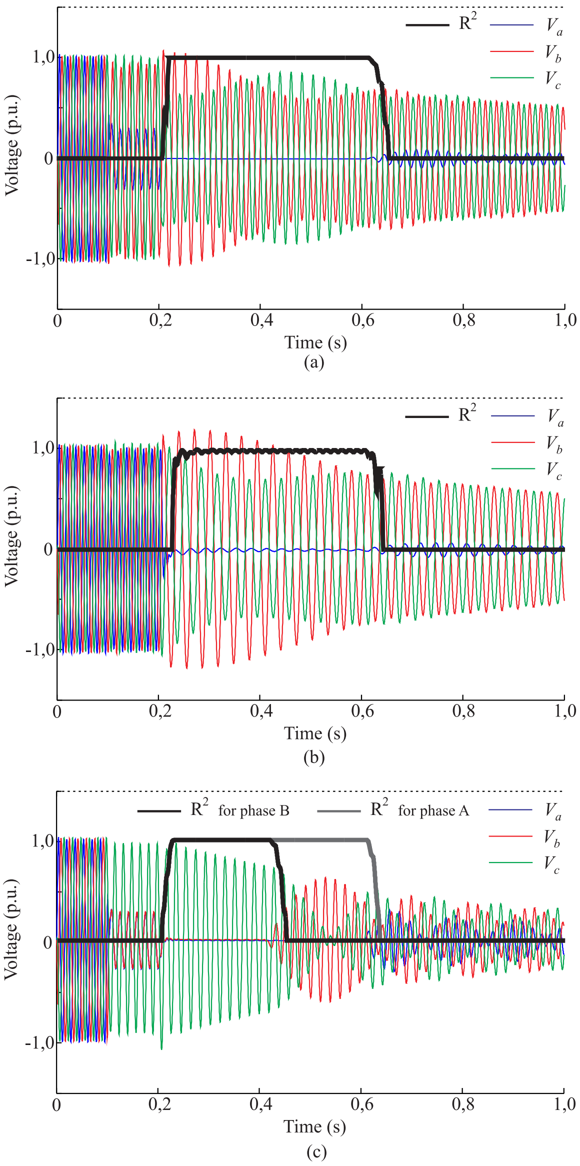

Fig. 10. Line side voltages and arc extinction time determination using R^2: (a) 58% compensation, SPG fault at Milagres and $r_{fault} = 0.1\ \Omega$; (b) 29% compensation, SPG fault at S. J. Piaui and $r_{fault} = 100\ \Omega$; (c) 80% compensation, DPG fault at mid span and $r_{fault} = 10\ \Omega$.

B. Switching Overvoltage Analysis

In order to properly evaluate the proposed approach, the statistical scatter with respect to the circuit-breaker operating time ($\Delta T_{statistic}$) must be considered. A description of typical values for this scatter can be found in [1]. $T_{operating}$ is given as a function of the rated operating time of the circuit-breaker (T_{rated}) and $\Delta T_{statistic}$, as follows:

$$T_{operating} = T_{rated} + \Delta T_{statistic} \ . \qquad (12)$$

Variations in the operating conditions, such as: contacts aging and wearing, stored energy of the drive and ambient temperature, can be compensated by sensors or adaptive control [2]. However there are still inherent statistical scatter related to the operating time. These effects are taken into account using a Gaussian probability distribution and a scatter of 2 ms.

TABLE II
MAXIMUM OVERVOLTAGE VALUES WITH PROBABILITY OF OCCURRENCE SMALLER OR EQUAL TO 2% (VBASE = 550 KV).

Operating condition	Maximum overvoltage (p.u.)					
	Closing			Reclosing		
	MOA	PIR	CS	MOA	PIR	CS
80% comp.	2,05	1,60	1,75	2,40	1,80	1,30
58% comp.	2,10	1,70	1,80	2,55	1,85	1,45
29% comp.	2,25	1,85	1,85	2,65	1,95	1,65

MOA - Metal Oxide Arrester.
PIR - Pre-insertion resistor and MOA.
CS - Controlled switching and MOA.

The proposed procedure performance is compared to the pre-insertion resistors method (PIR), using a resistance of 400 Ω and a insertion time of 8 ms, which are typical values used at the Brazilian Power System. Still, for comparison purposes, a situation in which there are only MOA at line ends during the switching operations is evaluated.

For each case, a total of 400 statistical simulations was performed and the maximum overvoltages values along the line, with probability of occurrence smaller or equal to 2%, are shown in Fig. 11. The overvoltages were evaluated at the line ends and at 25, 50 and 75% of its total length. It is observed that the use of PIR or controlled switching (proposed approach) in conjunction with surge arresters limit the switching overvoltages efficiently and the obtaining voltage levels are much smaller than those obtained with surge arresters only.

In order to make the comparative analysis easier, the maximum overvoltages values with probability of occurrence smaller or equal to 2% for each situation considered is shown in Table II. The better results obtained with the proposed approach, which eliminate the need for PIR, were due to the good accuracy on estimating the reference signals ahead in time, which allows the determination of appropriate instants for the circuit-breakers to close.

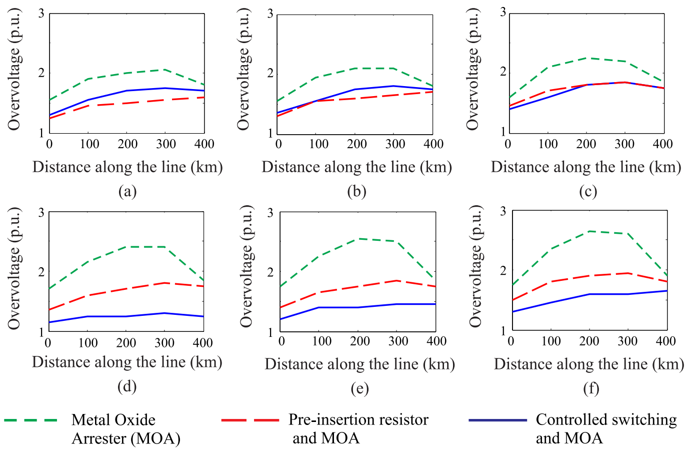

Fig. 11. Overvoltages along the line: (a) Closing (80% compensation); (b) Closing (58% compensation); (c) Closing (29% compensation); (d) Reclosing (80% compensation); (e) Reclosing (58% compensation); (f) Reclosing (29% compensation).

Using the proposed procedure, the line side voltage for a line reclosing is presented in Fig. 12. It is observed that overvoltages are low and that the dead times required to reclose the line were far below the 500 ms typically used, reducing the total time in which the line is out of service.

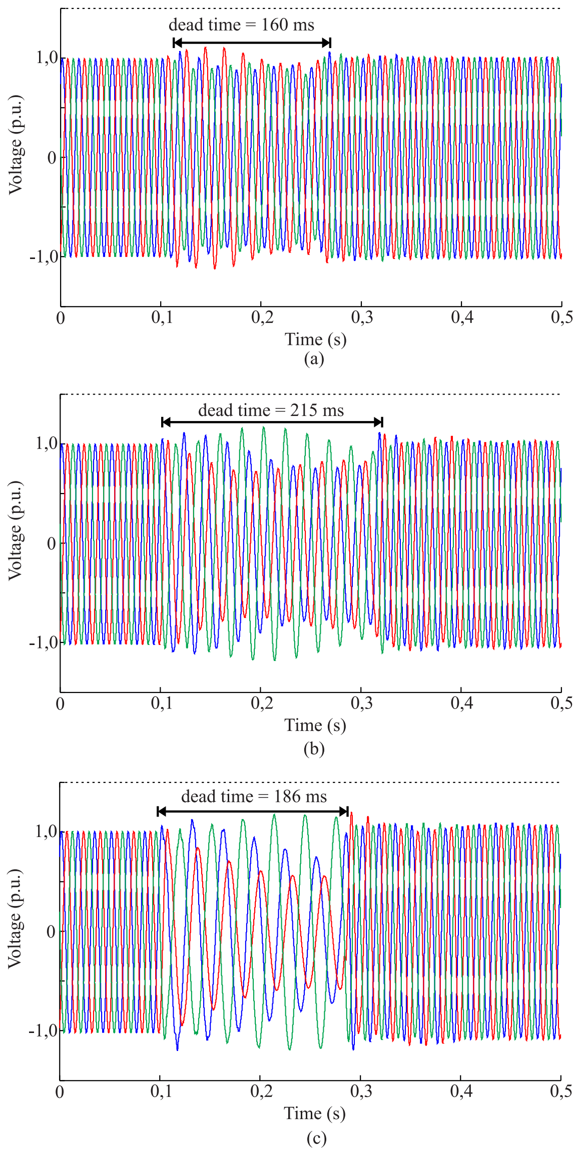

Fig. 12. Line side voltage due to line reclosing. (a) 80% shunt compensated line. (b) 58% shunt compensated line. (c) 29% shunt compensated line.

VI. Conclusion

An analysis of the line side voltage characteristic for shunt compensated transmission lines, including faults along the lines, was performed. Based on this analysis, a procedure for controlled switching of shunt compensated transmission lines was proposed and evaluated by means of digital simulations using the ATP. By using simple techniques for signal analysis, it was possible to identify the extinction time for single and double-phase to ground faults, accurately predict the suitable making instants for line closing and reclosing and to reduce the switchings surges.

The arc extinction time determination may be very important to safely reduce the line dead time and as a consequence reduce the power system restoration time. Still, reclosing the line onto fault can be avoided if the arc has not been extinguished during the line dead time.

Regarding the switching surges mitigation by the proposed approach, at the most suitable situation, the overvoltages were limited to nearly 1.30 p.u. while at the most adverse situation, the overvoltages were limited to 1.85 p.u. For pre-insertion resistors, at the most suitable situation, the overvoltages were limited to 1.60 p.u. while at the most adverse situation, the overvoltages were limited to 1.95 p.u. This indicates that the use of the proposed procedure eliminate the need for PIR, which may reduce the manufacturing and maintenance costs of transmission line circuit-breakers.

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