Evaluation of a Controlled Switching Technique for Transmission Lines with Series Compensation

D. Barros, W. Neves, K. Dantas

***Abstract*—In this work, an existing controlled switching technique for shunt compensated lines is applied to lines with series capacitors banks (SCB) to evaluate the feasibility of this solution to reduce the switching overvoltages. A 500 kV power system is modeled in the Alternative Transients Program (ATP), and different cases of line reclosing due to faults were simulated, considering all SCB operating conditions, i.e., the series capacitor may be either by-passed (partially or completely) or not during a fault. According to the results, one concludes that controlled switching can be applied to series compensated lines, ensuring overvoltages smaller than 1.8 pu, except for one case where the maximum overvoltage was a bit over 2.0 pu. Therefore, some cases must be further investigated due to the presence of DC and subsynchronous signals components, which may pose difficulties in the application of controlled switching as shown for one of the cases presented in this paper.**

***Keywords*—Transmission line, series compensation, trapped charge, switching overvoltages, controlled switching.**

I. Introduction

IN extra-high voltage (EHV) and ultra-high voltage (UHV) systems, the transient switching overvoltages define the insulation level, which has a direct impact on system cost [1]. Therefore, it is fundamental to apply solutions to reduce the magnitude of these switching surges. Controlled switching techniques have been widely used for this purpose. Most of the existing techniques have been developed for shunt compensated lines [2], [3], [4], [5], [6]. However, the number of lines with series reactive compensation has increased. In the Brazilian Interconnected Power System, there are more than 70 lines in extra-high voltage (EHV) and ultra-high voltage (UHV) operating with series capacitor banks (SCB). Thus, it is important to evaluate the feasibility of applying controlled switching to series compensated lines.

The presence of series capacitors affects the line-side voltage waveform. Due to the SCB protection system, the series capacitor may be by-passed, which may pose difficulties on estimation of trapped charge. This is a fundamental step for the successful application of controlled switching in reclosing operations. Besides, when the SCB remains in the line, the trapped charge is not distributed uniformly along the line due to the voltage across the series capacitor [7]. Some works address the application of controlled switching to series compensated lines. In [8], the controlled switching performance is assessed for a purely series compensated line, with SCB in the middle of the line, for reclosing operations due to a phase-to-ground BG fault. In [9], controlled switching is applied to different configurations of series compensated lines, but only reclosing cases not caused by a fault are analyzed. Thus, the influence of SCB protection was not taken into account.

In this work, based on trapped charge analysis, an existing controlled switching technique for shunt compensated lines [6] is extended to series compensated lines for reclosing operations caused by faults. Additionally, the effects of the SCB operating conditions are included. Digital simulations were performed on a 500 kV power system via the Alternative Transients Program (ATP). The switching overvoltages were limited to 1.8 pu for most cases.

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II. Series Compensation in Transmisson Lines

Series compensation consists of the installation of series capacitors in the line and is used to reduce the total series reactance of the line, increasing the transmission capability, improving the system stability, besides other benefits. In Fig. 1, a typical scheme of the SCB is shown.

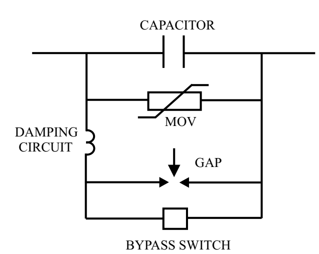

Fig. 1. A typical scheme of series capacitor bank.

The SCB is made up of capacitive elements and a protection system, including metal oxide varistor (MOV), spark gap, damping circuit, and bypass switch. The MOV is responsible for protecting the series capacitor against overvoltages, allowing the SCB to remain in line. However, when the MOV energy dissipation capacity is exceeded, the SCB will be by-passed. The spark gap is specified to operate under such conditions. The SCB total by-pass is obtained by the bypass switch, and the damping circuit is designed to limit capacitor discharge current in such situations.

In Fig. 2, the schemes of lines with series capacitors and shunt reactors evaluated in this work are shown. The influence of the SCB location and its position relative to the shunt reactors in the series capacitor over the line voltage profile has been considered.

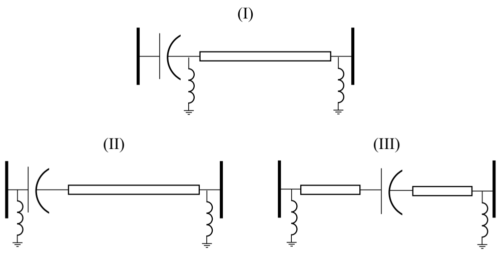

Fig. 2. The schemes of transmission lines with series capacitor and shunt reactor.

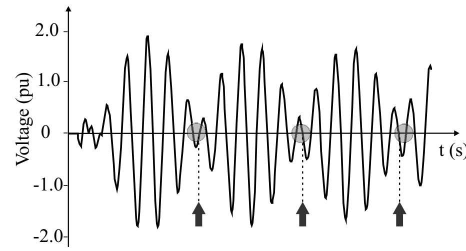

Fig. 4. The voltage across the circuit breaker poles for high shunt compensation degree.

III. Principles of Controlled Switching of Transmission Lines

Controlled switching refers to techniques used for controlling the operation instants of the circuit breakers based on the reference electrical signals in order to reduce the magnitude of the overvoltages [10]. For transmission lines, following de-energization, the optimum instants for closing, during either an energizing or reclosing switching, are zero crossings of the voltage across the circuit breaker contacts. In Fig. 3, a basic controlled switching scheme is shown.

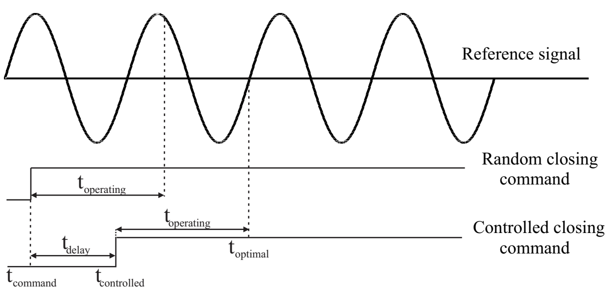

Fig. 3. Controlled switching scheme.

In a typical closing operation, the closing command is given at some random time, $t_{command}$, and after the circuit breaker operating time, its contacts are closed. In the illustrated case, the operation occurs at a time close to the voltage peak. In controlled closing, an intentional delay is given, t_{delay}, to ensure overvoltage reductions, considering the time used for internal operations by the controller and the mechanical closing time of the circuit breaker. For transmission line closing operations, the optimum instants correspond to zero crossing instants of the voltage across the circuit breaker contacts and that is the reference signal, as shown in Fig. 3.

In EHV and UHV transmission system, the most common line arrangement is obtained by employing shunt reactors. In Fig. 4, a typical reference signal for a shunt compensated line with a high degree of shunt compensation after a line opening is illustrated. It has an oscillatory behavior, ranging from 30 to 50 Hz [11]. For a reclosing operation, the optimum instants correspond to zero crossing instants present in regions of minimum beat of the reference signal, as indicated by arrows in Fig. 4.

Although the configuration with shunt reactors is the most common, the number of lines with SCB has increased. However, there are few publications that address the application of controlled switching to series compensated lines [7], [8], [9]. One of its particularities are the SCB operating conditions that may vary due to its protection system, along with the impact on the line trapped charge, and consequently, on the reference signal.

In this work, the use of controlled switching for lines with series capacitors and shunt reactors will be evaluated. For this application, the reference signal has an oscillatory behavior as in shunt compensated lines. The particularities for series compensated lines will be addressed in the next section.

IV. Trapped Charge on Series Compensated Lines

When the line break opens due to a fault, the automatic reclosing occurs after a given time known as dead time, with the presence of the line trapped charge. In shunt compensated lines, the trapped charge has oscillatory and uniform behavior along the line. In cases of lines with series capacitors and shunt reactors, the trapped charge has oscillatory behavior, but the SCB may be partially or completely by-passed due to the fault. Thus, the trapped charge waveform may be affected by the SCB operating conditions.

In this section, the trapped charge waveform on lines with series capacitors and shunt reactors is evaluated. Fig. 5 shows a scheme with the SCB operating conditions when line opening is caused by an internal fault. In this case, the SBC may be by-passed if the MOV energy dissipation capability is exceeded. Therefore, it is necessary to monitor the electrical current and energy of MOV. The by-pass strategy adopted in the present study is typically used by a Brazilian utility [12]. When the by-pass conditions are fulfilled at only one phase, the SCB is partially by-passed. If it occurs in more than one phase, the SBC will be completely by-passed.

For cases with complete by-pass, the trapped charge on the line will be the same for the trapped charge on shunt compensated lines, i.e., it has a uniform characteristic along the line. However, if the by-pass is partial, or the SCB remains in the line, the trapped charge will not be uniform along the line due to the voltage across the series capacitor. These are the cases evaluated by the present paper.

A 550 kV power system with a 400 km long line has been modeled with the ATP, as shown in Fig. 6, to evaluate the trapped charge on series compensated lines. The system data are presented in Tables I, II, and III. The distributed parameter transmission line model was used in this work.

The circuit breaker was modeled based on data from a 550 kV gas circuit breaker, with a rate of decrease of dielectric

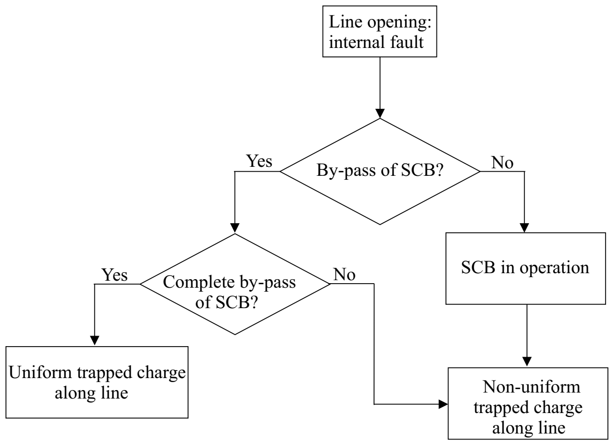

Fig. 5. Scheme with the SCB operating conditions.

strength (RDDS) of 0.9 pu a mechanical scatter of ± 1.0 ms, modeled by a normal distribution function [13]. So, the pre-arcing effects and the mechanical scatter of circuit breaker operating time were considered in the digital simulations.

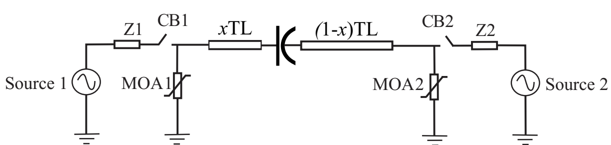

Fig. 6. Scheme of power system implemented in ATP.

TABLE I
SOURCE DATA

Voltage (pu)		Zero sequence		Positive sequence	
1	2	$R_0(\Omega)$	$X_0(\Omega)$	$R_1(\Omega)$	$X_1(\Omega)$
$1\angle 0^\circ$	$0.99\angle -10^\circ$	1.1268	20.838	0.9681	28.513

TABLE II
SEQUENCE PARAMETERS OF THE LINE

Sequence	R(Ω/km)	X (Ω/km)	$\omega C(\mu S/km)$
Zero	0.3996	0.9921	3.0839
Positive	0.0333	0.3170	5.2033

Several cases were simulated to evaluate the trapped charge waveform behavior. However, only some cases were selected in which series compensation either remains in operation or it is by-passed, partially or completely, contemplating all the SCB operating conditions. For all cases, the degree of shunt compensation used was 70%; whereas, for series compensation, 40 and 50%. The faults are applied around 0.9 s, with a duration of 15 cycles. The line opening occurs before 0.2 s, and the fault is cleared around 0.35 s.

For a phase-to-ground CG fault at 100 km from the local terminal of the line with a series compensation degree of 50%, the SCB is partially by-passed in schemes I and II and is not

TABLE III
V-I CHARACTERISTICS OF 420 KV METAL OXIDE ARRESTER (MOA) OF TRANSMISSION LINE AND METAL OXIDE VARISTOR (MOV) OF SERIES CAPACITOR BANK.

Transmission line (MOA)		Series capacitor bank (MOV)	
Current (kA)	V (kV)	Current (kA)	V (kV)
0.001	643.72	0.0001	209.38
0.010	681.23	0.0005	221.87
0.050	721;27	0.001	231.25
0.100	738.70	0.010	238.75
0.200	756.14	0.050	245.75
0.400	775.75	0.100	248.75
0.700	793.18	1.0	259.37
1.000	806.26	10.0	276.87
2.000	830.23	100.0	309.37
5.000	873.81	-	-

by-passed in scheme III. As shown in Fig. 7, the waveform of the trapped charge in phase C in the three schemes is similar to that of the shunt compensated line. In this case, it can be stated that the series compensation did not have a significant impact on the line-side voltage.

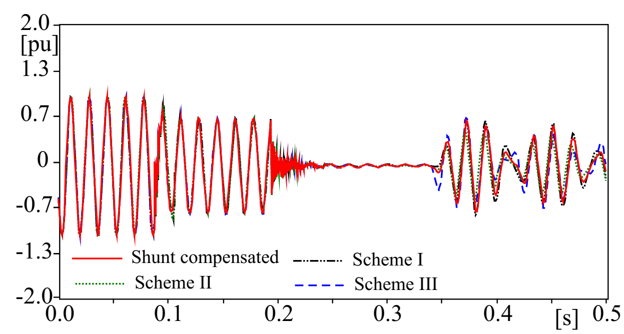

Fig. 7. The trapped charge at local terminal on lines with series and shunt compensation when the line opening is due to a phase-to-ground CG fault (phase C).

For a phase-to-phase BC fault at 100 km from the local terminal of the line with a series compensation degree of 50%, the SCB is completely by-passed in schemes I and II, and is partially by-passed in scheme III. As expected, the trapped charge waveforms for schemes I and II are the same as the one for shunt compensated line as shown in Fig. 8. While for scheme III, there is a small difference due to the voltage across the series capacitors that were not by-passed (phases A and B).

For a phase-to-ground AG fault at 300 km from the local terminal of the line with 40% of series compensation, the SCB was not by-passed in the three evaluated schemes. As shown in Fig. 9, the trapped charge waveforms are similar for schemes II and III, but both of these schemes are different from that of the shunt compensated line. In addition, the presence of subsynchronous components is observed for schemes I and II. In scheme I, there is a DC component. The impact of the series compensation on the trapped charge is better analyzed in Fig.

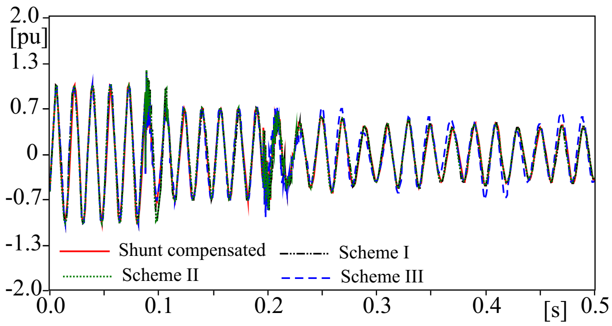

Fig. 8. The trapped charge at local terminal on lines with series and shunt compensation when the line opening is due to a phase-to-phase BC fault (phase B).

10, where the line-side voltages in phase A seen at the local and remote terminals for scheme I are shown. As expected, the trapped charge is not distributed uniformly along the line due to the voltage across the series capacitors, which may affect the efficiency of controlled switching.

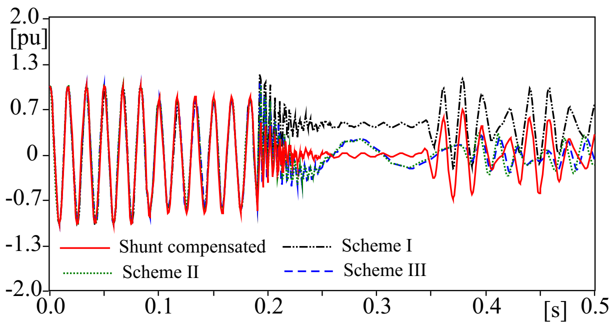

Fig. 9. The trapped charge at local terminal on lines with series and shunt compensation when the line opening is due to a phase-to-ground AG fault (phase A).

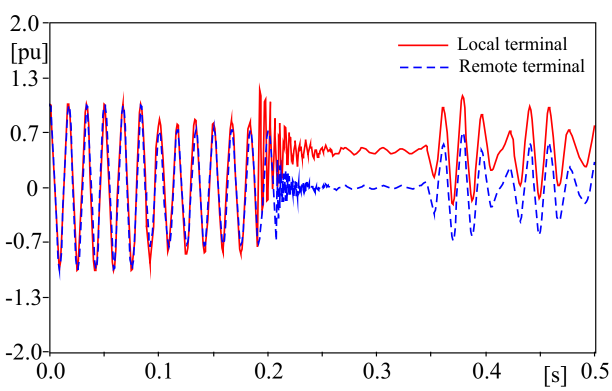

Fig. 10. The trapped charge at local and remote terminals on scheme I when the line opening is due to a phase-to-ground AG fault from 300 km (phase A).

For a phase-to-phase-to-ground BCG fault at 300 km from the local terminal, with 50% of series compensation, the SCB is completely by-passed in scheme I, and partially by-passed in schemes II and III. In Fig. 11, the trapped charge on phase C for all schemes evaluated are shown. The difference is more significant in scheme III. The line-side voltages at local and remote terminals for scheme III (phase C) are shown in Fig. 12. However, when the fault is cleared, about 0.35 s, this difference is not significant.

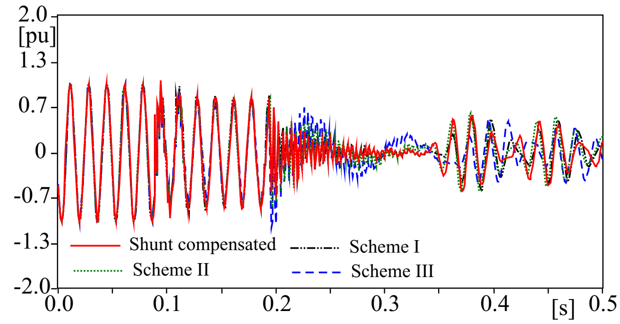

Fig. 11. The trapped charge at local terminal on lines with series and shunt compensation when the line opening is due to a phase-to-phase-to-ground BCG fault from 300 km (phase C).

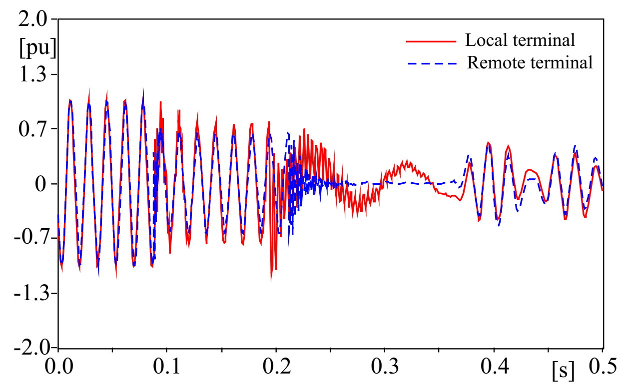

Fig. 12. The trapped charge at local and remote terminals on scheme III when the line opening is due to a phase-to-phase-to-ground BCG fault from 300 km (phase C).

According to the cases presented in this section, the impact of the series compensation on the trapped charge waveform on the line is more significant when the SCB remains on the line, and consequently, the voltage signal seen at the local terminal and that at the remote terminal may be different due to the voltage across the series capacitor. In addition, the line-side voltage signals may have DC and subsynchronous components, which may render the application of controlled switching techniques difficult. Despite the particularities imposed by series compensation, it was found that the trapped charge waveforms on series compensated lines resemble those of the shunt compensated line.

V. Controlled Switching Evaluated Technique

In this work, a technique developed for shunt compensated lines is applied to lines with series and shunt compensation [6]. The method is based on a zero crossing algorithm to estimate the reference signals in the future instants in order to compute the optimum circuit breaker making instants. The main steps of the method are illustrated in Fig. 13.

For this technique, the reference signals are the line and source sides voltage. The first step consists on attenuating the high frequency components - the voltage signals using a third-order Butterworth low-pass filter with a cutoff frequency

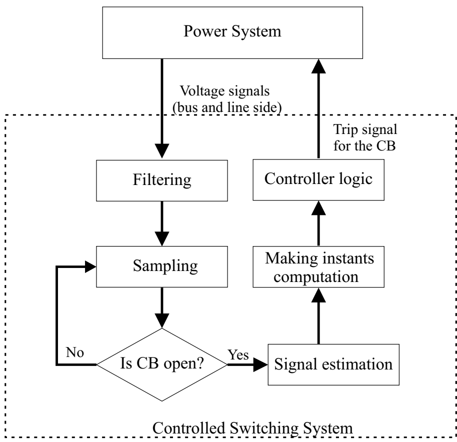

Fig. 13. The main steps of the controlled switching technique selected.

187.89 Hz. Then, the filtered signals are sampled at 960 Hz. When the closing command is given, the reference signals are estimated in future instants based on the detection of zero crossing. Thus, the optimum instants present in the regions of the minimum beat of the reference signals are calculated.

VI. Results and Analysis

In this section, the chosen controlled switching technique is applied for the reclosing of series compensated lines. The same power system presented in Fig. 6 is used, and the same cases shown in the IV section are considered here. The results are presented from the overvoltages profile along the line, where the maximum overvoltages with a probability of occurrence less or equal to 2% have been used for a total of 50 statistical simulations.

The overvoltage curves for the three evaluated schemes are shown in Fig. 14, 15, 16, and 17. For schemes II and III, the overvoltages along the line for all cases are less than 2.0 pu.

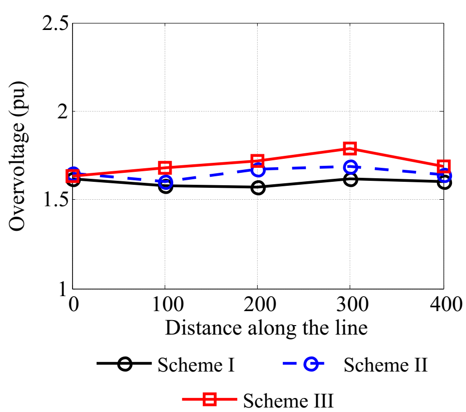

Fig. 14. Overvoltages along the line with series compensation (schemes I, II, and III) when the line opening is due to a phase-to-ground CG fault from 100 km.

For scheme I, when the reclosing occurs due to a phase-to-ground AG fault at 300 km from the local terminal, the maximum overvoltage is more than 2.0 pu. In this case, as shown in section IV, the SCB remains on the line. So, the voltage across the series capacitor causes a significant difference between the line side voltages at the local and

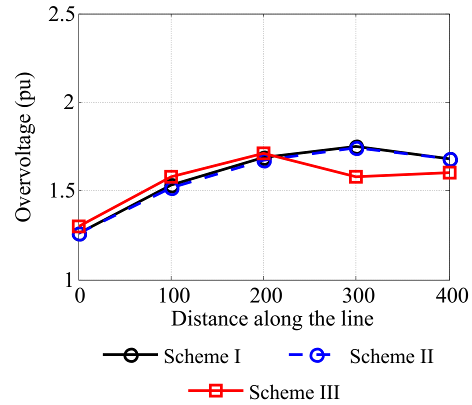

Fig. 15. Overvoltages along the line with series compensation (schemes I, II, and III) when the line opening is due to a phase-to-phase BC fault from 100 km.

remote terminals as shown in Fig. 10. This affects the reference signal to controlled switching - voltage across the circuit breaker. Therefore, the zero-crossing instants determined by the voltages at the local terminal are different from those after the SCB in the scheme I, reducing the efficiency of the controlled switching.

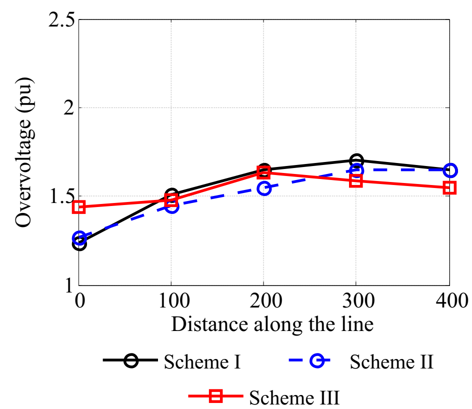

Fig. 16. Overvoltages along the line with series compensation (schemes I, II, and III) when the line opening is due to a phase-to-phase-to-ground BCG fault from 300 km.

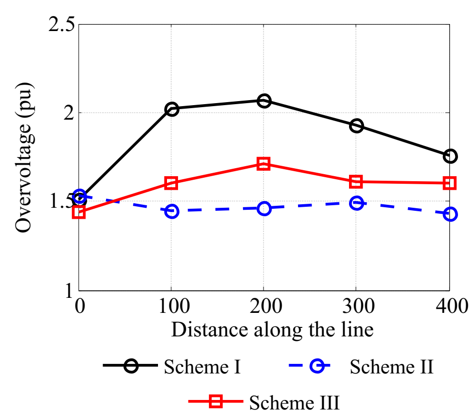

Fig. 17. Overvoltages along the line with series compensation (schemes I, II, and III) when the line opening is due to a phase-to-ground AG fault from 300 km.

In Table IV, the maximum overvoltages for all evaluated cases are presented and compared with the maximum overvoltages when not applied to a controlled switching technique. In satisfactory cases, the overvoltages are reduced by up to 30% with controlled switching. Such results show the potentiality of controlled switching for series compensated lines by applying a technique for shunt compensated lines.

TABLE IV
MAXIMUM OVERVOLTAGES FOR FAULT CASES IN LINES WITH SERIES AND SHUNT COMPENSATION.

Fault cases	Maximum overvoltages					
	Scheme I		Scheme II		Scheme III	
	CS	No CS	CS	No CS	CS	No CS
CG (100 km)	1.62	2.15	1.69	2.32	1.79	2.21
BC (100 km)	1.75	2.22	1,74	2.38	1.71	2.17
BCG (300 km)	1.70	2.22	1,65	2.14	1.63	2.27
AG (300 km)	2.07	2.43	1,53	2.18	1.71	2.20

VII. CONCLUSIONS

In this work, the performance of controlled switching for series compensated lines was evaluated using an existing technique applied to shunt compensated lines and extended to series compensated transmission lines. Three configurations of lines with series capacitors and shunt reactors were analyzed considering the SCB operating conditions, i.e., series capacitors may be by-passed during a fault. According to the presented results, it was verified the potentiality of the controlled switching application to series compensated lines.

It has been observed that the impact of the series compensation on the trapped charge waveform is more significant when the SCB is not by-passed due to the voltage on the series capacitor, which results in a non-uniform distribution of the trapped charge along the line. However, with the application of the controlled switching method, overvoltages smaller than 1.8 pu were obtained, except for a case of phase-to-ground AG fault in scheme I. Therefore, it is interesting to investigate the influence of DC and subsynchronous components due to the presence of the series capacitor in the line in order to further improve controlled switching techniques for this application.

VIII. ACKNOWLEDGMENT

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