Controlled Switching of Transmission Line with Series Compensation

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

***Abstract*—Most existing controlled switching techniques applied on transmission lines were developed for shunt reactor compensated lines. In this work, the effect of series compensation on the controlled switching of transmission lines is evaluated. The assessment is based on simulations on a 500 kV transmission line using ATP (Alternative Transients Program). Three-phase reclosing operations without fault occurrence on the line are analyzed. Several series compensation schemes are evaluated. From the results obtained, one can see that the controlled switching algorithms used in uncompensated lines are suitable for series compensated lines. Furthermore, controlled switching algorithms used in shunt reactor compensated lines are suitable for series compensated lines with shunt reactors.**

***Keywords*: transmission lines, series compensation, transient overvoltage, controlled switching, shunt compensation.**

I. Introduction

IN extra-high voltage (EHV) and ultra-high voltage (UHV) power transmission system, switching transient overvoltages determine the insulation level which has a direct impact on the costs of transmission systems [1]. Switching surges are unavoidable, which calls for the application of a set of procedures in order to reduce their magnitude. Thanks to many technological advancements in the area of sensors and digital relays [2], controlled switching techniques have gained increased importance in recent years – from the late 1990's to present days.

Controlled switching is the term used to describe the use of electronic devices for controlling the operation of circuit breaker contacts – during either its opening or its closing – by monitoring reference signals [3]. Several techniques covering a variety of applications have been reported in the literature. In order to secure the success of controlled switching, it is important to consider a number of factors, ranging from the system operating conditions to the actual features of the circuit breaker. In long transmission lines, the line length and the degree of reactive compensation strongly affect the surges waveforms [1].

Most techniques have been developed for use in shunt compensated lines [4], [5], [6], [7]. However, the number of series compensated transmission lines has increased in such a way that it has become most important to consider the application of controlled switching to these lines.

This paper presents an evaluation of the impact of series compensation on controlled switching of transmission lines. Three-phase reclosing operations on a 500 kV line were performed on the ATP. The series compensation is modeled as a lumped capacitive element. Different configurations regarding the placement of the series capacitor along the line have been analyzed, including configurations with shunt reactors.

II. Basics on Controlled Switching

During typical closing operations, the closing command is given at some random instant, $t_{command}$, so that after the circuit breaker operating time, $t_{operation}$, the contacts will be closed. In controlled closing, the command is delayed so as to ensure that closing will occur only at zero crossing of the reference signal, reducing the generated surges. In Fig. 1, a diagram illustrates the sequence of events following controlled switching.

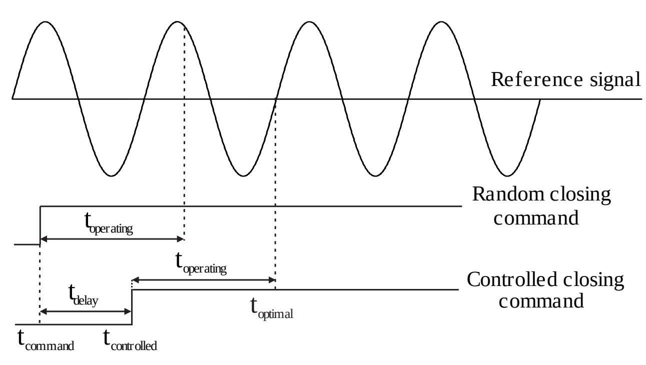

Fig. 1. Controlled switching scheme.

To ensure the efficacy of controlled switching, it is essential to know the main features of the circuit breaker. The mechanical scatter of contacts and the breaker's rate of decrease of dielectric strength (RDDS) can cause deviations in the optimum closing instants [8]. The mechanical scatter

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corresponds to statistical variations in the circuit breaker operating time which is a limitation inherent to controlled switching. At the same time the RDDS is associated to the decrease of the withstand voltage during closing operation. Hence, circuit breakers used in controlled switching should exhibit low mechanical scatter and high RDDS.

The present work features transmission line reclosing operations. The closing optimal instants are those which occur at zero crossing of voltage signals across the circuit breaker poles. In general, these operations take place during some unexpected interruption of power supply, so that automatic reclosing will get the system back to operation as quickly as possible. Due to a delay at the outset of the circuit breaker closing contact – known as dead time – the line remains off for 0.5 to 1.5 s [9].

By disconnecting an unloaded line, the current will be interrupted only at zero crossing, i.e. at its maximum voltage. On uncompensated lines – due to its predominantly capacitive behavior – the trapped charge will remain around ± 1.0 pu along several cycles. At the presence of shunt reactors, the trapped charge decay time will depend on the degree of shunt compensation. In this case, the trapped charge will assume an oscillatory behavior caused by the exchange of energy between the line capacitance and the reactor's inductance.

The strategy adopted for controlled switching is not so simple due to the presence of trapped charge. On uncompensated lines, as the trapped charge remains around ± 1.0 pu along several cycles, the optimum instants are those of either minimum or maximum voltages, depending on trapped charge polarity, as shown by the arrows in Fig. 2.

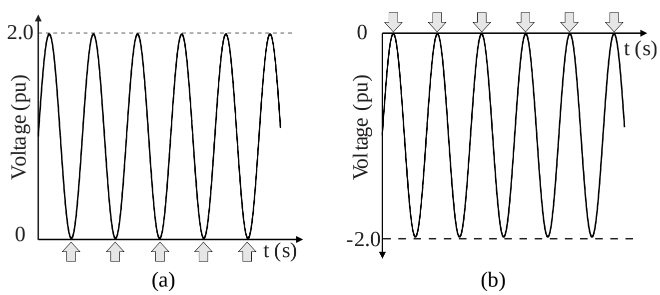

Fig. 2. Voltage across the circuit breaker poles for shunt reactor compensated line with trapped charge with: (a) negative polarity; (b) positive polarity.

Due to the oscillatory behavior of trapped charges in shunt reactor compensated lines, the optimal making instants will correspond to zero-crossing instants present in regions of minimum beat of signal to make sure that closing will occur at low voltages in spite of inaccuracies during operation instants. The higher the degree of compensation, the better defined will be the regions with a minimum pulse of the reference signal. Such occurrence makes it easier to select the closing optimal instants, as shown by the arrows in Fig. 3.

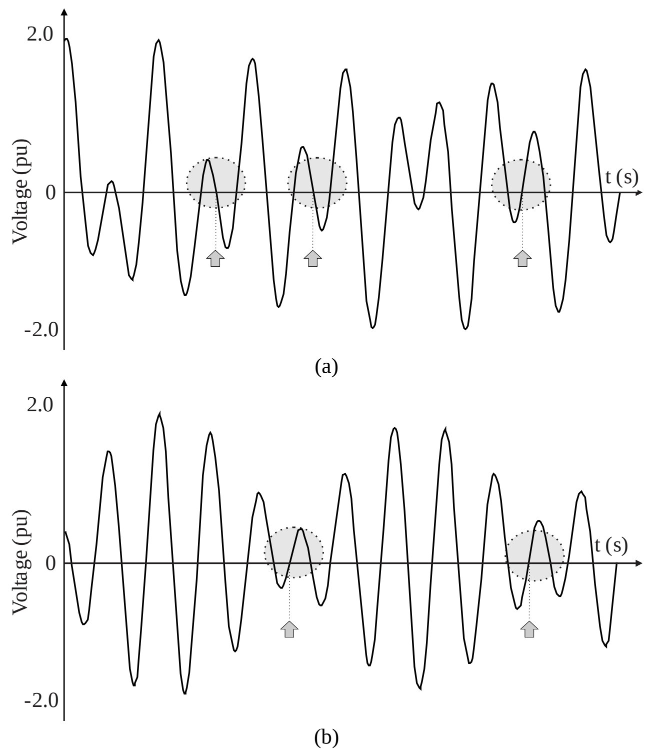

Fig. 3. Voltage across the circuit breaker poles for: (a) high shunt compensation degree; (b) low shunt compensation degree.

A. Controlled Switching Technique

In this paper, we have used a controlled switching technique developed for use on uncompensated and shunt reactor compensated transmission lines [4]. This technique is used in reclosing operations of lines with series compensation in order to assess both its feasibility and the impact of series compensation on controlled switching.

The technique is based on zero crossing of reference signals (line side and source side voltage signals) to predict the optimum instants of closure. The stages of this technique: (i) filtering and sampling of reference signals; (ii) polarity and zero crossing detection; (ii) reference signals estimation and making instants calculation; (iii) and controller's logic.

The filtering stage is carried out with the purpose of eliminating high frequency components. A third-order Butterworth low-pass filter with cutoff frequency of 187.89 Hz is used [4]. After filtering, the signals are sampled. The sampling frequency is 960 Hz, which it is commonly used on digital relays [10].

During reclosing of lines with shunt reactive compensation, the detection of the zero crossing of line side and source side voltage signals is carried out. For uncompensated lines, the detection of trapped charge polarity is performed. Then it is possible to determine the amplitude and the period of reference signals.

At the moment when the switching command is given, based on the latest values determined for amplitude, period and zero crossing, one can estimate the reference signals for future instants. From this, it is possible to predict a set of optimal instants.

The controller's logic is to delay the moment of the breaker's closing command so that the operation will take place at the optimum instant. In order to reduce the effect of electromagnetic coupling between the phases, the instants are chosen in such a way that the interval between the closing of the first phase and that of the last phase will be the least possible.

III. Series Compensation on Transmission Lines

Series compensation is implemented through the installation of series capacitor banks along a transmission line. In Brazil, the National Interconnected System has already installed more than 40 banks of series capacitors [11].

A typical value to the degree of series compensation may range from 50%, to 80% at most. Such degree of compensation is given by the ratio between capacitive bank reactance, X_c, and total line series reactance, X_l:

$$k_{series} = \frac{X_c}{X_l} \tag{1}$$

A. Series Capacitor Bank

A series capacitor bank is not merely an arrangement of capacitive elements; it includes a protection system against overvoltages. Fig. 4 shows a typical scheme of a series capacitor bank [12]. The protection system includes a metal oxide varistor (MOV), spark gap, damping circuit, and bypass switch.

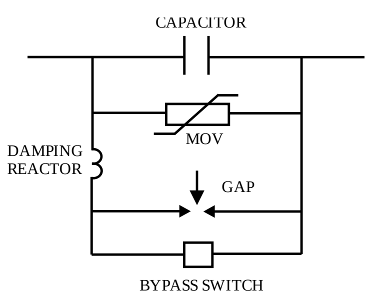

Fig. 4. Typical circuit of series capacitor bank.

A capacitor bank protection system is usually designed in two parts: (i) finding the MOV ratings; (ii) specifying the bypass control strategy [13]. For the first part, the energy and voltage MOV ratings are defined by external faults. An external fault is the one that does not occur in the same line section where the series capacitor is installed. The bypassing strategy is defined by internal faults, i.e. faults located inside a series compensated line.

In case of external faults, the bank protection is covered by the MOV. In case of internal faults, the series capacitor is allowed to be bypassed if the MOV energy setting value is exceeded. The damping circuit is designed to discharge the capacitor in such situations.

For the series compensated lines controlled switching, the operating conditions of the capacitor bank make it difficult to estimate the line side voltage [14] – a key step for the correct calculation of the optimal making instants.

The location of the capacitor bank on the transmission line represents an important issue in series compensation. In general, the optimum position of the capacitor bank is the center of the transmission line [15],[16]. This will secure the most effective use of series capacitive reactance. However, other alternatives may also be considered: such as positioning it at the line terminals or at a given distance from the terminals. The first alternative is by far the most economically feasible, since the series capacitor bank is installed in the substation terminal, rendering installation and maintenance much easier. Thus, selecting the optimum location will certainly depend on a number of factors, including the main features of the power system and the desired application, since the location will certainly have an impact on various aspects: (i) efficacy of series compensation; (ii) voltage profile along the line; (iii) line and capacitor bank protection; and (iv) capacitor bank maintenance [15]. Moreover, when shunt reactors are applied to series compensated lines, their position relative to the series capacitor will be considered. The shunt reactors can be located on the bus side or the line side of series capacitor. Fig. 5 illustrates the schemes of series and shunt compensated lines evaluated in this paper.

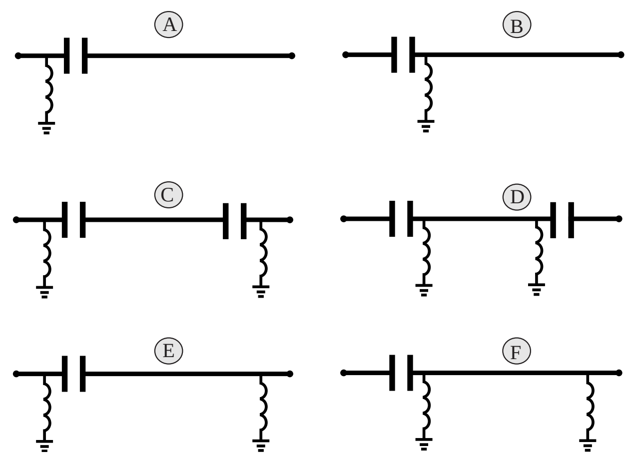

Fig. 5. Schemes of series and shunt compensated lines.

IV. Simulations

An assessment of the effect of controlled series compensation in transmission lines controlled switching is obtained via ATP simulations. Three-phase reclosing operations are simulated in a simplified electrical system based on data from a Brazilian 500 kV North-Northeastern System. Then the electrical system data used for the case studies are presented together with the methodology employed to evaluate the effect of series compensation on controlled switching.

A. Electric System Data

The electric power system used in all case studies was that of a 500 kV line, 400 km long, with two voltage sources and their equivalent impedances. The system's schematic diagram is illustrated in Fig. 6. Metal oxide arresters are connected at both line terminals. Tables I, II, III, and IV present the system's data.

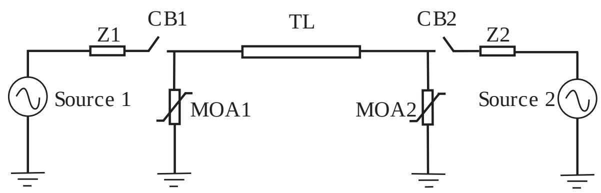

Fig. 6. Scheme of power system used in the cases studies.

TABLE I
SEQUENCE PARAMETERS OF THE LINE

Sequence	R (Ω/km)	X (Ω/km)	ωC (μ℧/km)
Zero	0.3996	0.9921	3.0839
Positive	0.0333	0.3170	5.2033

TABLE II
V – I CHARACTERISTIC OF 420 KV METAL OXIDE ARRESTER

Current (kA)	Phase-to-ground voltage (kV)
0.001	643.72
0.010	681.23
0.050	721.27
0.100	738.70
0.200	756.14
0.400	775.75
0.700	793.18
1.000	806.26
2.000	830.23
5.000	873.81

TABLE III
SOURCE VOLTAGE (V_{BASE} = 550 KV)

Source	Amplitude (pu)	Phase (º)
Source 1	1.00	0
Source 2	0.99	-10

TABLE IV
SOURCE IMPEDANCE

Source	Zero sequence		Positive sequence	
	R_0 (Ω)	X_0 (Ω)	R_1 (Ω)	X_1 (Ω)
Source 1	1.1268	20.838	0.9681	28.513
Source 2	1.1268	20.838	0.9681	28.513

B. ATP Simulations

On the ATP simulations, the series compensation is modeled as a lumped capacitive element so that the entire closing operation will be held on the transmission line.

Three-phase reclosing operations are simulated under different operating conditions: lines with series compensation only, and lines with series and shunt reactor compensation. In the cases of series and shunt compensated lines, the schemes showed in Fig. 5 are evaluated, considering the following locations of the shunt reactor relative to the series capacitor: (i) bus side series capacitor; (ii) line side series capacitor. Moreover, two degrees of compensation are considered: 50% and 70%.

In order to model the circuit breaker, data from a 550 kV gas circuit breaker were used: closing time standard deviation of 0.30 ms and RDDS (Rate of Decrease of Dielectric Strength) of 0.9 pu [17].

Results will be presented from the overvoltages profile along the transmission line, where the maximum overvoltages values with probability of occurrence equal or less to 2% have been used [18]. For each case evaluated, 100 statistical simulations were performed.

V. RESULTS AND ANALYSIS

The assessment of series compensation in controlled switching comprises two parts. Firstly, we evaluate the effect of series compensation on controlled switching of lines with series capacitors only. Secondly, we evaluate the cases of lines with both series capacitors and shunt reactors.

1) Purely series compensated lines

In the case of purely series compensated lines, three configurations are assessed: (i) a series capacitor only in the line sending terminal; (ii) a series capacitor only in the line receiving terminal; (iii) a series capacitors at both ends of the line, as indicated in Fig. 8. Fig. 9 shows the overvoltages profiles along the line for the aforementioned cases.

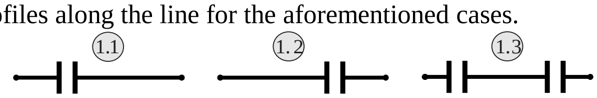

Fig. 8. Schemes of purely series compensated lines.

Fig. 9(a) shows all overvoltage curves for the three configurations evaluated, taking into account the 50% compensation degree. For all three configurations analyzed, we have observed that the controlled switching was satisfactorily applied; similar to that observed on the uncompensated lines. The same has been observed in lines with 70% series compensation, as shown in Fig. 9(b).

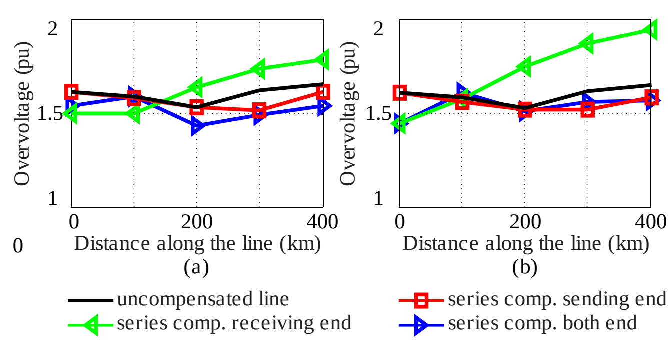

Fig. 9. Overvoltages along the purely series compensated line with: (a) 50% series compensation; (b) 70% series compensation.

Among all configurations evaluated, the line with only series capacitor at the line receiving terminal exhibited the highest overvoltage values, as described in Table V. For the uncompensated line, the maximum overvoltage was 1.65 pu.

TABLE V
MAXIMUM OVERVOLTAGES VALUES ON PURELY SERIES COMPENSATED LINES

Operating condition	Maximum overvoltages (pu)		
	Series capacitor at:		
	Sending end (1.1)	Receiving end (1.2)	Both ends (1.3)
50% comp.	1.59	1.78	1.61
70% comp.	1.61	1.95	1.61

2) *Line with shunt and series compensation*

For lines presenting both types of compensation, the following settings have been evaluated: (i) series and shunt compensation in only one line terminal; (ii) shunt and series compensation at both line terminals; (iii) shunt compensation at both line terminals, and series compensation in only one line terminal.

In all cases, the position of the shunt reactor relative to the series capacitor has been investigated, including: (a) the shunt reactor on the line side series capacitor; (b) the shunt reactor on the bus side series capacitor. The overvoltages profiles along the line are presented with a fixed value to shunt compensation in order to evaluate the series compensation influence.

Fig. 10 shows all overvoltages curves along the line for the compensation reactive schemes presented in Fig. 11.

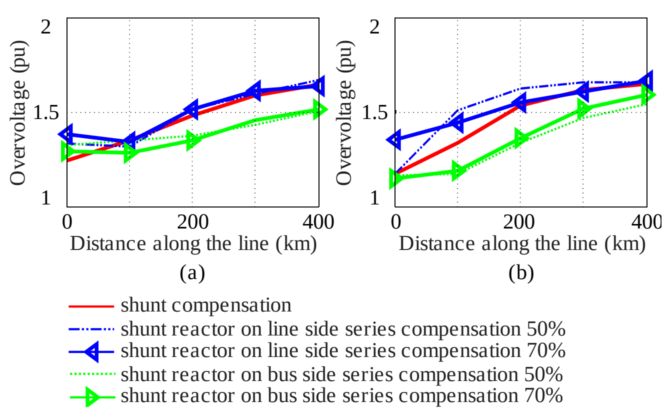

Fig. 10. Overvoltages along the line: (a) 50% shunt compensation; (b) 70% shunt compensation.

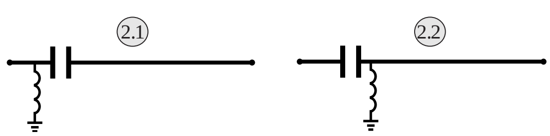

Fig. 11. Schemes of series compensated lines with shunt reactor at line sending terminal.

It has been observed that for all the cases evaluated, the efficacy of controlled switching was most satisfactory, reducing overvoltages to less than 2.0 pu. Besides, for configuration with shunt reactors on the bus side series capacitors, surge reduction was seen to be far more significant than the reduction obtained for the line with only shunt compensation. As regards the compensation degree for both shunt and series compensation there has been observed no significant difference where the reduction of overvoltages is concerned. This is illustrated in Table VI, where the maximum overvoltage values for each configuration are presented.

TABLE VI
MAXIMUM OVERVOLTAGES VALUES ON SERIES COMPENSATED LINES WITH SHUNT REACTOR AT LINE SENDING TERMINAL

Series Compensation	Shunt Compensation			
	50%		70%	
	Bus side (2.1)	Line Side (2.2)	Bus side (2.1)	Line side (2.2)
50%	1.50	1.66	1.59	1.66
70%	1.52	1.64	1.54	1.65

Fig. 12 shows overvoltages profile curves along the line with reactive compensation at its receiving terminal. The schemes are shown in Fig. 13.

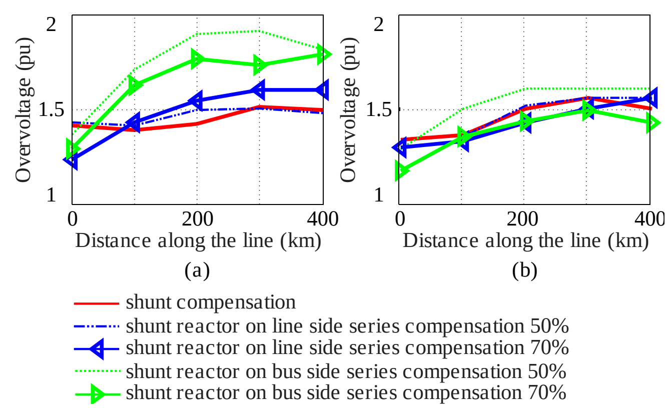

Fig. 12. Overvoltages along the line with reactive compensation on receiving terminal: (a) 50% shunt compensation; (b) 70% shunt compensation.

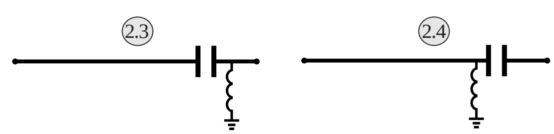

Fig. 13. Schemes of series compensated lines with shunt reactor at line receiving terminal.

In all cases, overvoltages were kept below 2.0 pu, with efficacy comparable to that obtained in shunt compensated lines. The highest overvoltages were observed for all cases where the compensation shunt was 50%, with the shunt reactor on the bus side of series capacitor. Table VII shows the maximum values of overvoltages for the cases investigated.

TABLE VII
MAXIMUM OVERVOLTAGES VALUES ON SERIES COMPENSATED LINES WITH SHUNT REACTOR AT LINE RECEIVING TERMINAL

Series Compensation	Shunt Compensation			
	50%		70%	
	Bus side (2.3)	Line Side (2.4)	Bus side (2.3)	Line side (2.4)
50%	1.91	1.51	1.48	1.55
70%	1.79	1.60	1.60	1.55

Fig. 14 shows the maximum overvoltages values along the line of the configurations with reactive compensation at both line terminals. The schemes are shown in Fig. 15.

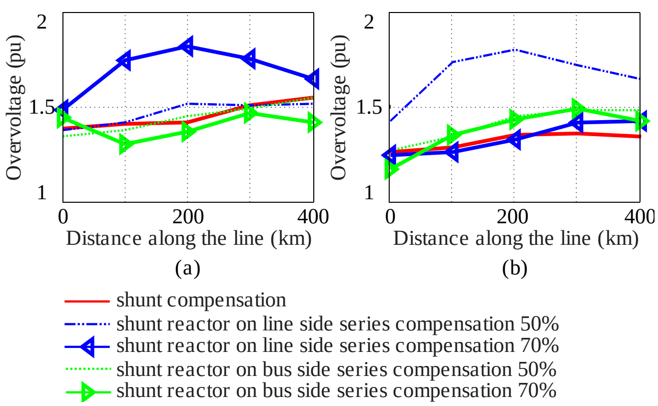

Fig. 14. Overvoltages along the line with reactive compensation at both line ends: (a) 50% shunt compensation; (b) 70% shunt compensation.

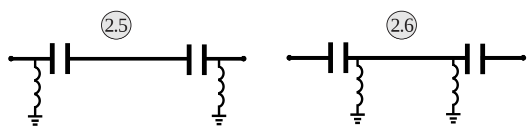

Fig. 15. Schemes of series compensated lines with shunt reactor at both line terminals.

As observed, in most cases, overvoltages were less than 1.5 pu. Maximum overvoltages were noticed for configurations with the shunt reactor on the line side of series capacitor as demonstrated by the following cases: lines with 50% shunt compensation and those with 70% series compensation; line with 70% shunt compensation and 50% series compensation. When comparing with the cases that have been previously evaluated, it becomes visible that the overvoltages are smaller when the reactive compensation is equally distributed at both ends of the line, as shown in Table VIII.

TABLE VIII
MAXIMUM OVERVOLTAGES VALUES ON SERIES COMPENSATED LINES WITH SHUNT REACTOR AT BOTH LINE TERMINALS

Series Compensation	Shunt Compensation			
	50%		70%	
	Bus side (2.5)	Line Side (2.6)	Bus side (2.5)	Line side (2.6)
50%	1.55	1.52	1.48	1.42
70%	1.48	1.82	1.48	1.80

Fig. 16 exhibits overvoltages profiles along the line in the cases where shunt reactors is placed at both ends of the line, and a series capacitor is placed only at the line sending terminal. The schemes are shown in Fig.17.

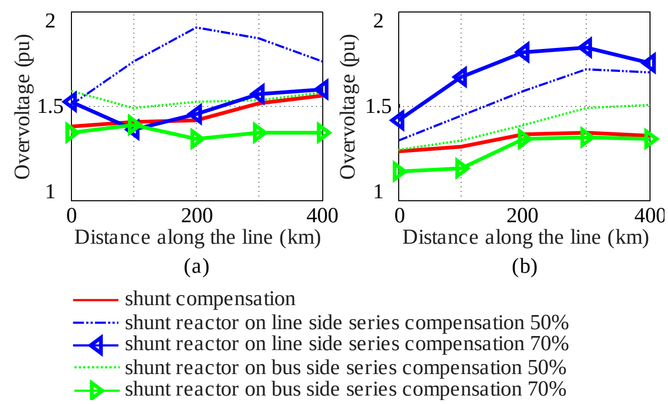

Fig. 16. Overvoltages along the line with series compensation at line sending terminal, and shunt compensation at both line terminals: (a) 50% shunt compensation; (b) 70% shunt compensation.

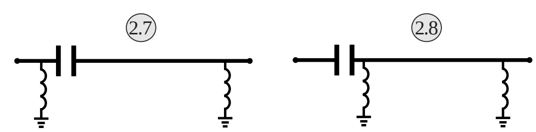

Fig. 17. Schemes of line with series capacitor at sending terminal and shunt reactor at both line terminals.

As shown in Figure 17, controlled switching has been successfully applied to the configurations evaluated. Its performance can be comparable to that obtained in shunt reactor compensated lines. Table IX shows the overvoltage maximum values.

TABLE IX
MAXIMUM OVERVOLTAGES VALUES ON LINES WITH SERIES CAPACITOR AT SENDING TERMINAL AND SHUNT REACTOR AT BOTH LINE TERMINALS

Series Compensation	Shunt Compensation			
	50%		70%	
	Bus side (2.7)	Line Side (2.8)	Bus side (2.7)	Line side (2.8)
50%	1.58	1.91	1.33	1.80
70%	1.40	1.59	1.50	1.69

Lastly, the results obtained for cases in which the shunt reactors are installed at both terminals and the series capacitor is installed only at the line receiving end (Fig. 19), are shown in Fig. 18.

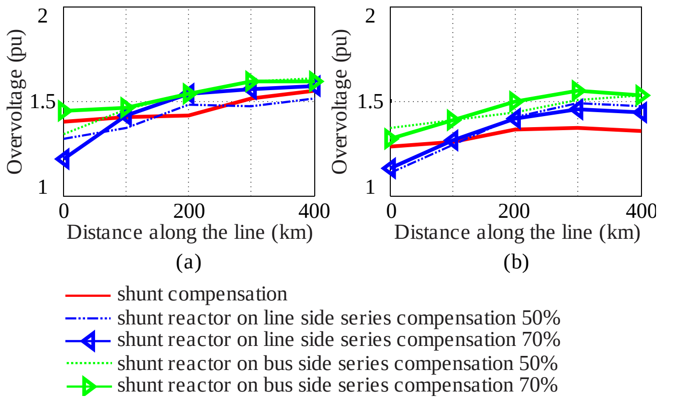

Fig. 18. Overvoltages along the line with reactive compensation on receiving terminal: (a) 50% shunt compensation; (b) 70% shunt compensation.

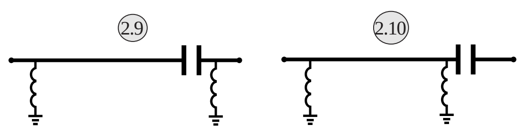

Fig. 19. Schemes of line with series capacitor at receiving terminal and shunt reactor at both line terminals.

The overvoltage reduction was found to be most satisfactory in all cases, with irrelevant differences between configurations. Table X shows the maximum values of overvoltages in the cases studied.

TABLE X
MAXIMUM OVERVOLTAGES VALUES ON LINES WITH SERIES CAPACITOR AT RECEIVING TERMINAL AND SHUNT REACTOR AT BOTH LINE TERMINALS

Series Compensation	Shunt Compensation			
	50%		70%	
	Bus side (2.9)	Line Side (2.10)	Bus side (2.9)	Line side (2.10)
50%	1.62	1.51	1.56	1.46
70%	1.60	1.58	1.53	1.49

For the present study, we have observed that, should the series capacitor remain in operation throughout the reclosing operation, the effect of series compensation in the system would not render unfeasible the application of the same controlled switching strategy adopted for uncompensated lines and shunt reactor compensated lines. However, a series capacitor bank is not only made up of capacitors, but it is also equipped with a protection system against overvoltage.

Generally, series capacitors are protected by the MOV, should there occur external faults. On the other hand, in case of internal faults – if the energy absorbed by the MOV exceeds the predetermined threshold value in the capacitor bank project – the capacitor bank will be partially or completely bypassed. Consequently, the line side voltage signals will be unpredictable, making it difficult to implement an essential stage of the controlled switching: the estimation of these voltage signals.

As a continuation of the present study, we suggest that further series compensation cases should be investigated, enabling us to choose the most appropriate strategies for controlled switching of transmission lines.

VI. Conclusions

The present study evaluated the impact of series compensation on transmission lines controlled switching. This study was motivated by the increasing use of series capacitor banks in transmission systems. Besides, most existing controlled switching techniques were originally developed for use in shunt compensated lines. Simulations of controlled three-phase reclosing operations in a 500 kV line were implemented by using the ATP software. The series compensation was modeled as a lumped capacitive element. Different configurations regarding the allocation of this equipment were evaluated, including the analysis of lines with shunt and series compensation.

A controlled switching technique originally developed for uncompensated and shunt reactor compensated lines was used in this study. Considering the results obtained, we observed that those controlled switching techniques can be applied to series compensated lines as well. For purely series compensated lines, the controlled switching strategy used for uncompensated lines can be applied, ensuring, in this way, a reduction of overvoltage along the line. Moreover, in lines with both shunt reactors and series capacitors, the strategy adopted for shunt reactor compensated lines can also be used to reduce surges. However, for these simulations, only the effect of series capacitance in the system was considered.

Considering the protection system against overvoltages, the capacitor bank operating conditions may be varied, and the capacitor may be partially or completely bypassed. This makes it difficult to estimate the line voltage signals, which would represent a crucial step towards the correct calculation of the optimum closing instants. Therefore, it is important to investigate the operation of the capacitor bank protection system so as to decide on an accurate strategy to secure an effective controlled switching.

VII. Acknowledgements

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VIII. References

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