

On Applying Controlled Switching to Transmission Lines: Case Studies

Karcus M. C. Dantas, Washington L. A. Neves, Damásio Fernandes Jr., Gustavo A. Cardoso, Luiz C. Fonseca

Abstract—The goal of this work is to evaluate the controlled switching method when applied to different transmission lines at the North-Northeast Brazilian Power System Grid taking into account trapped charges and shunt compensation effects. The controlled switching algorithm is implemented in the Alternative Transients Program (ATP) using the MODELS language and its performance is compared to the pre-insertion resistors method by means of EMTP simulations. Situations where transmission lines are transposed and not transposed are considered. The results attest the efficiency of the controlled switching method, limiting switching overvoltages to 1.45 per unit for shunt compensated transmission lines.

Index Terms—Controlled Switching, Electromagnetic Transients, Switching Overvoltages, Transmission Lines

I. INTRODUCTION

CONTROLLED switching is the term used to describe the application of electronic control devices to control the mechanical closing or opening of circuit breaker contacts [1], [2]. It has been a desirable method for stress reduction and in particular for reduction of switching overvoltages, becoming an issue of widespread interest to the utilities and manufacturers [3], [4]. Its benefit and feasibility were presented by CIGRE Task Force 13.00.1, with emphasis on mitigation of switching surges and related economical features due to the reduction of insulation levels of large capacitor banks, elimination of circuit breakers auxiliary chamber, compaction of transmission lines and reduction of arresters rating [5], [6].

Regarding to line circuit-breakers, controlled closing and re-closing may provide an increase of power apparatus life time and improvement on power quality. In addition, it eliminates the need for pre-insertion resistors, and may limit switching overvoltages to acceptable values, especially when used in conjunction with surge arresters [7]. The suitable making instant for controlled switching of an unloaded line is the time in which the voltage across the circuit breaker contacts for each phase is zero and the predicted time span between the closing instant of the first and the last pole is as small as possible [8].

This work was supported by Brazilian National Research Council (CNPq). K. M. C. Dantas, W. L. A. Neves, D. Fernandes Jr. and G. A. Cardoso are with Department of Electrical Engineering at Federal University of Campina Grande, 882 Aprígio Veloso Av, Bodocongó, Campina Grande - PB, CEP: 58.109-970, Brazil. E-mail: (karcus, waneves, damasio, gcardoso)@ee.ufcg.edu.br. Luiz C. Fonseca is with Companhia Hidro Elétrica do São Francisco (CHESF), 333 Delmiro Golveia St, San Martin, Recife - PE, CEP: 50.761-901, Brazil. E-mail: lfonseca@chesf.gov.br.

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This paper aims to evaluate the controlled switching method when applied to different transmission lines at the North-Northeast Brazilian Power System Grid taking into account trapped charges and shunt compensation effects. The method is based on a very simple zero crossing algorithm with constraints and is implemented in the Alternative Transients Program (ATP) [9] using the MODELS language [10].

Controlled switching has been evaluated by means of EMTP simulations using fully transposed transmission lines [8]. Here, situations where transmission lines are not 100% balanced are considered and the controlled switching performance is compared to the pre-insertion resistors method. The results attest the efficiency of the controlled switching, limiting switching overvoltages to 1.45 per unit for shunt compensated transmission lines considering all case studies. Besides, the controlled switching method performed well for both 100% and not 100% balanced transmission lines.

II. CONTROLLED SWITCHING FUNDAMENTALS

Normally, the closing command for the circuit-breaker is 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 ($T_{operating}$). In Fig. 1 it is shown the timing sequence for controlled closing. 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 $t_{command}$.

$T_{operating}$ is the time interval between energizing the closing circuit of the circuit-breaker and the mechanical contact touch. A typical value for this interval is 50 ms. The interval T_{delay} added to the instant $t_{command}$ can be determined by two subintervals:

- $T_{compute}$: internal processing interval of the *Controlled Switching System* to find $t_{optimal}$;
- $T_{synchronize}$: interval for synchronization with predicted $t_{optimal}$, considering $T_{operating}$.

Transmission line re-closing operations are normally performed with trapped charge on the line. For shunt compensated transmission lines, after the line de-energization, the trapped charge presents an oscillating characteristic due to the circuit formed by the line capacitance and the shunt reactors inductance. In this way, according to the degree of compensation, the line side voltage will present a sinusoidal waveshape with a frequency in the range of 30 to 55 Hz.

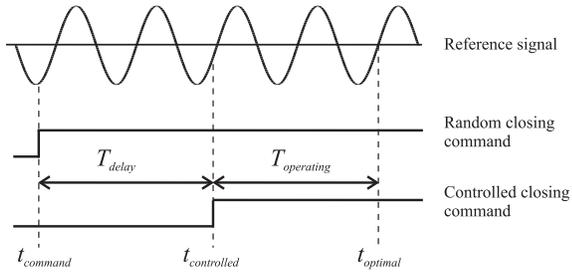


Fig. 1. Schematic controlled closing sequence.

In this case, the reference signal is the voltage across the circuit-breaker contacts, whose waveshape consequently depends on the degree of compensation and presents a non-periodic behavior. For high degree of compensation (Fig. 2), the voltage across the circuit-breaker contacts presents a well defined beat, on the other hand, for lower degree of compensation, a more complex waveshape is observed (Fig. 3). In both cases, the optimal making instants for each phase, which are indicated by arrows in Figs. 2 and 3, occur at the zero crossing and at the beat minimum of the reference signal. Thus, the pre-arcing effects during the closing operation can be minimized, increasing in this way the reliability of the controlled switching. In practice the oscillations on the line voltage will damp out slowly and do not affect significantly the predicted making instants.

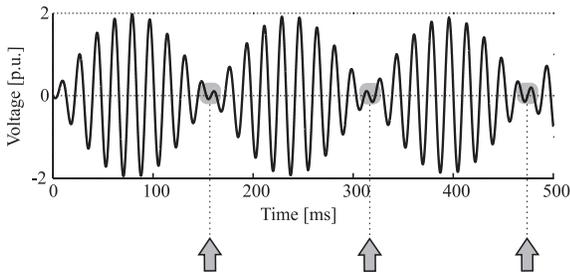


Fig. 2. Voltage across the circuit-breaker contacts for 80% shunt compensated transmission lines.

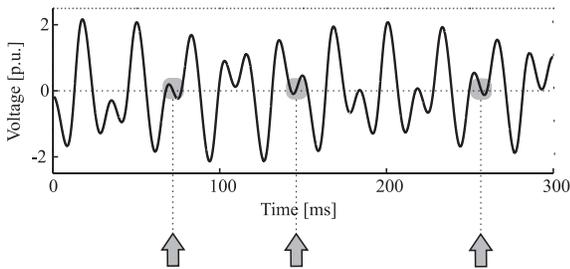


Fig. 3. Voltage across the circuit-breaker contacts for 30% shunt compensated transmission lines.

In order to estimate the optimal making instants for this operating condition and with the aim to reduce the required effort, the line side voltage and the source side voltage are evaluated apart, being necessary the monitoring of both signals. In this way, only sinusoidal signals are evaluated instead of complex signals such as those presented in Figs. 2 and 3. Afterwards, the source side and line side voltage signals are put together in order to obtain the voltage across the circuit-breaker contacts, which is the reference signal.

III. IMPLEMENTATION

The controlled switching method is based on a very simple zero crossing algorithm with constraints. It consists on estimating a reference signal to predict optimal making instants for each phase. These instants are determined in order to reduce the induced voltage at the line side caused by electromagnetic coupling effects. This is accomplished making the time span between the closing instant of the first and the last pole as small as possible [8].

The method was implemented in the Alternative Transients Program (ATP) using the MODELS language, which provides a dynamic interaction with the ATP, allowing the simulation of control devices such as required for the development of this work. MODELS turns the simulations more flexible, allowing the power system to be modified dynamically by means of routines implemented in this language. It is a language for general usage, based on the description of structures (models), with characteristics similar to object oriented programming. These models can be developed separately, grouped in libraries or used in other models as independent blocks [10]. In Fig. 4, it is shown the block diagram used to implement the proposed method for transmission line controlled switching.

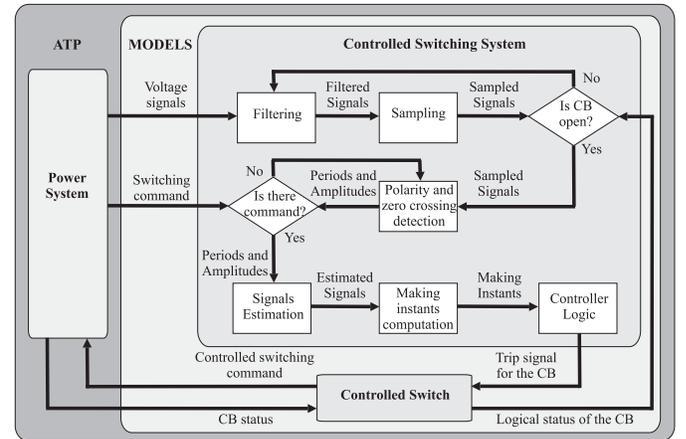


Fig. 4. Block diagram for controlled switching.

The *Controlled Switching System* (CSS), which was implemented in MODELS, receives the voltage signals from the power system (modeled in the ATP). Next, in order to minimize the effect of aliasing as well as to attenuate high frequency components, a third-order Butterworth low-pass filter with a cutoff frequency of 187.89 Hz is employed to the voltage signals [11].

After filtering, the signals are sampled using a rate of 960 Hz, which is commonly used on digital power system protection [12]. According to the sampling theory, this rate is enough to avoid aliasing effect, making possible the evaluation and estimation of the reference signals in future instants without introducing major errors related to signal treatment.

As soon as the line is de-energized it is detected the zero crossing of the source side and the line side voltage signals. A zero crossing is detected every time a voltage signal changes its polarity between two consecutive samples. At this moment, the amplitude of the sinusoidal signals are determined finding the highest absolute value between two consecutive zeros. In

addition, the period of these signals are determined by means of two consecutive zero crossing.

Then, when the switching command is issued and based on the last values determined for the period, amplitude and zero crossing of the sinusoidal signals, the CSS estimates the reference signals in future instants taking into account $T_{operating}$. In this way, a list of possible optimal making instants can be determined for each phase. Now, taking as reference the switching command, which occurs at a random instant $t_{command}$, the *Controller Logic* acts delaying this command for a time interval necessary to accomplish the switching operation of each phase at an optimal making instant in the future ($t_{optimal}$) in a way that the time span between the closing instant of the first and the last pole is as small as possible.

The *Controlled Switch* in the MODELS is responsible for the coordination of the switching command for the switches in the power system modeled at the ATP. These switches emulate the operation of the circuit-breaker. So, when the *Controller Logic* acts, the trip signal for the switches at the ATP is sent by MODELS and the switching command for the circuit-breaker is controlled via digital simulations. Yet, this *Controlled Switch* has the task of indicating the logic state of the circuit-breaker (open or closed) to the CSS, in order that the system may act as soon as the circuit-breaker is opened.

IV. CONTROLLED SWITCHING EVALUATION

The controlled switching method is evaluated by means of digital simulations via ATP. It is analyzed the re-closing of six 500 kV shunt compensated transmission lines at the North-Northeast Brazilian Power System Grid, whose electrical-geographic map is shown in Fig. 5. A dead time of 500 ms was considered for all case studies.

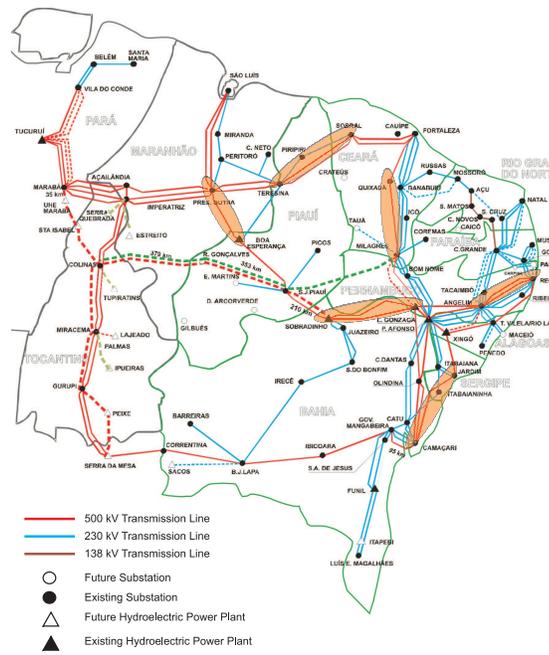


Fig. 5. North-Northeast Brazilian Power System Grid.

The sequence data of the lines as well as its extension are presented in Table I. In Table II, the transmission lines shunt compensation data are presented. The shunt reactors of Lines 1 and 3 have respectively a 150 Ω neutral resistance and a 585 Ω neutral reactor. The neutral of the other shunt reactors are solidly grounded. The reactor winding resistances range from 1.58 to 6.12 Ω . The geometry of Line 6 is shown in Fig. 6 and its conductor data in Table III.

TABLE I
TRANSMISSION LINES EXTENSIONS AND SEQUENCE PARAMETERS.

Lines	Sequence	R (Ω/km)	X (Ω/km)	ωC ($\mu\text{S}/\text{km}$)
Line 1 (169,0 km)	Zero	0,3996	0,9921	3,0839
	Positive	0,0333	0,3170	5,2033
Line 2 (268,7 km)	Zero	0,2416	0,8723	3,4484
	Positive	0,0255	0,2821	5,8808
Line 3 (205,6 km)	Zero	0,3818	1,407	3,246
	Positive	0,0246	0,3219	5,150
Line 4 (319,0 km)	Zero	0,3240	1,3580	2,781
	Positive	0,0227	0,3127	5,159
Line 5 (341,0 km)	Zero	0,2254	0,9437	3,5919
	Positive	0,0170	0,2685	6,2026
Line 6 (248,4 km)	Zero	0,3493	1,3490	3,538
	Positive	0,0252	0,2653	6,2794

TABLE II
SHUNT COMPENSATION DATA.

Transmission Line	Terminal Reactive Power (Mvar)		Compensation Degree (%)
	Sending	Receiving	
Line 1	-	100	45
Line 2	150	150	76
Line 3	200	104	115
Line 4	150	150	73
Line 5	292	146	83
Line 6	-	150	38

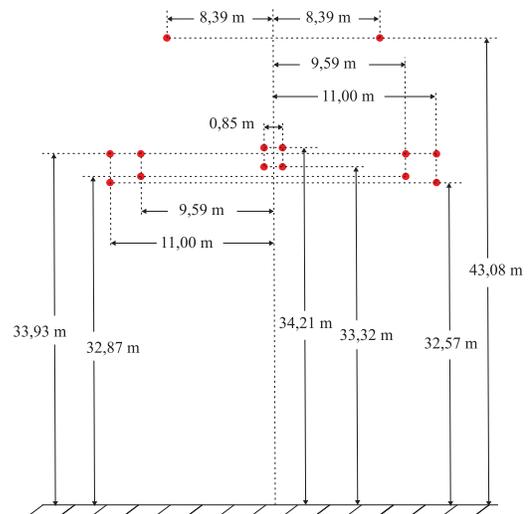


Fig. 6. Geometry of Line 6.

TABLE III
CONDUCTORS DATA OF LINE 6.

Parameters	Phase Conductor	Ground Wire
Type	Grosbeak	EHS 3/8"
Outside diameter (cm)	2,515	0,914
GMR (cm)	1,0211	0,8949
AC Resistance (Ω/km)	0,0996	4,307

A. Case Studies

In order to properly evaluate the method, statistical scatter with respect to the operating time of the circuit-breaker must be considered. In this way $T_{operating}$ is given as a function of the nominal operating time of the circuit-breaker ($T_{nominal}$) and of the statistical scatter on the operating time ($\Delta T_{statistic}$), as follows.

$$T_{operating} = T_{nominal} + \Delta T_{statistic} . \quad (1)$$

The statistical scatter can be represented by statistical switches, modeled at ATP, with a Gaussian probability distribution and described by a standard deviation σ . According to [1], the maximum scatter may be approximated by Equation (2). So, considering a maximum scatter of 2 ms, the standard deviation is approximately 0.67 ms.

$$\Delta T_{statistic} = 3\sigma . \quad (2)$$

Another characteristic that must be considered is the rate of decay of the dielectric strength of the circuit-breaker (dv_{CB}/dt). In order to avoid the pre-arcing effects, it was considered that the dv_{CB}/dt is greater than the maximum value of the power system voltage derivative [13].

For the case studies, the lines 1 to 5 are considered perfectly transposed and modelled using distributed constant-parameters. In addition, the steady-state is adjusted to 550 kV, which is the maximum normal operating condition at the 500 kV Brazilian Power System. The value of 550 kV is used as reference in this paper. For all simulations, 420 kV class metal oxide arresters (MOA) are connected at both terminals of the transmission lines and are modeled according to their V-I characteristic curves obtained from [4]. This MOA is normally used at the 500 kV Brazilian Power System and has a protection level of 830 kV at 2 kA.

The controlled switching performance is compared to the pre-insertion resistor's (PIR) method, using a resistance of 400 Ω and a insertion time of 8 ms, which are typical values used at the Brazilian Power System. The optimum resistor value is determined by means of studies on overvoltages along the lines due to the insertion and short-circuit of the resistors. It was not observed at the simulations significant difference at the voltage profile along the lines when using resistor values between 200 and 400 Ω .

For each case analyzed in this paper, a total of 300 statistical simulations was performed and the maximum overvoltage values along the lines are shown in Fig. 7. In order to make easier the comparative analysis of the used methods for mitigation of switching overvoltages in transmission lines, it is shown in Table IV the maximum overvoltage values for each situation considered.

From these statistical values, it can be observed that the application of pre-insertion resistor or controlled switching together with surge arresters are effective in reducing switching overvoltages along the lines. Among all cases, the maximum overvoltage value using the controlled switching method was 1.45 p.u., while using the pre-insertion resistor this value was 1.80 p.u.

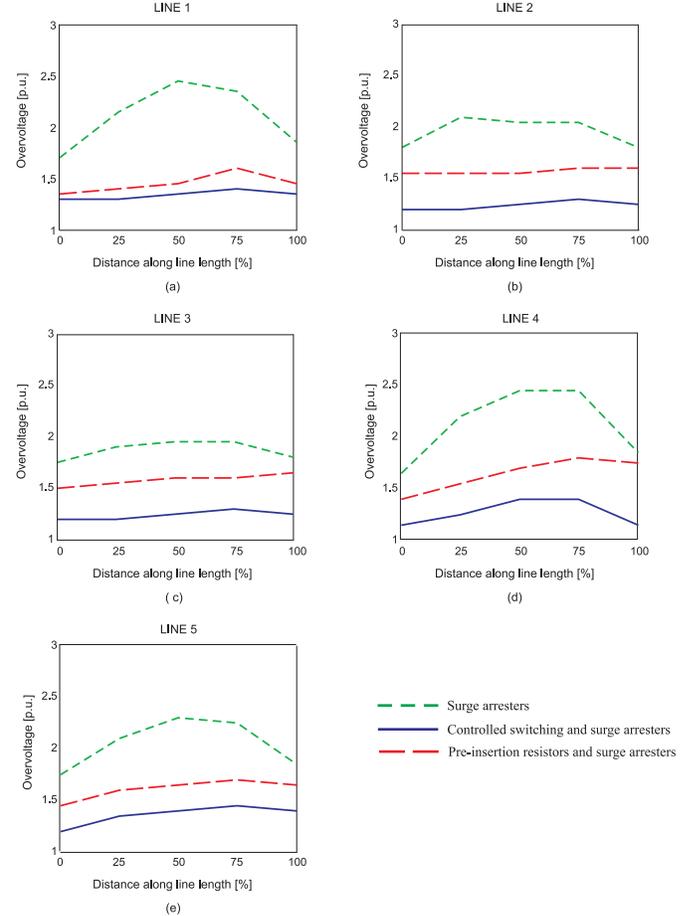


Fig. 7. Overvoltages along the transmission lines: (a) Line 1; (b) Line 2; (c) Line 3; (d) Line 4; (e) Line 5.

TABLE IV
MAXIMUM OVERVOLTAGE VALUES

Transmission Line	Overvoltage (p.u.)		
	MOA	PIR-MOA	CSS-MOA
Line 1	2,45	1,60	1,40
Line 2	2,05	1,60	1,30
Line 3	1,95	1,65	1,30
Line 4	2,35	1,80	1,40
Line 5	2,30	1,70	1,45

MOA - Metal Oxide Arrester.

PIR - Pre-insertion Resistor together with MOA.

CSS - Controlled Switching System together with MOA.

B. Transmission line with three transposition towers

At section IV-A the performance of the controlled switching method was evaluated using perfectly transposed transmission lines. This consideration contributes to the effectiveness of the method due to the fact that the negative and positive line

sequence parameters are the same. So, for shunt compensated transmission lines, the line side voltage after the line de-energization presents mainly only one frequency component, which is related to the positive sequence parameters.

However, in practical situations, the lines are not 100% balanced. On the other hand, at the Brazilian Power System Grid, normally it is used a transposition scheme known as $1/6 - 1/3 - 1/3 - 1/6$, which uses three transposition towers as illustrated in Fig. 8. In this way, the lines are divided into four parts, respectively with $1/6$, $1/3$, $1/3$ and $1/6$ of its length. In this section, the controlled switching method is applied to transmission line with this transposition scheme.

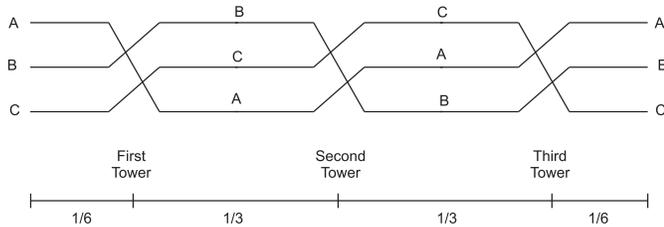


Fig. 8. Transposition scheme $1/6 - 1/3 - 1/3 - 1/6$.

Due to availability of data, Line 6 was used for this purpose. As a matter of comparison, the line was modeled with distributed constant parameters in two different ways: perfectly transposed and not transposed with the transposition scheme above. In Fig. 9 it is shown the line side voltages for the perfectly transposed line re-closing using the controlled switching method. It can be observed that during the re-closing operation, practically there is no overvoltages. In Fig. 10 it is shown the line side voltages for the same re-closing operation considering the line with the transposition scheme of Fig. 8. Once more, during the re-closing operation, practically there is no overvoltages, attesting the efficiency of the method.

In this way, it can be concluded that the performance of the controlled switching method was satisfactory for both cases: lines perfectly transposed and with the transposition scheme $1/6 - 1/3 - 1/3 - 1/6$. In fact, when using this transposition scheme, a certain degree of symmetry is attributed to the line. In this way, as illustrated in Fig. 11, it can be observed that the line side voltages for each phase are practically the same when considering a line perfectly transposed or with the transposition scheme mentioned above. This fact justify the good performance of the method for both situations.

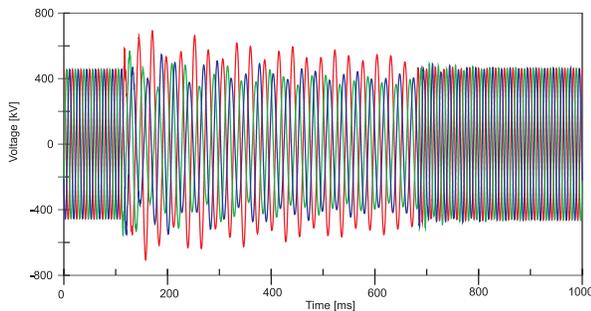


Fig. 9. Voltage signals for re-closing of a line perfectly transposed.

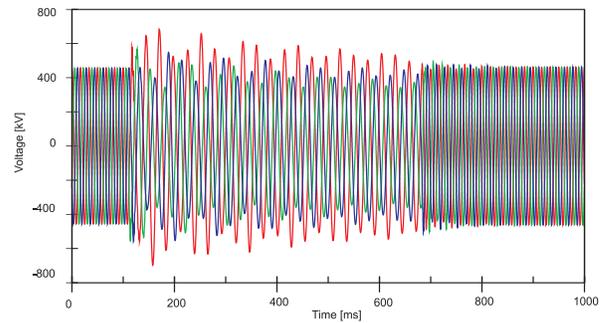
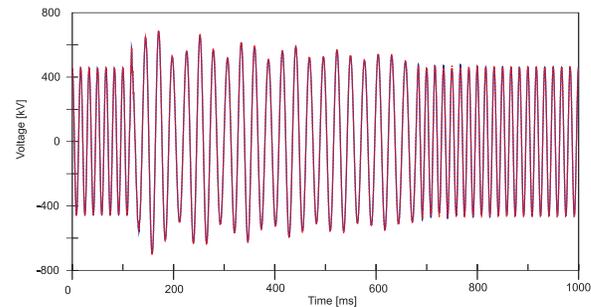
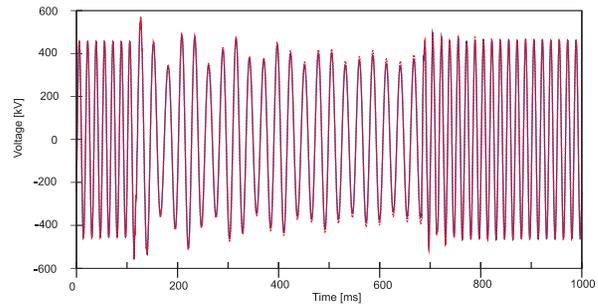


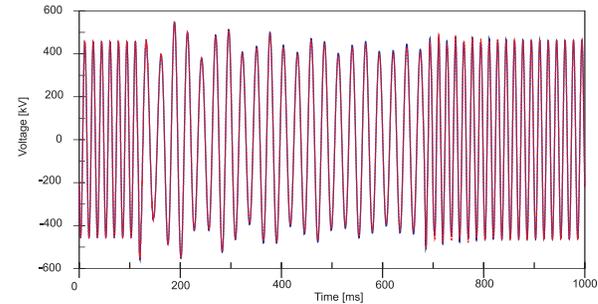
Fig. 10. Voltage signals for re-closing of a line with transposition scheme $1/6 - 1/3 - 1/3 - 1/6$.



(a) Voltage signals at phase A



(b) Voltage signals at phase B



(c) Voltage signals at phase C

— Line perfectly transposed
— Line with transposition scheme $1/6 - 1/3 - 1/3 - 1/6$

Fig. 11. Comparison of voltage signals: line perfectly transposed and line with transposition scheme $1/6 - 1/3 - 1/3 - 1/6$.

In Fig. 12 it is shown an actual oscillographic data for Line 1. It can be observed from this record the occurrence of a single-phase to ground fault, which cause the line de-energization and the line re-closing in the following. After de-energization, the phase with fault presents a voltage signal with

values relatively low, due to electromagnetic coupling effects. On the other hand, the health phases presents an oscillating voltage signal due to trapped charges on the line, similar to a sinusoidal wave with exponential decay. In this way, real situations, like this one, are appropriated to controlled switching method application.

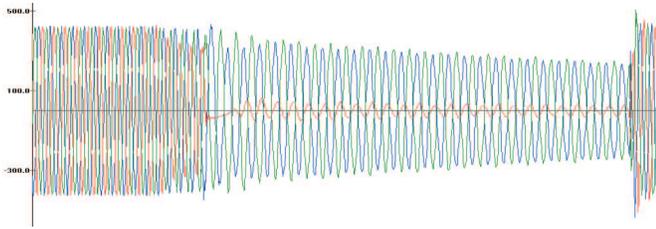


Fig. 12. Actual oscillographic data for Line 1.

V. CONCLUSIONS

The transmission line controlled switching method was evaluated by means of digital simulations via ATP assuming six different transmission lines of the North-Northeast 500 kV Brazilian Power System Grid. The performance of the method was evaluated assuming ideally transposed lines and real case transposed lines, all of them modelled using distributed constant parameters.

The results attest the efficiency of the method in reduce switching overvoltages for perfectly transposed transmission lines as well as for lines with transposition scheme 1/6 - 1/3 - 1/3 - 1/6, independently of the shunt reactor used. In addition, the method is independent of the transmission line model. For all case studies, the maximum overvoltages using the controlled switching method together with surge arresters at line ends were limited to 1.45 p.u. Yet, comparing the controlled switching method with traditional ones, it can be observed that the former has presented better performance than the pre-insertion resistor method. This is due to the fact that for re-closing of shunt compensated lines, the presented method always aims to accomplished the switching at the beat minimum of the reference signal.

An advantage of the controlled switching method is that it intends to avoid switching overvoltages acting directly on the cause of these overvoltages (electromagnetic travelling waves on the lines) which are proportional to the magnitude of the voltage across the circuit-breaker contacts at the closing instant. On the other hand, pre-insertion resistors and surge arresters are intended to fix up the problem limiting the overvoltages already initiated.

As a consequence, controlled closing of transmission lines eliminates the need of pre-insertion resistors, reducing in this way the costs of transmission line circuit breakers and may provide an increase of power apparatus life time and improvement on power quality. Besides, any switching strategy must be used together with surge arresters at line terminals in order to provide better results and security in case of malfunction of the Controlled Switching System.

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Karcius M. C. Dantas (S'04) was born at Campina Grande, Brazil, 1982. He received his B.Sc. and M.Sc. in Electrical Engineering from Federal University of Campina Grande (UFCG), in 2005 and 2007, respectively. He is currently a Ph.D. student at UFCG. His research interest are electromagnetic transients in power systems and power quality.

Washington L. A. Neves (M'95) is an Associate Professor in the Department of Electrical Engineering at UFCG, Campina Grande, Brazil. He received the B.Sc. and M.Sc. degrees in electrical engineering from UFPB, Brazil, in 1979 and 1982, respectively, and the Ph.D. degree from UBC, Vancouver, Canada, in 1995. From 1982 to 1985 he was with FEJ, Joinville, Brazil. He was a Visiting Researcher with the University of Alberta, Edmonton, Canada, from September 2004 to August 2005, and with UBC, Vancouver, Canada, from September to December 2005. His research interests are electromagnetic transients in power systems and power quality.

Damáio Fernandes Jr. (M'05) was born in Brazil in 1973. He received the B.Sc. and M.Sc. degrees in electrical engineering from Federal University of Paraíba, Brazil, in 1997 and 1999, respectively, and the Ph.D. degree in electrical engineering from Federal University of Campina Grande, Brazil, in 2004. Since 2003, he is with the Department of Electrical Engineering of Federal University of Campina Grande. His research interests are electromagnetic transients and optimization methods for power system applications.

Gustavo A. Cardoso was born at Itapetinga, Brazil, 1983. He received his B.Sc. in Electrical Engineering from Federal University of Campina Grande (UFCG), in 2006. He is currently a M.Sc. student at UFCG. His research interest are electromagnetic transients in power systems.

Luiz C. Fonseca was born in Brazil. He received his M.Sc. degree in electrical engineering from Federal University of Pernambuco, Recife, Brazil, in 2003. He is currently with the Companhia Hidro Elétrica do São Francisco (CHESF), Recife, PE, Brazil.