Parametric Analysis of Three-Phase Autoreclosing Method for Compensated Transmission Lines

P. Mestas, M. C. Tavares, A. M. Gole

***Abstract*-- A method to reduce overvoltages due to three-phase reclosing of shunt compensated transmission lines (TL) has been developed, implemented in hardware and validated via testing on a Real Time Digital Simulator (RTDS). After the identification of the type of fault, the algorithm detects the first minimum region of the voltage beating across the circuit breakers (CB). The method works independently of voltage zero crossing, reducing significantly the reclosure time. The present paper reports the parametric evaluation of the method including a large variety of compensation schemes, the transposition influence and the performance of the proposed method compared to the traditional pre-insertion resistor approach and another existing control method.**

***Keywords*: Controlled Switching, Switching Overvoltages, Three-phase reclosing, Shunt compensated transmission lines, Electromagnetic Transients.**

I. INTRODUCTION

ELECTRICAL power networks are dynamic systems, driven by the problem of balancing instantaneous demand and production of electricity. The supply and demand balance problem, coupled with management of faults within the system, requires that parts of any power network need to be switched on and off reliably and on-demand.

Switching operations in power networks are a common cause of transient disturbances. Depending on the network configuration and the characteristics of the switching condition, these transients can cause undesirable effects, not only on the switched load, but also on the entire network. These effects include reduction of equipment lifetime, breakdown of equipment in the substations, and degradation of power quality.

When dealing with transmission lines, an usual solution to this problem consists of using an auxiliary system comprising a so-called pre-insertion resistor in series with a pair of auxiliary contacts, said auxiliary system being mounted in parallel with the cut-off chamber. The auxiliary contacts are actuated a few instants before the contacting of the main contacts so as to insert the closing resistors in the circuit. With this two-step triggering it is possible to reduce closure overvoltages with great efficacy. This first solution, although very effective, has the drawback of being very costly [1], [2].

Controlled switching has become an economical substitute for closing resistors and is commonly used to reduce switching surges. This is a technique that uses an intelligent electronic device to control the timing of closing and opening of independent pole breakers with respect to the phase angle of an electrical reference voltage or current signal [3], [4].

When a single phase fault occurs (which account for more than 90% of line faults) on a high voltage line usually the elimination of the fault involves three-pole opening of the CB followed by almost immediate re-closing in the endeavor to obtain ensured continuity of service.

On reclosing, the CB contacts must be closed at the right time so as to limit overvoltage to an adequate value. This moment varies according to network configuration and must be determined by a closure algorithm in relation to the voltage signals measure on the network and supplied to the algorithm.

In addition, the implementation of this solution must consider important factors such as the existence (or not) of shunt reactive compensation.

It is also important to analyze the type of fault. If the TL is under external fault conditions, the voltage across the breaker shows a prominent beat especially for a high degree of compensation. For this case, the optimum reclosing instant is the voltage minimum across the breaker, i.e. during a period of minimum voltage beat.

On the other hand if the TL is under internal fault, the faulty phase condition influences the signal of the two healthy phases. Consequently, the signals shape obtained across CB are very complex and another analysis approach must be adopted.

The present work is focused on the parametric analysis of developed method for three-phase autoreclosure of shunt compensated TL under external fault conditions. The proposed method evaluates the voltage wave shape across the CB without taking the voltage zero crossings as a reference. With this signal, the detection algorithm is considerably simplified and the optimal instant for reclosing can be found faster. The algorithm was also implemented in hardware and validated via testing on a Real Time Digital Simulator.

The parametric analyses taking into account a variety of shunt compensation schemes, influence of series compensation, influence of different transposition schemes, and comparison of the proposed method performance to the traditional pre-insertion resistor approach and another existing control method are presented in the followings sections.

This work was supported by a grant from the National Council for Scientific and Technological Development (CNPq), CAPES and FAPESP, Brazil, and also through the Industrial Research Chair program of the NSERC, Canada.

P. Mestas and M.C. Tavares are with the School of Electrical and Computer Engineering, University of Campinas (UNICAMP), 13083-250, Campinas, SP, Brazil (e-mail: pmestasv,cristina@dsce.fee.unicamp.br).

A. M. Gole is with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB R3T 5V6 Canada (e-mail: gole@ee.umanitoba.ca).

Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands, June 14-17, 2011

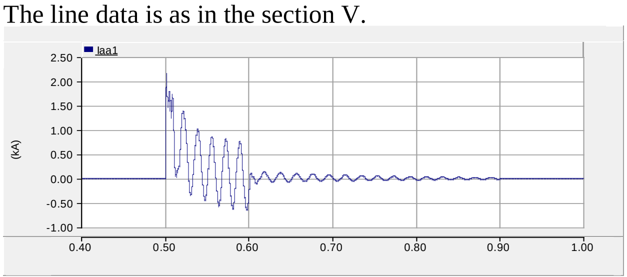
II. THREE-PHASE AUTO-RECLOSING OF TL WITH SHUNT REACTIVE COMPENSATION

For shunt compensated lines, the degree of compensation has an important effect on the voltage waveform across the CB contacts. Due to the oscillatory circuit formed by the shunt capacitance of the transmission line and the shunt compensator's inductance, the voltage across the CB contacts during reclosing is characterized by a beat. This beat occurs because the voltages at each pole have different frequencies, specifically, the system power frequency at source side, and the natural frequency both of the line and compensated equipment at the line side [5]-[8].

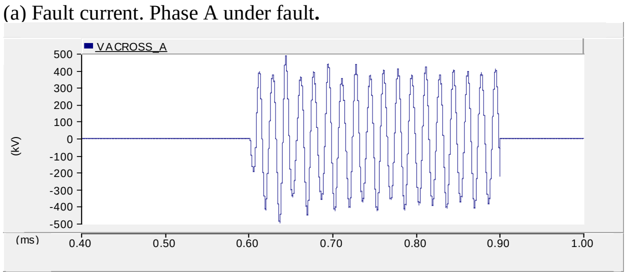
A. *Transmission line under internal fault*

The sequence of events for autoreclosing operations due to internal faults includes: fault occurrence, line tripping by CB of three phases to isolate the section under fault, fault extinction, and finally breaker reclosing to reenergize the line.

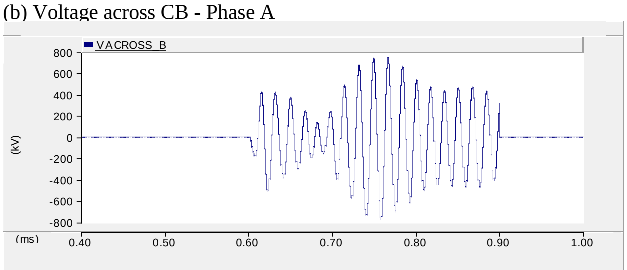
Fig. 1(a) show the fault current during reclosing of a 90 % shunt compensated TL. The three-phase tripping occurs 100 ms after fault. The fault extinction takes around 200 ms. The line data is as in the section V.



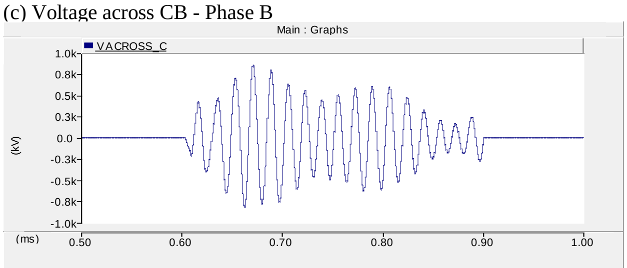
(a) Fault current. Phase A under fault.



(b) Voltage across CB - Phase A



(c) Voltage across CB - Phase B



(d) Voltage across CB - Phase C

Fig. 1. Fault current and voltage waveshape across the CB: 500-kV transmission line with 90% shunt compensation.

Fig. 1 (b)-(d) show the voltage waveshape across CB. The phase A (under fault) influences the signal of the two healthy phases (phases B and C), consequently the signals obtained are very complex and the expected beat is distorted.

B. *Transmission line under external fault*

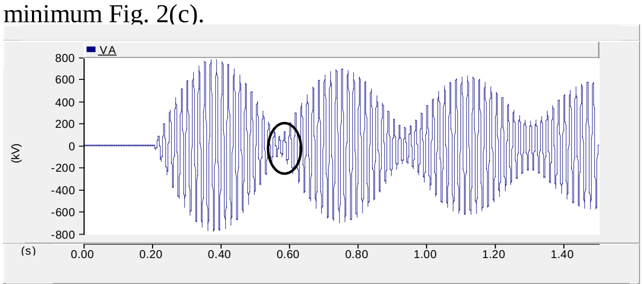
For this case, the sequence of events for autoreclosing operations includes automatic tripping of their associated CBs and subsequent reclosure, after a predetermined time interval. The voltage across the CB shows a clear beat and the waveshape is similar for the three phases.

The beat period depends on the degree of line compensation. In Fig. 2(a)-(c), respectively, waveforms are shown for the voltage across the CB for high (90 %), medium (70 %) and low (50 %) shunt compensation levels.

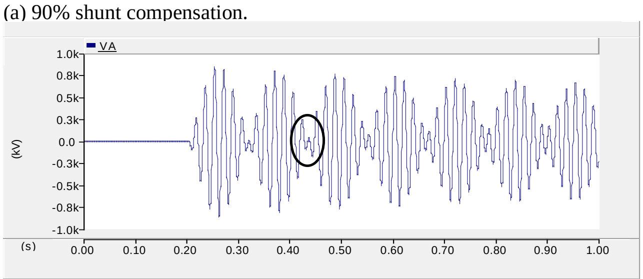
The drainage of the trapped charge produces a reduction of the voltage magnitude over time. This drainage is a function of the reactor quality factor. As a result, the maximum magnitude of the voltage beat tends to decrease and the minimum magnitude of the voltage beat tends to increase.

Based on these conditions, for a high-compensated line, the optimal region for reclosing should be the first minimum voltage beat across the CB as indicated in Fig. 2(a) by a circle.

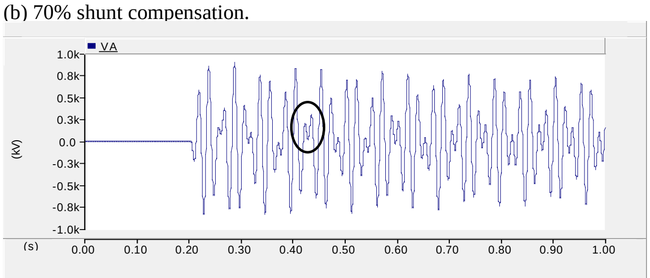
For a lower compensated line, the first minimum of the beat occurs too early. When the dead time for protection actuation is considered, a later minimum must be used. Assuming a typical dead time of 12 cycles of the fundamental frequency, the optimal region for three-phase reclosing corresponds to the second minimum Fig. 2(b) and the fourth minimum Fig. 2(c).



(a) 90% shunt compensation.



(b) 70% shunt compensation.



(c) 50% shunt compensation.

Fig. 2. Optimum making instants for various levels of shunt compensation: 500-kV transmission line.

III. Three-Phase Autoreclosing Method for Compensated Transmission Lines

Currently there is a three-phase autoreclosing method for compensated TL [5, 6] under external fault. This method identifies the region of minimum beat and sends an order to close the CB in the next similar region.

Three conditions must be met for identifying the region with minimum beat amplitude: the zero crossing of the voltage signal at the source side and the line side must occur at the same time, the derivative of both signals must have the same polarity and the amplitude of both signals must be the same.

The period T of the beat is obtained from two successive determinations of the minimum beat instant, and a timer at time T issues the trip signal after the last measurement.

When this approach is used for reclosing the poles reclose after the first minimum beat, which means a longer time with the line out of service; the overvoltage is larger when the poles reclose in subsequent minimum voltage regions and the beat period is difficult to measure when the compensation level is smaller (see Fig. 2c).

A. *Proposed controlled reclosing method*

To overcome the drawbacks mentioned in the previous paragraph, the proposed method [9, 10] sends the closing command appropriately such that the poles closing occurs in the first minimum voltage beat across the CB, after the protection dead time. This method is based on the voltage wave shape across the CB, independent of voltage zero crossing.

The three-phase voltages are continually monitored by potential transformers (PTs). For simulation purposes, the method manipulates actual voltages, but for the implementation at the protective equipment (relay) reduced magnitudes transformed by PTs will be used. PTs were supposed ideals and effects of the measuring have not been considered.

Further, although the system is three-phase, the algorithm needs the voltage of only one phase, which sends a signal to operate the three phases for reclosing at the same instant. This is because the minimum beat location is approximately the same for all three phases, regardless of the level of compensation.

First, the voltage at power system side and the voltage at the line side are measured to determine the voltage waveform V_{brk} across the CB as shown in Fig. 3. With signal processing, the envelope of the curve is determined and becomes the reference signal V_{ref}.

In order to attenuate high frequency components, a Butterworth low-pass filter is employed. The filtered signal V_{ref} will have a delay in relation to V_{brk}. The delay must be corrected. This correction is done automatically within the general algorithm.

Prior to breaker opening, V_{ref} has zero magnitude, so using a threshold comparator is identified the instant of CB contact opening t_{open}.

The beat half-period duration $T/2$ is identified by determination the point t_{max} at which V_{ref} achieves its first maximum.

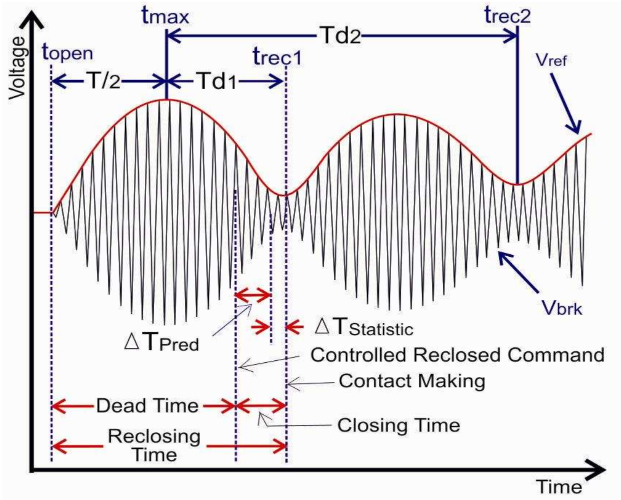


Fig. 3. Identification of optimum instants for TL reclosing

Hence, if the breaker reclosure signal is to be given at the next minimum beat, the delay for closing from the t_{max} instant is $T_{d1}=T/2$. The method has to adapt itself to any degree of shunt compensation. For example when the line is lightly compensated [e.g. as in Fig. 2(b)], $T_{d1}=T/2$ may be too short to process the reclosure signal due to protection dead time. In that case, the delay can be extended to $T_{d2}=3T/2$ where the next beat minimum occurs, or for smaller compensation levels [e.g. as in Fig. 2(c)], even to the following beat minimum time at $5T/2$. Note that unlike previous methods, this method does not rely on the zero crossing of the signal, and the delay to open can be determined well in advance at the point where the beat is at a maximum. A slight correction is made to the computed breaker closing time above to account for CB specific characteristics. This is explained in the following sub-section.

B. *Operating times*

Breaker operating times of real CB vary significantly with breaker type as well as operating and environmental conditions. Some of the operating time variations are predictable and some are purely statistical [11]. As shown at the Fig. 2, the CB reclosing time is expressed as the sum of three terms:

$$T_{rec} = T_{dead} + \Delta T_{Pred} + \Delta T_{Statistic}$$

The protection dead time T_{dead} is the interval of time between energizing the trip circuit to open the CB and the first re-establishment of current in any pole in the subsequent closing operation. The period ΔT_{Pred} is a predictable variation from CB closing coil energization to when the instants at which the mechanical contacts touch. Period $\Delta T_{Statistic}$ is a purely statistical variation of the operating time.

To account for these additional delays, the reclosure signal is reduced from the time T_{d1} obtained by the main control algorithm above by an amount $\Delta T_{Pred} + \overline{\Delta T_{Statistic}}$, where $\overline{\Delta T_{Statistic}}$ is the mean value of $\Delta T_{Statistic}$. This way the breaker closes as close as possible to optimum instant as shown in Fig 2. It is worth mentioning that the temporal proportions are merely illustrative.

C. *Advantages of the Proposed Controlled Switching Method*

The proposed method presents greater reliability in the determination of the *first* minimum voltage beat, after the protection dead time. The reclosing at the first minimum means a shorter out of service time for the transmission line. The reason why this becomes possible is that the determination of the first minimum beat point t_{rec1} (see Fig. 2) begins at the instant of maximum beat t_{max}, well in advance t_{rec1}. The previous method only starts calculation at the point t_{rec1}, so the earliest point to close becomes (approximately) t_{rec2}. Also, as the identification of the optimal closing time is obtained several power frequency periods in advance, this allows additional adjustment, if necessary, to account for poles spread and dielectric characteristics of the CB.

Also, for lower degree of compensation, the voltage across CB presents a less pronounced beat and some zero crossings are omitted [see Fig. 2(c)]. The earlier method based on zero crossing is hence less reliable as the period of the voltage beat may not be easily found. On the other hand, the proposed method is independent of the voltage zero crossing, which makes applicable for any degree of shunt compensation.

D. *Controller implementation in Physical Hardware*

The controller was implemented in a separated Processor Card (3PC) that contains three Analog Device's ADSP−21062 digital signal processors. These are the same cards that used in the RTDS simulator, and hence the graphical user interface of the RTDS was used to directly translate the schematic control diagram of the algorithm to assembly code for the controller. This greatly simplified the hardware implementation.

IV. Performance Evaluation on Real-time Digital Simulator

After off-line testing using electromagnetic transients simulation (PSCAD/EMTDC program), the proposed method was also implemented in physical hardware as mentioned in the preceding paragraph. This hardware was then tested on a real-time transients simulator. The real-time simulator accepts and generates signals in real-time and is thus virtually indistinguishable from the real system. Also modern real-time power system simulators can model large networks with considerable accuracy. Unlike off-line testing where the simulation only runs for a very limited time interval, real-time testing can be made to run continuously with the protection equipment connected in situ. Hence, hardware errors, signal interface errors, signal drifts and so on in the equipment under test can be identified and corrected. Hence real-time simulator based testing was used in this work. The particular simulator used was the RTDS from RTDS Technologies Inc.

A. *Testing of developed controller*

The interface with the controller was made through existing analog and digital inputs and outputs in the RTDS. The analogue output allows the connection to the oscilloscope to analyze the signals or physical magnitudes in real time.

To perform real-time tests, the controller itself has to be connected to the RTDS receiving the voltages from the digitally modeled system and sending the closing order signal to the CB modeled on the RTDS. As shown in Fig.4, the RTDS performs the digital simulation of power system and outputs the voltage at power system side and at the line side.

An Optical Analogue−Digital Converter (OADC) is used to convert these analogue voltages in digital output signals that can be interfaced to the controller. The OADC inputs have a maximum value of 10 V.

At the instant when the logic signal of a period identification finishes, an order is sent to reclose the CB. The trip is a digital signal, so the connection with RTDS is done through an optical isolation system using the Interface MUX Card (IMC).

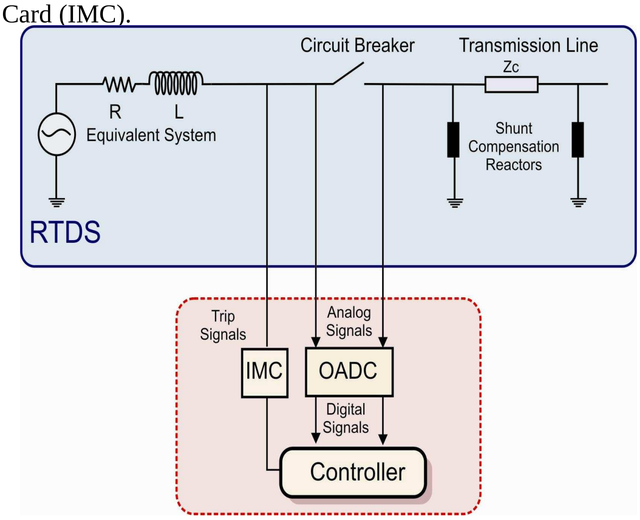


Fig. 4. Test setup with showing interfaced signals

V. Parametric Analysis of Proposed Method

The proposed method is evaluated through an actual 500 kV AC transmission system. Metal oxide arresters rated 420 kV have been assumed installed at either ends of all the TL segments. The TL parameters calculated for the fundamental frequency (60 Hz) are presented in Table I.

TABLE I
TRANSMISSION LINE PARAMETERS – 60 HZ.

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

A frequency dependent phase-domain transmission line model was used, which included skin effect of the conductor as well as the ground.

Table II shows the TL shunt compensation data. The scheme of compensation is composed by banks of three single-phase reactors (quality factor = 400) grounded through 800 Ω neutral reactors (quality factor = 50).

TABLE II
SHUNT COMPENSATION DATA.

Segments of TL	Long (km)	Reactive Power (MVAr)		Shunt Comp. Degree
		Sending	Receiving	
1st - (B1- B2)	250	136	200	100 %
2nd - (B2-B3)	320	200	150	70 %
3rd - (B3-B4)	230	150	200	100 %
4th - (B4-B5)	252	200	150	90 %

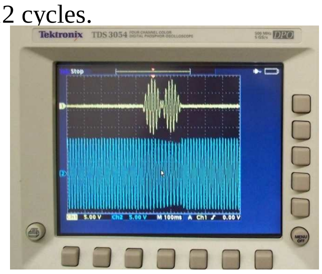
A. *Variety of shunt compensation schemes*

To consider the shunt compensation effects, the study was focused on the following lines sections:

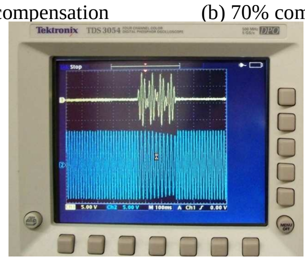
1) Final segment of the line that corresponds to a 252 km line section in between busses B4 and B5, including two shunt reactors with 50 % and 40 % compensation respectively (90 % total shunt compensation).
2) The 320 km line segment between busses B2 and B3 with the two connected shunt reactors (70 % total compensation).
3) The same final 252 km segment between B4 and B5 considered in 1), but this time with only one shunt reactor connected (50 % shunt compensation).

Fig. 5 shows oscillograms captured from the RTDS's analogue outputs for the three cases. The CB is closed at the first, second and fourth minimum voltage beat. In each case this is the earliest reclosure instant possible, considering a dead time for the protection of 12 cycles.

(a) 90% compensation



(b) 70% compensation



(c) 50% compensation

Fig. 5. Reclosing of TL using the developed controller.

Table III shows the difference between maximum voltage of the three phases across the CB and minimum voltage at region of minimum beat across the CB. This difference allows noting the advantage to reclose CB at the region of the minimum voltage beat across CB.

TABLE III
MAXIMUM VOLTAGE ACROSS CB

Compensa-tion degree	Maximum voltage across CB	Maximum voltage at region of minimum beat across CB
90 %	780 kV	125 kV (First minimum)
70 %	840 kV	160 kV (Second minimum)
50 %	900 kV	330 kV (Fourth minimum)

B. *Influence of series compensation*

For very long transmission lines, in addition to the shunt compensation it is used series capacitors, which increase transmission capacity, reduce system losses and improve the voltage profile of the LT. Table IV shows the series compensation data of the TL.

Fig. 6 shows the comparison between a TL with 90 % shunt compensation and the same TL with 90 % shunt compensation plus 50 % series compensation.

TABLE IV
SERIES COMPENSATION DATA

	Series Capacitor	
Line length (km)	Compensation Degree (%)	X_C (Ω)
900	50	95.432

The PSCAD/EMTDC simulations demonstrate that the beats across CB for TL with series compensation and TL without series compensation are very similar, so it is possible to conclude that series compensation does not interfere with the performance of developed method.

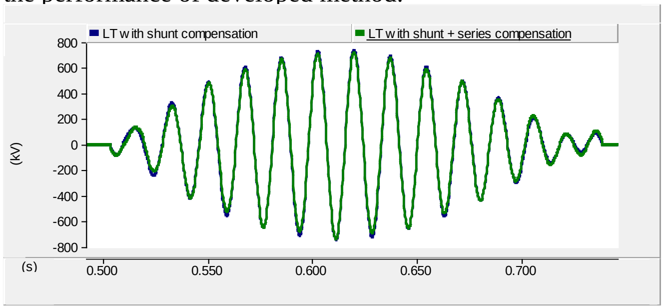


Figure 6: Comparison among shunt compensation TL vs. shunt+series compensation TL.

C. *Influence of transposition*

The performance of the controlled switching method was evaluated using perfectly transposed transmission lines at section A. For this reason the method increases its effectiveness because the negative and positive line sequence parameters are the same. Consequently, for shunt compensated TL, the line side voltage after the line deenergization shows mainly one component of frequency, associated to the positive sequence parameters.

However, the actual lines are not ideally transposed, or in other words, the line is not balanced for all the frequencies involved in electromagnetic transients. For higher frequencies signals the wavelengths are not much greater than the transposition cycle, and therefore the line transposition should be properly represented.

In general, the Brazilian Power System, uses the transposition scheme 1/6 - 1/3 - 1/3 - 1/6 (with three transposition towers). In order to determine the influence of transposition, the TL was modeled as follows: supposed ideally transposed and without transposition scheme.

The second segment of the system under study was used for the analysis. Fig. 7 shows the voltage across CB when the developed method was applied to an ideally transposed line and a line with the transposition scheme of 1/6 - 1/3 - 1/3 - 1/6. Therefore it can be concluded that the method performance was satisfactory for both cases.

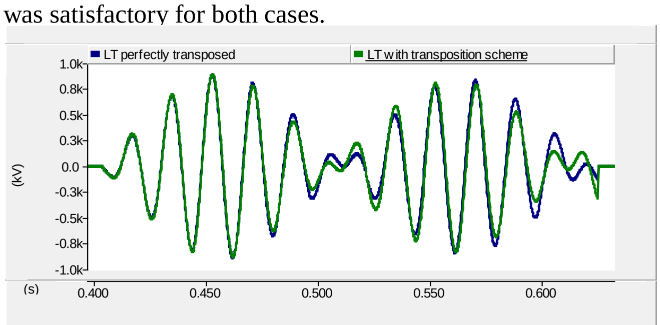


Figure 7: Comparison: LT perfectly transposed and LT with transposition scheme 1/6 - 1/3 - 1/3 - 1/6

TABLE V
MAXIMUM VOLTAGE ACROSS CB

	90 % shunt compensation		70 % shunt compensation		50 % shunt compensation	
	Voltage at receiving end (pu)	Reclosing time (ms)	Voltage at receiving end (pu)	Reclosing time (ms)	Voltage at receiving end (pu)	Reclosing time (ms)
Without overvoltage control	1.80	500	1.94	500	1.91	500
Pre-insertion resistor	1.53	500	1.42	500	1.85	500
Existing method	1.25	740	1.28	350	1.61	297
Proposed method	1.24	360	1.15	230	1.59	239

D. Comparison of different methods

The proposed reclosure algorithm (base case) was compared with the following situations that use alternate methods:

1) without any control of the reclosing time,
2) with the existing controlled reclosing method,
3) with the use of pre-insertion resistor.

Simulation case 1) is a hypothetical case conducted for with reclosing at a time halfway between the maximum and minimum beat typically 500 ms after breaker opening. It was conducted for comparative purpose only as it produces a ‘typical’ overvoltage value.

Simulation case 2) assumes reclosure using previously existing method. The CB closes at the second, third and fifth minimum voltage beat across the CB; for 90 %, 70 % and 50 % shunt compensated lines, respectively. These reclosing instants are ideal. In reality, the method may face additional difficulty because the exact period of the voltage zeros may not be found.

In simulation case 3) was used the pre-insertion resistor. In this study, an existing 400 Ω resistor was simulated, with insertion duration of 8 ms, beginning at 500 ms after line opening (typical value for Brazilian 500 kV transmission systems is in the range 500-1100 ms).

Table V summarizes the simulation results and includes breaker-reclosing times. The proposed method has lower overvoltages in comparison to the other methods, but significantly less compared to the commonly used pre-insertion resistor method.

Also, it can be seen that even though the overvoltage is only slightly smaller for the previously existing controlled reclosure method, the advantage that the proposed method has is a much-reduced reclosing time. It should be noted that the previously existing method was treated in an idealized manner, with its CB being closed at the second, third and fifth minimum voltage beats. This is optimistic, and in reality, the CB time would in all likelihood be further delayed (around 800 ms instead of 297 ms as reported) [5-Part II]. This is because particularly for low compensation levels, the CB voltage has a less than pronounced beat and even certain intervals where there is no zero crossing at all, making it difficult for the existing method to identify the optimal reclosing instance.

VI. CONCLUSIONS

A new method to control the three-phase reclosing of a transmission line under external fault that does not rely on zero crossing measurements was developed. The proposed method was implemented in physical hardware, and its successful operation was confirmed using Real Time Digital Simulator.

The controller is able to reduce the switching overvoltage and is able to ensure reclosure at the earliest possible time, thereby reducing the interruption of power energy.

In comparison to presently used methods, the controller presents greater reliability in the determination of the first minimum voltage beat, for any degree of shunt compensation.

The parametric analysis demonstrates that the proposed method works satisfactory with a variety of compensation schemes. The series compensation and the transposition do not influence the performance of the method.

VII. REFERENCES

[1] A. C. Legate, J. H. Brunke, J. J. Ray, and E. J. Yasuda, “Elimination of closing resistors on EHV circuit breakers”, IEEE Transactions on Power Delivery, vol. 3, no. 1, pp. 223.231, January 1988.

[2] A.C. Carvalho, M. Lacorte, O. Knudsen O, “Improved EHV line switching surge control by application of MO-arrester and controlled switching”, International Conference on Energy Management and Power Delivery, Proceedings of EMPD’95, 1995.

[3] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit Breakers- Planning, Specification and Testing of Controlled Switching Systems”, ELECTRA, No 197, pp. 23-33, August 2001.

[4] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit Breakers – Benefits and Economic Aspects”, ELECTRA, No 217, pp. 37-47, December 2004.

[5] K. Froehlich, A.C. Carvalho, B.L. Avent, C. Hoelzl, W. Hofbauer, D.F. Peelo, M. Stanek, P. Hoegg, J.H. Sawada, “Controlled closing on shunt reactor compensated transmission lines - Part I: Closing Control Device Development. Part II: Application of Closing Control Device for High-Speed Autoreclosing on BC Hydro 500 kV Transmission Line”, IEEE Transactions on Power Delivery, Vol. 12, No. 2, pp. 734 -746, April 1997.

[6] K. Dantas, W. L. Neves, D. Fernandes, G. Cardoso, L. Fonseca “Mitigation of switching overvoltages in transmission lines via controlled switching”. In: Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE.

[7] EPRI Transmission Line Reference Book - 345 kV and above (Second Edition), 1982, EPRI, Paolo Alto, California.

[8] H. Ito, “Current status and future trend of controlled switching system”, Mitsubishi Electric ADVANCE, March 2007.

[9] M. C. Tavares, P. Mestas, “Method for fast three-phase reclosing of shunt compensation transmission lines”, INPI. Prot. Patent 018080063302, Oct. 13, 2008.

[10] M. C. Tavares, P. Mestas, “Method for fast three-phase reclosing of shunt compensation transmission lines”, PCT Prot. Patent PCT/BR2009/000347, Oct. 09, 2009.

[11] D. Goldsworthy, T. Roseburg, D. Tziouvaras, J. Pope, “Controlled Switching of HVAC Circuit Breakers: Application Examples and Benefits”. In: 61st Annual Conference for Protective Relay Engineers, Texas, USA, 2008.

[12] “Real-Time Digital Simulator (RTDS) User’s Manual Set,” RTDS Technologies Inc., 2008.