REAL TIME DIGITAL SIMULATION TO PERFORMANCE EVALUATION OF AN ADAPTIVE THREE-PHASE AUTORECLOSING METHOD FOR COMPENSATED TRANSMISSION LINES

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Abstract - This paper presents a control method to reduce overvoltages due to three-phase reclosing for shunt compensated transmission lines (TL). The method detects the first minimum region of the voltage beating across the circuit breakers after protection dead time and works independently of voltage zero crossing, reducing significantly the reclosure time. Based on the proposed method, a controller was implemented and tested on a Real Time Digital Simulator (RTDS). Finally, a parametric evaluation is presented taking into account 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.

1. INTRODUCTION

Transmission systems are subject to overvoltage surges produced by transmission line switching operations. These overvoltages appear as traveling waves on the transmission network, occurring in a millisecond time frame as a result of circuit breaker (CB) operations.

The magnitude and shape of the switching overvoltages vary with the system parameters and network configuration. Even with the same system parameters and network configuration, the switching overvoltages are highly dependent on the characteristics of the CB operation and the point on wave where the switching operation takes place.

For line reclosing, the worst case occurs during three-phase autoreclosing of compensated TL, when the CB pole recloses with pre-existing trapped charge. Random switching of CB under these conditions generates high magnitudes of voltage and current transients, which may produce negative impacts for power systems. These impacts include reduction of equipment lifetime, breakdown of equipment in the substations, and degradation of power quality. Consequently, special overvoltage mitigation measures are employed to meet the insulation coordination considerations.

The most common practice has been to use closing resistors, which often are combined with metal-oxide surge arresters to improve reliability. However, this approach is expensive [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].

Current controlled switching methods to determine the optimum instant for reclosing of shunt compensated TL are based on voltage zero crossing across the CBs. This procedure requires complex logic because the line voltage is constantly changing and the compensation degree of TL influences directly the voltage waveshape.

The solution proposed in this paper was not to take the voltage zero crossings as a reference, as proposed by earlier researchers [5], [6], but to evaluate the voltage wave shape across the CB. With this signal, the detection algorithm is considerably simplified and the optimal instant for reclosing can be found faster. The reclosure of the CB occurs in the first minimum region of the voltage beat after protection dead time and allows the restoration of the normal power supply with the minimum possible time interruption.

In the following sections, the transient switching phenomena observed during auto-reclosing is reviewed. Next, the main features of a new method for detection of the optimum instant for reclosing are presented. The algorithm is then implemented in hardware and validated via testing on a Real Time Digital Simulator.

Finally, to complement the study, it is presented a parametric evaluation 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.

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2. THREE-PHASE LINE AUTO-RECLOSING FUNDAMENTALS

The sequence of events for autoreclosing operations due to external faults includes automatic tripping of their associated circuit breakers and subsequent reclosure, after a predetermined time interval.

When the line opens, an effective interruption occurs at the current zero crossing in each phase leaving a trapped charge on the line, which is not same on all phases. At the first interrupted phase, the voltage may reach 1.3 p.u [7].

If the line is reclosed with trapped charge, and when the system voltage is with opposite polarity to line voltage, the transient overvoltage could be very high. On the other hand, if the trapped charge is not drained by a transformer, a reactor, or a load, the line will remain charged for a long time, the decay of the trapped charge is very slow and is governed by climatic conditions. Thus the line stays charged for a long period after the current interruption, requiring about 2 to 5 minutes to discharge completely; or even up to 15 minutes in very dry conditions.

2.1 Three-phase line auto-reclosing without shunt reactive compensation

As mentioned in the introduction, breaker reclosing usually occurs on a line with trapped charge. In this case, the voltage waveform across the CB poles is a function of the degree of shunt compensation. For uncompensated lines, the waveform can be approximated with a function of the form $1-\cos(\Omega t)$, with a suitable value of Ω as shown in Fig. 1(a). The three-phase reclosing optimization of such an uncompensated line is straightforward, and is achieved by breaker closure at a valley of the voltage signal or when the voltage is around the voltage zero crossing [2].

2.2 Three-phase line auto-reclosing with shunt reactive compensation

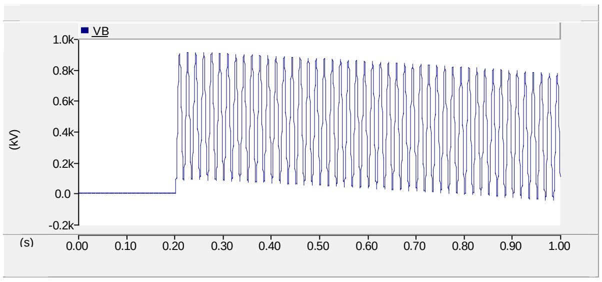
In the case of shunt compensated lines, the degree of compensation has an important effect on the voltage waveform across the CB poles. Due to the oscillatory circuit formed by the shunt capacitance of the transmission line and the shunt compensator's inductance, the voltage across the CB poles during reclosing is characterized by a beat [as in Fig. 1(b)-(d)]. This beat occurs because the voltages at each pole have different frequencies, specifically, the system power frequency at one side of the CB, and the natural frequency both of the compensated equipment and the line at the other side of the CB [5]-[8].

The beat period depends on the degree of line compensation. In Fig. 1(b)-(d), respectively, waveforms are shown for the voltage across the CB for high (90 %), medium (70 %) and low (50 %) shunt compensation levels. The line data is as in the section 6.

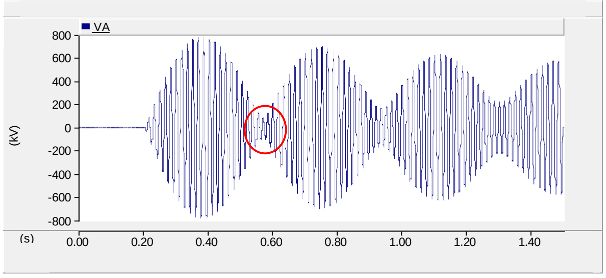
The drainage of the trapped charge produces a reduction of the voltage magnitude over time. This drainage is a function of the reactor quality factor. As a result, the maximum magnitude of the voltage beat tends to decrease and the minimum magnitude of the voltage beat tends to increase.

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. 1(b) by a circle.

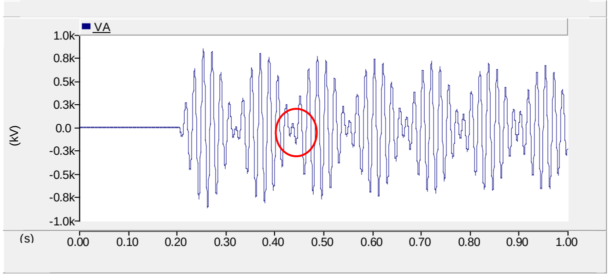
For a lower compensated line, the first minimum of the beat occurs too early. When the dead time for protection actuation is considered, a later minimum must be used. The dead time is the time required by the protection to process a breaker operation request and initiate the breaker opening. The breaker opens after an additional operating time, as is discussed later in section 4.2. 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.1(c) and the fourth minimum Fig. 1(d).



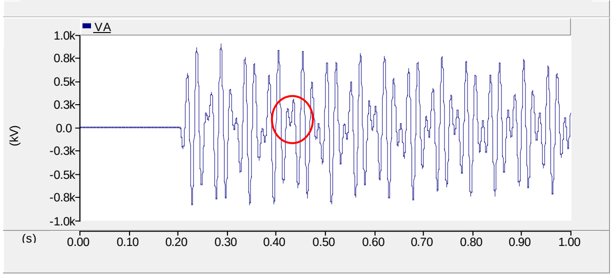
a) TL without compensation



b) TL with 90 % shunt compensation



c) TL with 70 % shunt compensation



d) TL with 50 % shunt compensation

Figure1: Voltage wave shape across CB. 500 kV system.

3. EXISTING CONTROLLED RECLOSING METHOD

The existing method described in [5, 6] 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. This condition is equivalent to having near-zero voltage across the breaker.

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.

The disadvantages of this approach are as follows:

- 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.
- The beat period is difficult to measure when the compensation level is smaller (see Fig. 1d).

4. 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.

4.1 Main Control Algorithm

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. 2. 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 Vref will have a delay in relation to Vbrk. 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}.

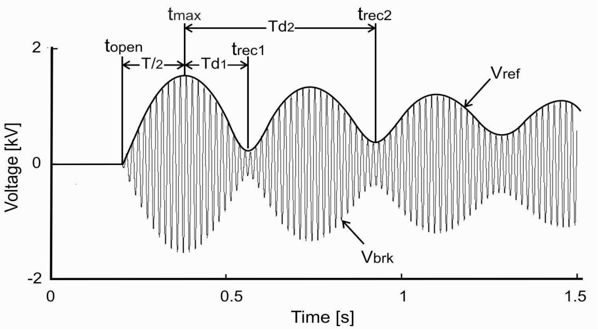


Figure 2: Identification of optimum instants for TL reclosing

The beat half-period duration $T/2$ is identified by determination the point t_{max} at which V_{ref} achieves its first maximum. 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. 1(c)], $T_{d1} = T/2$ 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. 1(d)], 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 hardware-specific characteristics. This is explained in the following sub-section.

4.2 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. 3, 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 3.

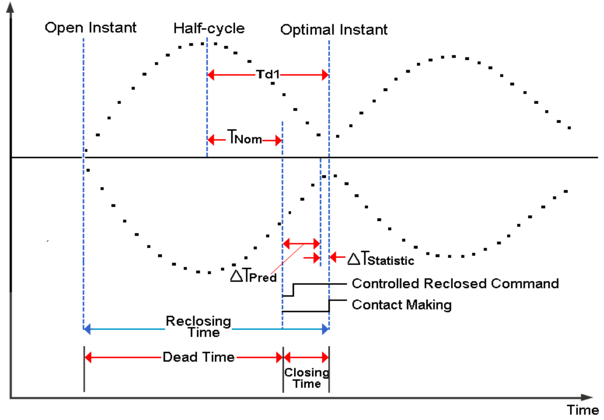


Figure 3: Reclosing Time Adjustment

4.3 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. 1(d)]. 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.

4.4 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 described below, 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.

5. 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. Real-time simulator based testing has the advantage that the controller algorithm can be evaluated as though connected to an actual system. This is because 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. and its properties are briefly discussed below.

5.1 Real-Time Digital Simulator (RTDS)

The RTDS is a special purpose massively parallel processing based computer designed to study Electromagnetic Transient Phenomena in real time. The RTDS is comprised of both specially designed hardware and software [12].

RTDS hardware basically is Digital Signal Processor (DSP) based and utilizes advanced parallel processing techniques in order to achieve the computation speeds required to maintain continuous real-time operation.

RTDS software includes extensive libraries of power system and control system components. All aspects of simulator operation, from constructing simulation circuits through to recording simulation results, are controlled through the user-friendly graphical interface. Power system and control system components may be interconnected to form the overall system for simulation using this graphical user interface. Similarly, the *Runtime* module of the RTDS provides a virtual 'control desk' enabling the user to interact with the simulation in real-time by modifying various parameters within the simulation.

5.2 Testing of developed controller

As the actual hardware is being used, it is important that all signals between the RTDS and the controller are appropriately scaled.

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 (Fig. 4).

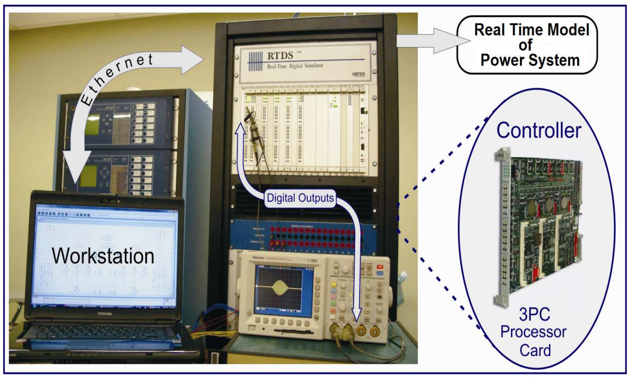


Figure 4. Hardware-in-loop testing of proposed controller.

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.5, 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).

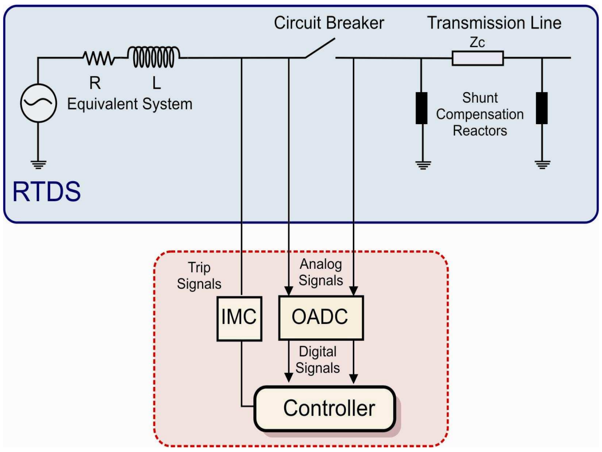


Figure 5: Test setup with showing interfaced signals

6. PARAMETRIC EVALUATION 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 1.

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

Table 1. TL Parameters – 60 Hz.

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

Table 2 shows the TL shunt compensation data. The scheme of compensation is composed by banks of three single-phase reactors grounded through a neutral reactor with quality factor of 400.

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 %

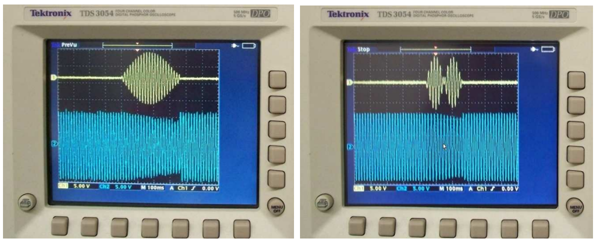
Table 2. Shunt compensation data

6.1 *Variety of shunt compensation schemes*

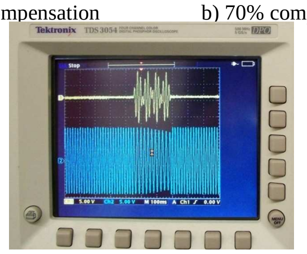
To consider the shunt compensation effects, the study was focused on the following lines sections:

A. 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).
B. The 320 km line segment between busses B2 and B3 with the two connected shunt reactors (70 % total compensation).
C. The same final 252 km segment between B4 and B5 considered in A), but this time with only one shunt reactor connected (50 % shunt compensation).

The RTDS's analogue output allows to analyze in real time the voltage signal across the CB as well as the voltage at the end of the transmission line (bus B5 and bus B3) for the above three cases. Fig. 6 shows oscillograms for the three cases (90 %, 70 % and 50 % shunt compensated lines) respectively, 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

Figure 6: Reclosing of TL using the developed controller.

Table 3 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 to note the advantage to reclose CB at the region of the minimum voltage beat 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)

Table 3. Maximum voltage across CB

6.2 *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 4 shows the series compensation data of the TL.

	Series Capacitor	
TL Long. (km)	Compensation Degree (%)	$|X_C|$ (Ω)
900	50	95.432

Table 4. Series compensation data

Fig. 7 shows the comparison among a TL with 90 % shunt compensation and the same TL with 90 % shunt compensation plus 50 % series compensation.

The PSCAD/EMTDC simulations demonstrates 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.

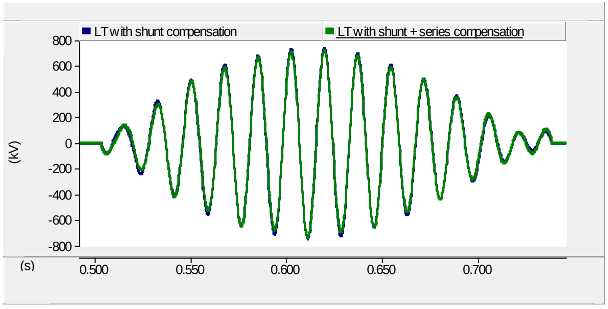


Figure 7: Comparison among shunt compensation TL vs. shunt-series compensation TL.

6.3 *Influence of transposition*

At section 6.1 the performance of the controlled switching method was evaluated using perfectly transposed transmission lines. This consideration contributes to the method effectiveness because the negative and positive line sequence parameters are the same. Therefore, for shunt compensated TL, the line side voltage after the line deenergization presents mainly one frequency component, related 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 a electromegnetic transient. For higher frequencies signals the wavelengths are not much greater than the transposition cycle, and therefore the line transposition should be properly represented.

The Brazilian Power System Grid normally uses a transposition scheme known as 1/6 - 1/3 - 1/3 - 1/6, which uses three transposition towers.

As a matter of comparison, the line was modeled in two different ways: perfectly transposed and not transposed with the transposition scheme as above.

The second segment of the system under study was used for the analyze. Fig. 8 shows the voltage across CB and the line side voltages respectively. The developed method was applied to a 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.

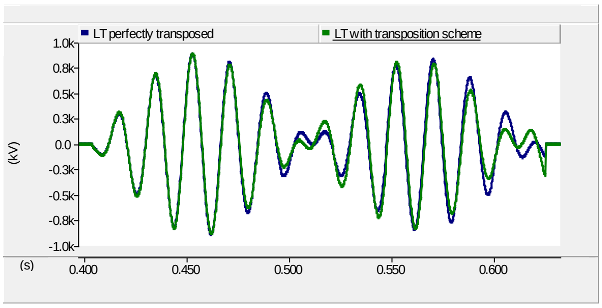


Figure 8: Comparison: LT perfectly transposed and LT with transposition scheme 1/6 - 1/3 - 1/3 - 1/6

6.4 *Comparison of different methods*

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

A. without any control of the reclosing time,
B. with the existing controlled reclosing method,
C. with the use of pre-insertion resistor.

Simulation case A) 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 B) 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 C) 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 5 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.

	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

Table 5. Overvoltages on receiving end of transmission line

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.

7. CONCLUSIONS

A new method to control the three-phase reclosing of a transmission line 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 work satisfactory with a variety of compensation schemes. The series compensation and the transposition do not influence the performance of the method.

The use of the adaptative three-phase controlled reclosing eliminates the need of pre-insertion resistors, reducing the costs of transmission line CBs. As a consequence, the controlled switching may provide an increase of power apparatus lifetime and improvement on power quality.

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

[10] 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.