Real Time Implementation of Transmission Line Controlled Switching

K. M. C. Dantas, W. L. A. Neves, D. Fernandes Jr., G. A. Cardoso, L. C. Fonseca

***Abstract*— A method for controlled switching of line circuit breakers is implemented in a prototype device for real time evaluation. The switching strategy consists on finding a suitable circuit breaker making instant and it is based on a very simple zero crossing algorithm. This device is used in connection with the RTDS™ (Real Time Digital Simulator). Data from the North-Northeast Brazilian Power System Grid are used to produce the case studies. Some line switching events are analyzed: line closing and re-closing taking into account trapped charges and shunt compensation effects. The proposed method is compared to the pre-insertion resistor (PIR) method and existing controlled switching methods. The simulations attest the efficiency of the proposed method, which is an important step to use the controlled switching device in connection with circuit breakers with no PIR.**

***Index Terms*— Controlled Switching, DSP, RTDS™, Switching Overvoltages, Transmission Lines.**

I. INTRODUCTION

CONTROLLED switching 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 [1], [2]. Its benefit and feasibility were presented by CIGRE Task Force 13.00.1, with emphasis on mitigation of switching surges and related economical features [3], [4].

Regarding to line circuit-breakers (CB), 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 reduce the circuit-breakers associated maintenance costs [5], [6]. In the last years, the efficiency of the transmission line controlled switching has been attested [7], [8], [9], [10], [11]. However, few works presented an experimental character aiming to build a controlled switching device.

In this work, a method for controlled switching of line circuit-breakers, which has been previously presented by the authors [12], is extended for real time evaluation using the RTDS™ (Real Time Digital Simulator) [13] in connection with a controlled switching device.

The method implementation is accomplished in two different ways:

- Using the *CBuilder* tool of the RTDS™, which is a software environment to build new components that can be incorporated into simulations and interact with the components already provided by the RTDS™ .
- Using a DSP (Digital Signal Processor) to develop a device control to synchronize the closing of the circuit breaker poles, which is capable to interact with the RTDS™ by means of its analog and digital input/output interfaces.

Data from the North-Northeast Brazilian Power System Grid are used to produce the case studies. Some line switching events are analyzed: line closing and re-closing taking into account trapped charges and shunt compensation effects. The proposed controlled switching method performance is compared to the pre-insertion resistor method and to existing methods [7], [11] in real time using the RTDS™.

II. BASICS ON CONTROLLED SWITCHING

The closing command for the circuit-breaker is normally 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. In this case, the optimal making instant is the zero crossing of the reference signal. 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 $t_{command}$.

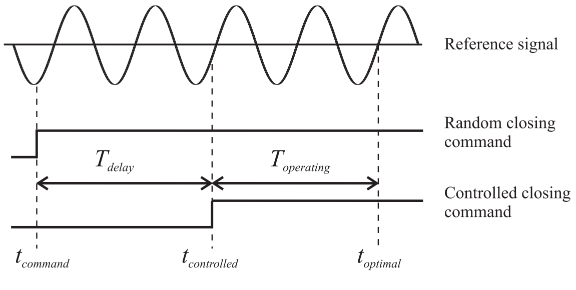

Fig. 1. Schematic controlled closing sequence.

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A. Transmission Line Closing

Transmission line closing, or energization, is a typical switching operation on power systems. During this operation, there is no trapped charge on the line and in this case, the optimal making instant for each transmission line phase is the zero crossing of the source side voltage, which is the reference signal for the controlled closing.

B. Shunt Compensated Transmission Line Re-closing

Transmission line re-closing operations are normally performed with trapped charge on the line. For shunt compensated 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, the line side voltage will present a sinusoidal waveshape with a frequency in the range of 30 to 55 Hz, depending on the degree of compensation [7]. In this case, the reference signal is the voltage across the circuit-breaker contacts. In Figs. 3 and 2, it is indicated the optimal making instants, for different degree of compensation, which occur at the zero crossing and at the minimum beat of the reference signal.

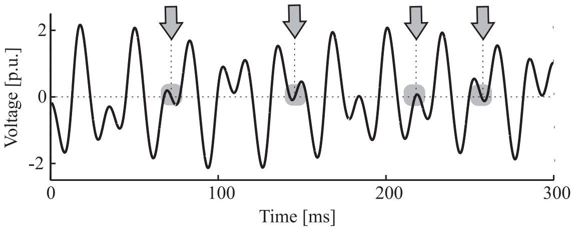

Fig. 2. Voltage across the circuit-breaker contacts for 30% shunt compensated transmission lines.

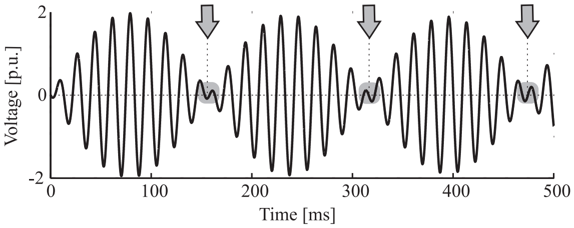

Fig. 3. Voltage across the circuit-breaker contacts for 80% shunt compensated transmission lines.

III. CONTROLLED SWITCHING METHOD

The application of controlled switching to transmission lines has been reported in literature since the 70's [14]. However, only during the 90's a method for controlled closing of shunt compensated lines was proposed and a device was developed [7]. That method predicts the optimal making instants based on the zero crossings of the voltage across the CB. However, for low compensation degrees, some zero crossings may not occur during the minimum beat of the reference signal, as illustrated in Fig. 2. In this way, the prediction of the optimal making instants is not guaranteed by that method [15].

In order to improve the efficiency and the reliability of the controlled switching of shunt compensated lines, a method has been proposed by the authors [12]. This method was developed to find the optimal making instants based on the zero crossing of the line side and source side voltages, regardless of the zero crossing of the voltage signal across the CB contacts.

In addition, the making instants are determined in order to have the smallest 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. In this way, the prediction of the optimal making instants is guaranteed by the proposed method. Its good performance has been proved for both shunt compensated and non-compensated lines, considering perfectly transposed lines as well as lines with the transposition scheme 1/6 - 1/3 - 1/3 - 1/6 [10], [12]. In Fig. 4, it is shown the flow chart that summarizes the proposed method implementation, which is extended here for real time evaluation.

A. Controlled Switching System *(CSS)*

The CSS receives voltage signals (source side and line side) from RTDS™. These signals are provided by potential transformers (PTs), which were considered to be ideal. An actual PT may cause phase and amplitude errors and corrections in their secondary voltage waveforms are necessary. Actually a full evaluation regarding the frequency response of the PTs must be carried out in order to properly estimate the PT influence on the timing sequence of the CSS. Our research group is working to overcome this problem as reported in [16].

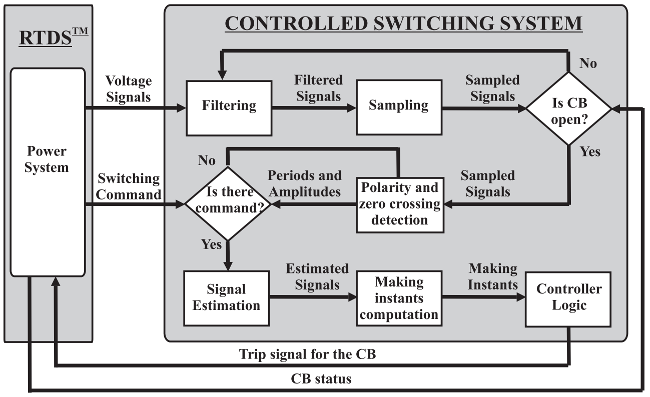

Fig. 4. Controlled Switching Method: flow chart.

B. Filtering and Sampling

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 was projected and employed to these voltage signals. After filtering, the signals are sampled using a rate of 960 samples/seconds. This rate is enough to reproduce the signal without aliasing effect and it is commonly used on digital power system protection.

C. Polarity and Zero Crossing Detection

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. In this way, the periods of these signals are determined by means of two consecutive zero crossing and their amplitudes are determined finding the highest absolute value between two consecutive zeroes.

D. Signals Estimation and Making Instants Computation

At the moment in which 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 predicts a list of possible optimal making instants for each phase, taking into account $T_{operating}$.

To accomplish this, only the line side and source side voltages are evaluated instead of complex signals such as those presented in Figs. 3 and 2. Afterwards, the source side and line side voltages are put together in order to obtain the desired optimal making instants, regardless of the phase, amplitude and frequency of these signals and also regardless of the voltage reference signal waveforms or minimum beats. An optimal making instant is identified when the slope (derivative) of both signals have the same direction at the time these signal cross, which means a zero crossing of the reference signal at its minimum beat.

To successfully accomplish the re-closing operation and respecting the protection dead time of the line, the optimal making instants chosen by the method are the ones immediately after the closing command.

E. Controller Logic

The *Controller Logic* is responsible for the coordination of the switching command and the switches that emulate the breakers in the power system modelled in the RTDS™. It acts delaying this command for a time interval necessary to accomplish the switching operation of each phase at a predicted optimal making instant. So, the trip signal for the switches at the RTDS™ is sent by the CSS and the switching command for the circuit-breaker is controlled.

IV. METHOD IMPLEMENTATION

The implementation of the method described at the previous section was accomplished in two different ways aiming the real time evaluation by means of the RTDS™. At first, the implementation took place at a software level, using the *CBuilder* tool of the RTDS™. At last, the method was implemented in a hardware, more specifically in a DSP, which can be characterized as a prototype for a controlled switching device. Details of the implementations are discussed next.

A. Implementation in Software

The RTDS™ comprises different software levels. At the lowest level it can be found the models for the power system components, which are basically the same models found in EMTP programs, but with some simplifications to achieve real-time simulations. At the highest level, it can be found the software *RSCAD*, which allows the construction and development of circuits and system components as well as simulation and visualization of these results.

Moreover, the *RSCAD* provides the *CBuilder* (Component Builder), which is a software environment for building new components using C language. So, using this tool, the models and algorithms developed by the user can be incorporated into real-time simulations and interact with the components already provided by the RTDS™.

B. Implementation in Hardware

In this work, the TMS320F2812 eZdsp ™ DSP [17] was used to develop a prototype of a controlled switching device. This DSP has 16 input channels with 12 bits analog to digital (A/D) converters and the voltage level of the input signals must range from 0 to 3 V. The A/D converters are responsible for the digitization of the analog voltage signals supplied by the RTDS™.

The RTDS™ provides closed-loop simulations of the modelled power system with external devices. The communication between the RTDS™ and these devices is done by means of the GT-I/O (Gigabit Transceiver - Input/Output) cards. The following GT-I/O cards were used in this work:

- *Gigabit Transceiver Analogue Output Card* (GTAO): This card is used to generate analog signals with peak values between ±10 V. These outputs are used to monitor the reference voltage signals required by the controlled switching method.
- *Gigabit Transceiver Digital Output Card* (GTDO): This card is used to generate digital signals from 7 to 24 V. These outputs are used to monitor the breaker status: open or closed.
- *Gigabit Transceiver Digital Input Card* (GTDI): This card is used as an input interface for digital signals (0-5 V) that come from external devices to the RTDS™. These inputs are used by the controlled switching device to command the closing of the breakers.

To adjust the voltage levels of the analog signals coming from the RTDS™ GTAO card to the voltage levels of the DSP input channels, it is necessary the conditioning of these signals. This conditioning was done through a simple electronic circuit, made on a printed circuit board .After conditioning, an analog third-order Butterworth low-pass filter with a cutoff frequency of 250 Hz, was used to minimize the aliasing effects and mitigate high frequency components. This cutoff frequency value was considered due to tolerances and limitations on market values of the electronic components used in the filter design (resistors, capacitors and integrated circuits). Then, the signals were sampled by the DSP A/D converters at a rate of 6.000 samples/second, and provided to the CSS implemented at the control device.

Furthermore, the DSP has PWM (Pulse Width Modulation) output signals, which are used to send the controlled command to the closing of the circuit breakers through the RTDS™ GTDI card. These outputs are controlled by registers and their status can be changed in any time. This allows the CSS to send the controlled command to the breaker immediately after the computation of the appropriate making instants.

V. METHOD EVALUATION

The method presented here was evaluated through real-time digital simulations of closing and re-closing of shunt compensated transmission lines, considering different switching operating conditions and making use of the RTDS™.

A. Power System

Based on actual data obtained from the 500 kV North-Northeast Brazilian Power System Grid, a simplified power system was used to evaluate the method (Fig. 5). It consists on a 400 km long 77% shunt compensated line with 200 Mvar shunt reactors and 420 kV class metal oxide arresters (MOA) connected at both ends of the line. This MOA is normally used at the 500 kV Brazilian Power System and has a protection level of 830 kV at 2 kA.Still, the system has two sources connected to the ends of the line through circuit breakers. The source voltage was adjusted to 550 kV, which is the maximum normal operating condition at the 500 kV Brazilian Power System. The system data are presented in Tables I, II and III.

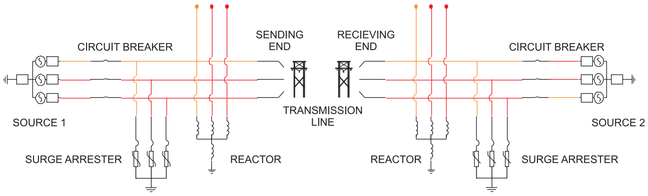

Fig. 5. Power system used for the method evaluation.

TABLE I

SEQUENCE PARAMETERS OF THE LINE.

Sequence	R (Ω/km)	X (Ω/km)	ωC ($\mu\mho$/km)
Zero	0,3996	0,9921	3,0839
Positive	0,0333	0,3170	5,2033

TABLE II

SOURCE VOLTAGE (V_{base} = 550 KV).

Source	Amplitude (p.u.)	Phase (°)
Source 1	1,00	0
Source 2	0,99	-10

TABLE III

SOURCE IMPEDANCE.

Source	Zero sequence		Positive sequence	
	R_0 (Ω)	X_0 (Ω)	R_1 (Ω)	X_1 (Ω)
Source 1	1,1268	20,838	0,9681	28,513
Source 2	1,1268	20,838	0,9681	28,513

B. Simulation Procedure

In order to properly evaluate the method, statistical scatter with respect to the operating time of the circuit-breaker must be considered. A description of typical values for this scatter can be found at [3]. 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.

$$T_{operating} = T_{nominal} + \Delta T_{statistic} \ . \tag{1}$$

Variations in the operating conditions, such as: contacts aging and wearing, stored energy of the drive and ambient temperature, can be compensated by sensors or adaptive control [5]. However there are still inherent statistical scatter related to the operating time. In RTDS™ these effects are taken into account using a Gaussian probability distribution. Here, the maximum scatter was assumed to be 2 ms.

$$\Delta T_{statistic} = 3\sigma \ . \tag{2}$$

Different line switching operating conditions were evaluated considering the sending end as the the first to be closed:

- Switching with reactors at both ends (77% shunt compensation);
- Switching with reactors only at the sending end (38% shunt compensation);

The controlled switching performance (implemented in software and in hardware) is compared to the pre-insertion resistors (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. Still, for comparison purposes, it is evaluated a situation in which there are only surge arresters at line ends during the switching operations. To achieve fair results in the comparison of the controlled switching performance, it was considered a statistical scatter with respect to the dead time of the line for the simulations of the above two cases.

For all case studies using controlled switching, it was considered a typical dead time of 500 ms, which is normally determined to satisfy transient stability concerns [18]. Regardless of the dead time, the re-closing operation using the proposed method, occurs immediately after the closing command at the predicted optimal making instants. In this way, if a smaller dead time were considered, the total out of service time of the line could be reduced.

C. Results

For each analyzed case in this paper, a total of 100 statistical simulations was performed and the maximum overvoltages values along the line, with probability of occurrence less or equal to 2%, are shown in Fig. 6. The overvoltages were evaluated at the line ends and at 25, 50 and 75% of its total length. It is observed that the use of PIR or CSS (via *CBuilder* or DSP) in conjunction with surge arresters limit the switching overvoltages efficiently and the obtaining voltage levels are much lower than those obtained only with surge arresters.

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 overvoltages values with probability of occurrence less or equal to 2% for each situation considered.

Based on the exposed data, for the most suitable situation for the CSS implemented in software, the overvoltages are limited to values that do not exceed 1.67 p.u. and at the most adverse situation, overvoltages are limited to 1.72 p.u. Moreover, in the case of the CSS implemented in hardware, at the most suitable situation, the overvoltages are limited to 1.68 p.u., while at the most adverse situation, the overvoltages are limited to 1.76 p.u. The difference between the results from software and hardware implementations of the CSS is justified by the inherent imprecision related to the acquisition and processing of the analog signals that come from the RTDS™. Concerning the performance of the PIR, at the most suitable situation, overvoltages are limited to 1.55 p.u., while at the most adverse situation, the overvoltages are limited to 1.84 p.u.

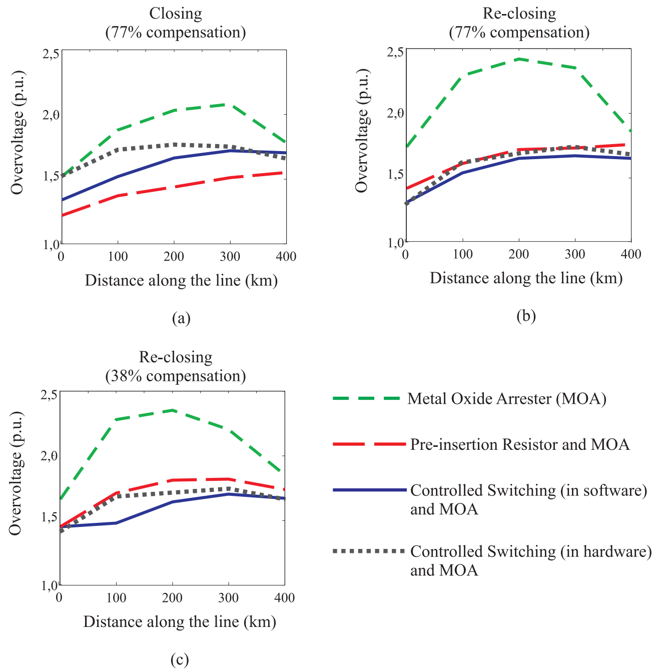

Fig. 6. Overvoltages along the line: (a) Closing (77% compensation); (b) Re-closing (77% compensation); (c) Re-closing (38% compensation).

TABLE IV

MAXIMUM OVERVOLTAGE VALUES WITH PROBABILITY OF OCCURRENCE LESS OR EQUAL TO 2% (VBASE = 550 KV).

Operating condition	Maximum overvoltage (p.u.)			
	MOA	PIR-MOA	CSS-MOA	CSH-MOA
Closing (77% compensation)	2.08	1,55	1,72	1,74
Re-closing (77% compensation)	2.45	1,78	1,67	1,68
Re-closing (38% compensation)	2.41	1,84	1,70	1,76

MOA - Metal Oxide Arrester.
PIR-MOA - Pre-insertion resistor and MOA.
CSS-MOA - Controlled switching (in software) and MOA.
CSH-MOA - Controlled switching (in hardware) and MOA.

Therefore, according to the digital simulation results in real time using the RTDS™, the use of controlled switching can eliminate the need for PIR. The results obtained with the CSS were due to the good precision on estimating the reference signals in future instants, which allows the determination of appropriate instants for the circuit breakers to close. However, the CSS performance with respect to the determination of the exact instant of zero crossing of the reference signals presented an error that varies randomly. Concerning the line re-closing operation, the average error for the determination of the appropriate instants was 0.4 ms. The maximum and minimum erros were respectively about 1.6 ms and 10 μs. These errors are acceptable, since this method looks for a zero crossing at the minimum beat of the reference signal and therefore does not cause high overvoltages. Regarding to the line closing operation, insignificant errors of the order of 10 μs were verified.

VI. COMPARISON WITH EXISTING METHODS

For all case studies, it was used the same power system and the same simulation procedure shown in Section V.

The method presented in [7] relies on pattern recognition and zero crossing of voltage signals are needed to find optimal making instants. More details of the algorithm regarding on how to determine the optimal making instants would be needed to a full implementation of that method. In spite of that, for the case studies shown in this paper, that method and the method presented here are expected to produce the same overvoltages because both would find the same zeroes for the voltage waveforms across the circuit-breakers.

However, if the transmission lines have lower compensation degrees, the method presented in [7] may pose difficulties on finding suitable making instants as discussed by their own authors in [15]. This difficulties are overcome by the method presented here as shown in Section III.

Another method for controlled switching of shunt-compensated lines can be found in [11]. That method is based on the evaluation of the voltage waveshape across the CB contacts to find the minimum beat region of this voltage. In this case, the re-closing operation must occur at the first minimum beat after the dead time of the line. The performance of that method in conjunction with the performance of the method presented here is shown in Fig. 7. It is presented in Table V the maximum overvoltages values with probability of occurrence less or equal to 2% for each method considered.

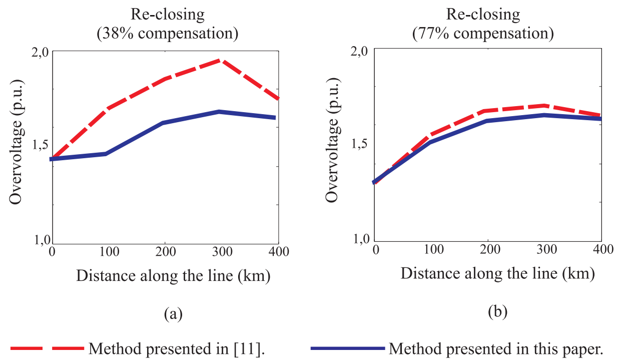

Fig. 7. Overvoltages along the line: (a) Re-closing (38% compensation); (b) Re-closing (77% compensation).

TABLE V

MAXIMUM OVERVOLTAGE VALUES WITH PROBABILITY OF OCCURRENCE LESS OR EQUAL TO 2% (VBASE = 550 KV).

Re-closing	Maximum overvoltage (p.u.)		
	Method 1	Method 2*	Method 3
77% compensation	1.67	1.67	1.70
38% compensation	1.70	1.70	1.96

Method 1 - Method presented here.
Method 2 - Method presented in [7]. *Expected results.
Method 3 - Method presented in [11].

Based on the exposed data, it can be observed that the method presented in [11] reached the highest overvoltages (1.96 p.u. at the most adverse situation) among all methods, including PIR. Which means an overvoltage value about 15% higher than the highest overvoltages obtained by the other controlled switching methods. This result is due to the fact that the method proposed in [11] does not looks for an optimal making instant, which is the zero crossing of the voltage across the CB contacts. Instead, the method looks only for a minimum beat of this signal.

In the case studies, the first minimum after the dead time of the line presents relatively high voltage values (about 0.55 p.u.), as illustrated in Fig. 8, due to the natural decay of the trapped charge in the line. So, closing at the minimum beat without looking for an optimal instant can diminish the controlled switching performance. Still, for lines with lower compensation degrees or higher values for the dead time, the results could be even more discrepant. Further, all evaluated methods realized the re-closing operations at the first minimum beat after the dead time. Thus, comparing the performance of all methods, it could not be observed any significant reduction on the re-closing time of the line.

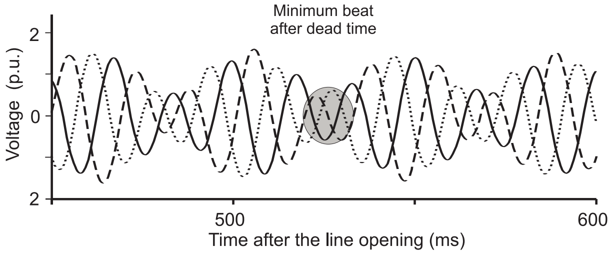

Fig. 8. Voltage across the CB contacts for 38% shunt compensation.

VII. CONCLUSIONS

A method for controlled switching of transmission lines was implemented in a prototype device capable to control the closing of the circuit breaker contacts. The possibility of real time implementation of the method is due to the fact that only simple signal processing techniques, such as zero crossing detection, are used. The presented work is an important step to use the controlled switching device in connection with circuit breakers with no PIR. If the CSS is to be used for breakers in service, those breakers must undergo type and routine tests. Still, further developments must be carried out in order to achieve a final product, such as the fulfillment of the requirements concerning electromagnetic compatibility [19].

The results proved the efficiency of the method in mitigating switching overvoltages due to line closing and re-closing, when comparing with traditional PIR and existing methods. Therefore, the controlled switching method can eliminate the need for pre-insertion resistors, increasing, in this way, the reliability of line circuit breakers and reducing its manufacturing and maintenance costs. Still, the controlled switching can reduce the transients originated from the power system switching and provide an improvement on power quality.

The use of controlled switching in conjunction with surge arresters located at the ends of the transmission lines provides further security in case of failure of the CSS. However, since many parameters of the electrical system can influence the switching surge levels, due to the peculiarities of each system and their transmission lines, the results presented in this work, a priori, should not be generalized and a detailed analysis of the presented method should be performed for each system.

VIII. ACKNOWLEDGEMENTS

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