Role of Controlled Switching on Transmission Line for SOV Mitigation-
A Review

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January 11, 2018

Abstract

In the deregulated competitive scenario of electricity market, the energy utilities across the world are focusing in delivering electricity with high reliability & quality. Controlled Switching of HVAC Circuit breakers play a dominant role in reducing switching transients thereby causing failure of equipment and deterioration of the power quality/reliability.

The paper describes the functioning of Controlled Switching techniques and their application in mitigating switching overvoltage. This paper elaborates the literature review on application of controlled switching devices on transmission lines for mitigating Switching over voltages. Different methods were proposed to implement the control switching scheme for mitigating switching over voltage on shunt and un-compensated transmission lines. Some are based on principles of zero voltage crossing, detection of polarity...
& maximum beat detection. All these methods have been
tested either on simulation software or field tested. Signifi-
cant developments have been noticed in this field with the
evolution of time and technology and literature reviews of
several authors reveals that it not only reduces switching
over voltages but also increase the reliability of power sys-
tems. The implementation of Controlled Switching Scheme
gives direct monetary benefits in terms of reduction in in-
sulation cost of apparatus and system.

**Key Words**: Controlled Switching, Switching Over-
Voltage (SOV), Alternative Transient Program, Surge Ar-
rester, Pre-insertion Resistor.

### 1 Introduction

Charging of unloaded transmission line causes power frequency
over-voltage in system. This over voltage may increase above 3.0pu
and adversely affects the power system. Pre-insertion resistor equipped
circuit breakers along with use of suitable surge arrestors mitigate
switching over voltage upto 2.0 pu. But these resistors pose some
reliability issues and maintenance cost. For achieving the mini-
imum switching over voltage, the circuit breaker is required to close
at zero crossing of Voltage wave [1].

In the later 90s, there are a very less number of Controlled
Switching devices installed across the world due to immaturity in
the technology. But due to versatile features of CSD, their popula-
tion increased upto 2400 in 2001 and consequently population rose
to 4500 in 2007[2].

Controlled Switching of HVAC Circuit Breakers is a technique
in which an intelligent electronic device is used to control the tripp-
ing/closing time of individual pole of three phase circuit breaker.
Conventionally, three phase circuit breakers having three individual
poles are operated at same instant of time with reference to phase
angle of reference voltage or current.

In controlled closing, there is an intended delay in closing of
individual poles for achieving the optimum point of closing. Opti-
mum point of closing is that instant which causes minimum SOV
in system. In the earlier decades, closing resistor was used to limit
the switching surges of transmission lines.

In absence of compensation, even after de-energization of unloaded transmission a dc trapped charge exists. During closing/auto-reclosing of shunt compensated transmission line, the difficulty arises in recognizing complexity of voltage wave shape across open breaker. As the degree of compensation increases, complexity of voltage wave decreases and it is easier to find zero crossing.

In case of tripping of a shunt compensated transmission lines, no any residual charge is left after the tripping but the voltage oscillates at a frequency determined by capacitance of lines and inductance of shunt reactor. Normally this frequency is lower than power frequency, oscillation causes voltage wave to be different from sinusoidal. Hence, difficulty arises in finding zero crossing in that case. Test demonstration shows that when two shunt reactors are connected at both ends of transmission lines the resonant frequency is about 45Hz while when only one shunt reactor is connected across 500kV transmission line, it oscillates at a frequency of 33Hz. Figure(1) indicates the line voltage waveform for shunt compensated transmission lines with higher degree of compensation and it is easy to recognize the beat minimum of line voltage wave undertaken as optimum point to close[4]. With the decrease in resonant oscillating frequency during lower degree of compensation, there may be some periods of voltage wave which are having no zero crossing as shown in fig.(2).

Fig. 1. Voltage waveshape after opening a shunt compensated transmission line with higher degree of compensation.
The pre-requisite for the application of Controlled Switching Scheme is availability of consistent circuit breakers. Presently SF6 type circuit breakers are installed in most of the utilities in EHV System. These breakers have consistent operating time of the order of 50ms tripping time and 20ms closing time over a wide range of operating conditions. CIGRE Task Force 13.00.1 studied the benefits of controlled closing and indicating the beat minimum being an optimal point for compensated transmission lines [3][4] in late 1995.

First micro-processor based Controlled Switching Device for use at BC Hydro Canada for controlled switching of 500KV Shunt compensated transmission line was developed [5][6] in 1997. The objective is to delay the pole closing instant so that pre-strike of contacts occur at optimum time window. The algorithm is designed to get adapted to any degree of compensation.

Controller takes 300ms to collect samples of voltage signals across circuit breaker to find optimum closing windows. The signal to be synchronized is sampled during one cycle and is stored in memory and similarly new sample is stored. If both the stored samples are matching, periodicity of signal is concluded. But if there is variation in both samples then another sample is collected for checking the similarity. From the data set obtained from signal, frequency and time difference between voltage zero crossing are evaluated.

From zero crossing data, pattern is recognized for about 100ms ahead the moment. This algorithm continuously sampled and recognized the signal till breaker receives command to close. After
receiving the closing command at the controller, controlled switching algorithm extends closing command to breaker with intentional delay so that next optimal closing instant is targeted. Algorithm predicts the occurrence of zero crossing of voltage wave for optimal closing. Signal Pattern recognition method used for finding zero crossing also consider scatter for various operations.

The role of IVT and CVT on controlled switching of un-compensated and shunt compensated transmission lines was added by [7] in their work. In case of un-compensated transmission lines equipped with IVT, trapped charge of healthy phase gets drained through IVT and faulty phase get drained through fault. In case of un-compensated lines with CVT, the trapped charge of healthy phase could not be drained whereas faulty phase gets drained through fault. The optimum closing time is related to breaker opening time and source side frequency. Author proposed new relationship for calculating optimum closing instant as given in equation (1) as:-

$$t_{close} = t_{open} + \frac{K}{f_{source}}$$  \hspace{1cm} (1)

$K$ is the number of cycles required for re-closing of working phases. The optimum instant for re-closing of un-compensated transmission lines with IVT is the zero crossing of source side volt-
For shunt compensated transmission lines, the optimum closing instant is the zero source crossing and the minimum line beat. In case of compensated transmission lines, oscillating line voltage wave appears across breaker. In this case line frequency is also accounted during calculating the optimum closing time. The optimum instant for re-closing of shunt compensated transmission is expressed as equation (2) which contain frequency parameter of both source side and line side as:

\[ t_{close} = t_{open} + \frac{K}{f_{source} - f_{line}} \]  

(2)

Simulations were carried out in EMTP/ATP on 400kV Transmission line and result showed that 2.1pu SOV attained for 30\% compensated line for SD of 0.25ms using controlled switching and surge arresters.

A new controlled switching algorithm was proposed [8] for auto-reclosing of shunt compensated line along with optimization of second and third pole energization instant. This algorithm uses signal analysis method to estimate future voltage wave across circuit breaker. Pattern recognition method is first approach which was applied on standard processor. This approach works on a loop and the sub-period is divided into individual time windows for voltage wave and its envelop is also calculated. Similar step is followed for second window. If a similarity established then switching instant could be estimated. Otherwise, first window will be deleted and second window is stored which serves as a reference for next sample. The algorithm was tested on 80\% and 30\% compensated transmission line.

Author used Prony Method as second approach for predicting the switching instant. This approach works on loop data windows. Prony method is helpful in minimizing squared error over all of the sampled data. This method adopts two processes for checking accuracy of estimated parameters. In first method, signal shape of 1st window is recalculated based on estimated parameters and comparison is done between measured and recalculated signal to estimate the quality. In the second method, estimated parameters are used to re-calculate and compare to the second window. This comparison is done at 3rd window and optimum switching instant is considered in forth window. The zero crossing of future voltage wave...
wave can be used as optimum switching instant.

![Pearcing voltage characteristics](image)

**Fig. 4** Pearcing voltage characteristics.

![Optimal Instant for energization](image)

**Fig. 5.** Optimal Instant for energization considering zero crossing and smallest voltage derivative.

During switching, if pearcing occurs it leads to high switching over voltage. For avoiding pearcing, zero crossing with smallest rate of rise of voltage will be selected with switching window. Author used fixed and variable time shifting method to predict closing point keeping in view of pearcing voltage characteristics in +ve direction. Simulations were carried out in EMTP for different pearcing voltage and are observed that no time shifting is required for lower values
voltage derivatives of the order of 60KV/ms. If there is zero crossing of other phases before the instant of smallest rise of voltage; then earlier zero crossing will be switching instant for the two phases and later will be switching instant for third phase.

Results of single phase reclosing using variable time shift shows no peaking and maximum switching voltage observed was 70kV. Prony method requires large computation hence poses burden on processor.

Controlled switching system using MODELS language in ATP was developed to minimize electro-magnetic coupling effect [10][11]. The system was tested on Northeast Brazilian Power System Grid. This method also uses zero crossing detection algorithm for identifying the possible favorable windows for breaker pole closing. Additionally, polarity of line side voltage is checked for minimizing the electromagnetic coupling effect between phases in line.

The bus voltage signal is fed to zero crossing algorithm for predicting the possible zero crossing. This algorithm evaluates both the Bus side and the line side voltage signals. In case of de-energized transmission line, bus side voltage and line side voltage have different magnitude and phasor. Line side voltage leaves different pattern for different level of compensation. Amplitude of voltage signals are determined by calculating absolute value between two zeros. Whereas periods of these signals are determined by comparing two consecutive zero crossings.

Also, auto-reclosing leaves trap charge in transmission line whose measurement is also required for optimum operation of controlled switching device. In this algorithm, DC component polarity is measured in event of auto-reclosing of un-compensated transmission line.
Figure-6 indicates the complete block diagram of control switching scheme having interactions with Power system through PT/CT, auxiliary contacts. This system consider the usual values of operating time of breaker pole and continuously stores the last value of period, amplitude, zero crossing of voltage signal and DC polarity in memory of Device. Upon receiving the closing command, Control Switching Scheme estimates the reference signals for future. When closing command is issued at $t_{\text{command}}$, $t_{\text{zero2}}$ becomes last zero crossing point and $S_{\text{ref}}$ is predicted signal is estimated as shown in figure (7) as $t_1$. As expressed in equation (5), the optimal instant for closing is $1/4$ cycles after zero crossing attaining $N_{\text{cycle}}$ to complete reclosing operation.
\[ S_{ref}(t) = A \sin(\omega_{sr}(t + \Delta T)) \] (3)

\[ \Delta T = T_{operating} + (t_{command} - t_{zero2}) \] (4)

\[ t_{optimal1} = t_{zero2} + \left( N_{cycles} + \frac{1}{4} \right)(2T_{sr}) \] (5)

Electromagnetic coupling effects were considered between phases in transmission lines during this method. This inter-phase coupling adversely affects the working of CSS in mitigating SOVs and can be minimized by closing the second and third phase as fast as possible. Delaying the closing command to second and third phase could enhance the coupling effect with the phase first charged. The use of CSS effectively reduces the SOVs to 1.55pu.

The fault conditions were not considered and simulated in controlled switching scheme earlier. A new algorithm was designed [12] which address the fault conditions occurred during auto-reclosing of shunt compensated transmission lines using Karrenbauer Matrix as operator. No such conditions are taken care by previous algorithms till 2011. Dead time for auto-reclosure operation is constant in conventional protection schemes of transmission lines. According to [12], two frequencies oscillate during opening / auto-reclosing of shunt compensated transmission lines namely mode-0 and mode-1[9]. Magnitude of oscillating frequencies are expressed as given by eq. (6) & (7) as:-

\[ f_1 = \frac{1}{2\pi \sqrt{L_{r1}C_{r1}}} \] (6)

\[ f_0 = \frac{1}{2\pi \sqrt{L_{m}C_{m}}} \] (7)

During occurrence of fault, the phase voltages are de-coupled to sequence voltages. Further during single phase to ground fault, the frequency of oscillations are governed by argument of cosine function of sequence voltage.

Consequently, after extinction of fault, the modal frequencies are de-coupled and circuit start oscillating as per mode-0&1 frequency. Author proposed co-efficient of Determination R2 to distinguish and evaluate the type of fault/extinction time happened on transmission line. R2 is continuously evaluated and actual dead time of transmission line is also calculated. By actually calculating
the dead time, the algorithm is designed to issue closing command after extinction of fault by measuring R2. In this way the dead time of closing operation is reduced and line can be closed earlier as compared to fixed dead time as discussed above. The scheme is simulated in Real Time Digital Simulator and type of fault is identified by calculating the value of R2. Author considers single phase to earth fault and double phase to earth fault in this study. Simulations are done on 500kV North-Brazilian Power System Grid.

Author also considers the mechanical scatter during closing operation and added this scatter to operating time of Circuit Breaker. 400 simulations were run on EMTP and is concluded that Switching Over voltage are considerably reduced on the line. This method not only reduced the SOV but also reduced the dead time, thus increases the reliability of transmission line.

Synchronous Switching Scheme designed by ABB having model Switch Synch PWC 600 [14] assume first phase to be closed which undergo first zero crossing and second phase will be closed after lead of 120 degree electrical and third phase will be energized after 240 degree of first phase.

Controlled switching scheme with trade name of RPH3 was developed by Areva Ltd. simulated on BC Hydro Engineering Canada [15]. This point on wave controller distinguish type of operation like simple closing and fast reclosing based on measurement of time duration. Identification is faulty phase is done by comparing the magnitude and phasor of current with stored data history. There are number of methods available with controller include Zero of source voltage, min/max source voltage, zero of sine voltage, min of beat pattern, prony method. Prony method is used to analyze voltage signal for 100ms, composed of magnitude, frequency, phase and damping factor. The algorithm create a set of optimum closing time in form of a array and best point is selected on the basis of minimum scatter and minimum time period from starting of reclosing window.

A controlled switching scheme for mitigating switching over voltage was designed considered Switching instant as a random variable [16]. Uniform Distribution and Gaussian distribution methods are considered as density functions. This scheme is based on conventional zero crossing algorithm. Different cases are studied i.e. standard deviation(SD) of closing instant of 86% around peak, 10%
SD around peak, 86% SD around zero crossing and 10% SD around zero crossing. Simulations show that minimum switching over voltage occurs with 10% SD near zero crossing in case of D as shown in fig.8.

Fig. 8. Different Cases for distribution of closing instant.

Case study was done on 400kV Transmission Line having line length of 200kms using Gaussian distribution. For larger value of SD, values of mean doesn’t affect over voltage. On the other hand smaller SD tends to reduce over voltage significantly. Authors prefer this approach for reducing switching over voltages of shunt compensated transmission lines because line voltage oscillates at a frequency below the fundamental frequency after the opening of line. The zero crossing algorithm can be applied for finding the zero of line voltage beat wave. However, in case of un-compensated transmission line, resonant frequency does not occur and leads to trapped charge hence zero crossing algorithm is not applicable in this case.

Second approach proposed by author is meant to mitigate over voltage of un-compensated transmission lines using polarity checking method. In case of un-compensated transmission lines, breaker must be switched on at an instant the polarity of DC component and bus voltage is identical. Controller device stores the polarity of DC component of last opening and based on last polarity, relay
predict the next zero crossing. If polarity of trapped charge is +ve, closing operation is executed at +V\textsubscript{m}/2 of source side voltage as shown in Fig. (9).

If polarity of DC component is -ve, optimal closing is done at -V\textsubscript{m}/2. By doing this the voltage across breaker is reduced which reduces over voltage occurrence in network. If operation is done at zero crossing, the voltage across breaker is +V\textsubscript{max} and similarly if operation done at peak again the voltage across breaker is +V\textsubscript{max}. Simulation results shows that if operation is done at +V\textsubscript{m}/2, the voltage at breaker will be +V\textsubscript{m}/2. Effect of positive and negative slope while charging is also simulated which shows closing at negative slope gives reduced over voltages.

A new method for implementing control switching scheme was developed in order to mitigate switching over-voltages on shunt compensated transmission lines based on Voltage envelop method [17][18][19][20]. During auto-reclosure of three phase shunt compensated transmission lines, the maximum magnitude of beat decreases with time and minimum magnitude tends to increase. Patricia proposed 1st beat minimum to re-close the highly compensated transmission lines. For lower degree of compensation, beat occur very frequently. Considering the dead time of protective relay, the optimum making instant is considered as 3T/2 or 5T/2.

Voltage signals are subjected to filtering process to drain high frequency signals for which a low pass butterworth filter is employed. The envelope of voltage signal is determined by evaluating its maximum value. The whole process works on maximum voltage magnitude crossing rather than zero crossing which might be missing for low compensated transmission lines.
The method offers greater reliability as compared to previous methods. Reclosure action is initiated earlier and transmission line is also be loaded earlier as the process of determining first minimum of beat begins early. In the previous schemes, voltage signal is sampled up to zero crossing and if only the next sample matches first, the closing command will be issued for next zero crossing. Hence, it requires one additional cycle to initiate closing. The method is tested offline on EMTDC program and physically tested on hardware using 3PC processor containing 3 analog ADSP-21062.

2 Discussion

Controlled Switching Scheme is beneficial to Power System during both short and long terms. Circuit breaker operating consistency is the prerequisite for implementing Controlled Switching Scheme. Most SF6 type HVAC circuit breakers installed across the world show greater consistency in opening and closing time. They have adequate RDDS rating so as to avoid pearcing with voltage derivative. The reduction in cost can be achieved in terms of reduced insulation requirement of apparatus and reduced rating of Surge Arrestor. Zero crossing technique is used by various authors to detect optimal making instant. Different scenarios were considered for evaluating the performance of proposed methods including different degree of compensations. Significant reduction in switching over voltage is achieved using controlled switching schemes discussed above.

All authors conducted comparative study to analyze the performance of Controlled Switching Scheme with PIR and Surge Arrester and the results showed that CSS are very efficient in mitigating Switching over voltage on shunt compensated and un-compensated transmission lines during normal closing and auto re-closing. Table I shows the performance of controlled switching schemes designed by authors described above.
It is concluded that major requirement for successful operation of CSS is the minimum voltage across the breaker during closing operation keeping in view the polarity of the trapped charge [21]. By implementing controlled switching for mitigating Switching Over voltage, power quality and reliability of Power System is also improved. Presently, Controlled Switching Devices are being manufactured by several agencies with trade name of CSD, Point on Wave controller etc. CSS are also helpful in uprating the useful life of circuit breakers in service.

Review of authors stated above shows that better model of CSS were presented with passage of time and technology. In 1997 first kind of CSS controller is used for mitigating SOV, it doesn't have feature for identifying the trap charge polarity. Thereafter, features were added to identify polarity and algorithms was designed to get adapted for auto-reclosing operation with various degree of compensation. Performance of CSS were continuously improved with adding new features like fault condition recognition in 2011.

### 3 Future Scope

CSS presently installed in industry are satisfactorily performed however there is still a scope for various addressing protection coordination issues. Considering the desirable features of CSS, a novel CSS model is that, voltage/current signals derived from source/line be fed to IED. This IED continuously store the samples voltage and virtually train the data set. Fault classification and other allied activities are concurrently executed by algorithm. New optimization
techniques can be applied to inherit all the essential features of CSS. The algorithm should be adapted to any degree of compensation and doesn’t depend on the dimensionality of space. Scheme should carefully examine the fault extinction time and continuously evaluate the dead time. Therefore if dead time is also optimized, the reliability of transmission line is increased along with reduction of SOV. Also, the CSS should be the integral part of circuit breaker as compared to those which are retrofitted. Retrofitting causes some suitability and modification difficulties in utilities.

References


