Dynamic Analysis of the Impact of TCSC on Distance Relay Operation

S. Jamali and H. Imani

Abstract— TCSC and its protective equipment present very complicated impedance characteristic which could affect distance protection operation. Under earth fault conditions, changes of symmetrical sequence currents influence the relay characteristic, Mho, Reactance or Directional. This paper presents studies on the effects of control strategy of TCSC such as Constant Impedance (CI) and Constant Current (CC) techniques on the apparent impedance measured by distance relays during faults. The simulation results show that distance relays overreach and lose their directional integrity with different control strategies. The work shows that not only the relay maloperation for the compensated lines, but also operation of the relays on adjacent lines are affected by TCSC.

Keywords: Distance relay, Thyristor controlled series compensator, Impedance measurement.

I. INTRODUCTION

THYRISTOR controlled series compensator (TCSC) is a series Flexible AC Transmission (FACTS) device which allows rapid and continuous changes of the transmission line impedance for achieving optimum operation. It has advantages such as regulating the power flow on a transmission line, damping inter-area power oscillations, mitigation subsynchronous resonance (SSR) and improving transient stability.

In spite of the above advantages TCSC introduces new power system dynamic problems which could affect the system protection and must be analyzed by the protection engineer. It is worth noting that not only during normal operation the capacitive reactance of TCSC is not fixed and depends on the operating point and control strategy, but also TCSC does not always transit to bypass mode for all the faults. When the fault current is large, it operates between the blocked and by-pass modes to protect the capacitor and MOV (Metal Oxide Varistor) against overvoltages. On the other hand, when the fault current is small, the MOV does not conduct and the TCSC branch remains in the vernier mode operation. Different modes taken by TCSC control system during the fault would change the impedance of the line significantly [1].

The results of a recent study show that series compensation by TCSC affects the distance protection on both the compensated line and adjacent lines. Some problem contain forward overreach of the protection of the lines including TCSC in their fault path; reverse overreach of the adjacent lines protection; and disabling directional discrimination to a fault by the relay [2].

The objective of this paper is to analyse and study the impact of TCSC with different control strategies on the performance of impedance-based protection relays under fault conditions. Transient behaviour of TCSC and distance relay is modelled by using MATLAB/SIMULINK Power System Blockset (PSB).

MATLAB contains many high level instructions and tools for power system design applications and algorithm developments. Since the SIMULINK toolbox of MATLAB provides excellent Graphical User Interface (GUI) and block modules, these features allow the user to rapidly and easily build and simulate system models at the same time [3]. For a complete analysis, the study system compensated with TCSC and relay model are simulated by SIMULINK block-sets.

The paper is organized as follows: Section II explains briefly the TCSC modelling and steady state modes of operation. Different TCSC modes of operation during a fault and their effects on protective relays are also analysed in this Section. In Section III, an analytical analysis of the TCSC dynamic is presented. Control structure; Constant Impedance (CI) and Constant Current (CC) control strategies are explained in section IV. In section V distance relay model; phasor estimation relay model and RL calculation relay model are presented. In section VI, Results of the simulations for studying system and distance relay model by MATLAB/SIMULINK and behaviour of a distance relay are shown for different control strategies (CI and CC). The conclusion of this paper is presented in section VII.

II. TCSC OPERATION MODEL AND FAULT HANDLING

Fig. 1 shows a TCSC module with different protective elements in the middle of a transmission system. As shown there are three transmission lines in this system and the relays RA1 and RB2 protect the main line against faults.

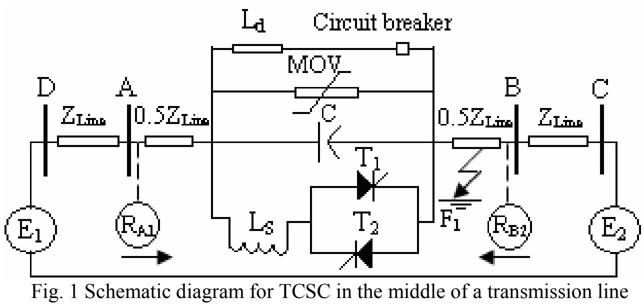

Fig. 1 Schematic diagram for TCSC in the middle of a transmission line

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Basically, the TCSC comprises a series capacitor C in parallel with a Thyristor-Controlled Reactor (TCR), *Ls*. A MOV is connected across the series capacitor to prevent the occurrence of high capacitor overvoltages. A circuit breaker is also installed across the TCSC module to bypass it if a severe fault or equipment malfunction occurs, this mode may be activated when the energy of MOV exceeds certain threshold level [4]. A current-limiting inductor L_d is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor-bypass operation.

There are different modes of operation for TCSC in the normal and fault conditions [2]. In normal operating conditions, there are four modes of operation, i.e. blocking mode, bypass mode, capacitive boost mode and inductive boost mode.

When the trigger pulses are applied to the thyristors at 0 and 180 degrees, the thyristors are kept in non-conducting state, the current passing through the valve becomes zero. In this case the TCSC is operating in blocking mode. In this mode as shown in Fig. 2, TCSC performs like a fixed series capacitor with a MOV parallel connection.

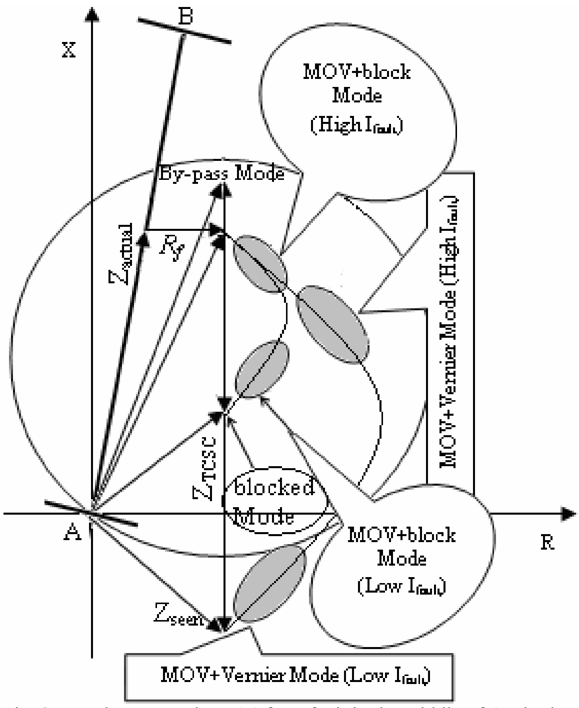


Fig. 2 Impedance seen by RA1 for a fault in the middle of AB in the presence of different modes of TCSC

In by-pass mode the trigger pulses are applied to the thyristors at 90 and 270 degrees, in this situation valve is kept in full conducting; so the TCSC behaves like the parallel connection of fixed capacitor with TCR branch inductance. In this mode the TCSC voltage does not have sinusoidal waveform and the TCR branch current is bigger than line current. Since X_S / X_C ratio is chosen between 0.1 to 0.3 ranges for practical applications, this mode is used for preventing the TCSC against overvoltages.

In capacitive boost mode or vernier mode the trigger pulses are supplied to the thyristors to maintain the TCSC capacitive reactance or line current at the desired values. The trigger pulse is supplied to the thyristor which has positive voltage just before the thyristor voltage crosses the zero in time axis, so the capacitor starts discharging via the valve. Discharge current is added to the line current and causes the total passing current through the capacitor to be increased. By increasing the TCSC total current the fundamental TCSC voltage is also increased in proportion to the capacitor charge current.

In this case there are two components for capacitor voltage that first one is controlled by firing angle applying to the thyristors (as first definition of firing angle; delay of trigger pulses from zero crossing of line current, other definition; delay of trigger pulses from zero crossing of capacitor voltage). The other TCSC voltage component is voltage caused by line current. The first one is controllable by changing instant of applying pulses to the thyristors and second one is uncontrollable and it depends on magnitude of line current. From the system point of view, this mode inserts capacitors to the line up to nearly three times the fixed capacitor. This is the normal operating mode of TCSC.

In inductive boost mode the circulating current in the TCSC thyristor branch is bigger than the line current. In this mode, large thyristor currents result and further the capacitor voltage waveform is very much distorted from its sinusoidal shape. In this mode the inductance of the line is increased and this property of TCSC can be applied for restricting of fault currents. This mode of TCSC may be also used for improvement of operation of the distance relays on transmission lines which are compensated with TCSC.

During a fault, different modes of operation could occur that incorporates the TCSC protection equipments. These modes are as follows:

- TCSC bypass operation without MOV;
- Capacitive boost mode with/without MOV;
- Blocked mode with/without MOV;
- Circuit breaker bypass;

Figure 1 can be used to estimate the apparent impedance seen by different relays. For simplicity, only three phase faults are considered. In this Figure, relay R_{A1} measures the impedance for 3-phase and phase-phase faults beyond the TCSC as:

$$Z_{seen} = Z_{actual} + R_F + Z_{t\,\mathrm{csc}} \quad (1)$$

Where Z_{seen} is the impedance measured by the relay, Z_{actual} is the line impedance between the relay and fault location, R_F is the fault resistance, and Z_{tcsc} is the TCSC impedance.

As mentioned in [7], since pre-fault system conditions cause remarkable effects on relay operation for single phase to earth fault, for single phase to earth fault case, (1) is changed to following equation as below:

$$Z_A = \frac{3Rf - 3\frac{Z_{0B}}{Z_{0A}+Z_{0B}}K_0 Z_{TCSC}}{\frac{Z_{\Sigma}(1-ph)}{Z_{1B}+Z_{1A}ph} + \frac{2Z_{1B}}{Z_{1A}+Z_{1B}} + \frac{Z_{0B}}{Z_{0A}+Z_{0B}}(1+3K_0)} + \ldots$$
$$PZ_{1L} + Z_{TCSC} \quad (2)$$

Where PZ_{1L} is the impedance value of line section between the fault and the relaying point, P is the per unit length of the line section between the fault and the relaying point and K_0 is the zero sequence compensation constant for single phase to earth fault [5], [7].

Equation (2) shows that, in single phase to earth fault situation, the operation of the relay installed on the transmission line which is compensated by TCSC, depends on fault resistance, compensation level, TCSC modes of operation under different fault conditions and operational and structural conditions of power system. In the presence of high fault resistance, the mho relay may underreach more than case which fault occurs with less fault resistance without installation of TCSC on the transmission line. By Comparing single phase to earth fault with phase-phase or three-phase fault in the presence of TCSC this result can be deduced that the relay installed on the compensated transmission line for phase to earth fault overreaches less than phase-phase or three-phase fault, because, operational and structural conditions and pre-fault load current in the single phase to earth fault causes relay more under-reaching.

Different possible TCSC modes of operation during a fault and the behaviour of the relays can be summarised as follows:

A. TCSC Bypass Operation

If the fault current is relatively high, then the MOV operation is not enough to decrease the capacitor voltage. If the MOV energy or current exceeds certain value, the TCSC goes to bypass mode. In this case, the distance relay would underreach slightly. Since bypass mode decreases the capacitor voltage considerably, TCSC bypass mode with MOV conduction is improbable, and the MOV operation is not necessary.

B. Capacitive Boost Mode With/ Without MOV

When the fault current is low, no transition from capacitive boost mode takes place. In this case a significant compensation exists, so distance relay overreaches considerably. This condition usually occurs when the fault is in the adjacent lines. When the fault current is high, MOV operates for decreasing the voltage across the capacitor. The MOV would not short out the capacitor as the circuit breaker would. This condition is usually very short but may be repeated several times during the fault period. The impedance of TCSC would be the parallel combination of the vernier mode impedance and the MOV in a lower resistance. The relay would overreach but less than previous case without MOV operation.

C. Blocked Mode With/Without MOV

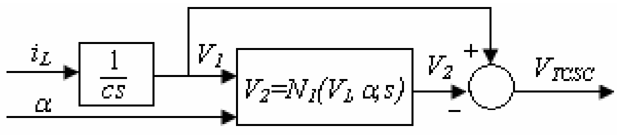
In some cases, for preventing overcurrent of the thyristors caused by the changing of the firing angle under conditions that the voltage phase of the capacitor changes suddenly, the thyristors would be blocked. In this case, the line is compensated by the fixed capacitor only. Distance relay overreaches less than the capacitive boost mode. This case might be accompanied by MOV operation.

D. Circuit Breaker Bypass

If the fault is not cleared within a certain time, then the TCSC transits to circuit breaker bypass mode. Since the series reactor in the circuit breaker is very small, the relay experiences the normal situation. This condition is used only for back-up protection.

III. Dynamic Behaviour of TCSC

The voltage across the TCSC capacitor contains an uncontrolled and a controlled component, and it is presumed that the line current is constant over one fundamental cycle. The uncontrolled component V_1, is a sinusoidal wave (unaffected by thyristor switching) and it is also directly related to the amplitude of the line current. The controlled component V_2 is a non-linear variable that depends on circuit variables, control strategies, reference values of impedance or current and TCR firing angle.



i_L – line current
V_1 – linear component of TCSC voltage
V_2 – non-linear component of TCSC voltage
α - firing angle
$N_1(V_1,\alpha,s)$ – Non-linear part dynamics

Fig. 3 TCSC model structure

As shown in Fig. 3, the controlled component is represented as a non-linear function of the uncontrolled component and firing angle. With this technique, $N_1(V_1,\alpha,s)$ gives the non-linear phenomena caused by thyristor switching influence and all internal interactions with capacitor voltage assuming only that the line current and V_1 are linear.

The fundamental components of reactor current i_{tcr} and the voltages V_1 and V_2 are selected as state variables and the non-linear state-space model is presented as:

$$sV_1 = \frac{1}{C} i_L \tag{3}$$

$$sV_2 = g \frac{1}{C} i_{tcr} \tag{4}$$

$$si_{tcr} = g \frac{1}{L_{tcr}} V_1 - g \frac{1}{L_{tcr}} V_2 \tag{5}$$

$$V_{TCSC} = V_1 - V_2 \tag{6}$$

Where in the mentioned equations g implies the switching function: $g=1$ for thyristor in conduction and $g=0$ for thyristor in blocking state.

As seen in Fig. 4 assuming the thyristor valve is initially open and the line current i_L produces voltage across TCSC. Supposing the thyristor controlled reactor L is to be turned on. At the instant of turn-on the TCSC voltage is negative, the line current is positive and thus charging the capacitor in the positive direction. Because of the negative voltage over the capacitor or TCSC, the TCR branch current becomes negative when the thyristor-controlled reactor is turned on. Here the reverse thyristor is conducting. The reverse thyristor stops conducting when the TCR branch current crosses zero in time axis as seen in Fig. 4. When none of the thyristors are conducting, the line and capacitor currents are equal.

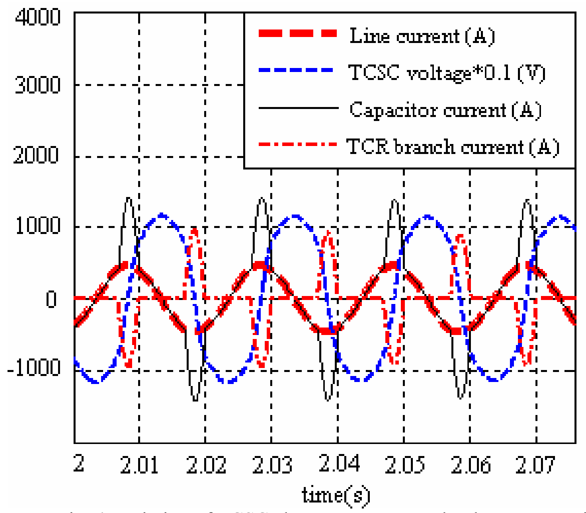


Fig. 4 Variation of TCSC elements current and voltage versus time

One half period later the procedure described above repeats but now the voltage drop over the capacitor or TCSC is positive, at the instant of turn-on the line current is negative and thus charging the capacitor in the negative direction. Because of the positive voltage over the capacitor, the TCR branch current becomes positive when the thyristor controlled reactor is turned on. Here the forward thyristor is conducting. The forward thyristor stops conducting when the TCR branch current crosses zero in time axis.

By regulating the conducting time for the thyristors, the total fundamental capacitive reactance of TCSC can be varied. From a fundamental frequency point of view the inserted capacitive reactance of the TCSC is therefore controllable.

IV. TCSC Control Structure

General structure of TCSC controller is represented in Fig. 5. The controller is implemented in MATLAB using Simpower control blocks. The TCSC controller is based on proportional-integral (PI) regulator. The derivative component controller feedback is compared with reference value and applied to the controller.

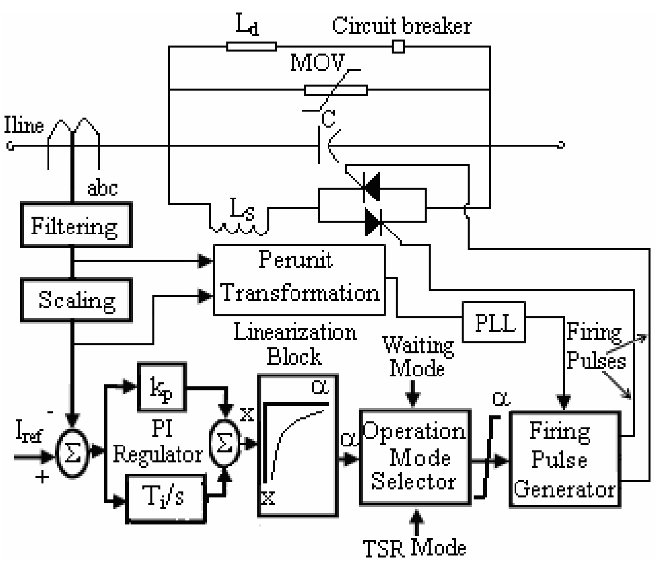


Fig. 5 Control structure and mode optioning of TCSC

For protecting the TCSC during faults, an operation mode selector block is used. In the severe fault situations the Thyristor Switch Reactor (TSR) mode is selected. In this case if the current or energy of Metal-Oxide Varistor (MOV) exceeds a certain limit, the TSR mode is activated. In this mode the thyristors are conducting at 90 and 270 degrees respectively and therefore sets the thyristors in full conduction. This mode contributes the MOV energy requirements decreasing and makes it possible to have fewer MOV columns installed in parallel with the TCSC equipment.

The waiting mode (blocked mode) operates during fault clearance time and makes it possible the dc offset voltage to be discharged. In this paper different disturbances are simulated and correctness of results is presented.

A. *TCSC CC Control Strategy*

In this approach the desired line-current magnitude is fed as a reference signal to the TCSC controller, which strives to maintain the actual line current at this value. The three-phase current is measured and rectified in the measurement unit.

The rectified signal is passed through a filter block and normalized to ensure per-unit consistency with the reference-current signal. The controller of each of three phases is identical. The controller is typically of the PI type that outputs the desired reactance signal within the preset limit.

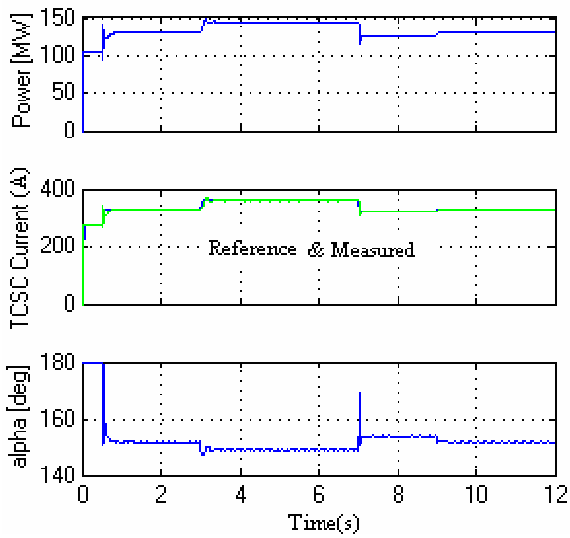


Fig. 6 Active power, TCSC current and firing angle in CI strategy

A lineariser block converts the reactance signal in to a firing angle signal. Firing angle is applied to firing pulse generator block for producing firing pulses. The control system is synchronized by the associated phase line current in pulse generator block. Firing pulses are applied to the thyristors valve for maintaining the associated phase line current on a desirable value. Simulation analysis is carried out to show the influence of the rating of the TCSC device on the relay operation. It is obvious that for the same operating point or degree of compensation, the higher rating of TCSC results the higher sensitivity of the controller. As shown in Fig. 6 by applying different values of the reference current to the current control model, the TCSC measured current follows the reference currents, it means that the transmission line current can be controlled at the desired value by this control strategy.

By increasing the transmission line current, active power transfer capability is also increased.

Fig. 7 shows the reactance characteristic of the implemented TCSC as a function of the firing angle. There is only one parallel resonance of capacitor and TCR for the range $0 < \alpha < 180^\circ$ at fundamental frequency. Near the resonance region, TCSC has very high impedance and this will result very large voltage dropping. Hence, it is necessary to operate the TCSC not more than a limit because the TCSC controlling is so difficult out of this region.

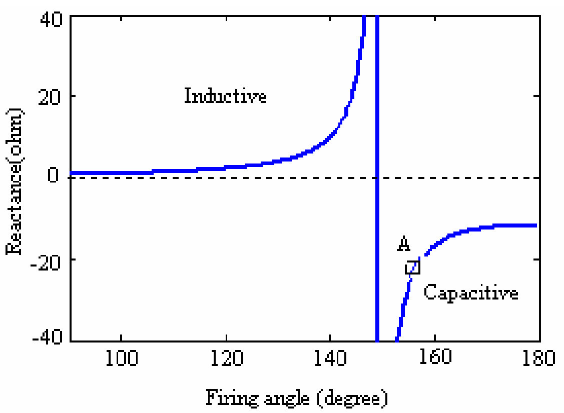


Fig. 7 TCSC steady-state impedance characteristic

As seen in Fig. 7 Point A is chosen as the operating point since it is the best compromise between a fast control and a safe operating condition, because the steady state operating point should be close enough to the parallel resonance region to permit fast modification of the system impedance for small variation of the firing angle.

B. TCSC CI Control Strategy

The TCSC impedance is computed from the measured voltage across the capacitor and the current passing through the TCSC.

The TCSC current signal is converted into a per-unit quantity and filtered, then fed to the Phase Lock Loop block (PLL) for the controller synchronization. The reference signal, Z_{ref} denotes the desired level of TCSC impedance, and the impedance controller has a PI structure. The remaining control-system components are similar with the CC controller.

By increasing reference value of impedance, the measured impedance of TCSC is also increased. By this control strategy the transfer power capability and line current can be controlled. As shown in Fig. 8 by controlling of TCSC impedance at the desired value, the line current and the power transferring through the transmission line can be changed.

By increasing impedance of TCSC in capacitive vernier mode the line current is increased and so power transfer capability of the power system becomes to high level transferring capability. This property of TCSC improves the transient stability of system.

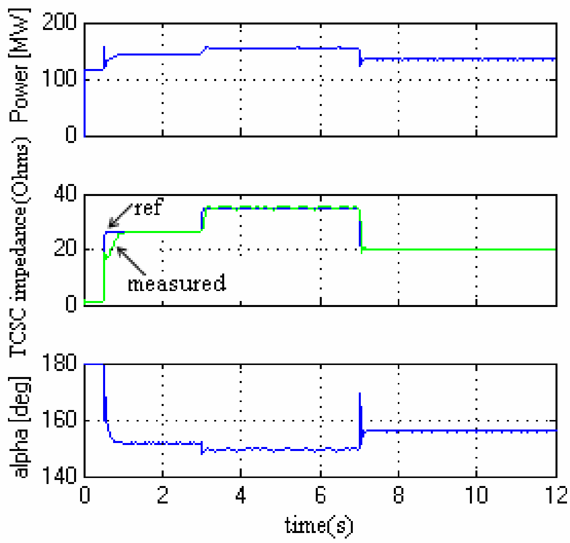


Fig. 8 Active power, TCSC impedance and firing angle in CC strategy

V. DISTANCE RELAY MODEL

Distance relays are used to calculate line impedance by measurement of voltages and currents. For Mho type distance relays, the relays compare the setting impedance with the measured impedance to asses if the fault is inside or outside the protected Zone. They issue a trip signal if the fault condition is detected [3].

Table 1 fault impedance calculation formula on different faults

Fault type	Formula
AG	$V_A/(I_A+3K_0I_0)$
BG	$V_B/(I_B+3K_0I_0)$
CG	$V_C/(I_C+3K_0I_0)$
AB or ABG	$(V_A-V_B)/(I_A-I_B)$
BC or BCG	$(V_B-V_C)/I_B-I_C)$
CA or CAG	$(V_C-V_A)/(I_C-I_A)$

In the above table *A,B* and C indicate phases; *G* is earth fault, *V* and *I* are phasors of voltage and current; $k_0=(Z_0-Z_1)/Z_1$, *where* Z_0 and Z_1 are impedances of line zero-sequence and positive-sequence respectively; I_0 is zero-sequence current.

A. Phasor Estimation by Using Mimic Filter

Different formula should be applied due to different fault types. Table 1 indicates calculation formula for all of the fault types. The fault detector can judge which fault type has occurred and by selecting suitable formula from table 1 calculates fault impedance at relaying point.

The Discrete Fourier Transformation (DFT) is the most popular technique to estimate fundamental phasors for digital relaying. The full-cycle DFT is described as following equation:

$$X = \frac{2}{N}\sum_{k=0}^{N-1} x_k e^{-j2\pi k/N} \quad (7)$$

Where X is complex phasor, x_k is the sample discrete data of the signal, and N is the number of samples per cycle.

In this work the higher frequency components is eliminated by using low pass anti-aliasing filters, but these filters cannot remove decaying dc components and reject low frequency components. Therefore by using a mimic filter the dc-offset components can be removed significantly [6].

Through this filter, the fundamental frequency signal (50Hz) should be passed without any changing. Assuming the gain of this filter equal 1 for 50Hz and the sample frequency is $f_s(f_s=1/T_s)$, finally the following formula can be obtained [6] .

$$\left|K(1+\tau f_s) - K\tau f_s \cos\omega T_s + jK\tau f_s \sin\omega T_s\right| = 1 \tag{8}$$

Where $\omega=2*\pi*50$, τ is the time constant for user definition and it is approximately calculated by *2*number of samples per cycle*. Gain K is calculated from (8). A block can be defined in SIMULINK for mimic filter by considering the above calculation. With the advantage that SIMULINK can easily simulate power system faults, the design and the test of protective relays can be achieved.

B. RL Calculation Based on Network Modelling

In this modelling at first, kind of fault is assessed by a program in MATLAB/SIMULINK and then associated formula is chosen from table 1.

Sampling from equivalent voltage and current is performed and these sampling data are applied to the relay model for reactance and resistance calculating. For dynamic analysis the impedance trajectory and mho relay characteristic are shown in the R-X plane.

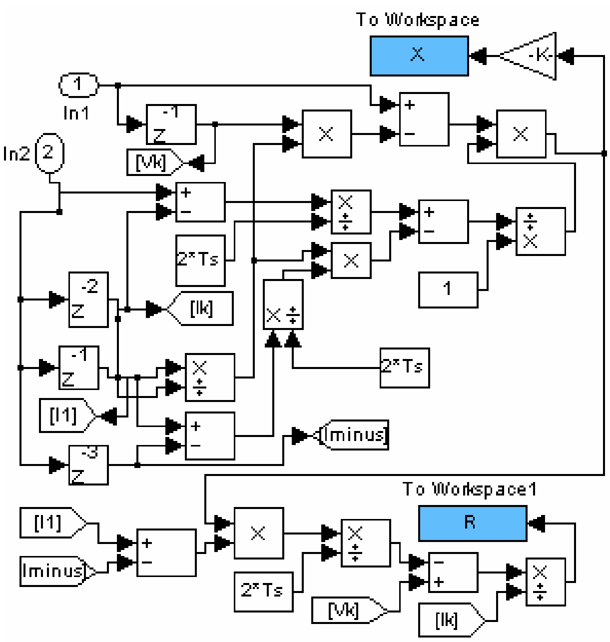


Fig. 9 RL calculation relay model in SIMULINK

The differential equation that relation between voltage and current is stated can be written as follow:

$$v = Ri + L\frac{di}{dt} \tag{9}$$

By substituting value of $\frac{di}{dt} = \frac{i_{k+1} - i_{k-1}}{2h}$ in the above equation the following matrix is obtained.

$$\begin{bmatrix} v_k \\ v_{k+1} \end{bmatrix} = \begin{bmatrix} i_k & \frac{i_{k+1} - i_{k-1}}{2h} \\ i_{k+1} & \frac{i_{k+2} - i_k}{2h} \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} \tag{10}$$

Where *h* (*Ts*) is the time interval between two samples, *R* and *L* denote resistance and inductance from relaying point to fault location respectively.

However by using the above matrix, without calculation the magnitude and phase of the applying signals to the distance relay, the impedance from the relaying point to fault location can be calculated directly with ease. However by putting four consecutive samples of voltage and current the calculations are performed and because of the derivation from current signal the dc decaying is removed. In this work the high frequency components problem is eliminated by applying a third order Butter-Worth filter in SIMULINK.

The relay model is simulated by MATLAB/SIMULINK simpower block-sets as seen in Fig. 9.

In Fig. 9, Im*inus*, *Ik*, *I*1 and *Vk* denote i_{k-1}, i_k, i_{k+1} and v_k respectively. The inputs 1 and 2 represent input voltage and current to the relay model that are modelled from table 1 formulas for different faults. For example for phase A to phase B fault, the input voltage and input current is $V_A - V_B$ and $I_A - I_B$ respectively.

VI. Simulation Study

Fig. 10 shows the single line diagram of the sample network used for simulation. The data for this network is presented in Table 2 for the 50Hz frequency simulation. TCSC is considered in the middle and it is assumed that the normal operating point of TCSC is 70% of line compensation and 40% in blocked mode. The behaviour of relays RD1, RA2 and RA1 for faults comprising TCSC and different control strategies of TCSC will be investigated. since the operation of relays RC1, RB2 and RB1 is same as relays RD1, RA2 and RA1 respectively, investigation of operation of relays RC1, RB2 and RB1 is not necessary here [1, 2].

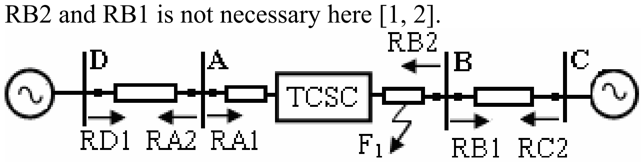


Fig. 10 Single line diagram of study system

The results are obtained by using MATLAB/SIMULINK software package. For each fault point, different fault types (three-phase, phase-phase and phase-earth) are tested. In this study, only the relays and fault points that are affected by TCSC are considered.

When the TCSC works in blocking mode, there is no difference between fixed and thyristor controlled series capacitors. In this simulation model, TCSC starts working at t=.5 s. The three-phase, phase-phase and single phase to earth faults are implemented on transmission lines at the time that the TCSC reaches to steady state operation point (t=2s) then the associated relays behaviour is evaluated. In these simulations sampling rating from current and voltage at relaying points are done with 64 samples per cycle.

Table 2 System data

LINES (AB, BC, CD)		
Length	[km]	100
Voltage	[kV]	500
Positive seq. impedance	[Ω/km]	0.0185+j0.3766
Positive seq. shunt capacitive reactance	[MΩ*km]	0.22789
Zero seq. impedance	[Ω/km]	0.3618+j1.2277
Zero seq. shunt capacitive reactance	[MΩ*km]	0.34513
SYSTEMS C & D		
Positive seq. impedance	[Ω]	1.43+j16.21
Zero seq. impedance	[Ω]	3.068+j28.746
System frequency	[Hz]	50
TCSC		
Main capacitor	[μF]	211.305
TCR inductance	[mH]	7.5
Ld in bypass breaker circuit	[mH]	0.2
MOV* reference current	[kA]	10
MOV reference voltage	[kV]	200
MOV exponent	[-]	24

*The v-i characteristics of MOV is commonly approximated by the equation $I=I_{ref}(V/V_{ref})^n$

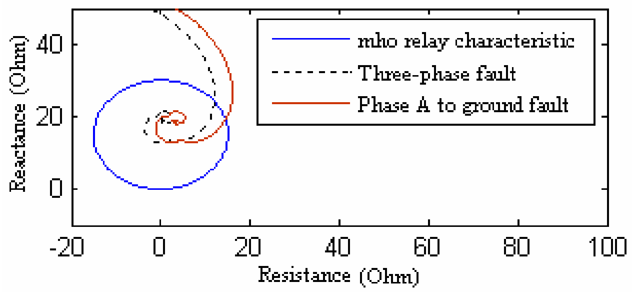


Fig. 11 Different faults on 50% AB before TCSC, relay RA1 (CI)

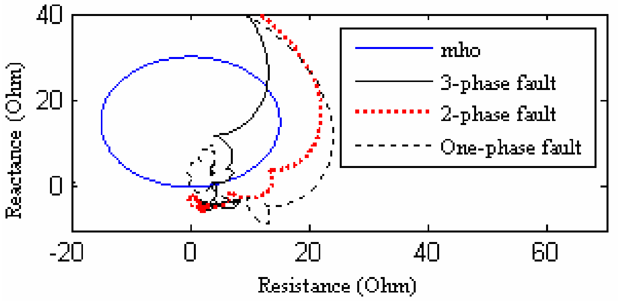


Fig. 12 Different faults on 50% AB after TCSC, relay RA1 (CI)

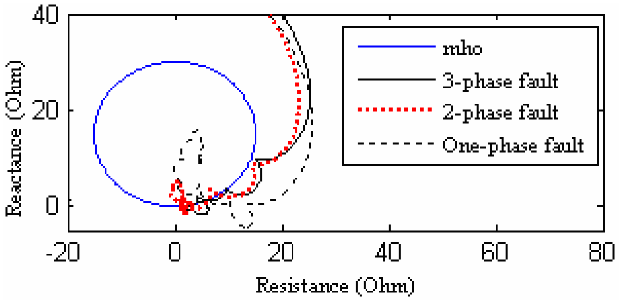


Fig. 13 Different faults on 65% AB, relay RA1 (CI)

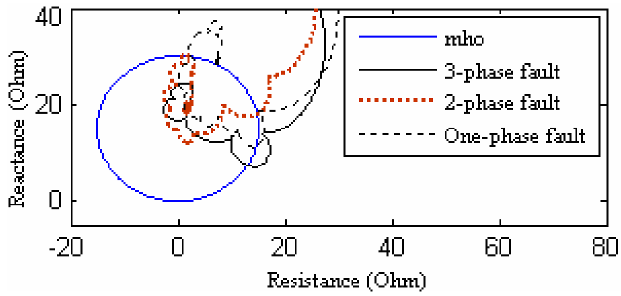


Fig. 14 Different faults on 20% BC, relay RA1 (CI)

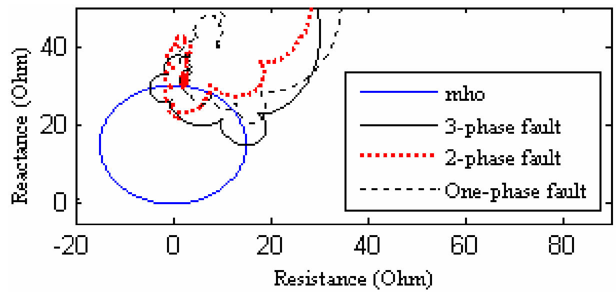


Fig.15 Different faults on 50% BC, relay RA1 (CI)

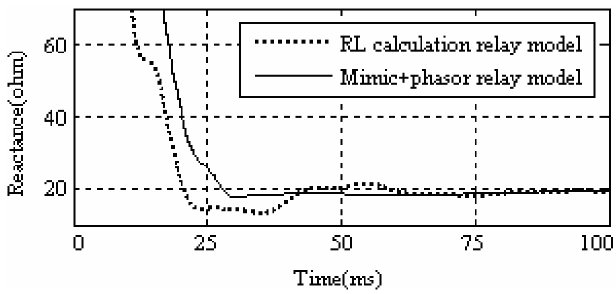


Fig. 16 Reactance versus time for two types of relays for 3-phase fault on 50% AB before TCSC, relay RA1

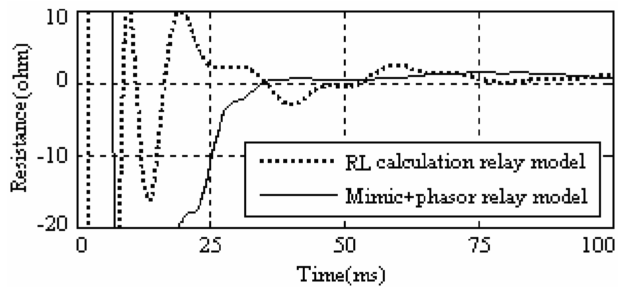


Fig. 17 Resistance versus time for two types of relays for 3-phase fault on 50% AB before TCSC, relay RA1

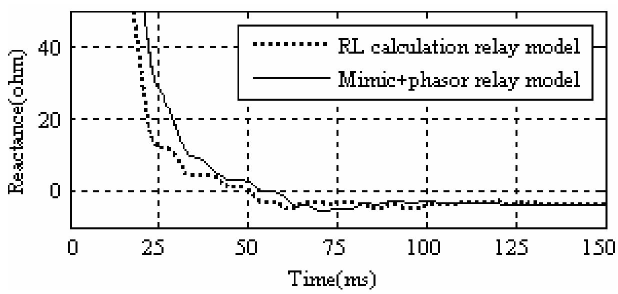


Fig. 18 Reactance versus time for two types of relays for 3-phase fault on 50% AB after TCSC, relay RA1 (CI)

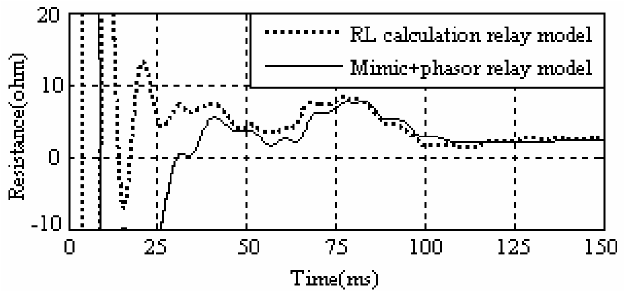


Fig. 19 Resistance versus time for two types of relays for 3-phase fault on 50% AB after TCSC, relay RA1 (CI)

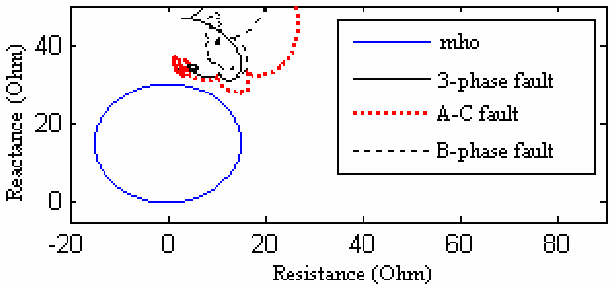


Fig. 20 Different Faults on 50% AB after TCSC, relay RD1 with MOV operation (CI)

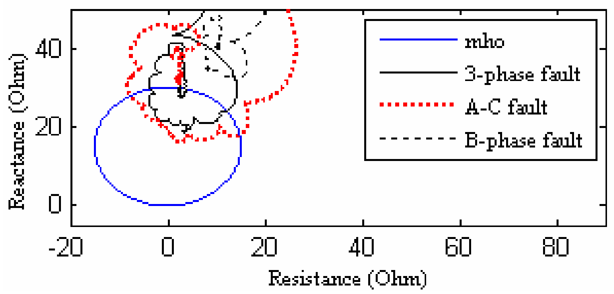


Fig. 21 Different Faults on 50% AB after TCSC, relay RD1 without MOV operation (CI)

The dynamic and transient simulations of the study system with two types of TCSC control strategy and two types of relay model are carried out using MATLAB/SIMULINK package. Figures 11-21 show the dynamic behaviour of the relays installed on the compensated and also adjacent transmission lines in the cases that TCSC is controlled by CI control strategy. Figures 22-26 show the dynamic behaviour of relays with CC control strategy of TCSC and Fig. 27 shows the dynamic behaviour of relay model in by-pass mode when MOV energy exceeds a certain limit.

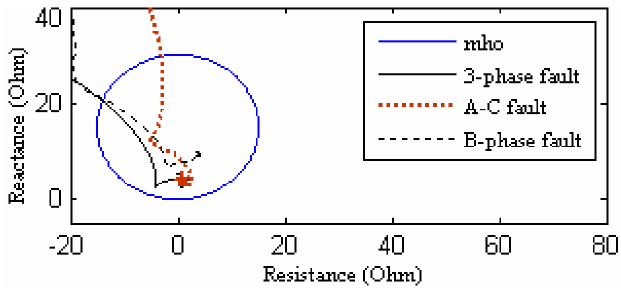


Fig. 22 Different faults on 50% AB after TCSC, relay RA1 (CC)

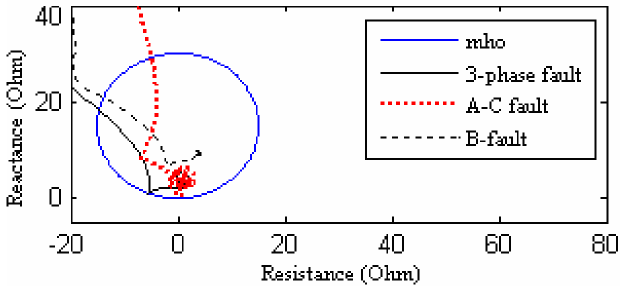


Fig. 23 Faults on 50% AB after TCSC, relay RA1 without MOV (CC)

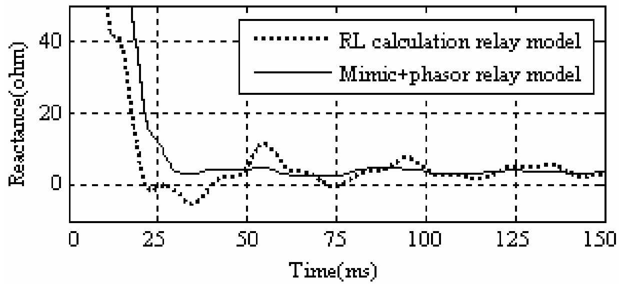


Fig.24. Reactance versus time for two types of relays for 3-phase fault on 50% AB after TCSC, relay RA1 (CC)

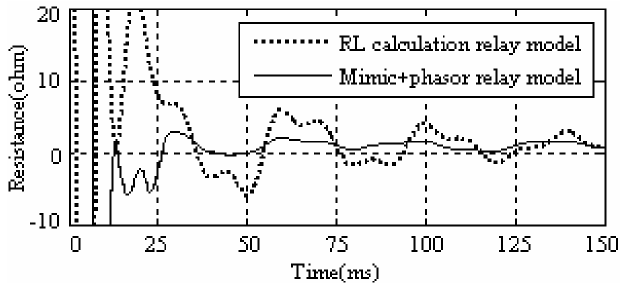


Fig.25 Resistance versus time for two types of relays for 3-phase fault on 50% AB after TCSC, relay RA1 (CC)

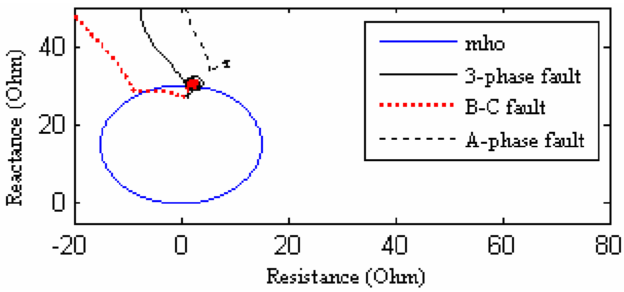


Fig. 26 Different faults on 20% BC after TCSC, relay RA1 (CC)

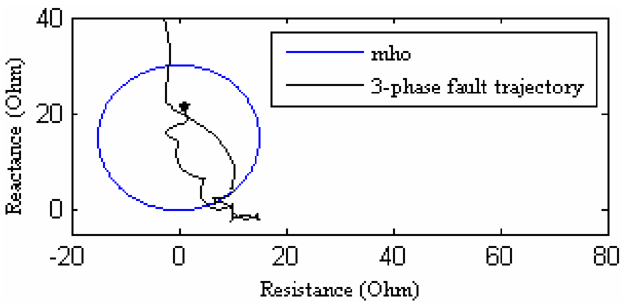


Fig. 27 3-phase fault on 50% AB after TCSC, relay RA1, TCSC bypass mode

By-pass mode with MOV operation is improbable because this mode decrease the MOV stress considerably.

As shown in Fig. 12 to 15 the relay RA1 for three-phase, phase-phase and single phase to earth faults over-reaches considerably. Although the reach point of relay RA1 is 80% line AB, but for three-phase and phase-phase faults on 40% line BC absolutely operates, it means that this relay over-reaches significantly for this point. On the other hand as seen in Fig. 12 this relay does not operate for faults except for single-phase to earth fault. It is obvious that the relay RA2 operates when relay RA1 detects fault in reverse Zone. For example in Fig. 12 the relay RA1 detects the three-phase and phase-phase faults in reverse Zone. Therefore in this case the relay RA2 operates for three-phase and phase-phase faults but does not operate for single phase to earth fault. The TCSC by CI control strategy has significant effects on relays mal-operation.

As shown in the simulation figures, CI and CC control strategies make different effects on distance relay operation. In CI the relay overreaches and loses the directional integrity more than case in which TCSC is controlled by CC. By comparing Fig. 12 with Fig. 22 the relay RA1 in Fig. 12 overreaches for different faults and does not see the phase-phase and 3-phase faults and does not operate, but in Fig. 22 the relay RA1 overreaches less than case as seen in Fig. 12 and sees the different faults in the front and operates correctly. As seen in Figs. 20-23 the MOV operation makes significant effects on the operation of relays. When MOV conducts, the compensation level of TCSC is decreased in proportion to the current that passes through the MOV. When the fault current is high, relay overreaches and loses the directional integrity less than case in which the fault current is low.

It is concluded that CC control strategy is better than CI control strategy for investigation of distance relays behaviour. In CC control strategy by increasing of measured current, TCSC mode is changed to blocking mode instantly and makes the relay overreaches less than case in which the TCSC is controlled by CI control strategy. As seen in Fig.27 when TCSC transits to bypass mode, relay RA1 under-reaches slightly and this mode can not affect more on distance relay operation.

VII. Conclusion

A detailed verification of the TCSC dynamic and transient impact on distance relay operation has been presented. Transient and dynamic behaviours of two model types of the relay have been simulated under different faults condition in the presence of two kinds of control strategy of TCSC. It has been shown that different operation modes of TCSC and MOV cause different effects on distance relay impedance measurement. By comparing CC control strategy with CI control strategy of TCSC, it has been concluded that distance relay overreaches in the CC control strategy and loses directional integrity less than the case in which TCSC is controlled by the CI control strategy.

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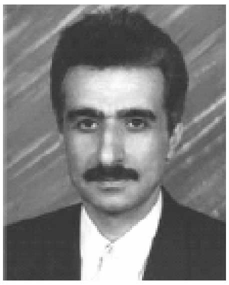

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