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An Adaptive Distance Protection of Mid-Point Series Compensated Transmission Line

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Abstract: Development of secure and accurate protection algorithm for thyristor-controlled series compensator (TCSC) transmission line is a very challenging task. This paper presents a high frequency transient based scheme for fault section identification on TCSC transmission line. The fault current signals are decomposed by Discrete Wavelet Transform (DWT) to obtain detail coefficients to detect faulty section. Further a new compensated Mho relay algorithm is proposed to protect the TCSC line. In this scheme Mho relay compensates the impedance, inserted by the TCSC in fault loop. The stability of the algorithm is tested for different types of faults considering wide variations in compensation level, fault resistances, inception angle, fault location and loading levels. Extensive simulation studies indicate that the proposed relay does not show any reaching mal-operation so it is reliable, accurate and secure. Assumed test system have been simulated in PSCAD/EMTDC and generated data have used for fault section identification by a MATLAB program.

Keywords: Compensation, fault section, TCSC, protection, wavelet transform.

INTRODUCTION

In power system it is required to improve the steady state power transmission capability of transmission line. FACTS compensator plays important role to make transmission line to transmit power up-to thermal limit with maintaining steady state and transient stability limit. One of the main FACTS device is Thyristor Controlled Series Compensator (TCSC), which can control power flow by compensating a portion of line reactance. TCSC is a combination of Thyristor Controlled Reactor (TCR) connected in parallel with a series capacitor. In modern power system, TCSC transmission lines are employed to enhance power transmission capability of transmission line, improvement in system stability, reduction in transmission losses and more power flow control [1]. However, the presence of TCSC in transmission line introduces reaching problems (distance measurements) and that affect Mho relay functionality. Around 80% of power system fault occur in overhead transmission lines. Mho distance relay has the inherent directional features and widely used for the protection of overhead transmission lines. Presence of TCSC at the mid-point of transmission line, severely affects selectivity and reliability of Mho relay which leads to an unsecure power system [2]. Presence of series capacitor is responsible for mal-operation of Mho relays, particularly the reaching characteristic of the relay [3]. In TCSC transmission line, tripping of distance relay depends upon the status of the TCSC impedance which is varying in nature. Presence of TCSC in the line creates under-reaching and over-reaching at the relay point in inductive and capacitive compensation respectively and that is a challenge to the protection engineer.

The protection of series compensated line is a challenging task. Several techniques, like Artificial Intelligence (AI) based Artificial Neural Network (ANN) and Fuzzy logic [4] have been suggested for protection of TCSC transmission line. These techniques use separate AI based relays to detect healthy or faulty condition of both phase and ground. However, there are some limitations of ANN based relay [5] such as multiple optimum solutions, dependability on input space and following heuristic path. In addition, AI techniques are time consuming algorithms as they need a lot of training and testing data. Therefore, for better classification algorithm, Support Vector Machine (SVM) [6, 15] is used for fault detection and classification in compensated transmission line. The Wavelet Transform (WT) based techniques [7] are also suggested due to their numerous benefits such as simultaneous localization in time and frequency domain, very fast computation and good resolution. Another such technique is voltage compensation based relay which on-line calculates the voltage across series compensated device and compensate it at relay location when the faults occurs [8]. Adaptive zonal setting in distance relaying technique via suitable communication channel can also be used [9]. Some other adaptive protection schemes [10-12] have also been proposed, but they are true only for some fixed degree of compensation and hence, the accuracy and reliability of these relays is not satisfactory. Protection of mid-point series compensated has been presented in [13, 14], which provides the section identification and adaptive protection for double circuit as well.. Differential phase angle of line current has been taken as the input feature for the more intelligent relay [16] which provides the robust solution. Accurate fault location calculation is also a challenging task in series compensated line. Some adaptive algorithms, identifies the error due to series capacitor-MOV and identifies the correct fault location [17-19].

This paper presents DWT based distance protection of series compensated line. A High Pass Filter (HPF) filter out High Frequency Transient (HFT) signals. Wavelet transform analyses the filtered current and classify the faulty section. Further, an advance compensated Mho relay is suggested for the protection of the TCSC transmission line. This paper is organized as follows. In section-II a line having TCSC at mid-point has been described. Section-III presents DWT based fault section identification scheme. In Section-IV, proposed protection algorithm has been illustrated and concluding remarks are given in section V.

TEST SYSTEM

A typical 220 kV, 50Hz, TCSC power transmission line is considered to develop and test the capability of the proposed protection algorithm of DWT base Mho relay. Test system is shown in fig. 1. It consists of two sources connected through a 200 km transmission line. Per km sequence impedances of transmission line in ohms are as: Z1 = 0.035+j0.507, Z2 = 0.035+j0.507 and Z0 = 0.363+j1.32. TCSC is placed at 100 km from the sending end generator which compensate the transmission lien up to 70 %. At TCSC connection point a simple RC-HPF is installed. The wavelet based distance relay monitors phase voltage and line current through a capacitor voltage transformer (CVT) and current transformer (CT) respectively [19].

The distance relay protection algorithm is a combination of conventional Mho relay and a compensated Mho relay scheme, if the fault occur in between bus A and TCSC point (Section I) the protection algorithm act as conventional Mho relay else it act as compensated Mho relay. A fast and reliable communication channel exist between bus A and TCSC point to transmit the thyristor firing angle (α) from TCSC substation to the Mho relay compensation unit. In compensation unit equivalent impedance inserted by the TCSC in the transmission line is calculated, which is a function of TCSC firing angle. TCSC compensates the transmission line in healthy and faulty conditions respectively by this impedance.

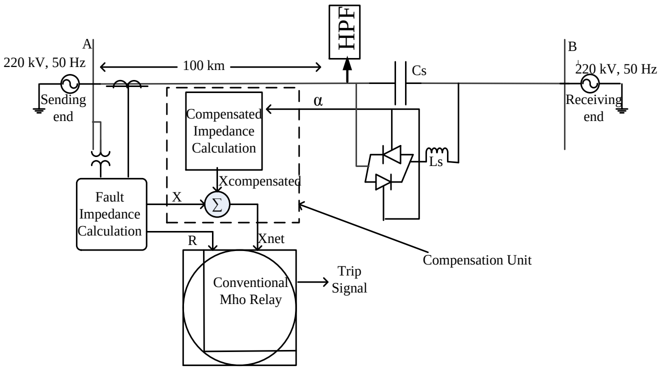


Fig. 1. Typical single line diagram of test system.

FAULT SECTION IDENTIFICATION SCHEME

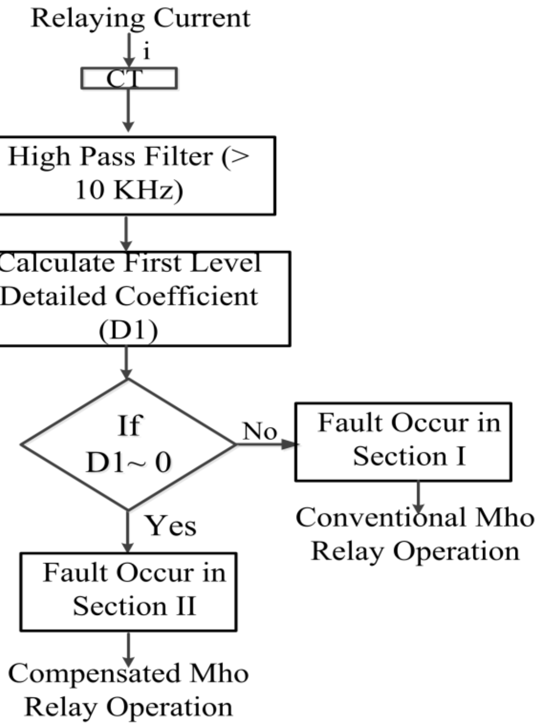
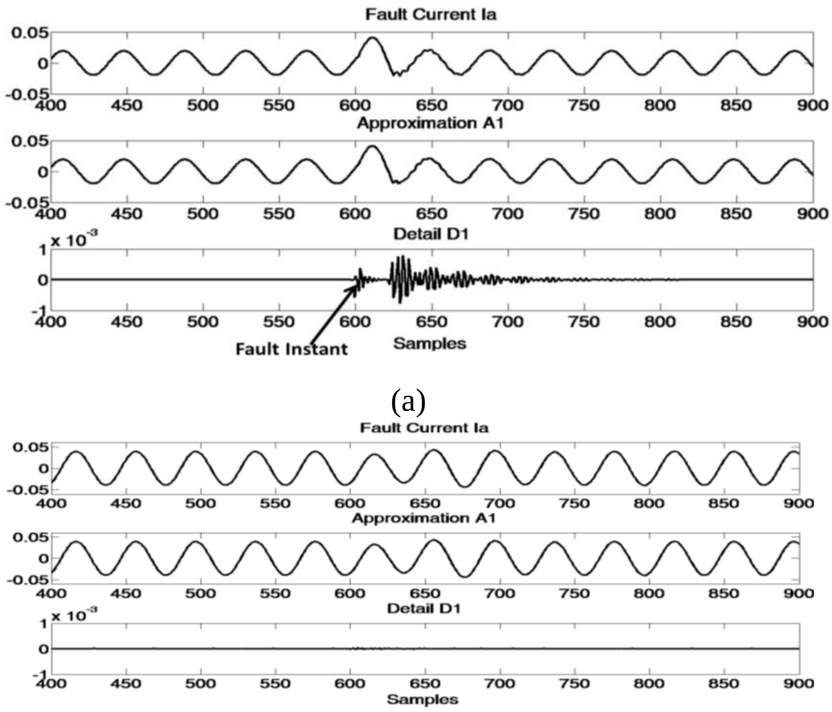


Fig. 2 Fault section identification algorithm

Proposed protection algorithm has two stages. In stage first, algorithm detects the section of line in which fault happens. In second stage, algorithm takes the protection action according to fault section. All the steps of the proposed algorithm are shown in Fig. 2. Three phase currents are measured through CT having turn ratio 1200:5 (saturation is neglected). Fault current passed through a HPF of 10 KHz cut-off frequency. DWT analyzed the filtered current at level 1 to calculated detailed coefficient D1, if D1 is present in the fault current then fault occur in section I and distance protection algorithm act as conventional Mho relay otherwise it will act as compensated Mho relay. The section identification scheme is based on calculating the values of detail coefficient "D1" of the current signals at sending end of the transmission line. Fault signal mainly consist of HFT having frequency range in between 10-100 KHz. The current signal is sampled as sampling frequency of 40 KHz. Signal is analyzed with DWT at level 1 to find spectral energy in different frequency band. Detailed coefficient D1 indicates the frequency band in between 10 to 20 KHz.



(a)

(b)

Fig.3. Frequency spectrum of fault current. (a) Without filter. (b) With filter

Frequency spectrum of the fault current is shown in Fig. 3 in which the fault occurs at 600th sample. Fig 3 (a) shows the spectral energy of different frequency band for any fault in between bus A and TCSC point. Fig 3 (b) indicates the transient frequency band for any fault beyond TCSC point and it can be depicted that high frequency components ($10 < f < 20$ KHz) are not present in the fault current. After fault section identification next step is to identify the faulty zone, next section of this work presents compensated Mho relay to identify weather the fault is in zone one or not.

FAULT ZONE IDENTIFICATION: COMPENSATED MHO RELAY

Fig. 4 shows the sequence diagram of TCSC transmission line for LG fault at n per unit length from the bus A. It is assumed that fault occurred at right side of the TCSC (section II).

Where,
I_{1s}, I_{2s} and I_{0s} are the sequence currents during fault.
V_{1T}, V_{2T} and V_{0T} are the sequence voltages across TCSC during fault.
I_{1f}, I_{2f} and I_{0f} are fault currents through fault resistance R_f.

The sequence voltages at the relay point can be expressed as [21]:

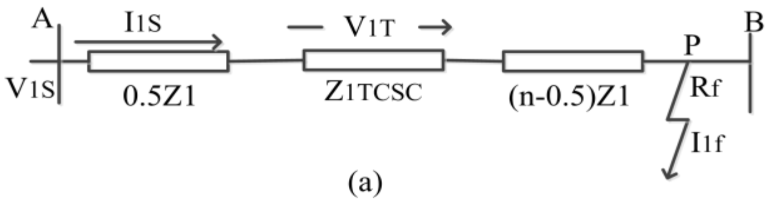
$$V_{1s} = 0.5\, I_{1s}\, Z_1 + V_{1T} + I_{1s}\,(n - 0.5)\, Z_1 + I_{1f}\, R_{1f} \qquad (1)$$

$$V_{2s} = 0.5\, I_{2s}\, Z_2 + V_{2T} + I_{2s}\,(n - 0.5)\, Z_2 + I_{2f}\, R_{2f} \qquad (2)$$

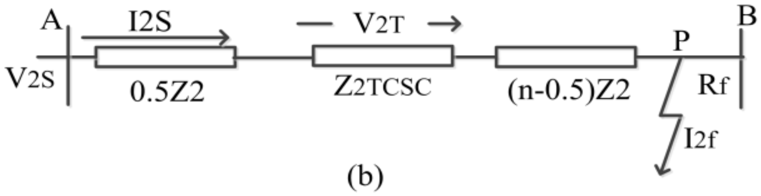
$$V_{0s} = 0.5\, I_{0s}\, Z_0 + V_{0T} + I_{0s}\,(n - 0.5)\, Z_0 + I_{0f}\, R_{0f} \qquad (3)$$

So apparent equivalent impedance (Zeq) at relay point can be calculated as:

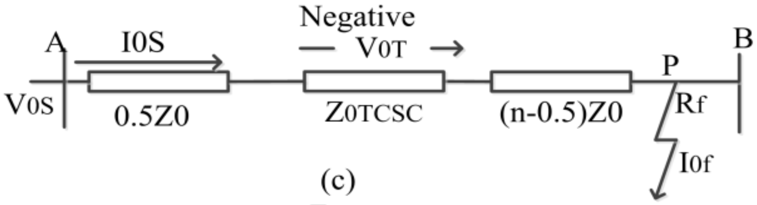
$$Z_{eq} = \frac{V_s}{I_{relay}} = (nZ_1) + \left(\frac{V_T}{I_{relay}}\right) + \left(\frac{R_f I_f}{I_{relay}}\right) \qquad (4)$$



(a)
Positive



(b)
Negative



(c)
Zero

Fig. 4 Sequence Network of the system during LG fault. (a) Positive. (b) Negative. (c) Zero

From equation (4) it can be seen that the apparent equivalent impedance seen by the conventional relay has three parts. First portion is the positive sequence impedance from relay point to fault point. Second portion is the impedance inserted by the TCSC; this impedance can be termed as compensated impedance (X_{comp}) which creates error in impedance measurement and third portion is the impedance due to fault resistance.

Computation of Compensated Impedance

The analysis of TCSC operation in the Vernier-control mode is performed based on the simplified TCSC circuit shown in Fig. 5. Transmission-line current is assumed to be the independent-input variable and is modeled as an external line current $i_L(t)$. It is further assumed that the line voltage is sinusoidal, as derived from actual measurements demonstrating that very few harmonics exist in the line current.

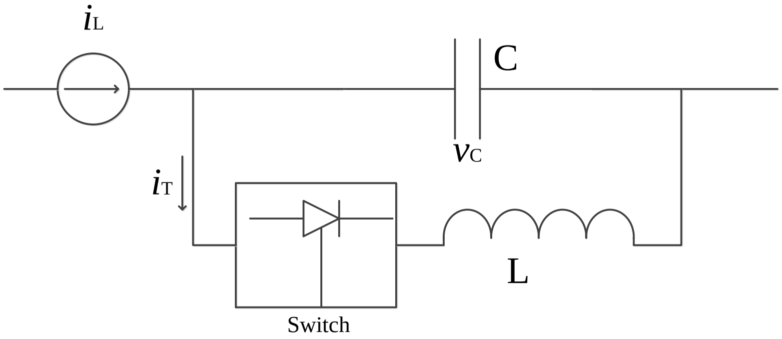


Fig.5. Simplified TCSC Circuit

A reactance characteristic of TCSC in inductive and capacitive mode is shown in Fig. 6 for the taken capacitive compensation of 25 %. Firing angle in between 35 to 45 degree, TCSC work in resonance mode at which series inductive and capacitive compensation become almost equal. In such region reactance inserted by TCSC is very high and totally avoidable.

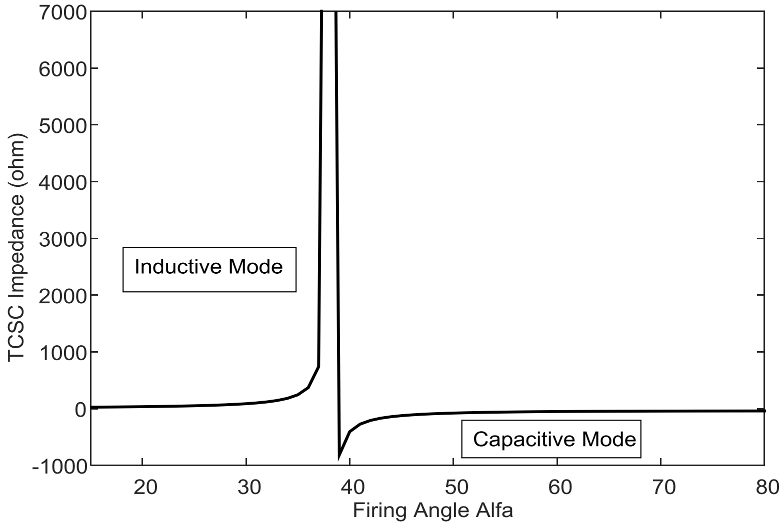


Fig.6. TCSC Characteristcs

The current through the fixed-series capacitor, C, is expressed as:

$$C\frac{dv_c}{dt} = i_L(t) - i_T(t) \qquad (5)$$

The thyristor-valve current, $i_T(t)$ is then described by

$$v_C(t) = L\frac{di_t}{dt} \qquad (6)$$

Let the line voltage across capacitor $v_C(t)$ be represented by

$$v_C(t) = V_m \cos\omega t \qquad (7)$$

The firing angle is generated using a reference signal which is delayed by an angle α (0 <α < π/2) with respect to the crest of the Voltage. Angle α is delay angle, which is assumed to be the same in both the positive and the negative cycle of conduction.

For a particular delay angle α, the current through indictor branch can be calculated as:

$$i_T(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v_C(t)dt = \frac{V}{\omega L}(\cos\omega t - \cos\alpha) \qquad (8)$$

Ratio of the line voltage and fundamental value of

$$X_{Ls}(\alpha) = X_L\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] \qquad (9)$$

Impedance inserted by TCSC is equivalent to compensated impedance (X_{comp}) which can be given by [1]:

$$X_{comp} = \frac{X_{cs} * X_{Ls}(\alpha)}{X_{cs} - X_{Ls}(\alpha)} \qquad (10)$$

Where, $X_{cs} = \frac{1}{\omega C_s}$

In actual practical installation of TCSC in the transmission line, TCSC equipped with the protection circuit. Protection circuit protects it from the high voltage surges and high fault current in the transmission line. Equipped protection circuit has the characteristics of highly non-linear impedance. TCSC itself has the non-linear characteristics. The parallel arrangement of both themselves creates a highly non-linear impedance characteristic. Therefore accurate calculation of the combination is necessary.

S. No.	Mode of Operation	Fault Time t=t1 (Sec)	Firing Angle (rad)	Error Due to TCSC	% Compensation	% Error
1	Inductive Mode	2	0.017	15.059	9.587	9.587
10		2	0.175	20.880	13.292	13.292
20		2	0.349	35.053	22.316	22.316
25		2	0.436	50.881	32.392	32.392
30		2	0.524	87.160	55.488	55.488
35		2	0.611	245.300	156.163	156.163
36	Resonance Condition (Avoidable region)	2	0.628	370.676	235.980	235.980
37		2	0.646	738.867	470.377	470.377
38		2	0.663	22738.190	14475.579	14475.579
39		2	0.681	-812.851	-517.477	-517.477
40		2	0.698	-405.032	-257.851	-257.851
41		2	0.716	-272.339	-173.377	-173.377
45	Capacitive Mode	2	0.785	-123.110	-78.374	-78.374
50		2	0.873	-77.693	-49.461	-49.461
60		2	1.047	-50.675	-32.260	-32.260
70		2	1.222	-42.583	-27.109	-27.109
80		2	1.396	-40.124	-25.544	-25.544
90		2	1.571	-39.789	-25.330	-25.330

Table 1 TCSC Compensation and error produced

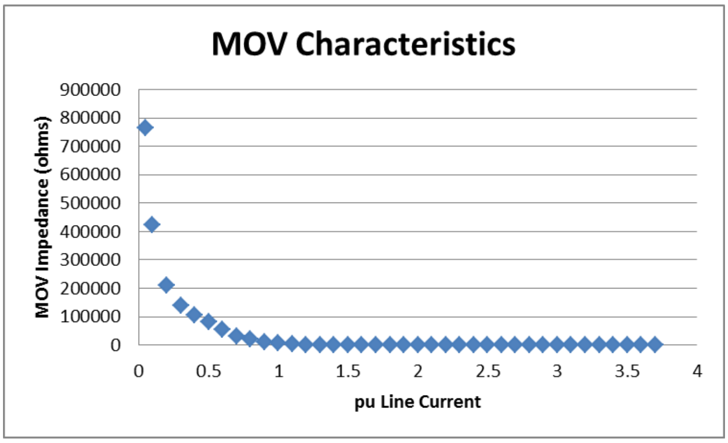


Fig.7 Designed MOV Characteristcs

Error produced by TCSC in impedance calculation is given in Table.1. For different compensation level, error has been calculated. In inductive as well capacitive mode of operation, error produced by TCSC increases as the % compensation level increases. From the table 1it is clear that in resonance mode of operation, error is very high therefore the operation of TCSC in such region is totally avoidable. In the proposed work, the equipped protection circuit impedance is modelled based on the relay current $i_L(t)$. MOV impedance characteristics have been designed as the curve given in Fig.7. For the different values of line fault current at relay end, MOV impedance has been measured to protect TCSC from higher value of fault current. Maximum 10 percent overloading in current is permissible and above that current, MOV impedance reduces drastically to bypass the over current. At higher value of current MOV impedance is almost negligible which generally occur in fault condition.

Complete data point of MOV characteristics has been given in appendix-I. MOV impedance ⍰M⍰ is a function of line current $i_L(t)$ and directly calculated from relay measurement unit. In general model Power equation the MOV impedance can be given as:

$$M = a*(i_L(t))^b + c \qquad (11)$$

Coefficients (with 95% confidence bounds):
a =5.398e+04 (4.565e+04, 6.23e+04)
b =-0.9014 (-0.9535, -0.8492)
c =-2.802e+04 (-3.579e+04, -2.025e+04)

PROPOSED MHO RELAY MODEL

Synchronized measurement of voltage and current based on accurate time reference takes place in between bus A and TCSC sub-station. Fig.8 describes the algorithm of the proposed Mho relay.

In this algorithm, the conventional Mho relay is altered by adding a fault impedance compensation unit. This unit computes the compensated impedance (X_{comp}) introduced by TCSC in fault loop which is a function of firing angle α (coming from TCSC substation via a fast communication channel) and line current at relay point. Relay takes voltage and current signal through CVT and CT respectively. Fault impedance Z (R and X) is calculated by conventional method at the relay point using fundamental and sequence components of fault voltage and current signal [20].Fast Fourier Transform decomposes the transient voltage and current into the fundamental quantity and sequence filter gives the positive and zero sequence value of current to measure gross fault impedance.

S. No	Firing Angle (Degree)	Fault Current (pu)	Xtcsc (ohm)	M(ohm)	Xeq(ohm)	% Error
1	1.000	3.700	15.059	0.753	0.717	0.457
2	10.000	2.800	20.880	1.044	0.994	0.633
3	19.000	1.900	32.920	11.711	8.638	5.499
4	20.000	1.800	35.053	82.793	24.627	15.678
5	25.000	1.300	50.881	1025.286	48.475	30.860
6	30.000	0.800	87.160	22175.206	86.819	55.271
7	35.000	0.300	245.300	140194.932	244.871	155.890
8	36.000	0.200	370.676	211850.941	370.029	235.568
9	37.000	0.100	738.867	422280.871	737.576	469.555
10	38.000	0.050	22738.190	765192.257	22082.008	14057.841

Table 2 Inductive Mode of operation

S. No.	Firing Angle (Degree)	Fault Current(pu)	Xtcsc(ohm)	M(ohm)	Xeq(ohm)	% Error
1	53.000	3.700	-65.401	0.753	0.753	0.479
2	60.000	3.000	-50.675	0.962	0.962	0.613
3	65.000	2.500	-45.547	1.193	1.193	0.759
4	71.000	1.900	-42.167	11.711	11.284	7.183
5	72.000	1.800	-41.798	82.793	37.312	23.754
6	80.000	1.000	-40.124	6624.730	40.123	25.543
7	85.000	0.500	-39.831	82396.292	39.831	25.357
8	90.000	0.050	-39.789	765192.257	39.789	25.330

Table 3 Capacitive Mode of operation

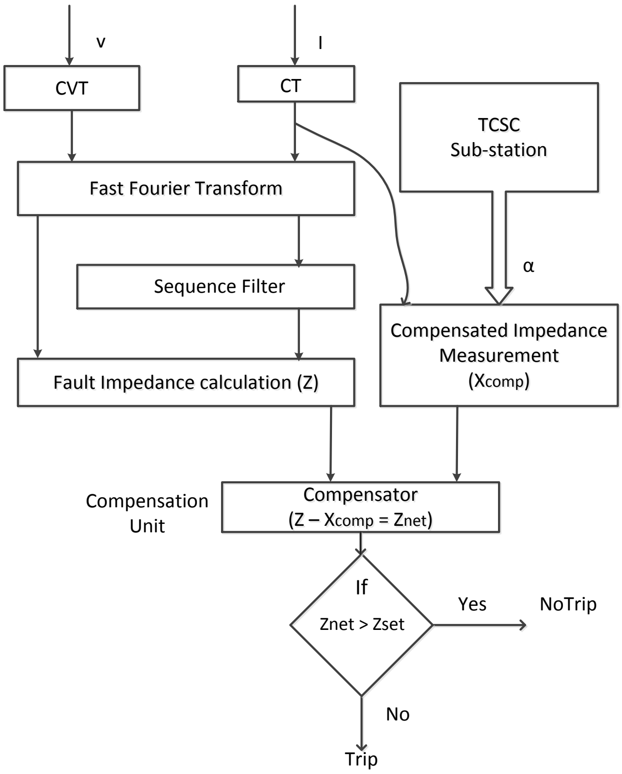


Fig. 8 Proposed compensated Mho relay algorithm

Compensation unit measure the equivalent error introduced by TCSC and MOV in all operating conditions. Proposed Mho relay compensation unit on-line calculates the compensated impedance (X_{comp}) of TCSC and simultaneously compensate it form the measured impedance (Z) at relay point. Finally net line fault impedance (Z_{net}= Z-X_{comp}) fed to Mho relay to decide whether the fault is within the reach (Zset, 85 % of transmission line) or not.

RESULTS AND DISCUSSIONS

Dynamics of TCSC and MOV w.r.t. error produced in actual impedance calculation in inductive and capacitive mode of operation has been presented in table 2 and table 3. Firing angle is totally independent of the per-unit fault current. TCSC reactance only depends on the delay angle (α) and MOV resistance (M) depends on the value of fault current. Equivalent reactance inserted by TCSC and MOV is highly dependent on the fault current. At higher values of fault current Xeq is very low and simultaneously create less error, which is clear from the tables. The proposed compensated Mho relay is tested on various types of faults like phase to ground and phase-to-phase fault and various operating conditions of transmission line having TCSC at mid-point. Lines to ground (LG) faults are created at several locations beyond the zone one of transmission line with different levels of capacitive compensation. Due to presence of capacitive compensation, net fault impedance of transmission line reduces. Therefore, conventional relay senses the fault beyond zone 1 and shows over-reaching effects at the typical test point location, 200 km from the sending end. On the other hand, proposed relay does not show any over-reaching effects. In capacitive boost mode for different level of compensation and loading, comparative behavior of conventional and the proposed relay are shown in Fig.9, which indicates that the fault impedance locus of conventional Mho relay enters the Mho circle while compensated Mho relay loci passes away from the circle. The difference between both the loci increases with compensation level. From the results, it is clear that the performance of the proposed Mho relay algorithm is far better than the conventional Mho relay. In inductive mode of operation, net fault impedance is higher than the actual fault impedance which produces error. Proposed relay subtract the error produced by TCSC in inductive mode and shifts the curve downward as shown in Fig.10. Although the proposed Mho relay has a few limitations if the fault is at the boundary of zone one, under certain operating conditions such as high loading angle and large fault resistance. However, it is found that the proposed Mho relay is highly accurate under normal loading conditions (load angle in between 20^o to 40^o) and fault resistance in between 0.01Ω to 50Ω for both LG and LL fault conditions and various operating modes of TCSC line. However, it is found that the proposed Mho relay is highly accurate under normal loading conditions (load angle in between 20^o to 40^o) and fault resistance in between 0.01Ω to 50Ω for both LG and LL fault conditions and various operating modes of TCSC line.

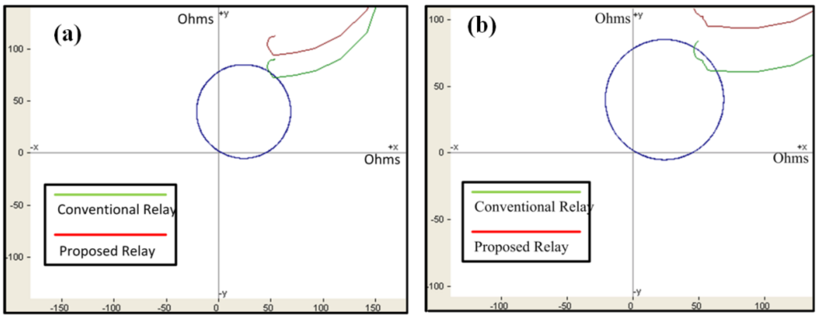


Fig. 9 Performance of conventional and proposed Mho relay in capacitive mode (a) at 175 km 15 % compensation, R_f =50 ohm and load angle 20^o (b) at 175 km 30 % compensation, R_f =50 ohm and load angle 30^o.

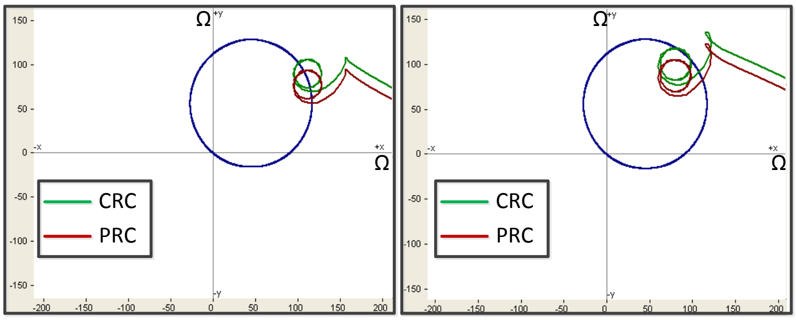


Fig. 10 Performance of conventional and proposed relay in inductive mode (a) at 175 km 15 % compensation, R_f =50 ohm and load angle 20^o (b) at 175 km 30 % compensation, R_f =50 ohm and load angle 30^o.

CONCLUSIONS

This paper describes a complete unit protection of series compensated transmission line having TCSC at mid-point. Assumed line has been fragmented in two sections, one before the TCSC and other after TCSC point. Fault zone identification algorithm in TCSC transmission line is affected by TCSC if presents in fault loop. Frequency spectrum of fault current is analyzed by DWT to find the faulty section in TCSC transmission line. Furthermore, a new compensated Mho relay algorithm is presented if TCSC is in fault loop. A detailed analysis of TCSC and MOV circuit has been demonstrated. Equivalent error inserted by TCSC in all the modes of operations has been calculated. Compensation unit compensates the impedance, inserted by the TCSC in fault loop by using the firing angle at TCSC sub-station and fault current at relay point. Simulation results indicate that first zone protection using compensated Mho relay is accurate, reliable and secure.

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Aneaxure-I

Fault Current	3.7	3.1	2.7	2.3	2	1.9	1.7	1.4	1.2	1	0.8	0.5	0.2	0.05
MOV Imp	0.75	0.93	1.09	1.32	1.55	11.71	205	587	1840	6624	22175	82396	211850	765192