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Fault Location Estimation in Thyristor Controlled Series Compensated Transmission Line

Falgun B. Patel[1], Pranav D. Raval[2]

[1]*P.G. Student Electrical Department, L.E. College, India*

[2]*P.G. Student Electrical Department, L.E. College, India*

ABSTRACT-

This paper considers the potential challenges faced by conventional distance relays in case of thyristor controlled series capacitor (TCSC) compensated transmission systems. The mal-operations of back-up relays can trigger large scale cascaded outages. Detailed analysis on mal-operation of different zones of distance relay due to TCSC operation wiil be carried out. The impact of TCSC on the relays of adjacent lines which provide back-up protection to the compensated line will observed. Finally, possible solutions to mitigate the problem associated with the impact of TCSC upon the conventional distance relays are discussed. The simulation studies are carried out on MATLAB environment. Mathematical modelling of TCSC and algorithm for distance protection is simulated and results are analyzed in different fault conditions.

Keywords—component; Fault location, Series compensated transmission line, Thyristor Controlled Series Capacitor (TCSC)

I. INTRODUCTION

Different types of fault in power systems are always threatening the continuous supply of the electric energy for consumers. This subject is very important for companies responsible for supplying electrical energy. Therefore, correct determination of the fault point is very vital for these companies to find and repair the problem in minimum maintenance time.

A fault locator is used for identifying fault location in a power transmission line. Operative algorithms in fault locators can be classified in two categories: first, algorithms based on the fundamental frequency component [1–4], and second, algorithms utilizing the higher frequency components of the fault signals such as methods developed based on traveling waves on the transmission lines [5–10].

The TCSC is an important member of Flexible AC Transmission System (FACTS) family; it is capable of changing the transmission line impedance and load current continuously [11]. A typical TCSC module consists of a series capacitor and a parallel path with a thyristor valve in series with an inductor known as the Thyristor Controlled Reactor (TCR). To protect these elements during the fault, a Metal Oxide Varistor (MOV), an air gap and a breaker are installed in parallel with the capacitor and TCR. A practical TCSC module is shown in Fig. 1 [12].

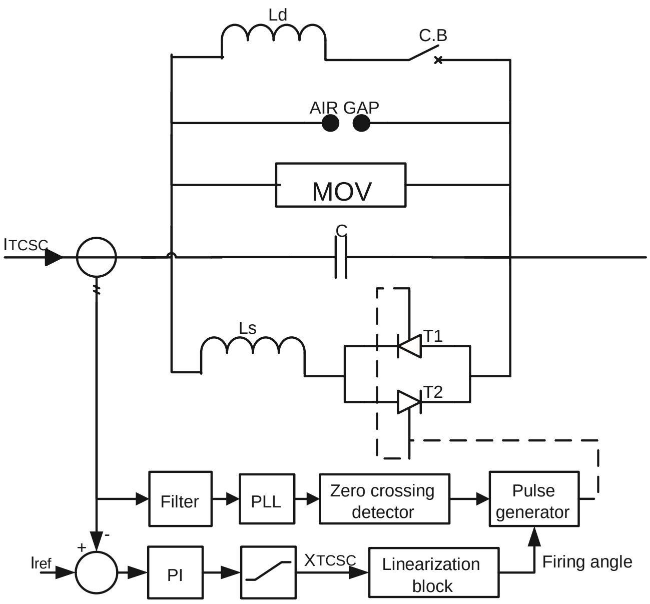

Fig. 1. Practical TCSC module

In this paper, a new algorithm for fault section identification and fault location in series compensated transmission lines with TCSC is proposed. The algorithm uses the transmission line distributed model and a time domain model for the TCSC. The algorithm requires synchronized current and voltage samples from both ends of the transmission line. Two points for fault location can be obtained, one in front and the other behind the TCSC. A new approach to identify the correct fault point is proposed in the present paper applying a new parameter TCSC in the middle. Many simulations carried out with ATP-EMTP software on the system confirm capability and accuracy of the proposed algorithm.

II. MODELING OF TCSC

A. TCSC operating modes

During fault, TCSC gives different operations depending upon the type of fault. Let we check various conditions of TCSCunder faultycondition.

2.1. Capacitive boost mode without MOVconduction

In a high impedance fault condition, a low fault current existsin the system. The lower fault current exerts less voltage acrossthe compensatorthantheprotectivevoltagelevelof TCSC(Fig.2(a)). Therefore, the MOV remains in high impedance mode, and fault will persist through TCSC continuously. Due to existence of compensation, the relay can overreach considerably, and also can lose its directional integrity.

2.2. Capacitive boost mode with MOVconduction

For a high-current fault case, the MOV conducts to decreasethe voltage across the SC(Fig.2(b)). However ,the MOV isfast enough to conduct and reset within a half-cycle. In thiscase, neither the MOV nor the circuit breaker would be shortoutthecapacitorcontinuously.Thisshort-durationconditionusuallyrepeated severaltimes duringthefaultperiod.Duringthiscondition,theTCSCimpedance wouldbetheparallelcombination of the capacitor and the MOV in a lower resistance mode. The relay would overreach but differently from the previous case without MOV operation.

2.3. Blocking mode

During fault transienttime, phase angle ofthevoltageacross capacitorchangesswiftly,whichchanges the firing angle of the TCSC rapidly in some cases. To avoid over current situation for this case, the thyristors are blockedbyfiringmechanism.Inthiscondition,theTCSCactslikeafixedseries capacitor only(Fig.8(c)).The relay would over reachasincaseoffixedSCwithMOV.However, thisoverreachislessthan the case,when the TCSC is in capacitive boost mode.

2.4. TCSC bypass operation

For a very heavy fault current condition, the MOV operationis notenoughtodecreasethecapacitor voltage.Thisleadstoward total thyristorconduction(bypassmodeFig.8(d)).Inthiscase,the distancerelaywould underreachduetothepresence of the reactor in circuit.

2.5.Circuit breaker bypass

If the fault is not cleared within a pre-specified time period, the TCSC transits to circuit breaker bypassed mode(Fig.8(e)).

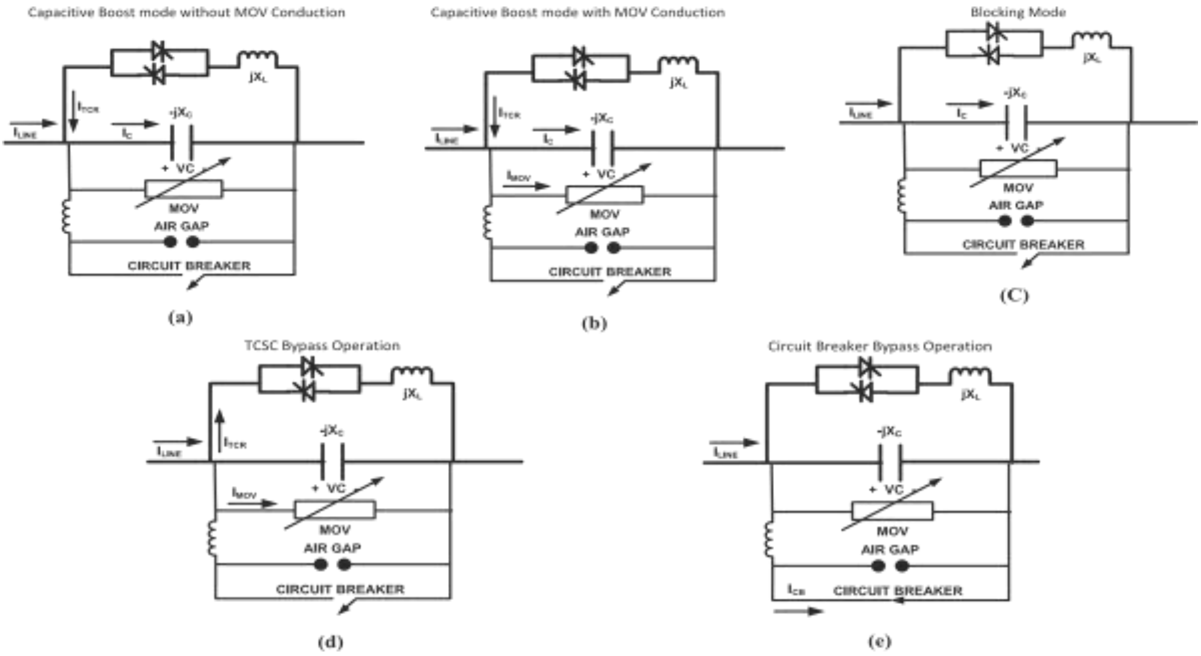

Fig. 2. TCSC operating modes during condition of fault.

B. The proposed algorithm for fault location

3.1. Fault location determination

Consider the series compensated transmission line with TCSC in the middle shown in Fig. 3. If a fault occurs in the first half of a transmission line between bus A and TCSC, fault loop seen from bus A does not include TCSC, however if fault is in the second half, between TCSC and bus B, the fault loop seen from bus A includes TCSC. In each case a related subroutine is used for identifying fault location.

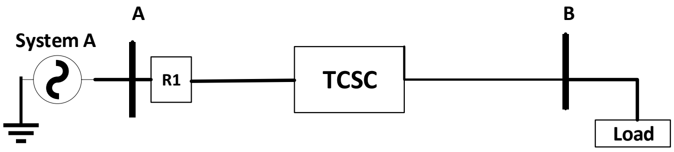

Fig. 3. Transmission line with TCSC in mid-point.

3.2. Fault in front of TCSC

At pre-fault condition, TCSC current can be calculated by voltage and current measured in bus A or B. If this current is passed to the filter and PLL, the zero crossing point of the current can be specified. Voltage of terminal T1 of TCSC can be calculated by the voltage and current of bus A, and the voltage of terminal T2 by voltage and current in bus B. Then TCSC voltage, VTCSC, will be determined. Therefore apparent reactance of TCSC is

$$X_{app} = Im\left(\frac{V_{TCSC}}{I_{TCSC}}\right)$$

When a fault occurs at distance x from bus A (in front of TCSC), voltage at fault point can be computed using two routes, one with bus A measured voltage and current samples, VxA(x,t), and the other with calculated voltage and current for terminal T1, VxT1(x,t). To obtain fault point the objective function should be minimized.

$$F(x) = \Sigma(VxA(x,t) - VxT(x,t))^2$$

C. System parametre

Inductance / km (L) = 1.044 mH,
Length of Line = 400 km,
Total line reactance X = 131.1929 Ω,
TCSC Capacitor (C) = 306 µF
TCSC Inductor (L) = 4.4 mH
Frequency = 50 Hz
Compensation =75%
Load = 750MW

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*D. **Fault location Algorithm***

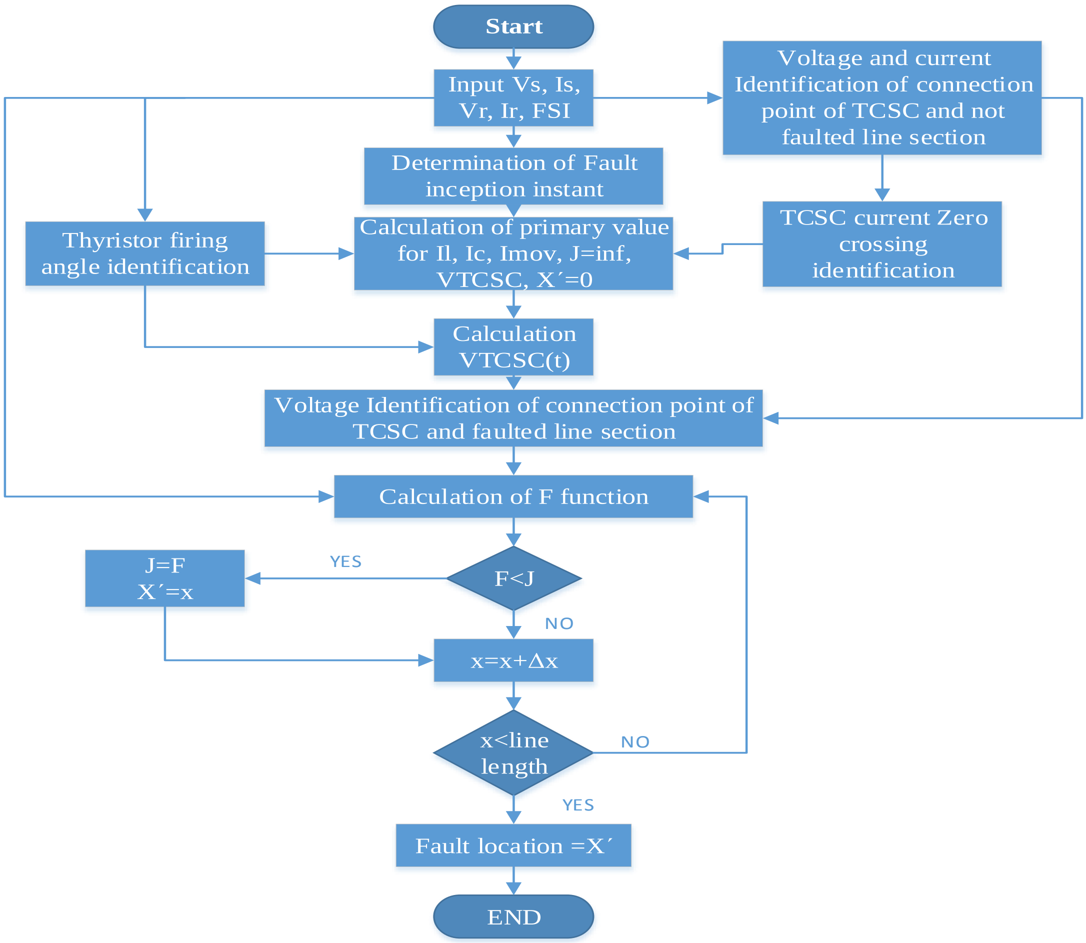


Fig. 4. Flow chart of proposed algorithm.

In objective function equation t = nT and T is the period of sampling and n is an arbitrary integer [5]. The fault location is the point x that minimizes the objective function F(x). Therefore the fault location in front of TCSC is obtained.

If difference between line ends current or voltage, and their values at previous cycle was significant at instant t (the fault inception instant had been before t) and protective relays detected a fault at instant t + Dt, $V_{xA}(x,t)$ and $V_{xT1}(x,t)$ are calculated by recorded data from instant t. Therefore fault detection time does not impact on this algorithm.

3.3. Fault behind of TCSC

For the fault location in this case, the procedure is same as in the previous case with some differences. Here, the voltage and current in terminal T1 is computed by bus A voltage and current using distributed model of the transmission line. Then the voltage and current in T2 are calculated by time domain model of TCSC.

The voltage of the fault point is calculated from the bus B measured voltage and current samples and the computed terminal T2 voltage and current. The fault location method is the same as case A.

Hence, for any fault, two fault points may be obtained of which one is correct. To identify the correct faulty section, a new indicator is used in the proposed algorithm.

*3.4. **Fault section identification***

Considering the series compensated transmission line in Fig. 4 and assuming that the load flow is from left to right, the phasor representation of the TCSC voltage and current can be calculated by considering the fundamental frequency:

$$\overline{V\iota(t)} = \int_{t-Ts}^{t} vi(t)\cos(2\pi f t)\,dt \; - j\int_{t-Ts}^{t} vi(t)\sin(2\pi f t)\,dt$$

$$\overline{I\iota(t)} = \int_{t-Ts}^{t} Ii(t)\cos(2\pi f t)\,dt \; - j\int_{t-Ts}^{t} Ii(t)\sin(2\pi f t)\,dt$$

where vi(t) and ii(t) are the instantaneous TCSC voltages and currents, f is the fundamental power frequency, Ts =1/f.

III. SIMULATION RESULTS OF MHO RELAY

Fig. 5 shows the $(V_{TCSC}|I_{T\iota}$ locus from fault inception instant to one cycle after it for a three-phase to ground fault which occurred in front of TCSC (in section A-T1) and Fig. 6 shows the result for the same fault occurred in the second half of the line (in section T2-B). These results are obtained from ATP-EMTP simulations on a

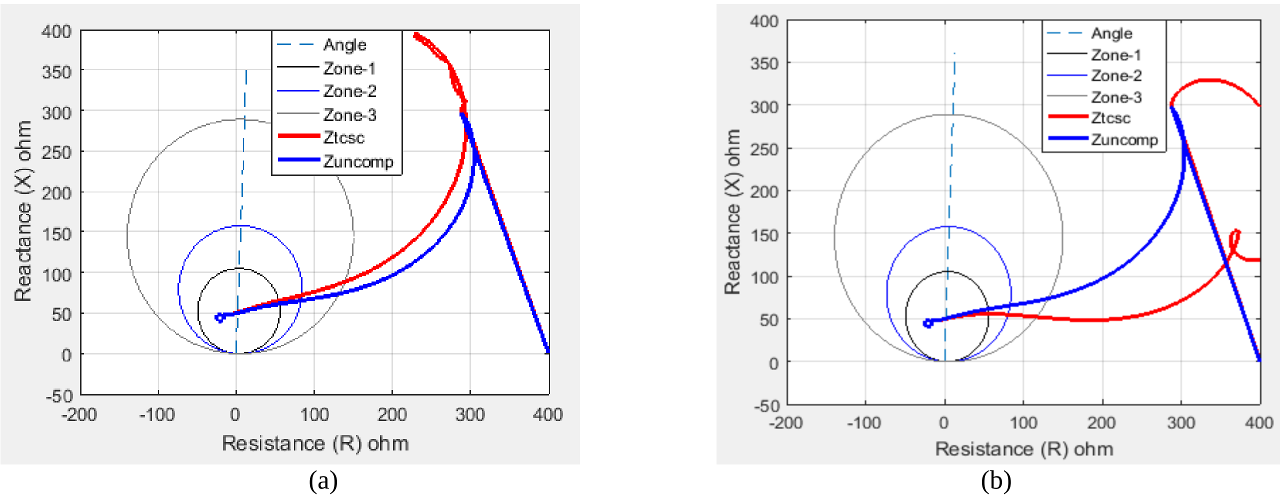
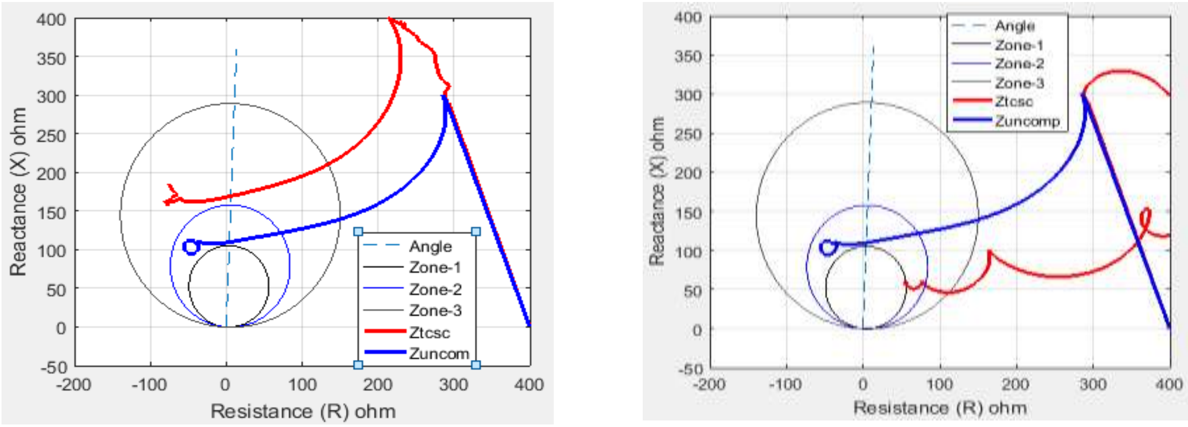
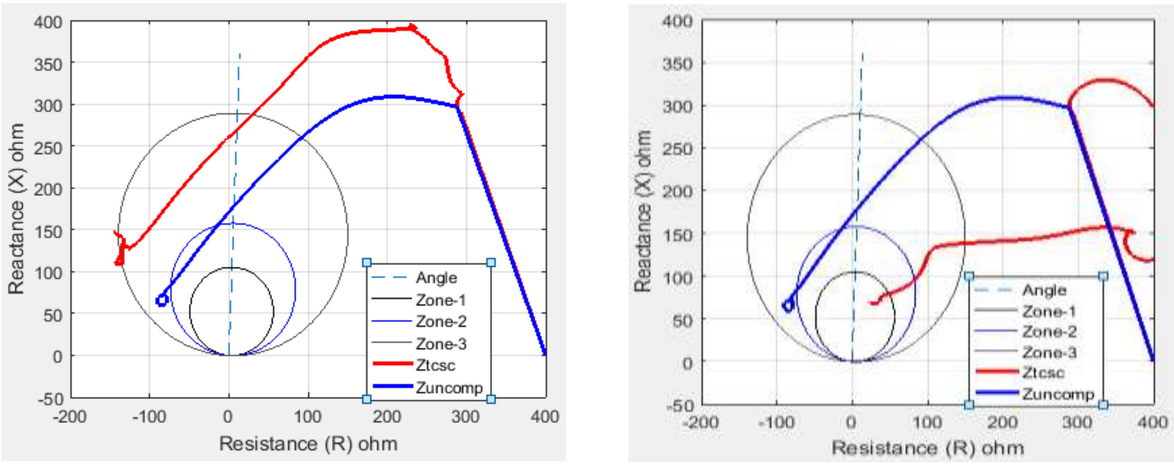


Fig. 5. Simulation results of at 150km LG Fault in compensated & uncompensated line; (a) Simulation results of α=25° at 150km LG Fault (Inductive mode) (b) Simulation results of α=85° at 150km LG Fault (Capacitive mode)



(a) (b)

Fig. 6. Simulation results of at 350km LG Fault in compensated & uncompensated line (a) Simulation results of α=85° at 350km LG Fault (Inductive mode) ; (b) Simulation results of α=85° at 350km LG Fault (Capacitive mode)



(a) (b)

Fig. 7. Simulation results of at 350km LLG Fault in compensated & uncompensated line (a) Simulation results of α=25° at 350km LLG Fault (Inductive mode); (b) Simulation results of α=85° at 350km LLG Fault (Capacitive mode)

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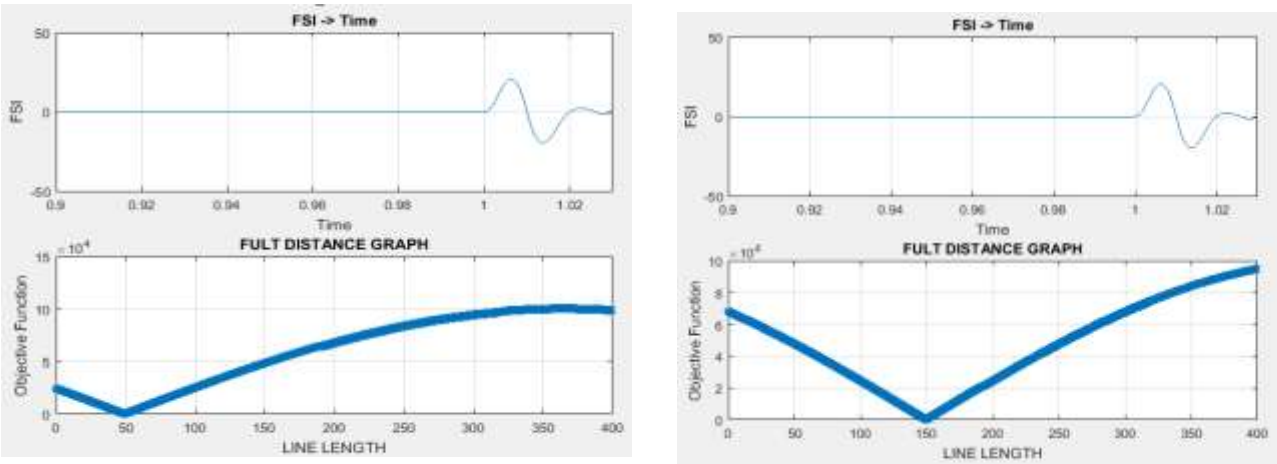
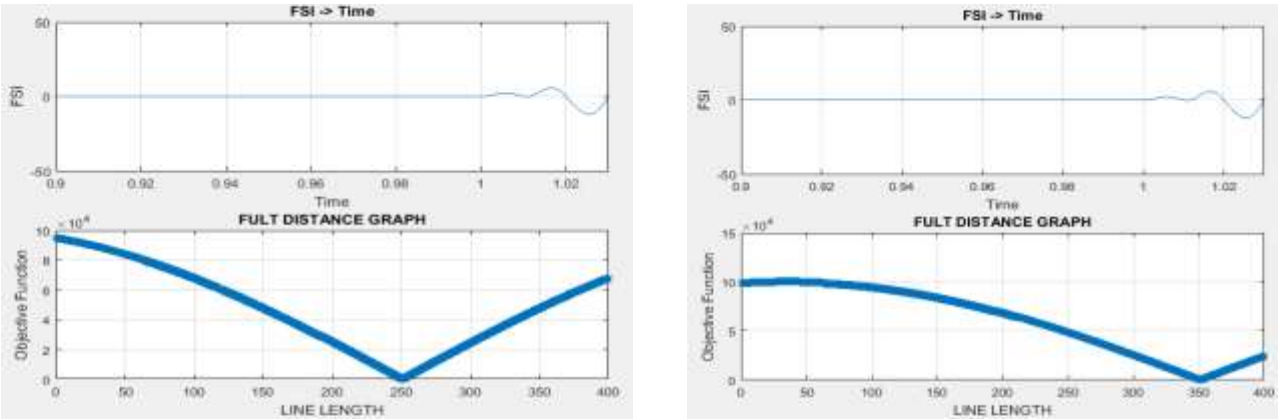
IV. SIMULATION RESULT OF FAULT LOCATION ALGORITHM



(a) (b)

Fig. 8. Simulation results of algorithm for before TCSC different fault location at α=25° °, Rf=10Ω LG
(a) Simulation results at 50km LG fault ; (b) Simulation results at 150 km LG fault



(a) (b)

Fig. 9. Simulation results of algorithm for after TCSC different fault location at α=25°, Rf=10Ω LG fault
(a) Simulation results at 250 km LG fault; (b) Simulation results at 350 km LG fault

5.1 Fault Section Indicater

This ratio locus in two cases illustrated in Figs. 5 and 6 revealed that when load flow is from left to right and the fault occurred in front of TCSC (between bus A and TCSC) the real part of the ratio experiences high negative values compared to the fault behind the TCSC. Different fault types, fault resistances and fault locations were simulated and comparable results have been obtained. Then the real part of the ratio can be considered as an indicator for the fault section determination. The Fault Section Indicator (FSI) is therefore defined as follows:

$$\text{FSIi(t)} = -real\left\{\frac{Vi(t)}{Ii(t)}\right\}$$

where real(.) indicates the real part function.

During the normal operation of TCSC, only the capacitor and the inductor thyristor branch conduct current, and FSIi(t) is equal to the real part of the TCSC impedance which is zero because no resistive element exists in the TCSC circuit. However, from the fault inception up to one cycle after it, FSIi(t) will have meaningful variations. If the fault takes place behind TCSC (between TCSC location and bus B), FSIi(t) for the faulted phase or phases will have negative values or transient small positive values in the first cycle after the fault.

However, if the fault occurs in front of TCSC (between bus A and TCSC) FSIi(t) will have transient positive values, bigger than a threshold value. It should be mentioned that if the load flow is from right to left and fault occurs between bus A and TCSC location, FSIi(t) will be the same as the fault between TCSC and bus B and vice versa i.e. for the fault between the TCSC location and bus B, FSIi(t) varies like FSIi(t) for the fault between bus A and TCSC in the former case.

The real part of the TCSC impedance is expected to be zero because it includes only capacitor and inductor elements and no resistive element is operated by considering the TCSC mode of the operation. In case the MOV operates to protect the TCSC capacitor from transient overvoltage during faults, it can be considered as a nonlinear resistance varying between infinite and zero depending on the overvoltage time intervals. Therefore an effective resistance for TCSC is seen during the fault.

V. EVALUATION OF THE PROPOSED ALGORITHM

The proposed algorithm has been tested and evaluated by the fault data obtained from simulations on a 400 kV transmission line with TCSC (Fig. 4). The overall system including the transmission line and the TCSC with its control system has been implemented in ATP-EMTP software environment. The line length was 400 km with a TCSC compensation rate is 75%. The transmission line and the TCSC data are given.

Different compensation rates were considered for the line by relevant firing angle of the TCSC thyristors; 25° and 85° The simulations were performed for fault resistance, 10Ω and the sampling frequency was considered to be 100 kHz. One cycle of post fault data are used to determine the fault location. Many simulations have been performed. The results of the simulations lead to a proper threshold value for FSI in this case study which is FSIth = 20.

Table.2 shows the FSIi and objective function for a three-phase to ground fault in 50 km distance from bus A. In this case the FSIi passes the threshold value i.e. 20 for three phases. Therefore the fault section is between bus A and TCSC, and the fault location is determined at distance 49.232 km from bus A. The error of the fault location in this case is 0.192%. The error is calculated by:

$$\text{Error} = \frac{X_e - X_a}{L_{length}} * 100$$

One of the most important fault places for protection system is 80% of the line length, because the faults before this point are in the first zone of the relay and the faults occurred after it are in the second zone. The prevalent fault location algorithms sometimes have mal-operation to identify the correct zone when the faults occurred near this place (80% of line length). The proposed algorithm was evaluated for faults in 79% and 81% of line length. The results in Table 10 show this algorithm is able to recognize the zones correctly. In this way, also the mal-operation of distance relays duo to series compensation is prevented. Therefore the proposed algorithm is robust against fault type, fault inception angle, compensation rate and fault resistance in thorough transmission line.

E. Tables

Fault inception angle = 90°, Rf=10Ω, Threshold value=20,

1 = FSI is bigger than the threshold value. 0 = FSI is smaller than the threshold value

Fault type	Scr firing angle (deg)	Fault location (km) Xa	FSI status a b c	Fault location estimation (km) Xe	Error (%)
a-g	25	50	1 - -	49.232	0.192
		150	1 - -	149.404	0.149
		170	1 - -	169.423	0.144
		250	0 - -	250.875	0.218
		350	0 - -	350.980	0.245
a-g	85	50	1 - -	49.232	0.192
		150	1 - -	149.404	0.149
		170	1 - -	169.423	0.144
		250	0 - -	249.656	0.086
		350	0 - -	349.827	0.043

Table 2. Calculation for LG fault error minimizing by fault location algorithm

Fault type	SCR firing angle (deg)	Fault location (km) Xa	FSI status a b c	Fault location estimation (km) Xe	Error (%)
ab-g	25	50	1 1 -	49.230	0.193
		150	1 1 -	149.400	0.150
		170	1 1 -	169.431	0.142
		250	0 0 -	250.807	0.201
		350	0 0 -	350.973	0.243

ab-g	85	50	1 1 -	49.230	0.193
		150	1 1 -	149.400	0.150
		170	1 1 -	169.431	0.142
		250	0 0 -	249.661	0.085
		350	0 0 -	349.826	0.044

Table 3. Calculation for LLG fault error minimizing by fault location algorithm

VI. CONCLUSION

In this paper, a new accurate algorithm for the fault location in advanced series compensated transmission lines (with TCSC) is presented. It requires synchronized information from two ends of the line. This proposed algorithm has faster and more accurate operation compared to others. A Fault Section Identifier (FSI) is introduced, calculated in the TCSC location by using the voltage and current of TCSC during a short time interval (less than one cycle) after fault inception. The FSI signal determines the faulty section, and its result is sent to the ends of the line. The proposed algorithm has been tested by simulations on a 400 kV; 400 km series compensated transmission line with TCSC. Different conditions such as various fault types, fault inception angles, fault resistances, power angles, line compensation rates and points of the fault were considered to show the robustness of the algorithm. It has been declared that in all case studies the proposed algorithm can determine correctly the faulty section without exception even at the line limits (near the line ends and near the TCSC location) and high resistance fault, and also the fault locations are effectively estimated by the algorithm so that the maximum percentage error is kept below 0.4%.

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