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A Novel Method For Fault Location In TCSC Compensated Three-Terminal Transmission Lines

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ABSTRACT: This paper proposed a detailed method to fault location in TCSC compensated three-terminal transmission lines. In the proposed algorithm, synchronous voltage and current samples from three ends of the transmission line are used to detection faulty section and then fault location. The distributed parameter line model in the time domain is applied because this model has a high accuracy for long line and doesn't need filter so this is another advantage of the proposed method compared to previous methods. Due to problems in the modeling of FACTS devices during fault location, our purposed method doesn't used modeling series FACTS devices. Basic of this method is converting three line networks to two line networks after recognizing the faulty section and solving accessing the fault distance. So to solve the problem of fault location before determining distance to faulty section, new method to determine fault location segment was showed and then by converting three line networks to two line networks, fault location algorithm was used so the proposed method includes two stages. Our proposed algorithm is not sensitive to the resistance of fault, the fault inception angle and fault type and low sensitivity to random noises. Also proposed algorithm do not dependent on compensator devices location and it's parameters. This method is good for all transmission lines that was compensate with any type of series compensator. Different type of fault in any different distance and situation simulated by using MATLAB/SIMULINK software on compensated three line network with thyristor (TCSC) control series capacitor. The results of computer simulations for different condition, confirm accuracy of proposed algorithm.

INTRODUCTION

The most important disorder occurs in the transmission system is short circuit. So determining exact fault location in transmission line is so important in maintaining, operation and recovery. Transmission line is an important part of power system and must be protected until system become steady, in this way if there was a short circuit, minimum damages occur on equipment. Protection from transmission line has three important parts:

Detecting fault
Classification of fault (depended on fault type) and
Determining fault section

Early detection of faults leads to departing faulty section from line so we can protect it from fault disadvantage effect. Classification of fault means detecting fault type. Recognizing exact faulty section to emergency renovation and compensate faulty line is necessary this leads to more Reliability in system. Till now different kind of algorithm introduced to fault location that has been used current and voltage phasors one or both sides of transmission line (Girgis, 1992; Nagasawa, 1992; Lin, 2002; Kalam, 1992; Izykowski, 2007; Fulczyk, 2007; Ibe, 1987; Johns, 1990; Sadeh, 2000; Song et.al, 2005; Jeyasurya, 1991; E.G. Silveira, 2007). This method used different model of transmission line. To solve finding distance problem in these lines different kind of method proposed. Most of them used the lumped and/or distributed model transmission line in frequency domain (Girgis, 1992; Nagasawa, 1992; Lin, 2002; Kalam, 1992; Izykowski, 2007; Fulczyk, 2007; Ibe, 1987). For example in (Girgis, 1992) to solving fault location in three terminal transmission line a method introduced that obtain all data of synchronously and asynchronously voltage and current phasors terminals. In (Nagasawa, 1992) to solving fault location problem in double circuit lines with three terminals discrepancies of corresponds currents used as a input data. In the recent two method lumped model of transmission line is used. Mr. Lin (Lin, 2002) by using two terminals data and distributed model transmission line in frequency domain proposed a method to fault location in transmission line.

The above methods of fault location in transmission line didn't used FACTS devices. Continuous growth of electric energy demand caused to increase across networks. Power system especially in transmission line cannot match with this growth. Finding a suitable way and construct new electric lines needed more investment. Power electronic introduced FACTS devices as toolls for optimizing system in transmission lines, by these tool problems in transmission line solved. If we want useful and reliable system must use FACTS devices. In fact, FACTS devices are effective way to solving more problem on transmission power system. FACTS devices has three important classifications:

(a) Shant
(b) Series and
(c) Composition of series and shant

FACTS devices are being presently employed for various applications such as (Miller THE, 1982; Song, 1992):

increasing power transmission capacity of the existing lines,
improving the steady state and dynamic stability limits,
improving damping of different types of power oscillations,
improving voltage stability,
reducing the problem of sub-synchronous resonance, and
improving HVDC link performance.

Researches about fault location compensated with FACTS devices are so little. One group of them used FACTS devices model in fault location algorithm (Sadeh, 2000; Saha, 1999; Al-Dabbagh, 2005; Samantaray, 2009), another group didn’t used FACTS devices model in their algorithm(Al-Dabbagh, 2005; Samantaray, 2009; Yu, 2002, 2000). Because during fault, changing operating mode of FACTS devices depend on operating point and control strategy, or it may be estimation of exact time mode is impossible, First group used research of error depending on model in fault location algorithm. But in second group this errors ignored. High accuracy in fault location for long transmission line reached by using distributed time domain model of transmission line (Silveira, 2007; Saha, 1999; Al-Dabbagh, 2005; Samantaray, 2009; Yu, 2002, 2000; Sadeh, 2006, 2009; Ibe AO, 1987; Ranjbar, 1992; Gopalakrishnan, 2000). In (Sadeh, 2000) to fault location in compensation series transmission line, proposed an algorithm. In this study distributed transmission line in time domain model was used and voltage and current samples taken synchronously from both ends of the line used in fault location. In this approach fault resistance and reference impedance ignored. In this algorithm compensation series model was used. In (Samantaray, 2009) fault location in transmission compensated line with UPFC based on differential equations that extract from synchronously phasor data in two terminals. It should be noted that this model used Wavelet transform and logic fuzzy approach to fault location. In proposed algorithm, transmission line modeled π and UPFC as admittance for fault location research. Recently references (Yu, 2002, 2000) proposed an exact method based on synchronously phasor measurement in compensated line with FACTS devices. Proposed algorithm in reference (Naghdi) to fault location in transmission line compensated with parallel FACTS devices. In this algorithm, modeling of FACTS devices during fault wasn’t used. In this method, voltage and current samples taken synchronously from both ends of the line used. This approach used distributed transmission line to fault location. In proposed algorithm is independent of the system structure, inception angle and fault resistance. This paper proposed a new method to fault location in three compensated transmission line with series FACTS devices. Basic of this approach is converting three terminal networks to two terminal after detecting faulty section and solving fault location. Proposed method can use in any compensated transmission line with series FACTS devices. In this method we used distributed transmission line model in time domain. Proposed algorithm is not sensitive to fault resistance, inception angle and fault type and there is no need to equivalent impedance reference. In addition this algorithm doesn’t depend on location and device compensated parameter.

Review On Fault Location Algorithm In Two Terminal Transmission Lines

Figure (1) shows three phase transmission line with distributed parameter. S and R shown in the figure represent the sending and receiving ends of the line and F is taken as an arbitrary point where a fault with resistance R_f at distance $X(x \le L_{line})$ from S along the line occurs (Sadeh, 2000).

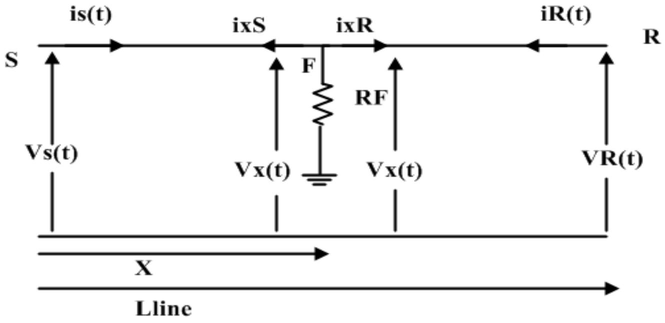

Figure1. Transmission Line With Distributed Parameter.

Figure(2) shows distributed model of SF segment in time domain.

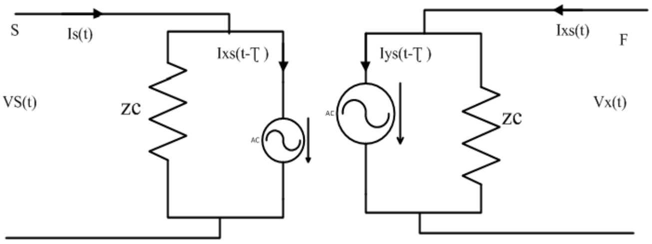

Figure2. Distributed model of the SF segment.

We can calculate the voltage and current at fault location as functions of sending end voltage and current as follows:

$$V_x(t) = (Z_c'^2[V_S(t+\tau) - Z_c' i_S(t+\tau)] + Z_c''^2[V_S(t-\tau) + Z_c'' i_S(t-\tau)] \qquad (1)$$

$$-\frac{Z_c' R'}{4}[\frac{\frac{R'}{2}}{Z_c'} V_S(t) + 2Z_c'' i_S(t)]) / 2Z_c^2$$

$$i_{xs}(t) = (Z'_c[V_s(t+\tau) - Z'_c is(t+\tau)] - Z''_c[V_S(t-\tau) - Z''_c i_s(t-\tau)] \qquad (2)$$

$$-\frac{R'}{4}[2V_s(t) - \frac{R'}{2} i_s(t)]) / 2Z_c^2$$

Similarly, the fault point voltage and current are calculated as functions of receiving end voltage and current are represented as follow :

$$V_x(t) = (Z_{rc}'^2[V_R(t+T-\tau) - Z'_{rc} i_R(t+T-\tau)] + Z_{rc}''^2[V_R(t-T+\tau) + Z''_{rc} i_R(t-T+\tau)] \qquad (3)$$

$$-\frac{Z'_{rc} R'}{4}[\frac{\frac{R'_r}{2}}{Z'_{rc}} V_R(t) + 2Z''_{rc} i_R(t)]) / 2Z_c^2$$

$$i_{xr}(t) = (Z'_{rc}[V_r(t+T-\tau) - Z'_{rc} i_r(t+T-\tau)] - Z''_{rc}[V_r(t-T+\tau) - Z''_{rc} i_r(t-T+\tau)] \qquad (4)$$

$$-\frac{R'_r}{4}[2V_r(t) - \frac{R'_r}{2} i_r(t)] / 2Z_c^2$$

In this equation we have:
τ = time elapsed for the wave propagating from S to F,
Zc = line surge impedance,
R' = line resistance from S to F,
T = time elapsed for the wave propagating from S to R,
R'_r = line resistance from R to F, and

$$Z'_c = Z_c + \frac{R'}{4}$$

$$Z''_c = Z_c - \frac{R'}{4}$$

$$Z'_{rc} = Z_c + \frac{R'_r}{4}$$

$$Z''_{rc} = Z_c - \frac{R'_r}{4}$$

Because of the continuity of the voltage along the transmission line, we can write equation 1 and 3 in equal form as:

$$F(V_S, i_S, V_R, i_R, t, \tau) = 0 \qquad (5)$$

To find the location of fault, first the equation (5) is discretized and then the following optimization problem is solved:

$$
\begin{aligned}
F = {} & (Z_c'^2[V_S(t+\tau) - Z_c' i_S(t+\tau)] + Z_c''^2[V_S(t-\tau) + Z_c'' i_S(t-\tau)] \\
& - \frac{Z_c' R'}{4}[\frac{\frac{R'}{2}}{Z_c'} V_S(t) + 2Z_c'' i_S(t)] \\
& -(Z_{rc}'^2[V_R(t+T-\tau) - Z_{rc}' i_R(t+T-\tau)] + Z_{rc}''^2[V_R(t-T+\tau) - Z_{rc}'' i_R(t-T+\tau)] \\
& - \frac{Z_{rc}' R_r'}{4}[\frac{\frac{R_r'}{2}}{Z_{rc}'} V_R(t) + 2Z_{rc}'' i_R(t)]) / 2Z_c^2
\end{aligned}
\tag{6}
$$

In this equation parameter is:

$$\tau = m\Delta t, t = k\Delta t$$

k, m = arbitrary integers

Δt = sampling step, and

By solving the optimization problem, m is proportional to the fault location is determined .As you see this equation (6) does not depended on fault resistance.

Fault Location In Three Terminal Transmission Lines

Fault location in three terminal transmission lines compensated with series FACTS devices execute in two part:

1. Determining faulty section
2. Determining fault location

Below these above parts explain separately:

Determining Faulty Section In Three Terminal Network With Series Facts Devices

To using algorithm in three terminal, networks showed in figure (3) assume that.

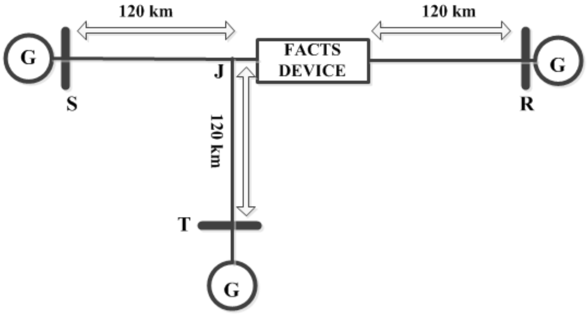

Figure3. Three Terminals Network.

Here T, R and S are our three terminals view point and J is Split point. Assume that one unknown short circuit with unknown location during transmission line is accure. In this case, the probability of occurrence of interfaces each section in T-J, R-J and S-J there will be. So we must examine all connection about circuit. To determining faulty section first get J voltage branching point by extensive S-J, R-T and T – J model without pay attention to fault in time domain.

$$
\begin{aligned}
V_{JT}(t) = {} & (Z_{CJT}'^2[V_T(t+T_1) - Z_{CJT}' i_T(t+T_1)] + Z_{CJT}''^2[V_T(t-T_1) + Z_{CJT}'' i_T(t-T_1)] \\
& -Z_{CJT}'[\frac{\frac{R_{JT}'}{2}}{Z_{CJT}'} V_T(t) + 2Z_{CJT}' i_T(t)]) / 2Z_{C1}{}^2
\end{aligned}
\tag{7}
$$

catching J voltage branching point by terminal voltage of R and S is as like as equation (7).

We consider the following criterion functions:

$$X_1 = \int \left|V_{JS}(t) - V_{JR}(t)\right| dt$$
$$X_2 = \int \left|V_{JS}(t) - V_{JT}(t)\right| dt \qquad (8)$$
$$X_3 = \int \left|V_{JR}(t) - V_{JT}(t)\right| dt$$

If one of these three criterion function was minimum, fault was in parts that there is not criterion function. In other word, if in one of these three parts fault accrued, one of these integral is smaller than others and two other criterion are bigger. For example if X_3 is minimum, it means that fault is in SJ segment. So voltage measuring of J by terminal information S (V_{JS}) has an error, measuring J voltage can done by two other terminals in accurate way. In this case X_3 has smaller quantities as compared with X_2 and X_1 and X_2 and X_1 has bigger quantities. So after measuring these three criterion function, faulty sections determined by one algorithm. In follow you can see flow chart to determine faulty section.

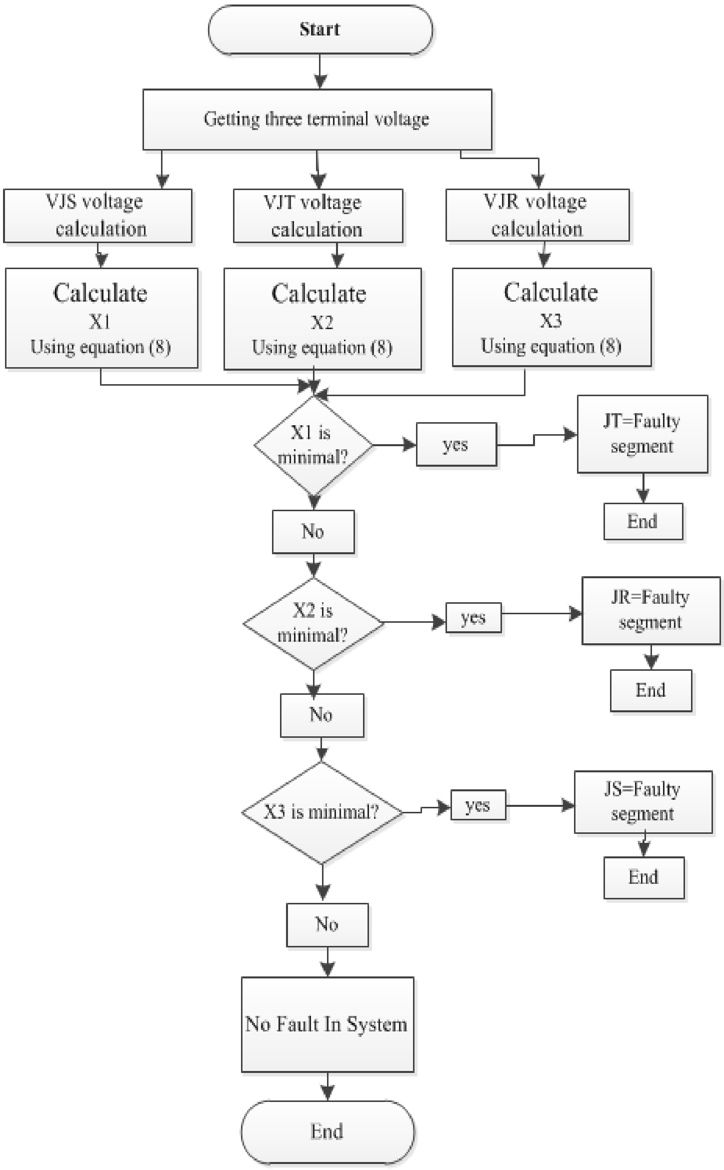

Figure 4. Faulty section flow chart.

Fault Location In Three Terminal Networks With Series Facts Devices

Second step fault locating process, locating fault was identified in the first process as part of is affected by the fault. After determining faulty section to appointing distance to faulty section three terminal networks converted to two terminal networks and location algorithm continues. If fault was in SJ segment, Healthy segment (TJ) removed, and because of compensated devices and examination of its effect on algorithm, RJ segment cannot removed. In this manner a two terminal network (R and S terminals) will have. If fault was in RJ segment, two other sections deleted and by catching J voltage point by S and R voltage terminal, applying fault location algorithm. In proposed algorithm type of series compensator used was not important. In fact, in this approach series compensation devices assume as a black box and any data like forming structure or TCR characteristic or thyristor in its structure, control system operation and… ignored. Compensation devices divided transmission line to two parts. First part from sending end (S-bus) to left-hand side of compensator (A-bus) and second part from right-hand side of compensator (B-bus) to the receiving end (R-bus) of transmission line, assume that the fault positions are assumed to be in the second part of the line.

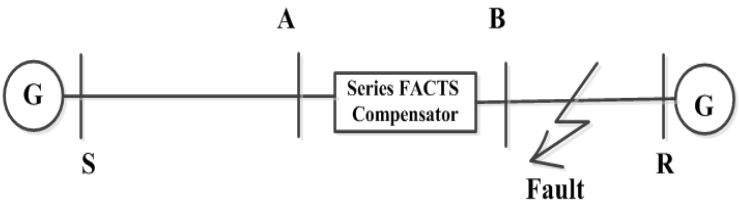

Figure 5. One-line diagram of a series FACTS compensated transmission line.

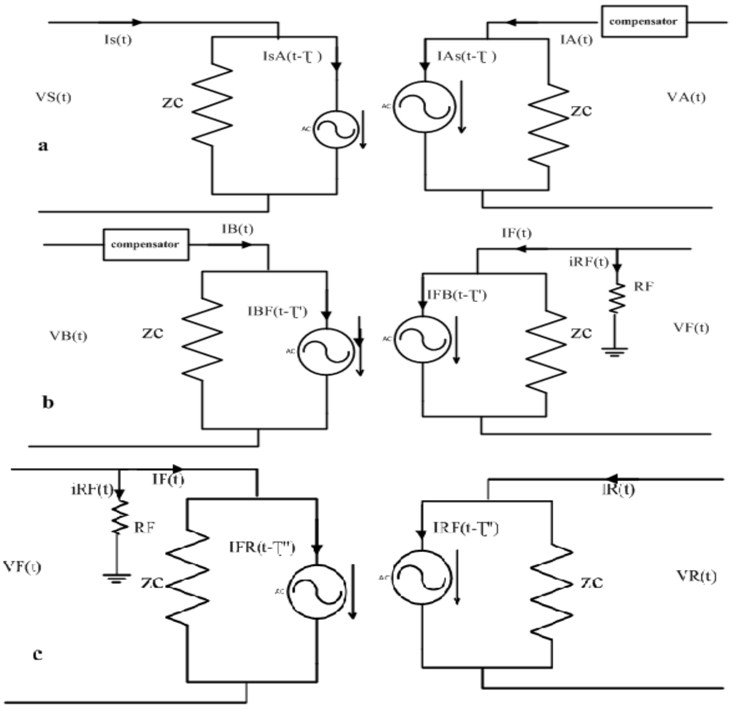

Figure 6. Distributed time domain line model: (a) from sending end (S) to the left hand side of compensator (A), (b) from right-hand side of compensator (B) to the fault point (F), and (c) from fault point (F) to receiving end (R).

Proposed algorithm is a returning algorithm as follow:

First Stage

First by using partial differential equation of long transmission line and the record fault data at the end of sending bus as a boundary conditions, the post-fault voltages and currents along the line from sending end to the left-hand side of the compensator are obtained (i.e. V_A, i_A are calculated).

Second Stage

since series FACTS devices compensator has no effect on current, left and right side of the current can assume equal $-i_A = i_B$. But because voltage of the right side of compensator (V_B) is unknown, just for first iteration right side and left side voltage assume without difference (for first iteration , these two voltage assume equal) so we can find first quantities for fault location.

Third Stage

By using calculated data (V_B, i_B) and receiveing Bus data (V_R, i_R) we can solve optimization equation, in fact in this equation V_B, i_B must replace V_S, i_S. In this level fault location was calculated. After fault location, we can calculate fault resistance by using least square estimation method that. Till now primary quantities collection got and in next repetition we try to improve that.

Fourth Stage

After fault location, by executing differential equation partial model and fault data in receiveing terminal as a boundary conditions, voltage and fault current ($V_F(t), i'_F$) calculated. By having fault voltage R_F and $V_F(t)$, fault current i_{RF} can be calculated. If we applying KCL law in F point we will have:

$$i_F(t) = -(i_{RF}(t) + i_{F'}(t)) \qquad (9)$$

Fifth Stage

Again by using partial differential equation of long transmission line and calculated data in fault location as a boundary conditions, determined voltage and current in right side of compensator. By replacing (V_B, i_B) with quantities in third level this algorithm repeated till fault location is properly determined. If the fault occurred on the left side of the compensator we use similar algorithm to fault location. You can see algorithm flow chart in this figure 7.

using proposed method to asymmetrical fault location

A simple transmission line has three phases. In a three-phase transmission line, the voltages and currents of the line are related to self- and mutual coupling distributed parameters of the phases and this relation is expressed by the partial differential equations in the time. this relation explained by differential equation that have partial derivatives in time domain as follow:

$$\frac{\partial V}{\partial X} + L\frac{\partial I}{\partial t} = -RI$$
$$C\frac{\partial V}{\partial t} + \frac{\partial I}{\partial X} = 0 \qquad (10)$$

In above equation R, L and C are 3×3 resistance, inductance and capacitance (in per unit length of the line) matrices, respectively and I and V are third-order column vectors representing voltages and currents. Eq.(10) are solved in two stages: first the matrices are diagonalized by applying the concept of modal analysis, then the resulting component equations are solved by the method of characteristics (Yu CS, Liu CW, Yu SL, Jiang JA. 2002). In time domain to converting asymmetrical networks to three symmetrical networks Modal transfer was used. To converting differential equation with partial derivatives (equation in phase domain) to independent equation in Modal domain Wedepohl, Karrenbauer was used. Above equation in Modal domain are as follow:

$$\frac{\partial V^k}{\partial X} + l^k\frac{\partial i^k}{\partial t} = -r^k i^k$$
$$C^k\frac{\partial V^k}{\partial t} + \frac{\partial i^k}{\partial X} = 0 \qquad (11)$$

On that K=0.1,2 shows modal quantities.

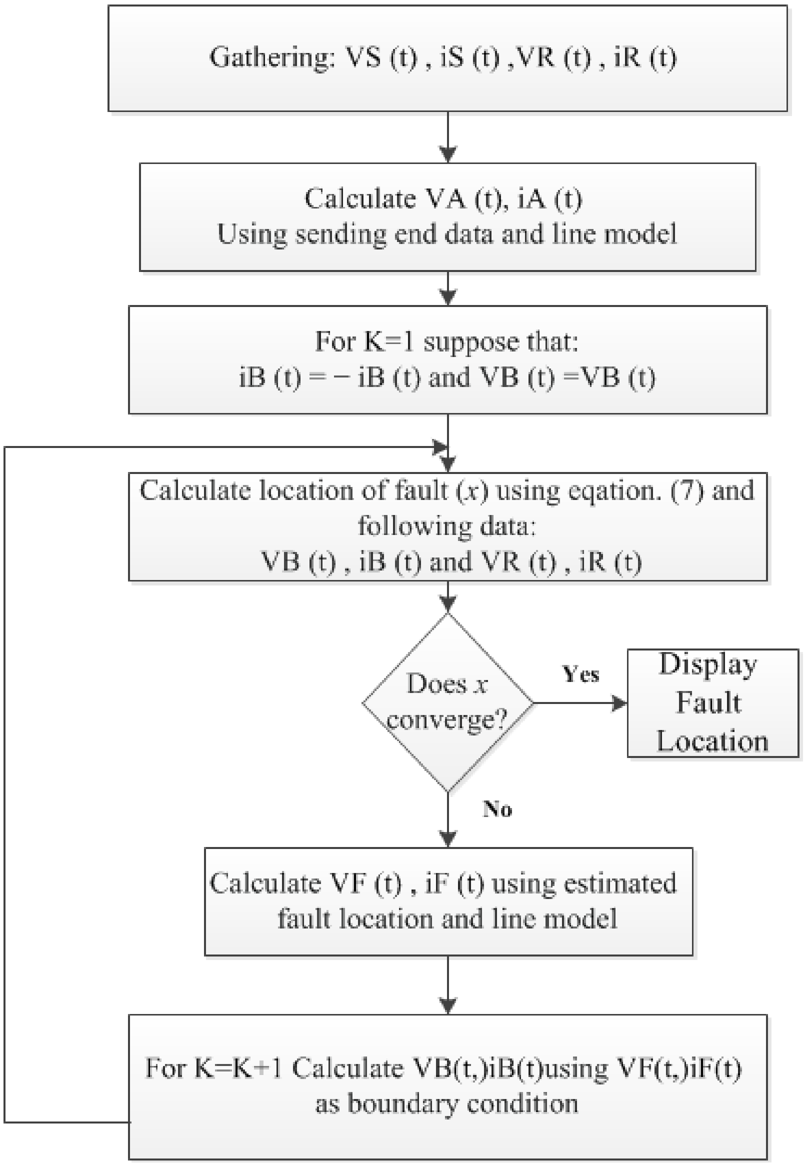

Figure 7. Flow chart of the proposed fault location method.

Proposed Method Evaluation

Simulation of proposed method to execute for a three terminal 400 KV transmission line that has series FACTS devices in RJ segment at 120 km from R terminal (at the end of RJ segment) done by MATLAB software. Transmission line and TCSC parameter attached in appendix. Results from executing first stage of fault location shows accuracy and correctness of algorithm in recognition faulty section. Results shows that aforementioned criteria in any short circuit recognized well in faulty section. Also given that to obtain the criteria function are not used the specification and resources constants, power system structure changes and thevenin model of network will not have any effect on the algorithm. You can see first level of algorithm results in tables (1).

Table 1. Detection faulty section – single-phase-to-ground.

	Faulty segment SJ- $R_F = 1\Omega$			Faulty segment RJ- $R_F = 10\Omega$			Faulty segment TJ- $R_F = 50\Omega$		
	Criterion Function								
Location	X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3
15	423.2	420.1	6.8	283.5	4.04	282.3	3.714	91.71	91.26
20	317.8	319.8	4.804	235.9	3.432	235.9	3.339	83.6	81.39
35	186.4	185.9	4.302	154.2	3.352	156	3.53	67.91	7041
50	127.8	124.3	4.71	111.8	3.358	109.3	3.231	57.47	57.38
75	79.27	76.87	4.761	71.02	3.336	69.87	3.062	41.09	41
90	54.1	53.62	4.251	49.72	3.133	49.29	3.479	29.64	29.28

105	33.24	31.34	5.946	30.28	3.589	28.92	3.635	18.76	18.49

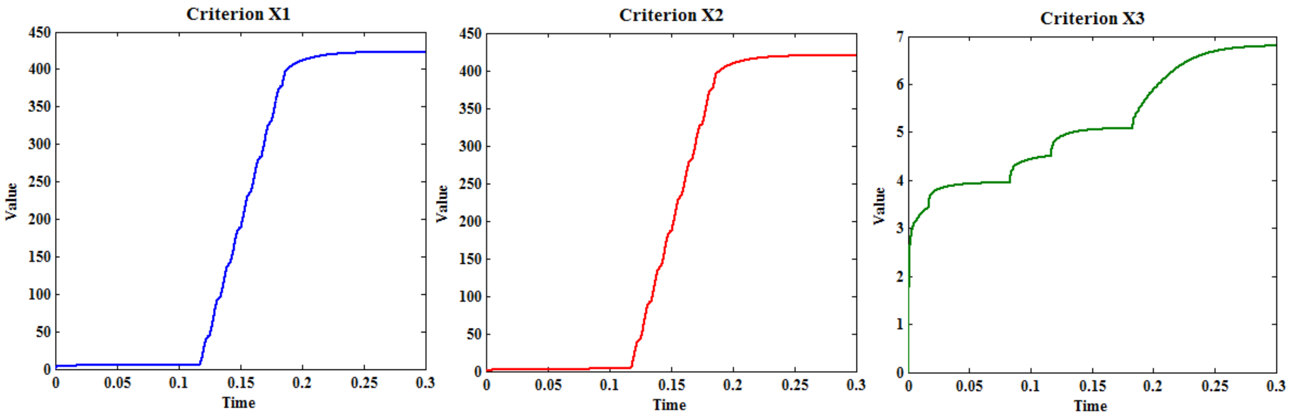

Figure 8. Criterion function defined in equation (4.19) for single-phase short circuit at SJ segment at 15 km Behind the compensator

To examination algorithm accuracy in second level of fault location, assume that unknown fault is accur in SJ segment, and first process of fault location (determining faulty section) done. So safe part of the line (TJ part) deleted and three terminal network converted to two terminal with R and S terminal. So for assuring from accuracy and correctness of proposed algorithm, Some results of simulations performed on a power system is presented. Different simulation with different type of circuit, different fault resistance, different inception fault angle and different fault location was done and their results shown in table (2). Results from simulations shows that in any short circuit, faulty section with criterion function that is said in part (3-1) correctly recognized and distance estimating to fault location did not depended to type of short circuit, fault resistance, inception fault angle and compensator model. In the simulation results the distance between samples are 50 microseconds equivalent to sampling frequency of 20 kHz is considered. The error of the fault location is expressed in terms of percentage of total line length as follows:

$$\%Error = \frac{Calulated \quad Dis. - Actual \quad Dis.}{Line \quad Length} \times 100. \qquad (12)$$

Assume that single-phase short circuit occurs at 45 km from bus A (left side of compensator). The fault inception angle has been assumed to be 0^0 and fault resistance is assumed to be 1Ω. Fault is in SJ segment. Fault location and fault resistance according to algorithm is as below:
calculated fault distance: 45.0807;
calculated fault resistance: 1.0846;
the location error: %0.033625and
the fault resistance error: 0.0846.
As another example, three-phase short circuit occurs at 82 km from bus A (left side of compensator). The fault inception angle has been assumed to be 0^0 and fault resistance is assumed to be 50Ω. Fault is in TJ segment. Fault location and fault resistance according to algorithm is as below:
calculated fault distance: 82.0443;
calculated fault resistance: 50.0623;
the location error: %0.01845and
the fault resistance error: 0.0623.

Table2. The results of the proposed algorithm with different fault resistances - fault in SJ segment.

		$R_f = 1\Omega$		$R_f = 10\Omega$		$R_f = 50\Omega$	
Fault Type	Actual Location Of Fault(Km)	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%
LG	8	8.6198	0.2582	8.6198	0.2582	8.6198	0.2582
	25	25.1983	0.08262	25.1983	0.08262	24.5581	-0.1841
	59	59.0840	0.035	59.0840	0.035	59.0840	0.035
	66	66.0751	0.03129	66.0751	0.03129	66.0751	0.03129
	104	104.0406	0.01691	104.0406	0.01691	104.0406	0.01691
	119	119.0416	0.0173	119.0416	0.0173	119.0416	0.0173
LLG	8	8.6198	0.2582	8.6198	0.2582	8.6198	0.2582
	25	24.5581	-0.1841	24.5581	-0.1841	24.5581	-0.1841
	59	59.0840	0.035	59.0840	0.035	59.0840	0.035
	66	66.0751	0.03129	66.0751	0.03129	66.0751	0.03129
	104	104.0406	0.01691	104.0406	0.01691	104.0406	0.01691
	119	118.9072	-0.0386	118.9072	-0.0386	118.9072	-0.0386
LL	8	8.6198	0.2582	8.6198	0.2582	8.6198	0.2582
	25	24.5581	-0.1841	24.5581	-0.1841	24.5581	-0.1841
	59	59.0840	0.035	59.0840	0.035	59.0840	0.035
	66	66.0751	0.03129	66.0751	0.03129	66.0751	0.03129
	104	104.0406	0.01691	104.0406	0.01691	104.0406	0.01691
	119	118.9072	-0.0386	118.9072	-0.0386	118.9072	-0.0386
LLLG	8	8.5277	0.2198	8.5277	0.2198	8.5277	0.2198
	25	25.1689	0.07037	25.1689	0.07037	25.1689	0.07037
	59	59.0715	0.02979	59.0715	0.02979	59.0715	0.02979
	66	65.8326	-0.06975	65.8326	-0.06975	65.8326	-0.06975
	104	103.8938	-0.0442	103.8938	-0.0442	103.8938	-0.0442
	119	119.0355	0.01479	119.0355	0.01479	119.0355	0.01479

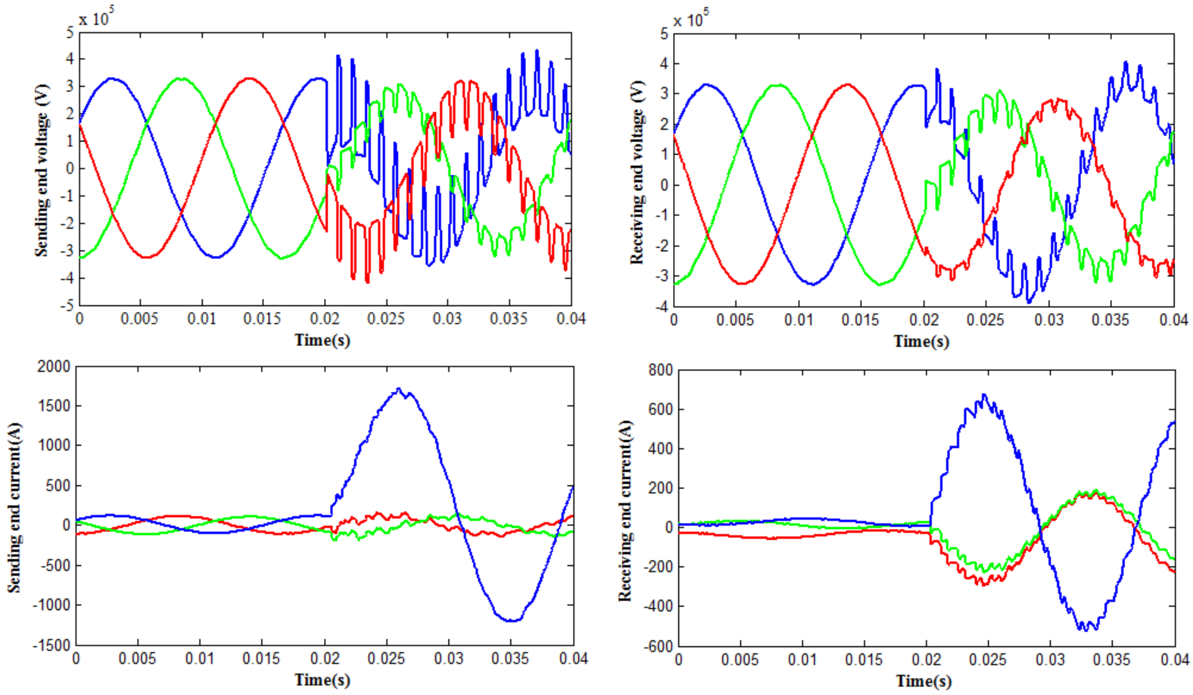

Figure9. Simulation results for a single-phase-to-ground at SJ segment at 45 km Behind the compensator.

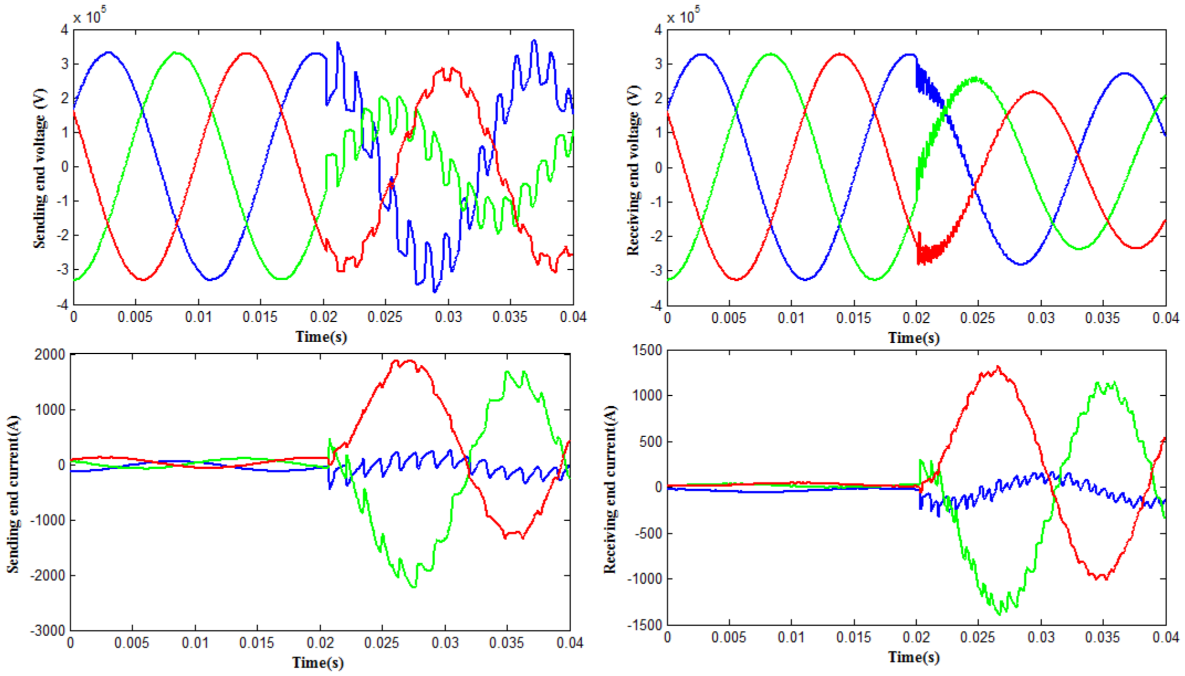

Figure10. Simulation results for a double-phase-to-ground at SJ segment at 45 km Behind the compensator.

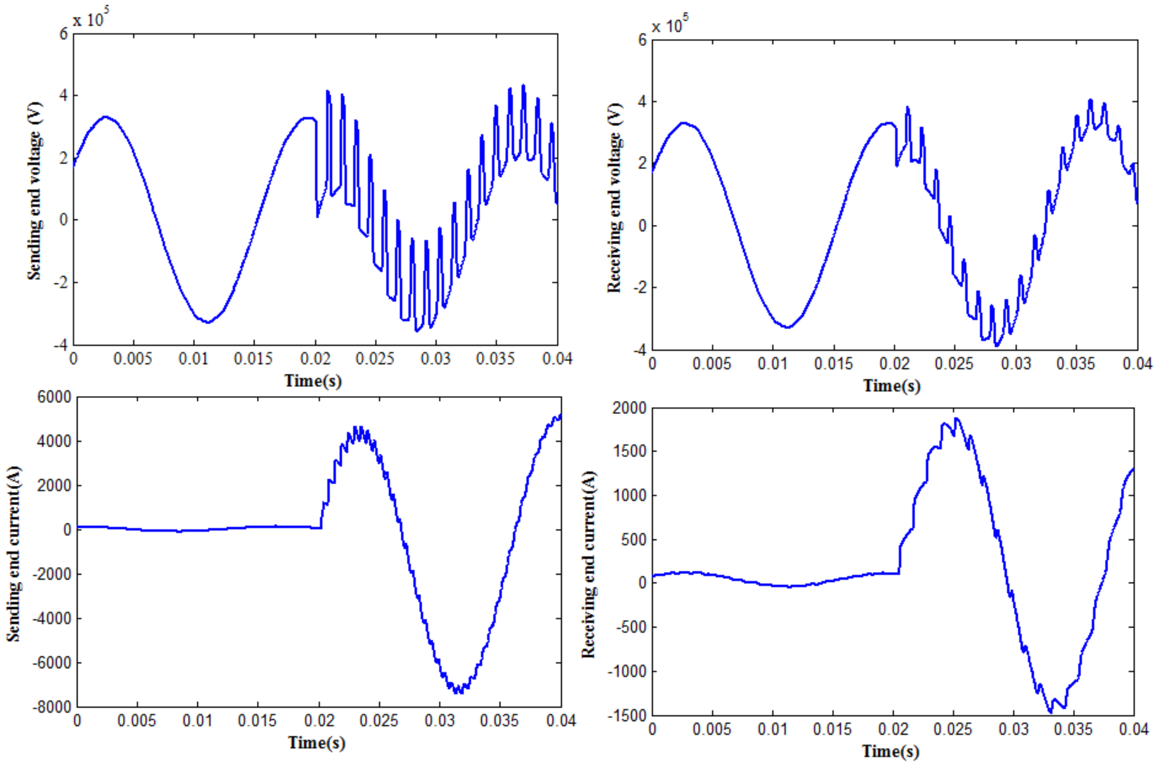

Figure11. Simulation results for a three-phase-to-ground at SJ segment at 45 km Behind the compensator.

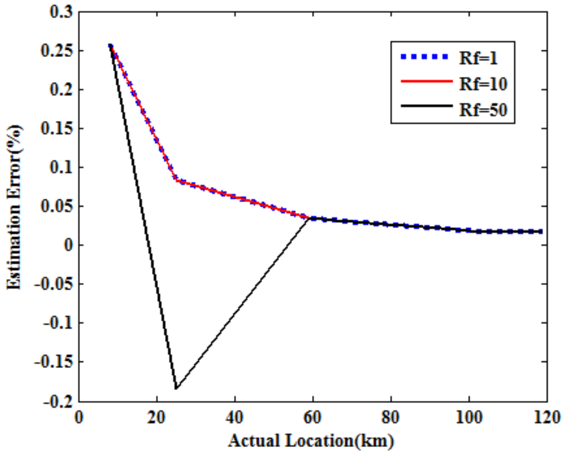

Figure12. Error comparison of single-phase -to-ground in the behind compensator with different resistors.

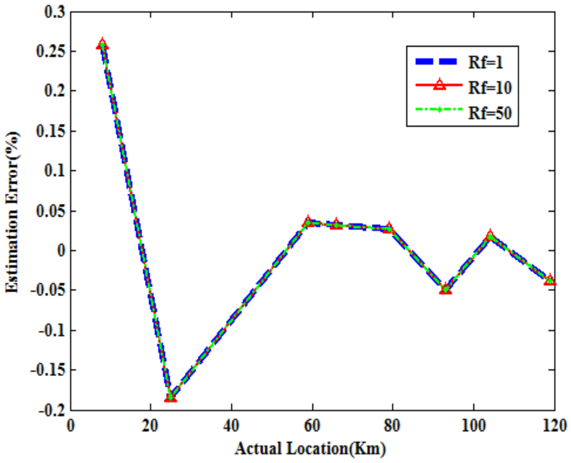

Figure13. Error comparison of double-phase short circuit in the behind compensator with different resistors.

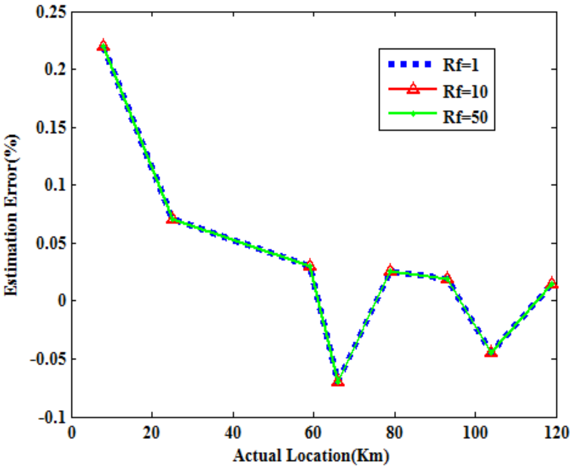

Figure14. Error comparison of three-phase -to-ground in the behind compensator with different resistors.

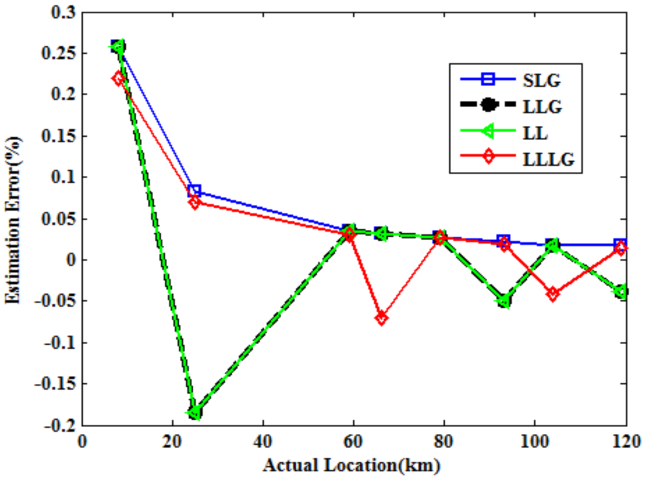

Figure15. Comparison of error percentage of different faults type in the behind compensator with $R_f = 1\Omega$.

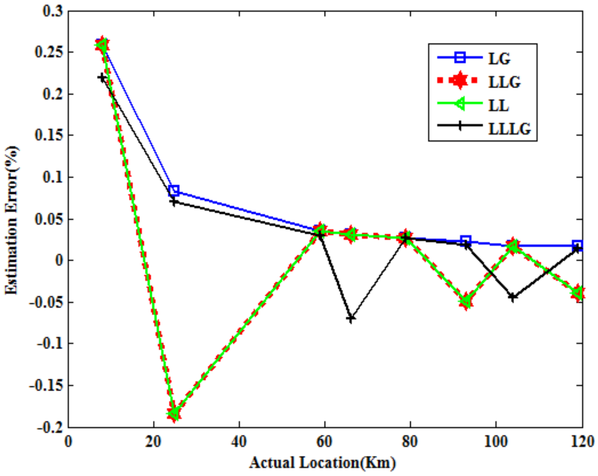

Figure16. comparison of error percentage of different faults type in the behind compensator with $R_f = 10\Omega$.

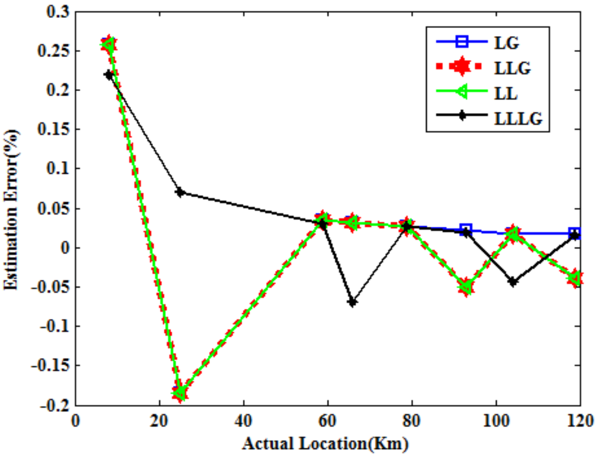

Figure17. Comparison of error percentage of different faults type in the behind compensator with $R_f = 50\Omega$.

Table 3. The results of the proposed algorithm with different fault resistances - fault in RJ segment.

		$R_f = 1\Omega$		$R_f = 10\Omega$		$R_f = 50\Omega$	
Fault Type	Actual Location Of Fault(Km)	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%
LG	15	15.2912	0.2426	15.2912	0.2426	15.2912	0.2426
	35	35.1248	0.104	35.1248	0.104	35.1248	0.104
	50	50.08738	0.0728	50.08738	0.0728	50.08738	0.0728
	75	74.8448	-0.1293	74.8448	-0.1293	74.8448	-0.1293
	90	90.04854	0.04045	90.04854	0.04045	90.04854	0.04045
LLG	15	15.2912	0.2426	15.2912	0.2426	15.2912	0.2426
	35	35.1248	0.104	35.1248	0.104	35.1248	0.104
	50	50.08738	0.0728	50.08738	0.0728	50.08738	0.0728
	75	74.8448	-0.1293	74.8448	-0.1293	74.8448	-0.1293
	90	90.04854	0.04045	90.04854	0.04045	90.04854	0.04045
LL	15	15.2912	0.2426	15.2912	0.2426	15.2912	0.2426
	35	35.1248	0.104	35.1248	0.104	35.1248	0.104
	50	50.08738	0.0728	50.08738	0.0728	50.08738	0.0728
	75	74.8448	-0.1293	74.8448	-0.1293	74.8448	-0.1293
	90	90.04854	0.04045	90.04854	0.04045	90.04854	0.04045
LLLG	15	15.2421	0.2017	15.2421	0.2017	15.2421	0.2017
	35	35.1037	0.08641	35.1037	0.08641	35.1037	0.08641
	50	49.7672	-0.194	49.7672	-0.194	49.7672	-0.194
	75	75.0582	0.0485	75.0582	0.0485	75.0582	0.0485
	90	90.01510	0.01258	90.01510	0.01258	90.01510	0.01258

In order to evaluate the accuracy of the proposed algorithm, two cases are considered. In the rest of this section, some of the obtained results are presented and discussed:

1. ***Different fault inception angls:*** In order to analyze the effect of the fault inception angle on the accuracy of the proposed method, a variety of simulations has been carried out, considering different fault inception angles. Some of the results are presented in Table 4. The fault resistance is assumed to be 1Ω. The TCSC is installed at 120 km from the sending end. Based on the presented results in this table, it can be concluded that the accuracy of the algorithm is not sensitive to the fault inception angle. Also, it can be found that the maximum of absolute errors is -0.0541% when single-phase-to-ground fault occurs at 85 km from the sending end.

Table 4. Results Of Running The Proposed Algorithm With Respect To Different Fault Inception Angles.

		Fault inception angle= 0^0		Fault inception angle= 45^0		Fault inception angle= 90^0		Fault inception angle= 135^0	
Fault Type	Actual Location Of Fault (Km)	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%	Calculated Location Of Fault (Km)	Error%
LG	45	45.11019	0.046	45.11019	0.046	45.11019	0.046	45.11019	0.046
	85	84.87	-0.0541	84.87	-0.0541	84.87	-0.0541	84.87	-0.0541
LLG	45	45.11019	0.046	45.11019	0.046	45.11019	0.046	45.11019	0.046
	85	85.04966	0.0206	85.04966	0.0206	85.04966	0.0206	85.04966	0.0206
LL	45	45.11019	0.046	45.11019	0.046	45.11019	0.046	45.11019	0.046
	85	85.04966	0.0206	85.04966	0.0206	85.04966	0.0206	85.04966	0.0206
LLLG	45	45.0938	0.039	45.0938	0.039	45.0938	0.039	45.0938	0.039
	85	85.04966	0.0206	85.04966	0.0206	85.04966	0.0206	85.04966	0.0206

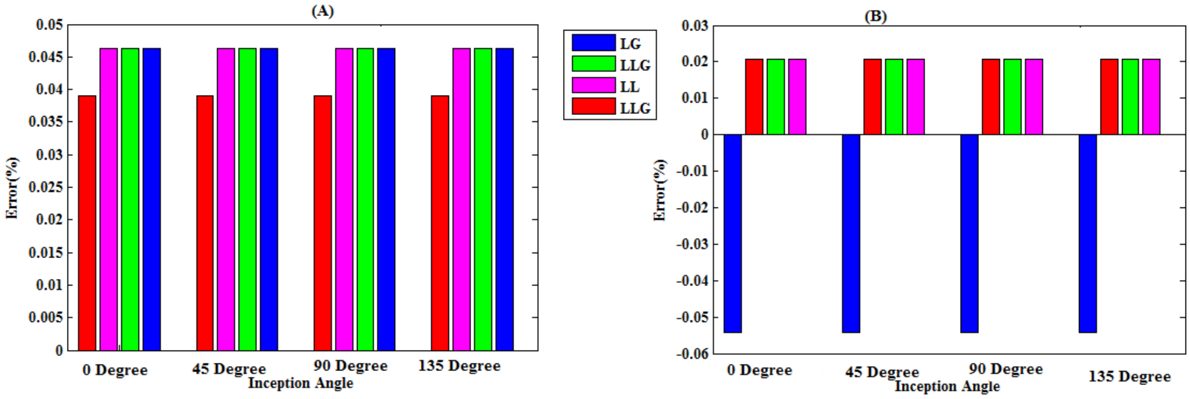

Figure14. Error comparison of the faults types and Different Fault Inception Angles (A) at 45 km from Behind the compensator (b) at a 85 km from Behind the compensator.

2. ***Effect of noise in the measurements:*** To examination measuring fault effect on accuracy and correctness of proposed algorithm, voltage and current samples at two end of transmission line exposed to accidental noisier and fault location done via their signals according to above model. The TCSC is installed at 120 km from the sending end, and fault resistance is 1Ω and the fault inception angle is 0^{0}. To considering measuring fault effects in accuracy of proposed algorithm for different location, to study the influence of the measurement errors on the accuracy of the proposed algorithm for different locations of fault, the voltage and current samples obtained from MATLAB/SIMULINK are subjected to perturbations. The error are generated randomly between -2.5% and 2.5% for each measured voltage and current samples of buses S and R and then are fed into the proposed fault-location algorithm. Results from fault location for different type of fault and fault location shown in table 5. Maximum absolute fault is 0.3778 in 104 Km from sending end for single-phase-to-ground fault. Simulation result showed that accuracy in proposed method was so high.

Table 5. Results of running the proposed algorithm in the presence of noise in the measurement.

Fault Type	Actual Location Of Fault(Km)	Calculated Location Of Fault (Km)	Error%
LG	8	8.6336	0.264
	25	25.2871	0.1196
	59	58.8027	-0.0822
	66	66.2957	0.1232
	104	104.9068	0.3778
	119	119.7337	0.3057
LLG	8	8.6336	0.1196
	25	25.2871	-0.2172
	59	58.4787	-0.2172
	66	65.8236	-0.0735
	104	104.3426	0.1427
	119	118.7415	-0.1077
LL	8	8.6336	0.264
	25	25.2871	0.1196
	59	58.4787	-0.2172
	66	65.8236	-0.0735
	104	104.3426	0.1427
	119	118.7415	-0.1077
LLLG	8	8.6336	0.264
	25	25.2871	0.1196
	59	58.4787	-0.2172
	66	65.8236	-0.0735
	104	104.3426	0.1427
	119	118.7415	-0.1077

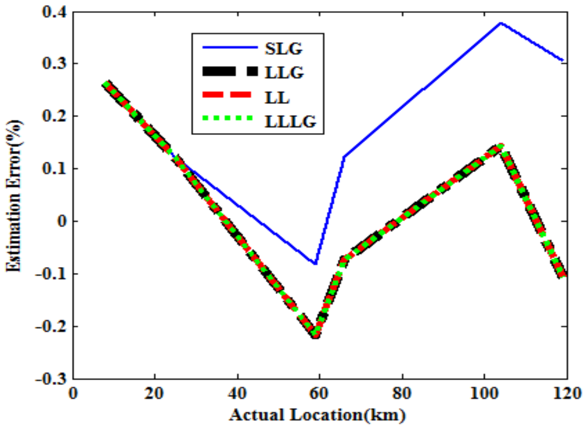

Figure15. Comparison of fault type error percentile with $R_f = 1\Omega$ Despite the noise in the measurement.

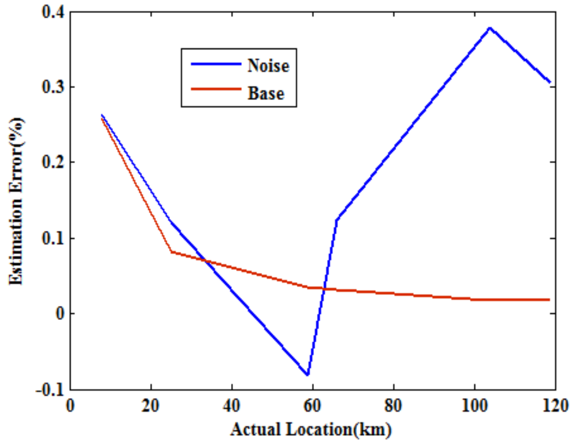

Figure16. Comparison of single-phase short circuit error percentile with $R_f = 1\Omega$ in two normal and noisier mode.

Reviews the results obtained indicate the following items:
Maximum Error less than 0.3 percent.
the proposed algorithm is independent of fault resistance.
the proposed algorithm is independent of the Fault Inception Angles.
variations proposed algorithm is very small respect to the kind the faults.

CONCLUSION

In this paper we proposed a method to determining faulty section and fault location algorithm for three terminal transmission line with series FACTS devices. Proposed method calculates exact location of fault by distributed transmission line model in the time domain. Since this approach used exact transmission line model, fault location is so accurate. Basic of this method is converting three terminal networks by series FACTS devices to two terminals after finding faulty section and then solving fault location problem. Because of the difficulties in modeling of FACTS devices have during fault, this algorithm doesn’t need compensator model and control system operation during fault time in transsmission line so this algorithm can use for any transmission line with series FACTS devices. Several simulations with different situation on network tested and its result from proposed algorithm evaluating shows that this algorithm is independent from inception fault angle and fault resistance. The results confirm the high accuracy of the algorithm in all cases so that the maximum error observed is less than 0.4 percent.

The strengths of the paper is as follows:

- Using the distributed time domain line model for a transmission line: This model has a high accuracy in long lines.
- No need for filters: Result in deletion of errors caused by frequency response of the filter and thus have higher accuracy.
- The proposed method is not sensitive for fault resistance.
- The proposed method is not sensitive for fault inception angles.
- The proposed method is not sensitive to the type of series FACTS devices are used.
- The proposed method is not sensitive to applied Faults (symmetrical and asymmetrical).

- The proposed method is not sensitive to location and parameters of FACTS devices.
- Low sensitivity to random noises.

APPENDIX

A. *TRANSMISSION LINE*

Positive sequence		*Zero sequence*	
$r_1(\Omega / km)$	0.0275	$r_0(\Omega / km)$	0.275
$l_1(mH / km)$	1.00268	$l_0(mH / km)$	3.26798
$c_1(\mu F / km)$	0.013	$c_0(\mu F / km)$	0.0085

B. *TCSC*

TCR Inductance:0.043 (H)
TCSC Capacitance:21.977(μF)

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