Fault Location Algorithm for Three-Terminal Transmission Lines: Distributed Time Domain Line Model

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Abstract-Conventional fault location methods using one-terminal voltages and currents are not applicable to multi-terminal transmission lines. However, for determination of fault location in three-terminal lines at least voltages and currents of two terminals are necessary. There have been some techniques presented to solve fault location problem for multi-terminal transmission lines. In these methods lumped or distributed frequency domain models are used for transmission lines. In multi-terminal lines, faulty section should be detected before fault location estimation. In this paper, two methods based on time domain transmission line model are presented to identify the faulty section and to determine the location of faults for three terminal transmission lines. In the first method, samples of voltages and currents from all terminals are used while in the second method only the data of two terminals is used for calculating the location of the fault. The proposed algorithms are independent of fault resistance, insensitive to load current and fault inception angle. Furthermore they do not require any knowledge of source impedance and also fault type classification is not necessary. Filtering of dc and high frequency component of waves are not required. The results of computer simulation using EMTP/ATP software confirm the accuracy and precision of the proposed methods.

Keywords: Fault location algorithm, Three-terminal transmission lines, Distributed time domain line model

1. INTRODUCTION

Determination of the distance to the location of fault in transmission lines has been considered to be an important problem for electrical engineers. So far, different algorithms have been presented to solve fault location problem in which the data of one terminal or all terminals have been used. In addition, various models of transmission line have been applied. Conventional fault location methods using one terminal voltages and currents are not applicable to multi-terminal transmission lines. For fault locating in three terminal lines at least voltages and currents of two terminals are required. There have been some techniques presented to solve fault location problem on multi-terminal transmission lines. In these methods lumped or distributed frequency domain models have been used to model the transmission lines. In multi-terminal lines, before estimation of fault location, faulty section should be detected [1-4]. For example [1] proposes a method for solving the problem of fault location in three-terminal transmission lines in which synchronous and asynchronous data for all terminals are required. In [2], the differences between currents in those lines have been used as the input data in a two circuit lines with three-terminal. In these two methods lumped models have been used for transmission lines. Lin for fault locating in transmission lines with three-terminal, has suggested a method utilizing distributed model of transmission lines in frequency domain [3]. This method uses the information of two-terminal assuming generation in third terminal. In [4], the algorithm proposed by Johns [5] for two-terminal lines has been extended to three-terminal transmission lines using the frequency domain distributed model of the lines.

In this paper, two techniques based on distributed time domain transmission line are proposed to identify the faulty section and to determine the location of fault in three-terminal transmission lines. In the first method the data of all terminals are used while in the second method benefits the advantage of voltage and current samples taken at only two terminals. Furthermore, the methods do not require filtering of dc offset and high frequency component of the recorded signals. The proposed methods detect the fault location regardless of the type of third terminal (with or without generation), while previously proposed methods work only in the case that the third bus is a generation bus. In addition, the proposed algorithms are independent of fault resistance, insensitive to load current, fault inception angle and do not require any knowledge of source impedance and fault type classification. In this research the C.T's model does not considered but it can be included without any problem.

The validity of proposed methods have been investigated applied to the 400 kV three terminal transmission line using EMTP/ATP software. The simulation results confirm the accuracy of the proposed methods.

2. DISTRIBUTED TIME DOMAIN TRANSMISSION LINE MODEL

Fig. 1 shows the one line diagram of three-phase transmission line with distributed parameters. In this figure S and R are transmission line terminals and F is a fault point along the line that has a distance x from S terminal. The distributed model of S-F part is shown in fig. 2 [6].

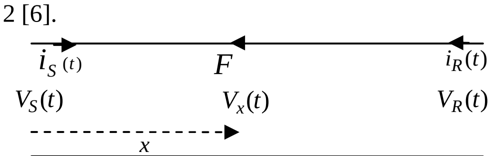

Figure 1: Transmission line with distributed parameters

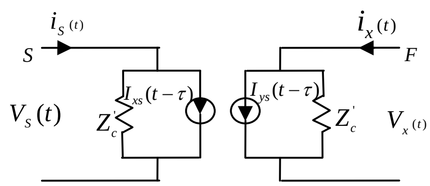

Figure 2: Distributed model of S-F line section

Based on fig. 2, I_{xS} and I_{yS} are explained as:

$$I_{xs}(t-\tau) = -\frac{R'/4}{Z_C'^2}[V_S(t-\tau)+Z_C'' i_S(t-\tau)] - \frac{Z_C}{Z_C'^2}[V_x(t-\tau)+Z_C'' i_x(t-\tau)] \quad (1)$$

$$I_{ys}(t-\tau) = -\frac{R'/4}{Z_C'^2}[V_x(t-\tau)+Z_C'' i_x(t-\tau)] - \frac{Z_C}{Z_C'^2}[V_S(t-\tau)+Z_C'' i_S(t-\tau)] \quad (2)$$

where τ is wave propagation time from S-terminal to fault point, Z_c is transmission line surge impedance and R' is line resistance between S-terminal and the faulted point, and also we have:

$$Z_C' = Z_C + R'/4 \qquad Z_C'' = Z_C - R'/4$$

3. FAULT LOCATION IN TWO TERMINAL TRANSMISSION LINES

Using the distributed model of the line in fig. 2 and replacing i_x in eqs 1 and 2 we obtain:

$$\begin{aligned} V_{xS}(t) = (&Z_C'^2[V_S(t+\tau) - Z_C' i_S(t+\tau)] \\ &+ Z_C''^2[V_S(t-\tau)+Z_C'' i_S(t-\tau)] \\ &- \frac{Z_C' R'}{4}[\frac{R'/2}{Z_C'}V_S(t)+2Z_C'' i_S(t)])/2Z_C^2 \end{aligned} \quad (3)$$

Applying similar procedure, the fault point voltage as a function of voltage and current at the receiving end can be written as follows:

$$\begin{aligned} V_{xR}(t) = (&Z_{rC}'^2[V_R(t+T-\tau) - Z_{rC}' i_R(t+T-\tau)] \\ &+ Z_{rC}''^2[V_R(t-T+\tau)+Z_{rC}'' i_R(t-T+\tau)] \\ &- \frac{Z_{rC}' R_r'}{4}[\frac{R_r'/2}{Z_{rC}'}V_R(t)+2Z_{rC}'' i_R(t)])/2Z_C^2 \end{aligned} \quad (4)$$

where, T is wave propagation time from S to R-terminal, and R_r' is line resistance between R-terminal and faulted point, also we have:

$$Z_{rC}' = Z_C + R_r'/4 \qquad Z_{rC}'' = Z_C - R_r'/4$$

Because of voltage continuity along the transmission line, eqs. 3 and 4 can be combined leading to:

$$V_{xS}(t) - V_{xR}(t) = F(V_S, i_S, V_R, i_R, t, \tau) = 0 \quad (5)$$

In eq. 5, the distance from S-Terminal to the location of fault (x) does not appear explicitly. However, it is implicitly included in τ , $Z_C', Z_C'', Z_{rC}', Z_{rC}'', R'$ and R_r'. To calculate the location of the fault, first we replace it with a discrete equation and then we solve the following optimization problem:

$$Min \quad obj(m) = \underset{m}{Min} \sum_k F^2(V_S, i_S, V_R, i_R, k, m) \quad (6)$$

where $m\Delta t = \tau$ *and* $k\Delta t = t$ in which Δt is the sampling time and m, k are arbitrary integers.

In [7], for applying the above-mentioned algorithm to asymmetrical fault, voltages and currents are transferred from time domain to modal domain [8]. Then, introducing the objective function, the location of fault is calculated through minimizing the objective function. However, as the speed of traveling waves in zero mode (ground mode) and first mode (aerial mode) are not the same, the error in determining fault location is much more than the symmetrical fault calculations in which only one mode is used for calculation. In [9], this fact has been used that every independent equations in modal domain are similar to the equation of one phase transmission line. Now, converting eqs. 3 and 4 from time domain to modal domains we can write:

$$\begin{aligned} V_{xS}^m(t) = (&Z_{Cm}'^2[V_S^m(t+\tau_m) - Z_{Cm}' i_S^m(t+\tau_m)] \\ &+ Z_{Cm}''^2[V_S^m(t-\tau_m)+Z_{Cm}'' i_S^m(t-\tau_m)] \\ &- \frac{Z_{Cm}' R_m'}{4}[\frac{R_m'/2}{Z_{Cm}'}V_S^m(t)+2Z_{Cm}'' i_S^m(t)])/2Z_{Cm}^2 \end{aligned} \quad (7)$$

$$\begin{aligned} V_{xR}^m(t) = (&Z_{rCm}'^2[V_R^m(t+T_m-\tau_m) - Z_{rCm}' i_R^m(t+T_m-\tau_m)] \\ &+ Z_{rCm}''^2[V_r^m(t-T_m+\tau_m)+Z_{rCm}'' i_r^m(t-T_m+\tau_m)] \\ &- \frac{Z_{rCm}' R_{rm}'}{4}[\frac{R_{rm}'/2}{Z_{rCm}'}V_r^m(t)+2Z_{rCm}'' i_r^m(t)])/2Z_{Cm}^2 \end{aligned} \quad (8)$$

Transferring the asymmetrical three-phase system to three symmetrical systems, optimization function F in mode m can be written as follows:

$$V_{xS}^m(t) - V_{xR}^m(t) = F(V_S^m, i_S^m, V_R^m, i_R^m, t, \tau_m) = 0 \quad (9)$$

In eqs. 7, 8 and 9 m=0, 1 and 2 refer to modes 0, 1 and 2 respectively. Other parameters are the same as expressed in eqs. 3 and 4 in mode m. In this way determining fault location in transmission lines can be done using zero mode or first mode independently Then, mode 1 will be used for calculating the fault location in both symmetrical and asymmetrical faults irrespective of the type of the fault, while zero mode will be used only in the case that faulty point is grounded. A novel merit of this method is that fault classification is not necessary if we use mode 1 for determining the fault location. This is due to the fact that mode 1 appears in any type of faults.

4. FAULT LOCATION IN THREE TERMINAL TRANSMISSION LINES

In fig. 3, different fault locations have been shown in three terminal transmission lines:

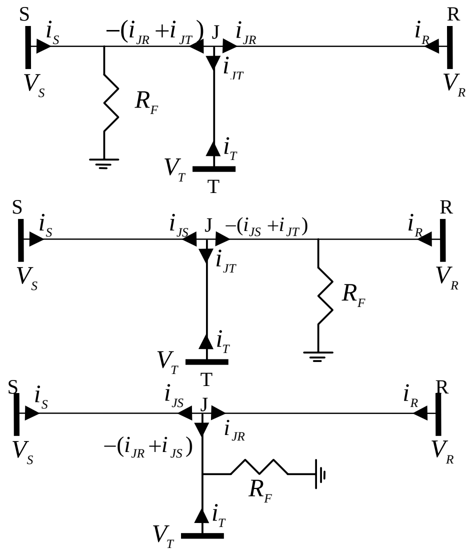

Figure 3: Different locations of fault

Fault location algorithm in three terminal transmission lines can be divided into two steps:

1- Fault section detection
2- Calculating of distance to the fault point

4 -1- Fault location using data of three terminals

4-1-1- Fault section detection

1- By using of model of lines *S-J*, *R-J* and *T-J*, mode 1 or 0 of voltages of junction (J) is computed.
2- Three criterion functions have been defined as:

$$X_1=\int\left|V_{JS}^{(m)}(t)-V_{JR}^{(m)}(t)\right|dt \qquad (10\text{-a})$$

$$X_2=\int\left|V_{JS}^{(m)}(t)-V_{JT}^{(m)}(t)\right|dt \qquad (10\text{-b})$$

$$X_3=\int\left|V_{JR}^{(m)}(t)-V_{JT}^{(m)}(t)\right|dt \qquad (10\text{-c})$$

3- In eq. 10, the minimum value of X_1, X_2 and X_3 is determined. The section between the junction and the terminal, which its data is not exist in that criterion, is the faulty section. For example if X_1 is being minimum, fault is occurred in section *J-T*.

4-1-2- Determination the distance to fault

After determining the faulty section, for calculating the location of fault, three-terminal system should be converted to two-terminal system. For more explanation, assume that the fault occurred in *R-J* section in fig. 3, the voltage of junction (J) has been computed by using distributed model of *T-J* or *S-J* parts. Also for computing of $i_{JR}(t)$, currents $i_{JS}(t)$ and $i_{JT}(t)$ should be calculated by using time domain distributed model of *T-J* and *S-J* sections.

According to the above procedures, three-terminal network in fig. 3 will be converted to two-terminal network, which is shown in fig. 4.

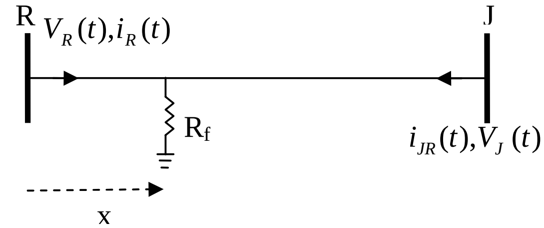

Figure 4: Three-terminal network which be converted to two-terminal network

In fig. 4 $i_{JR}(t)=-(i_{JS}(t)+i_{JT}(t))$ and $i_{JS}(t)$ and $i_{JT}(t)$ are defined in fig. 3.

In this step, by using of fault location algorithm for two terminal lines [9] the location of fault is determined.

4 -2- Fault location using data of two terminals

4 -2 -1 Fault location with generation in third terminal

4 -2-1-1- Fault in section S-J

1- Internal voltage of generator of third terminal V_E(t) can be calculated using prefault samples of voltages and currents in terminals *S* and *R*.
2- The voltage at the point of *J* has been computed by using voltages and currents samples in *R*- terminal.
3- We assume that internal voltage in third terminal during the fault is constant, then:

$$V_E(t)-V_T(t)=R_S i_T(t)+L_S\frac{di_T(t)}{dt} \qquad (11)$$

where, R_S and L_S are resistance and inductance of generator in third terminal, respectively.
4- Voltage at the branch point $V_J(t)$ has been calculated in step 2, then:

$$\begin{aligned}V_J(t)=(&Z_{tC}^{'2}[V_T(t+T_3)-Z_{tC}^{'}i_T(t+T_3)]\\&+Z_{tC}^{''2}[V_T(t-T_3)+Z_{tC}^{''}i_T(t-T_3)]\\&-\frac{Z_{tC}^{'}R_t^{'}}{4}[\frac{R_t^{'}/2}{Z_{tC}^{'}}V_T(t)+2Z_{tC}^{''}i_T(t)]/2Z_{tC}^{2}\end{aligned} \qquad (12)$$

where, T_3 is wave propagation time from *T*-terminal to junction point (*J*), Z_{tC} is transmission line surge impedance of section *T-J* and $R_t^{'}$ is line resistance between *T* and *J* terminals also, we have:

$Z_{tC}^{'}=Z_{tC}+R_t^{'}/4 \qquad Z_{tC}^{''}=Z_{tC}-R_t^{'}/4$

5- Eqs. 11 and 12 must be solved for $V_T(t)$ and $I_T(t)$.
6- With changing three-terminal network to a two-terminal network and then by using information of both two ends of transmission line, distance to the place of fault can be calculated [9].

For solving the problem of fault location in *R-J* section, all of the steps 1 to 6 should be done with suitable changes in parameters.

If we use distributed time domain transmission line model, solving of eqs. 11 and 12 simultaneously are very difficult, so for making it easy to finding location of fault, we consider some assumption:
1- Branched transmission line has been considered like short line.

2- Voltage and current in the branched point can be estimated before fault with considering lines *S-J* and *R-J* as short line.

With considering these assumptions in the proposed method, fault location can be divided into three steps.

a- Internal voltage in third terminal is calculated using prefault data.

b- Faulty section should be detected.

c- Determining the location of fault.

Considering these assumptions, voltage $V_J(t)$ and current $I_{JT}(t)$ will be calculated as:

$$i_T(t) = -i_{JT}(t) \text{ and } i_{JT}(t) = -(i_S(t) + i_R(t)) \quad (13)$$

$$V_J(t) = V_S(t) - R_{lS} i_S(t) - L_{lS} \frac{di_S(t)}{dt} \quad (14)$$

where L_{ls} and R_{ls} are inductance and resistance of *S-J* line and voltages and currents are defined in fig. 3. Third terminal voltage can be calculated as:

$$V_T(t) = V_J(t) - R_{lT} i_{JT}(t) - L_S \frac{di_{JT}(t)}{dt} \quad (15)$$

where R_{lt} and L_{lt} are resistance and inductance of line *J-T*. Finally, internal voltage in the generator of third terminal is as:

$$V_E(t) = V_T(t) + R_s i_T(t) + L_S \frac{di_T(t)}{dt} \quad (16)$$

where, R_s and L_s are resistance and inductance of the Thevenin equivalent of the generator of third terminal.

Up to now, the internal voltage of generator in third terminal has been calculated. If fault happened in *S-J* or *R-J* sections, for calculating current in T-terminal we uses this equation:

$$V_E(t) - V_J(t) = (R_s + R_{lT}) i_T(t) + (L_S + L_{lT}) \frac{di_T(t)}{dt} \quad (17)$$

with solving eq. 17 by numerical method, the current of third terminal will be calculated.

4 -2-1-2 Fault in junction line (section T-J)

1- Voltage and current in branched point are calculated using voltages and currents samples in two main terminals (S and R).

2- Because the fault has occurred in the branched line, therefore, post fault voltage and current in third terminal cannot be calculated as before. However, voltages and currents in branched point have been calculated in step 1, so using common ways of fault location algorithm, such as [10], which uses voltage and current samples of one terminal of transmission line, location of fault can be calculated.

4-2-1-3- Fault section detection

For fault section detection, we assume that the transmission line is two-terminal and branched point and branched line have not been considered. The problem of fault location in transmission lines with two-terminal should be solved [9]. The calculated distance is called D_i, then:

If $D_i > L_{SJ}$ *R-J* is faulty section.

If $D_i < L_{SJ}$ *S-J* is faulty section.

If $D_i = L_{SJ}$ *T-J* is faulty section.

In this step, if fault is occurred in section *S-J* or *R-J*, we have voltages and currents in all terminals. Therefore by converting three-terminal network to two-terminal network faulted point can be determined. Otherwise, if fault is occurred in section *T-J*, voltage and current of junction point can be computed. Then three-terminal network can be converted to two-terminal network and by a fault location algorithm that use voltage and current samples in one terminal, location of fault will be determined.

4-2-1-4- Performance evaluation

In order to investigate the accuracy of the proposed algorithm, in this section the results of computer simulation are presented. Fig. 5 shows a three-phase 400kV three–terminal transmission line with generation in third terminal. Parameters of this simple power system are presented in appendix. A single line to ground fault (SLG) in phase a occurred at arbitrary point at a distance *x* from S-terminal in *S-J* section. For *x* equal to 80 km, voltage and current of phase a at the S terminal are shown in figs. 6 and 7. In addition, the objective function defined in eq. 6 is drawn in figs. 8 and 9. Distance to faulted point is calculated 80.32 km for both cases (using two or three terminal data).

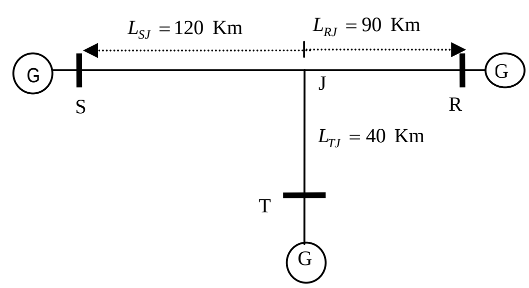

Figure 5: The simple power system for simulation

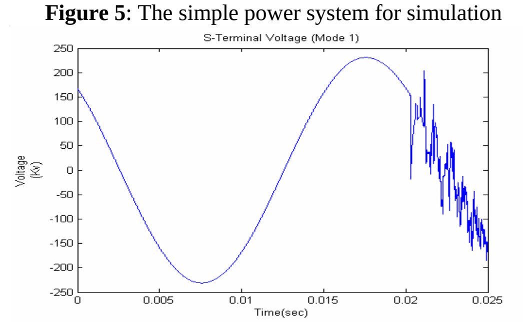

Figure 6: S-terminal voltage

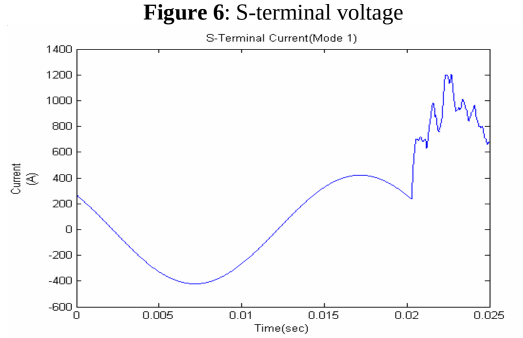

Figure 7: S-terminal current

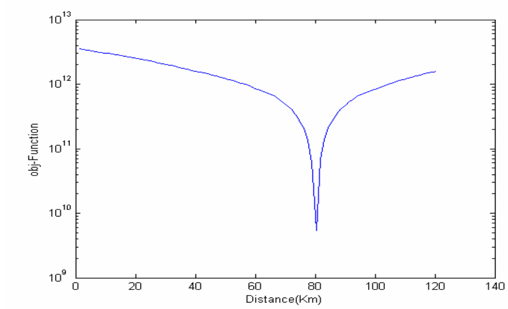

Figure 8: Objective function using three terminal data when there is generation at T-terminal

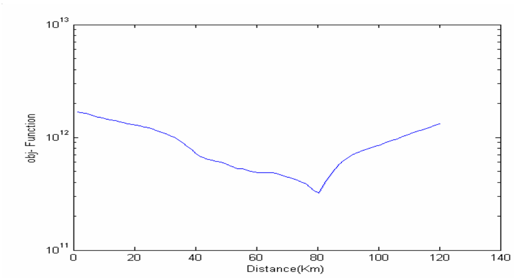

Figure 9: Objective function using two terminal data when there is generation at T-terminal

To estimate the accuracy of the fault distance calculation, the proposed algorithm has been tested for a different location of fault points and different sections of fault. Some of the results are summarized in tables 1 and 2 for fault in sections *S-J* and *R-J* respectively. For fault in section, *T-J* the algorithm that is presented in [10] has been used. The D_i criteria function for faulty section detection is shown in fig. 10 and table 3 shows the distance to the fault point for different locations of fault point in this section. Also fig. 11 shows voltage integral criteria function [10] that in this paper for calculating of this function mode 1 of voltage has been used.

Actual Location to fault from S-terminal	Calculated Location to fault (computing with 2-terminal data)	Calculated Location to fault (computing with 3-terminal data)
5	4.15	5.54
20	20.77	19.39
40	40.16	40.16
115	114.95	114.95

Table 1: Fault location in section S-J with generation in T-terminal

Actual Location to fault from R-terminal	Calculated Location to fault (computing with 2-terminal data)	Calculated Location to fault (computing with 3-terminal data)
5	5.54	5.54
30	30.47	30.47
70	70.63	70.63
85	85.86	85.48

Table 2: Fault location in section R-J with generation in T-terminal

Actual Location to fault from Junction(J)	Calculated Location to fault (computing with 2-terminal data)	Calculated Location to fault (computing with 3-terminal data)
10	10.53	9.69
20	20.61	19.39
30	30.30	30.47

Table 3: Fault location in section T-J with generation in T-terminal

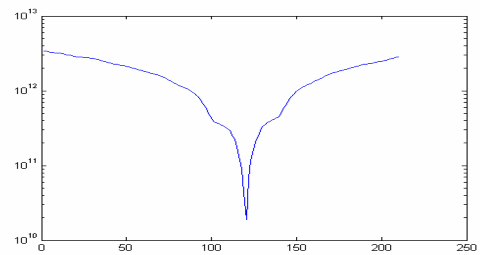

Figure 10: *Di* criteria function

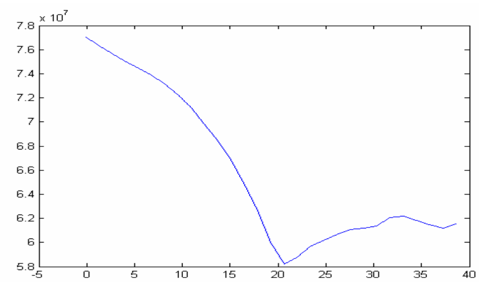

Figure 11: Voltage integral criteria function [10]

4-2-2- Determination of fault location when there is no generation at the third terminal

In the more usual case of networks with three terminals, when voltages and currents in two main terminals which have some generation, are known, if fault happens in any of two main sections, the network can not be converted to a two terminal network. This is because there is no generation at the third terminal. Therefore, only the information of two main terminals will be utilized for detection of the faulty section. In such cases determination of fault location will be achieved using the time domain methods which require only the information of voltage and current in one of the terminals of the network. In such a situation, as the voltage at the faulty point is minimum [10], and as there is no generation at the third terminal, the fault current related with this terminal will be zero. Furthermore, the current flown into the section with no generation from two other sections is very small and can be neglected for determination of fault location and the proposed method in part (4-2-1-3) can be used for detection of faulty section. To explain the proposed algorithm in more detail, depending on the location of fault, two different categories for determination of fault location can be distinguished as below:

4-2-2-1- Fault happens in main sections(S-J or R-J)

In this case, as explained before, the current in the section with no generation and consequently that section can be neglected. Therefore, assuming a two terminal network, using the information at two main terminals, the location of the fault can be determined [7].

4-2-2-2- Fault happens in junction section (J-T) with no generation

In this case, using the information of two main terminals, voltage and current at junction point are computed. Then, the distances to the location of fault is calculated applying one of fault location methods which uses the information of one terminal.

4-2-2-3- Performance evaluation of the proposed algorithm

To investigate the accuracy of the proposed algorithm, the simulation results for the simplified system shown in fig. 5 are presented in this section that there is no generation at T-terminal. A single line to ground fault (SLG) in phase a occurs at an arbitrary point with a distance *x* from S-terminal in section *S-J*. Fig. 12 shows the objective optimization function assuming *x* equal to 60 km. Using the proposed algorithm the distance to the faulted point is calculated as 59.55 km. Using the information of three terminals, then the distance will also be calculated as 59.55 km. This shows the accuracy of the proposed method. Furthermore, the proposed algorithm has been applied for determination of fault location for more different cases. Some of the results are summarized in tables 4 and 5 for faults in sections *S-J* and *R-J* respectively.

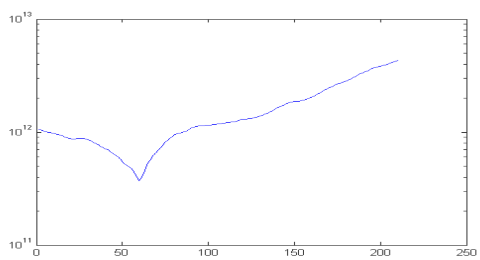

Figure 12: Objective function using two terminal data when there is no generation at T-terminal

Locate to fault	Locate to fault (computing with 2-terminal data)	Locate to fault (computing with 3-terminal data)
10	9.69	9.69
60	59.55	59.55
85	84.86	84.48
115	114.95	114.95

Table 4: Fault happens in section S-J without generation in T-terminal

Locate to fault	Locate to fault (computing with 2-terminal data)	Locate to fault (computing with 3-terminal data)
10	9.69	9.69
50	49.86	49.86
80	80.32	80.32

Table 5: Fault happens in section R-J when there is no generation at T-terminal

5. CONCLUSION

In this paper, two new algorithms for determination of fault location in transmission networks with three terminal lines are proposed. The methods use distributed time domain model of transmission lines. The approaches rely on converting network with three terminals to the network with two terminals after fault section detection. The proposed methods are very advantageous because while their accuracy is very good they are not sensitive to fault resistance, inception angle and the load of the lines. Furthermore, filtering of dc offset and high frequency components are not required for data acquisition. As the method is in time domain, the needed data window is very narrow.

REFERENCES

[1] A. Girgis, D.G. Hart and W.L. Peterson, "A New Fault Location Technique for Two and Three Terminal Lines", IEEE Trans. on Power Delivery, Vol. 7, No. 1,pp. 98-107 , Jan. 1992.

[2] T. Nagasawa, et al, "Development of a New Fault Locator Algorithm for Multi-Terminal Two Parallel Transmission Lines", IEEE Trans. on Power Delivery. Vol. 7, No. 3, pp. 1516-1537 July 1992.

[3] Y.H. Lin and C.W. Liu "A New Fault Locator Algorithm For Three Terminal Transmission Lines using Two Terminal Synchronized Voltage and Current Phasors", IEEE Trans. on Power Delivery, Vol. 17, No. 2, pp. 452-459. April 2002.

[4] A. Kalam and A.T. Johns "Accurate Fault Location Technique for Multi Terminal EHV Line", IEE International Conference on Advances in Power System Control, Operation and Management, Nov. 1991, Hong Kong

[5] A.T. Johns and S. Jamali, "Accurate Fault Location Technique for Power Transmission Lines", IEE Proc. Vol. 137, Pt. C, No. 6,pp. 395-402. Nov. 1990.

[6] H. Dommel, "Digital Computer Solution of Electromagnetic Transient in Single and Multi Phase Networks", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-88 . No.4, pp. 388-399, Apr. 1969.

[7] J. Sadeh, et al, "Accurate Fault Location Algorithm for Series Compensated Lines", *IEEE*

Trans. on Power Delivery, Vol. 15, No. 3, pp. 1027-1033, July 2000.

[8] A.O. Ibe , B.J. Cory "A Traveling Wave Fault Location for Two and Three Terminal Networks", IEEE Trans. on Power Delivery, Vol. 1, No.2, pp. 283-288, April 1986.

[9] E. Kamyab, J. Sadeh and M.H. Javidi, "Adaptive Fault Location Algorithm for Transmission Lines," 12th Iranian Conference on Electrical Engineering, ICEE'04, May 2004, Iran (in Persian).

[10] A.M. Ranjbar, et al, "A New Approach for Fault Location Problem on Power Lines", IEEE Trans. on Power Delivery, Vol. 7, No. 1.pp. 146-151, Jan. 1992.

APPENDIX

Parameters of power system in fig. 5 are shown as:

Transmission lines parameters

$R^+ = 0.0275\Omega/km$ $R^0 = 0.275\Omega/km$

$L^+ = 1.00268mH/km$ $L^0 = 3.26798mH/km$

$C^+ = 0.013\mu F/km$ $C^0 = 0.0085\mu F/km$

Generator parameters

$R^+ = 1.31\Omega$ $R^0 = 2.33\Omega$

$L^+ = 47.75mH$ $L^+ = 84.67mH$