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# A New Fault Location Algorithm for Compensated Transmission Line Using Distributed Time Domain Model

**Javad Sadeh**
Ferdowsi University of Mashhad
sadeh@um.ac.ir

**Aniseh Adinehzadeh**
Ferdowsi University of Mashhad
Aniseh_adinehzadeh@yahoo.com

***Abstract:*** *This paper presents an accurate fault location algorithm for compensated transmission line. The distributed time domain model is used for modelling of the transmission line. This algorithm does not utilize the compensated device model and does not need any knowledge about the operation mode of the compensated device to compute the voltage drop during the fault period. Samples of voltage and current at both ends of the line are taken synchronously and used to calculate the location of fault. Besides the location of fault, the proposed algorithm estimates the fault resistance accurately. The proposed algorithm is not sensitive to fault resistance and does not require any knowledge of source impedances. The proposed method has been tested using EMTP/ATP model of a 400kV, 300km transmission line, which is compensated by a compensator device. The results of computer simulation confirm the accuracy of the proposed method.*

**Keywords:** Fault location algorithm, Distributed time domain line model, Compensated transmission line.

## 1 Introduction

The electric generators in power system are used to supply energy to the consumers. The transmission lines that are the interface between generators and consumers transmit electrical power to the consumers. Therefore it is necessary that transmission line against disturbances which occur in power system being safe or when the fault occur on transmission line, the fault point is distinguished until the system could be recovered and restored. For finding the location of fault, accurate and quick devices are needed to specify the location of fault accurately. These devices help to be distinguished the place of fault when permanent or temporary fault occur on a system. The location of permanent faults will facilitate quickly repair and restoration. While accurate location of transient (temporary) faults will aid in preventive maintenance. Several fault location algorithms have been proposed and applied for determining the point of fault on transmission line. Some of them are based on current and voltage phasors [1-7]. The fault location algorithms that use current and voltage phasors need the fundamental component of voltage and current in one end or two ends of the line. In the fault location algorithm with using of current and voltage phasors, the lumped or distributed frequency domain line model can be used. The fault location algorithms which used lumped model have a good accuracy in short transmission line, but when it used in long transmission line, it have a significant error. Therefore in order to consider the capacitive effect which ignored in lumped model, some papers have been used $\pi$ model of transmission line [1,3]. Using more exact model for transmission line, will result more exact results. Therefore in some researches distributed frequency domain model of transmission line are used [6-7]. Having flexible transmission line and controlling the power flow is done by compensator device that controls power flow of transmission line [8-9]. Some of fault location algorithms in compensated transmission line use the model of compensator device to find the location of fault but using this approach errors are induced by the inaccuracy of compensator device model or the uncertainty in operation mode of compensator device [10-11]. Some of fault location algorithms in compensated transmission line that use phasors of current and voltage doesn't need to model a compensator device but need to filter the dc component and harmonics that are in the waveforms [12]. Dc component and harmonics create some problems in filtering process. An alternative method for this problem is using the partial differential equation of transmission line that there is no need to filter these components [13-16]. In this way the lumped and distributed time domain model of transmission line is used. To achieve high accuracy in fault location for long transmission line the distributed time domain of transmission line have been used [15-16].

In this paper we introduce a new fault location algorithm in compensated transmission line. This algorithm does not need to filter the dc and other harmonics components that present in the voltage and current signals. Also the proposed fault location algorithm does not use the model of compensator device and there is no need to any knowledge of the operation mode of the compensator. If the line is compensated by any type of compensator, the algorithm is independent of its type and its model. The suggested technique takes advantage of post-fault voltage and current samples taken from both ends of line synchronously. The proposed algorithm is independent of location and parameters of compensator device. The sampling rate affects the accuracy of fault location algorithm. Higher accuracy is achieved using lower sampling period. In this paper the sampling period (Δt) is chosen to be 0.1msec. In this algorithm the samples of voltages and currents are assumed to be synchronous. Otherwise according to [17] the samples could be synchronized. The algorithm has been tested for a wide variety of simulated fault conditions such as different fault inception angles, different fault resistances, symmetrical and unsymmetrical faults. The results are very good in most of the cases and the error is kept below 0.5%.

# 2 Proposed Fault Location Method

## 2.1 Transmission Line Modelling and Two-End Fault Location Method

A single-phase model of a three-phase transmission line with distributed parameters is shown in Fig.1. In this figure $S$ and $R$ represent the sending and receiving ends and F is taken as an arbitrary point which occur a fault with resistance $R_f$ at distance $x$ ($x \le L_{line}$) from S along the line. The distributed model of the SF segment is shown in Fig.2 [16].

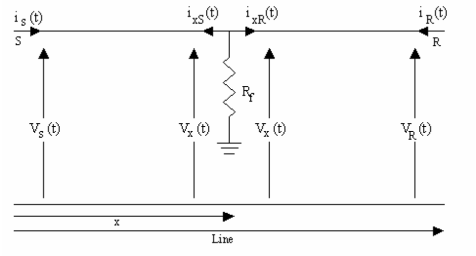

Fig. 1. Transmission line with distributed parameters

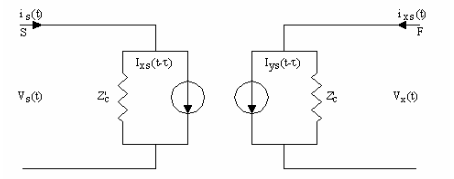

Fig. 2. Distributed model of the SF segment

The voltage and current at fault point as functions of sending end voltage and current are as follows [16]:

$$\begin{aligned} V_x(t) &= (Z'^2_c\,[V_s(t+\tau) - Z'_c\,i_s(t+\tau)] + Z''^2_c\,[V_s(t-\tau) \\ &+ Z''_c\,i_s(t-\tau)] - \frac{Z'_c R'}{4}\,[\,\frac{R'/2}{Z'_c}\,V_s(t) + 2\,Z''_c\,i_s(t)]\,)\,/2\,Z^2_c \end{aligned} \tag{1}$$

$$\begin{aligned} i_{xs}(t) &= (Z'_c\,[V_s(t+\tau) - Z'_c\,i_s(t+\tau)] - Z''_c\,[V_s(t-\tau) \\ &+ Z''_c\,i_s(t-\tau)] - \frac{R'}{4}\,[\,2\,V_s(t) - \frac{R'}{2}\,i_s(t)]\,)\,/2\,Z^2_c \end{aligned} \tag{2}$$

$\tau$ = Time elapsed for the wave propagation from $S$ to $F$

$Z_c$ = Characteristic impedance

$R'$ = Line resistance from $S$ to $F$

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

The fault point voltage and current as function of receiving end voltage and current are as follows [16]:

$$\begin{aligned} V_x(t) &= (Z'^2_{rc}\,[V_r(t+T-\tau) - Z'_{rc}\,i_r(t+T-\tau)] \\ &+ Z''^2_{rc}\,[V_r(t-T+\tau) + Z''_{rc}\,i_r(t-T+\tau)] \\ &- \frac{Z'_{rc} R'_r}{4}\,[\,\frac{R'_r/2}{Z'_{rc}}\,V_r(t) + 2\,Z''_{rc}\,i_r(t)]\,)\,/2\,Z^2_c \end{aligned} \tag{3}$$

$$
\begin{aligned}
i_{xr}(t) = {} & (Z'_{rc}\ [V_r(t+T-\tau)\ -\ Z'_{rc}\ i_r(t+T-\tau)] \\
& - Z''_{rc}\ [V_r(t-T+\tau)\ +\ Z''_{rc}\ i_r(t-T+\tau)] \\
& -\ \frac{R'_r}{4}\ [\ 2\ V_r(t)\ -\ \frac{R'_r}{2}\ i_r(t)]\ )\ /2\ Z_c^2
\end{aligned}
\tag{4}
$$

Where:

$T$ = Time elapsed for the wave propagation from $S$ to $R$

$R'_r$ = Line resistance from $R$ to $F$

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

Because of continuity of the voltage along the transmission line, (1) and (3) can be combined; leading to:

$$
F\ (\ V_s,\ i_s,\ V_r,\ i_r,\ t,\ \tau)\ =\ 0 \tag{5}
$$

In the above equation the F function is defined as follows:

$$
\begin{aligned}
F\ =\ & (Z_c'^2\ [V_s(t+\tau)\ \text{-}\ Z'_c\ i_s(t+\tau)] + Z_c''^2\ [V_s(t-\tau) \\
& +\ Z''_c\ i_s(t\text{-}\tau t\text{-}\tau)]\frac{Z'_c\ R'}{4}\ [\ \frac{R'/2}{Z'_c}\ V_s(t)\ +\ 2\ Z''_c\ i_s(t)] \\
& -\ (Z_{rc}'^2\ [V_r(t+T-\tau)\ \text{-}\ Z'_{rc}\ i_r(t+T-\tau)] \\
& + Z_{rc}''^2\ [V_r(t\text{-}T+\tau)\ +\ Z''_{rc}\ i_r(t\text{-}T+\tau)] \\
& \text{-}\ \frac{Z'_{rc}\ R'_r}{4}\ [\ \frac{R'_r/2}{Z'_{rc}}\ V_r(t)\ +\ 2\ Z''_{rc}\ i_r(t)])\ )\ /2\ Z_c^2
\end{aligned}
\tag{6}
$$

The distance to the fault point does not appear explicitly in (5), and is hidden in the surge travelling time $\tau$. Furthermore $\tau$ does not appear as a variable in (5), but as the value on which the voltage and current depend. For finding the location of fault at first the equation is discretized and then the following optimization problem is solved:

$$
\underset{m}{Min}\ J(m)\ =\ \underset{m}{Min}\ \sum_k F^2(\ V_s,\ i_s,\ V_r,\ i_r,\ k,\ m\ ) \tag{7}
$$

Where:
$m\ \Delta t = \tau$,
$k\ \Delta t = t$
$\Delta t$ = Sampling step,
$m\ ,\ k$ = arbitrary integers

## 2.2 Fault Location Algorithm for Compensated Transmission Line

We assume that the compensator device is installed in the midpoint of the transmission line. In our discussion the type of compensator is not important. Without loss of generality and just for simplicity, we supposed this compensator is a series capacitor along with its over voltage protection (MOV). The compensator divides the line into two parts, i.e. from sending end to the compensated position and from the compensator position to the receiving end of transmission line.

In the following discussion we consider the fault locator which installed in the sending end and the fault positions are assumed to be in the second part of the line. For the other fault locator and the fault positions in the first part of the line, the discussions are similar.

According to the above description the proposed fault location algorithm considers three distributed time domain models for transmission line as follows: (figs. 3a-3c)

1- Distributed time domain model from sending bus to left-hand side of compensator (line1).
2- Distributed time domain model from right-hand side of compensator to fault location (line2).
3- Distributed time domain model from fault point to receiving bus (line3)

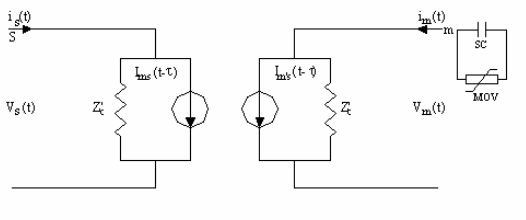

Fig. 3a. Distributed time domain model from sending end to the left-hand side of compensator

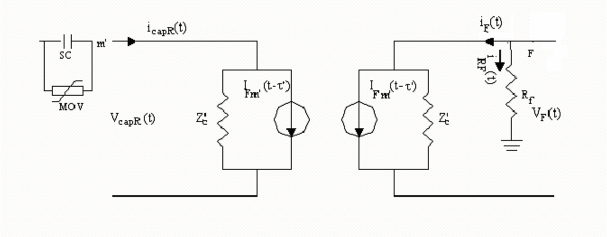

Fig. 3b. Distributed time domain model from right-hand side of compensator to the fault location

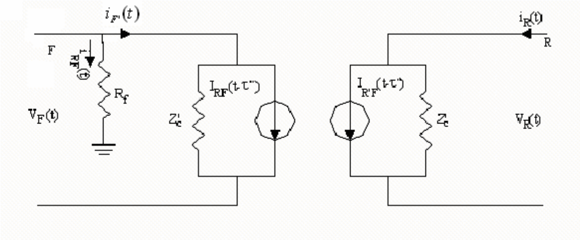

Fig. 3c. Distributed time domain model from fault location to receiving end

The proposed fault location method is a recursive algorithm, which described as follows:

At first using the partial differential equations of the long transmission line and the fault data at the sending end as boundary conditions, the post fault voltages and currents along the line from sending end to the left-hand side of compensator are obtained (i.e. we have $V_m(t),\ i_m(t)$).

Since the voltage of right-hand side of compensator ($V_{capR}(t)$) is unknown, for the first iteration we ignore the difference between voltage of left- and right-hand side of compensator and the current come into the compensator is assumed to be equal to the current come out from compensator, therefore we have:

$$V_{capR}(t) = V_m(t) \quad i_{capR}(t) = -i_m(t) \tag{8}$$

Now these values (i.e. voltage and current of right-hand side of compensator) along with the data of the receiving end of the line ($V_R, i_R$), are applied to solve the optimization problem described in (7). After determining the fault point, the fault resistance will be calculated [15]. Until now we obtained feasible initial values and in the next iterations we will try to correct them. Upon determine the fault position, applying the partial differential equations of the line and the fault data at the receiving end as boundary conditions, the post fault voltage and current of the fault point ($V_F$ , $i_{F'}$) are calculated.

Having $V_F$ and $R_f$, the fault current ($i_{RF}$) is calculated. The current of the receiving end of the line (2) can be obtained using equation (9):

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

Again using the partial differential equations of the line and the data calculated at the receiving end of line (2) as boundary conditions, the voltage and current of the right-hand side of compensator are determined. The calculated voltage in this step is replaced with the estimated right-hand side of compensator and above procedure is repeated until location of fault accurately determined. Utilizing the proposed method in the different conditions shows a few iterations is needed to obtain the correct location of fault.

In the next section, the proposed algorithm is evaluated under different conditions.

## 3 Performance Evaluation

The proposed method has been tested for a 400kV, 300km, three phase compensated transmission line. The compensator is installed in the middle of line. A three phase short circuit occurs at 94km in front of compensator. The voltage and current at sending and receiving terminals are shown in Figs. 4-7 for two cycles, one cycle before and one cycle after the fault.

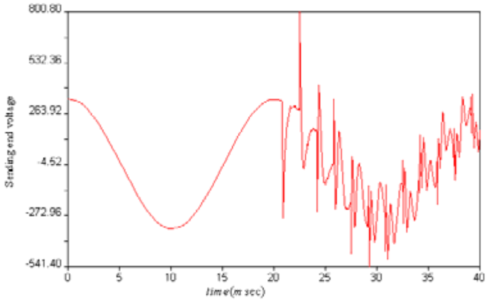

Fig. 4. Sending end voltage for three phase short circuit at 94 km in front of the compensator

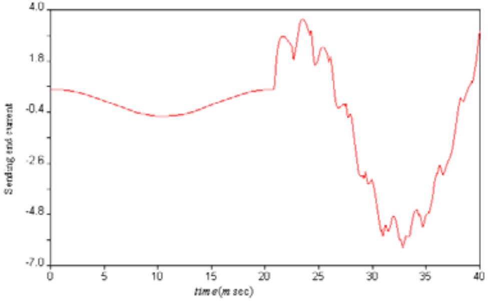

Fig. 5. Sending end current for three phase short circuit at 94 km in front of the compensator

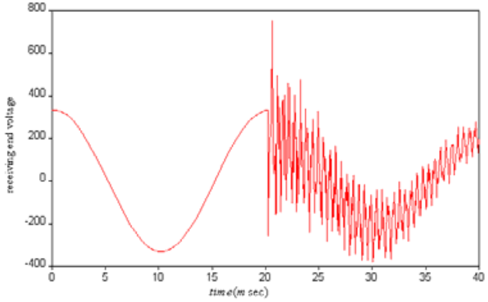

Fig. 6. Receiving end voltage for three phase short circuit at 94 km in front of the compensator

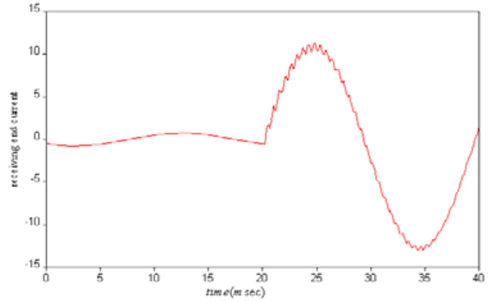

Fig. 7. Receiving end current for three phase short circuit at 94 km in front of the compensator

The fault inception angle has been assumed to be zero degree and fault resistance is assumed 3Ω. According to the previous section, with solving the optimization problem, the fault location and fault resistance are obtained accurately.
Fault distance is: 94.0649
Fault resistance is: 3.012
The location error is: 0.0216%
The fault resistance error is: 0.004
As another example, we consider a single line to ground at 94km after compensator. The fault inception angle and fault resistance are the same as the previous case (Figs. 8-11).
In this case the fault location and fault resistance are obtained accurately too:
Fault distance is: 94.1729
Fault resistance is: 3.0883
The location error is: 0.0576%
The fault resistance error is: 0.0294

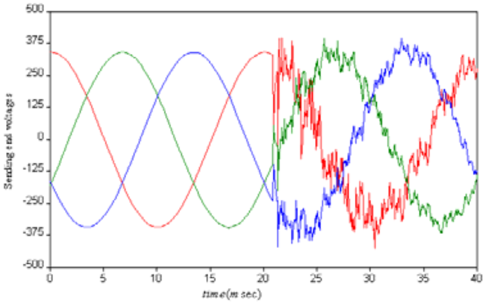

Fig. 8. Sending end voltages for single phase short circuit at 94 km in front of the compensator

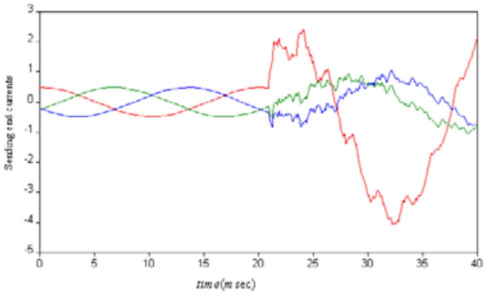

Fig. 9. Sending end currents for single phase short circuit at 94 km in front of the compensator

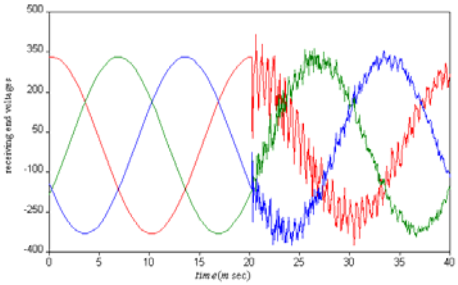

Fig. 10. Receiving end voltages for single phase short circuit at 94 km in front of the compensator

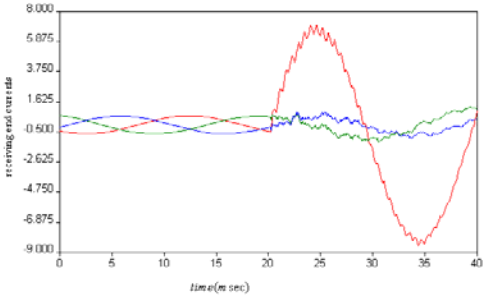

Fig. 11. Receiving end currents for single phase short circuit at 94 km in front of the compensator

The proposed algorithm has been tested for a wide variety of simulated fault conditions. Some of results are summarized in Tables I and II. In Table I the results of fault location when faults occur in front of compensator device and fault inception angle is zero, are shown whereas in Table II the same results for 90 degree fault inception angle are presented.

According to the presented results in the below tables, it can be seen that the proposed algorithm for symmetrical and unsymmetrical faults is independent of fault inception angle and fault resistance. The fault location algorithm estimates the location of fault and fault resistance accurately in almost all the cases and the error is kept below 0.5%.

Table 1: Estimation of Fault Location in Front of Compensator Device, Zero Degree Fault Inception Angle and Different Fault Resistances

| Actual Fault Location<br>Error percentage | 6 km | 62 km | 105 km | 130 km | 144 km |
|---|---|---|---|---|---|
| Three phase fault ($R_f = 0$) | -0.0403 | -0.09 | 0.2743 | -0.2203 | 0.012 |
| Single phase fault ($R_f = 0$) | -0.1535 | -0.3549 | 0.084 | 0.0601 | 0.010 |
| Three phase fault ($R_f = 3$) | -0.0403 | -0.09 | 0.2743 | -0.2203 | 0.012 |
| Single phase fault ($R_f = 3$) | -0.1535 | -0.3549 | 0.084 | 0.0601 | 0.010 |
| Three phase fault ($R_f = 10$) | -0.0403 | -0.09 | 0.2743 | -0.2203 | 0.012 |
| Single phase fault ($R_f = 10$) | -0.1535 | -0.3549 | 0.084 | 0.0601 | 0.010 |

Table 2: Estimation of Fault Location in Front of Compensator Device, 90 Degree Fault Inception Angle and Different Fault Resistances

| Actual Fault Location / Error percentage | 6 km | 62 km | 94 km | 130 km | 144 km |
|---|---|---|---|---|---|
| Three phase fault ($R_f = 0$) | -0.0403 | -0.09 | 0.0216 | -0.220 | 0.012 |
| Single phase fault ($R_f = 0$) | -0.1535 | -0.3549 | 0.0576 | 0.060 | 0.010 |
| Three phase fault ($R_f = 3$) | -0.0403 | -0.09 | 0.0216 | -0.220 | 0.012 |
| Single phase fault ($R_f = 3$) | -0.1535 | -0.3549 | 0.0576 | 0.060 | 0.010 |
| Three phase fault ($R_f = 10$) | -0.0403 | -0.09 | 0.0216 | -0.220 | 0.012 |
| Single phase fault ($R_f = 10$) | -0.1535 | -0.3549 | 0.0576 | -0.863 | 0.010 |

## 4 Conclusion

In this paper a new and accurate fault location algorithm is proposed for compensated transmission line. The proposed fault location algorithm calculates the exact location of fault using distributed time domain model of transmission line. The suggested algorithm does not utilize the compensator device model and knowledge of the operation mode of compensator device to compute the voltage drop during fault. The presented results show that the proposed algorithm is located fault accurately for wide variety of simulated fault conditions such as symmetrical and unsymmetrical faults, different fault inception angles and different fault resistances.

The results are very good in almost all the cases and the error is kept below 0.5%

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