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Accurate fault location algorithm for transmission line in the presence of series connected FACTS devices

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ABSTRACT

This paper presents a new and accurate fault location algorithm based on distributed time domain line model for a transmission line compensated with series connected FACTS device. In the proposed algorithm, in order to compute the voltage drop across the series device during the fault period, the series device model and knowledge about the operating mode of the compensating device are not utilized. For this reason, the proposed technique can be easily applied to any series FACTS compensated line. Samples of voltage and current at both ends of the line are taken synchronously and used to calculate the location and resistance of the fault. The proposed algorithm is not sensitive to fault resistance and fault inception angle and does not require any knowledge of equivalent source impedances. This method has been tested using EMTP/ATP model of a 400 kV, 300 km transmission line compensated with a series FACTS device. The results of computer simulations for different operating conditions demonstrate the very high accuracy and robustness of the algorithm.

1. Introduction

A transmission line is an essential component of the electric power system and its protection is necessary for ensuring system stability and minimizing damage to equipments due to short circuits that might happen on the transmission lines. Transmission line protection consists of three main tasks, namely detection, classification and location of the faults. Fast detection of a transmission line fault enables quick isolation of the faulty line from service and hence, protecting it from the harmful effects of the fault. Classification of faults means identification of the type of fault, and this information is required for fault location. Accurate fault location is necessary for facilitating quick repair and restoration of the faulty line, to improve reliability and availability of the power supply.

Several fault location algorithms have been proposed and applied for determining the location of fault on transmission lines. Some of them are based on using current and voltage phasors [1–7]. These algorithms use current and voltage phasors need to calculate the fundamental component of voltage and current in one end or two ends of the line. In these algorithms, the lumped or distributed frequency domain line model are used. The fault location algorithms which used lumped model have a good accuracy in short transmission line, but when used in long transmission line, it suffers a significant error. Therefore in order to take into account the capacitive effect which was ignored in series lumped model, some papers have been used π model of the transmission line [1,3]. Using more accurate model for transmission line will result in more accurate results. Therefore in some researches distributed model of transmission line have been used [6,7].

Over the last decade FACTS devices have become popular and are turning into a very effective solution for many power system transmission problems. FACTS devices can be broadly classified into three types: (a) shunt (b) series and (c) composite series and shunt. FACTS devices are being presently employed for various applications such as [8,9]:

- 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.

There have been few reports studying the effect of series FACTS devices on the performance of fault location algorithms [10–15]. Almost all of them use the model of compensating device to find the location of fault but using this approach, errors are induced by the inaccuracy of compensating device model or the uncertainty in operating mode of compensator device [10–14]. The main objective of the work presented in [14] is to develop a method based on the Artificial Neural Network (ANN) and a deterministic approach for estimating the voltage across the non-linear series capacitor

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(capacitor and MOV) using the locally available line current. It is assumed that the compensating device model and its operating mode are known. The presented method in [14] is restricted to fixed series capacitor compensation and can not use for other series connected FACTS devices, such as thyristor controlled series capacitor (TCSC). The algorithm proposed in [15] uses current and voltage phasors and does not need to model the compensating device but needs to filter the DC component and harmonics that are presented in these waveforms. Generally, DC and other frequency components create some problems in filtering process. An alternative solution for this problem is to use the partial differential equation of transmission line model in which there is no need to filter these components [12,16–19]. In these methods, the lumped and/or distributed time domain model of transmission line can be used. To achieve high accuracy in fault location for long transmission lines, applying the distributed time domain model of the transmission line has been recommended [16–19].

This paper introduces a new and accurate fault location algorithm in a compensated transmission line by a series connected FACTS device. The proposed algorithm does not use the model of the compensator device and there is no need for any knowledge of the operating mode of the compensator. Moreover, this algorithm does not need to filter the DC and other frequency components that are presented in the voltage and current signals. The suggested technique takes advantage of the post-fault voltage and current samples taken synchronously from both ends of the line. In addition, the presented algorithm is independent of location and parameters of compensator device. In order to evaluate the accuracy of the proposed algorithm, it has been tested for a wide variety of simulated fault conditions such as different fault locations, different fault inception angles, different fault resistances and different fault types. 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 modeling and two-end fault location method

A single-phase model of a three-phase transmission line with distributed parameters is shown in Fig. 1. 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 ($x \leqslant L_{line}$) from S along the line occurs. The distributed model of the SF segment is shown in Fig. 2 [16]:

The voltage and current at fault location can be computed as functions of sending end voltage and current as follows [12]:

$$V_x(t) = \Big(Z_c'^2[V_s(t+\tau) - Z_c' i_s(t+\tau)] + Z_c''^2[V_s(t-\tau) + Z_c'' i_s(t-\tau)] - \frac{Z_c' R'}{4}\left[\frac{R'/2}{Z_c'}V_s(t) + 2Z_c'' i_s(t)\right]\Big)\Big/2Z_c^2 \quad (1)$$

$$i_{xs}(t) = \Big(Z_c'[V_s(t+\tau) - Z_c' i_s(t+\tau)] - Z_c''[V_s(t-\tau) + Z_c'' i_s(t-\tau)] - \frac{R'}{4}[2V_s(t) - \frac{R'}{2} i_s(t)]\Big)\Big/2Z_c^2 \quad (2)$$

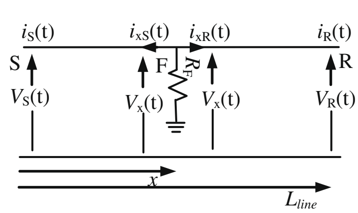

Fig. 1. Transmission line with distributed parameters.

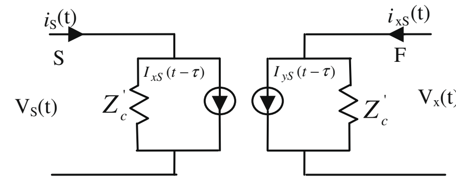

Fig. 2. Distributed model of the SF segment.

where:

τ = time elapsed for the wave propagating from S to F,
Z_c = line surge impedance,
R' = line resistance from S to F, and
$Z_c' = Z_c + R'/4 \quad Z_c'' = Z_c - R'/4$.

Similarly, the fault point voltage and current are calculated as functions of receiving end voltage and current and are represented as follow [12,16]:

$$V_x(t) = \Big(Z_{rc}'^2[V_R(t+T-\tau) - Z_{rc}' i_R(t+T-\tau)] + Z_{rc}''^2[V_R(t-T+\tau) + Z_{rc}'' i_R(t-T+\tau)] - \frac{Z_{rc}' R_r'}{4}\left[\frac{R_r'/2}{Z_{rc}'}V_R(t) + 2Z_{rc}'' i_R(t)\right]\Big)\Big/2Z_c^2 \quad (3)$$

$$i_{xR}(t) = \Big(Z_{rc}'[V_R(t+T-\tau) - Z_{rc}' i_R(t+T-\tau)] - Z_{rc}''[V_R(t-T+\tau) + Z_{rc}'' i_R(t-T+\tau)] - \frac{R_r'}{4}\left[2V_R(t) - \frac{R_r'}{2} i_R(t)\right]\Big)\Big/2Z_c^2 \quad (4)$$

where:

T = time elapsed for the wave propagating from S to R,
R_r' = line resistance from R to F, and
$Z_{rc}' = Z_c + R_r'/4 \quad Z_{rc}'' = Z_c - R_r'/4$.

Because of the continuity of the voltage along the transmission line, Eqs. (1) and (3) can be combined; resulting in:

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

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

$$F = \Big(Z_c'^2[V_s(t+\tau) - Z_c' i_s(t+\tau)] + Z_c''^2[V_s(t-\tau) + Z_c'' i_s(t-\tau)] - \frac{Z_c' R'}{4}\left[\frac{R'/2}{Z_c'}V_s(t) + 2Z_c'' i_s(t)\right] - \Big(Z_{rc}'^2[V_R(t+T-\tau) - Z_{rc}' i_R(t+T-\tau)] + Z_{rc}''^2[V_R(t-T+\tau) + Z_{rc}'' i_R(t-T+\tau)] - \frac{Z_{rc}' R_r'}{4}\left[\frac{R_r'/2}{Z_{rc}'}V_R(t) + 2Z_{rc}'' i_R(t)\right]\Big)\Big)\Big/2Z_c^2. \quad (6)$$

The distance to the fault location does not appear explicitly in Eq. (5), and is hidden in the surge traveling time τ. Furthermore, τ does not appear as a variable in Eq. (5), but as the value on which the voltage and current depend. To find the location of fault first the equation is discretized and then the following optimization problem is solved:

$$\operatorname*{Min}_m J(m) = \operatorname*{Min}_m \sum_k F^2(V_S, i_S, V_R, i_R, k, m) \quad (7)$$

where:

$k\ \Delta t = t$,
$m\ \Delta t = \tau$,
Δt = sampling step, and
k, m = arbitrary integers.

2.2. Proposed fault location algorithm for series FACTS compensated transmission line

2.2.1. Symmetrical fault case

Without loss of generality, we assume that the compensator device is installed in the midpoint of the transmission line (Fig. 3). The type of compensator is not important in the presented algorithm. The compensator divides the line into two parts, i.e. part one from sending end (S-bus) to left-hand side of compensator (LH-Bus) and second part from right-hand side of compensator (RH-bus) to the receiving end (R-bus) of transmission line. In the following discussion it is assumed that the fault locator is installed at 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 follow (Fig. 4a and c):

(1) distributed time domain line model from the sending bus (S) to the left-hand side of compensator (LH);
(2) distributed time domain line model from the right-hand side of the compensator (RH) to fault position (F); and
(3) distributed time domain line model from the fault point (F) to receiving bus (R).

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

At first using the partial differential equations of the long transmission line, and the recorded 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 the compensator are obtained (i.e. $V_{LH}(t)$ and $i_{LH}(t)$ are calculated). Since the series FACTS compensation device does not influence the current flowing through it, the current flow into the left-hand side of the series FACTS device will be equal to the current flowing out from the right-hand side of it, that is, $i_{RH}(t) = -i_{LH}(t)$. But because the voltage of the right-hand side of compensator (V_{RH}) is unknown (that is, the voltage drop of the series compensated FACTS device is unknown), just for the first iteration we ignore the difference between the voltages of the left- and right-hand side of the compensator to obtain a feasible initial value of fault location.

Now the calculated data (i.e. voltage and current at the right-hand side of the compensator $V_{RH}(t), i_{RH}(t)$) along with the data of the receiving end of the line ($V_R(t), i_R$), are used to solve the optimization problem described in Eq. (7), replacing (V_S, i_S) with (V_{RH}, i_{RH}). After locating (determining) the fault point, the fault resistance will be calculated using least square estimation method, as explained in [12]. Up to this point, a feasible set of initial values are obtained and in the next iterations we will try to correct them.

Upon determine the fault position, applying the partial differential equation model of the line and the fault data at the receiving end as boundary conditions, the post-fault voltage and current of the fault point ($V_F(t), i_{F'}$) are calculated. Having $V_F(t)$ and R_F, the fault current (i_{RF}) can be calculated. Application of KCL at the fault point (F) we have:

$$i_F(t) = -(i_{F'}(t) + i_{RF}(t)). \tag{8}$$

Again using the partial differential equation model of the line and the data calculated at the fault point as boundary conditions, the voltage and current of the right-hand side of the compensator are determined. The estimated right-hand side of the compensator in the previous iteration is replaced with the calculated voltage in the new iteration. The above procedure is repeated until location of the fault is determined accurately. Utilizing the proposed method in the different conditions shows a few iterations is needed to obtain the exact location of the fault. The different steps of the proposed method are shown (summarized) in the flowchart in Fig. 5.

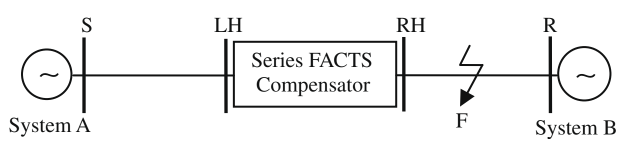

Fig. 3. One-line diagram of a series FACTS compensated transmission line.

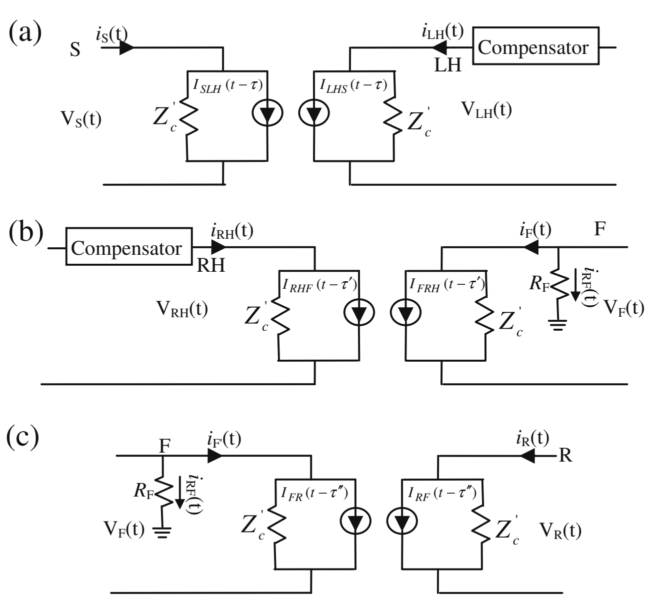

Fig. 4. Distributed time domain line model: (a) from sending end (S) to the left-hand side of compensator (LH), (b) from right-hand side of compensator (RH) to the fault point (F), and (c) from fault point (F) to receiving end (R).

2.2.2. Unsymmetrical fault case

In the previous section, the proposed algorithm was explained for symmetrical faults but it can be extended to find the position of unsymmetrical faults by using the concept of modal transformation. In the next part of this section, the suggested algorithm is explained.

2.3. Mathematical model and method of solution

The 3-phase transmission line model is characterised by the following set of hyperbolic partial differential equations [14]:

$$\begin{cases} \frac{\partial \mathbf{V}}{\partial x} + \mathbf{L}\frac{\partial \mathbf{I}}{\partial t} = -\mathbf{RI} \\ \mathbf{C}\frac{\partial \mathbf{V}}{\partial t} + \frac{\partial \mathbf{I}}{\partial x} = \mathbf{0} \end{cases} \tag{9}$$

where $\mathbf{R}$, $\mathbf{L}$ and $\mathbf{C}$ are 3×3 resistance, inductance and capacitance (in per unit length of the line) matrices, respectively; $\mathbf{V}$ and $\mathbf{I}$ are third-order column vectors representing voltages and currents. Eq. (9) 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 [14].

2.4. Phase to modal transformation

Transformation matrices $\mathbf{M_1}$ and $\mathbf{M_2}$ are determined from a solution of the eigenvalue problem on the matrix product $\mathbf{LC}$. $\mathbf{M_1}$ is a matrix whose elements are the eigenvectors of $\mathbf{LC}$, and $\mathbf{M_2}$ is

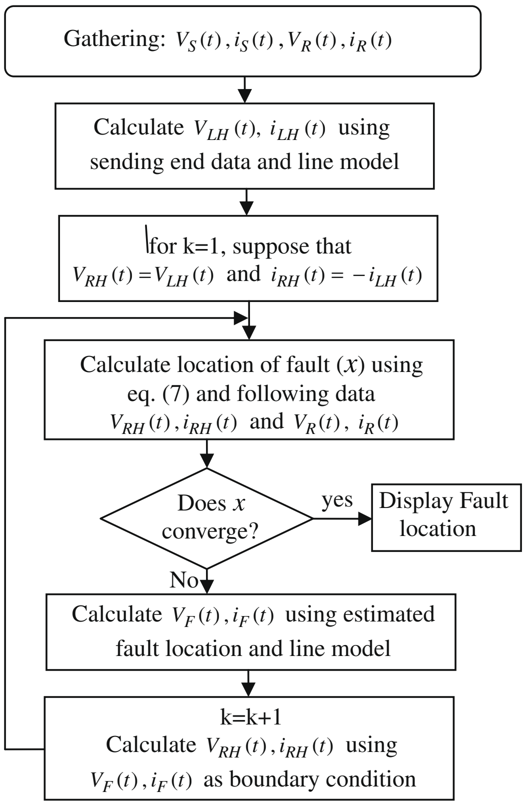

Fig. 5. Flowchart of the proposed fault location method.

the inverse of the transpose of $\mathbf{M_1}$ ($\mathbf{M}_2 = (\mathbf{M}_1^t)^{-1}$). $\mathbf{M_1}$ and $\mathbf{M_2}$ are employed to transform the variable in (9) from phase to modal domain as follow:

$$\begin{aligned}
\mathbf{V}^{(m)} &= \mathbf{M}_1^{-1}\mathbf{V} \\
\mathbf{I}^{(m)} &= \mathbf{M}_2^{-1}\mathbf{I} \\
\mathbf{R}^{(m)} &= \mathbf{M}_1^{-1}\mathbf{R}\mathbf{M}_2 \\
\mathbf{L}^{(m)} &= \mathbf{M}_1^{-1}\mathbf{L}\mathbf{M}_2 \\
\mathbf{C}^{(m)} &= \mathbf{M}_2^{-1}\mathbf{C}\mathbf{M}_1
\end{aligned} \tag{10}$$

In the above equations exponent (m) represents the modal component. Replacing **R**, **L**, **C**, **V** and **I** of (9) with their modal equivalents defined in (10) we obtain:

$$\begin{aligned}
&\frac{\partial}{\partial x}\begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} l_0 & 0 & 0 \\ 0 & l_1 & 0 \\ 0 & 0 & l_2 \end{bmatrix} \frac{\partial}{\partial t}\begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} = -\begin{bmatrix} r_0 & 0 & 0 \\ 0 & r_1 & 0 \\ 0 & 0 & r_2 \end{bmatrix} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} \\
&\times \begin{bmatrix} c_0 & 0 & 0 \\ 0 & c_1 & 0 \\ 0 & 0 & c_2 \end{bmatrix} \frac{\partial}{\partial t}\begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} + \frac{\partial}{\partial x}\begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} = \mathbf{0}
\end{aligned} \tag{11}$$

On expansion, (11) will yield three pairs of independent equations of the form:

$$\begin{cases} \frac{\partial v_k}{\partial x} + l_k \frac{\partial i_k}{\partial t} = -r_k i_k \\ c_k \frac{\partial v_k}{\partial t} + \frac{\partial i_k}{\partial x} = 0 \end{cases} \tag{12}$$

where $k = 0, 1, 2$ represent the modal quantities.

Eq. (12) refers to a single mode and in all respects is similar to the single-phase transmission line model. This equation is solved

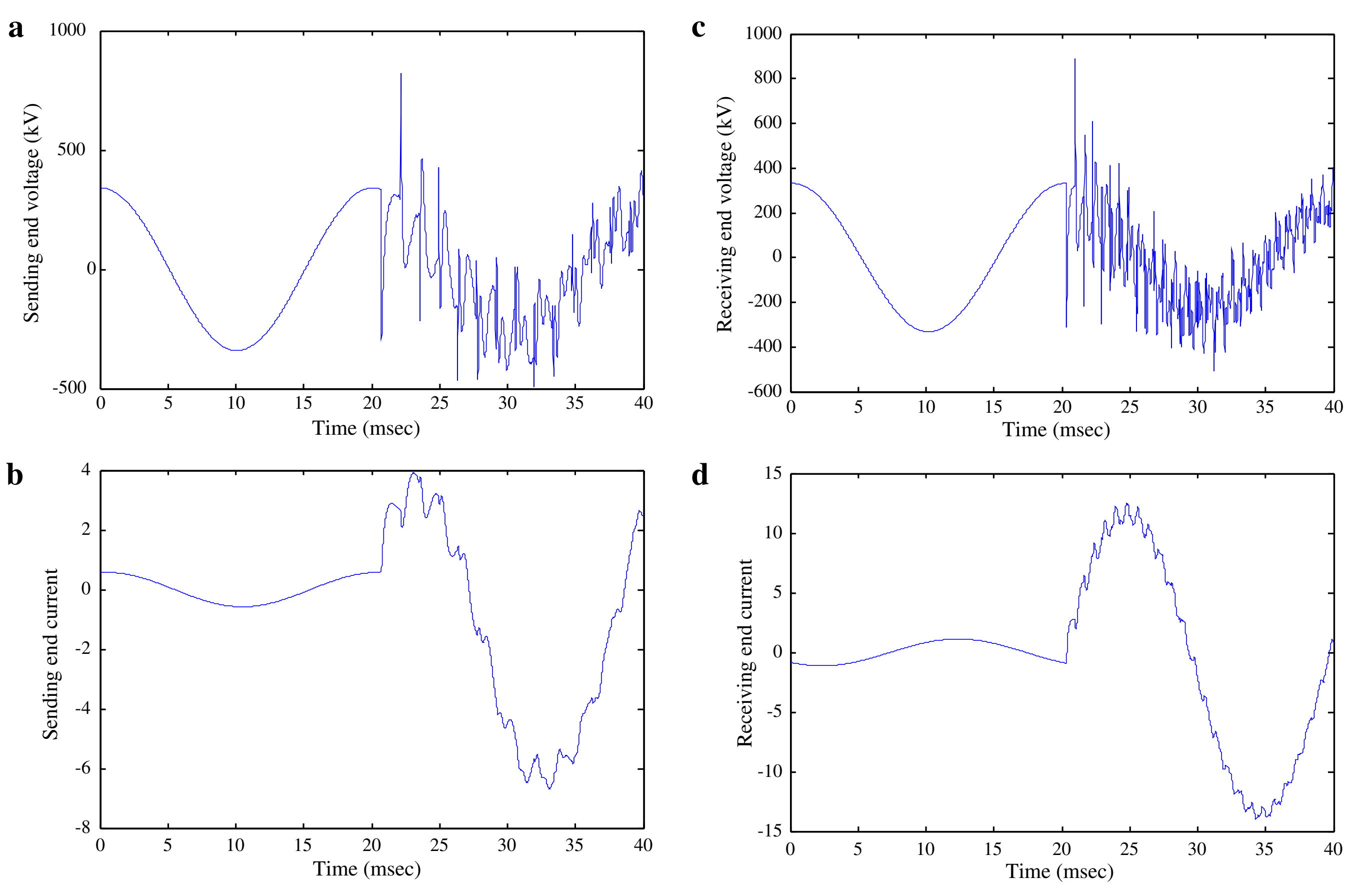

Fig. 6. Simulation results for a three-phase short circuit at 94 km in front of the compensator: (a) sending end voltage a-phase, (b) sending end current a-phase, (c) receiving end voltage a-phase, and (d) receiving end current a-phase.

by the characteristic method that is described in [14]. When the three pairs of equations are solved, phase voltages and currents are obtained by modal to phase transformation as given by:

$$\begin{aligned} \mathbf{V} &= \mathbf{M}_1\mathbf{V}^{(m)} \\ \mathbf{I} &= \mathbf{M}_2\mathbf{I}^{(m)}. \end{aligned} \tag{13}$$

Having the current and voltage, we can solve an optimization problem as illustrated in (7) to find the position of fault.

3. Performance evaluation

The proposed method was tested by simulating a 400 kV, 300 km, three-phase compensated transmission line as shown in Fig. 3. The compensator is installed in the middle of the line. All the systems are modeled by ATP software. The transmission line is simulated using the distributed parameter model. The simulation studies are performed at a sampling rate of 40 kHz. The algorithm is tested for various conditions, such as different fault types and locations, different fault inception angles, and different fault resistances. For instance suppose that a three-phase short circuit occurs at 94 km in front of compensator. The voltage and current at sending and receiving ends are shown in Fig. 6 for two cycles (40 ms), one cycle before the fault occurs and one cycle after.

The fault inception angle has been assumed to be 90° and fault resistance is assumed to be 3 Ω. By using the presented algorithm in section *II-B.1*, the fault location and fault resistance are obtained as follow:

calculated fault distance: 94.0649;
calculated fault resistance: 3.012;
the location error: 0.0216%; and
the fault resistance error: 0.012.

As another example, a single line to ground fault at the same location as previous example was considered. Simulated results for this condition are shown in Fig. 7. The fault inception angle and fault resistance are the same as those in the previous case.

In this case, the fault location and fault resistance are calculated accurately too as follows:

calculated fault distance: 94.1729;
calculated fault resistance: 3.0883;
the location error: 0.0576%; and
the fault resistance error: 0.0883.

The proposed algorithm has been tested for a wide variety of simulated fault conditions. Some of the results are summarized in Tables 1 and 2. In Table 1, the results of fault location when faults occur in front of compensator device and zero fault inception angle, are shown whereas in Table 2 the same results for 90° fault inception angle are presented.

According to the results presented in these tables, it is 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 and resistance of fault accurately in almost all the cases so that the error is kept below 0.5%. The obtained results for the same fault conditions are

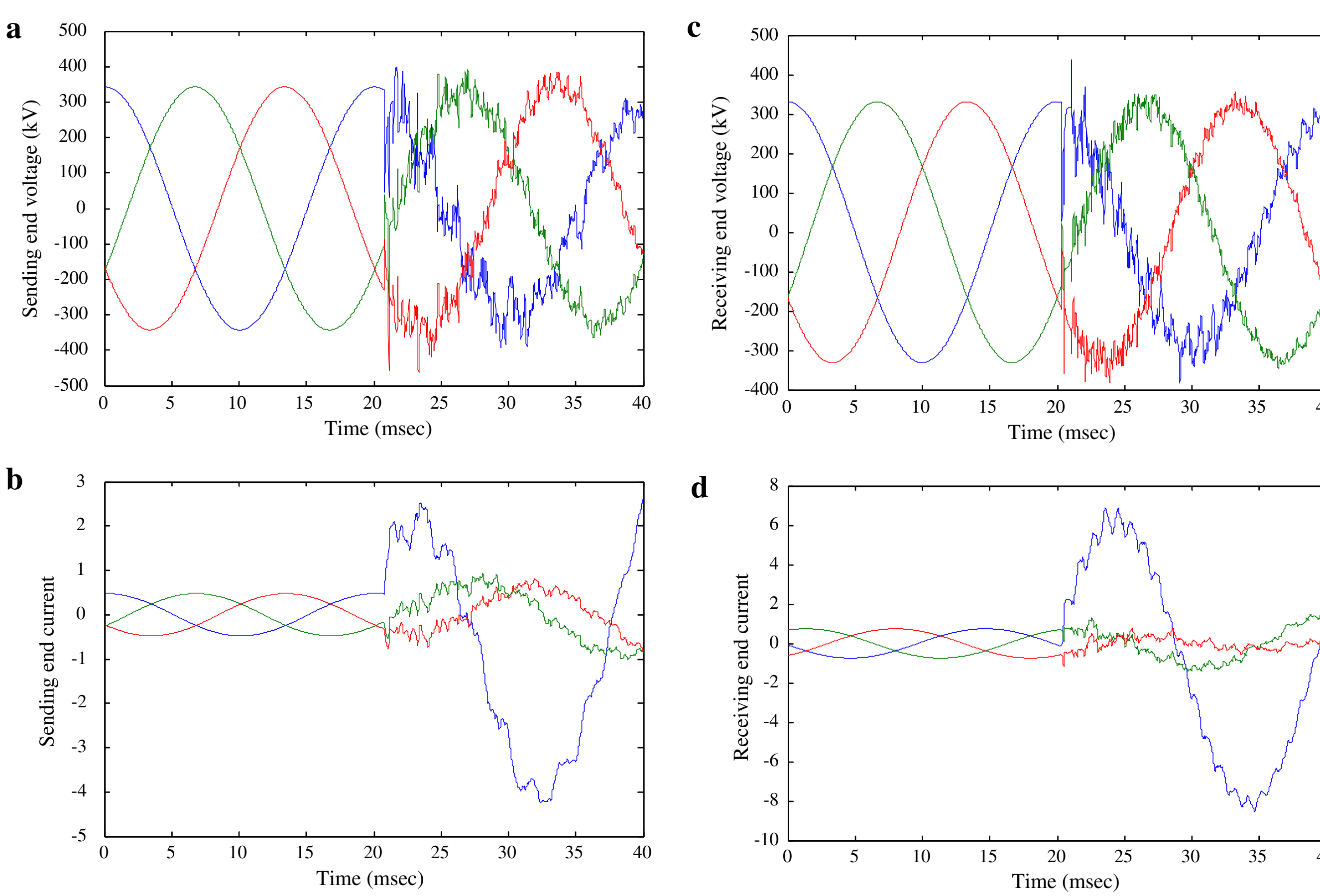

Fig. 7. Simulation results for a single-phase short circuit at 94 km in front of the compensator: (a) sending end voltages, (b) sending end currents, (c) receiving end voltages, and (d) receiving end currents.

Table 1
Fault location error percentage for faults in front of compensator device, 0° fault inception angle and different fault resistances.

Error percentage	Actual fault location								
	6 km	20 km	58 km	62 km	94 km	105 km	130 km	140 km	144 km
Three-phase fault (R_f = 0)	−0.0403	0.1922	0.2635	−0.09	0.0216	0.2743	−0.2203	0.3658	0.0123
Single-phase fault (R_f = 0)	−0.1535	−0.2038	0.0552	−0.3549	0.0576	0.084	0.0601	0.4198	0.0097
Three-phase fault (R_f = 3)	−0.0403	0.1922	0.2635	−0.09	0.0216	0.2743	−0.2203	0.3658	0.0123
Single-phase fault (R_f = 3)	−0.1535	−0.2038	0.0552	−0.3549	0.0576	0.084	0.0601	0.4198	0.0097
Three-phase fault (R_f = 10)	−0.0403	0.1922	0.2635	−0.09	0.0216	0.2743	−0.2203	0.3658	0.0123
Single-phase fault (R_f = 10)	−0.1535	−0.2038	0.0552	−0.3549	0.0576	0.084	0.0601	0.4198	0.0097

Table 2
Fault location error percentage for faults in front of compensator device, 90° fault inception angle and different fault resistances.

Error percentage	Actual fault location								
	6 km	20 km	58 km	62 km	94 km	105 km	130 km	140 km	144 km
Three-phase fault (R_f = 0)	−0.0403	0.1922	0.2635	−0.09	0.0216	0.2743	−0.2203	0.3658	0.0123
Single-phase fault (R_f = 0)	−0.1535	−0.2038	0.0552	−0.3549	0.0576	0.084	0.0601	0.4198	0.0097
Three-phase fault (R_f = 3)	−0.0403	0.1922	0.2635	−0.09	0.0216	0.2743	−0.2203	0.3658	0.0123
Single-phase fault (R_f = 3)	−0.1535	−0.2038	0.0552	−0.3549	0.0576	0.084	0.0601	0.4198	0.0097
Three-phase fault (R_f = 10)	−0.0403	0.1922	0.2635	−0.09	0.0216	0.2743	−0.2203	0.3658	0.0123
Single-phase fault (R_f = 10)	−0.1535	−0.2038	0.0552	−0.3549	0.0576	0.084	0.0601	0.4198	0.0097

better than those as published in [14], where the error is reported greater than 1% using ANN.

4. Conclusion

In this paper, a new and accurate fault location algorithm is proposed for the series FACTS compensated transmission line. The proposed algorithm calculates the exact location of fault using distributed time domain model of the transmission line. Since the algorithm is executed in the time domain, filtering of DC and other frequency components that are presented in the voltage and current signals do not need. Moreover, the suggested algorithm does not utilize the compensator device model and the knowledge of the compensator device operating mode to compute the voltage drop during fault. This is the salient advantage of the proposed method. The presented results show that the proposed algorithm finds the fault location accurately for a wide variety of simulated fault conditions such as symmetrical and unsymmetrical faults, different fault locations, different fault inception angles and different fault resistances. The accuracy of proposed method is very high in almost all the cases and the error is kept below 0.5%.

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