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ORIGINAL PAPER

A new fault-location method for HVDC transmission-line based on DC components of voltage and current under line parameter uncertainty

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Abstract In this paper, a new time-domain-based method is proposed for fault location in HVDC transmission lines. In the proposed method, an equation is derived for locating the fault for different transmission-line models (lumped-line model, π-line model, and distributed-line model). Then, a method is suggested to precisely determine the transmission-line resistance using DC component of voltage and current at the both terminals (pre-fault). The performance of the proposed method is evaluated based on a test system by the PSCAD/EMTDC and MATLAB software. The performance and precision of the proposed methods are evaluated for short-circuit fault in different conditions, such as different fault resistances, difference fault distances, different minimum injected current of the inverter during the fault, and different pre-fault conditions. The simulation results confirm that the proposed method is much more accurate in locating faults compared to other counterparts.

Keywords HVDC transmission lines · Fault location · Voltage and current harmonic components · Direct current

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Nomenclature

x	Fault distance (distance between the fault location and the rectifier terminal)
R	Defined as the resistance per unit of the line length
L	Defined as the inductance per unit of the line length
C	Capacitance of the line in per unit
$U_f^{rec}(t)$	Voltage of the fault location based on the rectifier data
$i_{rec}(t)$	The recorded current at the rectifier terminal
$U_{rec}(t)$	The recorded voltages at the rectifier terminal
l	Total transmission-line length
$u_{inv}(t)$	The recorded voltage at the inverter terminal
u_f^{inv}(t)	Voltage of the fault point based on the inverter data
$i_{inv}(t)$	The recorded current at the inverter terminal
u_{rec} (DC)	DC component of the recorded voltage at the rectifier terminal
u_{inv} (DC)	DC component of the recorded voltage at the inverter terminal
i_{rec} (DC)	DC component of the recorded current at the rectifier terminal
i_{inv} (DC)	DC component of current at the inverter terminal
u_F	Fault point voltage
R_F	Fault resistance
I_F	Fault current at the fault point
x_{actual}	The actual and real fault distance
$x_{calculated}$	The calculated fault distance
l_t	Total length of line

FFT	Fast Fourier transform
u_{rec} (DC)	DC component of the voltage at the rectifier terminal

1 Introduction

The AC transmission systems have three wires which cause to increase the nodes. It can cause increase in the inrush current and fault statistics [1–3]. Therefore, the use of HVDC transmission systems is raising as a supplement or even replacement of AC transmission systems recently. Nowadays, many HVDC systems are being used throughout the world, and many others are under construction. These systems transfer a large amount of electrical power over long distances by overhead or cable transmission lines, which are more economical due to the minimum technical problems. In addition, HVDC systems are also used for improving the stability, getting lower loss, and improving the controllability. Regarding vast improvements in manufacturing semiconductor devices with higher power and lower prices in recent years, the HVDC power transmissions have received more attention lately [4–7]. Similar to AC transmission lines, these lines are vulnerable to different faults due to conditions, such as extreme weather conditions, equipment failures, and external object contacts. It is important to locate faults accurately to speed up the service restoration and to improve the reliability consequently. Over the years, several fault-location algorithms have been presented for HVDC transmission lines. These methods can be classified into three main categories: traveling wave methods [8–10], time-domain methods [11], and intelligent methods [12,13]. Each one has some advantage and disadvantage. The traveling wave methods have fast response and high accuracy, but they require high sampling rate and accurate wave head detector. The intelligent methods need data bank. The accuracy of intelligent methods highly depends on the quality of data and information in data bank. The time-domain methods locate the fault distance using the differential equations. The accuracy of these methods depends on the line parameters.

A new fault-location algorithm based on variable speed traveling waves has been presented for HVDC transmission lines in [8]. In [9], an algorithm for locating the HVDC line faults in a system consisting of overhead and HVDC cable has been presented using the measurements obtained at the inverter terminals and rectifiers combination line. In [10], the natural frequency has been used for locating fault in HVDC transmission lines. In this method, pattern recognition is used to find the natural frequency from the voltage signal at single terminal. This method is from the category of traveling wave methods. Despite the advantages of the traveling waves methods, they have few drawbacks: requiring to necessary experience and skills to detect wave head and requiring to high sampling rate. The accuracy of this method is very depended on line parameters.

In [12], the Pearson correlation coefficient is used to locate the faults in HVDC transmission lines. While this method solves some problems of traveling wave methods, its accuracy highly depends on line parameters. Furthermore, the method needs data bank which should be updated with each change.

A fault-location method has been presented for HVDC transmission line using genetic algorithm in [13]. In this method, the line parameters and fault distance are used as variables for GA coding. The drawback of this method is its inaccuracy and also its dependency to the GA options.

A differential equation in the time domain is used for locating fault in HVDC transmission lines in [11]. This method uses π-line model and is accurate. The drawback of this method is its dependency to the line parameters. Furthermore, its accuracy highly depends on used voltage and current data (in specific time intervals).

These methods have recently been studied to locate faults in HVDC transmission lines. The disadvantages of these methods are the need for data bank, the dependence to the line parameters, and the complexity of the relationships [14].

In this paper, a new method is proposed for locating fault in HVDC transmission line which is based on a new time-domain method. This method simplify the fault-location equations in three line model (lumped-line model, π-line model, and distributed-line model) and extracting the one simple equation for lumped, π-line model and distributed-line model. This simple equation is depended on DC component of recorded post fault voltage and current at both terminals and resistance of line model. Then, according to line parameters changes in its life duration and different operation conditions, the resistance of line model is determined using DC component of pre-fault voltage and current at both terminals. The results of fault location are obtained in a test system by the PSCAD/EMTDC and MATLAB software. The performance precision of the proposed methods is evaluated for short-circuit fault in difference conditions, such as different fault resistances, different fault distances, different minimum injected currents of the inverter during the fault, and different pre-fault conditions. The simulation results verified that the proposed method is highly accurate in locating faults.

This paper is organized in three parts. In Sect. 2, the description of the proposed method is explained for locating fault in HVDC transmission line. Then, the simulation results are presented and described for evaluating the accuracy of the proposed method. Finally, Sect. 4 concludes the paper.

2 Description of the proposed method

In this part, three line models are described for fault location in HVDC transmission lines using direct current and voltage harmonic components. The lumped model of the transmission line is used in the first step. In this method, it is assumed that the parameters of the transmission lines are given; this parameters are used in the fault-location procedure. Because the HVDC transmission lines are used in long distances, the π-line model and distributed-line model of transmission lines in time domain are used to locate the fault distance accurately. In this method, fault-location process is performed using transmission-line parameters and simultaneous data of two terminals. This method considers the fault distance as an unknown variable which will be calculated. The used data of this method are the simultaneous samples of voltage and current in both the sides of the transmission line after fault occurrence.

2.1 Fault locating based on the lumped-line model

Consider Fig. 1 that shows the compact model of a lumped transmission line. Assume that a fault is occurred in point F (fault location) in distance of x from rectifier terminal.

If it is assumed that the transmission-line parameters and the distance between the fault location and rectifier terminal are given, the voltage of the fault location could be calculated based on the rectifier terminal data:

$$u_{\text{rec}}(t) = Rxi_{\text{rec}}(t) + Lx\frac{\mathrm{d}i_{\text{rec}}(t)}{\mathrm{d}t} + u_{\text{F}}(t) \tag{1}$$

$$u_{\text{F}}^{\text{rec}}(t) = u_{\text{rec}}(t) - \left(Rxi_{\text{rec}}(t) + Lx\frac{\mathrm{d}i_{\text{rec}}(t)}{\mathrm{d}t}\right) \tag{2}$$

where x is the distance between the fault location and the rectifier terminal. R and L are defined as the resistance and inductance per unit of the line length, respectively. Moreover $U_{\text{rec}}(t)$ and $U_{\text{f}}^{\text{rec}}(t)$ are the voltages of the rectifier terminal and fault location; $i_{\text{rec}}(t)$ is the current of rectifier terminal.

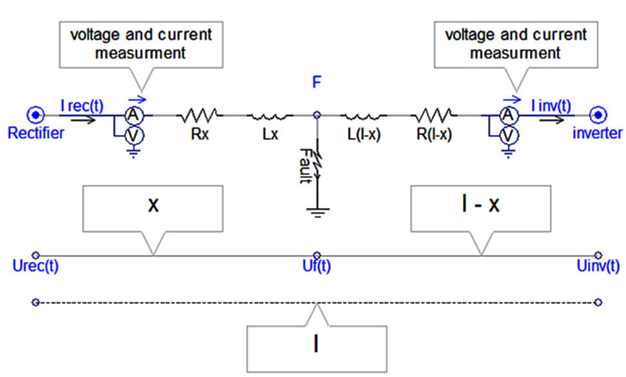

Fig. 1 Fault occurrence in dual terminals line of lumped-line complex model

According to Eq. (1), the distance between the fault location and rectifier terminal is calculated based on the voltage of the fault location:

$$x = \frac{u_{\text{rec}}(t) - R_{\text{F}}(i_{\text{rec}}(t) - i_{\text{inv}}(t))}{Ri_{\text{rec}}(t) + L\frac{\mathrm{d}i_{\text{rec}}(t)}{\mathrm{d}t}} \tag{3}$$

where R_{F} is the fault resistance.

Because Eq. (3) depends on the fault resistance and the fault resistance is unknown during the fault, this equation could not be used for fault-location calculation. Hence, based on the transmission-line parameters and voltage and current of the rectifier and inverter, the fault location could be determined.

Similarly, using the compact model of the line between the point F and inverter terminal, the fault voltage could be calculated by data of the inverter terminal:

$$u_{\text{f}}^{\text{inv}}(t) = R(l-x)\,i_{\text{inv}}(t) + L(l-x)\frac{\mathrm{d}i_{\text{inv}}(t)}{\mathrm{d}t} + u_{\text{inv}}(t) \tag{4}$$

where l is the total transmission-line length; $u_{\text{inv}}(t)$ and $u_{\text{f}}^{\text{inv}}(t)$ are voltages of the inverter and fault location based on the inverter data; $i_{\text{inv}}(t)$ is the current of the inverter terminal. On the other hand, general equation of the rectifier voltage based on the inverter voltage and transmission-line parameters is calculated as:

$$u_{\text{rec}}(t) = Rxi_{\text{rec}}(t) + Lx\frac{\mathrm{d}i_{\text{rec}}(t)}{\mathrm{d}t} + R(l-x)\,i_{\text{inv}}(t) + L(l-x)\frac{\mathrm{d}i_{\text{inv}}(t)}{\mathrm{d}t} + u_{\text{inv}}(t) \tag{5}$$

$$x = \frac{u_{\text{rec}}(t) - u_{\text{inv}}(t) - Rli_{\text{inv}}(t) - Lx\frac{\mathrm{d}i_{\text{inv}}(t)}{\mathrm{d}t}}{R(i_{\text{rec}}(t) - i_{\text{inv}}(t)) + L\left(\frac{\mathrm{d}i_{\text{rec}}(t)}{\mathrm{d}t} - \frac{\mathrm{d}i_{\text{inv}}(t)}{\mathrm{d}t}\right)}. \tag{6}$$

Equation (6) indicates the fault location based on the first order equations of voltage and current. Because the fault-location calculation by differential equations is complicated for the simplicity, it is decided to analyze the DC values of the voltage, current, and their associated parameters; this analyze is simpler and more accurate. Hence, by taking the Fast Fourier transform (FFT) of the voltage and current of rectifier and inverter and calculation of the DC component, we have

$$x = \frac{u_{\text{rec}}(\text{DC}) - u_{\text{inv}}(\text{DC}) - Rli_{\text{inv}}(\text{DC})}{R(i_{\text{rec}}(\text{DC}) - i_{\text{inv}}(\text{DC}))} \tag{7}$$

where $u_{\text{rec}}(\text{DC})$ and $u_{\text{inv}}(\text{DC})$ are the DC component of the voltage at the rectifier terminal and inverter terminal,

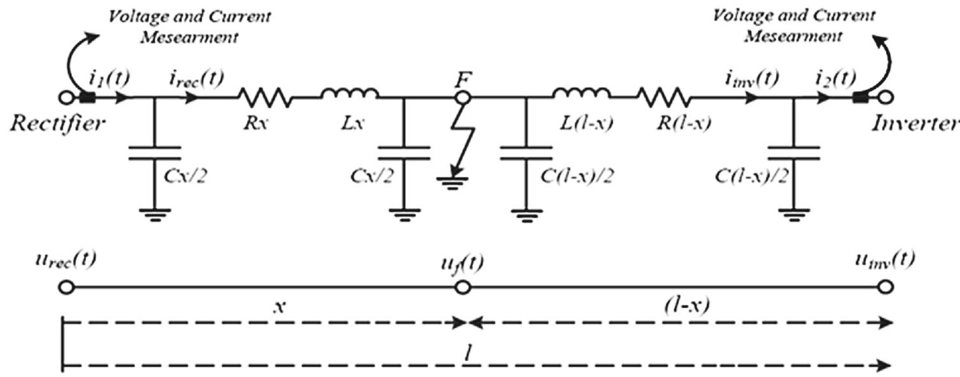

Fig. 2 Circuitry of the HVDC line with a fault in point F

respectively. Furthermore, i_{rec} (DC) and i_{inv} (DC) are the DC component of current at the rectifier terminal and inverter terminal, respectively. Using the transmission-line parameters and measured values of voltage and current in both line terminals, fault locating is possible by Eq. (7).

Because Eq. (7) is a linear function of the only unknown parameter (fault location), for each sample of measured voltage and current in both the sides of line, one possible answer exists for fault location. Hence, the obtained equation is depended on the data of the rectifier terminal. Only the line resistance which is a linear element of the transmission line is considered in the calculation; therefore, there is less error in the calculation of the fault location. Because the proposed fault-location formula (Eq. 7) is depended on resistance among the line parameters which it can be estimated. While in differential equation (Eq. 6), the fault distance is depended on line parameters (R, L and C). Estimating three parameters increase the fault distance error rather than estimating one line parameter.

2.2 Fault location based on the π-line model:

In this part, a general method of fault locating in HVDC transmission lines is proposed. In this case, it is assumed that the transmission-line parameters are given. The fault-location procedure is conducted by simultaneous voltage and current measurement of both terminals. This method is based on the π model of the transmission line. The associated equations of transmission line are used in the time domain. Finally, similar the previous section, the DC components of the current and voltage are extracted, and the final equation is obtained. Figure 2 shows a single-pole HVDC transmission line with length l. In this figure, the π model of the line between the rectifier and inverter terminals is shown.

Assume that according to Fig. 2, a fault is occurred in point F in distance of x from the rectifier terminal.

If we assume that the parameters of transmission line and fault distance to rectifier terminal are given, the voltage of the fault location could be calculated by rectifier terminal data as below:

$$u_{\mathrm{f}}^{\mathrm{rec}}(t) = u_{\mathrm{rec}}(t) - Rx\,i_{\mathrm{rec}}(t) - Lx\frac{\mathrm{d}i_{\mathrm{rec}}(t)}{\mathrm{d}t} \tag{8}$$

$$u_{\mathrm{f}}^{\mathrm{rec}}(t) = u_{\mathrm{rec}}(t) - Rx\left(i_1(t) - \frac{C}{2}x\frac{\mathrm{d}u_{\mathrm{rec}}(t)}{\mathrm{d}t}\right) - Lx\frac{d}{\mathrm{d}t}\left(i_1(t) - \frac{C}{2}x\frac{\mathrm{d}u_{\mathrm{rec}}(t)}{\mathrm{d}t}\right) \tag{9}$$

where x is the distance between the fault location and rectifier terminal; l is the total transmission-line length; R, L, and C are the resistance, inductance, and capacitance of the line in per unit, respectively.

Similarly, using the inverter data and the compact model of the line between the point F and inverter terminal, fault-location voltage could be determined as

$$u_{\mathrm{f}}^{\mathrm{inv}}(t) = u_{\mathrm{inv}}(t) + R(l-x)i_{\mathrm{inv}}(t) + L(l-x)\frac{\mathrm{d}i_{\mathrm{inv}}(t)}{\mathrm{d}t} \tag{10}$$

$$u_{\mathrm{f}}^{\mathrm{inv}}(t) = u_{\mathrm{inv}}(t) + R(l-x)\left(i_2(t) + \frac{C}{2}(l-x)\frac{\mathrm{d}u_{\mathrm{inv}}(t)}{\mathrm{d}t}\right) + L(l-x)\frac{d}{\mathrm{d}t}\left(i_2(t) + \frac{C}{2}(l-x)\frac{\mathrm{d}u_{\mathrm{inv}}(t)}{\mathrm{d}t}\right) \tag{11}$$

where variables $u_{\mathrm{inv}}(t)$ and $u_{\mathrm{f}}^{\mathrm{inv}}(t)$ are voltage of the inverter and fault location based on the inverter side data. $i_{\mathrm{inv}}(t)$ and $i_2(t)$ are current of the inverter side.

According to the π-line model, fault voltage, currents equations of rectifier, inverter, and transmission line, it could be written that

$$i_1(t) = i_{\mathrm{rec}}(t) - C\frac{\mathrm{d}v_{\mathrm{rec}}(t)}{\mathrm{d}t} \tag{12}$$

$$i_2(t) = i_{\mathrm{inv}}(t) + C\frac{\mathrm{d}v_{\mathrm{rec}}(t)}{\mathrm{d}t} \tag{13}$$

$$u_{\mathrm{F}}(t) = R_{\mathrm{F}} I_{\mathrm{F}} = R_{\mathrm{F}}(i_{\mathrm{rec}} - i_{\mathrm{inv}}) \tag{14}$$

where u_{F} is the fault voltage, R_{F} is the resistance fault, and I_{F} is the imposed current of the fault to the transmission line.

The above equations are only used for fault voltage calculation, and they are depended on the fault resistance which is an unknown value. Therefore, these equations are not suitable for fault-location procedure. Hence, an equation should be obtained that determines the location of fault using transmission-line terminals data and their parameters. Therefore, according to Eqs. (12) and (13) (which indicate the transmission-line current), the equation of rectifier voltage is obtained by the voltage of fault in the transmission line:

$$u_{\text{rec}}(t) = Rx\left(i_2(t) - C\frac{\mathrm{d}v_{\text{rec}}(t)}{\mathrm{d}t}\right) + Lx\frac{d}{\mathrm{d}t}\left(i_2(t) - C\frac{\mathrm{d}v_{\text{rec}}(t)}{\mathrm{d}t}\right) + u_{\text{F}}(t). \quad (15)$$

To remove the fault voltage which is an unknown value, its value in Eq. (11) is substituted in Eq. (15); after simplification, to determine the fault location based on the terminal data and transmission-line data, x value is obtained as

$$u_{\text{rec}} - u_{\text{inv}} - Rl\left(i_2(t) - C\frac{\mathrm{d}u_{\text{inv}}(t)}{\mathrm{d}t}\right) - Ll\left(\frac{\mathrm{d}i_2(t)}{\mathrm{d}t} - C\frac{\mathrm{d}^2u_{\text{inv}}(t)}{\mathrm{d}t^2}\right) = x\left(R\left(i_1(t) - C\frac{\mathrm{d}u_{\text{rec}}(t)}{\mathrm{d}t}\right) + L\left(\frac{\mathrm{d}i_1(t)}{\mathrm{d}t} - C\frac{\mathrm{d}^2u_{\text{rec}}(t)}{\mathrm{d}t^2}\right) - Ri_2(t) - RC\frac{\mathrm{d}u_{\text{inv}}(t)}{\mathrm{d}t} - L\frac{\mathrm{d}i_{\text{inv}}(t)}{\mathrm{d}t} - LC\frac{\mathrm{d}^2u_{\text{inv}}(t)}{\mathrm{d}t^2}\right). \quad (16)$$

After the simplification, to obtain the fault location, the general differential equation is Eq. (17). This equation indicates the fault location as the second-order differential equations of voltage and current, as the same as in Sect. 2. A values of DC voltage and current and their associated parameters are analyzed in this case. This makes the fault-location process easier and more accurate:

$$x = \frac{u_{\text{rec}}(t) - u_{\text{inv}}(t) - Rl\left(i_2(t) - C\frac{\mathrm{d}u_{\text{inv}}(t)}{\mathrm{d}t}\right) - Ll\left(\frac{\mathrm{d}i_2(t)}{\mathrm{d}t} - C\frac{\mathrm{d}^2u_{\text{inv}}(t)}{\mathrm{d}t^2}\right)}{R\left(i_1(t) - i_2(t) - C\frac{\mathrm{d}u_{\text{inv}}(t)}{\mathrm{d}t}\right) + L\left(\frac{\mathrm{d}i_1(t)}{\mathrm{d}t} - \frac{\mathrm{d}i_2(t)}{\mathrm{d}t} - C\frac{\mathrm{d}^2u_{\text{rec}}(t)}{\mathrm{d}t^2} - C\frac{\mathrm{d}^2u_{\text{inv}}(t)}{\mathrm{d}t^2}\right)}. \quad (17)$$

Therefore, taking the FFT of the rectifier and inverter voltage and current and DC component extraction, we have

$$x = \frac{u_{\text{rec}}(\text{DC}) - u_{\text{inv}}(\text{DC}) - Rli_2(\text{DC})}{R\left(i_1(\text{DC}) - i_2(\text{DC})\right)}. \quad (18)$$

2.3 Fault location based on the distributed-line model

In this part, the distributed-line model is selected as a complete line model for analyzing fault location. According to reference [15], the equivalent circuit (π circuit) of distributed-line model is similar to equivalent circuit of π-line model. The difference of these circuit models is line parameters that the line parameter of distributed-line model is R′, L′, and C′. Consequently, the equation set for determining the fault distance is a same as equation set of π-line model that is mentioned above. According to line parameters difference, Eqs. (17) and (18) can be rewritten in (19) and (20):

$$x = \frac{u_{\text{rec}}(t) - u_{\text{inv}}(t) - R\prime l\left(i_2(t) - C'\frac{\mathrm{d}u_{\text{inv}}(t)}{\mathrm{d}t}\right) - L\prime l\left(\frac{\mathrm{d}i_2(t)}{\mathrm{d}t} - C\prime\frac{\mathrm{d}^2u_{\text{inv}}(t)}{\mathrm{d}t^2}\right)}{R\prime\left(i_1(t) - i_2(t) - C\prime\frac{\mathrm{d}u_{\text{inv}}(t)}{\mathrm{d}t}\right) + L\prime\left(\frac{\mathrm{d}i_1(t)}{\mathrm{d}t} - \frac{\mathrm{d}i_2(t)}{\mathrm{d}t} - C\prime\frac{\mathrm{d}^2u_{\text{rec}}(t)}{\mathrm{d}t^2} - C\prime\frac{\mathrm{d}^2u_{\text{inv}}(t)}{\mathrm{d}t^2}\right)} \quad (19)$$

$$x = \frac{u_{\text{rec}}(\text{DC}) - u_{\text{inv}}(\text{DC}) - R\prime li_2(\text{DC})}{R\prime\left(i_1(\text{DC}) - i_2(\text{DC})\right)}. \quad (20)$$

According to Eqs. (7), (18), and (20), it can be seen that the three fault distance equations are the same and it is not depended on the line model. The fault-location process could be performed using the transmission-line parameters (only resistance), and voltage and current measurement values in both terminals. A similar descriptive in Sect. 2. A in this case, Eqs. (18) and (20) are a linear function respect to fault distance as unknown parameter. Hence, for each sample of the measured voltage and current in both sides of the line terminals, one answer exists for fault location. Therefore, by substituting the voltage, current, and parameters of the transmission line in the mentioned equations, the location of fault is calculated.

According to the obtained equations (7), (18), and (20), it can be known that they are only depended on resistance of HVDC transmission-line model. Therefore, a method is proposed for calculating the resistance of HVDC transmission-line model. The circuit diagram of HVDC transmission line in pre-fault is shown in Fig. 3a for lumped-line model, π-line model, and distributed-line model, respectively.

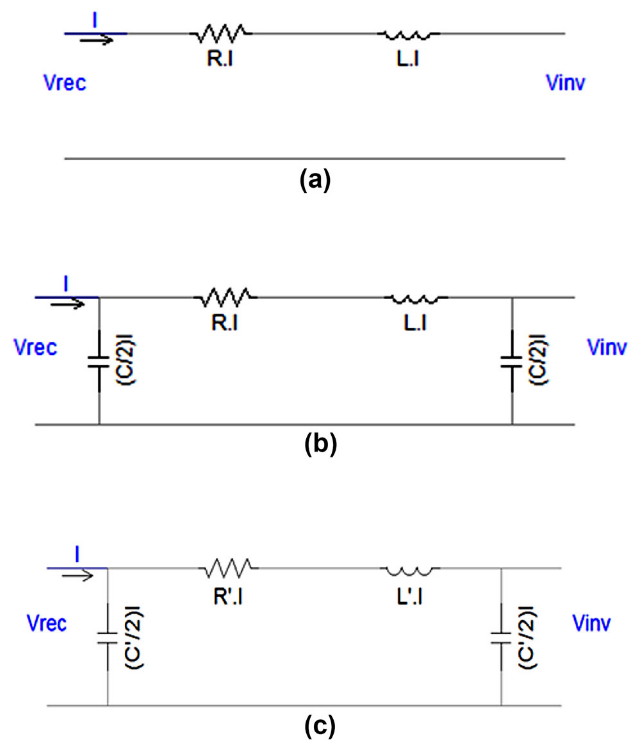

Fig. 3 Pre-fault circuit of HVDC line. **a** Lumped-line model. **b** π-line model. **c** Distributed-line model

According to Fig 3a, Eq. (21) can be rewritten which is a KVL[1] in that circuit:

$$U_{rec}(t) = Rl I_{inv}(t) + Ll\frac{di_{inv}(t)}{dt} + U_{inv}(t)$$

$$I_{inv}(t) = I_{rec}(t)\,. \tag{21}$$

By extracting the DC component of voltage and current at the both sides (inverter and rectifier), this equation can be edited by the following equation:

$$U_{rec}(DC) = R\,l\,I_{rec}(DC) + L\,l\frac{di_{rec}(DC)}{dt} + U_{inv}(DC)\,. \tag{22}$$

The Part 2 of Eq. (22), $\left(Ll\frac{di_{rec}(DC)}{dt}\right)$ is equal to zero. This equation is rewritten in Eq. (23). According to this equation, R can be calculated by Eq. (24):

$$U_{rec}(DC) = R\,l\,I_{rec}(DC) + U_{inv}(DC) \tag{23}$$

$$R = \frac{U_{rec}(DC) - U_{inv}(DC)}{l\,I_{rec}(DC)}. \tag{24}$$

In mentioned circuit and equations, the capacitance line model is not considered, while it is a natural line parameter. The KVL on the circuit of Fig. 3b is written in Eq. (25) by considering the all line parameter (R, L, and C). This equation can be rewritten in Eq. (26) by extracting DC component and knowing that the differential of a dc component is equal to zero. In continue, the resistance of HVDC transmission line is obtained using Eq. (27):

$$U_{rec}(t) = Rl\left(I_{rec}(t) - \frac{c}{2}l\frac{du_{rec}(t)}{dt}\right) + Ll\frac{d}{dt}I_{rec}(t) - L\frac{l^2c}{2}\frac{du_{rec}(t)}{dt^2} + U_{inv}(t) \tag{25}$$

$$U_{rec}(DC) = R\,l\,(I_{rec}(DC)) + U_{inv}(DC) \tag{26}$$

$$R = \frac{U_{rec}(DC) - U_{inv}(DC)}{l\,I_{rec}(DC)}. \tag{27}$$

Furthermore, a same as π-line model, Eqs. (25) and (26) can be rewritten for distributed-line model [Eqs. (28) and (29)]. Thus, with eliminating the inductance and capacitance effect in DC state, Eq. (30) is obtained. In comparison of this equation with Eq. (27), it can be known that the inductance and capacitance effect can be ignored in DC mode. Consequently, $\sinh(\gamma l)$ is equal to γl and R' is equal to R:

$$U_{rec}(t) = R'\,l\left(I_{rec}(t) - \frac{c'}{2}l\frac{du_{rec}(t)}{dt}\right) + L'\,l\frac{d}{dt}I_{rec}(t) - L'\frac{l^2c'}{2}\frac{du_{rec}(t)}{dt^2} + U_{inv}(t) \tag{28}$$

$$U_{rec}(DC) = R'\,l\,(I_{rec}(DC)) + U_{inv}(DC) \tag{29}$$

$$R' = \frac{U_{rec}(DC) - U_{inv}(DC)}{l\,I_{rec}(DC)}. \tag{30}$$

According to Eqs. (23), (27), and (30), it can be concluded that the three equations is a same. It means that the resistance of HVDC line model is depended on DC components of voltage and current at the inverter and rectifier terminal and is in-depended on the line model.

3 Simulation results

3.1 Case study

In this part, to evaluate the performance and accuracy of the proposed method, a single-pole 12 pulses HVDC system with terminal and line equipment is simulated similar to Fig. 4. This system is based on the single-pole test system of Cigre [16]. Here, a real π transmission line substitutes the simple model of the transmission line. Moreover, filters are installed in the DC terminals.

The parameters' data of the HVDC transmission-line system (per length unit) are shown in Table 1. The required data

[1] Kirchhoff voltage law.

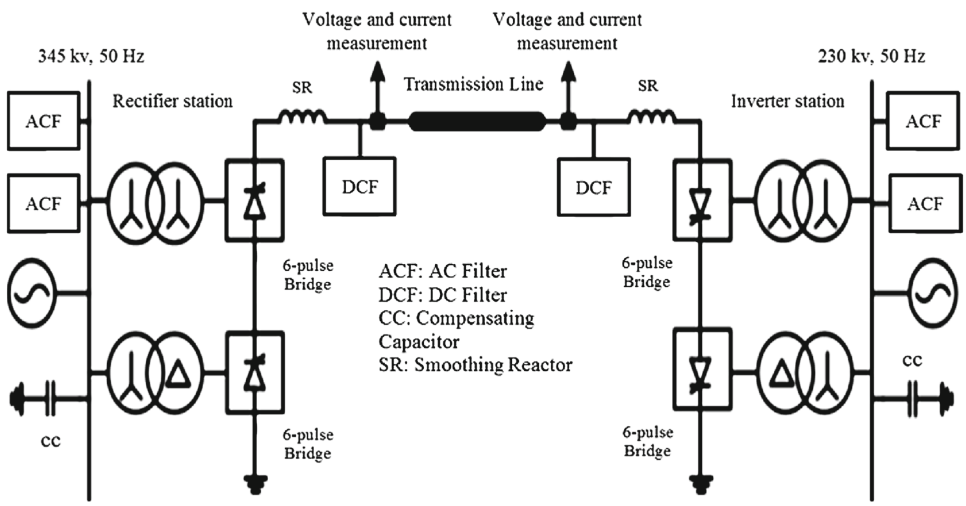

Fig. 4 Case study test system [16]

Table 1 π model data of transmission line

$R_{\text{line}} = 0.0279\ \frac{\Omega}{\text{km}}$
$L_{\text{line}} = 2.2363\ \frac{\text{mH}}{\text{km}}$
$C_{\text{line}} = 10\ \frac{\text{nF}}{\text{km}}$

of the fault-location algorithm in different line models are obtained using the simulation of PSCAD/EMTDC. Then, the MATLAB software is used to implement the proposed method.

In this paper, at first resistance of line model is estimated using Eqs. (24), (27), and (30) and pre-fault data of DC component of voltage and current. Then, the location of fault is determined using Eqs. (7), (18), and (20). To evaluate the proposed method, different faults under different conditions (different fault resistances and different locations of fault) are simulated and its accuracy is analyzed using the following equation:

$$\%\,\text{Error} = \frac{|x_{\text{actual}} - x_{\text{calculated}}|}{l} \times 100 \qquad (31)$$

where x_{actual} is the actual fault location from the rectifier terminal of transmission line; $x_{\text{calculated}}$ is the calculated fault location; and l is the total length of the line.

3.2 Performance evaluation of the proposed method

The performance of the proposed method is evaluated under different fault distances and different fault resistances. According to Eqs. (7), (27), and (30) and four samples of voltage and current data, a fault location is determined.

It should be noted that the locations of the voltage and current measurements are in both sides of the transmission line and in front of the DC filter (Fig. 4).

By taking the FFT of the voltage and current of the rectifier and inverter terminals and extraction of the DC components of the voltage and current, their values are used in the fault-location procedure.

3.2.1 Fault distance effect on the accuracy of the proposed method

Let us assume that a single-pole fault to ground with zero fault resistance is occurred in the distance of 300 km of the rectifier terminal. Fault is occurred at $t = 1.5$ s and fault clearance time is 2s.

The voltage and current of the inverter and rectifier terminals are shown in Figs. 4 and 5. In these figures, to present the waveforms more clearly, the data are shown a few seconds before and after the fault, while to solve the fault-location problem, 10ms-width time window is selected from the voltage and current samples. This selection is done immediately after the fault occurrence.

To obtain the best answer for the fault-location problem, close to the 10 ms after the occurring fault is evaluated in analyzing DC component of the voltage and current. This leads to high accuracy in fault-location process. To evaluate the performance accuracy of the proposed method, a few single pole to ground faults is simulated in different fault distances with zero fault impedance (Fig. 6).

As it can be seen from Table 2, error percentage of the fault-locating process never exceeds 0.0054 for the single pole to ground fault. This proceed that the proposed method has the high accuracy and it is not depended on the line model.

3.2.2 Fault resistance effect on the accuracy of the proposed method

In this section, with attention to fault resistance is an effective factor on the fault-location precise, the accuracy of the

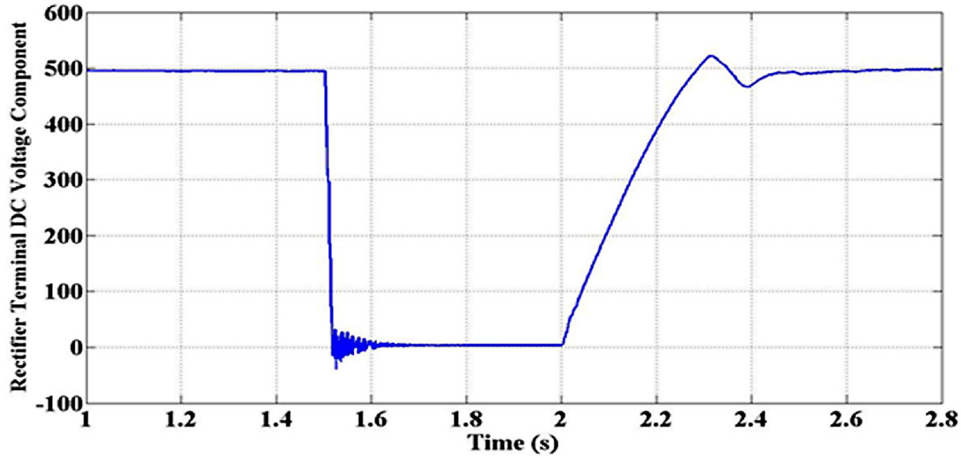

Fig. 5 Waveform of the DC component of the transmission-line model

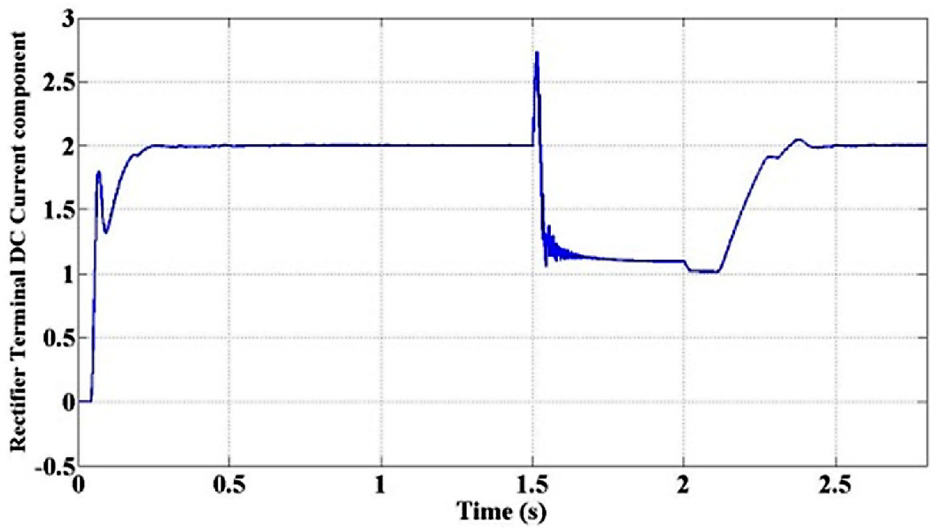

Fig. 6 Waveform of the DC component of the transmission-line model

Table 2 Fault locating results for single pole to ground fault

Actual fault location (km)	50	200	300	350
Calculated fault location (km)	50.0007	200.0147	300.0015	350.0218
Error percent	0.0019	0.0036	0.0037	0.0054

proposed method performance is evaluated and verified by short-circuit simulation in nine different fault locations [10, 50, 100, 150, 200, 250, 300, 350, and 390 km] and six different fault resistances (5, 10, 30, 50, 70 and 90). Results of the proposed method are shown in Table 3. According to this table, it can be seen that the maximum error is 0.0885 and it can be concluded that the fault resistance does not have considerable effect on the accuracy of the proposed method.

3.3 Evaluation of the operation point before fault occurrence on the accuracy of the proposed method

In this sub-part, the performance accuracy of the proposed method is evaluated by changing before fault current under different resistances and different locations. The current change for no-load condition is considered 1 and 1.5 kA.

Results of the proposed method for the mentioned cases are given in Table 4 based on the calculated error percentage. These results indicate the accurate performance of the proposed algorithms. Moreover, it is shown that the proposed algorithms do not affect the operation point condition before the fault occurrence.

3.4 Effect evaluation of the minimum injected current of the inverter during the fault on the accuracy of the proposed method

In this part, injected current of the inverter is set to zero to evaluate its effect on the proposed method during the fault.

Table 3 Fault-locating results for single pole to ground fault

Fault resistance (Ω)	Fault distance (km)								
	10	50	100	150	200	250	300	350	390
	Error percentage of the calculated fault locating								
5	0.06	0.01	0.04	0.01	0.01	0.06	0.06	0.02	0.05
10	0.01	0.05	0.01	0.03	0.04	0.07	0.05	0.08	0.03
30	0.02	0.01	0.02	0.00	0.01	0.06	0.05	0.08	0.02
50	0.02	0.04	0.07	0.04	0.03	0.06	0.07	0.04	0.06
70	0.04	0.05	0.04	0.01	0.04	0.02	0.01	0.02	0.02
90	0.04	0.02	0.01	0.02	0.02	0.08	0.06	0.04	0.04

Table 4 Results of the single pole to ground fault locating and current change before fault

	Fault location (km)	Fault resistance (Ω)	Fault location (km)	Fault resistance (Ω)
	10	5	390	90
No-load current (error percentage)	0.0168		0.0318	
Current of 1 kA (error percentage)	0.0310		0.0711	
Current of 1.5 kA (error percentage)	0.0428		0.0933	

Table 5 Results of the single pole to ground fault locating considering zero injected current of inverter during the fault

	Fault location (km)	Fault resistance (Ω)	Fault location (km)	Fault resistance (Ω)
	10	90	300	0
Error percentage	0.0542		0.0100	

Table 6 Comparing the accuracy of the proposed method with other presented methods

References	[10]	[12]	The proposed method
Total length (km)	1000	1438	400
Maximum error percentage (%)	0.5	0.45	0.12

To evaluate the proposed method performance accuracy, it is assumed that the single pole to ground fault with zero resistance is occurred in distance of 300 km from the rectifier terminal.

Fault-locating results in case of zero inverter injected current is shown in Table 5 for a single pole to ground fault with different resistances (0 and 90 Ω) and random distances of 10 and 300 km from the rectifier terminals. With attention to this table, it can be seen that the proposed algorithm is not affected by the zero inverter injected current. In addition, the fault-location error percentage never exceeds 0.12.

3.4.1 comparing the accuracy of the proposed method with other presented methods

In comparing the results of the proposed method with the results of the presented method in [12,15] in different locations and resistances, it can be seen that the maximum value of the error percentage of the proposed method is 0.12 %, while the maximum value of the error percentage of the different fault-location methods is 0.6 %. This shows that the error percentage of the proposed method is much lower than the differential equations methods (Table 6).

4 Conclusion

In this paper, a new method for locating fault is proposed. The method is described in two parts. In the first part, lumped-line model, π-line model, and distributed-line model are analyzed for locating fault in HVDC transmission line using time-domain method, and an equation is determined for locating fault. The obtained fault-location equations of three line models are simplified to the same equation with respect to fault distance. The fault-location equation is depended on post fault DC component of voltage and current data and only resistance of line model. Then, in the second part, the resistance of line model is determined using pre-fault

DC component of voltage and current data. According to the obtained results, it can be concluded that the proposed method is accurate in determining the actual location of fault and the maximum fault-location error never exceeds 0.12 % under different fault distances, different fault resistances, and different minimum injected current of the inverter during the fault and different pre-fault conditions. The proposed method has shown to be much more accurate in locating faults compared to its other counterparts.

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