8th Conference on Recent Research in Science and Technology
هشتمین همایش پژوهش های نوین در علوم و فناوری
زمستان ۱۳۹۵
Winter 2017

Natural Frequency Based Protection for Star-Connected Multiterminal VSC-HVDC Transmission Lines

Amir Kalantari[1], Seyyed Ghodratollah Seifossadat[2] , Hossein Emami[3], Alireza Sina[4]
[1] Production Technology Research Institute (PTRI) of Iranian Academi Center for Education, culture and Research (ACECR) of Khuzestan, Ahwaz, Iran, a.kalantari70@gmail.com
[2] Electrical Department of Engineering Faculty, Shahid Chamran University, Ahwaz, Iran
[3] Production Technology Research Institute (PTRI) of Iranian Academi Center for Education, culture and Research (ACECR) of Khuzestan, Ahwaz, Iran
[4] Production Technology Research Institute (PTRI) of Iranian Academi Center for Education, culture and Research (ACECR) of Khuzestan, Ahwaz, Iran

ABSTRACT

In this paper, a fault locating method based on natural frequency has been proposed for VSC-HVDC star-connected multi-terminal lines. When fault occurs at the transmission lines, some transient travelling waves appear by the form of a frequency spectrum in the voltage and current signals and propagates from the fault location to the both sides of the line. In this method, by measuring the current signals at each terminal without the need of determining the arrive time of transient waves and synchronous link to other terminals, the fault-produced frequency spectrum could be determined at each terminal and then by determining the dominant frequency component and calculating the velocity of the waves at each line, the faulty terminal and fault location would be detected. To determine the dominant frequency component, Fourier transform analysis (FFT) was used in this algorithm. Simulation results show that the proposed method is satisfactory and with appropriate accuracy and speed is able to determine the occurred faults on the protected lines.

Keywords: Fault location, Multiterminal VSC-HVDC, Natural Frequency, Fourier Transform

1. INTRODUCTION

HVDC system technology is expanding significantly due to advantages such as high capacity power transmission, energy transmission over long distances, low losses and fast control capability. One of the important features HVDC lines is connection between DC transmission lines from countries with different frequency resources. By this feature, in this paper is presented a new protection algorithm. HVDC systems in different areas may be connected to each other with various topologies such as point to point, mesh and star[1]. Most of the HVDC transmission lines have to pass the complex areas under inclement weather conditions due to power transmission in long distances. Thus in various sectors of a muti terminal HVDC system may occur fault. Protection technice in a muti terminal HVDC system must ability to detected faults with Speed and high accuracy in various sectors of protection area.

Now days, fault location techniques based traveling waves are used as primary protection for HVDC transmission lines[2]. These methods have high accuracy and speed[3-6]. In general, these method's algorithms can be divided into two categories: 1- single terminal. 2- two terminal.To detect fault location,the single terminal method measures arrival time of primary and secondary traveling waves. Accuracy in detecting the fault location decreases, When interference phenomenon is occurred because discovering the secondary wave become harder. In addition, these algorithms require a high sampling frequency from data measurement. In two terminal method to detect fault location, the arrival time of intial traveling wave to each terminal must be recognized. In this method for cordination between the terminals, a Telecommunication channel need and Synchronous communication must be made by the global position system (GPS) [7,8] that this subject can increase costs. Furthermore, when a fault occur with high resistance, to recognize arrival time of the waves is hard in measurement location due to weak them. These cases are some of the factors which can cause limitation in implimentation.

In [9] from the measured data in each terminal is used to fault location in a two terminal HVDC system. fault location is estimated by calculation the voltage distribution curve in different points of a transmission line. In this method, fault location with high accuracy rely to correct calculation of the distribution voltage. constant frequency have been used to calculate the transmission line parameters. In addition, results show, the presented algorithm is sensitive to changes of the transmission line resistance, surge impedance and propagation velocity. In [2] the transmission line parameters dependence to frequency have been considered and a protection algorithm has been presented for two terminal HVDC transmission line. In this method to calculate the distributed voltage and current, a limited frequency range is used until 600 HZ that waiver from the high frequency factors can cause error in calculation. Furthermore, accuracy decrease in calculation, and fault location isn't estimated exactly because part of this method, Simplified model transmission line (RL model) is used.

In [10,11] protection methods based on single terminal traveling waves have been presented for AC systems. According to the intial domain of traveling waves depending on the voltage at the moment fault, if fault occur at the moment of voltage zero crossing, due to the attenuation in propagation the refelction traveling waves aren't identification correctly. A new method is proposed Using harmonics measurement in the current signal [12]. This algorithm just determine fault occurrence in DC line and fault location isn't determined.In [13] an protection algorithm is presented for star connected three terminal HVDC lines. In this method detection of the location of dc line faults rely on the accurate calculation arrival time of the intial traveling waves. To implement this algorithm require synchronous communication and high frequency. For faulted leg identification in three terminal transmission lines is used length of the lines to compare the distance of the fault with reference to each three terminals [14].

In this method presents a novel algorithm to fault location in multiterminal HVDC transmission lines, using natural frwquency. In this method fault location is estimated using only the current signal measurement and identification of the frequency spectrum in each terminal. The following, in the next section, the relationship between fault location and frequency spectrum is described, in the third section, the proposed algorithm is designed for a three terminal VSC-HVDC system with star connected and in the last section, the result simulation is shown.

2. Natural Frequency Based Fault Location Theory

Figure 1 shows the circuit diagram of a transmission line with two conductors. Each terminal voltage in Laplace domain can be expressed as follows [15]

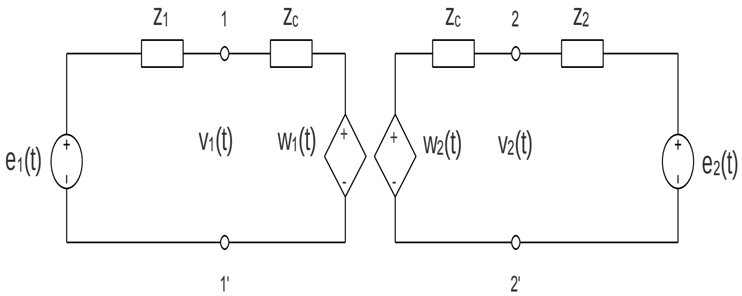


Fig. 1. *Equivalent circuit of a two conductor transmission line*

$$V_1(s) = \frac{z_1(s)}{z_1(s)+z_c(s)} W_1(s) + \frac{z_c(s)}{z_1(s)+z_c(s)} E_1(s) \qquad (1)$$

$$V_2(s) = \frac{z_2(s)}{z_2(s)+z_c(s)} W_2(s) + \frac{z_c(s)}{z_2(s)+z_c(s)} E_2(s) \qquad (2)$$

Where $V_1(s)$ and $V_2(s)$ are the Laplace form of terminal voltages $E_1(s)$, and $E_2(s)$ are the Laplace form of the equivalent Thevenin voltage sources of systems 1 and 2. $z_1(s)$ and $z_2(s)$ are respectively, the Laplace form of the equivalent impedance of system 1 and system 2. $z_c(s)$ is the characteristic impedance of the line. The state variables $W_1(s)$ and $W_2(s)$ are defined as

$$W_1(s) = \frac{p(s)}{1-\Gamma_1(s)\Gamma_2(s)p^2(s)} \left[\frac{2z_c(s)}{z_2(s)+z_c(s)} E_2(s) + \Gamma_2(s)p(s) \frac{2z_c(s)}{z_1(s)+z_2(s)} E_1(s) \right] \qquad (3)$$

$$W_2(s) = \frac{p(s)}{1-\Gamma_1(s)\Gamma_2(s)p^2(s)} \left[\frac{2z_c(s)}{z_1(s)+z_c(s)} E_1(s) + \Gamma_1(s)p(s) \frac{2z_c(s)}{z_2(s)+z_c(s)} E_2(s) \right] \qquad (4)$$

Where $\Gamma_1(s)$ and $\Gamma_2(s)$ are the Laplace form of the voltage reflection coefficients at line terminals as shown in (5) and (6), respectively

$$\Gamma_1(s) = |\Gamma_1|e^{j\theta_1} = \frac{z_1(s) - z_c(s)}{z_1(s) + z_c(s)} \quad (5)$$

$$\Gamma_2(s) = |\Gamma_2|e^{j\theta_2} = \frac{z_2(s) - z_c(s)}{z_2(s) + z_c(s)} \quad (6)$$

$p(s)$ is a delay operator of the line in the Laplace domain

$$p(s) = e^{-sT} \quad (7)$$

$T = \frac{L}{v}$ is travel time from one terminal to another terminal. The natural frequencies of the transmission line can be calculated as the roots of

$$H(S) = \frac{1}{1 - P(s)\Gamma_1(s)P(s)\Gamma_2(s)} \quad (8)$$

There are infinite amounts of roots. Therefore traveling waves have infinite oscillation components. These components make a frequency spectrum. The natural frequencies by the fault can be obtained by (9)

$$1 - P(s)\Gamma_1(s)P(s)\Gamma_2(s) = 0 \quad (9)$$

In Eq (9), $s = \sigma + j\omega$ is root of the characteristic equation. It has a real part and a imaginary part. Real part is related to natural frequency energy attenuation coefficient and the imaginary part shows the components of frequency spectrum. With rewrite Eq (9), the frequency spectrum can be calculated by the imaginary part of equation (10)

$$|\Gamma_1|e^{j\theta_1}|\Gamma_2|e^{j\theta_2} = e^{\frac{2(\sigma+j\omega)L}{v}} \quad (10)$$

$$f = \frac{v}{4\pi L}(\theta_1 + \theta_2 + 2k\pi) \quad (11)$$

Where, k is integer, v is the propagation speed of the natural frequency and L is related to the length of the line. When a fault occurs in two terminal HVDC system at d distance from terminal 1, the equivalent circuit can be considered in fig.2. The reflection coefficient of fault point for voltage traveling waves can be expressed by equation (12)

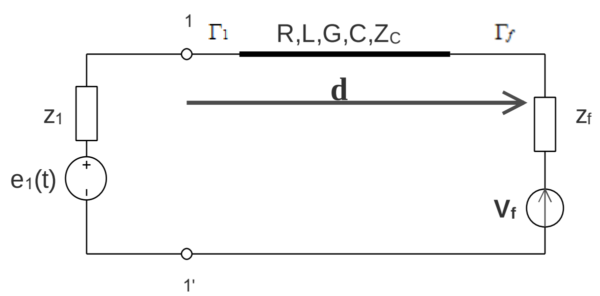


Fig. 2. *The fault component of distributed parameter HVDC transmission line*

$$\Gamma_f(s) = |\Gamma_f|e^{j\theta_f} = \frac{-z_c}{z_c + 2z_f} \quad (12)$$

The propagation time of traveling waves from fault point to the measurement station (terminal 1) is $T = \frac{d}{v}$. therefore, the natural frequencies is calculated in similar previous steps by the equation (13) and (14)

$$|\Gamma_1|e^{j\theta_1}|\Gamma_f|e^{j\theta_f} = e^{\frac{2sd}{v}} \qquad (13)$$

$$f = \frac{v}{4\pi d}(\theta_1 + \theta_f + 2k\pi) \qquad (14)$$

Large shunt capacitors on each terminal in a VSC-HVDC system is used that it causes, in high frequency the impedance system is estimated the following (15)

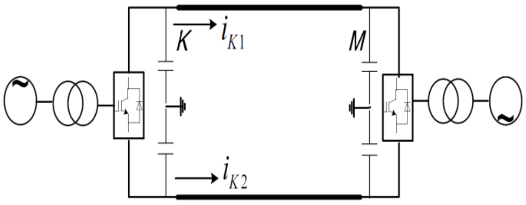


Fig. 3. *The equivalent circuit of two-pole VSC-HVDC transmission line [16]*

$$z_1 = \frac{1}{j\omega c_s} \qquad (15)$$

In this situation, the characteristic impedance is much greater than the system impedance. Thus, Γ_1 and θ_1 become recpectively -1 and π in equation (5) and the traveling waves have a complete reflection from VSC-HVDC system side. In equation (12), the fault impedance is much smaller than the characteristic impedance. Thus, $\Gamma_f = -1$ and $\theta_f = \pi$ are considered and the fault distance can be calculated for each natural frequency by (16)

$$d = \frac{kv_k}{2f_k} \qquad (16)$$

Each components of the frequency spectrum can be used in fault location, but according to the amplitude of dominant natural frequency is much greater than other components, so it is used for calculation of fault location.

$$d = \frac{v_1}{2f_1} \qquad (17)$$

Where v_1 and f_1 are the velocity of propagation of the dominant natural frequency and dominant natural frequency recpectivly.

3. Proposed Algorithm Based Natural Frequency in Three Terminal VSC-HVDC System

Fig.4 shows a star connected three terminal VSC-HVDC system. When a fault (F_1) accurs in AD sector, the distance to the fault from terminal A can be calculated by the measurement data in each terminal. We can express characteristic equation of the natural frequencies in terminal A by (18)

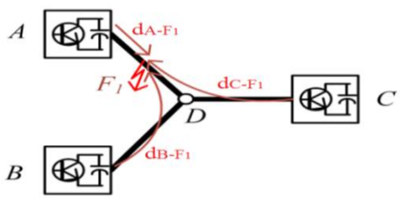


Fig. 4. *DC line fault F_1 inside the AD line*

$$|\Gamma_1|e^{j\theta_1}|\Gamma_f|e^{j\theta_f} = e^{2sT} \quad (18)$$

Where $|\Gamma_1|$ and θ_1 are the amplitude and angle of reflection coefficient from terminal A. $|\Gamma_f|$ and θ_f are the amplitude and angle of reflection coefficient from fault place. Time of the frequency spectrum propagation from fault to terminal A is $T = \frac{d_{A-F_1}}{v_1}$ that d_{A-F_1} and v_1 are the distance of the fault to terminal A, and the velocity of propagation of the frequency spectrum in AD sector, respectively. With substituting $T = \frac{d_{A-F_1}}{v_1}$ into (18) ,the frequency spectrum due the fault can be calculated from (20)

$$|\Gamma_1|e^{j\theta_1}|\Gamma_f|e^{j\theta_f} = e^{\frac{2d_{A-F_1}}{v_1}(\sigma+j\omega_n)} \quad (19)$$

$$f_{n1} = \frac{v_1(\theta_1 + \theta_f + 2k\pi)}{4\pi d_{A-F_1}} \quad (20)$$

In a VSC-HVDC system $\theta_1 = \theta_f = \pi$ .Therefore fault location is estimated by the dominant frequency and the velocity of propagation as follows

$$d_{A-F_1} = \frac{v_1}{2f_{11}} \quad (21)$$

Where f_{11} is dominant frequency in terminal A side. The distance of the fault to terminal A can be calculated by the data of the terminal B

$$|\Gamma_2|e^{j\theta_2}|\Gamma_f|e^{j\theta_f} = e^{2ST} \quad (22)$$

Where $|\Gamma_2|$ and θ_2 are the amplitude and angle of reflection coefficient from terminal B. in (22), $T = \frac{L_1 - d_{A-F_1}}{v_1} + \frac{L_2}{v_2}$ is the time of propagation of the frequency spectrum from fault to terminal B that L_1 and L_2 are length of the AD and BD lines, v_1 and v_2 are the velocity of propagation of the frequency spectrum due the fault in AD and BD sectors, respectively. With substituting T into (22) ,the frequency spectrum due the fault in terminal B can be calculated from (24)

$$|\Gamma_2|e^{j\theta_2}|\Gamma_f|e^{j\theta_f} = e^{2(\sigma+j\omega_n)\left(\frac{L_1 - d_{A-F_1}}{v_1} + \frac{L_2}{v_2}\right)} \quad (23)$$

$$f_{n2} = \frac{(\theta_2 + \theta_f + 2k\pi)}{4\pi\left(\frac{L_1 - d_{A-F_1}}{v_1} + \frac{L_2}{v_2}\right)} \quad (24)$$

Where f_{n2} is frequency spectrum in terminal B side. With substituting $\theta_2 = \theta_f = \pi$ into (24), d_{A-F_1} is calculated by (25)

$$d_{A-F_1} = L_1 - \left(\frac{1}{2f_{12}} - \frac{L_2}{v_2}\right)v_1 \quad (25)$$

Where f_{12} is dominant frequency component in terminal B side. The distance of the fault to terminal A is calculated by the data of terminal C. $T = \frac{L_1 - d_{A-F_1}}{v_1} + \frac{L_3}{v_3}$ is the time of propagation of the frequency spectrum from fault point to terminal C. The characteristic equation of the frequency spectrum can be obtaind as

$$|\Gamma_3| e^{j\theta_3} |\Gamma_f| e^{j\theta_f} = e^{2(\sigma + j\omega_n)\left(\frac{L_1 - d_{A-F_1}}{v_1} + \frac{L_3}{v_3}\right)} \quad (26)$$

Where $|\Gamma_3|$ and θ_3 are the amplitude and angle of reflection coefficient from terminal C. L_3 and v_3 are the length of CD sector and the velocity of propagation of the frequency spectrum, respectively. The frequency spectrum is obtained using imaginary part of (26)

$$f_{n3} = \frac{(\theta_3 + \theta_f + 2k\pi)}{4\pi\left(\frac{L_1 - d_{A-F_1}}{v_1} + \frac{L_3}{v_3}\right)} \quad (27)$$

Similarly to previous steps, d_{A-F_1} is calculated using (28)

$$d_{A-F_1} = L_1 - \left(\frac{1}{2f_{13}} - \frac{L_3}{v_3}\right) v_1 \quad (28)$$

Where f_{13} is dominant frequency component in terminal C side. Similarly to first state it is assumed, fault (F_2) occurs in BD sector of fig.5. The distance of the fault to terminal B (d_{B-F_2}) can be obtained using the measurement data of each terminal

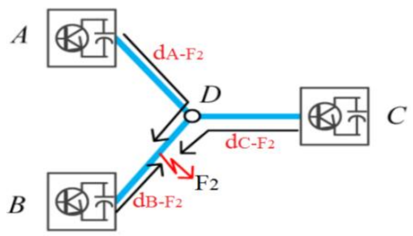


Fig. 5. *DC line fault F_2 inside the BD line*

$$f_{n2} = \frac{v_2(\theta_2 + \theta_f + 2k\pi)}{4\pi d_{B-F_2}} \quad (29)$$

$$f_{n1} = \frac{(\theta_1 + \theta_f + 2k\pi)}{4\pi\left(\frac{L_2 - d_{B-F_2}}{v_2} + \frac{L_1}{v_1}\right)} \quad (30)$$

$$f_{n3} = \frac{(\theta_3 + \theta_f + 2k\pi)}{4\pi\left(\frac{L_2 - d_{B-F_2}}{v_2} + \frac{L_3}{v_3}\right)} \quad (31)$$

The equations (29), (30) and (31) show the frequency spectrum in terminals A, B and C, respectively. Three equations is obtained to calculation the distance of the fault to terminal B as follows

$$d_{B-F_2} = \frac{v_2}{2f_{12}} \quad (32)$$

$$d_{B-F_2} = L_2 - \left(\frac{1}{2f_{11}} - \frac{L_1}{v_1}\right) v_2 \tag{33}$$

$$d_{B-F_2} = L_2 - \left(\frac{1}{2f_{13}} - \frac{L_3}{v_3}\right) v_2 \tag{34}$$

In the last case, if a fault (F_3) occurs in CD sector of fig.6, the distance of the fault to terminal C can be calculated using the measurement data of each terminals

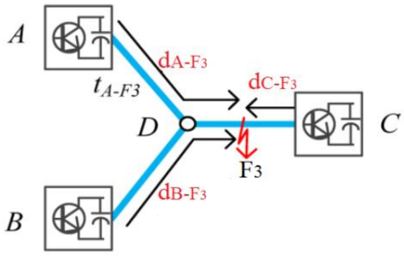


Fig. 6. *DC line fault F_3 inside the CD line*

$$d_{C-F_3} = \frac{v_3}{2f_{13}} \tag{35}$$

$$d_{C-F_3} = L_3 - \left(\frac{1}{2f_{11}} - \frac{L_1}{v_1}\right) v_3 \tag{36}$$

$$d_{C-F_3} = L_3 - \left(\frac{1}{2f_{12}} - \frac{L_2}{v_2}\right) v_3 \tag{37}$$

We assumed that the fault has occurred in AD, BD and CD. But in practical state, we don't know where the fault occurs. Therefore, at first the faulty line must be identified then the distance of the fault can be calculated. When a fault occurs in each terminals, at first step, equations (38)-(46) must be calculated then R_A , R_B and R_C must be obtained by (47-49). R_A is maximum if fault occurs in AD and R_B is maximum if fault occurs in BD, likewise for CD, R_C is maximum.

$$d_{A_1} = \frac{v_1}{2f_{11}} \tag{38}$$

$$d_{A_2} = L_1 - \left(\frac{1}{2f_{12}} - \frac{L_2}{v_2}\right) v_1 \tag{39}$$

$$d_{A_3} = L_1 - \left(\frac{1}{2f_{13}} - \frac{L_3}{v_3}\right) v_1 \tag{40}$$

$$d_{B_1} = \frac{v_2}{2f_{12}} \tag{41}$$

$$d_{B_2} = L_2 - \left(\frac{1}{2f_{11}} - \frac{L_1}{v_1}\right) v_2 \tag{42}$$

$$d_{B_3} = L_2 - \left(\frac{1}{2f_{13}} - \frac{L_3}{v_3}\right) v_2 \quad (43)$$

$$d_{C_1} = \frac{v_3}{2f_{13}} \quad (44)$$

$$d_{C_2} = L_3 - \left(\frac{1}{2f_{11}} - \frac{L_1}{v_1}\right) v_3 \quad (45)$$

$$d_{C_3} = L_3 - \left(\frac{1}{2f_{12}} - \frac{L_2}{v_2}\right) v_3 \quad (46)$$

$$R_A = \frac{minimum\left(|d_{A_1}|, |d_{A_2}|, |d_{A_3}|\right)}{maximum\left(|d_{A_1}|, |d_{A_2}|, |d_{A_3}|\right)} \quad (47)$$

$$R_B = \frac{minimum\left(|d_{B_1}|, |d_{B_2}|, |d_{B_3}|\right)}{maximum\left(|d_{B_1}|, |d_{B_2}|, |d_{B_3}|\right)} \quad (48)$$

$$R_C = \frac{minimum\left(|d_{C_1}|, |d_{C_2}|, |d_{C_3}|\right)}{maximum\left(|d_{C_1}|, |d_{C_2}|, |d_{C_3}|\right)} \quad (49)$$

After identification the faulty line, fault location can be estimated easily. It is d_{W1}. W is faulty line that is detected using (47)-(49). In this method, to identify the dominant frequency component, fourier transform is used to analyze the current signals. Interference occurs in travelling waves due to the mutual inductance between the poles that modal transformation can be used to solve this problem[9]. The dominant frequency and the velocity of propagation is calculated using current signal 1-mode.

$$S = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \quad (50)$$

$$i_m = S^{-1} i, \quad i_m = \begin{bmatrix} i_1 \\ i_0 \end{bmatrix}, \quad i = \begin{bmatrix} i_+ \\ i_- \end{bmatrix} \quad (51)$$

Where, S is the decoupling matrix, i_0 and i_1 are the modal components, i_+ and i_- are the positive line current and negative line current, respectively. The velocity of propagation of the dominant frequency is obtained using by (52)

$$v = \frac{\omega}{\beta} \quad (52)$$

Where ω is the radian frequency and β is the phase coefficient that represents the phase angle variation of the travelling wave propagation along the transmission line. The faulty segment identification and fault calculation is showed in fig.7.

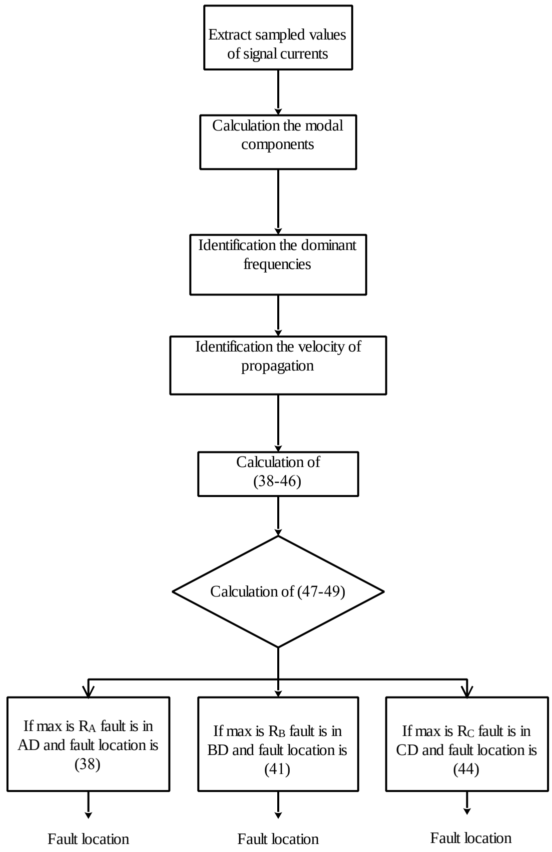


Fig. 7. *Faulty line identification and fault location method*

In this algorithm, the reflection coefficient is considered equal to (-1) due to the characteristic impedance is greater than the fault impedance. The real part of the reflection coefficient is changed but the imaginary part is unchanged if the resistance of the fault increase. Therefore, the frequency spectrum of the fault isn't dependent on the fault resistance, and the reflection angle will remain equal to π . If each fault type occurs in a VSC-HVDC transmission line, the travelling waves propagate from fault point to each terminal. This method can estimate the fault location by using to identify the dominant frequency components in measurement stations. Therefore, this algorithm don't rely on fault type.

4. Simulated Case Study

A star connected three terminal VSC-HVDC system has been used in simulation studies. A schematic diagram of the test network is shown in fig.8. All of the simulation were carried out with PSCAD/EMTDC and the fault location algorithm was implement in MATLAB. The length of the transmission lines have been shown in fig.8. OH lines are represented by using distributed parameter transmission line models in PSCAD/EMTDC, and the tower structure is shown in fig.9. The equal shunt capacitors between the positive and negative poles are $1000\mu f$. The data are sampled at a frequency of 100 kHz and the total data window is about 10 ms long. Simulations were performed in PSCAD/EMTDC with a solution time step of $0.1\mu s$ to ensure that the high-frequency components will be present in the current signal. The current limits are taken as -50-50 KA. 1-mode components of the signals current are used in the simulations.

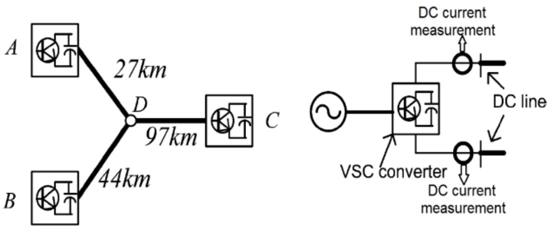


Fig. 8. *The network topology, lines length and measured terminal current signal*

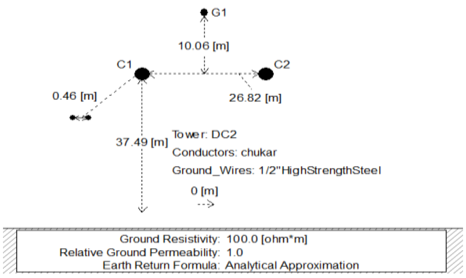
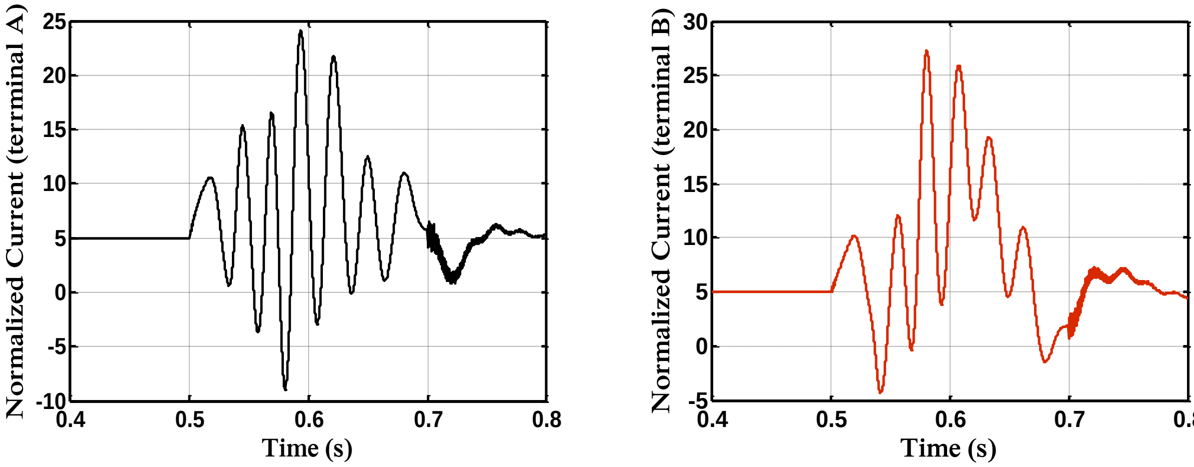
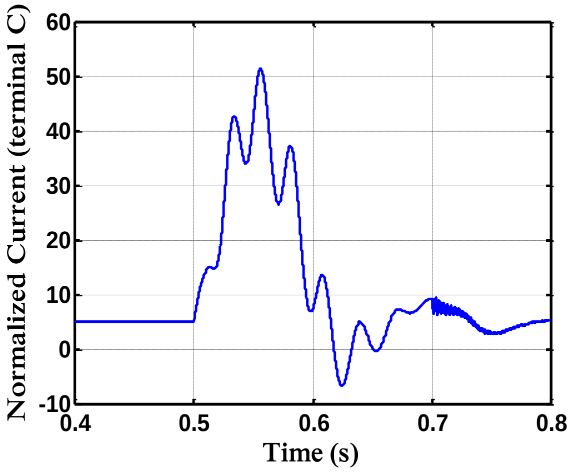


Fig. 9. *Tower structure of the VSC-HVDC lines*

A single-pole short circuit fault in line CD, 45 km away from terminal C occurs at $t = 0.5\ sec$ and it is removed at $t = 0.7\ sec$. The normalized current signals in each terminal are shown in fig.10. The current signal of terminal C has showed reaction faster than other current signals due to the fault has been near terminal C. Due to the less attenuation, the travelling waves of terminal C have larger amplitude compared with other frequency spectrums.



(a) (b)



(c)

Fig. 10. *Normalized dc-line current signals. (a) Terminal A. (b) Terminal B. (c) Terminal C*

The frequency spectrums of the measured current signals have been shown in fig.11. the dominant frequencies components can be identified using by fig.11. They are $f_{11} = 1855\ HZ$, $f_{12} = 1560\ HZ$ and $f_{13} = 3320\ HZ$ for terminals A, B and C, respectively. The dominant frequency of terminal C is larger than dominant frequencies of terminals A and B due to the less attenuation in propagation.

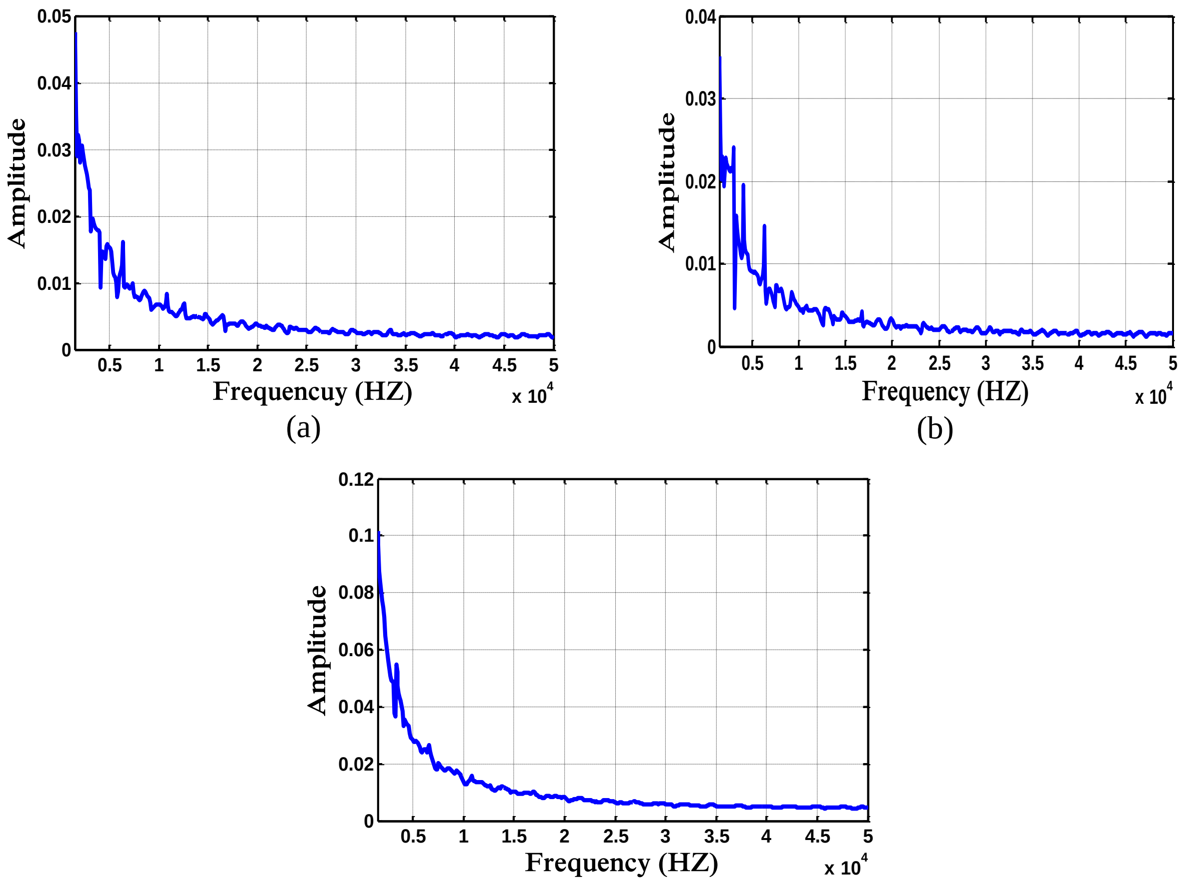


Fig. 11. *Spectra of travelling wave currents. (a) Terminal A. (b) Terminal B. (c) Terminal C*

The velocity of propagation of a frequency component is equal in every sector AD, BD and CD because the structure of transmission lines have been considered similar. The velocities of propagation of f_{11} , f_{12} and f_{13} are $296784.29\frac{km}{s}$, $296699.45\frac{km}{s}$ and $297051.96\frac{km}{s}$, respectively. To identify the faulty line and fault location, first step all the equations (21), (25), (28), (32)-(34) and (35)-(37) must be calculated

$$d_{A1} = 79.99\ KM\ , d_{A2} = -24.09\ KM\ , d_{A3} = -25.26\ KM$$
$$d_{B1} = 95.09\ KM\ , d_{B2} = -8.99\ KM\ , d_{B3} = 96.26\ KM$$
$$d_{C1} = 44.73\ KM\ , d_{C2} = 44\ KM\ , d_{C3} = 45.90\ KM$$

In this case R_A , R_B and R_C are 0.3, 0.09 and 0.95, respectively. Therefore, the faulty line is CD sector of the terminal C, and the distance of the fault to terminal C is estimated $d_f = d_{C1} = 44.73\ KM$. To further investigate the proposed algorithm, in table 1 one-pole to ground fault is applied in different point of the studied system. The results of the table 1 shows this method to identify the faulty line and fault location have reasonable accuracy.

Table. 1. *Calculated fault distances for one-pole to ground faults*

Fault distance	**Natural frequencies** (HZ)	d_A (KM)	d_B (KM)	d_C (KM)	R_A	R_B	R_C	d_f (KM)
10 KM AD	$f_{11} = 14645$ $f_{12} = 2500$ $f_{13} = 1321$	$d_{A1} = 10.17$ $d_{A2} = 11.60$ $d_{A3} = 11.70$	$d_{B1} = 59.39$ $d_{B2} = 60.820$ $d_{B3} = 28.70$	$d_{C1} = 112.29$ $d_{C2} = 113.82$ $d_{C3} = 81.60$	0.86	0.47	0.72	10.17
15 KM AD	$f_{11} = 9277$ $f_{12} = 2730$ $f_{13} = 1389$	$d_{A1} = 16.05$ $d_{A2} = 16.61$ $d_{A3} = 17.20$	$d_{B1} = 54.39$ $d_{B2} = 54.94$ $d_{B3} = 34.20$	$d_{C1} = 106.79$ $d_{C2} = 107.94$ $d_{C3} = 86.60$	0.93	0.62	0.81	16.05
18 KM BD	$f_{11} = 2900$ $f_{12} = 8007$ $f_{13} = 1200$	$d_{A1} = 15.21$ $d_{A2} = 52.39$ $d_{A3} = 0.37$	$d_{B1} = 18.60$ $d_{B2} = 19.78$ $d_{B3} = 17.37$	$d_{C1} = 123.62$ $d_{C2} = 72.78$ $d_{C3} = 122.39$	0.007	0.87	0.58	18.60
30 KM BD	$f_{11} = 3906$ $f_{12} = 4687$ $f_{13} = 1323$	$d_{A1} = 38.02$ $d_{A2} = 39.30$ $d_{A3} = 11.86$	$d_{B1} = 31.69$ $d_{B2} = 32.97$ $d_{B3} = 28.86$	$d_{C1} = 112.13$ $d_{C2} = 85.97$ $d_{C3} = 109.30$	0.3	0.87	0.76	31.69
20 KM CD	$f_{11} = 1456$ $f_{12} = 1250$ $f_{13} = 7225$	$d_{A1} = 101.26$ $d_{A2} = -47.67$ $d_{A3} = 103.4$	$d_{B1} = 118.67$ $d_{B2} = -30.2$ $d_{B3} = 120.4$	$d_{C1} = 20.59$ $d_{C2} = 22.73$ $d_{C3} = 22.32$	0.46	0.25	0.9	20.59
70 KM CD	$f_{11} = 2800$ $f_{12} = 2152$ $f_{13} = 2100$	$d_{A1} = 53.03$ $d_{A2} = 2.03$ $d_{A3} = 53.3$	$d_{B1} = 68.96$ $d_{B2} = 17.97$ $d_{B3} = 70.3$	$d_{C1} = 70.69$ $d_{C2} = 70.96$ $d_{C3} = 72.03$	0.03	0.25	0.98	70.69

Conclusions

In this paper a novel algorithm to identify the faulty line and fault location in star connected multi terminal VSC-HVDC systems was proposed. If the dominant frequencies and the velocities of the propagation have been calculated accurately, the proposed algorithm can be used to identify the faulty line and to locate faults when a instability occurs in studied system.Fourier transform has been used to detect the frequency spectrum of the fault in each terminal and the dominant frequency component is calculated correctly. The proposed algorithm has been simulated in a star connected three terminal VSC-HVDC system. The results show this method can estimate the faulty line and fault location with high speed and suitable accuracy using only measured current signals and without need to synchronous communication, high sampling frequency and surge arrival time.

REFERENCES

[1] O. G. Bellmunt, J. Liang, J. Ekanayake, R. King, and N. Jenkins, "Topologies of multiterminal HVDC-VSC transmission for large offshore wind farms," *Elect. Power Syst. Res., vol. 81, pp. 271–281, Feb 2011.*

[2] J. Suonan, J. Zhang, Z. Jiao, L. Yang , and G. Song, "Distance protection for HVDC transmission lines considering frequency-dependent parameters," *IEEE Trans. Power Del, vol. 28, no. 2, April 2013.*

[3] M.B.Dewe, S.Sankar , and J.Arrillaga, "Application of satellite time references to HVDC fault location," *IEEE Trans. Power Del., vol. 8, no. 3, pp. 1295–1302, Jul 1993.*

[4] P. Chen, B. Xu , and J. Li, "A traveling wave based fault locating system for HVDC transmission lines," *in Proc. Int. Conf. PowerCon, Chongqing, China, 2006, pp. 1–4.*

[5] L. Shang, G. Herold, J. Jaeger, R. Krebs , and A. Kumar, "High-speed fault identification and protection for HVDC line using wavelet technique," *in Proc. IEEE Porto Power Tech Conf., Porto, Portugal, 2001, pp. 1–5.*

[6] P. K. Murthy, J. Amarnath, S. Kamakshiah , and B. P. Singh, "Wavelet transform approach for detection and location of faults in HVDC system," *in Proc. IEEE Region 10 3rd Int. Conf. Industrial and Information Systems, Kharagpur, India, 2008, pp. 1–6.*

[7] Z. Q. Bo, G. Weller, T. Lomas, and M. A. Redfern, "Positional protection of transmission systems using global positioning system, " *IEEE Trans. Power Del., 2000, 15, (4), pp. 1163–1168.*

[8] W. Zhao, Y. H. Song, and W. R. Chen, "Improved GPS travelling wave fault locator for power cables by using wavelet analysis," *Int. J. Electr. Power Energy Syst., 2011, 23, (5), pp. 403–411.*

[9] J. Suonan, S. Gao, G. Song, Z. Jiao , and X. Kang, " A novel fault-location method for HVDC transmission lines,"*IEEE Trans.Power Del, vol.25,no.2, April 2010*.

[10] A. Elhaffar , and M. Lehtonen , "Travelling waves based earth fault location in 400 kV transmission network using single end measurement," *Power System & High Voltage Engineering Helsinki University of Technology, Finland 2004.*

[11] N. E. Eng , and K. Ramar,"Single-ended traveling wave based fault location on two terminal transmission lines," *In IEEE TENCON, Singapore. 23rd–26th November, 2009. p. 1–4. ISBN: 978-1-4244-4547-9.*

[12] Z. X. Dong, and T. N. Ling,"A transient harmonic current protection scheme for HVDC transmission line," *IEEE Trans.Power Del,vol.27,no.4, October 2012.*

[13] O. M. K. K. Nanayakkara, A. D. Rajapakse, and R.Wachal, " Traveling-wave based line fault location in star-connected multiterminal HVDC systems," *IEEE Trans. Power Del, vol. 27, no. 4, October 2012.*

[14] M. da Silva, M. Oleskovicz, and D. V. Coury, "A fault locator for three-terminal lines based on wavelet transform applied to synchronized current and voltage signals," *in Proc. IEEE Power Energy Soc. Transm. Distrib. Conf. Expo: Latin America, 2006, pp. 1–6.*

[15] Z. Y. He, K. Liao, X. P. Li , S. Lin , J. W. Yang , and R. K. mai, " Natural frequency-based line fault location in HVDC lines ," *IEEE Trans. Power Del, vol. 29, no. 2, April 2014.*

[16] S. G. Bing , C. X. Lei , G. S. Ping , S. Jiale , and L. Guang , "Natural frequency based protection and fault location for VSC-HVDC transmission lines," *Advanced Power System Automation and Protection (APAP), 2011 International Conference on , vol. 1 , pp.177 -182.*