Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2017) 25: 2846 – 2859
© TÜBİTAK
doi:10.3906/elk-1605-200

Development of PMU-based backup wide area protection for power systems considering HIF detection

Saeed ASGHARIGOAVR*, **Heresh SEYEDI**
Faculty of Electrical & Computer Engineering, University of Tabriz, Tabriz, Iran

Received: 19.05.2016 • **Accepted/Published Online:** 05.11.2016 • **Final Version:** 30.07.2017

Abstract: In this paper a wavelet packet transform (WPT)-based algorithm is proposed to develop and improve the backup wide area protection for power systems equipped with phasor measurement units (PMUs). Faults on power systems such as high impedance faults (HIFs) have specific characteristics that include high frequency components that can be extracted using the WPT, which is one of the important methods in signal processing. The proposed idea uses power system voltage and current, measured by voltage and current transformers, respectively, and calculates high frequency information of voltage and current waveforms. Afterwards, the differences of voltage coefficients of each phase at each bus with remote buses are compared with a threshold value to detect HIFs in a power system. In addition, differences of current coefficients of each phase of transmission lines in local and remote terminals are compared with a threshold value for discovering the faulted line. The sum of the current coefficients of all feeders connected to the same bus, for each phase, is compared with a threshold value for discriminating the faulted bus. This algorithm is able to detect the regular fault types. It should be noted that for using PMUs and their time-synchronized systems with high-speed GPS communication links, it is necessary to access the power system's real-time data at local and remote terminals. The presented method is simulated by MATLAB software on the New England Power Network. Simulation results show that the algorithm has sufficient security and dependability.

Key words: Fault detection, GPS, high impedance fault, phasor measurement unit, wavelet packet transform, wide area protection

1. Introduction

As power systems grow and become increasingly complicated, the application of distance relays as backup protection faces certain problems such as time coordination and fault impedance [1]. Hence, employing wide area differential backup protection for buses and connected lines could operate better than conventional distance protection and alleviate its problems [2]. In addition, the distance protection method is designed to operate for faults occurring between the relay location (with minimum impedance) and the reach point impedance [3]. However, the fault impedance may take the fault outside the reach point of the relay. Therefore, the distance relay cannot detect the fault in zone one [4]. An adaptive phasor measurement unit (PMU)-based protection scheme for transposed/untransposed parallel transmission lines was proposed in [5]. The development of this scheme is based on synchronized phasor measurements and distributed parameter lines at both ends of the lines. In [6], a PMU-based fault detection/location technique for transmission lines considering arcing fault discrimination was presented, achieved by the combination of fault detection and location indices. In addition, a

*Correspondence: s.asghari66@gmail.com

new technique for fault classification and faulted section identification in transmission lines based on S transform and support vector machines was presented in [7]. In this field, a wide area backup protection scheme for shipboard applications is suggested to suit the needs of shipboard applications, because conventional backup protection has faced problems when applied to short cables [8]. In addition, a backup wide area protection technique for power transmission grids using PMUs was proposed in [9]. This method depends on comparing positive sequence voltage magnitudes of power system buses to recognize the nearest bus to the fault. Then the positive sequence current angles of both terminals of lines connected to that bus are compared to detect the faulted line.

The fault that occurs in a power system may be a high impedance fault (HIF) instead of a regular fault. In [1–9], different fault detection and backup wide area protection schemes were proposed, while in [10–21] methods for detecting and discriminating HIFs were presented.

HIF current is generally not significantly different from load current in no-fault conditions. Therefore, conventional overcurrent relays cannot detect it simply. Moreover, HIFs occur when a conductor makes contact with dry ground, trees, highly resistive soil, etc. and detection of these faults is necessary due to the fires caused by HIFs [10]. HIFs usually include some arcing and nonlinear characteristics, which are caused by fault impedance. Thus, these characteristics could be helpful to detect HIFs in power systems with the aid of signal processing methods like the wavelet packet transform (WPT) [11]. Many studies have been carried out about HIF detection during the last years. Some HIF detection algorithms using the discrete wavelet transform were suggested in [10,11]. In [12], a protection technique based on current asymmetry was proposed. Some low frequency-based algorithms were also suggested for HIF protection [13,14]. Furthermore, several papers presented HIF protection methods based on artificial neural networks [15,16] and intelligent systems [17,18]. Additionally, an approach to the classification of faults of high-voltage transmission lines using the WPT was proposed in [19]. In [20], the WPT was employed to calculate root mean square value. In [21], an algorithm based on WPT for power transmission line protection was proposed. The pilot protection method was used to increase security and dependability. In this technique, measurements of voltages and currents of each phase at local terminals of transmission lines, which are connected to the same bus, are imported into the algorithm.

This paper provides a new method for backup wide area protection for detection/location of both high current faults (regular faults) and low current faults (HIFs). This method is based on the comparison of voltage coefficients of each bus with adjacent buses for each phase to detect the fault occurrence. Furthermore, comparing the current coefficients at both local and remote terminals of transmission lines for each phase to discover the fault location is proposed if it occurs on lines. In addition, comparison of current coefficients of each phase at all terminals that are connected to the same bus is used to distinguish the faulted bus. All fault types will be investigated in this paper. The proposed method uses time-synchronized phasor measurements, which are processed in the system protection center (SPC). This ability provides power system control and protection using a high-speed communication system and GPS.

2. Backup wide area protection

As power systems grow, system-wide disturbances in electrical power systems become a critical problem for power system protection and stability due to their vastness and complexity. When an intense power system disturbance occurs, some protection and control actions are needed to prevent power system degradation, restore it to a normal condition, and minimize the effects of disturbance. Therefore, to cope with these problems, wide area protection systems and wide area measurements are widely employed in power systems for protection, control, management, and monitoring.

Recently, the fast development of communication technology and the advent of synchronized phasor measurements and computer-based relays have added another dimension to the field of wide area protection. The PMU is generally installed in power system strategic substations and provides all sufficient measurements including frequency, bus voltage, and line current magnitudes and angles.

In [9], a new technique based on a PMU for power transmission line protection was proposed. This method is mainly based on two components: bus voltage magnitudes and absolute differences of line current angles at both terminals. The first component is used for fault detection. It is clear that voltage drop occurs during a fault condition. Thus, this component is able to detect fault occurrences. The second component is used to identify the faulted line. When a fault occurs on a transmission line, the fault current angle at one of the line terminals changes by about 180° toward the fault point. Therefore, the faulted line could be determined using this component. In other words, the proposed technique in [9] suggests a two-part algorithm for transmission line protection in power systems. This algorithm measures positive sequence voltage magnitudes by PMUs for all buses and flags the lowest bus voltage if it is less than a threshold value. As a result, the nearest bus to the fault is determined. The algorithm then measures the absolute difference of positive sequence current angles of both terminals of transmission lines that are connected to the marked bus. Hence, the faulted line is identified by comparing the absolute values with a threshold value.

3. HIF protection method

The HIF is a complicated phenomenon that consists of three principal characteristics, which are observable in all HIFs. The first one is the build-up feature, which is defined as increasing HIF current magnitude during transient conditions. This characteristic may not appear in steady-state conditions [22]. The second HIF characteristic is nonlinearity, which is created by odd harmonics. Moreover, an asymmetry feature, which is described as the third main characteristic of the HIF, is related to DC offset and current magnitude difference between positive and negative half cycles [23]. The Emanuel arc model that is employed in this case study for modeling HIFs was presented in [21,24]. This model includes HIF main characteristics and all frequency components. Therefore, it is similar to real HIF features, which are recorded from many power systems. Figure 1 shows the mentioned model that is applied to a sample power system during six cycles [21].

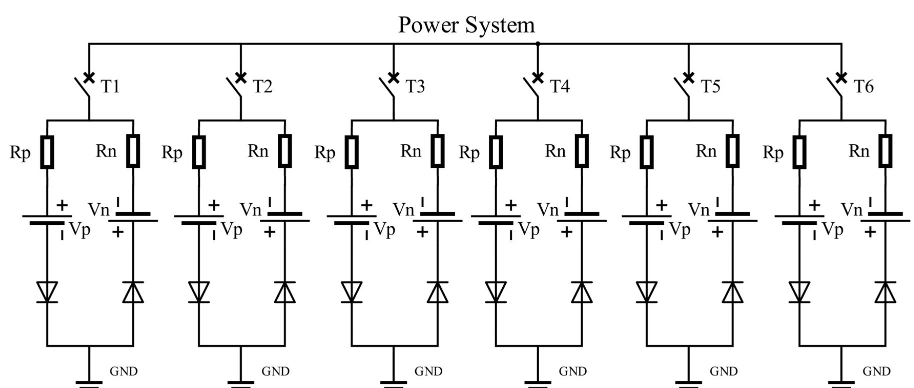

Figure 1. High impedance fault model [21].

The WPT is a generalization of wavelet decomposition that offers a richer signal analysis in which more detailed components are decomposed. In the WPT, the input signal is bisected to high-frequency and low-frequency components in each level. The most important advantage of the WPT versus other wavelet transforms is its accurate detailed results of signal decomposition in a limited spectrum, which makes it effective in signal processing [21,26]. The Daubechies-4 (Db4) wavelet that was selected as a mother wavelet in [21] is one of the appropriate orthogonal wavelets, due to its high performance and simple application in the digital world [21,25]. A two-stage algorithm based on WPT for HIF protection of power transmission lines was proposed in [21]. The first part uses the voltage waveform to detect HIFs. In this technique, information of the voltage waveform is applied to the WPT after sampling, and high-frequency data of the voltage, i.e. WPT coefficients, are achieved for each phase. Afterwards, differences of coefficients of each phase from other phases are computed and compared with a threshold value. These calculations are done for each sample. If a certain number of these values are greater than the threshold value, HIF occurrence is confirmed. The second part of the algorithm is zone discrimination. This part of the algorithm uses the current waveform to distinguish the faulted line. After sampling the current signal, sample data are imported to the WPT and coefficients are obtained for each phase. Differences of coefficients of each phase from other phases are calculated and compared with both lines' threshold values to discriminate the faulted line.

In [21], furthermore, pilot protection methods such as DUTT, POTT, and PUTT were employed to increase protection system security and dependability.

4. Improved wide area backup protection

In this section, the existing wide area backup protection is improved in order to make it capable of detecting both regular and high impedance faults. In addition, the developed scheme is able to detect both line and busbar faults. The presented algorithm consists of three main parts. The first part is fault detection, which is based on voltage waveform received by PMUs from potential transformers (PTs). Applying 200 kHz sampling frequency, 4000 samples are achieved in each cycle of voltage waveform. WPT with the aid of the Db4 wavelet is used to calculate high-frequency components of the sampled waveforms. Hence, these 4000 samples are applied to the WPT, and consequently data of the 30th node of the wavelet packet tree, which contains the highest frequency data of the signal, are obtained by PMU processors and then sent to the SPC to minimize processing in the SPC. This node consists of 250 coefficients due to 4-level decomposition, inasmuch as samples are classified in high- and low-frequency categories in each level of decomposition of the WPT. Therefore, it is the best node for detecting low-amplitude and high-frequency disturbances on voltage waveforms. Afterwards, output information of the WPT are sent to the SPC from all PMUs to continue the rest of the algorithm in the SPC. Figure 2 shows the fault detection flowchart of the proposed algorithm. Cva,l, Cva,r, Cvb,l, Cvb,r, Cvc,l, and Cvc,r are absolute values of voltage coefficients of the local and remote terminals during the last cycle for the A, B, and C phases, respectively. The coefficient is computed for each sample during the last cycle. After computing coefficients for the A, B, and C phases at selected buses of the power system, absolute values of (Cva,l – Cva,r), (Cvb,l – Cvb,r), and (Cvc,l – Cvc,r) are calculated at each bus and compared with a threshold value, V_{th}. This means that differences of voltage coefficients in local and remote buses are computed for each phase. If any of these absolute values become greater than the threshold value, it indicates a warning condition for the power system. F is the number of these conditions that are counted by the algorithm and T is the minimum number of high amplitude (higher than the threshold value) absolute values of voltage coefficients during a fault condition in one cycle, which is set to 30 based on many simulation studies. If F exceeds T during the last cycle, the algorithm detects the fault condition. This one-cycle delay enhances the security of the proposed scheme.

The second part of the algorithm is fault discrimination on transmission lines. This part of the algorithm uses current waveforms, which are measured by current transformers (CTs). Moreover, the sampling frequency in this part is equal to that of the previous part of the algorithm. Hence, 4000 samples for each cycle of current waveforms of all lines are obtained by PMUs. The 15th node on the wavelet packet tree is selected, since this node contains the lowest frequency information of the waveform. Due to low-frequency and high-amplitude components, which are presented in the current waveform in fault conditions, the 15th node is the best node to analyze the current waveform. This node consists of 250 coefficients of the current signal because of 4-level decomposition. Afterwards, output information of the WPT is sent to the SPC from all PMUs. The faulted line location algorithm is shown in Figure 3. Cia,l, Cia,r, Cib,l, Cib,r, Cic,l, and Cic,r are sums of the current coefficients during the last cycle at both ends (local and remote terminals) of the transmission lines for the A, B, and C phases, respectively. Differences of coefficients of both ends of the lines ([Cia,l – Cia,r], [Cib,l – Cib,r], and [Cic,l – Cic,r]) at each phase are calculated and compared with a threshold value, A_{th}. If any of these differences are greater than the threshold value, the faulted line and also the faulted phase are accurately identified by the presented algorithm. The proposed algorithm is able to detect all fault types such as HIFs and regular faults and recognize their locations all over the transmission lines. Moreover, the security and dependability of the suggested algorithm are very high, since the output of the algorithm depends on the information of many buses of the power grid, not just a limited section of the network.

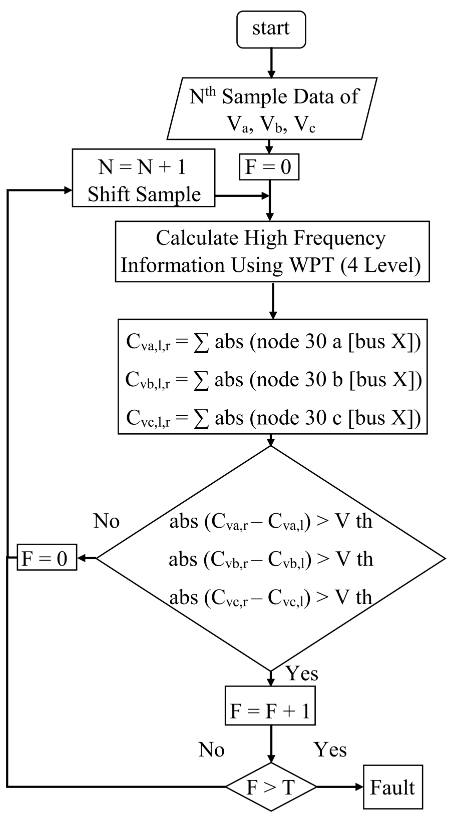

Figure 2. Fault detection algorithm.

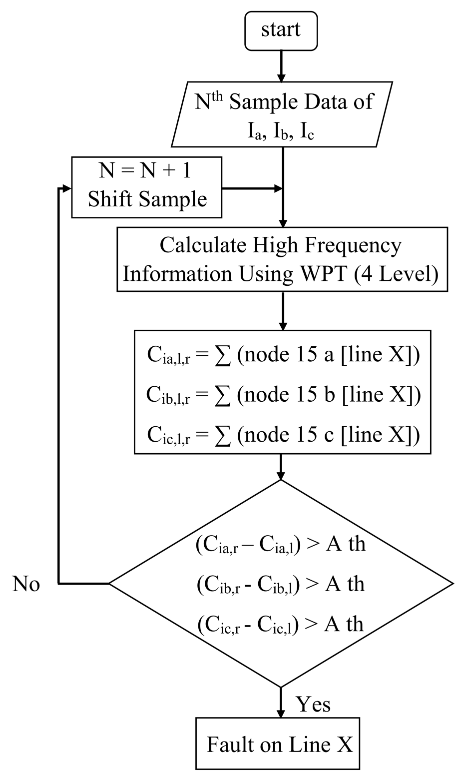

Figure 3. Faulted line discrimination algorithm.

Busbar protection is one of the important cases in protection studies. Therefore, the third part of the proposed algorithm is allocated to faulted bus diagnosis. In addition to the regular faults, HIFs may occur in substations in which the busbar conductor type is not a solid, tubular, or flat busbar. In some substations, especially with the ring structure, cables are used as busbars. In this condition, the probability of HIF occurrence can be investigated. In this case, the algorithm uses current waveforms of every feeder connected to the same bus. Therefore, 4000 samples of each cycle of current signals are applied to the WPT and information of the 15th node is achieved. This section of the algorithm is shown in Figure 4. Cia,s, Cib,s, Cic,s (where "s" is related to source), Cia,l, Cib,l, Cic,l (where "l" is related to line), Cia,o, Cib,o, and Cic,o (where "o" is related to load) are sums of the absolute values of current coefficients, computed by PMUs with the WPT during the last cycle for every feeder and sent to the SPC. Afterwards, values of (Cia,s + Cia,l + Cia,o), (Cib,s + Cib,l + Cib,o), and (Cic,s + Cic,l + Cic,o) are calculated in the SPC and compared with threshold value B_{th}. If any of these values exceed the threshold value, the faulted bus is recognized. The presented algorithm is able to identify both regular faults and HIFs in a substation.

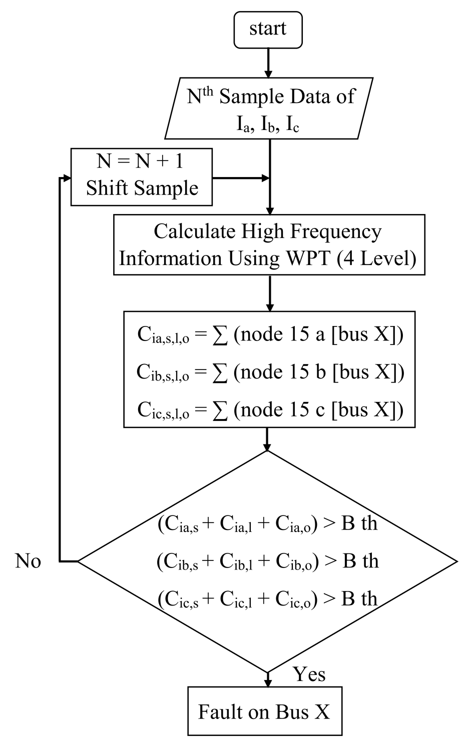

Figure 4. Faulted bus discrimination algorithm.

5. Simulation results

In this section, simulation studies are performed on a part of the New England Power Network as shown in Figure 5. As depicted in the figure, buses 21, 22, 23, and 24 and lines 1, 2, and 3 are selected to implement the simulation studies. Furthermore, voltage, current, and coefficient waveforms of a HIF are shown in Figures 6, 7, and 8, respectively. To demonstrate the technique abilities, HIFs and regular fault types considering fault location, fault inception angle, etc. are evaluated using MATLAB. In order to save space, only samples of simulation results are given.

5.1. Fault location

Coefficients of voltage waveform are not constant and depend on the fault location. Therefore, it is predictable that reducing the distance between fault location and substation increases the values of coefficients. The presented algorithm calculates the difference of coefficients (Cva,b23 − Cva,b22) related to buses 23 and 22, respectively. Therefore, it is clear that the difference value of the output of the algorithm should be high for

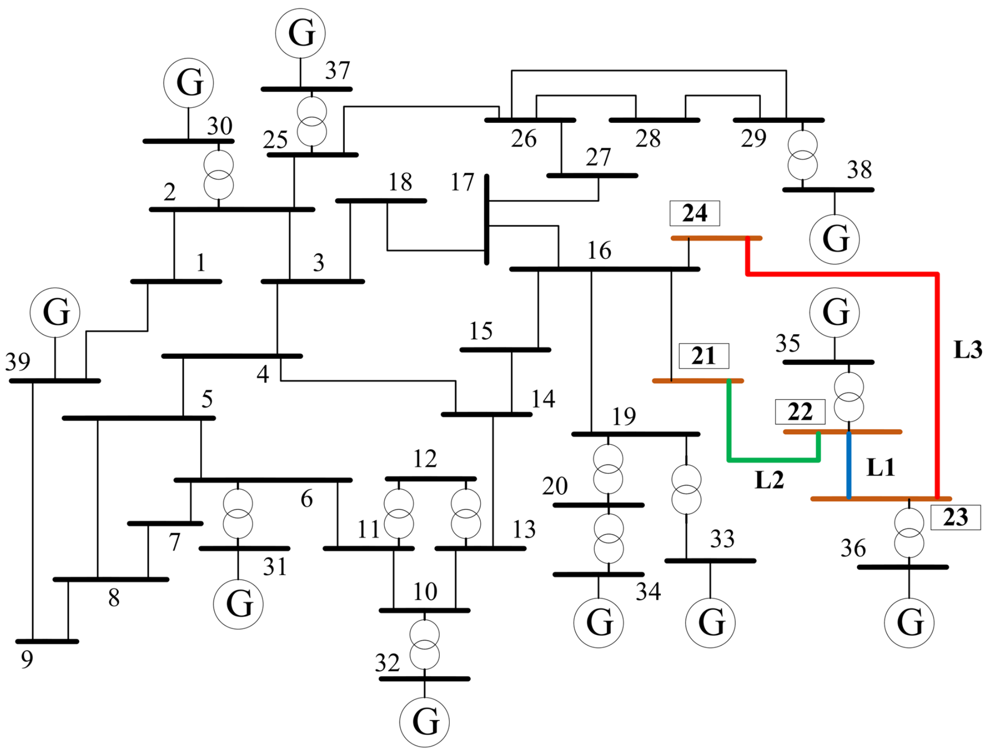

Figure 5. New England Power Grid.

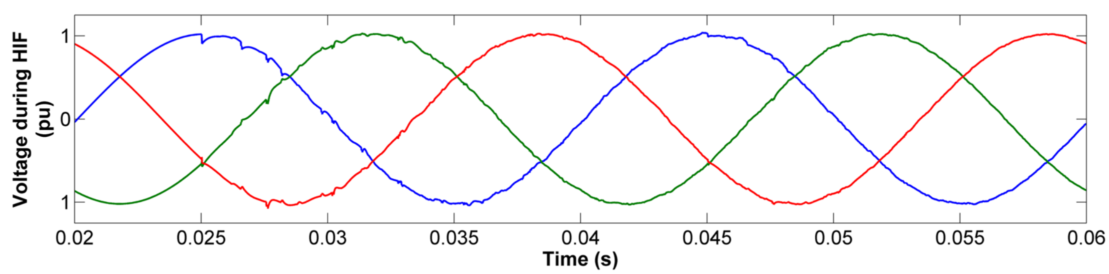

Figure 6. Three phase voltage waveform during HIF.

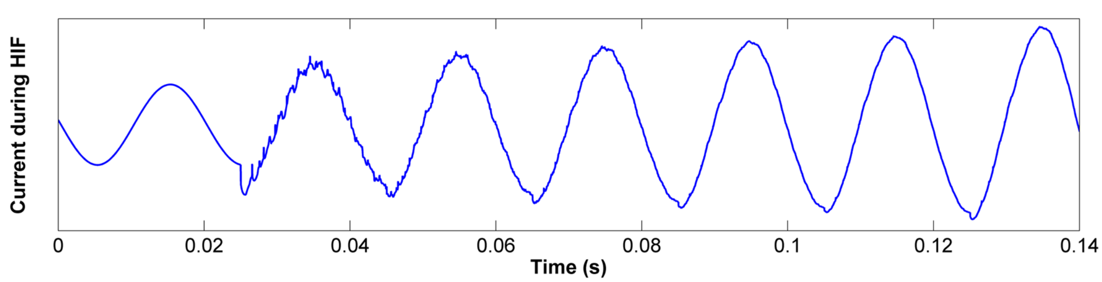

Figure 7. Current of phase A during HIF.

faults at both sides of the line and low for faults at the middle of the line. Different fault locations on line 1 (the line that connects b22 and b23) are simulated and the dependence of coefficients on the fault location is shown in Figure 9. Faults in the middle of the line, which produces the lowest difference of coefficients, are the worst case and the threshold value should be lower than the lowest difference value with an acceptable margin. In

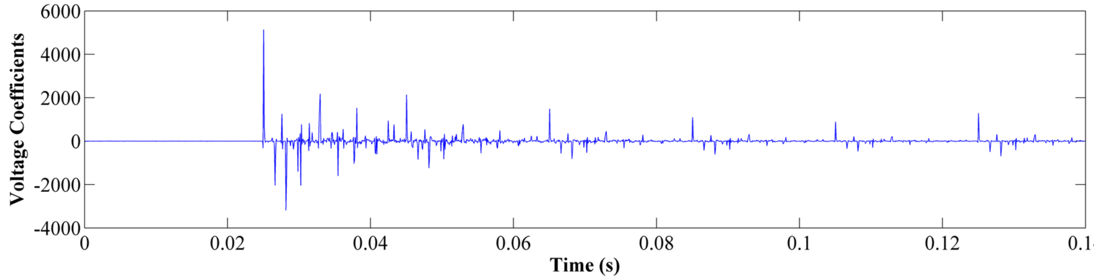

Figure 8. Voltage coefficients of phase A during HIF.

this case, the threshold value should be set to less than 4000 to detect all faults on line 1. Moreover, all faults in the next sections will be tested in the middle of transmission lines to examine the security of the algorithm.

5.2. Fault inception angle

In addition to the fault location, voltage coefficients depend on the function of the fault inception angle. Figure 10 shows coefficients for different fault inception angles during one cycle. The fault is located at the middle of line 1 and the fault type is a single line to ground HIF on phase A. As shown in the figure, the lowest difference of coefficients is produced in the zero fault inception angle. In this case, the coefficient is equal to 2000. Hence, the threshold value should be lower than 2000. As a result, it is set to 1000 to protect all faults with various inception angles and locations with an acceptable margin.

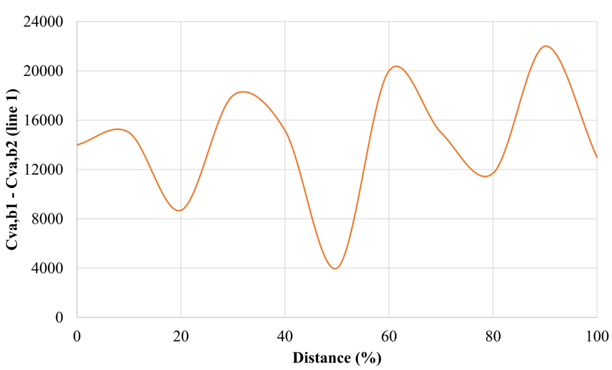

Figure 9. Effect of different fault locations on line 1.

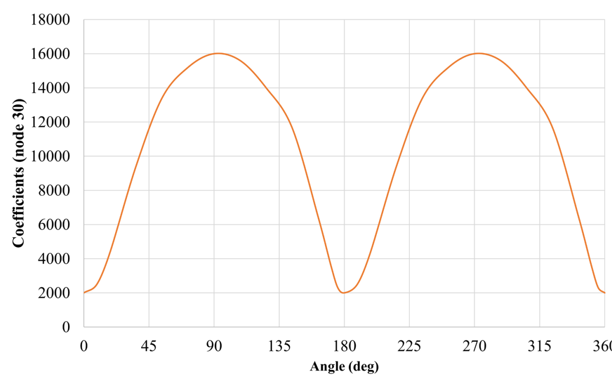

Figure 10. Effect of different fault inception angles.

5.3. Double-phase and three-phase faults

In some rare situations in power systems, HIFs may occur between two or three phases due to the contact of conductors with a tree. This condition is also studied to show the proposed technique's dependability, security, and sensitivity. The HIF occurs at the middle of the line 1 between phases A and B and phases A, B, and C, respectively. Figures 11 and 12 compare the difference values of phases for line 1.

5.4. Response time of the algorithm

Figure 11 shows the differences of voltage coefficients before and after the fault occurrence. The proposed algorithm detects the fault at the middle of line 1 with 0 degree inception angle in less than 0.5 ms. In addition, a time delay is added to increase the security of the algorithm.

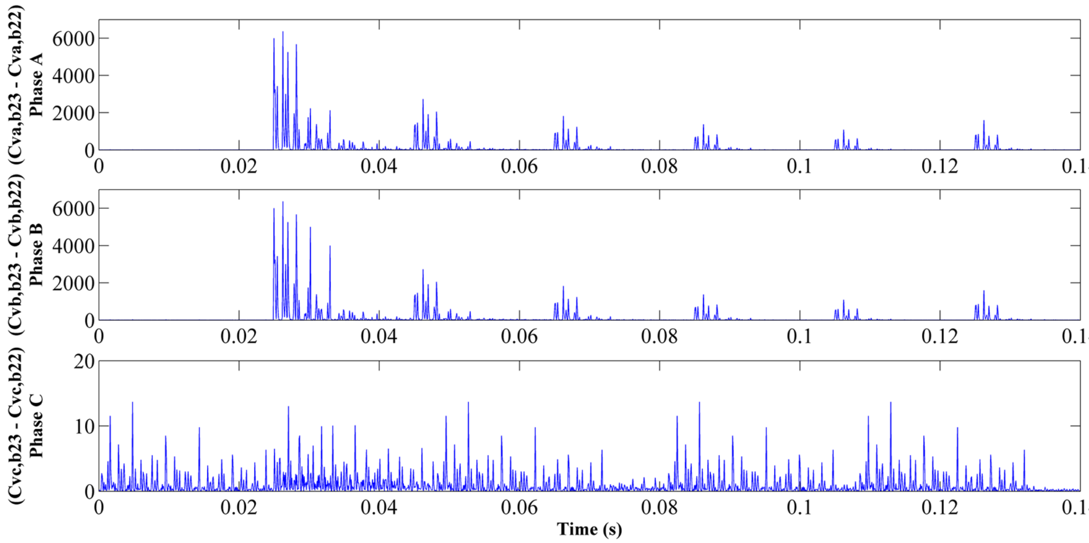

Figure 11. Phase to phase HIF discrimination.

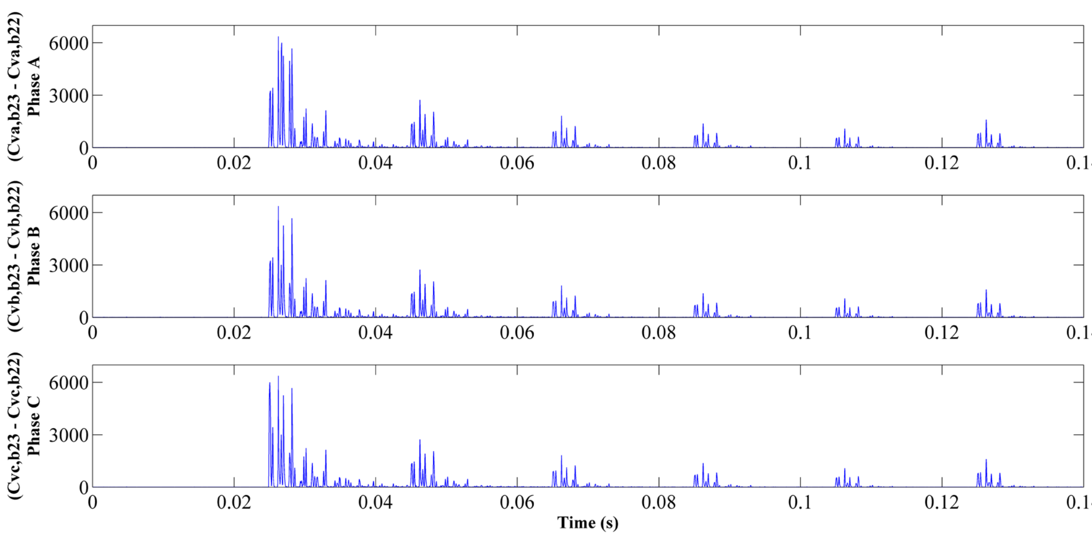

Figure 12. Three phase HIF.

5.5. Faulted line discrimination

In this part, difference values of current coefficients of the 15th node of the wavelet packet tree are calculated as described in Section 4 and shown in Figure 13. Current waveform information is achieved by current transformers that are located on the ends of line 1 (bus 23 and bus 22). The fault is a single line to ground HIF at the middle of line 1 with 0 degree inception angle on phase A. As shown in the figure, in this technique, there are significant differences between the faulted line and other lines. Hence, the threshold value can be selected with a great margin. The lowest value for line 1 is higher than 18,000 and the highest value for other lines is less than 10,000. Thus, the threshold value should be set to 14,000 to detect all faults on line 1.

5.6. Faulted bus discrimination

In this section, HIF recognition on the bus is examined. As shown in Figure 14 and described in Section 4, the HIF occurs at phase A of bus 23 and performance of the algorithm is analyzed for phases A and B at bus 23.

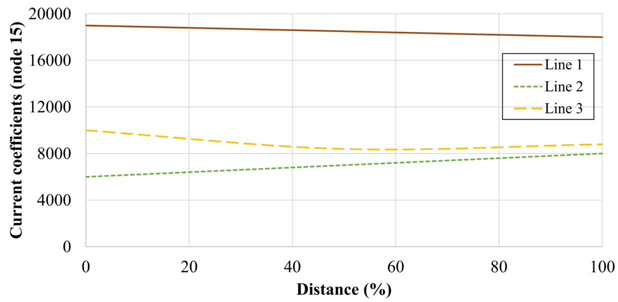

Figure 13. Faulted line discrimination.

According to the figure, there is a great difference between the faulted phase and the other phase. Hence, the threshold value can be chosen easily. It is clear that the highest value for phase B is less than 1e-11. Therefore, the threshold value is set to 50 to detect all faults on the bus. Consequently, the algorithm is able to distinguish the faulted bus and discriminates the faulted phase on the bus.

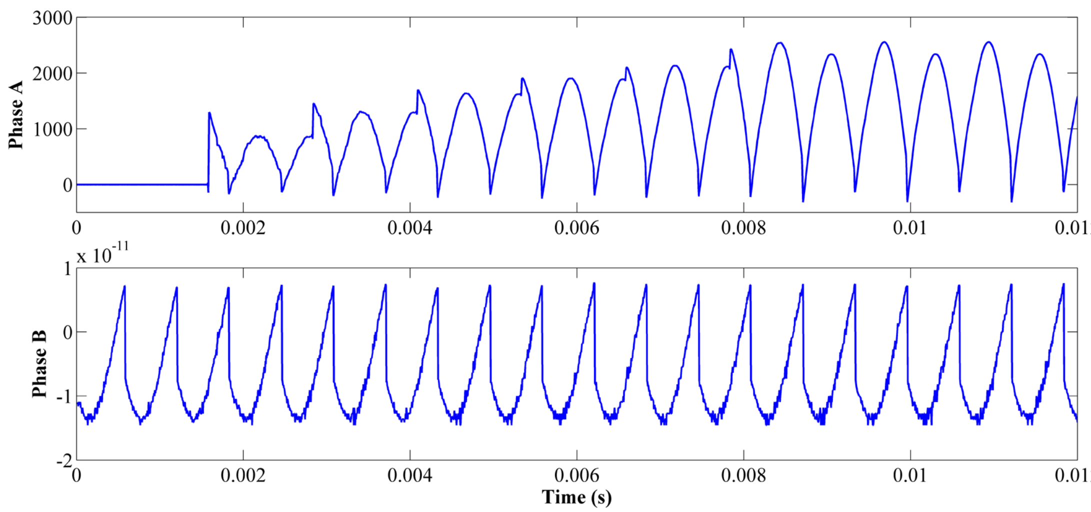

Figure 14. Faulted bus discrimination algorithm response.

5.7. Regular fault

As mentioned in previous sections, the proposed algorithm is also able to detect regular faults. A single phase to ground short circuit at the middle of line 1 with 0 degree inception angle is simulated. As shown in Figure 15, unlike the other areas, there are plenty of voltage coefficients that are higher than 300 in the area between b23 and b22 (line 1). Therefore, the voltage algorithm is also able to distinguish the fault location.

According to Figure 16, the algorithm's ability in faulted phase discrimination is obvious. In this case, a single line to ground short circuit at phase A with 0 degree inception angle at the middle of line 1 is simulated. In other words, the suggested algorithm is able to recognize the faulted phase by comparing voltage coefficient differences. Thus, single phase reclosing is possible.

Moreover, as depicted in Figure 17, the proposed algorithm is able to detect a two phase to ground regular fault between phases A and B on the middle of line 1 with 0 degree inception angle.

According to Figure 18, the presented algorithm is able to distinguish the faulted line from other lines. In this case, single phase to ground regular faults occur all over line 1 with 0 degree inception angle. As shown

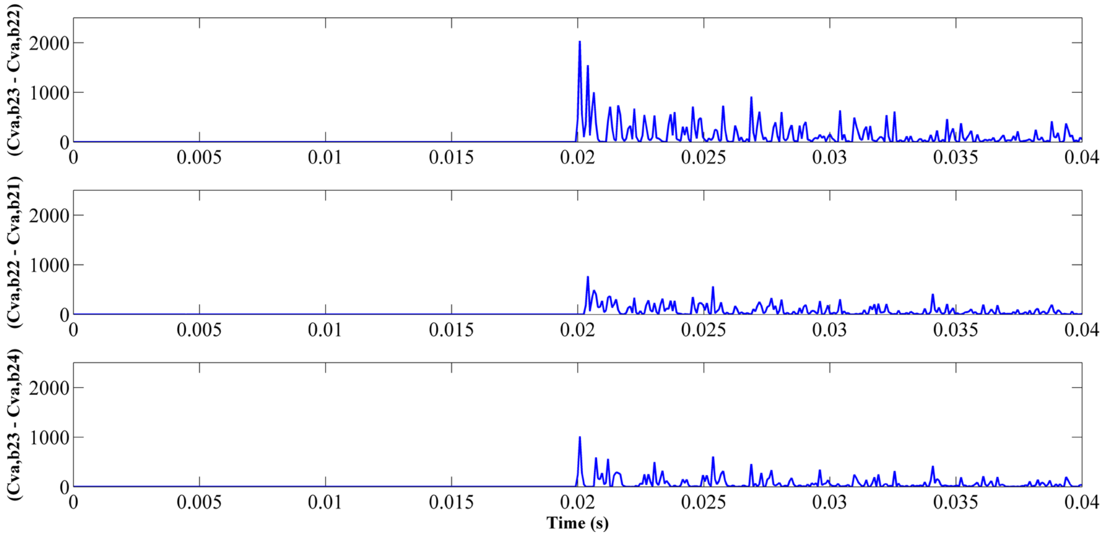

Figure 15. Performance of the algorithm for regular faults.

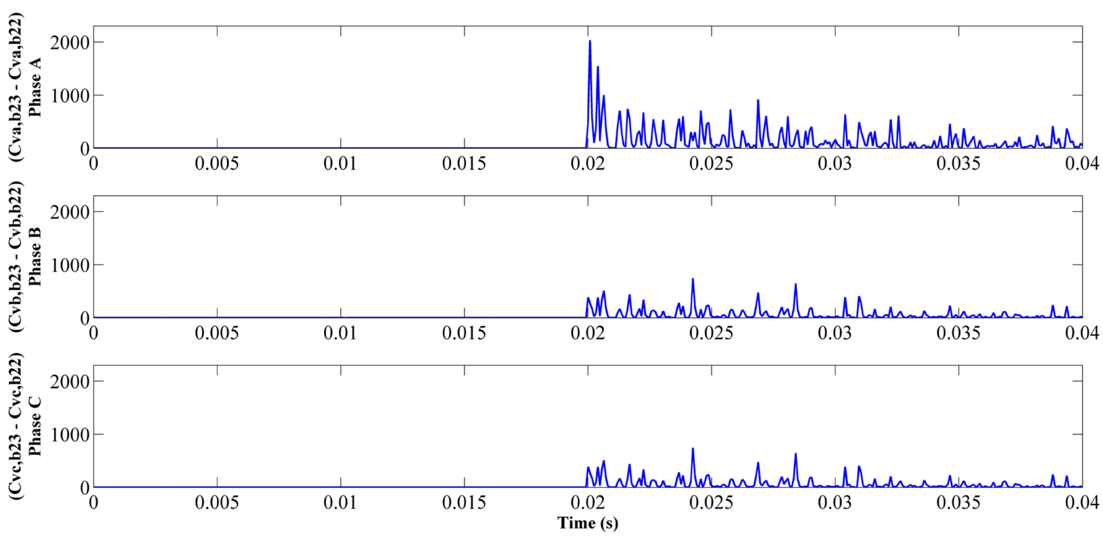

Figure 16. Faulted phase discrimination for regular faults.

in the figure, the minimum value of the current coefficient of line 1 is higher than 16,000 and the maximum value of the other lines is less than 9000. Thus, the threshold value should be 12,500 to detect all faults on line 1 with an acceptable margin.

As shown in Figure 19, the capability of the proposed algorithm in faulted bus and faulted phase identification is demonstrated by selecting 50 for the threshold value. In this case, a single line to ground regular fault on phase A of bus 23 occurs and the result is compared with phase B at the same bus.

6. Conclusion

We have presented a wide area protection technique based on PMUs to distinguish regular faults and HIFs on high-voltage power transmission lines and buses using WPT. The proposed method is based on voltage and current signals measured by PTs and CTs, respectively. Various simulations for different fault conditions such

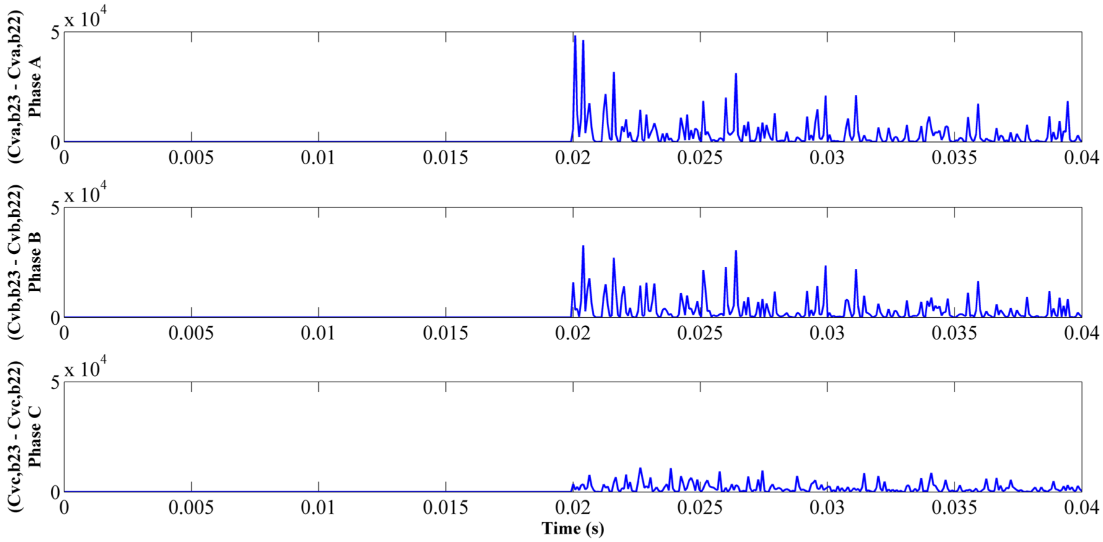

Figure 17. Phase to phase fault discrimination.

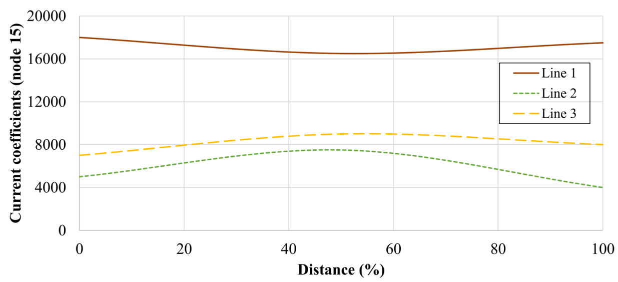

Figure 18. Faulted line discrimination.

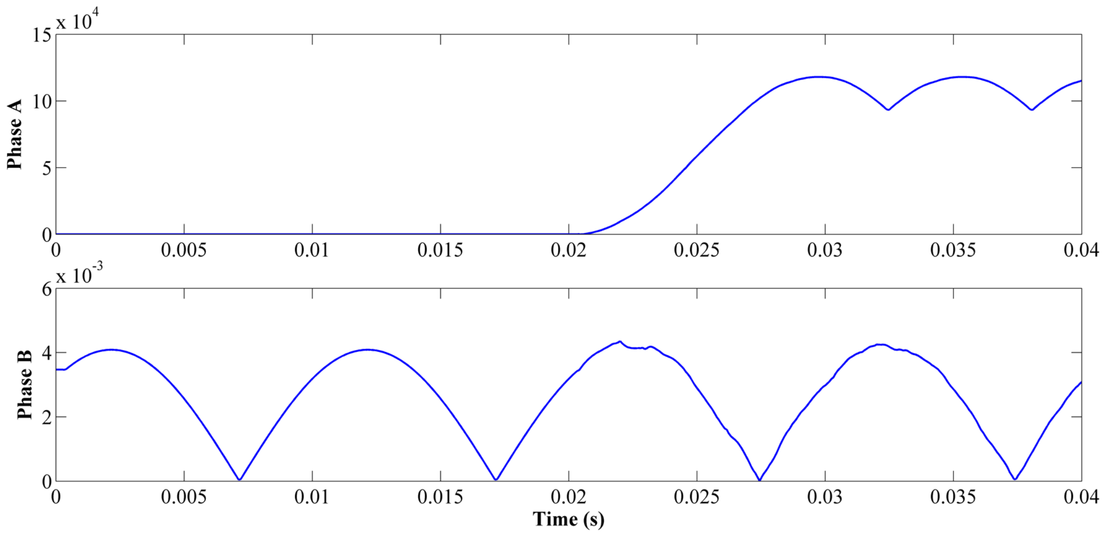

Figure 19. Faulted bus identification.

as different inception angles, different fault locations, and different fault types have been performed for a sample power system using MATLAB to show the reliability, sensitivity, and stability of the algorithm. The presented scheme has detected the faulted phase, line, and bus all over the power grid in a fraction of a second successfully. This algorithm has appropriate operation for the following reasons:

- Using PMUs for accessing time-synchronized information of power systems.
- Using GPS systems to obtain high-speed communication links.
- Using local and remote terminal information for highly reliable responses of the algorithm.
- Distinguishing both HIFs and regular faults.
- Providing protection for both the line and the busbar.

References

[1] AsghariGovar S, Seyedi H. Adaptive CWT-based transmission line differential protection scheme considering cross-country faults and CT saturation. IET Gener Transm Dis 2016; 10: 2035-2041.

[2] Serizawa U, Myoujin M, Kitamura K, Sugaya N, Hori N, Takeuchi A, Shuto I, Inukai M. Wide-area current differential backup protection employing broadband communications and time transfer systems. IEEE T Power Deliver 1998; 13: 1046-1052.

[3] Horowitz SH, Phadke AG. Power System Relaying. 2nd ed. New York, NY, USA: John Wiley & Sons, 2008.

[4] Eissa MM. New principle for transmission line protection using phase portrait plane. IET Gener Transm Dis 2009; 3: 49-56.

[5] Chen CS, Liu CW, Jiang, JA. A new adaptive PMU based protection scheme for transposed/untransposed parallel transmission lines. IEEE T Power Deliver 2002; 17: 395-404.

[6] Lin YH, Liu CW, Chen CS. A new PMU-based fault detection/location technique for transmission lines with consideration of arcing fault discrimination-Part I: Theory and algorithms. IEEE T Power Deliver 2004; 19: 1587-1593.

[7] Çöteli R. A combined protective scheme for fault classification and identification of faulty section in series compensated transmission lines. Turk J Electr Eng Co 2013; 21: 1842-1856.

[8] Tang J, McLaren PG. A wide area differential backup protection scheme for shipboard application. IEEE T Power Deliver 2006; 21: 1183-1190.

[9] Eissa MM, Elshahat MM, Elanwar M. A novel back up wide area protection technique for power transmission grids using phasor measurement unit. IEEE T Power Deliver 2010; 25: 270-278.

[10] Lai TM, Snider LA, Lo E, Sutanto D. High-impedance fault detection using discrete wavelet transform and frequency range and RMS conversion. IEEE T Power Deliver 2005; 20: 397-407.

[11] Bakar AHA, Ali MS, Tan CK, Mokhlis H, Arof H, Illias HA. High impedance fault location in 11 kV underground distribution systems using wavelet transforms. Int J Elec Power 2014; 55: 723-730.

[12] Sultan AF, Swift GW, Fedirchuk DJ. Detecting arcing downed-wires using fault current flicker and half-cycle asymmetry. IEEE T Power Deliver 1994; 9: 461-470.

[13] Zamora I, Sagastabeitia KJ, Zamora JJ. New method for detecting low current faults in electrical distribution systems. IEEE T Power Deliver 2007; 22: 2072-2079.

[14] Zamora JJ, Zamora I, Mazón AJ, Sagastabeitia KJ. Optimal frequency value to detect low current faults superposing voltage tones. IEEE T Power Deliver 2008; 23: 1773-1779.

[15] Samantaray SR, Dash PK, Upadhyay SK. Adaptive Kalman filter and neural network based high impedance fault detection in power distribution networks. Int J Elec Power 2009; 31: 167-172.

[16] Michalik M, Rebizant W, Lee SJ, Kang SH. New ANN-based algorithms for detecting HIFs in multigrounded MV networks. IEEE T Power Deliver 2008; 23: 58-66.

[17] Etemadi AH, Sanaye-Pasand M. High-impedance fault detection using multi-resolution signal decomposition and adaptive neural fuzzy inference system. IET Gener Transm Dis 2008; 2: 110-118.

[18] Samantaray SR. Ensemble decision trees for high impedance fault detection in power distribution network. Int J Elec Power 2012; 43: 1048-1055.

[19] Hooshmand RA, Modarresi J. A new combined method for RMS calculation based on wavelet packet and Hilbert transform. Turk J Electr Eng Co 2016; 24: 3178-3197.

[20] Yumurtacı M, Gökmen G, Kocaman Ç, Ergin S, Kılıç O. Classification of short-circuit faults in high-voltage energy transmission line using energy of instantaneous active power components-based common vector approach. Turk J Electr Eng Co 2016; 24: 1901-1915.

[21] Mahari A, Seyedi H. High impedance fault protection in transmission lines using a WPT-based algorithm. Int J Elec Power 2015; 67: 537-545.

[22] Nam SR, Park JK, Kang YC, Kim TH. A modeling method of a high impedance fault in a distribution system using two series time-varying resistances in EMTP. In: IEEE 2001 Power Engineering Society Summer Meeting; 2001. pp. 1175-1180.

[23] Aboul-Zahab EM, Eldin EST, Ibrahim DK, Saleh SM. High impedance fault detection in mutually coupled double-ended transmission lines using high frequency disturbances. In: IEEE 2008 Power System Conference; March 2008. pp. 412-419.

[24] Sedighi AR, Haghifam MR. Simulation of high impedance ground fault In electrical power distribution systems. In: IEEE 2010 International Conference on Power System Technology; 2010. pp. 1-7.

[25] Percival DB, Walden AT. Wavelet Methods for Time Series Analysis. Vol. 4. Cambridge, UK: Cambridge University Press, 2006.

[26] Ghaffarzadeh N, Behrooz V. A new protection scheme for high impedance fault detection using wavelet packet transform. Adv Electr Comput En 2010; 10: 17-20.