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DWT-Based Investigation of phase currents for Detecting High Impedance Faults Due to Leaning Trees in Unearthed MV Networks

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***Abstract* — In this paper, features of earth faults due to leaning trees are extracted from the network phase currents using the discrete wavelet transform (DWT). Due to the associated arc reignitions, the initial transients in the electrical network give behavioral traits. The detection security is also enhanced because the DWT is responded to a periodicity of the initial transients. The absolute sum of the DWT detail d3 coefficient corresponding to the frequency band 12.5-6.25 kHz is computed over one power cycle for each phase current of each feeder where the sampling frequency is 100 kHz. It is found that the faulty phase has the highest absolute sum when it is compared with the other healthy phases. Similarly, the absolute sum of the faulty feeder is the highest when the comparison is carried out with respect to other feeders. Therefore, two Logic Functions are suggested to determine the faulty phase and the faulty feeder. The fault due to a leaning tree occurring at different locations in an unearthed 20 kV network is simulated by ATP/EMTP and the arc model is implemented using the universal arc representation.**

***Index Terms*— Arc model, DWT, high impedance arcing faults, initial transients.**

I. Introduction

THE faults which especially occur in rural networks with overhead lines are often due to leaning trees. These faults are categorized as high impedance arcing faults due to the tree resistance (several hundred ohms) and the associated arcs [1]. Such faults often draw small currents which cannot be detected by conventional relays [2].

Features of the high impedance faults are extracted and investigated for the detection purposes. Several filters such as the Fast Fourier Transform, Kalman Filter and Fractal and Wavelet Transforms are used for localizing the fault features. Therefore, numerous detection algorithms have been motivated, depending on harmonics [2]-[6]. However, such techniques have not been applied for identifying faults due to leaning trees.

The transients produced in electrical networks due to faults often depend on the neutral point treatments. They can be completely isolated from ground, earthed through impedance or solidly earthed at their neutral. In Nordic Countries, the neutral is commonly unearthed and compensated MV networks are increasingly being used [7]. The system used in this study is a 20 kV unearthed network.

There is an important trait for the unearthed system during the earth fault that the directionality of the residual currents in the healthy and faulty branches with respect to a residual voltage is obvious and this is used as a protection function [7]. However, the fault resistance associated with a leaning tree is very high, which limits its detection based on current amplitudes. Furthermore, for implementing such technique, it is required both current and voltage transducers.

In this paper, the impact of the arc reignition periodicity on the network currents is used to detect this difficult fault. The initial transients in the vicinity of the current zero-crossing lead to fingerprints boosting a secure fault detection. These initial transients are localized based on the DWT detail coefficient of the feeder currents to detect the fault reliably. The absolute sum over a period of one power cycle is computed. Logic Functions are introduced to determine the faulty phase and also the faulty feeder. The proposed algorithm is evaluated with different feeder lengths of 20 kV unearthed network. The system is simulated in ATP/EMTP and ATPDraw is used as a graphical interface. The fault model is implemented using the universal arc representation.

II. Proposed Technique Principles

The proposed technique mainly depends on DWT for the fault detection. The scenario of the fault detection and the faulty feeder location can be generalized using Figure 1. At measuring node of each feeder, phase currents are measured and they are extracted using DWT. The absolute sum of the detail d3 coefficient corresponding to the frequency band 12.5-6.25 kHz is computed over one cycle period of the power frequency for the fault detection purpose where the sampling frequency is 100 kHz. A timer is used for determining the fault period and it can be implemented using a samples counter. Under certain circumstances controlled by wind speeds, the tree can move towards and away from the electrical network and the fault features can be repeated several times. Therefore, a counter can be added and used to determine a number of fault events.

In order to find out the faulty phase, the absolute sum over one power cycle of the detail d3 of each phase is evaluated

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using a Logic Function. How this Logic Function is implemented will be discussed in subsection IV-B. A further Logic Function is used to determine the faulty feeder. The selectivity of the faulty phase and feeder is taken into consideration after the fault detection is achieved.

III. Simulated System

A. 20 kV MV Network

Figure 2 illustrates a single line diagram of an unearthed 20 kV, 5 feeder distribution network simulated using ATP/EMTP, in which the processing is created by ATPDraw [8]. The feeder lines are represented using the frequency dependent JMarti model consistent with the feeder configuration given in the Appendix. The neutral of the main transformer is isolated. Although this network is not intentionally connected to the earth, it is grounded by the natural phases to ground capacitances. Therefore, the phase fault current is very low allowing a high continuity of service. However, such a network is subjected to transient overvoltages. The current distributions in unearthed networks during ground faults are addressed in [7].

B. Fault Modeling

An experiment was performed to measure the characteristics of faults due to leaning trees occurring in a 20 kV distribution network [1]. This fault type is modeled using two series parts: a high resistance and a dynamic arc model. For the considered case study, the resistance is equal to 140 kΩ and the arc is modeled depending upon thermal equilibrium that is adapted as following [1], [9]:

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \tag{1}$$

$$G = \frac{|i|}{V_{arc}} \tag{2}$$

$$\tau = Ae^{Bg} \tag{3}$$

where g is the time-varying arc conductance, G is the stationary arc conductance, $|i|$ is the absolute value of the arc current, V_{arc} is a constant arc voltage parameter, τ is the arc time constant and A and B are constants. In [1], the parameters V_{arc}, A and B were found to be 2520V, 5.6E-7 and 395917, respectively. Considering the conductance at each zero crossing, the dielectric is represented by a variable resistance until the instant of reignition. It is represented using a ramp function of 0.5 MΩ/*ms* for a period of 1 *ms* after the zero-crossing and then 4 MΩ/ms until the reignition instant.

Considering the bilateral interaction between the EMTP power network and the transient analysis control system (TACS) field, the arcing equations (1), (2) and (3) are implemented using the universal arc representation [10]. With the help of Fig. 3, the current is transposed into the TACS field using type 91 sensors. This is used as an input to the arc model that is solved in the TACS exploiting integrator device type 58 with the aid of FORTRAN expressions. In the next step, the computed arc resistance is sent back into the network using TACS controlled resistance type 91 and so on. Accordingly, the arcing fault interaction with the network and corresponding transients are simulated. Control signals are generated to distinguish between arcing and dielectric periods and therefore to fulfill the reignition instant after each zero-crossing. The aforementioned MV network and the fault modeling are combined in a single arrangement, as shown in the ATPDraw circuit illustrated in the Appendix to describe the network behavior during this fault.

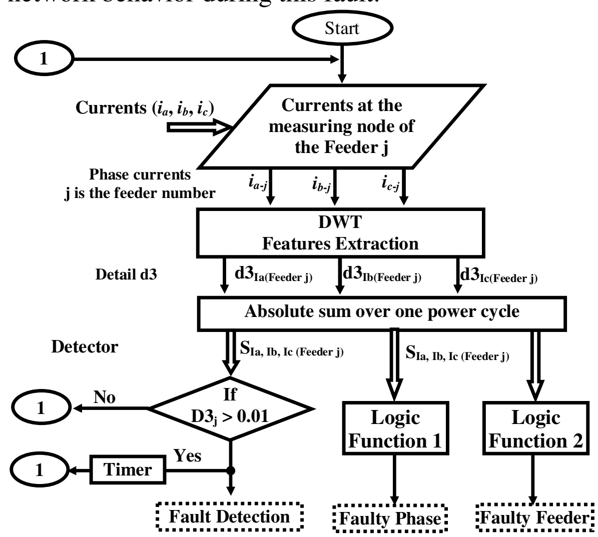


Fig. 1 The proposed detection technique.

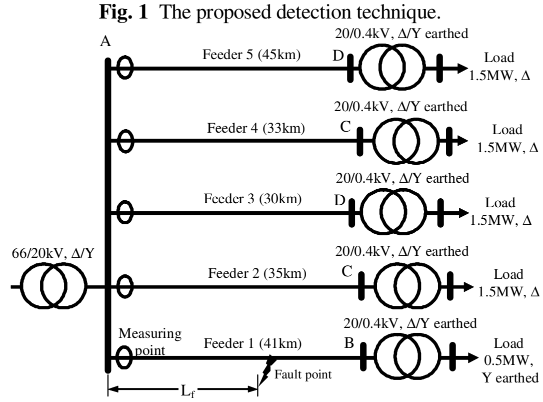


Fig. 2 Simulated system for a substation energized 251 km distribution network.

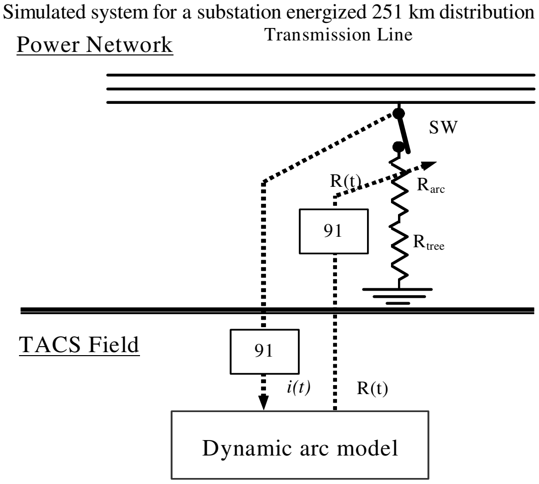


Fig. 3 EMTP network of the high impedance arcing fault.

C. *Fault Test Case Waveforms*

Referring to the simulated system shown in Fig. 2, phase-a to ground fault occurring at the end of Feeder 1 and corresponding current waveforms are shown in Fig. 4 when this fault occurred at 26 *ms*. The impact of fault disturbance on the phase currents is very small as depicted in the enlarged view. Although, the initial transients due to arc reignitions are not obvious in the waveforms because the fault resistance is very high, the waveforms contain information that is correlated with the transients due arc reignitions. It is required to extract this information using a suitable signal processing technique such as DWT.

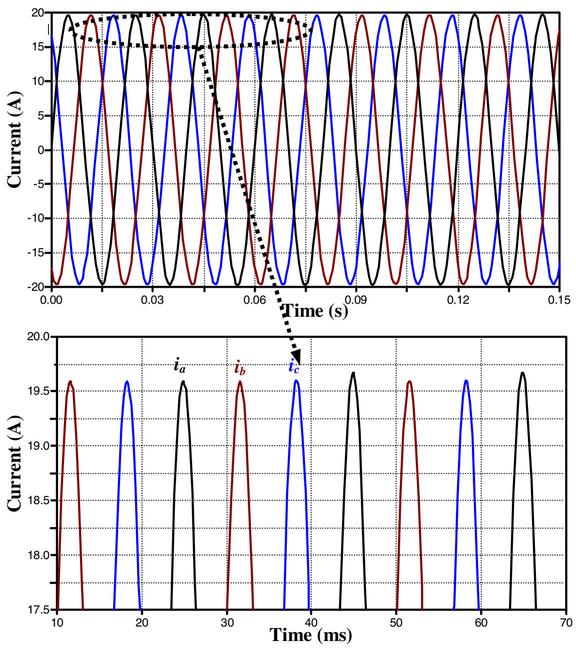


Fig. 4 Enlarged view of phase current waveforms when the fault occurred at the end of Feeder 1.

IV. DWT-Based Fault Detection

Wavelets are families of functions generated from one single function, called the mother wavelet, by means of scaling and translating operations. The scaling operation is used to dilate and compress the mother wavelet to obtain the respective high and low frequency information of the function to be analyzed. Then the translation is used to obtain the time information. In this way a family of scaled and translated wavelets is created and it serves as the base for representing the function to be analyzed [11]. The DWT is in the form:

$$DWT_{\psi} f(m,k) = \frac{1}{\sqrt{a_o^m}} \sum_n x(n) \psi\left(\frac{k - n b_o a_o^m}{a_o^m}\right) \quad (6)$$

where $\psi(.)$ is the mother wavelet that is discretely dilated and translated by a_o^m and $nb_o a_o^m$, respectively. a_o and b_o are fixed values with $a_o>1$ and $b_o>0$. m and n are integers. In the case of the dyadic transform, which can be viewed as a special kind of DWT spectral analyzer, $a_o=2$ and $b_o=1$. DWT can be implemented using a multi-stage filter with down sampling of the output of the low-pass filter.

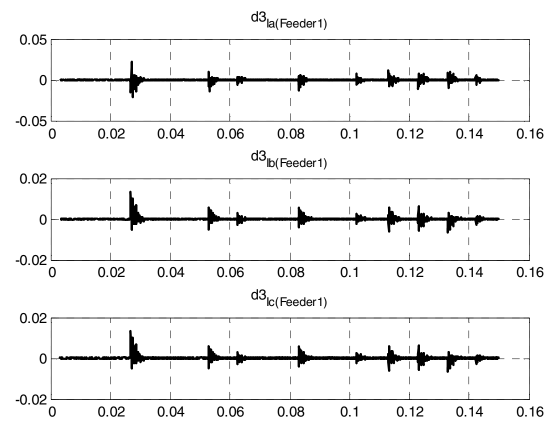
A. *Fault Detection*

Several wavelet families were tested to extract the fault features using the Wavelet toolbox incorporated into the MATLAB program [12]. Daubechies wavelet 14 (db14) is appropriate for localizing this fault. The Details d3 including the frequency band 12.5-6.25 kHz are investigated, in which the sampling frequency is 100 kHz. The sampling rate can be reduced to 50 or 25 kHz but the used coefficients will be details d2 or d1, respectively.

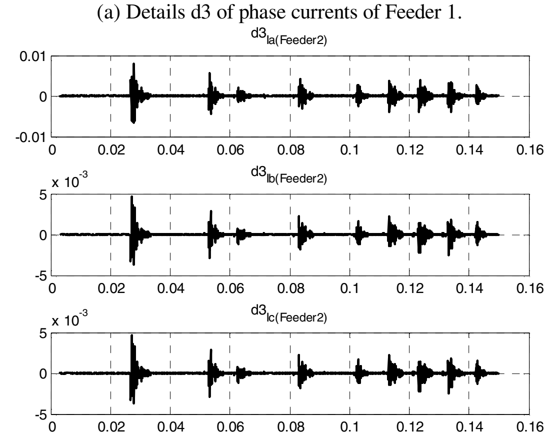
For the fault case depicted in Fig. 4, features of the phase current waveforms measured for different feeders are analyzed using DWT as shown in Fig. 5. It is obvious that the initial transients due to arc reignitions are frequently localized throughout the network feeders. To find flags used as fault detectors, the absolute sum value of the detail d3 over a period of the power frequency is computed in a discrete form at each measuring node, as in [13]:

$$S(k) = \sum_{n=k-N+1}^{k} \left| d3(n) \right| \quad (7)$$

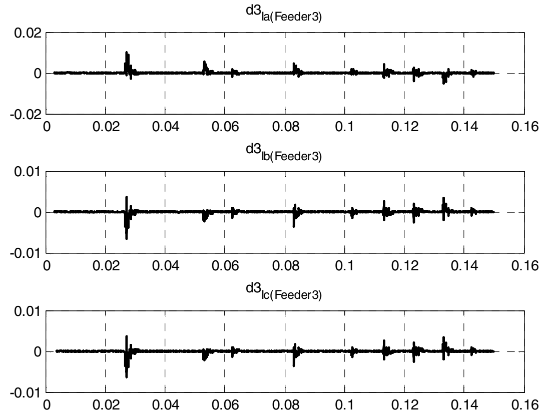
where n is used for carrying out a sliding window covering 20 *ms* and N is a number of window samples. The performance of the detectors S for different measuring locations is shown in Fig. 6, in which the detectors all over the network respond to the fault disturbance. This confirms the fault existence. Moreover, the considered detectors are high not only at the starting instant of the fault events but also during the fault period that improves the protection security.



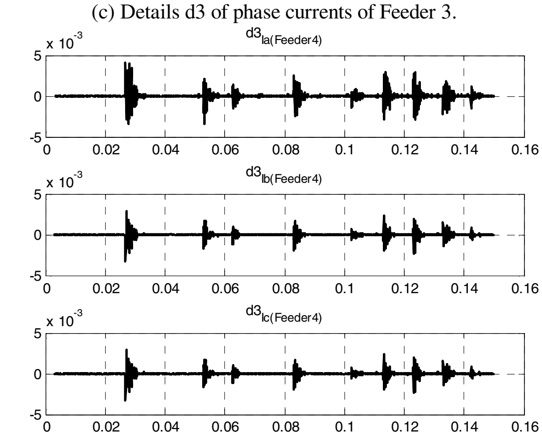
(a) Details d3 of phase currents of Feeder 1.



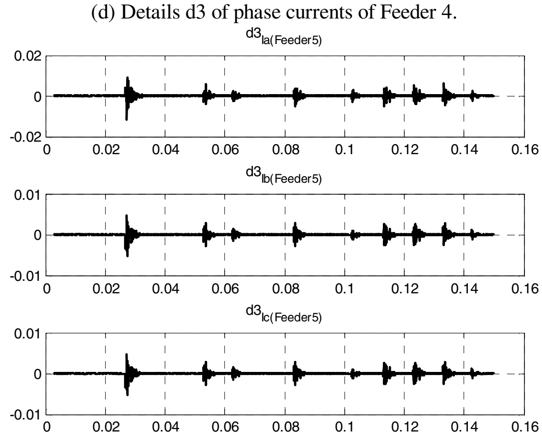
(b) Details d3 of phase currents of Feeder 2.



(c) Details d3 of phase currents of Feeder 3.



(d) Details d3 of phase currents of Feeder 4.



(e) Details d3 of phase currents of Feeder 5.

Fig. 5 Details d3 of phase currents throughout the network feeders.

B. Fault Selectivity

It should be noted that the aforementioned detectors can only localize the fault event; however, it is required to determine the faulty phase and faulty section. Regarding the faulty phase determination it can be concluded with the aid of Figs. 6, in which the details d3 absolute sum of the faulty phase is the greatest. Similarly, the details d3 absolute sum of the faulty feeder is the greatest when a comparison is carried out between the feeders as shown in Fig. 7. This is also observed when the fault point is changed to be L_f = 7 km. Such information can be extracted using Logic Circuits.

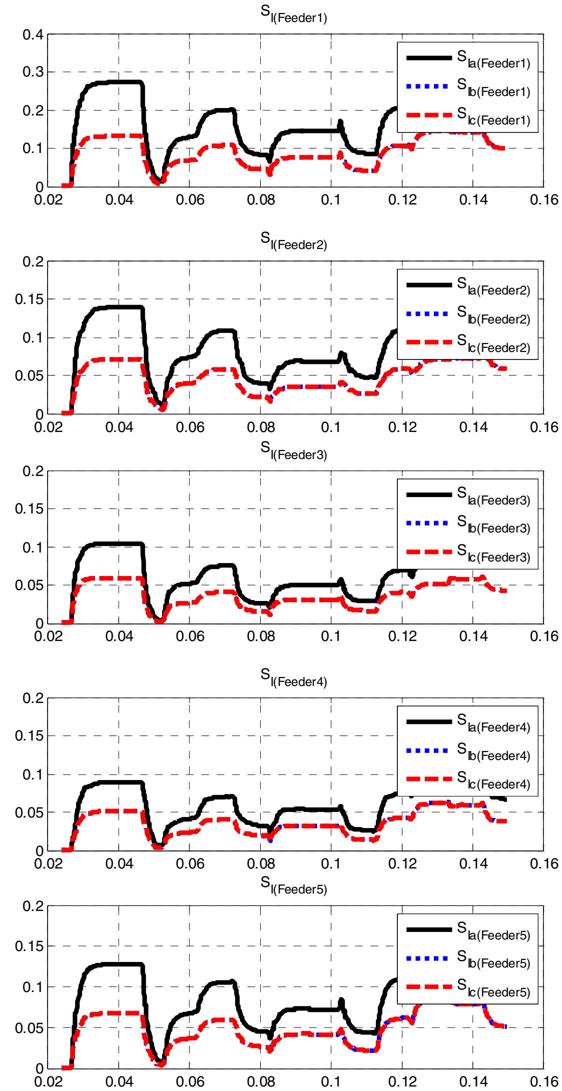


Fig. 6 Absolute sum of the details d3 of the phase currents

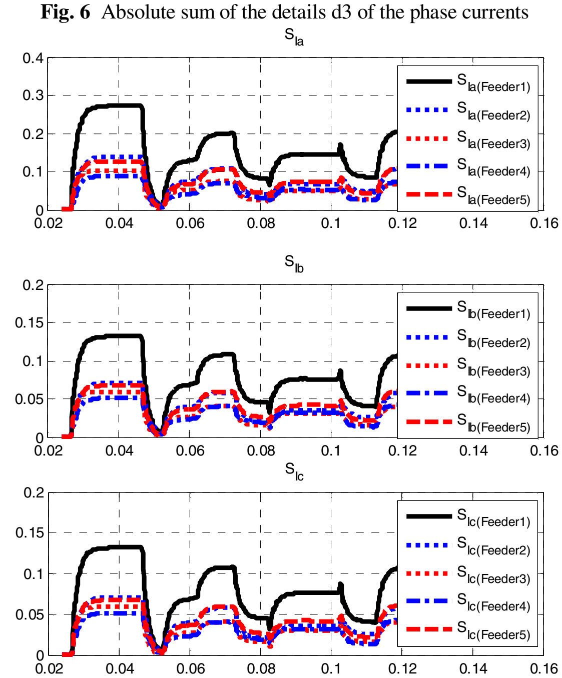
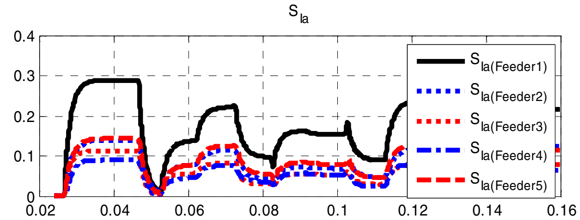
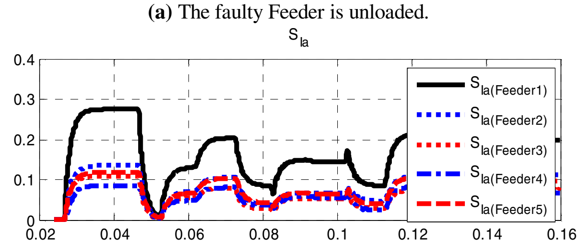


Fig. 7 Comparison between absolute sum of details d3 of different feeders at each phase.



(a) The faulty Feeder is unloaded.



(b) Feeder 4 and 5 are unloaded

Fig. 8 Performance of the absolute sum for different load conditions.

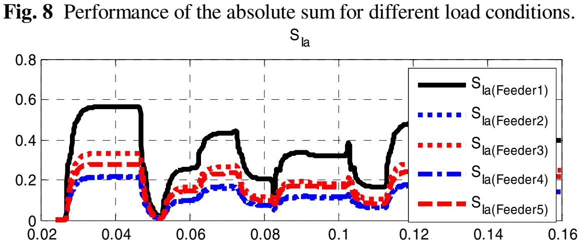
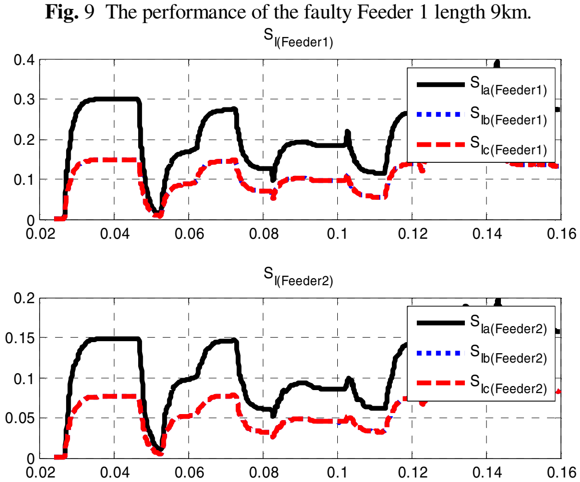
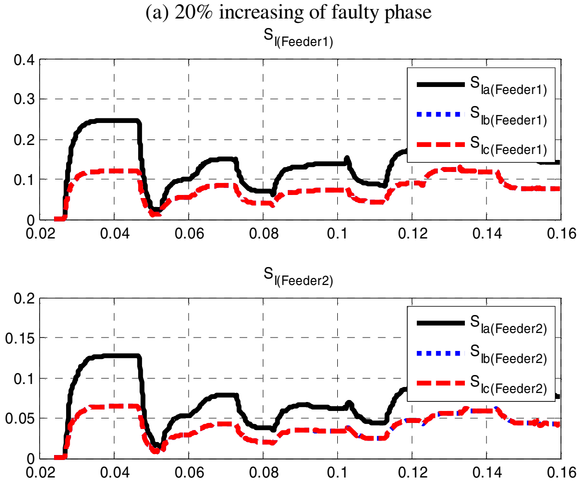


Fig. 9 The performance of the faulty Feeder 1 length 9km.



(a) 20% increasing of faulty phase



(b) 20% reduction of faulty phase

Fig. 10 The performance of the absolute sum during balanced voltage.

These observations can be tested at different load currents such as when the faulty feeder is unloaded and in another case when both feeders 4 and 5 are unloaded. In these two cases, the absolute sum *S* of faulty feeder is the highest as shown in Fig 8. Figure 9 confirms this performance when the faulty feeder length is 9 km not 41 km. Other test cases are carried out when the faulty phase voltage is changed by ± 20% as shown in Fig. 10, in which, the absolute sum of faulty phase is the highest. All these cases ensure that the absolute sum of the faulty feeder is the highest when it is compared with the other healthy feeders and the absolute sum of the faulty phase is the highest when it is compared with the other phases.

Regarding an arc furnace load that can make a conflicting in the concluded performance of the absolute sum *S*, this load type is terminated at low voltage levels that is 220V or greater. The source of this load is complicated and it is connected to bus PCC (point of common coupling) [14]. This source contains two series transformers: HV/MV transformer and an arc furnace transformer controlled by a complicated controller and its connection is Δ/Δ to prevent third harmonic and zero sequence components. This load with its source is directly connected to the HV level at bus PCC without transmission in medium or low voltage levels. Therefore, the zero sequence due to arc furnace loads is not propagated throughout the network. However, the earth fault features are mainly propagated based on zero-sequence coupling of MV feeders.

C. *Proposed Logic Functions*

Figures 11 and 12 illustrate a proposed technique that can be used for estimating the faulty phase where the inputs of the Logic Functions are the differences of the absolute sum *S* of each phase. When the difference D is positive, it will be considered 1 and when it is zero or negative value, it is considered zero. When the fault is phase-a to ground, D_{ab} is positive while D_{ca} is negative. In this case, the Logic Output Phase_a is High and other outputs are Low whatever the status of D_{bc}. In the same manner the performance when the fault is phase-b or phase-c to ground.

Figure 13 summarizes the corresponding Logic Functions that can be used for determining the faulty phase. The differences of the absolute sum *S* of each feeder are used as inputs for the second Logic Function. When the fault is in Feeder 1, D_{12} and D_{13} are positive while D_{51} and D_{41} are negative. Consequently, the Logic output Feeder_1 is High and the other outputs are Low whatever the status of other differences D.

V. Conclusion

Sensitive and secure detection technique of faults due to leaning trees has been attained using DWT. The fault features have been extracted from the phase currents and therefore it is only needed for measuring currents disregarding voltages. The absolute sum has been computed over a power cycle. The periodicity of the arc reignitions gives a specific performance for the DWT with this fault type and the results enhance this fault detection. Using the proposed Logic Functions, the faulty phase and feeder have been determined exploiting the differences in the absolute sum of the phase currents for different feeders during the fault.

Appendix

Figure A illustrates the considered ATPDraw network. It contains the MV network shown in Fig. 2 and the universal arc representation illustrated in Fig. 3. The feeders are represented using a frequency dependent JMarti model. Their configuration is shown in Fig. B.

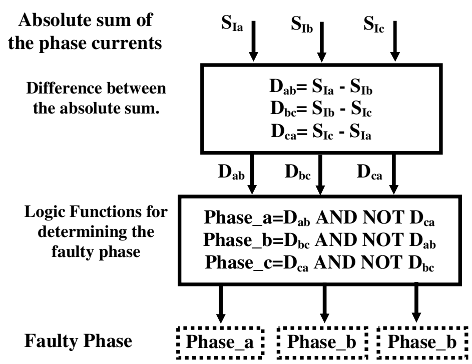


Fig. 11 Faulty phase selectivity.

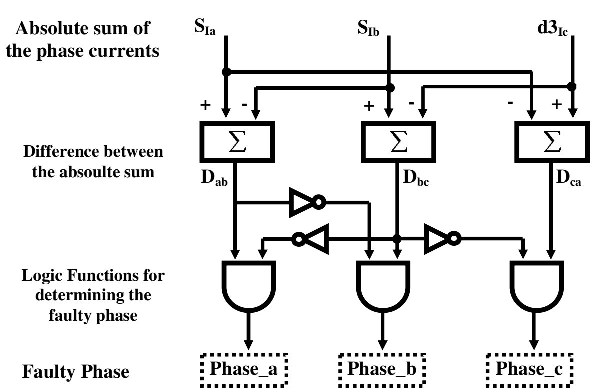


Fig. 12 The equivalent Logic circuit for determining the faulty phase.

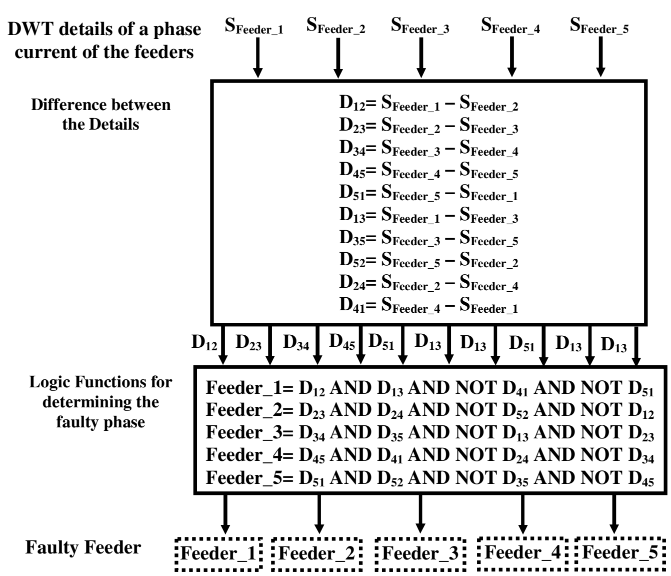


Fig. 13 Faulty feeder determination.

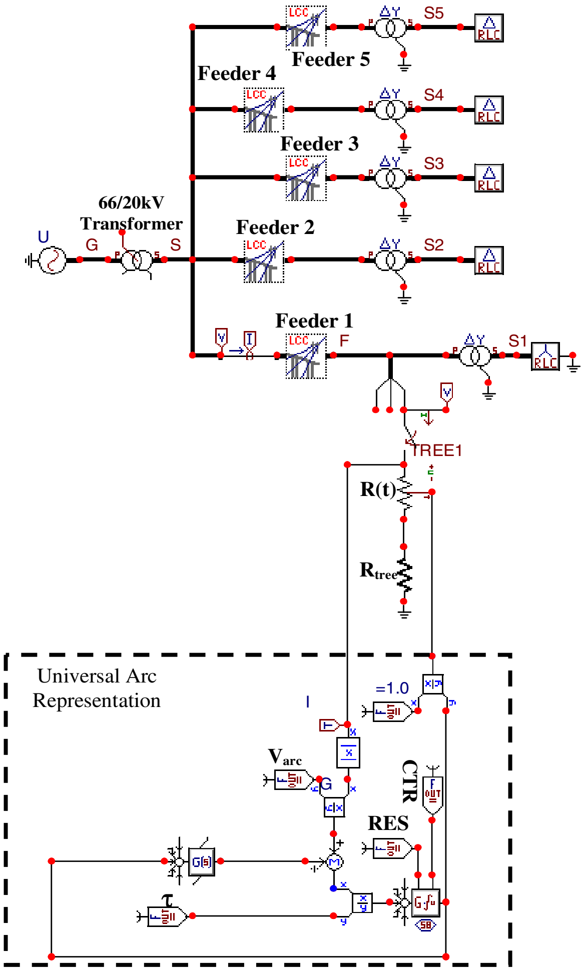


Fig. A Fig. A The ATPDraw network.

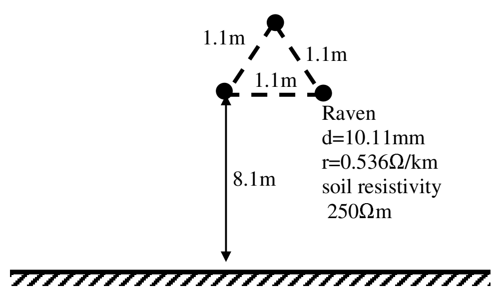


Fig. B The feeder configuration.

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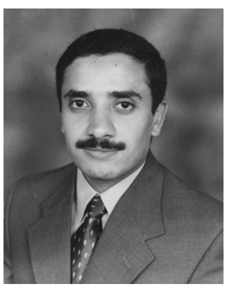

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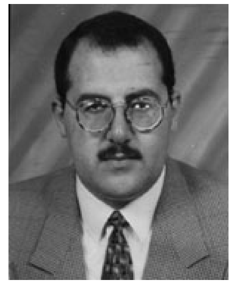

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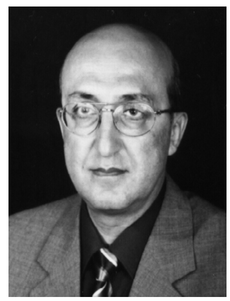

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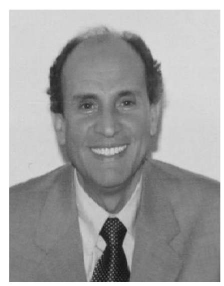

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