Non-Linear HIF Detection and Classification for Egyptian 500 kV Transmission Line

Saber Mohamed Saleh, Member IEEE  
Ministry of Electricity and Energy, Cairo, Egypt  
sabermssh@yahoo.com

Doaa khalil Ibrahim, Member IEEE  
Faculty of Engineering, Cairo University  
doakhalil73@hotmail.com

Abstract—High impedance faults (HIFs) are difficult to be detected or classified by overcurrent or distance relays. This paper presents a scheme for high impedance fault detection and classification in extra high voltage transmission line. The scheme recognizes the distortion of the current waveforms caused by the arcs usually associated with HIF using a discrete wavelet transform (DWT) based pattern recognition. The scheme uses a recursive method to sum the absolute values of the high frequency signal generated of line current signals measured at one substation end over one cycle. Proposed detector and classifier are tested under a variety of fault conditions on Egyptian 500kV transmission line system by extensive simulation studies using HIF model of distribution system that modified to transmission lines. In addition, a real time HIF data recorded is used to validate the performance of the proposed scheme. All achieved results clearly reveal that the proposed scheme can accurately detect and classify HIFs in the transmission lines unaffected by fault type, fault inception angle, fault resistance, and fault location.

Index Terms—High impedance faults (HIF), fault detection and classification, Wavelet Transform, Transmission line.

I. INTRODUCTION

Transmission line is one of the main components in every electric power system. Possibility of experiencing faults on transmission line is generally higher than the other components. When fault occurs in a transmission line it is important to detect the fault location and type in order to make necessary repair and to restore power as soon as possible without any maloperation. The time required to detect the fault in the line will affect the quality of power. The speed and accuracy of digital relays of transmission lines can be improved by accurate and fast fault detection and classification. Detection of high impedance faults (HIFs) with high reliability is a challenge for protection engineers. The protection reliability is measured by dependability and security. A high level of dependability occurs when the faults are correctly recognized. On the other hand, a high level of security occurs when the faults are not falsely indicated. A high dependability forces a lower security level and vice versa. The dilemma is to find a sensitive high impedance detector with conserving on protection security. The high impedance faults result when an unwanted electrical contact is made with a road surface, sidewalk, sod, tree limb, some other surface or object which restrict the flow of fault currents to a level below that reliably detectable and classified by conventional protection devices. Such faults can be earth or phase faults. The failure of HIF detection and classification may lead to potential hazards to human beings and potential fire [1].

HIFs on electrical transmission line involve arcing and/or nonlinear characteristics of fault impedance which cause cyclical pattern and distortion. Several researchers in recent years have presented many techniques aimed for detecting HIF more effectively. The objective of most detection schemes is to evaluate the special features in patterns of the voltages and currents in HIFs. These techniques include discrete wavelet transform [1-3], down-conductor fault detection and location via a voltage based method [4], and development of a fuzzy inference system based on genetic algorithm [5].

This paper describes a fault detection and classification algorithms that involves capturing the current signals generated in transmission line under HIFs at one end. It will be shown that the used algorithm improves the performance of HIF detection and classification based on discrete wavelet transform. The detection and classification processes are performed through signal decomposition, thresholding of the wavelet transform coefficients, and duration time. The threshold value is determined by weighting the absolute sum value for one cycle in a moving window scheme. This includes decision logic for the limitation of false trip decision. A HIF field recorded data and ATP simulations ensured the verification of the proposed fault detection and classification in Egyptian 500 kV transmission line. The results also showed that the proposed scheme is robust to fault type, fault inception angle, fault resistance, and fault location. In addition, it has great capability for discrimination between HIFs and switching events.

II. DISCRETE WAVELET TRANSFORM

DWT analysis was developed as an alternative method to the short time Fourier Transform (STFT) to overcome problems related to its frequency and time resolution properties. More specifically, unlike the STFT which provides uniform time resolution for all frequencies, the DWT provides high time resolution and low frequency resolution for high frequencies and high frequency resolution and low time resolution for low frequencies. DWT provides a compact representation of a signal in time and frequency domains. The DWT is defined by the following equation:

\[ W(j,k) = \sum_n \sum_k x(k)2^{-j/2}\psi(2^{-j} n - k) \]  

Where: \( \psi(t) \) that called mother wavelet is a time function with finite energy and fast decay. The DWT analysis can be
performed using a fast, pyramidal algorithm related to multirate filter banks [6]-[7].

As a multirate filter bank, the DWT can be viewed as a constant Q filterbank with octave spacing between the centers of the filters. Each subband contains half the samples of the neighboring higher frequency subband. In the pyramidal algorithm, the signal is analyzed at different frequency bands with different resolution by decomposing the signal into a coarse approximation and detail information. The coarse approximation is then further decomposed using the same wavelet decomposition step. This is achieved by successive highpass and lowpass filtering of the time domain signal and is defined by the following equations:

\[
y_{\text{high}}[k] = \sum_{n=1}^{\text{step}} x[n]g[2k-n] \\
y_{\text{low}}[k] = \sum_{n=1}^{\text{step}} x[n]h[2k-n]
\]

Where \( y_{\text{high}}[k], y_{\text{low}}[k] \) are the outputs of the highpass \((g)\) and lowpass \((h)\) filters, respectively, the Daubechie4 coefficient wavelet family (db4) [8] are applied.

III. HIGH IMPEDANCE FAULT MODEL

There is an increasing demand for detailed and accurate modeling techniques for predicting the transient response of power system caused in particular by high impedance arcing faults. This is particularly in relation to the design and development of improved equipment and new protection techniques. An accurate prediction of the fault transients requires a detailed and comprehensive representation of all the components in a system; furthermore the transient studies have to be conducted into the frequency range well above the normal power frequency.

The HIF is a complex phenomenon and exhibits a very highly nonlinear behavior. The most distinctive characteristics are buildup, shoulder, nonlinearity and asymmetry. In the buildup, the fault current grows to its maximum value in about tens of cycles and in the shoulder; the buildup is ceased for a few cycles. The non-linearity arises from the fact that the voltage-current characteristic curve of HIF is nonlinear. It is observed that fault current has different waveform for positive and negative half cycle which is called asymmetry. Buildup and shoulder disappear in the steady state after HIF, while nonlinearity and asymmetry exist at every cycle after HIF.

Some models of HIF have been proposed in the past. Based on the arc theory, a more realistic model of HIF is proposed in [9] and modified in [10]. In this model, the HIF is presented by two resistances connected in series and takes the form:

\[
R(t) = R_1(t) + R_2(t)
\]

In this equation, \( R_1(t) \) has a periodic characteristic and is used to present nonlinearity and asymmetry. The value of \( R_1(t) \) is obtained from the voltage and current characteristic during the steady state as shown in Fig. 1. When the voltage of the faulted branch \( v(t) \) is in the range of \( v_n < v(t) < v_{n+1} \) and the corresponding current is \( i(t), R_1(t) \) is given by:

\[
R_1(t) = \frac{v(t)}{i(t)} = \frac{v(t)}{i_n + \frac{i_{n+1} - i_n}{v_{n+1} - v_n} \times (v(t) - v_n)}
\]

Where \( n \) is the point number on voltage-current characteristic.
B- Fault Classifier Algorithm:

- In order to classify fault type: 3LG, DLG, LL or SLG, the absolute sum over one faulty cycle of the detail d1 of each phase is evaluated using logic functions, in which, the absolute sum of the faulty phase is the highest one when it is compared with the absolute sum of other phases. The selectivity of the faulty phase is taken into consideration after the fault detection is achieved.

- Fig. 2b shows the HIF classification decoder logic, where Sa, Sb, and Sc are the input select to this decoder while, D and T are enabled the logic circuit. D is the detection decision and its value becomes "1" at HIF exist while, T is the difference between the absolute sum of the two phases at DLG and LL faults; If the value of T is greater than a tolerance of 0.2 then, the fault is considered to be DLG and its value becomes "1" otherwise the fault is considered as LL and its value becomes "0".

Fig. 2a Proposed detection algorithm flowchart.

Fig. 2b Proposed classification decoder logic.

V. SIMULATION RESULTS

The scheme testing was carried out through simulation analysis using ATP-EMTP for the Egyptian 500 kV studied line that shown in Fig. 3 (simulation details are given in the appendix). A complete simulation studies to present current signals of a one pre-fault cycle and another cycle after fault occurrence for different effects such as fault types at different fault locations, fault inception angles, and switching events are tested. Some of these results will be shown in the following subsections.

Fig. 3 Single line diagram of the 500 kV T.L.
A. EFFECT OF FAULT TYPES AND LOCATIONS

The absolute sum values of d1 associated with the three-phase currents for each phase are used to detect faults and classify types. As expected, the magnitude of the faulted phases is much higher than the healthy phases. The very significant difference between the faulted and healthy phases is retained for different fault types. Different HIFs types covering all the line length are examined. In all the test cases, the fault types are correctly identified.

1. Single line to ground fault (SLG)

Fig. 4 indicates the fault detection and classification response for single line to ground fault (SLG) at different location from the CB1 side. As expected, the magnitude of the faulted phase high frequency current is much higher than the threshold value. Since the line length was 145km, based on the results obtained, it can be concluded, that the accurate results were obtained for the full range of fault locations.

2. Double line to ground fault (DLG)

Fig. 5 indicates the fault detection and classification response for double line to ground fault (DLG) at different location from the CB1 side. As expected, the magnitudes of the only two faulted phases' high frequency currents are higher than the threshold value. In addition, a difference which is greater than the tolerance T is achieved that ensured ground fault occurrence.

3. Line to line fault (LL)

Fig. 6 indicates the fault detection and classification response for line to line fault (LL) at different location from the CB1 side. As expected, the magnitudes of both two faulted phases' high frequency currents are equal and much higher than the threshold value while the healthy one is nearly zero.

4. Three phase Fault (3LG)

Fig. 7 indicates the fault detection and classification response for three phase fault to ground (3LG) at different location from the CB1 side. As expected, the magnitudes of all phases' high frequency currents are much higher than the threshold value.

Fig. 4 Sum values of d1 for SLG (AG) HIF at different locations.

Fig. 5 Sum values of d1 for DLG (ABG) HIF at different locations.

Fig. 6 Sum values of d1 for LL (AB) HIF at different locations.

Fig. 7 Sum values of d1 for 3LG (ABCG) HIF at different locations.
B. EFFECT OF FAULT INCEPTION ANGLE
The effectiveness of the proposed scheme is also tested for fault cases with different fault inception angles. Fig. 8 depicted the absolute sum values of \( d_1 \) for each phase current for different fault types at 72.5 km from the CB1 as a function of fault inception angle. As expected, the magnitude of the faulted phase is much higher than the threshold value in all cases that ensure high dependability since the threshold value had been specified using results of extensive fault cases.

C. SWITCH ON OPERATION CONTAMINATED WITH HIF
Fig. 9 depicted the absolute sum value of \( d_1 \) associated with the three-phase currents for different types of HIF at 100 km from the CB1 and simultaneously the circuit closed with the fault occurs. As expected, the magnitude of the faulted phases is much higher than the threshold value that ensure a contaminated normal switching event with a faulty case which essentially required to activate a trip condition.

D. SWITCH ON OPERATION WITHOUT HIF
To ensure the validation of any fault detector, such as the type proposed in this paper, it is important to ensure that it is secure under non-fault events such as capacitor and line switching, arc furnace loads, etc. Fig. 10 depicted the absolute sum value of \( d_1 \) associated with the three-phase currents for switching on source. The magnitudes of the \( d_1 \) currents are much lower than the threshold value that ensures non trip condition.

VII. PRACTICAL REAL FAULT DATA VALIDATION
In order to further demonstrate the algorithm efficiency, a real fault recorded is used to test the effectiveness of the proposed scheme. Fig. 11a describes the fault data recorded from the digital fault recorder of the Samalut 500 kV transmission circuit in 09/09/2008 at 06:44:49. The recorded case indicated that the actual fault was SLG HIF and the directional earth fault tripped the circuit after 0.488 s from fault instant. The proposed scheme detected such fault case after 0.02 s using current signals only as shown in Fig. 11b. The sampling frequency used is 6.4 kHz (128 samples / cycle for 50 Hz system) and the 500 kV threshold value was selected to be "3" since the digital fault recorder filtered the high frequency content to its one tenth value.
This paper proposes a scheme for transmission line fault detection and classification under high impedance faults using the discrete wavelet transform. The DWT-based technique presented herein has a number of distinct advantages over other traditional HIF detection techniques.

1. It can be used for fault detection and classification in a presence of HIF contaminated with other effects (switch on to fault, load rejection, and switching off/on operation).

2. It has the inherent attribute of distinguishing between the faulted phase(s) and healthy phase(s) therefore this is a significant advantage for transmission systems in which single-pole tripping is employed, and which therefore requires phase selection.

3. It is based on current signals only.

4. It is independent on the load variation and unbalanced conditions.

5. It is based on one side currents only.

6. Its response has been verified using both simulation results and real field data.

This technique is simple, accurate, and fast. It can be used for updating, improving, and refurbishing of the existing protection systems, since this algorithm can be added to the existing digital relay microprocessor.

**VII. CONCLUSION**

The symmetric RL coupled line model of a 500 kV transmission line is used to study the fault analysis in this paper with typical Egyptian transmission line parameters as shown in Table 1.

**REFERENCES**


**APPENDIX**

**TABLE 1 PARAMETERS OF THE STUDIED SYSTEM**

<table>
<thead>
<tr>
<th>System voltage 500 kV, system frequency 50 Hz</th>
<th>Sources</th>
</tr>
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<tbody>
<tr>
<td><strong>E_{Elkureimat} = 500\angle -5^\circ</strong>, Z_{SElkureimat} = 0.175 + j17.5(\Omega)**</td>
<td></td>
</tr>
<tr>
<td><strong>E_{Samalut} = 500\angle 0^\circ</strong>, Z_{SSamalut} = 4.25 + j27.5(\Omega)**</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th>Transmission line parameters</th>
<th>Positive sequence parameters:</th>
<th>Zero sequence parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>R = 0.0217(\Omega/km)</td>
<td>R = 0.247(\Omega/km)</td>
<td></td>
</tr>
<tr>
<td>XL = 0.302(\Omega/km)</td>
<td>XL = 0.78(\Omega/km)</td>
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**BIOGRAPHIES**

**Saber Mohamed Saleh** (IEEE M’10) was born in Egypt in July 1975. He is graduated from Helwan University, Faculty of Engineering, Electrical Power and Machines Department in 2000 and received the M.Sc. and Ph.D. in digital protection from Cairo University at 2005 and 2009, respectively. From 2001 he worked for Ministry of Electricity and Energy, Kureimat Power Station 2627 MW, Egypt as a Protection & Maintenance Department Manager. Dr. S. Saleh’s research interests include utilization and generation of electric power, and digital protection of power system.

**Doaa Khalil Ibrahim** (IEEE M’06) was born in Egypt in Dec. 1973. She graduated from Cairo University, Faculty of Engineering, Electrical Power and Machines Department in 1996 and received the M.Sc. and Ph.D. in digital protection from Cairo University at 2001 and 2005, respectively. From 1996 till 2005 she was a demonstrator and research assistant in Cairo University. In September 2005, she became an assistant professor with Cairo University. From October 2005 till Dec.2008, Dr. D. Khalil was contributing in a World Bank Project in Higher Education Development in Egypt. From January 2009, she contributes in the Program of Continuous Improvement and Qualification for Accreditation in Higher Education in Egypt. Her research interests include digital protection of power system, utilization and generation of electric power and renewable energy sources.