A Novel Approach to Decaying DC offset Removal in Current Signals of Digital Relays

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Abstract—In this paper a new method for estimation and removal of decaying dc offset from fault current signal using Least Median of Squares Regression (LMSR) method is proposed. Fault currents tend to include a dc decaying component. This component decreases the accuracy and speed of the protective relaying operation. The proposed method can estimate and eliminate the dc decaying component from fault current signals after one cycle from the fault instant. The dc decaying magnitude and time constant are estimated exactly during one cycle. The dc decaying component is eliminated by subtracting the dc value at each sampling instant. To verify the performance of the proposed method, we performed a dc component estimation test and distance protection test using PSCAD/EMTDC. The results of the PSCAD/EMTDC simulation showed that the proposed method can estimate dc components exactly from fault currents and can be applied to digital protection relays for phasor extraction.

Keywords—Digital relaying; Decaying Dc offset; DC estimation; Least Median of Squares Regression Method

I. INTRODUCTION

Distance relay is the common protection used in the transmission lines. When a fault occurs, the protective distance relay must operate very quickly with secure operation to isolate the faulty section and maintains system stability. The more speed protective relay, the less faulty period in the power system and thus the electrical equipment will be prevented from damage and its life time will increase.

In digital distance protection of transmission lines, if there is a fault on the system, the voltage and current waveforms contain harmonics and decaying DC components. The relay of the fault locator needs the fundamental component to identify the location of this fault. As such, the presence of harmonics and DC components will reduce the accuracy of the digital relay, and a method is needed to filter out these components as well as the noise in the signals. Many well-known filtering techniques have been used for this purpose, and some calculations resulting in accuracy and convergence speed give us helpful guides.

In digital protection relaying, the discrete Fourier transform (DFT) is the most preferable method to extract the fundamental phasor quantities from waveforms [1]. DFT has immunity from harmonic components and has a relatively fast response time for the fundamental component calculation. However, the DFT is not immune from the dc component, and the decaying dc component in the fault current can cause undesirable oscillations in the DFT results [2], [3]. In [4], an innovative decaying dc component estimation algorithm is proposed to obtain the magnitude and time constant through integrating fault currents during one cycle; then an accurate estimation of synchro phasor is obtained after the dc components are removed from the fault current signal. Some methods such as the algorithm described in improve the operation of DFT operation [5]. This is immune to decaying dc components regardless of its initial magnitude and time constant, needs one cycle and two extra samples to obtain the exact magnitude and time constant.

In the dc component filtering method, this extracts the fundamental components only from the original signal without a dc component calculation. In [2], a mimic filter was proposed to remove the decaying dc component over a wide range of time constants. The decaying DC offset can be completely removed only when the time constant of the DC component matches with the one assumed in the mimic filter.

Recently, an adaptive compensation method to remove a decaying dc offset component from the fault signals has been described in [6] and [7]. The dc component filtering method achieves satisfactory performance when the time constant of the dc component is equal to the time constant of the filter. However, this is usually not the case in power systems because the time constant and magnitude of the decaying dc component are characterized by the system configuration, fault resistance, and fault position. The other method is the dc estimation method, which calculates the dc component and subtracts it from the original signal to obtain the fundamental component only. In [8] presents an efficient method for removing exponentially decaying DC offset from fault currents. Instantaneous value of the actual exponentially decaying DC offset is calculated by integrating the input signal.

In [9] presents a novel scheme for removing a decaying DC-offset from both current and voltage measurements irrespective of the time constant. The technique is based on stationary wavelet transform (SWT) cascaded with a differentiator.
A modified DFT algorithm to efficiently compute and eliminate the dc component using full-cycle or half-cycle data windows has been proposed in [3],[10]. These algorithms can improve the performance of phasor estimation with minimal increment of computational cost under an asynchronous sampling scheme [11]. The technique for removal of a decaying dc offset on phasor estimates using the DFT is described in [12]. An adaptive phasor estimation algorithm to suppress the effect of an exponential decaying dc component based on the weighting least square (LS) technique is proposed [13]. This approach has the advantage of removal of the decaying dc offset regardless of its initial magnitude and time constant, while the disadvantage of the method is that the dc component is determined by the complex calculation procedure. The performance of the DFT-based filter depends on its window length. A short data window will give a fast response but not accurate results. The most suitable data window length depends on the fault location. As the distance between the relay point and the fault point increases, the data window length depends on its window length. A short data window will give a fast response but not accurate results. The most suitable data window length depends on the fault location. As the distance between the relay point and the fault point increases, the data window length may increase to provide secured operation, and vice versa to provide high speed operation, which cannot be achieved by fixed data window techniques [7].

The aforementioned algorithms can be classified into two models: 1) the dynamic phasor model and 2) dc component model. The dynamic phasor model-based algorithms are mainly to improve the accuracy of phasor estimation under the dynamic conditions, while ignoring the impact of decaying dc components. The dc component model-based algorithms take effort to eliminate the errors caused by decaying dc components without considering dynamic characteristics. Therefore, these algorithms have difficulties in properly expressing the analysed signal so that the estimation errors arise when the fault current contains both dynamic characteristics and decaying dc components.

In this paper, we describe a new method call Least Median of Squares Regression (LMSR) [14] to estimate and eliminate the decaying dc component in a fault current signal. The decaying current signal was obtained by eliminating the dc component from the fault current at each sampling instant [15]. We evaluated the performance of the proposed method using PSCAD/EMTDC [16]. For evaluation of the method, we performed dc component estimation tests with several dc component cases. The distance protection test was performed with a sample power system. The results of the test cases showed that the proposed method can estimate the dc component exactly from fault currents and can be applied to digital protection schemes for phasor extraction.

II. PROPOSED METHOD

All the above problems come from nonlinearity in DC offset estimation. Generally, the fault current not only has a fundamental component but also harmonics and a decaying dc component. Fundamental and harmonic components can be represented as a sinusoidal function. The decaying dc component can be represented as a decaying exponential function. So the fault current can be mathematically expressed

\[ i(t) = I_0 e^{-t/\tau} + \sum_{k=1}^{p} I_k \sin(k\omega_0 t + \theta_k) \]  

(1)

Where \( I_0 \) is the magnitude of the decaying dc offset, \( \omega_0 \) is the time constant of the decaying dc offset, \( k \) is the harmonic order \( I_k \) is the magnitude of the \( k_{\text{th}} \) harmonic component \( \theta_k \) is the phase angle of the \( k_{\text{th}} \) harmonic component, \( P \) is the maximum harmonic order. In this paper, the highly robust method of least median of squares (LMS) is chosen for estimating decaying dc component.

Classical least squares regression consists of minimizing the sum of the squared residuals. Many authors have produced more robust versions of this estimator by replacing the square by something else, such as the absolute value. [18]-[19] The classical linear model is given by

\[ y_i = x_{i1} \theta_1 + \ldots + x_{ip} \theta_p + c_i (i = 1,2,\ldots,n) \]  

(2)

where the error \( c_i \) is usually assumed to be normally distributed with mean zero and standard deviation \( \sigma \). The aim of multiple regressions is to estimate \( \theta = [\theta_1, \theta_2, \ldots, \theta_p]^T \) from the data \( \{x_{i1}, \ldots, x_{ip}, y_i\} \). The most popular estimate \( \hat{\theta} \) goes back to Gauss or Legendre and corresponds to

\[ \min_{\theta} \sum_{i=1}^{n} r_i^2 \]  

(3)

Where the residuals \( r_i \) equal \( y_i - x_{i1} \theta_1 - \ldots - x_{ip} \theta_p \).

In this article a different approach is introduced in which the sum is replaced by the median of the squared residuals. The resulting estimator can resist the effect of nearly 50% of contamination in the data. This method of regression was given by Siegel (1982), who proposed the repeated median with a 50% breakdown point. Indeed, 50% is the best that can be expected (for larger amounts of contamination, it becomes impossible to distinguish between the "good" and the "bad" parts of the sample). Siegel's estimator is defined as follows:

For any \( p \) observations \( (x_{i1}, y_{i1}), \ldots, (x_{ip}, y_{ip}) \), which determine a unique parameter vector, the \( j \)th coordinate of this vector is denoted by \( \theta_j \) the repeated median is then defined coordinate wise as

\[ \theta_j = \text{med}(...(\text{med}(\text{med}_{i_{<i_p}}(\theta_{j1}, \ldots, \theta_{jp})))... \]  

(4)

This estimator can be calculated explicitly, but is not equivariant for linear transformations of the \( x_i \). It was applied to a biological problem by Siegel and Benson (1982). The least median of squares (LMS) estimator, given by:

\[ \min_{\theta} \text{med} r_i^2 \]  

(5)
It can be shown that the LMS satisfies $\epsilon^* = 50\%$. ($\epsilon^*$ is the smallest percentage of contaminated data that can cause the estimator to take on arbitrarily large aberrant values. In the case of least squares $\epsilon^* = 0$). The most important thing about this method is that there always exists a solution to (5).

III. SIMULATION RESULTS

In order to verify the performance of the proposed method, two types of simulation tests were performed with PSCAD/EMTDC (Static test and dynamic test).

A. Static Simulation Test

The first simulation test is a static test. In this test, several sampled signals, which contained a dc component, were applied to verify the performance of the dc component. The calculated time constants and fundamental components were compared to the applied signals. Test signals consisted of a fundamental component and a dc component with different magnitudes and time constants. The ratio of the magnitude of the fundamental component and the decaying dc component was set to 0.25, 0.5, 0.75 and 1.0 pu. The time constants used for the performance evaluation were 5, 35, 75 and 100 ms. Also, the sampling rate was set to 51 samples per cycle.

Table I shows the estimated time constants using the proposed method for the applied time constant and ratio of magnitude changes. It can be seen from Table I that the estimated time constants of the test signal exhibited good agreement with the applied value. In the case of 100 ms and ratio 1.0, the error between the applied and estimated time constant was 1.33%.

![Table I. Estimated Time Constants](image)

<table>
<thead>
<tr>
<th>$I_r$ (p.u)</th>
<th>The time constants of input signal</th>
<th>5 ms</th>
<th>35 ms</th>
<th>75 ms</th>
<th>100 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 pu</td>
<td>5.172 35.189 75.211 100.208</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 pu</td>
<td>5.159 35.162 75.173 100.159</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75 pu</td>
<td>5.152 35.155 75.162 100.143</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 pu</td>
<td>5.148 35.151 75.156 100.133</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1, shows the applied signal and estimated dc value in the time-domain simulation. It took one cycle to estimate the dc value from the first appearance of the dc decaying component.

![Fig. 1. Applied signal and calculated dc value](image)

From the results, the magnitude and time constant of a decaying dc component can be accurately estimated from the input signal by using this method. Comparing this method with some previous methods [4, 2, 7] it is concluded that the estimation is more precise. For instance the calculation error in estimation of dc component with time constant of 100ms and the amplitude of 1pu is 1.33%, while this value is about 3.14% in [4].

B. Dynamic Simulation Test

The second simulation test was a dynamic test. In this test, the proposed algorithm was applied to the distance relaying scheme in the sample power system and the performance of the distance relaying was compared to the cases of some other method.

In order to demonstrate the effectiveness of the proposed method used for the distance relay study, an extensive simulation on PSCAD/EMTDC was performed. As mentioned before, various conditions, such as fault locations and fault resistance, were considered in the test studies.

A set of simulation tests was verified using the configuration of the power system shown in Fig. 2. The simulated system was a 230-kV, 100-km transmission line with sources at both terminals [12].

![Fig. 2. Single line diagram of a test system](image)
As mentioned before, different factors affect the magnitude and time constant of decaying dc component. Some of the most important of these factors are: the type of the fault, the location of the fault, and the resistance of the fault. In order to investigate the robustness of proposed method, both three phase and single line to ground short circuit faults in three different location and fault resistance is applied to the test system. The actual and estimated magnitude and time constant of dc component, while the fault type is three phase short circuit and $R_f=0.001\,\Omega$ are summarized in table II.

**TABLE II.** the actual and estimated values of decaying dc component in three phase short circuit and $R_f=0.001\,\Omega$

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Estimated values</th>
<th>Actual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>magnitude (pu)</td>
<td>Time constant (ms)</td>
</tr>
<tr>
<td>10 km</td>
<td>1.812</td>
<td>24.12</td>
</tr>
<tr>
<td>50 km</td>
<td>1.664</td>
<td>24.19</td>
</tr>
<tr>
<td>90 km</td>
<td>1.364</td>
<td>24.28</td>
</tr>
</tbody>
</table>

For instance three phase current waveform is depicted in Fig. 3, for three phase short circuit at 10km from bus1. The actual and estimated magnitude and time constant of dc component, while the fault type is three phase short circuit and $R_f=10\,\Omega$ are shown in table III.

**TABLE III.** the actual and estimated values of decaying dc component in three phase short circuit and $R_f=10\,\Omega$

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Estimated values</th>
<th>Actual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>magnitude (pu)</td>
<td>Time constant (ms)</td>
</tr>
<tr>
<td>10 km</td>
<td>1.343</td>
<td>12.39</td>
</tr>
<tr>
<td>50 km</td>
<td>1.181</td>
<td>12.43</td>
</tr>
<tr>
<td>90 km</td>
<td>0.998</td>
<td>12.47</td>
</tr>
</tbody>
</table>

The actual and estimated magnitude and time constant of dc component, while the fault type is single line to ground short circuit and $R_f=0.001\,\Omega$ are shown in table IV.

**TABLE IV.** the actual and estimated values of decaying dc component in single line to ground short circuit and $R_f=0.001\,\Omega$

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Estimated values</th>
<th>Actual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>magnitude (pu)</td>
<td>Time constant (ms)</td>
</tr>
<tr>
<td>10 km</td>
<td>1.701</td>
<td>23.75</td>
</tr>
<tr>
<td>50 km</td>
<td>1.433</td>
<td>23.76</td>
</tr>
<tr>
<td>90 km</td>
<td>1.094</td>
<td>23.41</td>
</tr>
</tbody>
</table>

The three phase current waveform is illustrated in Fig. 4, while it is assumed that fault is occurred at phase A at 10km from bus1.

**Fig. 3.** Three phase current waveform for three phase short circuit at 10km from bus1

**Fig. 4.** Three phase current waveform for single phase to ground short circuit at 10km from bus1

The actual and estimated magnitude and time constant of dc component, while the fault type is single phase to ground short circuit and $R_f=10\,\Omega$ are shown in table V.

**TABLE V.** The actual and estimated values of decaying dc component in single phase to ground short circuit and $R_f=10\,\Omega$

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Estimated values</th>
<th>Actual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>magnitude (pu)</td>
<td>Time constant (ms)</td>
</tr>
<tr>
<td>10 km</td>
<td>0.828</td>
<td>12.24</td>
</tr>
<tr>
<td>50 km</td>
<td>0.638</td>
<td>12.36</td>
</tr>
<tr>
<td>90 km</td>
<td>0.526</td>
<td>12.37</td>
</tr>
</tbody>
</table>

From the above table it can be concluded that the least median square method’s ability in estimation of magnitude and time constant of dc component is highly acceptable. The error between the actual and estimated values while the fault is occurred at the middle of the line is summarized in table VI.
dc component estimation and elimination for digital relaying. Also, this method is suitable for the relay installed near power faults and can be applied to digital protection relays. The proposed method can estimate dc components exactly from results of the PSCAD/EMTDC simulation showed that the test and distance protection test using PSCAD/EMTDC. The proposed method, we performed a dc component estimation in certain situation in some methods such as DFT and LS is precise estimation of both magnitude and time constant of decaying dc during the fault period. Moreover, the time constant and amplitude of decaying dc are unknown and can be estimated from input data. In other words, the result convergence is independent of variation of input data.

3- One of the most advantages of this method is the precise estimation of both magnitude and time constant of decaying dc component in comparison with the presented method in the literature while the precision of data estimation in a certain situation in some methods such as DFT and LS is respectively near to 14.5% and 2.1%, this value is approximately 1.5% in the proposed method.

IV. DISCUSSION

In this section the proposed method is compared with other presented method:

1- Some of the previous presented method such as digital filtering [2] didn’t have the ability to eliminate decaying dc component, while this presented method can coordinate itself with different kinds of faults and their location. Immediately after sampling of input signal in a cycle, this method is able to estimate stable and precise output.

2- In some methods such as LS (least square) [13] if the data are dispersed impossible or inaccurate estimation will be resulted, where as in proposed method the variation of input data wouldn’t affect the estimation process. In other words, the result convergence is independent of variation of input data.

3- One of the most advantages of this method is the precise estimation of both magnitude and time constant of decaying dc component in comparison with the presented method in the literature while the precision of data estimation in a certain situation in some methods such as DFT and LS is respectively near to 14.5% and 2.1%, this value is approximately 1.5% in the proposed method.

V. CONCLUSION

The current and voltage signals contain serious harmonics and decaying dc during the fault period. Moreover, the time constant and amplitude of decaying dc are unknown and associated with the fault resistance, fault position and fault beginning time.

In this paper we propose a new method based on decaying dc component estimation and elimination for digital relaying. The dc decaying magnitude and time constant are estimated exactly during one cycle. To verify the performance of the proposed method, we performed a dc component estimation test and distance protection test using PSCAD/EMTDC. The results of the PSCAD/EMTDC simulation showed that the proposed method can estimate dc components exactly from fault currents and can be applied to digital protection relays. Also, this method is suitable for the relay installed near power plants. Comparing this method with some previous methods, it is concluded that the estimation in this method is more precise.

A comprehensive set of simulation results through static and dynamic tests has shown that the least median of squares regression method proposed in this paper is more accurate.

REFERENCES


### TABLE VI. Estimation error in different situation

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault resistance</th>
<th>Magnitude estimation error</th>
<th>Time constant estimation error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three phase</td>
<td>0.001Ω</td>
<td>1.46 %</td>
<td>1.12 %</td>
</tr>
<tr>
<td>Three phase</td>
<td>10Ω</td>
<td>1.81 %</td>
<td>1.22 %</td>
</tr>
<tr>
<td>Single phase to ground</td>
<td>0.001Ω</td>
<td>1.63 %</td>
<td>1.58 %</td>
</tr>
<tr>
<td>Single phase to ground</td>
<td>10Ω</td>
<td>1.26 %</td>
<td>1.56 %</td>
</tr>
</tbody>
</table>