AN ALGORITHM FOR IMPROVEMENT THE ACCURACY OF PHASOR ESTIMATION IN THE PRESENCE OF A DECAYING DC COMPONENT IN CURRENT SIGNAL

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ABSTRACT

This paper presents a novel and computationally efficient algorithm for improving the accuracy of phasor estimation in the presence of a decaying DC (DDC) component in current signals during transmission-line faults. In digital protective relays, the discrete Fourier transform (DFT) is widely used to estimate the phasor of the fundamental-frequency component. However, the presence of a DDC component in the current signal may introduce significant errors into the estimated phasor parameters. The proposed algorithm compensates for the DFT estimation error caused by the DDC component. The method consists of two stages. In the first stage, the fault-current samples are summed over a one-cycle data window, and the window is successively shifted by one sample to generate a sequence of summed values. In the second stage, a logarithmic transformation is employed to estimate the DDC parameters. The algorithm requires only $N+4$ samples of the processed signal, where N samples correspond to one period of the fundamental component. In this framework, closed-form analytical expressions are derived for estimating the DDC parameters. The proposed method was evaluated using computer-generated signals, and the simulation results demonstrate strong robustness to noise and higher-order harmonics in the processed current signal.

Keywords: Phasor estimation, Fault current, DFT, Logarithmic transformation, DDC.

INTRODUCTION

Power systems are inherently exposed to fault conditions. Digital protective relays are therefore employed to ensure secure and dependable system operation, and their performance relies heavily on accurate phasor estimation of the fundamental and, in some applications, higher-order

harmonic components. Consequently, phasor estimation remains a key functional requirement in digital and numerical protection algorithms [1].

The principal performance criteria for phasor estimation algorithms are accuracy, response time, and computational complexity. During fault conditions, the measured current signal commonly contains a decaying DC (DDC) component superimposed on the periodic waveform. The presence of this component, together with harmonics and noise, substantially degrades the accuracy and convergence speed of phasor estimation algorithms. As a result, the operating speed and dependability of protection functions may be adversely affected [2].

A variety of digital signal-processing techniques have been employed for phasor estimation, including the discrete Fourier transform (DFT), discrete wavelet transform (DWT), least-squares (LS) methods, and artificial-intelligence-based approaches. Among these, the DFT remains the most widely used algorithm in digital and numerical relays. The DFT provides inherent selectivity with respect to harmonics, exhibits good robustness to white noise, has low computational complexity, converges rapidly, and is straightforward to implement. Nevertheless, because the DDC component is aperiodic and possesses a broad frequency spectrum, it introduces significant errors into DFT-based phasor estimates [3].

In continuous phasor estimation, the DDC component causes oscillatory behavior in the DFT output, making additional compensation techniques necessary in order to achieve the required accuracy and convergence speed [4].

The estimation and removal of the DDC component play a crucial role in DFT-based phasor estimation. Numerous methods have been proposed in the literature to improve the performance of DFT-based estimators under fault conditions. In general, these methods can be classified into two broad groups [5].

The first group is based on filtering the DDC component from the fault-current signal prior to phasor estimation. The DFT is then applied to the filtered signal. In [6], a digital mimic filter was proposed for eliminating the effect of the DDC component. However, complete compensation is achieved only when the actual DDC time constant is equal to the time constant assumed in the mimic filter design. In [7], a Kalman-filter-based approach was proposed for the same purpose, but accurate elimination again depends on the agreement between the actual DDC time constant and the time constant embedded in the state-transition model.

In the second group, the phasor is first estimated by means of the DFT, after which the error introduced by the DDC component is estimated and removed. In [8], the DDC-induced error in the phasor parameters is estimated and compensated using three consecutive phasors calculated by the DFT. Although the algorithm requires only $N + 2$ samples, its performance is sensitive to white noise. In [9], the DDC-induced error is estimated using the output of a second DFT filter tuned to the n-th harmonic; however, the method is also notably sensitive to white noise. In [10], the error introduced by the DDC component is estimated using the outputs of DFT filters applied separately to the even and odd subsets of samples.

In [11], three modified algorithms were proposed for correcting DFT errors caused by DDC components. In the first algorithm, the output of the sine filter is modeled as the sum of a sinusoidal component and a linear function, and the unknown model parameters are estimated by the least-squares method. In the second algorithm, all DDC components at the output of the sine filter are approximated by a single equivalent DDC for each sample index, and the corresponding parameters are then estimated using the Prony method. For this signal model, the Prony method provides efficient and noise-robust parameter estimation. In addition, analytical expressions were derived for the unknown parameters, leading to a computationally efficient implementation. In the third algorithm, the sine-filter output is first processed by a notch filter, which transforms the signal into a simpler form containing only DDC terms. These terms are then approximated by a single equivalent DDC, whose parameters are again estimated using the Prony method, resulting in even more compact analytical expressions.

Motivated by the need for fast and computationally efficient compensation methods, this paper proposes a novel algorithm for improving phasor estimation accuracy in the presence of a

decaying DC component in current signals during transmission-line faults. The proposed method compensates for the DFT estimation error caused by the DDC component in two stages:

- In the first stage, the fault-current samples are summed over a one-cycle data window, and the window is successively shifted by one sample to generate a sequence of summed values.
- In the second stage, a logarithmic transformation is applied to estimate the DDC parameters.

The algorithm requires only $N+4$ samples of the processed signal, where N samples correspond to one fundamental period. Within this framework, closed-form analytical expressions are derived for accurate estimation of the DDC parameters.

The key advantages and scientific contribution of the proposed algorithm, relative to the DFT-based methods published so far, are:

- **Robustness to random noise in the processed signal**, which is generally a weak point of previously published DFT-based methods. Because the DFT distributes a single-tone component across neighboring bins under spectral leakage, broadband random noise raises the noise floor in every bin and directly biases the amplitude and phase estimates; an algorithm that remains accurate under these conditions is therefore of clear practical value for real, noisy measurements.
- **Satisfactory accuracy when the frequency deviates from its nominal value.** This criterion is very rarely used to test algorithms in previously published work, precisely because the proposed algorithms tend to be sensitive to any mismatch between the actual signal frequency and the nominal frequency. Such a mismatch violates the coherent-sampling assumption (an integer number of periods within the analysis window), producing spectral leakage and the picket-fence effect; demonstrating accuracy under off-nominal frequency conditions is thus a demanding and meaningful test of robustness.
- **Robustness to multiple DDC.**
- **Computational simplicity and fast response time**, which makes the method well suited to real-time or embedded implementation, where a low operation count and short processing latency are often as important as the estimation accuracy itself.

PROPOSED ALGORITHM

Discrete Fourier Transform

Assuming that sinusoidal components above the $\left(\frac{N}{2}-1\right)$-th harmonic are sufficiently attenuated by a low-pass filter, the discrete fault-current signal measured by the protective relay can be expressed as:

$$i[n]=\sum_{j=1}^{N/2-1} A_j \cos\left(\frac{2\pi j}{N}n+\varphi_j\right)+D\,\mathrm{e}^{-\frac{nT_s}{\tau}}+e(n) \tag{1}$$

where τ and D denote the time constant and amplitude of the exponentially decaying DC component, respectively; A_j and φ_j represent the amplitude and phase angle of the j-th harmonic component; T_s is the sampling interval; and N is the number of samples per cycle. The phasor corresponding to the fundamental-frequency component is given by:

$$\begin{aligned} I_{RF}&=\frac{2}{N}\sum_{n=0}^{N-1} i[n]\cos\left(\frac{2\pi}{N}n\right)\\ I_{IF}&=\frac{2}{N}\sum_{n=0}^{N-1} i[n]\sin\left(\frac{2\pi}{N}n\right)\end{aligned} \tag{2}$$

where I_{RF} and I_{IF} denote the real and imaginary parts of the fundamental-frequency phasor, respectively. The DFT-based estimate of the phasor can be written as:

$$I_{RF} = A_1 \cos\left(\frac{2\pi}{N}k + \varphi_1\right) + D_{RF}$$
$$I_{IF} = -A_1 \sin\left(\frac{2\pi}{N}k + \varphi_1\right) + D_{IF} \quad (3)$$

where D_{RF} and D_{IF} represent the contributions of the decaying DC component to the real and imaginary parts of the estimated phasor, respectively.

$$D_{RF} = D\left(E^N - 1\right)\frac{E\cos\frac{2\pi}{N} - 1}{E^2 - 2E\cos\frac{2\pi}{N} + 1};\ E = e^{-\frac{T_S}{\tau}} \quad (4)$$

$$D_{IF} = D\left(E^N - 1\right)\frac{-E\sin\frac{2\pi}{N}}{E^2 - 2E\cos\frac{2\pi}{N} + 1};\ E = e^{-\frac{T_S}{\tau}} \quad (5)$$

Although the DFT is simple and computationally efficient, its estimate of the fundamental-frequency phasor is affected by errors introduced by the DDC component.

Estimation of DDC-Induced Errors in the Real and Imaginary Components of the Phasor

By summing the fault-current samples over a one-cycle data window, the following expression is obtained:

$$I_0 = \sum_{n=0}^{N-1} i[n] = \sum_{n=0}^{N-1}\left(\sum_{j=1}^{N/2-1} A_j \cos\left(\frac{2\pi j}{N}n + \varphi_j\right) + D\,\mathrm{e}^{-\frac{nT_s}{\tau}} + e(n)\right) \quad (6)$$

After simplification, the above expression can be written as:

$$I_0 = D\frac{E^N - 1}{E - 1};\ E = e^{-\frac{T_S}{\tau}} \quad (7)$$

By shifting the data window by an arbitrary number of samples, the following sequence is obtained:

$$I_0(k) = \sum_{n=0}^{N-1} i[n+k], \quad k = 0,1,\ldots,m \quad (8)$$

where *m* is the number of consecutive shifts of the data window.
After evaluation, this expression becomes:

$$I_0(k) = CE^k, \quad k = 0,1,\ldots,m \quad (9)$$

where *C* is given by:

$$C = D\frac{E^N - 1}{E - 1} \quad (10)$$

For each k in expression (9), a nonlinear relation is obtained between the unknowns *C, E* and the known $I_0(k)$. This yields an overdetermined nonlinear system of equations:

$$\begin{aligned} I_0[0] &= C \\ I_0[1] &= CE \\ &\vdots \\ I_0[m-1] &= CE^{m-1} \\ I_0[m] &= CE^{m} \end{aligned} \tag{11}$$

Each of the equations of the over-determined system (11) is nonlinear, of power-law form, with unknowns C and E. By taking the logarithm of each of these equations, a linear relation is obtained between the unknowns — which are now log C and log E — allowing the previous nonlinear problem to be solved by the simple method of linear regression, i.e. the least-squares method.

The resulting system can be solved by means of a logarithmic transformation. By applying the logarithm to each equation, the nonlinear system is converted into an overdetermined linear system:

$$\begin{aligned} \log C &= \log I_0[0], \\ \log C + \log E &= \log I_0[1], \\ &\vdots \\ \log C + (m-1)\log E &= \log I_0[m]. \end{aligned} \tag{12}$$

The above overdetermined linear system can be written in matrix form as:

$$\mathbf{A}\cdot\mathbf{X} = \mathbf{Y} \tag{13}$$

where

$$\mathrm{A} = \begin{pmatrix} 1 & 0 \\ 1 & 1 \\ \vdots & \vdots \\ 1 & m-1 \end{pmatrix}, \quad \mathrm{X} = \begin{pmatrix} \log C \\ \log E \end{pmatrix}, \quad \mathrm{Y} = \begin{pmatrix} \log I_0[0] \\ \log I_0[1] \\ \vdots \\ \log I_0[m] \end{pmatrix}. \tag{14}$$

By solving this system using the least-squares method, the following result is obtained:

$$\mathbf{X} = \left(\mathbf{A}^{T}\mathbf{A}\right)^{-1}\mathbf{A}^{T}\mathbf{Y} \tag{15}$$

After simplification, one obtains:

$$\begin{aligned} \log C &= \frac{2}{m(m+1)}\left((2m-1)\sum_{k=1}^{m}\log I_0[k] - 3\sum_{k=1}^{m}(k-1)\log I_0[k]\right) \\ \log E &= \frac{2}{m(m+1)}\left(-3\sum_{k=1}^{m}\log I_0[k] + \frac{6}{m-1}\sum_{k=1}^{m}(k-1)\log I_0[k]\right) \end{aligned} \tag{16}$$

By taking the antilogarithm of the above expressions, the parameters C and E are determined. The DDC-induced contributions to the real and imaginary components of the phasor can then be calculated as:

$$D_{IF} = -\frac{2\cdot C\cdot E\cdot(E-1)\sin\frac{2\pi}{N}}{N\cdot\left(E^2 - 2E\cos\frac{2\pi}{N} + 1\right)} \tag{17}$$

$$D_{RF} = -D_{IF}\frac{E\cos\frac{2\pi}{N}-1}{\sin\frac{2\pi}{N}} \tag{18}$$

Finally, the fundamental-frequency phasor is obtained from:

$$\begin{aligned} A_1 &= \sqrt{\left(I_{RF}-D_{RF}\right)^2+\left(I_{IF}-D_{IF}\right)^2} \\ \varphi_1 &= arctg\frac{-I_{IF}+D_{IF}}{I_{RF}-D_{RF}} \end{aligned} \tag{19}$$

PERFORMANCE EVALUATION OF THE PROPOSED ALGORITHM

To evaluate the performance of the proposed algorithm, several computer-generated test signals were considered under different operating conditions. For all examined signals, the following parameters were defined [5]:

- number of samples per cycle, $N = 32$
- fundamental frequency, $f = 50Hz$
- sampling frequency, $f_S = 1600Hz$
- DDC time constants, τ=0.01s and τ=0.1s
- magnitude of the fundamental component, $A_1 = 1\,p.u.$
- phase angle of the fundamental component, $\varphi_1 = 60^\circ$
- signal-to-noise ratio (SNR) $SNR = 40\ dB$ and $SNR = 20\ dB$.

The noise level relative to the useful signal is measured as the signal-to-noise ratio (SNR — Signal to Noise Ratio) and is expressed in dB (decibels):

$$\mathrm{SNR} = 20\log\frac{A}{\sqrt{2}\sigma} \tag{20}$$

In the above relation, A is the amplitude of the fundamental harmonic, and σ is its standard deviation.

To assess the accuracy and precision of the proposed algorithm in estimating the magnitude of the fundamental current phasor, the mean values and standard deviations of the estimated amplitude were calculated. For comparison, the same statistical measures were also determined for the conventional DFT method without DDC correction. All reported statistics were obtained from 200 simulation runs. The exact amplitude value was $A_1 = 1p.u.$.

Performance Evaluation Under Harmonic Distortion and Noise

To examine the robustness of the proposed algorithm in the presence of harmonic distortion and measurement noise, the following test signal was considered [5]:

$$i[n] = \sum_{j=1}^{N/2-1}\frac{A_j}{n}\cos\left(\frac{2\pi j}{N}n - n\varphi_j\right) + A_1\,\mathrm{e}^{-\frac{nT_s}{\tau}} + white\ \ random\ noise \tag{21}$$

During transmission-line faults, the decaying DC component appears in the fault current as a consequence of the inductive nature of the network. Its time constant typically ranges from 0.5 to 5 cycles. Therefore, two different values of the time constant were used to evaluate the performance of the proposed algorithm.

In the first case, the time constant was set to $\tau = 0,01s$. The corresponding fault current waveform is shown in Figure 1.

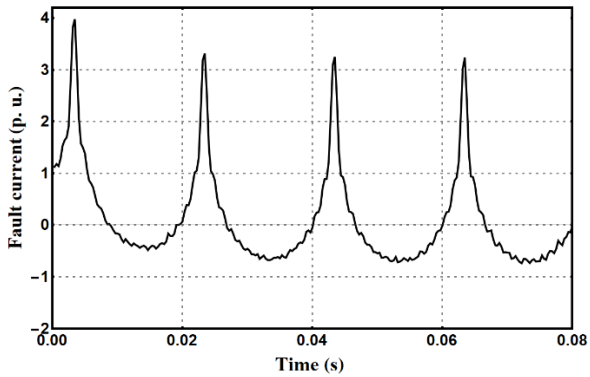


Figure 1. Fault current waveform for $\tau = 0,01s$

Table 1 lists the mean values and standard deviations obtained using the proposed algorithm, the DFT method without correction and algorithm proposed in reference [8].

Table 1. Mean values and standard deviations for the case in which the DDC time constant is set to $\tau = 0,01s$ **.**

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.999686	0.999919
	stand. dev.	0.0242654	0.0022948
DFT without correction	mean	1.27042	1.26941
	stand. dev.	0.0186295	0.0018004
Ref. [8]	mean	1.03498	1.00449
	stand. dev.	0.0266439	0,009898

In the second case, the time constant was set to $\tau = 0,1s$. The corresponding fault current waveform is shown in Figure 2.

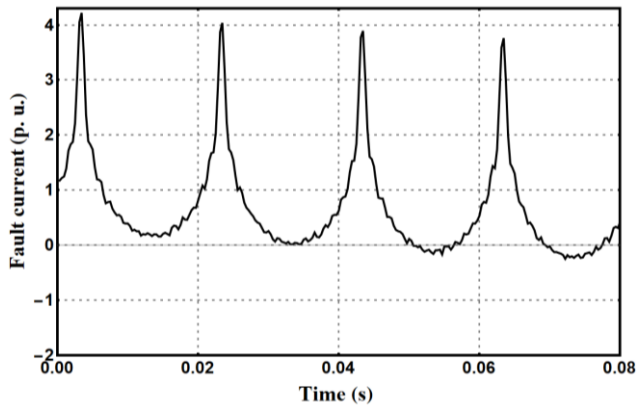


Figure 2. Fault current waveform for $\tau = 0,1s$

Table 2 lists the mean values and standard deviations obtained using the proposed algorithm , the DFT method without correction and algorithm proposed in reference **[8]**.

Table 2. Mean values and standard deviations for the case in which the DDC time constant is set to $\tau = 0,1s$ **.**

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.999167	0.999822
	stand. dev.	0.0229832	0.00221171
DFT without **correction**	mean	1.05458	1.05366
	stand. dev.	0.00170873	0.00184136
Ref. [8]	mean	1.03559	1.00485
	stand. dev.	0.028505	0.010106

The results in Tables 1 and 2 indicate that the proposed algorithm yields mean estimated amplitudes very close to the exact value under both noise levels and for both DDC time constants. In contrast, the conventional DFT method without correction exhibits substantial bias due to the presence of the DDC component.

Performance Evaluation in the Presence of Multiple Decaying DC Components

Current transformers (CTs) are commonly used to measure line currents in power systems. Under fault conditions, the CT secondary current may contain two exponentially decaying DC components, whereas the primary fault current typically contains only one such component. The additional DDC component arises from CT transient behavior and the burden connected to the secondary circuit.

To evaluate the influence of multiple DDC components on the performance of the proposed algorithm, the following test signal was used [5]:

$$i[n] = \sum_{j=1}^{N/2-1} \frac{A_j}{n} \cos\left(\frac{2\pi j}{N} n - n\varphi_j\right) + A_1 \mathrm{e}^{-\frac{nT_s}{\tau}} - 0,1A_1 \mathrm{e}^{-\frac{nT_s}{\tau_s}} + white\ \ random\ noise \quad (22)$$

Because the CT burden is usually small, the second DDC component decays slowly and is therefore characterized by a relatively large time constant. In this study, the time constant of the second DDC component was set to 20 cycles.

Table 3 presents the mean values and standard deviations for the proposed algorithm and the DFT method without correction when the time constant of the primary DDC component is set to $\tau = 0,01s$.

Table 3. Mean values and standard deviations for the case of multiple DDC components, with the primary DDC time constant set to $\tau = 0,01s$

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.99945	0.999655
	stand. dev.	0.020441	0.00220478
DFT without correction	mean	1.26874	1.26803
	stand. dev.	0.0170192	0.00187318
Ref. [8]	mean	1.03473	1.004446
	stand. dev.	0.025	0.01037

Table 4 presents the corresponding results when the time constant of the primary DDC component is set to $\tau = 0,1s$.

Table 4. Mean values and standard deviations for the case of multiple DDC components, with the primary DDC time constant set to $\tau = 0,1s$ **.**

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	0.999045	0.999632
	stand. dev.	0.023269	0.00224038
DFT without correction	mean	1.05233	1.05218
	stand. dev.	0.000179	0.001712
Ref. [8]	mean	1.08	1.00264
	stand. dev.	0.07716	0.004028

These results show that the proposed method preserves high estimation accuracy even when multiple DDC components are present, whereas the uncorrected DFT estimate remains significantly biased.

Performance Evaluation Under Off-Nominal Frequency Conditions

During transient conditions, the fundamental frequency may deviate from its nominal value, which may introduce both oscillatory and steady-state errors into phasor estimation. To evaluate the performance of the proposed algorithm under off-nominal frequency conditions, the test signal defined in the previous subsection was analyzed for frequencies of 49.5 Hz and 50.5 Hz [5].

Table 5 presents the mean values and standard deviations for the proposed algorithm and the DFT method without correction when the fundamental frequency is set to 49.5 Hz.

Table 5. Mean values and standard deviations for the case in which the fundamental frequency is 49.5 Hz.

Method	Criterion	SNR=20dB	SNR=40dB
Proposed algorithm	Mean	0.980717	0.981039
	stand. dev.	0.0250937	0.00242639
DFT without correction	Mean	1.27629	1.27618
	stand. dev.	0.016757	0.00184741
Ref. [8]	mean	1.0808	1.0225
	stand. dev.	0.06896	0.00851

Table 6 presents the corresponding results when the fundamental frequency is set to 50.5 Hz.

The results under off-nominal frequency conditions indicate that the proposed algorithm continues to outperform the conventional DFT without correction. Nevertheless, a small residual bias is observed, which is expected because the method is derived under nominal-frequency assumptions. This observation is consistent with recent literature, where frequency deviations remain a challenging condition for fixed-window DFT-based estimators.

Table 6. Mean values and standard deviations for the case in which the fundamental frequency is 50.5 Hz.

Method	criterion	SNR=20dB	SNR=40dB
Proposed algorithm	mean	1.02649	1.0259
	stand. dev.	0.023296	0.0024
DFT without correction	mean	1.26445	1.26251
	stand. dev.	0.017128	0.0016267
Ref. [8]	mean	1.11673	1.10318
	stand. dev.	0.091555	0.02006

CONCLUSIONS

This paper presented a novel DFT-based algorithm for improving phasor estimation accuracy in the presence of decaying DC components. The proposed method consists of two sequential processing stages. In the first stage, the fault-current samples are summed over a one-cycle data window, and the window is then successively shifted by one sample to generate a sequence used to estimate the DDC-induced error in the DFT output. In the second stage, the fundamental phasor is accurately determined by removing the estimated DDC contribution from the DFT result.

The simulation results demonstrate that the proposed algorithm provides:

- fast convergence,
- high robustness in the presence of harmonic distortion and noise,

- reliable performance when multiple DDC components are present in the fault-current signal, and
- satisfactory operation under off-nominal frequency conditions.

Because of its fast dynamic response, high estimation accuracy, and robustness under adverse operating conditions, the proposed algorithm appears well suited for real-time protection applications in electric power systems.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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