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Short communication

Online algorithm for removal of decaying DC-offset from fault currents

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ABSTRACT

This paper 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. The DC component is removed by subtracting the DC value at each sampling instant. The Discrete Fourier Transform (DFT) is applied to the result to extract the phasor of the fundamental component. Different transient signals are investigated. The results show that the proposed method is accurate and easy to implement.

1. Introduction

Input signals, for variety of measurements in protection applications, contain noise, such as DC offset and harmonics, which must be filtered to retain the required fundamental frequency signal. Discrete Fourier Transform (DFT) is widely used technique that can distinguish harmonics using simple computations if the assumptions described in [1] are satisfied. However, during any fault period, the voltage and current signals include large harmonics and DC offset. The DC offset severely inhibits the search for a correct fundamental frequency signal and delays the convergence time [2]. Furthermore, when the signal analyzed contains an exponentially decaying DC offset, the estimated phasor using DFT may have an error of up to 15% [3]. This is not acceptable for protective relays.

Different methods have been developed to eliminate the decaying DC offset [1–4]. Some methods either have estimation problems or give oscillating output as a function of the time constant of the exponential component of the signal [1,2]. Other methods either are complex and therefore, unsuitable for use in real time in a digital device, or they need more than one fundamental period [3,4].

This paper presents a method to remove the actual exponentially decaying DC offset from fault currents. The proposed method is compared to the full-cycle conventional DFT and to recently developed techniques to obtain the fundamental frequency signals, it requires a small number of samples (10 samples) and a delay of exactly one cycle to compute and eliminate the DC offset.

2. Proposed method

Considering that the fault current contains fundamental, harmonics and decaying DC components [1–4], the fault current can be mathematically expressed

$$i(t) = Ae^{-t/\tau} + \sum_{k=1}^{M} A_k \cos(k\omega_1 t + \varphi_k) \tag{1}$$

where A is the amplitude of the decaying DC component, M is the maximum harmonic order, τ is the time constant, ω_1 is the angular frequency of the fundamental component, A_k and φ_k are the amplitude and the angle of the kth harmonic, respectively

The second term of (1) is periodic and has the properties of periodic functions, that is the difference between two samples separated in time by a fundamental frequency period (T) is zero. Meanwhile, it is a combination of trigonometric functions, so its integral during one period is also zero. Applying these properties to (1) gives the following equations

$$\begin{aligned} i(t+T) - i(t) &= Ae^{-(t+T)/\tau} - Ae^{-t/\tau} \\ &= Ae^{-t/\tau}(e^{-T/\tau} - 1) = x(t) \end{aligned} \tag{2}$$

Integrating Eq. (1) gives

$$\begin{aligned} u(t) &= \int i(t)dt = \int \left(Ae^{-t/\tau} + \sum_{k=1}^{M} A_k \cos(k\omega_1 t + \varphi_k) \right) dt \\ &= -A\tau e^{-t/\tau} + \sum_{k=1}^{M} \frac{A_k}{k\omega_1} \sin(k\omega_1 t + \varphi_k) + \text{Constant} \end{aligned} \tag{3}$$

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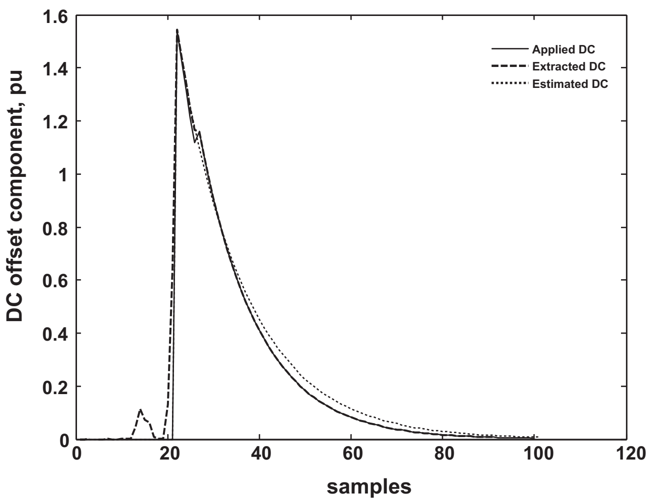

Fig. 1. Extracted and estimated DC offset.

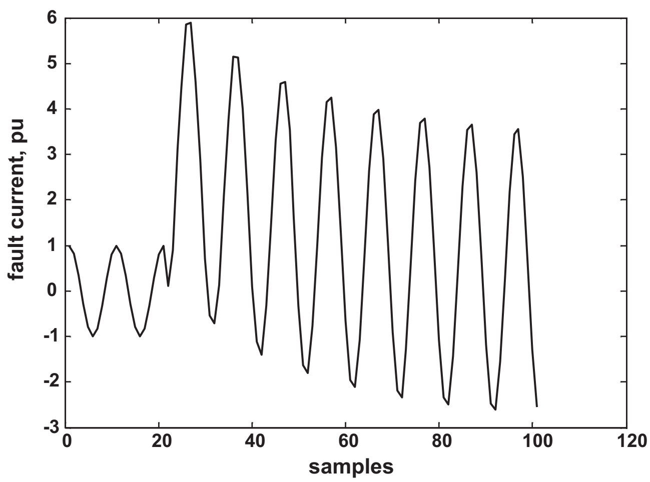

Fig. 2. Applied signal.

The second component of Eq. (3) is also periodic, thus

$$u(t+T)-u(t) = \int_t^{t+T} Ae^{-t/\tau}dt = (-A\tau e^{-t/\tau})\Big|_t^{t+T} = -A\tau e^{-(t+T)/\tau}+A\tau e^{-t/\tau} = -A\tau e^{-t/\tau}(e^{-T/\tau}-1) = y(t) \quad (4)$$

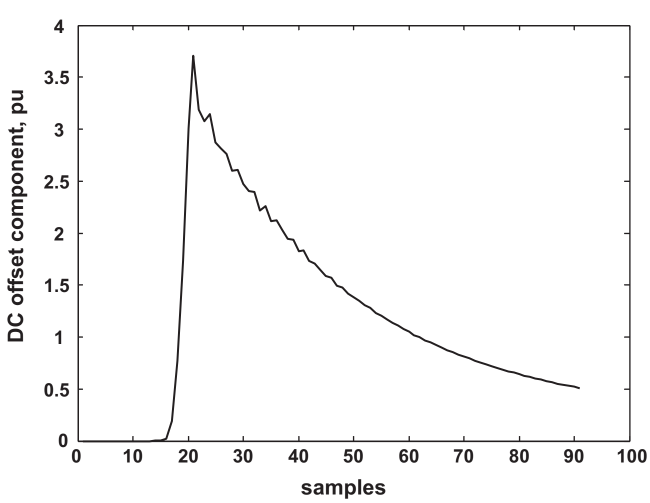

Fig. 3. Extracted DC offset.

Table 1
Magnitude variation obtained with off-nominal frequency.

τ (ms)	I_{dc}/I_f	The frequency of input signal (Hz)				
		49.8	49.9	50	50.1	50.2
25	Min A_1	2.9262	2.9602	3.000	2.9817	2.9708
	Max A_1	3.0659	3.0079	3.000	3.0123	3.0174
50	Min A_1	2.9525	2.9758	3.000	2.9889	2.9795
	Max A_1	3.0165	3.0094	3.000	3.0126	3.0182

From (2) and (4), if the value of fault current and its integral during any period from instant t to $t+T$ is available, the following equation can be used to calculate the time constant (τ) at each instant as

$$\tau(t) = -\frac{y(t)}{x(t)} \quad (5)$$

Using Eqs. (2) and (5) the instantaneous value of the DC offset can be calculated as:

$$Ae^{-t/\tau(t)} = -\frac{x(t)}{e^{-T/\tau(t)}-1} \quad (6)$$

In (5) and (6), $x(t)$ and $y(t)$ are obtained from the measured and integrated fault current, respectively, at the instants (t) and $(t+T)$. Obtained, actual DC component is subtracted from the input signal and DFT can be applied to the result to extract the fundamental component.

Using Eq. (5), the time constant, from the practical point of view, can be calculated without computational burden and without Taylor series expansion, which, to get accurate results, requires high number of samples to make the sampling period (Δt) much lower than the time constant of the power system [4].

In the other hand, DC offset can be estimated from the first fundamental period data and subtracted from the original fault current at a sampling instant. From (2), the DC value at time t is calculated with a time constant and the original signal of the fault current. The DC value for the next sampling instant can be calculated by multiplying previous DC values by an exponential increment as shown below

$$Ae^{-t/\tau} = \frac{x(t)}{(e^{-T/\tau}-1)} \quad (7)$$

$$Ae^{-(t+\Delta t)/\tau} = \frac{x(t+\Delta t)}{(e^{-T/\tau}-1)} = Ae^{-t/\tau} \quad Ae^{-\Delta t/\tau} = \frac{x(t)}{(e^{-T/\tau}-1)}e^{-\Delta t/\tau} \quad (8)$$

However, to apply the proposed algorithm to the fault current and estimate DC offset, one cycle of sample data must be available. The time constant of the decaying DC component can be calculated by applying $t=0$ to (5). Therefore, the following equation is obtained:

$$\tau = -\frac{y(0)}{x(0)} = \frac{u(T)-u(0)}{i(T)-i(0)} \quad (9)$$

Eq. (9) requires that the instant, at which the fault current occurs must be detected. Knowing the time constant, and applying Eqs. (7) and (8) the DC value can be directly calculated at a sampling instant.

Thus, to apply the proposed algorithm to the fault current and estimate DC offset, one cycle of sample data must be available. Estimated DC offset can be subtracted from the original signal and then DFT can be applied to the result to extract the fundamental component.

3. Results and discussion

The proposed method has been tested for several simulated sampled signals, which contained DC component with different τ and ratios of the fundamental and DC components (I_f/I_{dc}). The sampling rate was set to 10 samples per cycle. Fig. 1 shows extracted,

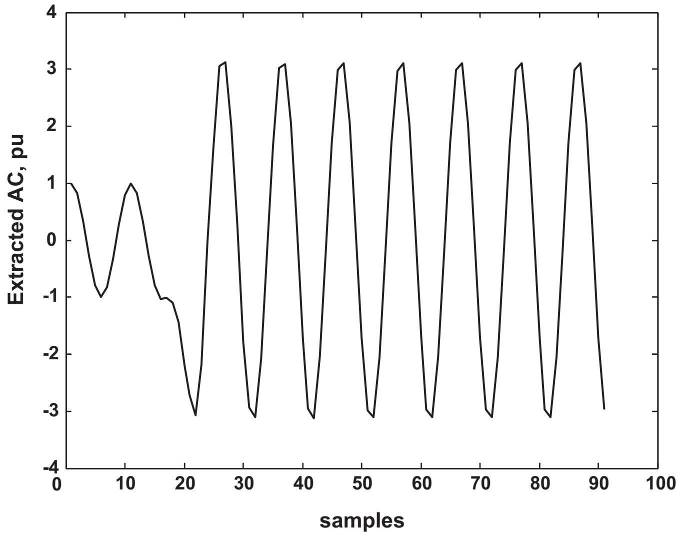

Fig. 4. AC component of the fault current.

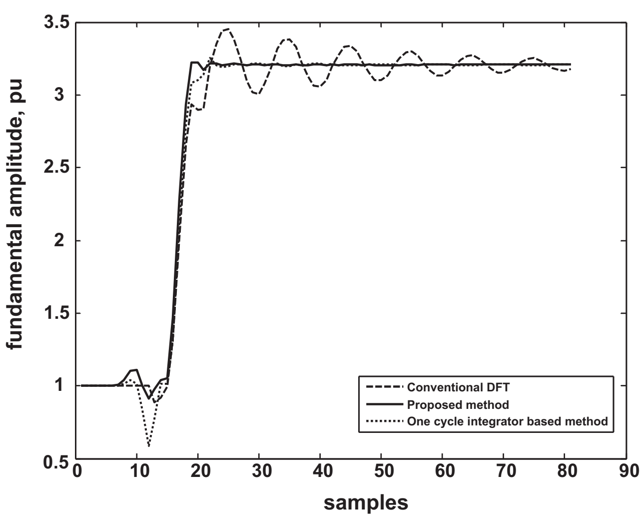

Fig. 5. Magnitude of the fundamental component.

estimated, and applied DC offset for a 50 HZ simulated fault current, where the signal contained two DC components of $I_f/I_{dc} = 0.6$ and 1 and $\tau = 25$ ms. The result shows that the proposed method gives much better agreement of the extracted and DC offset than estimating the DC offset by one cycle integration. The method is also tested for off-nominal frequency. Results, in Table 1, provided for $I_f/I_{dc} = 0.6$ and $\tau = 25$ and 50 ms, show that the proposed method efficiently extracts the fundamental component of the fault current in case of the frequency change, with maximum error of about 2.46% at system frequency of 49.8 and $\tau = 25$.

The proposed method was applied to a 50 Hz fault current in Fig. 2. This signal is a phase current of a three-phase fault obtained by the software ATP-EMTP. Fig. 3 shows the extracted DC offset component. It took one cycle to start extracting the DC value from the first appearance of the DC decaying component. After the DC offset is removed from the input current, the time-domain AC current of the applied signal is extracted as shown in Fig. 4. The amplitude of the fundamental component using the proposed algorithm is calculated as shown in Fig. 5. As a comparison, the results of applying conventional DFT and the one cycle integrating based method [4] are also provided. Conventional DFT and one cycle integrating based method had an oscillation in the fundamental component and required more time to obtain a stable output.

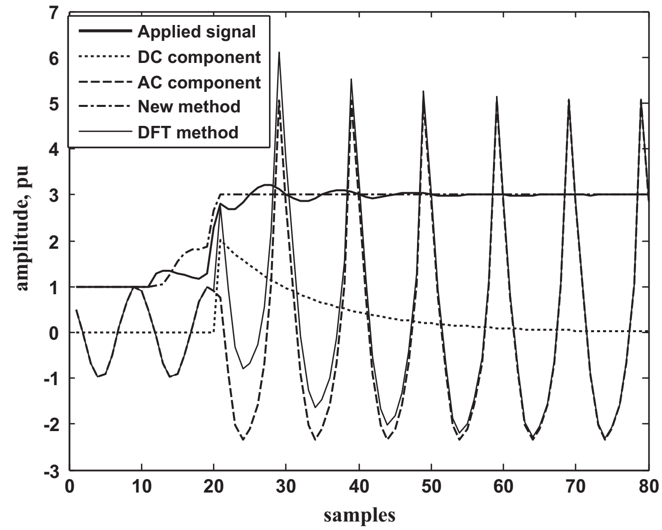

Fig. 6. Application of the proposed method to a harmonic contaminated fault current.

To show that the proposed method is capable of working in the presence of harmonics, the proposed method is applied to a harmonic contaminated fault current, simulated according to Eq. (1), where $A = 2$ pu, $M = 7$, $A_1 = 1$ pu, $\varphi_1 = \pi/3$ rad, $A_k = A_1/k$, $\varphi_k = k\varphi_1$, and $\tau = 25$ ms. Fig. 6 shows that, in case of harmonics presence, the DC offset component is accurately extracted. The fundamental and the AC components of the fault current are also perfectly calculated.

4. Conclusion

An online algorithm for removing DC offset from fault current is presented. The method accurately extracts the actual DC from fault currents with a delay of one fundamental cycle. Simulation results show that the proposed algorithm has faster convergence and better accuracy than the conventional DFT and the one cycle integrating based method.

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