A Method for Estimating an Instantaneous Phasor Based on a Modified Notch Filter

Soon-Ryul Nam†, Jin-Man Sohn Sang-Hee Kang* and Jong-Keun Park****

Abstract - A method for estimating the instantaneous phasor of a fault current signal is proposed for high-speed distance protection that is immune to a DC-offset. The method uses a modified notch filter in order to eliminate the power frequency component from the fault current signal. Since the output of the modified notch filter is the delayed DC-offset, delay compensation results in the same waveform as the original DC-offset. Subtracting the obtained DC-offset from the fault current signal yields a sinusoidal waveform, which becomes the real part of the instantaneous phasor. The imaginary part of the instantaneous phasor is based on the first difference of the fault current signal. Since a DC-offset also appears in the first difference, the DC-offset is removed from the first difference using the results of the delay compensation. The performance of the proposed method was evaluated for a-phase to ground faults on a 345 kV 100 km overhead transmission line. The Electromagnetic Transient Program was utilized to generate fault current signals for different fault locations and fault inception angles. The performance evaluation showed that the proposed method can estimate the instantaneous phasor of a fault current signal with high speed and high accuracy.

Keywords: DC-offset, Distance protection, Estimation, First difference, Instantaneous phasor, Modified notch filter.

1. Introduction

The continuous expansion of power systems in both scale and complexity has imposed a requirement for fast fault clearance to improve system stability and reliability. If a fault in an important transmission line is not identified and removed as quickly as possible, it could lead to widespread damage in the power system. In order to prevent the damage from spreading to the healthy parts of the power system, protective relays need to detect the faults within sub-cycles of the power frequency. This makes the challenge more difficult, since less data are provided to extract the desired frequency component.

Most distance relays are based on estimating the phasors of the voltage and current signals. In order to estimate the current phasor accurately, the DC-offset should be removed from the fault current signal. Since the DC-offset is a non-periodic signal and its frequency spectrum encompasses all frequencies, the presence of the DC offset can result in almost a twenty percent error in phasor estimation, depending on the algorithm used.

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Over the last two decades, a number of techniques have been proposed to deal with the DC-offset problem [1-8]. One approach to eliminating the effect of the DC-offset is to assume a specific time constant for the DC-offset. In [1], a digital mimic filter has been proposed to sift out the decaying DC-offset over a broad range of time constants. The DC-offset can be removed completely when the time constant of the DC-offset matches the one assumed in the mimic filter. However, this is unrealistic because the time constant varies with the fault conditions, such as the system configuration, fault location, and fault impedance. Application of state-variable models can be used to develop estimators in the form of a Kalman filter [2-3]. Like the mimic filter, the Kalman filter is also sensitive to variations in the time constant. A Kalman filter will only be effective in removing a DC-offset if its time constant is the same as the one modeled in the state transition matrix.

Another approach is to estimate the parameters of the DC-offset. In [4], a least error square (LES) algorithm has been proposed to suppress the effect of the DC-offset, which is linearized by including only the first two terms of the Taylor series expansion. The recursive LES algorithm [5] can be introduced to reduce the computation burden. LES-based algorithms can successfully suppress the effect of the DC-offset over a certain range of time constants. When the time constant is small, however, the performance of these algorithms decreases due to the linearization. Several DFT-based algorithms have also been proposed to eliminate the influence of the DC-offset. A novel Fourier filter algorithm [6] has been suggested to estimate the parameters of the DC-offset using three successive outputs of the fundamental frequency DFT. Since this algorithm makes use of one cycle plus two samples, its response speed is slower than other DFT-based algorithms by two samples. To cope with this drawback, one output of the harmonic DFT is used to estimate the parameters of a DC-offset in [7] and two partial summations of one cycle samples are used in [8]. Although these DFT-based algorithms are good at estimating the phasor, they are unsuitable for high-speed distance protection due to the time delay of one or more cycles.

In order to realize high-speed distance protection that is immune to a DC-offset, this paper proposes a method for estimating an instantaneous phasor based on a modified notch filter. The performance of the proposed method is evaluated for a-phase to ground (a-g) faults on a 345 kV 100 km overhead transmission line. Using the fault current signals generated by the Electromagnetic Transient Program (EMTP), we show that the proposed method can estimate the instantaneous phasor of a fault current signal with both high speed and high accuracy.

2. Phasor Estimation

We assumed that a fault occurs at a time origin and that the fault current signal consists of a DC-offset and a power frequency component. Based on this assumption, the discretized fault current, which is pre-conditioned by a low-pass filter, is expressed as:

$$i_L[n] = i_{ac}[n] + i_{dc}[n] = A \cdot \cos(\omega n \Delta t + \phi) + B \cdot \alpha^n \quad (1)$$

Where

ω = angular power frequency,
τ = time constant of the DC-offset,
N = number of samples per system cycle,
α = $e^{-\frac{\Delta t}{\tau}}$
Δt = $\frac{2\pi}{\omega}\frac{1}{N}$.

2.1 Improved Fourier Algorithm [8]

The operating principle of the improved Fourier algorithm used in [8] is described briefly. The real and imaginary parts of the DFT are given as:

$$I_C[n] = \frac{2}{N}\sum_{k=1}^{N} i_L[n+k-N] \cdot \cos(\omega \cdot k\Delta t) \quad (2\text{-}1)$$

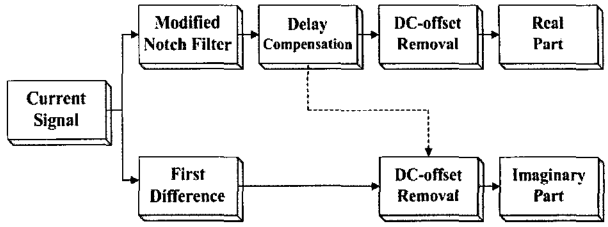


Fig. 1. Schematic of the procedure for estimating the instantaneous phasor.

$$I_S[n] = -\frac{2}{N}\sum_{k=1}^{N} i_L[n+k-N] \cdot \sin(\omega \cdot k\Delta t) \quad (2\text{-}2)$$

In order to remove the effect of the DC-offset, two partial summations are defined as:

$$S_1[n] = \sum_{k=1}^{N/2} i_L[n+2k-N-1] \quad (3\text{-}1)$$

$$S_2[n] = \sum_{k=1}^{N/2} i_L[n+2k-N] \quad (3\text{-}2)$$

Using the partial summations in (3), the compensated real and imaginary parts are given by:

$$I_R[n] = I_C[n] + (1 - \alpha\cos(\frac{2\pi}{N}))C(\alpha)S_1[n] \quad (4\text{-}1)$$

$$I_I[n] = I_S[n] - \alpha\sin(\frac{2\pi}{N})C(\alpha)S_1[n] \quad (4\text{-}2)$$

where

$$C(\alpha) = \frac{2}{N} \cdot \frac{\alpha^2 - 1}{\alpha^2 - 2\alpha\cos(\frac{2\pi}{N}) + 1}, \quad \alpha = \frac{S_2[n]}{S_1[n]}$$

Although this algorithm is good at estimating the phasor, it is unsuitable for high-speed distance protection due to the one-cycle time delay. To cope with this drawback, the instantaneous phasor estimation will be applied during the transient time of the improved Fourier algorithm.

2.2 Instantaneous Phasor Estimation

A schematic of the procedure for the instantaneous phasor estimation is shown in Fig. 1. The estimation uses a modified notch filter to eliminate iac[n] from iL[n] of (1). Since the output of the modified notch filter is the delayed waveform of idc[n], delay compensation results in the same waveform as idc[n]. The real part of the instantaneous phasor is obtained by subtracting the obtained DC-offset from iL[n]. The imaginary part is based on the first difference of iL[n]. The DC-offset contained in the first difference is removed using the results of the delay compensation.

2.2.1 Modified Notch Filter

The second-order analog notch filter has the following standard transfer function:

$$H_a(s) = \frac{s^2 + \Omega_o^2}{s^2 + 2\zeta\Omega_0 s + \Omega_o^2} \tag{5}$$

where, Ω0 and ζ are the notch angular frequency and damping ratio, respectively. It is easily found that the notch filter of (5) satisfies the following conditions.

$$|H_a(j\Omega_o)| = 0 \tag{6}$$

$$|H_a(j0)| = |H_a(j\infty)| = 1 \tag{7}$$

Since we use the notch filter to remove the power frequency component, Ω0 is fixed at 120π in 60 Hz systems.

In order to evaluate the response speed of a filter, the settling time is defined as the amount of time required for the damped oscillations of the transient to stay within ± 2% of the steady-state value. The step response of the standard notch filter given in (5) has a settling time between 11.7 and 88.5 ms, depending on the value of ζ. Since these settling times are too long to be used for high-speed distance protection directly, the standard notch filter must be modified to improve the response speed. This modification can be achieved by alleviating one of the conditions given in (6) or (7). Since the first condition (6) must be unchanged, considering the role of the notch filter, the second condition (7) is alleviated as in the following equation:

$$H_m(s) = \frac{s^2 + \Omega_o^2}{A^2 s^2 + 2\zeta A\Omega_0 s + \Omega_o^2} \tag{8}$$

The step response of (8) is given by

$$C_m(s) = \frac{1}{s} \cdot H_m(s)$$
$$= \frac{1}{s} - \frac{k_1(s+\zeta\omega_n) + k_2\omega_n\sqrt{1-\zeta^2}}{(s+\zeta\omega_n)^2 + (\omega_n\sqrt{1-\zeta^2})^2} \tag{9}$$

where

$$\omega_n = \frac{\Omega_0}{A},\quad k_1 = \frac{A^2-1}{A^2},\quad k_2 = \frac{A^2+1}{A^2}\frac{\zeta}{\sqrt{1-\zeta^2}}$$

or in the time domain

$$c_m(t) = 1 - \sqrt{k_1^2 + k_2^2} \cdot e^{-\zeta\omega_n t} \cos(\omega_n\sqrt{1-\zeta^2}\, t - \phi_n) \tag{10}$$

where

$$\phi_n = \tan^{-1}\left(\frac{k_2}{k_1}\right)$$

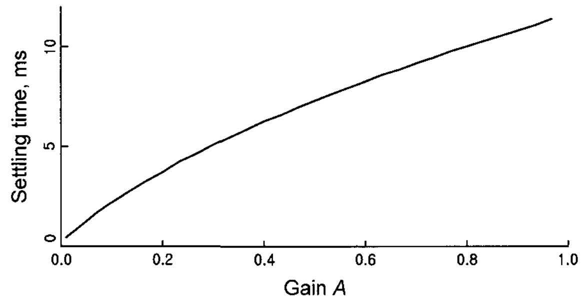


Fig. 2. Variation of the settling times with the gain A.

For each A and ζ, we can find the settling time, ts, for which cm(t) reaches and stays within ± 2% of the steady-state value. After finding ts, the following optimization problem must be solved in order to determine parameters A and α:

$$\hat{A} = \max(A)$$
$$\hat{\zeta} = \arg\min(t_s(\hat{A}, \zeta)) \tag{11}$$

such that $t_s(A,\zeta) \le T_s, 0 < A \le 1, 0 < \zeta \le 1$

where, Ts : maximum of the permissible settling time.

Fig. 2 indicates the results of solving (11). As seen in this figure, the settling time is linearly proportional to the value of A. This means that the settling time can be reduced by decreasing the value of A. However, since the high-frequency gain is inversely proportional to the value of A, attention is required to select the value of A.

The modified analog notch filter given in (8) should be converted into a digital type to be suitable for digital protection algorithms. This conversion is made by applying the bilinear transform to (8):

$$G_m(z) = H_m(s)\Big|_{s=\frac{2}{\Delta t}\frac{1-z^{-1}}{1+z^{-1}}} = \frac{\sum_{k=0}^{2} b(k) z^{-k}}{\sum_{k=0}^{2} a(k) z^{-k}} \tag{12}$$

where

$$\omega_0 = 2\tan^{-1}(\frac{\Delta t}{2}\Omega_0)$$
$$a(0) = \tan^2(\omega_0/2) + 2\zeta A\tan(\omega_0/2) + A^2$$
$$a(1) = 2(\tan(\omega_0/2)^2 - A^2)$$
$$a(2) = \tan^2(\omega_0/2) - 2\zeta A\tan(\omega_0/2) + A^2$$
$$b(0) = \tan(\omega_0/2)^2 + 1$$
$$b(1) = 2(\tan(\omega_0/2)^2 - 1)$$
$$b(2) = \tan(\omega_0/2)^2 + 1$$

From (12), the output of the modified notch filter, iM[n], is related to the input iL[n],

$$\sum_{k=0}^{2} a(k) i_M[n-k] = \sum_{k=0}^{2} b(k) i_L[n-k] = \sum_{k=0}^{2} b(k)\left(i_{ac}[n-k] + i_{dc}[n-k]\right) \quad (13)$$

2.2.2 Delay Compensation

Since the modified notch filter removes the power frequency component, iac[n] is taken away from (13). Moreover, the k-sample delayed DC-offset can be expressed as:

$$i_{dc}[n-k] = \alpha^k i_{dc}[n] \quad (14)$$

Substituting idc[n–k] of (14) into (13) yields

$$\sum_{k=0}^{2} a(k) i_M[n-k] = \left(\sum_{k=0}^{2} b(k)\alpha^k\right) i_{dc}[n] \quad (15)$$

Since iM[n] becomes a dc-offset with the same time constant as idc[n], (15) can be reduced to the following equation:

$$i_M[n] = \frac{q(\alpha)}{p(\alpha)} i_{dc}[n] \quad (16)$$

where

$$p(\alpha) = \sum_{k=0}^{2} a(k)\alpha^k, \quad q(\alpha) = \sum_{k=0}^{2} b(k)\alpha^k$$

From (16), the time delay caused by the modified notch filter serves to magnify the amplitude of the DC-offset by a factor $q(\alpha)/p(\alpha)$. Therefore, the delay compensation is achieved by reducing the magnitude of iM[n] as shown in the following equation:

$$i_C[n] = \frac{p(\alpha)}{q(\alpha)} i_M[n] \quad (17)$$

Here, α is given by

$$\alpha = \frac{i_M[n]}{i_M[n-1]} \quad (18)$$

When the magnitude of the DC-offset is large enough to ignore the effect of noise, the estimated α approaches a constant value. Although the magnitude of the DC-offset is so small that there is some variation in the estimated α, the phasor estimation is not significantly influenced by this variation because of the small magnitude of the DC-offset.

2.2.3 Instantaneous Phasor

Combining (1) and (17) yields

$$i_{ac}[n] = i_L[n] - i_C[n] \quad (19)$$

In this paper, iac[n] of (19) is used as the real part of the instantaneous phasor, iR[n]. In order to determine the imaginary part, which should be orthogonal to iR[n], the first difference of the fault current signal with a 2Δt interval is defined as

$$i_{2\Delta t}[n] = \frac{i_L[n] - i_L[n-2]}{2\sin(\omega\Delta t)} \quad (20)$$

Substituting iL[n] of (1) into (20) yields

$$i_{2\Delta t}[n] = A\cdot\sin(\omega(n-1)\Delta t + \phi) + \frac{1-\alpha^{-2}}{2\sin(\omega\Delta t)} B\alpha^n \quad (21)$$

Using (16) and (21), the imaginary part of the instantaneous phasor, iI[n], is expressed as:

$$i_I[n] = A\cdot\sin(\omega(n-1)\Delta t + \phi) = i_{2\Delta t}[n] - \frac{1-\alpha^{-2}}{2\sin(\omega\Delta t)}\frac{p(\alpha)}{q(\alpha)} i_M[n] \quad (22)$$

Finally, the instantaneous phasor, I[n], can be defined as:

$$\mathbf{I}[n] = i_R[n-1] + j\cdot i_I[n] = A\{\cos(\omega(n-1)\Delta t + \phi) + j\cdot\sin(\omega(n-1)\Delta t + \phi)\} \quad (23)$$

Since iI[n] of (22) is one-sample delayed from iR[n], iR[n–1] is used in (23).

2.3 Phasor Estimation Process

As mentioned above, the instantaneous phasor estimation is proposed to enhance the transient response of the improved Fourier algorithm. Since the improved Fourier algorithm performs well, except during the transient time corresponding to the first cycle after the fault occurs, the phasor-estimation process is based on the improved Fourier algorithm. The instantaneous phasor estimation is applied only during the transient time of the improved Fourier algorithm. The transient state can be easily detected by checking the magnitude change of the phasor. It should be noted that the instantaneous phasor of (23) is one-sample delayed from the phasor of the improved Fourier algorithm given in (4).

3. Performance Evaluation

3.1 Simulation Data

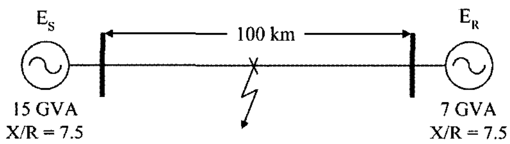


Fig. 3. Model system.

Table 1. Overhead transmission line parameters

Sequence	Parameter	Value	Unit
Positive Negative	R1, R2	0.0345	Ω/km
	L1, L2	0.9724	mH/km
	C1, C2	0.0117	μF/km
Zero	R0	0.2511	Ω/km
	L0	2.7058	mH/km
	C0	0.0045	μF/km

The performance of the method was evaluated for a-g faults on a 345 kV 100 km overhead transmission line as indicated in Fig. 3. The overhead transmission line parameters used in the simulations are given in Table 1. The EMTP was used to generate fault current signals for different fault locations and fault inception angles. The sampling frequency was set to 3,840 Hz: 64 samples per cycle in a 60 Hz system. The EMTP output was pre-conditioned by a second order Butterworth low-pass filter with the cutoff frequency of 960 Hz in order to reject high frequency components and prevent aliasing errors. The a-g faults incepted at four different angles (0°, 30°, 60°, and 90°) were considered at nine different fault distances (10 km ~ 90 km) from a relaying point. The zero crossing of a-phase voltage signal was chosen as reference angle.

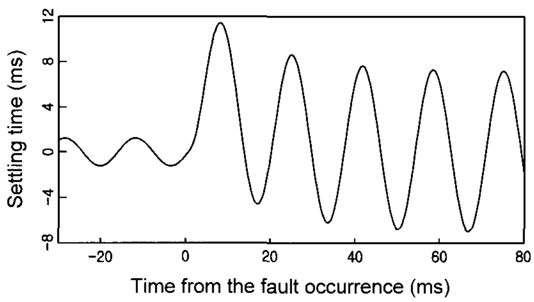
3.2 Performance of the Proposed Method

From solving (11) with Ts set to 4 ms, A and α become 0.219 and 0.880, respectively. Using these parameters in (12) yields

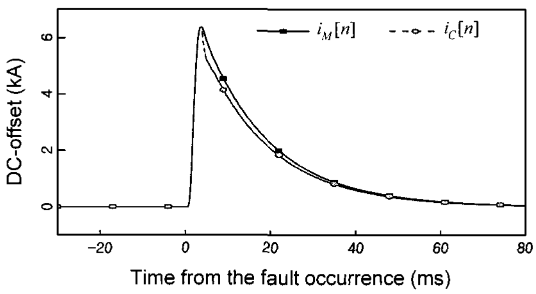
$$G_m(z) = \frac{1.0024z^0 - 1.9952z^{-1} + 1.0024z^{-2}}{0.0693z^0 - 0.0912z^{-1} + 0.0315z^{-2}} \qquad (24)$$

Fig. 4 displays the waveforms for 50 km 0° a-g fault. As shown in Fig. 4 (b), the delay compensation reduces the magnitude of the output of the modified notch filter by factor 0.9121. This factor is obtained by substituting the value of α, about 0.9838, into (16). It is also found that the compensated waveform has a settling time of about 6 ms caused by the low-pass filter and the modified notch filter.

Fig. 5 presents the results of the instantaneous phasor estimation for 50 km 0° a-g fault. Fig. 5 (a) and Fig. 5 (b) correspond to, respectively, the real and imaginary parts of the instantaneous phasor for 50 km 0° a-g fault. Due to the settling time of the low-pass filter and the modified notch filter, they have transient waveforms for about 6 ms from the onset of the fault.

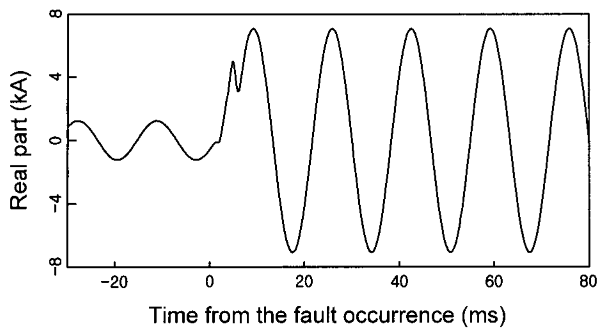


(a)

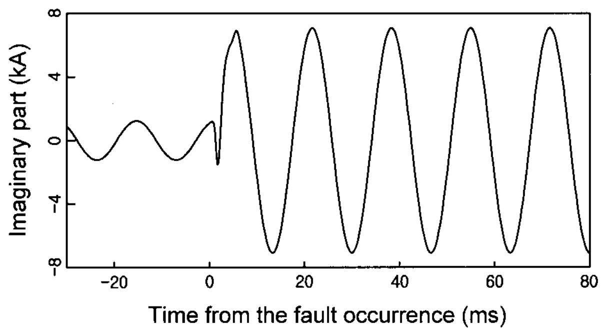


(b)

Fig. 4. Waveforms for 50 km 0° a-g fault: (a) Fault current signal waveform. (b) Output waveform of the modified notch filter and delay-compensated waveform.

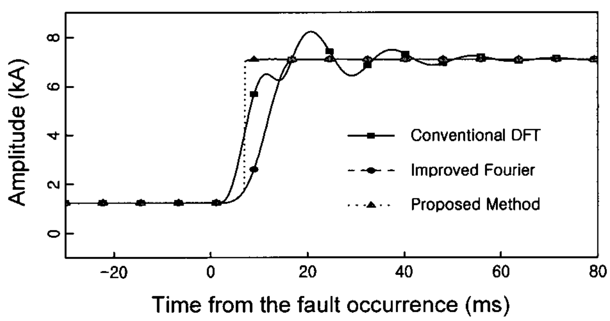


(a)

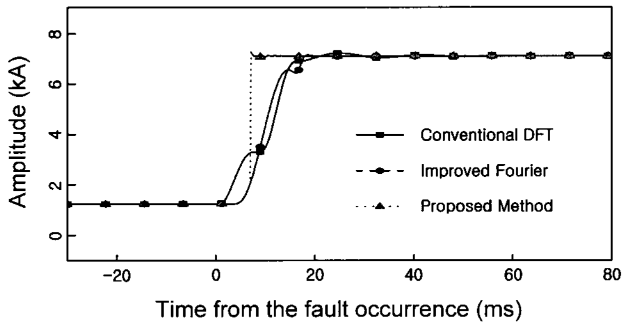


(b)

Fig. 5. Results of the instantaneous phasor estimation for 50 km 0° a-g fault: (a) Real part. (b) Imaginary part.

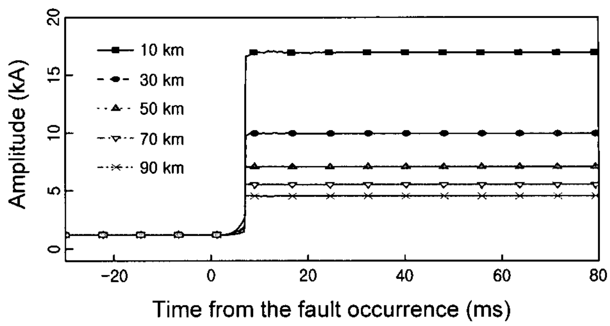


(a)

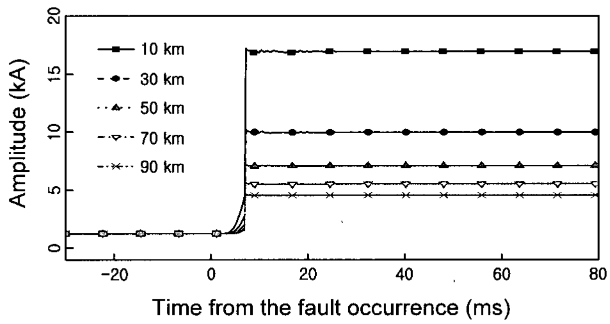


(b)

Fig. 6. Comparison of the time responses: (a) Fault inception angle of 0°. (b) Fault inception angle of 90°.



(a)



(b)

Fig. 7. Time responses of the proposed method for a-g faults: (a) Fault inception angle of 0°. (b) Fault inception angle of 90°.

Table 2. Maximum errors of the proposed method after a half cycle from the fault occurrence

Fault Distance	Maximum Error (%)			
	0°	30°	60°	90°
10 km	0.6063	0.7914	0.7865	0.8118
20 km	0.6728	0.8761	0.9170	0.7610
30 km	0.6025	0.8924	0.8469	0.7117
40 km	0.1848	0.7889	0.6485	0.4340
50 km	0.2336	0.8093	0.5818	0.3607
60 km	0.1960	0.7639	0.6268	0.4008
70 km	0.3772	0.7676	0.6852	0.5880
80 km	0.8259	0.8505	0.9829	0.5626
90 km	0.7728	0.8323	0.9169	0.6781

$$Error = \frac{|\,Estimated\ Amplitude - Actual\ Amplitude\,|}{Actual\ Amplitude} \times 100$$

Fig. 6 compares the time responses of the conventional DFT, the improved Fourier algorithm, and the proposed method for 50 km a-g faults. As expected, the time response of the conventional DFT has considerable oscillation caused by the DC-offset. Although the time response of the improved Fourier algorithm is rarely affected by the DC offset, the settling time of this algorithm is almost 20 ms, which is much longer than that of the proposed method, about 6 ms.

Fig. 7 shows the time responses of the proposed method for a-g faults and Table 2 summarizes the maximum errors after a half cycle following the fault occurrence. It is easily found that the time responses have similar patterns with the settling times of about 6 ms and that the maximum error is within 0.1 ~ 1.0%.

4. Conclusions

Instantaneous phasor estimation of a fault current signal was developed for high-speed distance protection that is immune to a DC-offset. The estimation is based on a modified notch filter, which is used to eliminate the power frequency component from the fault current signal. Since the output of the modified notch filter is the delayed DC-offset, delay compensation results in the same waveform as the original DC-offset. Subtracting the obtained DC-offset from the fault current signal yields the real part of the instantaneous phasor. The imaginary part of the instantaneous phasor is obtained by removing a DC-offset from the first difference of the fault current signal.

The performance of the proposed method was evaluated for a-phase to ground faults on a 345 kV 100 km overhead transmission line. The EMTP was used to generate fault current signals for different fault locations and fault inception angles. The evaluation results show that the proposed method operates reliably with a settling time of about 6 ms and that the maximum error is within 0.1 ~ 1.0% after a half cycle from the fault occurrence. Therefore, the instantaneous phasor estimation is considered useful for high-speed distance protection that is immune to a DC-offset.

Acknowledgements

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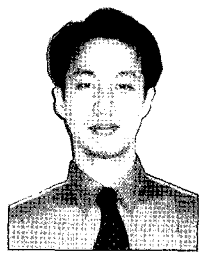

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