Modified Dynamic Phasor Estimation Algorithm for the Transient Signals of Distributed Generators

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***Abstract*—In this paper, a modified dynamic phasor estimation method for protection relays is proposed to calculate the dynamic phasor of a fundamental frequency component with time-variant amplitude. The fault current is assumed to be the combination of a decaying dc offset, a decaying fundamental frequency component and harmonics with constant amplitude. The exponential functions of the decaying dc offset and fundament frequency component are replaced by Taylor series. Then, the LS (Least Square) technique is used to estimate the magnitudes and the time constants of decaying components. The performance of the algorithm is evaluated by using computer-simulated signals based on simple equations and fault current signals collected from DFIG wind farm model in MATLAB Simulink. The test results indicate that the proposed algorithm can accurately estimate the decaying amplitude and the time constant of the fundamental frequency component.**

***Index Terms*—Distributed generators, modified dynamic phasor, phasor estimation, time-variant fault current.**

I. Introduction

NOWADAYS, there is much interest in connecting various sources of electrical energy, typically described as distributed energy resources (DERs), to electric power systems. Much of this interest is due to the demands of clean energy, high reliability, and enhanced power quality. DERs offer a variety of possibilities for energy conversion and electric power generation. Various energy sources and converters are used to generate electricity through PV arrays, wind turbines, fuel cells, microturbines, conventional diesel and natural gas reciprocating engines, gas-fired turbines, and energy storage technologies [1].

However, the installation of DERs in the power systems will create operating conflicts. The potential problems from the installation of DERs, such as changes in coordination of protective devices, nuisance trip, safety degradation and changes in the reach of protective relays, were discussed in [2], [3]. Adaptive protection schemes were proposed for distribution systems connected with wind generators [4], [5]. The protection of transmission lines connected to wind farms was discussed in [6]. An adaptive setting method was proposed for the distance relay to protect a transmission line connected to a wind farm [7]. All of these kinds of adaptive protection methods as well as traditional protection algorithms are based on estimating the phasors of the voltage and current signals.

Most of digital relays adopt discrete Fourier transform (DFT)-based algorithms to estimate the phasors of a voltage signal and a current signal. A fault current in the conventional power system is generally considered as the combination of an exponentially decaying dc component and sinusoidal components with the time-invariant amplitude. The time-variant amplitude of the sinusoidal component is only considered on pickup settings of generator protection relays for the multi-phase faults involving synchronous generators. It is because the time constant of the decaying sinusoidal component is long enough to not produce a significant error on the result of DFT. In order to estimate the accurate current phasor using DFT, the dc-offset should be removed from the fault current signal. For this purpose, several techniques have been proposed to reduce or remove the adverse effect of the decaying dc component on the result of phasor estimation using DFT-based method [8]–[12].

However, the fault currents delivered from distributed generators, especially small synchronous generators or doubly-fed induction generators (DFIG) directly connected to power systems have time-variant characteristics of the sinusoidal components with small time constants. These make the phasor estimation task more challenging since most algorithms to estimate the phasors of voltage and current are developed by presuming the time-invariant amplitude of a sinusoidal signal at a frequency. A new concept of the phasor estimation method referred to as dynamic phasor was proposed for estimating the time-variant amplitude and phase of a sinusoidal component during power system oscillation [13]. This method, however, is not suitable for applying to protection relays because a decaying dc component is not considered.

In this paper, a modified dynamic phasor estimation method for protection relays is proposed to calculate a dynamic phasor of a fundamental frequency component with time-variant amplitude. The fault current is assumed to be the combination of a decaying dc offset, a decaying fundamental frequency component and harmonics with constant amplitude. The exponential functions of the decaying dc offset and fundament frequency component are replaced by Taylor series. The LS (Least Square) technique is used to estimate the amplitudes and the time constants of the decaying components.

The performance of the proposed algorithm is evaluated by using computer-simulated signals based on simple equations and fault current signals generated using DFIG wind farm model in MATLAB Simulink. To demonstrate the performance of the proposed algorithm, the test results are compared to those of a

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DFT-based method which is called PS (partial sum)-based DFT [9]. The test results indicate that the proposed algorithm can accurately estimate the decaying amplitude and the time constant of the fundamental frequency component.

II. Characteristics of Short-Circuit Currents

A. Short Circuit Currents of a Synchronous Generator

It is well known that the behavior of synchronous generators during fault conditions is typically quantified by three reactance values: subtransient reactance (X_d''), which addresses generator behavior during the early time domain of a fault; transient reactance (X_d'), which addresses generator behavior during the medium time domain of the fault; and synchronous reactance (X_s), which addresses generator behavior during the long time domain of the fault. The duration of the time domains is addressed by two time constants: subtransient time constant (T_d'') and transient time constant (T_d') [1]. A fault current of A-phase can be expressed by an exponential equation with generator terminal voltage magnitude (V_T), all three generator reactances and both time constants as follows:

$$i_a(t) = \sqrt{2}V_T \left[\begin{array}{c} \frac{1}{X_d} + \left(\frac{1}{X_d'} - \frac{1}{X_d}\right) e^{-t/T_d'} \\ + \left(\frac{1}{X_d''} - \frac{1}{X_d'}\right) e^{-t/T_d''} \end{array} \right] \sin(\omega_0 t + \alpha). \tag{1}$$

B. Short Circuit Currents of a DFIG

In this section, the equation for the short-circuit current of a DFIG determined in [14] is briefly introduced.

Over the last couple of decades, several researches have been done to analysis the short-circuit current of induction generator [14]–[16]. The result formulas to describe the short circuit current are slightly different between each research. It is because the short-circuit behavior of an induction machine is strongly dependent on the machine and their controller characteristics. All of the researches, however, indicate that the short-circuit current of an induction generator consists of an ac component with a frequency which is equal to the rotor speed and a dc component. These two components decrease exponentially.

When a three-phase fault occurs at the stator terminal of a DFIG, the short-circuit current of A-phase is

$$i_a(t) = \frac{\sqrt{2}V_s}{X_s'} \left[\cos\alpha \cdot e^{-t/T_s'} + \left(\frac{L_m^2}{L_m L_r}\right) e^{-t/T_r'} \cos(\omega_s t + \alpha) \right] \tag{2}$$

where V_s is the magnitude of the stator voltage, X_s' is the transient stator reactance, T_s' and T_r' are the transient time constants for the damping of the dc component in stator and rotor, L_m is the mutual inductance between stator and rotor, L_r is the rotor inductance, and w_s is the synchronous rotational speed.

Although (1) and (2) are to describe the A-phase current for the three-phase fault at the generator terminal, these equations are also useful to understand a fault current supplied from distributed generations when a fault occurs in a neighboring distribution feeder or a transmission line. The fault current delivered from distributed generators during grid fault conditions has a time-variant characteristic of the sinusoidal component with

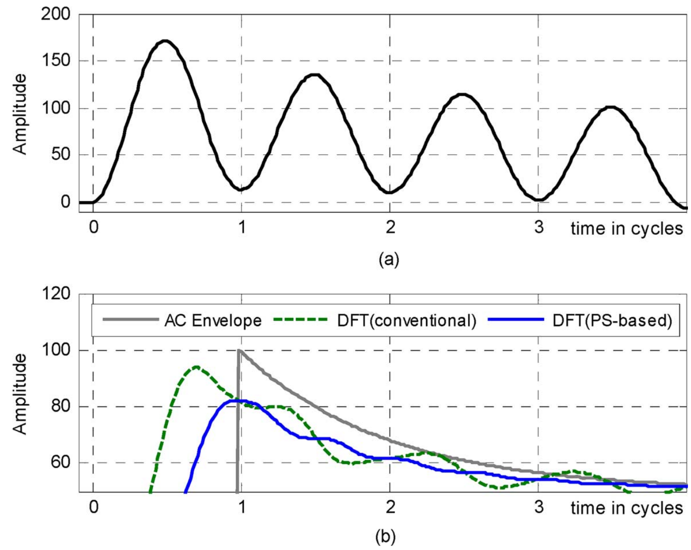

Fig. 1. Example of a short-circuit current with time-variant amplitude and its effect on DFT-based algorithms. (a) Short-circuit current. (b) Estimated amplitude.

a time constant. It may result in some significant error in the phasor value estimated by DFT. Fig. 1 shows an example wave form of the fault current which consists of a decaying fundamental frequency component and a decaying dc offset component. It also shows the effect of decaying amplitude characteristic of the sinusoidal component on the result of phasor estimation using DFT-based method. DFT is simple and easily to be implemented, but the output of DFT contains some errors due to both the decaying dc offset component and the decaying sinusoidal component. Since PS-based DFT is only designed to remove the adverse influence of the decaying dc offset, it does not cope effectively with the decaying sinusoidal component. Accordingly, the decaying amplitude characteristic of the sinusoidal component causes decrease and fluctuation in the amplitude value of the estimated phasor using a method assuming the constant amplitude of a sinusoidal signal at a frequency such as DFT. The estimated phasor value is smaller than the desired value, then it may result in the failure to trip or delayed operation of protection relays.

III. Modified Dynamic Phasor Estimation Algorithm

As refer to (1) and (2), the fault current delivered from distributed generators can be considered as the sum of a decaying dc offset component, a decaying fundamental frequency component and harmonics with constant amplitude. At time $\mathrm{t} = \mathrm{t}_1$, this wave form can be mathematically expressed as follows:

$$i(t_1) = A_0 e^{-t_1/\tau_{dc}} + \left(A_{1C} + A_{1D} e^{-t_1/\tau_{ac}}\right) \sin(w_0 t_1 + \varphi_1) + \sum_{k=2}^{M} A_k \sin(k w_0 t_1 + \varphi_k) \tag{3}$$

where A_0 and τ_{dc} are the amplitude and the time constant of the decaying dc component, w_0 is the fundamental frequency of the system, $A_{1C}, A_{1D}, \varphi_1$ and τ_{ac} are the constant amplitude, the decaying amplitude, the phase angle and the time constant of the decaying fundamental frequency component, respectively,

A_k and φ_k are the amplitude and the phase angle of the kth harmonic component, M is the highest order of the harmonic component present in the signal.

It is possible to expand $e^{-t_1/\tau}$ by using the Taylor series as follows:

$$e^{-t_1/\tau} = 1 - \frac{t_1}{\tau} + \frac{1}{2!}\left(\frac{t_1}{\tau}\right)^2 - \frac{1}{3!}\left(\frac{t_1}{\tau}\right)^3 + \dots \quad (4)$$

Higher order harmonics can be blocked by the signal conditioning equipment such as an analog low-pass filter. Using the Taylor series expansion in (4) and assuming that harmonic components higher than fifth order are effectively blocked by a low-pass filter and that even harmonics are hardly present in the power system signals, (3) can be represented as

$$\begin{aligned} i(t_1) = {} & a_{11}x_1 + a_{21}x_2 + a_{31}x_3 \\ & + a_{41}x_4 + a_{51}x_5 + a_{61}x_6 + a_{71}x_7 + a_{81}x_8 + a_{91}x_9 \\ & + a_{101}x_{10} + a_{111}x_{11} + a_{121}x_{12} + a_{131}x_{13} \end{aligned} \quad (5)$$

where

$$\begin{aligned} x_1 &= A_0, x_2 = -A_0(1/\tau_{dc}), x_3 = A_0(1/\tau_{dc}^2) \\ x_4 &= (A_{1C} + A_{1D})\cos\varphi_1, x_5 = -A_{1D}(1/\tau_{ac})\cos\varphi_1 \\ x_6 &= A_{1D}(1/\tau_{ac}^2)\cos\varphi_1, x_7 = (A_{1C} + A_{1D})\sin\varphi_1 \\ x_8 &= -A_{1D}(1/\tau_{ac})\sin\varphi_1, x_9 = A_{1D}(1/\tau_{ac}^2)\sin\varphi_1 \\ x_{10} &= A_3\cos\varphi_3, x_{11} = A_3\sin\varphi_3 \\ x_{12} &= A_5\sin\varphi_5 x_{13} = A_5\sin\varphi_5 \\ a_{11} &= 1, a_{21} = t_1, a_{31} = t_1^2/2 \\ a_{41} &= \sin(w_0t_1), a_{51} = t_1\cdot\sin(w_0t_1), a_{61} = t_1^2/2\cdot\sin(w_0t_1) \\ a_{71} &= \cos(w_0t_1), a_{81} = t_1\cdot\cos(w_0t_1), a_{91} = t_1^2/2\cdot\cos(w_0t_1) \\ a_{101} &= \sin(3w_0t_1), a_{111} = \cos(3w_0t_1) \\ a_{121} &= \sin(5w_0t_1), a_{131} = \cos(5w_0t_1) \end{aligned}$$

If the current is sampled with a specific time interval, Δt, (5) can be expanded to each current sample and the equations can be written in the matrix forms as follows:

$$\underset{m\times 1}{[i]} = \underset{m\times 13}{[A]}\ \underset{13\times 1}{[X]} \quad (6)$$

The elements of the matrix [A] depend on the time references and the sampling interval and those can be predetermined in an off-line mode. The matrix [i] made up of the sampled current data is also known.

If the number of current samples, m, is greater than 13, the number of unknown variables, the matrix [X] composed of the unknown variables can be determined by using the LS (Least Square) technique as follows:

$$[X] = [[A]^T[A]]^{-1}[A]^T\cdot[i] \quad (7)$$

Finally, the dynamic phasor of the fundamental frequency component can be obtained as follows:

$$x_4 + jx_7 = (A_{1C} + A_{1D})(\cos\varphi_1 + j\sin\varphi_1). \quad (8)$$

IV. Performance Evaluation

The performance of the proposed algorithm is evaluated by using computer-simulated signals based on simple equations and fault current signals generated by using DFIG wind farm model in MATLAB Simulink. To demonstrate the performance of the proposed algorithm, the test results are compared to those of PS(partial sum)-based DFT [9].

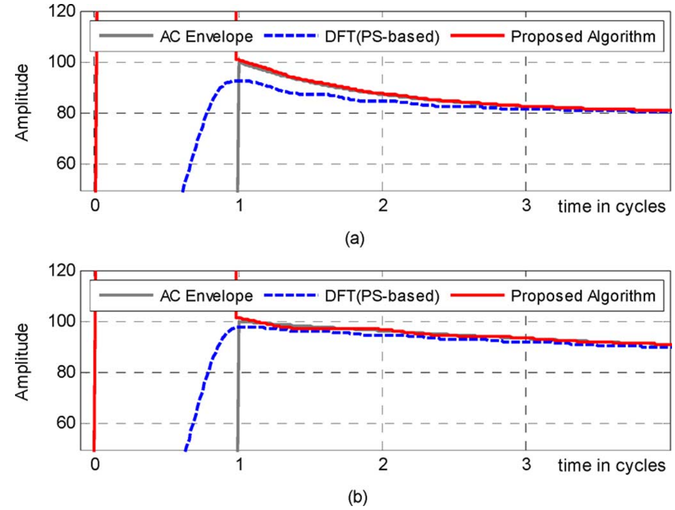

Fig. 2. Results for the Case 1 with $\tau_{ac} \neq \tau_{dc}$ condition. (a) $\tau_{dc} = 5.0$ Cycle, $\tau_{ac} = 1.0$ Cycle. (b) $\tau_{dc} = 1.0$ Cycle, $\tau_{ac} = 5.0$ Cycle.

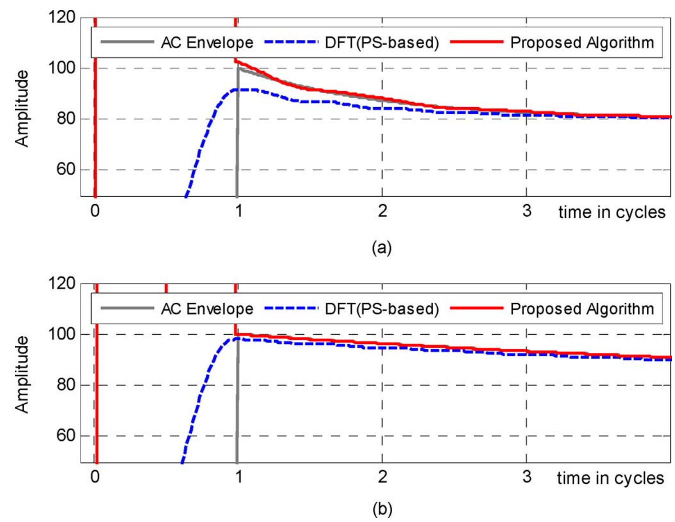

Fig. 3. Results for the Case 1 with $\tau_{ac} = \tau_{dc}$ condition. (a) $\tau_{dc} = \tau_{ac} = 1.0$ Cycle. (b) $\tau_{dc} = \tau_{ac} = 5.0$ Cycle.

A. Using Computer-Simulated Signals

In order to demonstrate the performance of the proposed algorithm, computer-simulated signals are used first for the test under various signal conditions. In this performance test, the sampling frequency is set to 3 840 Hz, i.e., 64 samples per cycle in a 60 Hz system and the number of current samples, m, is set to the number of samples per cycle.

Case 1. Constant Amplitude > Decaying Amplitude: In this case, the constant amplitude of the fundamental frequency component is greater than the decaying amplitude. The test signal used in this case is assumed as follows:

$$i_1(t) = 100e^{-t/\tau_{dc}} + \left(80 + 20e^{-t/\tau_{ac}}\right)\sin(w_0t). \quad (9)$$

Figs. 2 and 3 show the input signals for Case 1 and the estimated amplitudes of the fundamental frequency component by

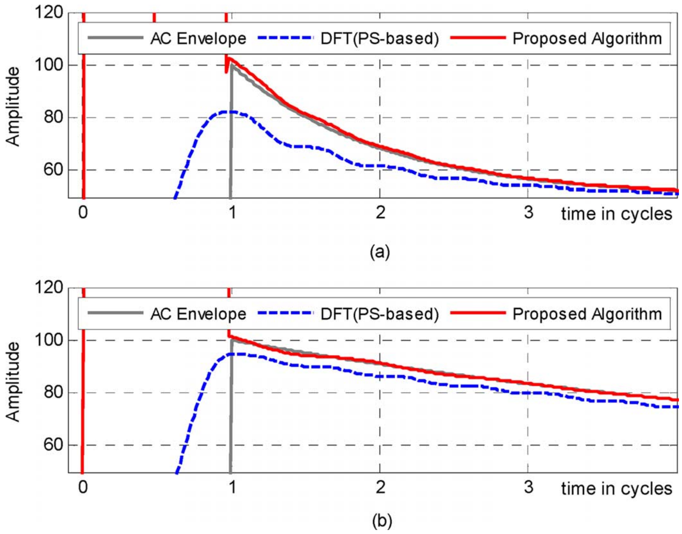

Fig. 4. Results for the Case 2 with $\tau_{ac} \neq \tau_{dc}$ condition. (a) $\tau_{dc} = 5.0$ Cycle, $\tau_{ac} = 1.0$ Cycle. (b) $\tau_{dc} = 1.0$ Cycle, $\tau_{ac} = 5.0$ Cycle.

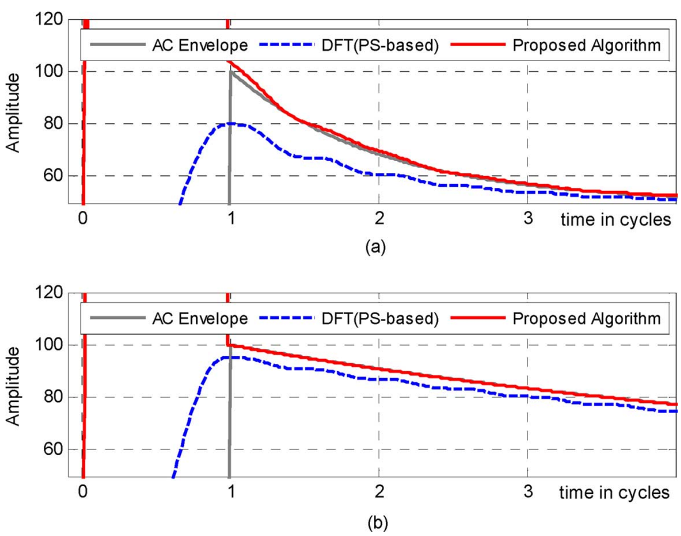

Fig. 5. Results for the Case 2 with $\tau_{ac} = \tau_{dc}$ condition. (a) $\tau_{dc} = \tau_{ac} = 1.0$ Cycle. b) $\tau_{dc} = \tau_{ac} = 5.0$ Cycle.

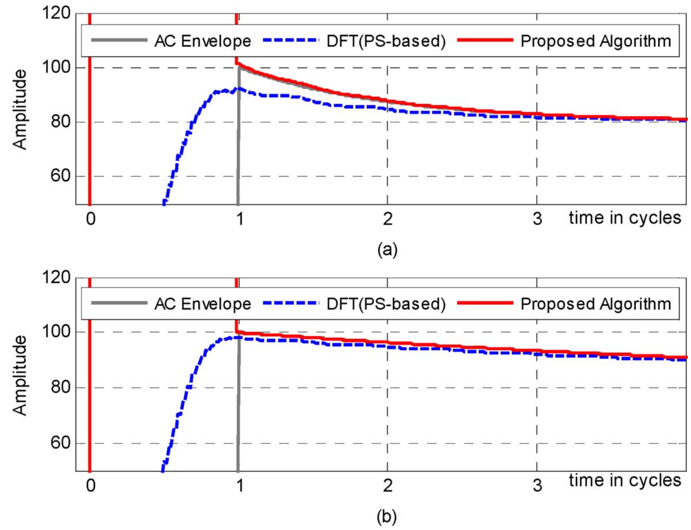

Fig. 6. Results for the Case 3 with $A_{1C} > A_{1D}$ condition as signal (11). (a) $\tau_{ac} = 1.0$ Cycle. (b) $\tau_{ac} = 5.0$ Cycle.

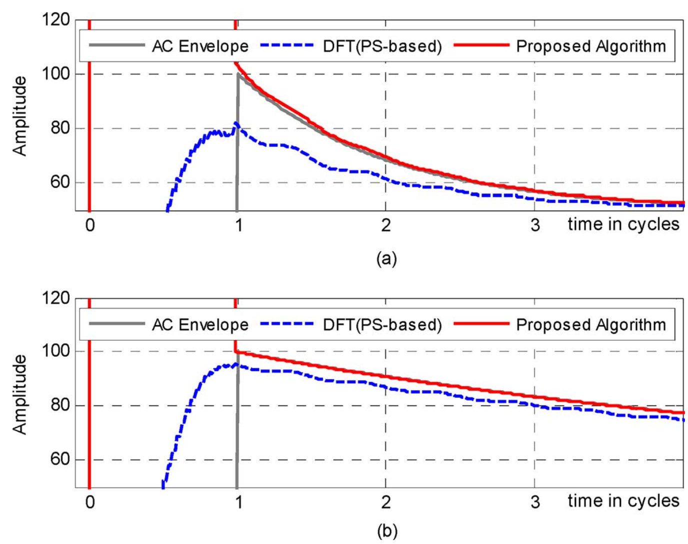

Fig. 7. Results for the Case 3 with $A_{1C} = A_{1D}$ condition as signal (12). (a) $\tau_{ac} = 1.0$ Cycle. (b) $\tau_{ac} = 5.0$ Cycle.

the PS-based DFT and the proposed method. Fig. 2 shows the estimated results for the case which the time constant of ac component is differ from that of dc component. In the case of Fig. 3, the two time constants are same. From these figures, it is easily figured out that the DFT-based algorithm produces some error if the input signals contains the exponentially decaying ac component and the error is increased when the time constant of the decaying ac component is small, regardless of the time constant of dc component.

DFT is based on the constant amplitude and phase of a sinusoidal signal at a frequency and DFT-based algorithms such as PS-based DFT are only designed to remove the adverse influence of the decaying dc offset on DFT. Therefore, the decaying ac component is treated as the decaying dc offset component on DFT-based algorithms. It is why the estimated amplitudes of fundamental frequency components by PS-based DFT are smaller than desired values.

On the other hand, the proposed algorithm is designed to differentiate the decaying ac component from the decaying dc component. Therefore, the estimated amplitude by proposed algorithm is much closer to the desired value.

Case 2. Constant Amplitude = Decaying Amplitude: In this case, the constant amplitude of the fundamental frequency component is equal to the decaying amplitude. The test signal used in this case is assumed as follows:

$$i_2(t) = 100e^{-t/\tau_{dc}} + (50 + 50e^{-t/\tau_{ac}})\sin(w_0 t). \quad (10)$$

Figs. 4 and 5 show the input signals for Case 2 and the estimated amplitudes of the fundamental frequency component by the PS-based DFT and the proposed method.

The error of PS-based DFT becomes much larger than that of Case 1. It is because the amplitude of decaying ac component is larger than that of Case 1. Consequently, a large amount of the decaying ac component compared to Case 1 is removed by the

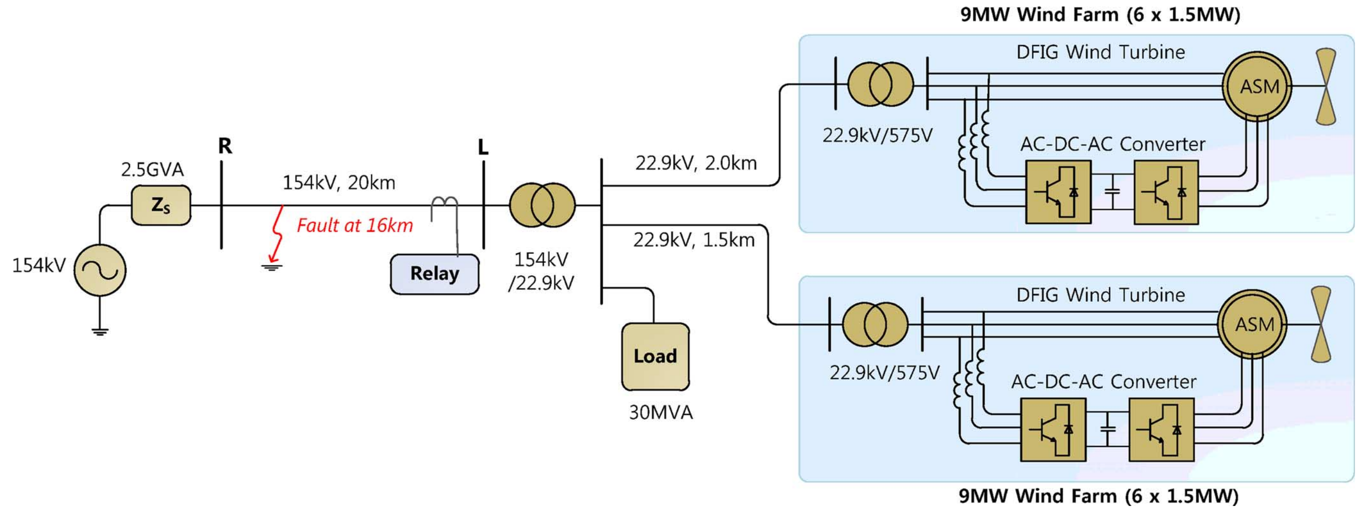

Fig. 8. Diagram of the model system.

function of PS-based DFT to eliminate the effect of the decaying dc offset.

On the other hand, the outputs of the proposed method are still much closer to the desired value.

Case 3. Decaying dc offset component = 0: In this case, the zero dc offset component is considered. The test signals used in this case are assumed as follows:

$$i_3(t) = (80 + 20e^{-t/\tau_{ac}})\sin(w_0 t) \quad (11)$$

$$i_4(t) = (50 + 50e^{-t/t\tau_{ac}})\sin(w_0 t). \quad (12)$$

Figs. 6 and 7 show the input signals, the estimated amplitudes of the fundamental frequency component by the PS-based DFT and the proposed method for Case 3. The results for this case do not much differ from the results for Case 1 and 2. Because the error of the PS-based DFT is caused by the decaying ac component, regardless of the existence of the decaying dc offset component.

B. Using Fault Current Signals Generated by DFIG Wind Farm Model in MATLAB Simulink

In this section, the performance evaluation of the proposed algorithm by using fault current signals generated by DFIG wind farm model in MATLAB Simulink is described.

During the normal operation, two wind farms each consisting of six units of 1.5 MW wind turbines supply totally 18 MW power to the load through 22.9 kV distribution feeders, as shown in Fig. 8. The basic wind farm and DFIG model were taken from [17]. Each wind turbine using a doubly-fed induction generator consists of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. In the simulations, the wind speed is maintained constant at 15 m/s. The control system uses a torque controller in order to maintain the rotor speed at 1.2 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar.

Double line to ground (A-B-ground) faults with fault resistances of 0 Ω and 10 Ω were applied on the 154 kV transmission line at the distance of 16 km from L bus. The fault currents are measured at L bus.

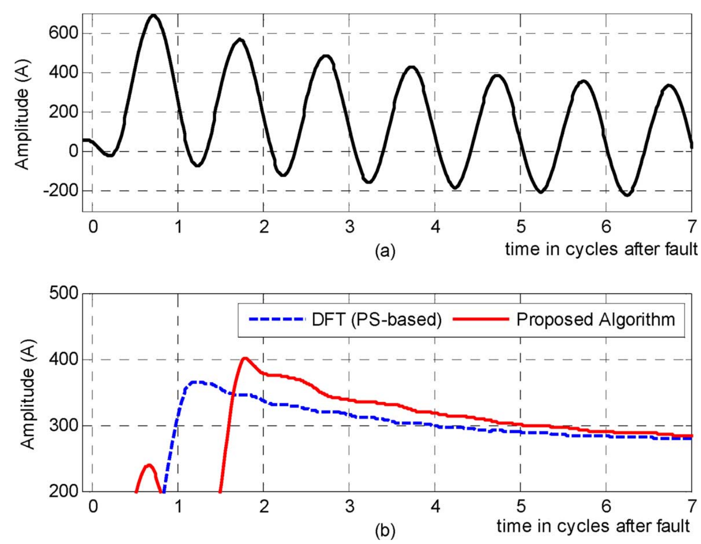

Fig. 9. A-phase current and amplitude estimation results ($R_F = 0\ \Omega$). (a) A-phase current measured at the relaying point. (b) Estimated amplitude.

For this performance test, the sampling frequency is set to 3 840 Hz, i.e., 64 samples per cycle in a 60 Hz system. The input signal is preprocessed by a 2nd order Butterworth low-pass filter with the gain of 0.1 at the stop-band cutoff frequency of 480 Hz in order to remove harmonics and to prevent aliasing errors. The number of current samples is set to 1.75 times the number of samples per cycle for stable outputs.

Figs. 9 and 10 show the wave forms of the A-phase currents measured at the relaying point and the estimated amplitudes of the fundamental frequency components by the PS-based DFT and the proposed algorithm. In this performance test, the time domain response of the PS-based DFT is faster than that of the proposed algorithm. It is because the PS-based DFT uses one cycle sample data, but the proposed algorithm uses 1.75 cycle sample data.

However, the estimated amplitudes by PS-based DFT are much smaller than the output of the proposed algorithm. Therefore, a protection relay only adopting the DFT-based algorithm to estimate the phasor of the fundamental frequency component may fail to trip or may have unnecessary time delay. If the

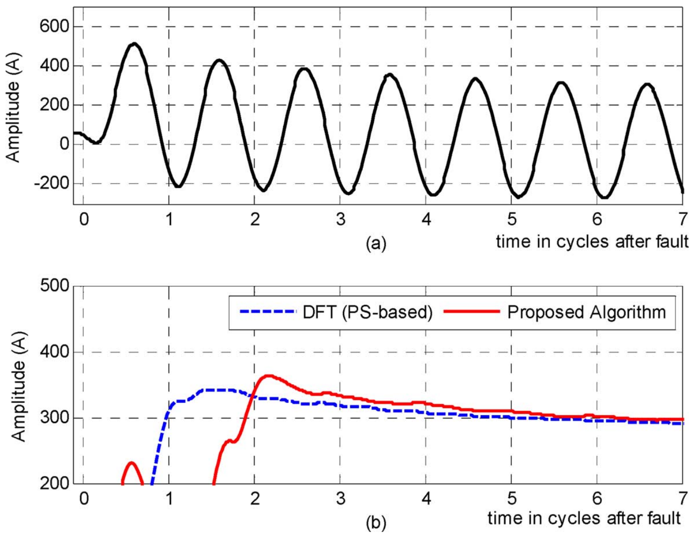

Fig. 10. A-phase current and amplitude estimation results ($R_F = 10\ \Omega$). (a) A-phase current measured at the relaying point. (b) Estimated amplitude.

proposed algorithm is applied to a protection relay, those kinds of mal-operation are prevented. Even in the worst case, the operation of the protective relay is delayed three quarters cycle more because the data window is 1.75 times the number of samples per cycle.

V. Conclusion

This paper proposes a modified dynamic phasor estimation method to estimate the dynamic phasor of the fundamental frequency component with time-variant amplitude. The exponential functions of the decaying dc offset and fundament frequency component is replaced by Taylor series and the least square technique is used to estimate the amplitudes and the time constants of the decaying components.

The performance of the proposed algorithm is evaluated by using computer-simulated signals based on simple equations and fault current signals generated by using DFIG wind farm model in MATLAB Simulink. The test results indicate that the proposed algorithm can accurately estimate the decaying amplitude and the time constant of the fundamental frequency component.

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