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

Dong-Gyu Lee, Sang-Hee Kang, and Soon-Ryul Nam, *Member, IEEE*

***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

Manuscript received November 27, 2012; accepted December 09, 2012. Date of publication December 28, 2012; date of current version February 27, 2013. This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (MEST) (2012 R1A1 A204 2252). Paper no. TSG-00824-2012.

D.-G. Lee is with the Power and Industrial Systems R&D Center, Hyosung Corporation, Anyang, Korea (e-mail: d.g.lee@hyosung.com).

S.-H. Kang and S.-R. Nam are with the Department of Electrical Engineering, Myongji University, Yongin 449-728, Korea (e-mail: shkang@mju.ac.kr, ptsouth@mju.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2012.2233772

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:

$$i_a(t) = \sqrt{2}V_T \begin{bmatrix} \frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right) e^{-t/T'_d} \\ + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right) e^{-t/T''_d} \end{bmatrix} \sin(\omega_0 t + \alpha). \tag{1}$$

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

$$i_a(t) = \frac{\sqrt{2}V_s}{X'_s}\Bigg[\cos\alpha \cdot e^{-t/T'_s} + \left(\frac{L_m^2}{L_m L_r}\right) e^{-t/T'_r}\cos(\omega_s t + \alpha)\Bigg] \tag{2}$$

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

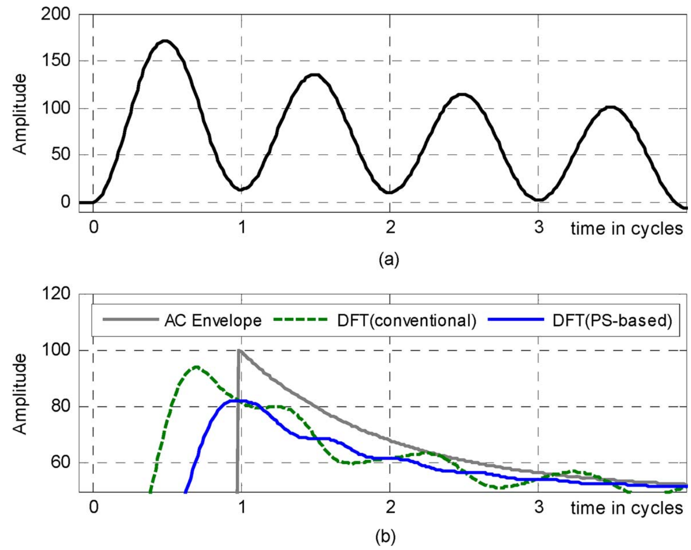

Fig. 1. Example of a short-circuit current with time-variant amplitude and its effect on DFT-based algorithms. (a) Short-circuit current. (b) Estimated amplitude.

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,