Available online at www.sciencedirect.com

ScienceDirect

Electric Power Systems Research 77 (2007) 1646–1653

ELECTRIC POWER SYSTEMS RESEARCH

www.elsevier.com/locate/epsr

Accurate phasor measurement for transmission line protection in the presence of shunt capacitor banks

Soon-Ryul Nam [a,*], Sang-Hee Kang [a], Jong-Keun Park [b]

[a] *Department of Electrical Engineering and Next-Generation Power Technology Center, Myongji University, Korea*
[b] *School of Electrical Engineering, Seoul National University, Korea*

Received 21 February 2006; received in revised form 3 October 2006; accepted 20 November 2006
Available online 27 December 2006

Abstract

This paper proposes a phasor measurement algorithm for transmission systems compensated with shunt capacitor banks. Since the shunt capacitor banks tend to lower the resonant frequencies, the dominant component, which has the lowest resonant frequency, is insufficiently attenuated by a low-pass filter and has an adverse influence on the phasor measurement of the fundamental component in a fault current signal. This paper theoretically investigates the dominant frequency in the presence of shunt capacitor banks and presents a phasor measurement algorithm immune to the dominant component and DC-offset. The performance of the algorithm is evaluated for a-phase to ground (a–g) faults on a 154-kV transmission system compensated with shunt capacitor banks. The evaluation results indicate that the algorithm can measure the phasor reliably and satisfactorily, although the fault current signal is distorted with the dominant component and DC-offset. The paper concludes by describing the hardware implementation of the algorithm on a prototype unit based on a digital signal processor.

Keywords: DC-offset; Fault current signal; Dominant component; Phasor measurement; Shunt capacitor banks

1. Introduction

The number of applications of shunt capacitor banks in substations has increased significantly. This is primarily due to the voltage regulation problems associated with the increasing loads on existing transmission systems. They are usually installed at the major buses on transmission systems to provide voltage support for large areas. These shunt capacitor banks tend to lower the resonant frequencies induced by a fault [1,2] and hence a low-pass filter insufficiently attenuates the resonant components. In particular, the dominant component, which is defined as the damped component with the lowest resonant frequency, has an adverse influence on the phasor measurement of the fundamental component in a fault current signal. Since the dominant component is an exponentially decaying component similar to the DC-offset, it cannot be removed completely despite using orthogonal transforms. Therefore, both the dominant component and DC-offset should be considered when measuring the phasor using orthogonal transforms or other techniques. Over the last two decades, several techniques have been proposed to deal with the DC-offset [3–12]. One approach for eliminating the effect of the DC-offset is to assume a specific time constant for the DC-offset [3–8]. Although the methods in this approach are useful for the assumed conditions, they cannot be applied universally because the time constant depends on the system conditions, such as the system configuration, fault location, and size of the shunt capacitor banks. Another approach is to measure the parameters of the DC-offset [9–12]. The methods in this approach have the advantage of measuring the phasor regardless of the DC-offset time constant. However, they also produce errors when the fault current signal is distorted with any damped high-frequency components, such as the dominant component.

This paper investigates the dominant frequency theoretically and presents a phasor measurement algorithm immune to the dominant component and DC-offset. The performance of the algorithm was evaluated for a-phase to ground (a–g) faults on a 154-kV transmission system compensated with shunt capacitor banks. Using the data generated by the EMTP (ElectroMagnetic Transient Program), the algorithm could measure the phasor of

* Corresponding author. Tel.: +82 31 330 6361; fax: +82 31 330 6816.
E-mail address: ptsouth@mju.ac.kr (S.-R. Nam).

0378-7796/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2006.11.008

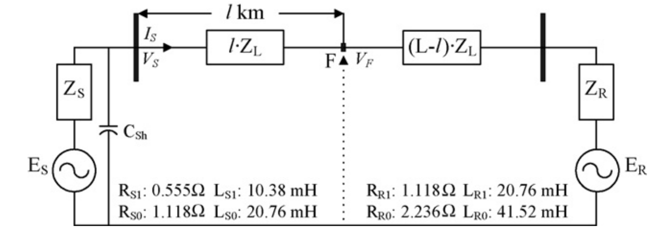

Fig. 1. Single-line diagram of the 154-kV transmission system compensated with shunt capacitor banks.

the fundamental component with high accuracy. The paper concludes by describing how the algorithm was implemented and tested on a digital signal processor (DSP)-based prototype unit.

2. Dominant frequency

The system used for this study is shown in Fig. 1. To provide reactive power, ungrounded-wye shunt capacitor banks were installed at the sending end of a 154-kV 100-km overhead transmission line, for which the parameters are given in Table 1.

When an a–g fault occurs at a fault point F located l km from a relaying point S, the Thévenin impedance viewed from F has a minimum magnitude at resonant frequencies ω_r. Since the dominant frequency ω_d is defined as the lowest of these resonant frequencies, ω_d can be expressed as

$$\omega_d(l) = \min(\omega_r(l)) = \min(\underset{\omega}{\operatorname{argmin}}|Z_{th}(\omega, l)|) \tag{1}$$

Assuming that the pre-fault voltage at F is $v_F(t) = V_F \sin(\omega_f t + \theta_F)$, where V_F, ω_f, and θ_F are the peak voltage, fundamental frequency, and fault inception angle, respectively, then the superimposed voltage for the a–g fault is given by $\Delta v_F(t) = -V_F \sin(\omega_f t + \theta_F)$. With reference to the superimposed sequence network shown in Fig. 2, the Thévenin impedance Z_{th} can be expressed as

$$Z_{th}(\omega, l) = \frac{\Delta V_F}{\Delta I_F} = \frac{\sum_{k=0,1,2} \Delta V_{Fk}}{\sum_{k=0,1,2} \Delta I_{Fk}} \tag{2}$$

where ΔV_{Fk} and ΔI_{Fk} are the superimposed sequence voltage and current at the fault point, respectively. The letter k = 0, 1, and 2 denotes the zero, positive, and negative sequences, respectively. Using the distributed-parameter line model, ΔV_{Fk} and ΔI_{Fk} can be written in terms of ΔI_{Sk}, which is the superimposed sequence current at the relaying point, as shown by the following equations:

$$\Delta V_{Fk} = Z_{Vk} \Delta I_{Sk} \tag{3}$$

$$\Delta I_{Fk} = \frac{Z_{Ik}}{Z_{Ck}} \Delta I_{Sk} \tag{4}$$

where

$$Z_{Vk} = Z_{Sk}^{Eq} \cosh \gamma_k l + Z_{Ck} \sinh \gamma_k l,$$

$$Z_{Ik} = Z_{Sk}^{Eq} \sinh \gamma_k l + Z_{Ck} \cosh \gamma_k l,$$

$$Z_{Ck} = \sqrt{\frac{z_k}{y_k}} = \sqrt{\frac{R_k + j\omega L_k}{j\omega C_k}},$$

$$\gamma_k = \sqrt{z_k y_k} = \sqrt{(R_k + j\omega L_k)(j\omega C_k)},$$

$$Z_{S0}^{Eq} = Z_{S0}, \quad Z_{S1}^{Eq} = Z_{S2}^{Eq} = \frac{Z_{S1}}{1 + j\omega C_{Sh} Z_{S1}}.$$

Z_{Ck} and γ_k are the characteristic impedance and propagation constant of the sequence network shown in Fig. 2, respectively.

Substituting ΔI_{Sk} from (3) into (4) yields

$$\Delta I_{Fk} = \frac{Z_{Ik}}{Z_{Ck}} \frac{\Delta V_{Fk}}{Z_{Vk}} \tag{5}$$

It is well known that ΔI_{Fk} satisfies the following relationship for a–g faults

$$\begin{bmatrix} \Delta V_{F0} \\ \Delta V_{F1} \\ \Delta V_{F2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{j2\pi/3} & e^{j4\pi/3} \\ 1 & e^{j4\pi/3} & e^{j2\pi/3} \end{bmatrix} \times \begin{bmatrix} \Delta V_{Fa} \\ \Delta V_{Fb} \\ \Delta V_{Fc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{j2\pi/3} & e^{j4\pi/3} \\ 1 & e^{j4\pi/3} & e^{j2\pi/3} \end{bmatrix} \times \begin{bmatrix} \Delta V_F \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

which implies that

$$\Delta V_{F0} = \Delta V_{F1} = \Delta V_{F1} = \frac{\Delta V_F}{3} \tag{7}$$

The combination of (2), (5) and (7) yields

$$Z_{th}(\omega, l) = \frac{3 \times \Delta V_{F0}}{\Delta V_{F0} \times \sum_{k=0,1,2} (Z_{Ik}/Z_{Ck})(1/Z_{Vk})} = \frac{3}{\sum_{k=0,1,2} (Z_{Ik}/Z_{Ck} Z_{Vk})} \tag{8}$$

Table 1
The 154 kV overhead transmission line parameters

Sequence	Parameter	Value	Unit
Positive, negative	R_1, R_2	0.0420	Ω/km
	L_1, L_2	0.8625	mH/km
	C_1, C_2	0.0132	µF/km
Zero	R_0	0.1793	Ω/km
	L_0	2.4750	mH/km
	C_0	0.0044	µF/km

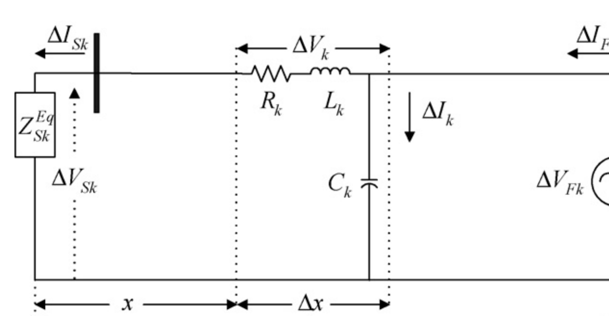

Fig. 2. Superimposed sequence network.