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Novel adaptive reclosing scheme using wavelet transform in distribution system with battery energy storage system

Hun-Chul Seo[a], Sang-Bong Rhee[b,*]

[a] School of IT Engineering, Yonam Institute of Technology, Jinju, Republic of Korea
[b] Department of Electrical Engineering, Yeungnam University, Gyeongsan, Republic of Korea

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ABSTRACT

Most distribution systems are operated in an unbalanced state; hence, neutral currents can be generated by unbalanced currents in three-phase four-wire distribution systems. This paper proposes a novel adaptive reclosing scheme that uses the neutral current in a distribution system with a battery energy storage system (BESS). The BESS, which operates as an uninterruptible power supply, is connected to the load side. In the proposed scheme, there are two circuit breakers (CBs) at the source and load sides. The wavelet transform of neutral current is performed using symlets 5 mother wavelet at level 2. The summation of the absolute values of level 2 detail coefficients is calculated, and the absolute value of the differentiation of this summation is proposed as a new index for detecting fault clearance. The CB at the source side is reclosed after detecting fault clearance using ADSum. Then, the CB at the load side is reclosed after the completion of a synchronism check. To verify the proposed scheme, the BESS is modeled using the ATP-ElectroMagnetic Transients Program. In addition, various simulations are conducted according to fault types and fault clearance times. Simulation results show that successful adaptive reclosing is possible in the distribution system with the BESS.

1. Introduction

Battery energy storage systems (BESSs) have been widely applied in power distribution systems for several purposes such as frequency regulation, peak load shaving, and uninterruptible power supply (UPS). A field test of BESSs for frequency regulation has been conducted at the Jochon Substation in Jeju, Korea. As an increasing number of BESSs are being used in power distribution networks, utility companies should adapt or change their procedures considering the interconnection of these systems. For this, several studies have been performed on the grid connection of large-capacity BESSs. In [1–6], coordinated control and planning for output smoothing through the integration of renewable energy and BESSs have been discussed. In [7–17], power sharing and management, control, and scheduling strategies using BESSs for energy management and demand response have been discussed. In [18–23], the application and control of BESSs for frequency regulation have been studied. In [24,8,25–28], the planning, scheduling, and dispatch of distribution networks or microgrids with BESSs have been discussed. These previous studies have not discussed the protection study on the procedures for the operation of a distribution system with a BESS. However, a protection study for a distribution system with a BESS has been performed. In [29], the new challenges and countermeasures in reclosing considering BESSs have been investigated. This study focused only on the utilization of a BESS for frequency regulation and peak load shaving and did not discuss the issues related to reclosing to utilize the BESS as a UPS. In [30,31], reclosing has been studied considering a BESS as a UPS. However, the reclosing scheme in [30] cannot be applied to three-phase loads, and the reclosing scheme in [31] were based on fixed dead time. These are the limitations of these studies. This paper proposes a novel adaptive reclosing scheme to overcome these limitations.

The operation sequence of a recloser in the distribution system of the Korea Electric Power Corporation (KEPCO) has the fixed dead times of 0.5 s and 15 s. Distinguishing permanent faults from temporary faults in reclosing sequences is extremely important. However, conventional reclosing adopts a fixed dead time, irrespective of whether a fault is temporary or permanent [32]. This leads to have dead time despite fault clearance before reclosing, which is a disadvantage of conventional reclosing. In transmission systems, various reclosing schemes have been proposed to detect fault clearance and reduce dead time [32–41]. However, these methods cannot be applied to distribution

* Corresponding author.
E-mail addresses: hunchul0119@hanmail.net (H.-C. Seo), rrsd@yu.ac.kr (S.-B. Rhee).

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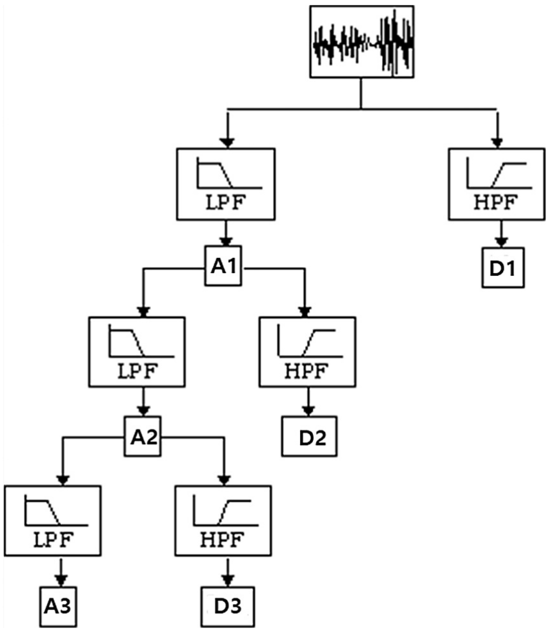

Fig. 1. Filter bank representation of the discrete wavelet transform.

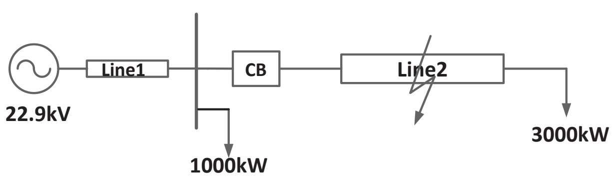

Fig. 2. Typical Korean distribution system.

systems owing to several reasons such as the configuration and short length of distribution systems. Only a few studies have examined the reclosing in distribution systems [42–44]. However, they do not consider BESSs. To overcome these limitations, in this study, a novel adaptive reclosing scheme is proposed for a distribution system with a BESS as a UPS.

A wavelet transform (WT) is a mathematical tool used in numerous fields for signal and image processing applications. WTs can be used on a broad frequency range, rather than a specific frequency domain. This makes them considerable useful for analyzing transient phenomena in a power system [45]. WTs have been applied to several protection studies such as wide-area protection [46,47], fault detection in transmission systems [48–51], microgrid protection [52], and transformer protection [53]. Therefore, they can be applied to the proposed reclosing algorithm.

This paper proposes an adaptive reclosing scheme using the WT in a distribution system with a BESS. The proposed scheme focuses on the operation of the BESS as a UPS. A new index is proposed to detect fault clearance using a WT. In addition, a novel adaptive reclosing scheme that uses this new index is proposed, and it is verified by simulating various fault conditions using ATP- ElectroMagnetic Transient Program (EMTP).

The remainder of the paper is organized as follows: Section 2 discusses the theory of WTs. Section 3 describes the proposed novel adaptive reclosing scheme that uses the WT of neutral current in a distribution system with a BESS. The new index used to detect fault clearance using the WT and the procedure of selecting the mother wavelet (MW) based on this new index are discussed. In addition, the configuration and flowchart of the proposed adaptive reclosing scheme are discussed. In Section 4, the simulation results obtained for different fault types and fault clearance times are described. Finally, the conclusions derived from the study are presented in Section 5.

2. Wavelet transform

A WT can extract time and frequency information simultaneously from an original signal [45,46]. The discrete wavelet transform (DWT) of a signal is defined as

$$DWT(m,k) = \frac{1}{\sqrt{a_0^m}} \sum_{k=1}^{N} x(n) g\left(\frac{k - n a_0^m b_0}{a_0^m}\right) \tag{1}$$

where $x(n)$ is the input signal, $g(n)$ is the MW, a_0^m is a scale parameter, $na_0^m b_0$ is the time shift of $g(n)$, and scaling parameter "a" and translation parameter "b" are functions of integer parameter m [45,46].

In general, the low-frequency components of a signal represent its identity and the high-frequency components represent its detailed characteristics. In a WT, these characteristics are defined as approximation (A) and detail (D). In this process, the original signal, S, can be represented as follows [45]:

$$S = D_1 + D_2 + \cdots + D_n + A_n \tag{2}$$

The implementation of the DWT with a filter bank is computationally efficient. The output of a high-pass filter provides the detailed information of the high-frequency components of the signal. Moreover, low-frequency components are split further to obtain more details of the input signal. Any wavelet can be implemented using this technique [45]. The DWT can be represented as a tree of low- and high- pass filters, as shown in Fig. 1. The original signal is successively decomposed into components of lower resolution, while high-frequency components are not analyzed further. If a WT is used, it is possible to extract the components at any frequency band, and the extracted components can be used to analyze various signals.

There are several types of MWs, including Haar, Daubechies (db) N, and Symlets N. MWs can be classified according to their length and characteristics. The characteristics of MWs affect the detection performance at the instant of fault clearance. Furthermore, because the wavelets used in signal analysis can be obtained by scaling and shifting the MW, the selection of the MW for detecting the instant of fault clearance is considerably important [44].

3. Novel adaptive reclosing scheme using wavelet transform of neutral current

3.1. New index to detect fault clearance

The Korean distribution system is a multi-grounded 22.9 kV Y-connected three-phase four-wire system [54]. Most distribution systems are typically operated in an unbalanced state. Consequently, unbalanced loads can generate neutral currents during steady state operation. This implies that neutral current will always flow in a neutral line, even though symmetrical faults occur in distribution systems. Therefore, this study uses neutral current in the novel adaptive reclosing scheme.

New indexes are developed to determine the characteristics of neutral current at the fault clearance instant using a WT. After performing the WT, the summation of the absolute values of level 2 detail coefficients (Sumd) is calculated as follows:

$$Sumd(j) = \sum_{j=1}^{SN} |d2(j)| \tag{3}$$

where SN is the sampling number, and d2 is the level 2 detail coefficient. The signals with high frequencies develop through switching action at the fault clearance instant. Generally, the frequency of switching transients is lower than that of lightning transients. Therefore, we exclude the level 1 detail coefficient (D1) (shown in Fig. 1), which extracts the band with the highest frequency in the signal. In the case of the switching transients generated in the distribution system, the waveforms have a higher frequency than that in