Electrical Power and Energy Systems 105 (2019) 521–528

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Development of protective schemes for hybrid AC/DC low-voltage distribution system

Chul-Ho Noh[a], Chul-Hwan Kim[a,*], Gi-Hyeon Gwon[b], Muhammad Omer Khan[a], Saeed Zaman Jamali[a]

[a] College of Information of Communication Engineering, Sungkyunkwan University, Suwon, Republic of Korea
[b] Yonam Institute of Technology, Jinju, Republic of Korea

ARTICLE INFO

Keywords:
Hybrid AC/DC low-voltage (LV) distribution system
Low-voltage DC (LVDC) distribution system
Power system protection
Protective coordination
Transient analysis

ABSTRACT

As the interest in DC-based power system increases, the low-voltage DC (LVDC) distribution system is gaining attention. Until now, however, the related studies and developments are still not mature to commercialize the system. This corresponds to the protection system as well. In fact, previous studies have dealt with protection schemes targeting only the LVDC distribution system although the system is closely influenced by the low-voltage AC (LVAC) distribution system–hybrid AC/DC low-voltage (LV) distribution system. However, most literatures reporting the hybrid AC/DC LV distribution system do not focus on the protection scheme. Thus, in the work, the protective schemes for the hybrid AC/DC LV distribution system are developed and coordinated. The transient analysis on the events in both systems is first conducted; subsequently, the protection schemes for each system are developed. Finally, two proposed protection schemes are coordinated using the state diagram and their performances are verified through simulations using the electromagnetic transients program (EMTP).

1. Introduction

Currently, DC-based power systems are gaining attention in distribution and transmission systems. This trend resulted from the development of power electronic converters, introduction of distributed generation (DG), and increase of digital loads. Therefore, researchers have conducted various studies to develop conventional power systems that can accommodate these changes. In particular, low-voltage DC (LVDC) distribution systems are still in the development stage because some challenges need to be resolved [1–3]. One of them is to develop novel protection schemes for the LVDC distribution system, considering the fault characteristic due to power electronic converters. In this regard, many studies have dealt with various protection issues. Refs. [1–4] studied the aspect that should become a priority in the protection scheme for DC faults. Based on the fault analysis, they have concluded that the protection scheme for DC faults can detect and isolate DC faults rapidly, primarily with the current derivative. Refs. [5–6] proposed the protective coordination for the LVDC distribution system, and [7–8] considered the interconnections with DGs. Additional topics such as the detection of high-impedance fault, current-limiter, and fault location are discussed in [9–12]. As reviewed, however, most protection schemes proposed in the existing literatures targeted only the LVDC distribution system itself.

In the case DC network is being coupled to an AC network, LVDC distribution systems are generally supplied through two conversion stages: a transformer and an AC/DC converter. In this regard, the low-voltage AC (LVAC) distribution system for AC loads is on the upstream of the LVDC distribution system with respect to efficiency and cost. Such a hybrid AC/DC low-voltage (LV) system, called the hybrid AC/DC LV microgrid or hybrid AC/DC LV distribution system according to their topologies, have been studied in many literatures so far. However, the existing literatures rarely discuss the protection scheme for the hybrid AC/DC LV distribution system. Refs. [13–21] presents the methods to control power flow in a hybrid AC/DC LV system. The control schemes to improve the system power quality are discussed in [22–24]. Moreover, [25–28] proposed cooperative control schemes among converters in a hybrid AC/DC LV system. Moreover, the existing protection schemes for DC systems are not suitable for protecting the hybrid AC/DC LV distribution system. That is because they hardly consider the impacts by disturbance in the upstream AC systems.

The work therefore proposes the protective schemes for the hybrid AC/DC LV distribution system based on transient phenomena by disturbance in both LVAC and LVDC distribution systems. And then, the performance is verified by simulations using the electromagnetic

* Corresponding author.
E-mail address: chkim@skku.edu (C.-H. Kim).

https://doi.org/10.1016/j.ijepes.2018.08.030
Received 20 May 2018; Received in revised form 31 July 2018; Accepted 22 August 2018

transients program (EMTP). The proposed protective scheme coordinates two protection systems for both LVAC distribution system and LVDC one. In this regard, each protection system adopts typical factors: current magnitude for LVAC distribution system and current derivative for LVDC one. Thus, the main contribution of this work is how to coordinate two protection systems by using new circuit breaker (CB_{IT}) in front of an AC/DC converter, which is proposed on the basis of the transient analysis in this paper. Especially, the state diagram is applied to discriminate the operation of individual protection systems and coordinate them. This work achieves not only the protection of each distribution system similar to the conventional ones, but also assures the normal operation even under fault conditions of other distribution system. Especially, the protective weak point of the existing protection schemes for DC distribution system, which cannot protect some transient phenomena due to the events in LVAC distribution system, can be solved in this study as well.

The remainder of this paper consists of four sections. In Section 2, the transient analysis performed according to the events in the LVAC and LVDC distribution system is discussed (LADS and LDDS stand for LVAC and LVDC distribution systems hereinafter). Section 3 proposes the protective schemes for the hybrid AC/DC LV distribution system and coordinates them. In this section, each protection scheme for both distribution systems is described initially. Subsequently, in Section 4, the performance of the proposed scheme is verified by simulations using the EMTP. Finally, conclusions are presented in Section 5.

2. Transient analysis in hybrid AC/DC LV distribution system

The concept of a hybrid AC/DC LV distribution system is illustrated first in this section. A hybrid AC/DC LV distribution system includes an upstream LADS supplying the LDDS, as shown in Fig. 1. The hybrid AC/DC LV distribution system includes a transformer and an AC/DC converter at the input terminals of the LADS and LDDS, respectively. The transformer plays role to supply LVAC power to LADS by stepping down input voltage level, but it is regarded as the ideal voltage source in this paper. On the other hand, the AC/DC converter is controlled using a pulse width modulation (PWM) technique used to rectify the AC voltage into a DC voltage. In particular, the AC/DC converter is to be protected in the development of the protective schemes for a hybrid AC/DC LV distribution system. Moreover, DC/DC converters are installed in front of DC loads, which is to transform voltage level to the required level by using a duty ratio control scheme. The two types of circuit breakers in Fig. 1 represent a mechanical circuit breaker for the LADS (ACCB) and a solid state circuit breaker for the LDDS (DCCB). The solid state circuit breaker is applied due to the requirements for rapid interruption of DC fault. The solid state circuit breakers have become valid options for protecting DC fault because of its fast operation speed while the mechanical circuit breaker has the limitation [29].

Last, it is adopted TN-S grounding system connected with the middle point of AC/DC converter. That is because the fault detection is easier in the TN-S grounding system than in IT one [30]. In addition, the target system has low possibility to be touched by human contrary to telecom power systems or the system of customer-end.

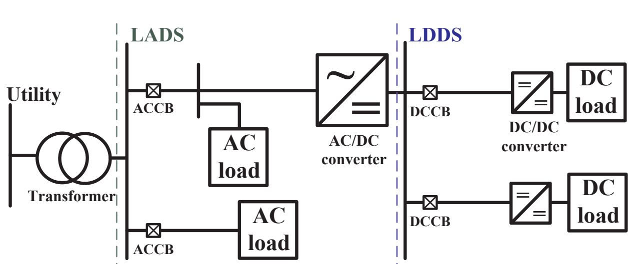

Fig. 1. Concept of a hybrid LV distribution system.

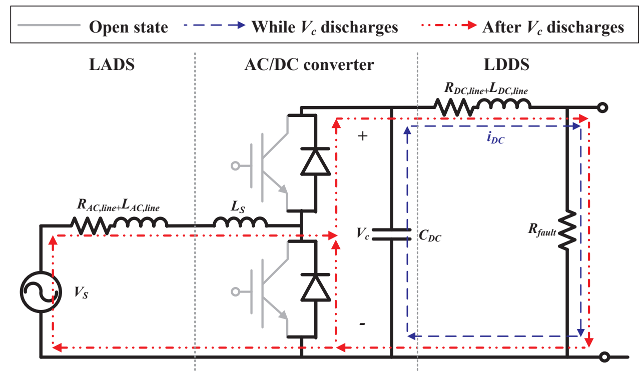

Fig. 2. Current flow due to DC fault.

2.1. Transient analysis by events in LDDS

This section presents the results of the transient analysis under the DC fault state and the DCCB opening state shown in Fig. 2, which shows the equivalent circuit of one phase in the LADS.

When a fault occurs in the LDDS, the capacitor (C_{DC}) in the AC/DC converter starts to discharge, resulting in a capacitive discharge current (i_{DC}) along a series RLC path in Fig. 2 [31]. It has a very short time constant and contribute to high fault currents [32]. To prevent the semiconductor switches from being damaged, they are deliberately opened at that time. The manufacturers define its maximum overcurrent capability to be 2–3 times the nominal current during various milliseconds [29,33]. The current increases and decreases dramatically while the capacitor voltage (V_c) discharges, and is in the form of an underdamped sinusoidal current expressed by

$$i_{DC}(t) = e^{-(R_{eq}/2L_{eq})t} A \sin(\omega t + \alpha), \tag{1}$$

where R_{eq} and L_{eq} denote the equivalent values of resistance and inductance in a fault current loop, respectively. A represents the current magnitude and ω represents the resonant frequency. For reference, (1) is the modified form from the original one by using a formula of a trigonometrical function. Finally, α denotes the damping factor. The equation of voltage transients for V_C can be expressed as integral form of (1) because it is directly related with the capacitive discharge current.

The fault is contributed by both the energy stored in the line inductance ($L_{DC,line}$) and the AC source immediately after V_c is fully discharged, causing the current flow through the AC/DC converter as shown in Fig. 2 [34]. The two currents can be respectively expressed by

$$i_L(t) = -I_{L0} e^{(-R_{eq,L}/2L_{eq,L})(t-t_C)} \tag{2}$$

$$i_s(t) = V_s/R_{eq,S} + (I_{s0} - V_s/R_{eq,S}) e^{(-R_{eq,S}/L_{eq,S})(t-t_C)} \tag{3}$$

where I_{L0} and I_{S0} denote the initial value of the current resulting from the discharge of $L_{DC,line}$ and AC source, respectively. $R_{eq,L}$, $L_{eq,L}$, $R_{eq,S}$, and $L_{eq,S}$ represent the equivalent values of resistance and inductance on the corresponding paths, respectively. In addition, V_S means the AC input voltage level and t_C represents the time when V_c is fully discharged. Since the semiconductor switches are opened, the anti-parallel diodes become the path for the currents, resulting in the diodes being damaged. Thus, the DC fault must be interrupted before V_c is fully discharged. Moreover, the DC fault adversely affects the LADS by a higher current and voltage sag. This means that the circuit breaker (ACCB) in the LADS could be opened if the DC fault is not interrupted quickly enough.

Next, the DC fault is interrupted by opening the circuit breaker in the LDDS. Subsequently, two distribution systems are isolated from each other and the LADS can be normally operated with a smaller load current than that under the prefault state. This is because only the AC loads are supplied.