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Review

Protection of multi-terminal and distributed DC systems: Design challenges and techniques

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ABSTRACT

The DC power system is an effective architecture that achieves more reliable power with higher efficiency, leading to a better integration of energy sources with fewer power electronic converters. However, the protection of DC power systems, especially multi-source distribution systems and multi-terminal dc lines, involves many challenges. Through extensive study, this paper presents the key requirements for the protection of these systems, such as personal safety, fault detection and location capabilities, equipment survivability and ride-through capability. Various grounding topologies utilized in DC systems are detailed and their advantages and limitations are compared in terms of personal safety, transient short circuit current behavior, fault detection and protection capabilities, and insulation requirements. In multi-source systems, the proper design and coordination of circuit breakers and disconnecting switches are very important to rapidly isolate the faulted area and restore the system. In this paper, different circuit breaker technologies and configurations have been studied and their performances are compared. Moreover, this paper presents a comprehensive overview of various fault detection and location techniques suggested in the literature. The requirements and applications of these techniques are discussed and areas for future research are indicated.

Contents

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1. Introduction

In the last decade, multi-terminal and distributed DC power systems have been widely researched and developed, having numerous advantages over the existing AC network, such as higher energy efficiency, improved reliability, higher power quality, better energy systems integration and eco-friendliness [1,2]. High voltage DC (HVDC) transmission lines have been increasingly used to provide a cost-effective solution for transferring power over long distances with enhanced power flow controllability [3–5]. Also, multi-terminal HVDC grids offer a better integration of renewable energy resources like offshore wind farms and photovoltaic generations [6]. At lower voltage and power levels, medium voltage DC (MVDC) and low voltage DC (LVDC) distribution systems can be effectively utilized in various systems, such as electric traction systems, telecommunication and data centers, and for shipboard and aircraft systems [1–5]. Moreover, DC distribution systems have the potential to better support future smart grids in realizing a high penetration of distributed renewables and electric vehicles [5].

While the advantages of the DC architecture are significant, the protection of multiterminal and distribution DC systems has posed many challenges, such as accurate fault detection and location, proper grounding schemes, proper design of DC circuit breakers, fast isolation of faulted areas and self-reconfiguration capabilities, along with the lack of standards and guidelines. An advanced protection scheme should have self-diagnosing and self-healing capabilities to reduce damage caused by short circuit faults and to provide continuous power to loads, even during system faults [2,7]. The self-diagnosing capability of the system requires a well-designed protection scheme to be able to detect a fault very quickly and accurately locate the faulted area. Also, to realize the self-healing capability of the system, the switching devices should be properly designed and coordinated to enable fast transition from a fault condition to a normal operation. Moreover, choosing the appropriate grounding scheme is an important issue that involves many aspects of the power system, such as the reliability of the system, personal safety, transient overvoltage and insulation coordination of the system [8,9].

This paper is organized as follows. Section 2 discusses the key requirements for the protection of DC power systems, which are the equipment survivability, personal safety, fault detection and location capabilities, system reconfigurability and ride-through capability. In Section 3, different fault currents in DC systems are analyzed to provide guidelines to accurately set the protective relays and to properly design the protective devices. Also, various grounding topologies of DC power systems are explained in Section 4 and their advantages and limitations are compared. These topologies are ungrounded, resistance grounded and solidly grounded systems. In Section 5, different DC circuit breaker technologies are reviewed and the performances of these breakers are compared. Also, Section 6 explains various fault detection and location techniques suggested in the literature. The requirements and applications, as well as the advantages and limitations of each protection technique, are discussed. These techniques are differential protection, handshaking protection, traveling wave protection, distance protection, event-based protection and artificial intelligence protection. Finally, conclusions are given in Section 7.

2. DC power system protection requirements

Designing a protection system is a comprehensive issue that involves many challenges. In this section, the key requirements of DC system protection are discussed and design challenges are addressed.

2.1. Equipment survivability

DC fault currents are severe in transients, which can cause considerable damage to the equipment, such as the power electronic converters and sensitive loads. In a DC system, the power supplies are the major fault current sources, however, the capacitors at the DC bus terminal and DC filters significantly contribute to fault currents, which cause very high short circuit currents during the transient fault periods [2]. Thus, the proper design of a protection system requires careful analysis of its fault current characteristics. Section 3 discusses the fault current characteristics of different sources under various fault impedances.

The amount of energy absorbed by a device during a fault is proportional to the integral of i^2 over the transient fault period [10,11]. Thus, the maximum fault current amplitude, its shape and the fault clearing time are important factors that should be considered for a safe operation of the device. An advanced DC system should employ a protection scheme that quickly identifies a fault event and utilizes fast circuit breakers to minimize the fault clearing time and the maximum short circuit current. In this paper, various circuit breaker technologies and fault detection schemes are presented and analyzed in Sections 5 and 6, respectively.

2.2. Personal safety

Personal safety is one of the essential requirements of an electrical protection system. Particularly, arc flash can cause substantial injury to employees working on or near electrical equipment and can create further damage to the system. Thus, it is important to identify arc flash risk levels within the DC system and to adopt the necessary safety measures [12–14]. Moreover, the concern regarding retained charges on equipment and power lines is more significant for DC systems than it has been for AC [14]. As a result, the touch potential should be well considered when designing a DC system. This requires a proper strategy for the system grounding, which will be discussed in Section 4.

2.3. Fault detection and location capabilities

One of the most important aspects of a protection system is the fault detection and location algorithms embedded on the protec-