Mitigation of voltage unbalance by using static load transfer switch in bipolar low voltage DC distribution system

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A B S T R A C T
In this paper, a method is proposed to mitigate voltage unbalance and to reduce power loss due to neutral current in a bipolar Low-Voltage DC (LVDC) distribution system by using a static load transfer switch (SLTS). Furthermore, an algorithm to determine the proper position of loads by using the SLTS is presented; this algorithm is developed by considering the neutral current at each load point. The underlying strategy of the SLTS method is that a local substation generates switching signals by using the proposed algorithm on the basis of data measured by a DC/DC converter; thereafter, SLTSs, which are placed in the DC/DC converter, are operated to reconfigure the structure of loads. To evaluate the performance of the proposed method, the conventional method for calculating the percent voltage unbalance for an AC system is modified and made applicable for a DC system. The modeling of a 1500 V bipolar LVDC distribution system carried out using the ElectroMagnetic Transients Program (EMTP) is also presented herein. Finally, a simulation carried out by employing the SLTS method under various load conditions is presented; the results show a decrease in power loss and mitigation of voltage unbalance.

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1. Introduction

Toward the end of the 19th century, the AC power system was adopted as an effective means of electricity generation and delivery. This was because the voltage of AC power can be easily transformed to high levels so that the power can be transmitted over long distances. Nowadays, however, the LVDC distribution system is attracting a lot of attention as a replacement for the AC power system. In [1], the market of DC distribution system is growing steadily according to statistical results. This LVDC distribution system is possible to adopt the voltage level of 1500 V since the range of low voltage for DC is between 75 V and 1500 V according to Low Voltage Directive (LVD) 2006/95/EC [2,3].

In recent times, electronic loads have continued to increase gradually and the use of renewable energy has become widespread. These elements need power conversion; therefore, use of the LVDC distribution system results in more effective power supply to electronic loads owing to the elimination of conversion stages [4–7]. Diverse researches on LVDC distribution systems for industrial [8], traction [9], and shipboard use [10], as well as on the development of simulation models for the LVDC system [11] are being conducted actively.

An interesting issue with the LVDC distribution system is the voltage unbalance phenomenon, which can be caused by an asymmetric configuration of loads, especially in a bipolar-type LVDC distribution system [12]. The advantage of a bipolar LVDC distribution system is that high efficiency and high-quality power supply can be achieved satisfactorily [13]. However, loads are not always connected with positive and negative poles equally, and thus, it leads to load unbalance. This unbalanced load condition due to hourly variations can cause unbalanced voltages [14]. In the power system, there are several power quality issues. The voltage unbalance is one of those issues and disturb the system efficiency [15]. Several techniques for mitigating voltage unbalance in an AC system have been proposed such as using Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC) [16–20]. These methods are to mitigate the voltage unbalance by controlling reactive power. However, they are improper to apply to LVDC distribution system due to the absence of reactive power. On the other hand, in order to solve the voltage unbalance problem in bipolar LVDC system, the voltage balancer with DC/DC converter is proposed [13,21]. In addition, with the continuous improvement of the quality of power supply requirements, buck-boost and dual-buck half-bridge type balancer, which have the capability adjusting the DC voltage and improving the reliability, has been proposed [22,23]. In a previous study [24], it was shown that a distribution system can be balanced by balancing the loads through the...
reconfiguration technique. Such load reconfiguration can mitigate voltage unbalance because load unbalance is one of its principal causes.

In this study, we have attempted to mitigate voltage unbalance via the reconfiguration of load connections with grid. It is unfeasible to mitigate the voltage unbalance in a DC system through reactive compensation achieved using a STATCOM or SVC. In addition, considering cost efficiency, we intend to develop a method to mitigate voltage unbalance without using any additional facilities. Therefore, on the basis of the load transfer technique, which is an effective method for balancing loads [25], we developed a novel method to mitigate voltage unbalance by using Static Load Transfer Switch (SLTS). In the LVDC distribution system, a DC/DC converter including static switches is necessarily connected to the load. Therefore, we suggest the use of a static switch, which can provide load transfer, instead of using any additional switchgear with contact [26]. Furthermore, we present an algorithm to operate the SLTS by considering the decrease in neutral current. Finally, to verify the performance of the proposed SLTS method, we modeled a simple bipolar LVDC distribution system and conducted simulations for different cases by using Electromagnetic Transients Program (EMTP). This paper is organized as follows. Section 2 describes the load and voltage unbalance in a bipolar LVDC distribution system. In Section 3, concept, feasibility, and principle of the proposed SLTS method are discussed. Section 4 presents the simulation results and discussion in detail. Finally, the conclusions are given in Section 5.

2. Analysis of bipolar LVDC distribution system

2.1. Characteristic of bipolar LVDC distribution system

The LVDC distribution system has two basic structures according to the number of poles: unipolar and bipolar [7], as shown in Fig. 1. According to the policy by distribution system operators, unipolar or bipolar system can be applied to their system. The consideration on which system type is better is beyond the scope of this paper. In this paper, we’ve focused on the situation where the bipolar system is adopted.

A unipolar system uses two conductors and has one voltage level that is between those of the positive and negative poles. On the other hand, a bipolar system with three wires has three voltage levels, namely, positive-to-ground, negative-to-ground, and pole-to-pole voltage [6]. Thus, on the load side, a DC/DC converter can select the source voltage from three voltage levels. In addition, if the output capacitors of positive and negative pole are independent on each other in bipolar system, a short circuit occurring on one load side does not affect other loads. Moreover, additional power lines contribute to preventing temporary overload at a single-pole load by sharing three voltage levels [13]. Since the continuity of power supplying is guaranteed in bipolar type, the bipolar system can achieve high power quality [27]. However, a bipolar system suffers from a problem: when the loads are non-identical, the system becomes unbalanced. In this case, a continuous current flow into the neutral line would occur; this causes power loss in the neutral line and creates an additional requirement of mitigating unbalance.

2.2. Load unbalance in bipolar LVDC distribution system

In a bipolar system, load unbalance can occur because loads with different capacities can be connected to a distribution system in general. We can obtain percent load unbalance (%LU), which is an indicator of the severity of load unbalance, by using Korea Electric Facility standards. In [28], the equation for calculating %LU for a three-phase and four-wire configuration is shown. To calculate %LU for a bipolar LVDC distribution system, we use an equation for a single-phase and three-wire case given by

\[
\%LU = \frac{|L_p - L_n|}{L_p + L_n}/2 \times 100
\]

where \(L_p\) and \(L_n\) are the total load capacity of positive and negative pole, respectively.

The Korea Electric Power Corporation (KEPCO) restricts %LU for a single-phase and three-wire distribution system to less than 40%. In (1), if \(L_n\) is presented as the proportion of itself to \(L_p\) using the ratio \((r = L_n/L_p)\), the calculation of the %LU is expressed as (2). Power utilities can consider the ratio obtained from (2) to restrict the load unbalance when they make the operating plan of distribution system.

\[
\%LU = 2|L_p - r \cdot L_p| \cdot 100/(L_p + r \cdot L_p) = 200 \cdot |1 - r|/(1 + r)
\]

When %LU is 40%, \(r\) is calculated to be 1.5. This means that the total load capacity of the negative pole, which is 1.5 times larger than that of the positive pole, is allowable according to KEPCO standard. However, although %LU of bipolar LVDC distribution systems satisfies the standard value, these systems can suffer from high voltage unbalance and neutral current flow. Therefore, we need to consider voltage unbalance in bipolar LVDC distribution systems even if the %LU is within the limit.

2.3. Voltage unbalance in bipolar LVDC distribution system

Unbalanced loads are the main cause of voltage unbalance in a distribution system. Customer load, which is mostly a single-pole load, changes continuously and thus causes unintended voltage unbalance. Therefore, most distribution systems contain a certain level of voltage unbalance according to system conditions. In particular, if a system has a hugely disproportionate configuration of loads and overloads or electric vehicles concentrated on a specific
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