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Improved design of an extra-high-voltage expansion substation connector through magnetic field analysis

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ABSTRACT

In many countries worldwide, the energy demand is growing faster than the transmission capacity. However, due to environmental constrains, social concerns and financial costs, the construction of new power transmission lines is an arduous task. In addition, power transmission systems are often loaded close to their nominal values. Therefore, improving power transmission system efficiency and reliability is a matter of concern. This work deals with a 400 kV, 3000 A, 50 Hz extra-high-voltage expansion substation connector used to connect two substation bus bars of 150 mm diameter each. This substation connector has four aluminum wires which provide the conductive path between both bus bars. Preliminary tests showed an unequal current distribution through the wires which was mainly attributed to the proximity effect. A three-dimensional finite elements method approach was applied to improve the design and evaluate the electromagnetic and thermal behavior of both the original and improved versions of the connector. Experimental tests made under laboratory conditions have validated the accuracy of the simulation method presented in this paper, which may be a valuable tool to assist the design process of substation connectors, therefore allowing improving both the thermal performance and reliability of the redesigned connectors.

1. Introduction

The constant increase in global energy demand combined with the growing share of disperse and renewable energy sources is promoting the construction and research in extra-high-voltage (EHV) and ultra-high-voltage (UHV) power transmission systems [1]. Furthermore, these transmission systems allow minimizing power loss and increasing the maximum load while minimizing financial costs [2].

Although substation connectors constitute only a very small portion of the total expenses of a power transmission system, they are amongst their weakest links. Therefore, failing connectors may lead to power system failures and consequently to costly repairs [3] and major economic and social consequences. However, very few studies analyzing their behavior under adverse conditions are found in the technical literature [4]. In recent years, bolted-type connectors have become very popular mainly because of the ease of assembly and disassembly compared to compression-type connectors. Substation connectors are a special group of bolted-type connectors. The electrical resistance offered by the substation connectors, which often

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carry large electrical currents, is a critical parameter in order to meet the electrical and thermal requirements imposed by the NEMA CC1 [5] and ANSI C119.4 [6] standards [3].

It is well-known that electromagnetic effects generated by AC magnetic fields in a single conductor are different from those occurring in multiple conductors [7]. For example, in a three-conductor flat configuration, AC power loss are higher in the outer conductors since they carry more current than that carried by the central conductor [7]. Moreover, the total AC power loss increase with decreasing distance between conductors. The different behavior between single and multiple conductor configurations are mainly due to eddy currents, skin and proximity effects [8]. Under AC supply, the electric current distribution over the conductor cross section is non-uniform due to the skin effect. When in the surrounding region there are other conductors carrying currents, they generate magnetic fields which distort even more the total magnetic field distribution. Hence, it results in a non-uniform magnetic field distribution, usually known as proximity effect due to the influence of the magnetic field of the nearby conductors [9]. Therefore, the resultant magnetic field distribution is greatly influenced by the different proximity effects between conductors. These effects will further influence the induced eddy currents, power loss and thermal dissipation [10] and must be taken into consideration when designing substation connectors. Proximity effects are important in diverse applications, including three-phase high current bus bars [8], windings of transformers and rotating machines [9] or induction domestic systems [10]. When dealing with electrical machines, proximity power loss due to eddy currents generated by AC magnetic fields become increasingly important as the power and speed increase [11].

In the case of parallel conductors, proximity effects may promote an unequal distribution of the currents among the different parallel paths. This current asymmetry is often minimized by transposing the conductors [12]. If this current asymmetry is not counteracted, the overall behavior of the affected device may be greatly influenced since higher power loss and hotspots are likely to occur.

Power loss may be split up into Joule loss (caused by the RMS or root mean square current), skin effect loss (they may be understood as an effective increase of the Joule loss due to the skin effect) and proximity loss (caused by eddy currents in the wires due to external magnetic fields) [13].

The expansion substation connectors dealt with have four aluminum wires which connect two substation bus bars. The wires provide the conductive path between both bus bars. Therefore, in order to optimize their thermal behavior, the highest potential consists in optimizing the connector geometry, i.e. the selection of the wires geometry and positioning.

Three-dimensional finite element modeling (3D-FEM) is an effective tool to carry out realistic simulations of complex problems [14]. Therefore, in the case of a substation connector with multiple wires and complex shape, 3D FEM is a useful tool to compute the unequal current distribution due to both proximity and skin effects [12] and to optimize its behavior. If a thermal FEM model is included, the thermal impact of such effects may be analyzed in detail. To this end, coupled magnetic eddy-current and thermal models are to model underground power cables [15]. As explained, comprehensive knowledge of the magnetic phenomena is vital in order to design optimized substation conductors. Therefore, during the design phase and with the assistance of FEM software, the substation connectors' performance may be accurately predicted and corrective actions may be applied in order to obtain improved geometries.

Thus, this work is aimed to develop a 3D FEM-based method to improve the design of EHV substation connectors with multiple wires. Design improvements are based on ensuring a balanced distribution of the currents through the different wires of the connector, which are achieved by generating a more uniform magnetic field distribution around these wires while guaranteeing an appropriate heat transmission surface. By this way, the connector thermal performance, life expectancy and reliability may be enhanced.

Regardless of the leading role of substation connectors in power transmission systems reliability, there are virtually no published technical works analyzing the magnetic field distribution and the thermal behavior when operating under nominal currents. Hence, this work makes a contribution to fill this gap.

The paper is organized as follows. Section 2 describes the substation connectors geometries analyzed, whereas Section 3 gives details about the magnetic and thermal 3D FEM models used in this work. Sections 4 and 5 describe, respectively, the simulation and experimental tests carried out to verify the suitability of the proposed methodology. Finally, the conclusions are settled in Section 6.

2. Substation connector configurations

This work deals with a 3000 A_{RMS}, 400 kV_{RMS} (line-to-line) expansion substation connector. The SSXH15 substation connector is made of a cast aluminum alloy whereas its hardware is made of stainless steel. The analyzed connector connects two 150 mm diameter aluminum substation bus bars applied in AC transmission systems. The conductive path between both aluminum bus bars is provided by means of four stranded aluminum wires. Fig. 1 shows a 3D view of the original connector with its main dimensions. Once manufactured, a preliminary factory test realized under laboratory conditions indicated an unequal distribution of the currents through the four aluminum wires. This effect was mainly attributed to the proximity effect due to the influence of the magnetic field of the nearby conductors. As a consequence of this unequal distribution of the currents through the four wires, unbalanced power loss and difficulty to pass the temperature rise test were expected. Therefore, it was concluded that a corrective action was required. To minimize the financial costs related to the connector improvement, it was decided to preserve the same body of the connector.