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Switching Functions Model of a Three-phase Voltage Source Converter (VSC)

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Abstract

The equivalent circuit of a three-leg, four-wire voltage source converter (VSC) is derived using switching functions. Simulations and experiments are conducted (i) to investigate the effects of the zero sequence on VSCs when a three-phase imbalance exists and (ii) to use the consistency of simulations and laboratory experiments to validate the equivalent circuit. The impact of a three-phase imbalance on the VSC has yet to be fully investigated because of the lack of an equivalent circuit to show rigorously how the zero sequence currents flow through the VSC.

Key words: Four-Wire Three-phase system, Switching function, Voltage source converter, Zero sequence

I. Introduction

Although the three-leg, four-wire voltage source converter (VSC) has existed for several decades, the VSC has no equivalent circuit. The motivation for having an equivalent circuit comes from the modular multilevel converter (MMC) [1], [2] which has an equivalent MMC circuit [3], [4]. If the VSC had an equivalent circuit, determining whether VSCs or MMCs better suited for series connections as in ultra high voltage direct current (UHVDC) for parallel connections, as in the multi-terminal HVDC, can be answered by comparing the VSCs and MMCs. This paper formulates and validates the equivalent circuit of the VSC.

Simulations and experiments have been planned to validate the effect of the zero sequence on the VSCs when the VSCs operate under a three-phase imbalance. The impact of the zero sequence has yet to studied previously because one cannot determine how the zero sequence flows through the VSC until the equivalent circuit is derived. Achieving consistency between simulation and experimental results corresponds to “killing two birds with one stone.”

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This paper joins predecessors, [5]-[13], in applying the switching function concept to develop the equivalent circuit. In this method, power electronic switches are approximated as ideal *ON–OFF* switches. Generally, a switching function $S = 1$ is used to designate the *ON* state, while $S = 0$ to designate the *OFF* state. The concept has been extended to $S =+ 1$ and $S = -1$ when the *ac* terminal of one phase is connected to the positive and negative *dc* bus, respectively.

This paper is the first to extend the switching function concept to $[S+1]/2$ and $[S-1]/2$ as a tool in the analytical derivation of the equivalent circuit. From the derivation, the VSC is modeled as ideal voltage sources on the *ac*-side and as ideal current sources on the *dc*-side. The derivation shows that the zero-sequence current (which often exists during three-phase imbalance) splits into equal halves that flow along the upper and lower *dc* buses. The equality of power of the *ac*-side to the *dc*-side is derived analytically. Most previous researchers and the authors of the present study applied the conservation of energy to relate the power of the *ac*-side to the *dc*-side.

Validation by simulations and experiments focuses on the impact of the zero sequence on VSCs. The study shows the following: (i) the zero-sequence is the cause of imbalance of the voltages of the upper and lower *dc* capacitors of the VSCs, which result in waveform distortions in the *ac* voltages; (ii) the capacitor voltage imbalance is self-correcting in VSCs operating under reference voltage control but not in VSCs operating under reference current control; (iii) in VSCs

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