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A controller for practical stability of capacitor voltages in a five-level diode-clamped converter

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Abstract

The balancing of the dc-link capacitor voltages represents the main technical challenge in multilevel diode-clamped converters. In particular, when the number of capacitors is greater than two, these power conversion systems must be actively controlled to achieve a correct voltage sharing. Focusing on the five-level diode-clamped converter topology, this paper deals with the voltage imbalance phenomenon from a control point of view. For that purpose, the voltage balancing objective is addressed as a problem of ensuring the practical stability of a nonlinear system under the presence of external disturbances. Considering this approach, a novel control method is proposed to regulate the outputs of the system. It is based on several steps, which should be carried out during the controller design stage, that lead to define a discrete-time controller with sampling frequency corresponding to the triple of the ac-source frequency. Finally, the performance of the proposed controller is analyzed under varying operating conditions to demonstrate the capability and viability of the controller to attain the control goals.

Keywords: Multilevel power converter, diode-clamped converter (DCC), practical stability, dc-link capacitor voltage balancing, stability analysis

1. Introduction

1.1. Background: multilevel power converters

Among the great variety of multilevel converter topologies [1, 34], the diode-clamped converter (DCC) has attracted special interest, particularly in medium-voltage and high-voltage applications for high-power systems, finding increased attention in academia as well as in industry [1, 18, 35]. In light of the world ever-rising demand for electrical energy, DCCs have emerged as an important solution due to the power levels reached by this power-conversion systems, and due to the attractive features and the more competitive performance they present, in comparison with conventional two-level converters.

The idea behind multilevel converters is that by augmenting the number of levels, the voltages generated by the converter have more possible steps producing staircase waveforms, which approach the sinusoidal waveforms and reduce the total harmonic distortion [35]. Thus, the generated voltages improve their quality as the number of levels increases, leading to multiple-step voltage waveforms with variable and controllable frequency, phase and amplitude. However, when the number of levels of the DCC is augmented, the structure of the converter becomes more complex. A greater number of power semiconductor switches, clamping diodes and dc-link capacitors is needed, increasing in this manner the device size and the assembly costs. Consequently, the difficulty of controlling the converter increases as well. In particular, the balancing of the dc-link capacitor voltages becomes extremely complicated, especially for topologies that present more than three levels, and it represents one of the major technical challenges in multilevel converters. For these topologies, the converters must be actively controlled to achieve a correct voltage sharing.

Concerning the five-level DCC, topology illustrated in Fig. 1 and considered in this paper, the phenomenon of voltage imbalance of the dc-link capacitors represents a critical issue. Besides deteriorating the performance of the system, it may result in unsatisfactory behavior of the converter. On account of the different capacitor charging times during instantaneous active power transfers, the capacitor voltages tend to rise or fall in an uncontrolled way. Consequently, they can even cause the operational failure of the converter.

In view of this, there is an essential need to keep balanced the capacitor voltages. Nevertheless, dealing with the voltage imbalance problem is not an easy task. Considering conventional modulation techniques, multilevel DCCs present some limitations [24, 39], for which an equal capacitor voltage sharing is not possible in all the operating conditions, if single multilevel inverters or rectifiers are considered. These theoretical and practical limits are related to the modulation index and the power factor. Due to this fact, the subject, that is, the balancing of the capacitor voltages, has been one of the most active research topics in the field of power electronics. It has been addressed in different ways, leading to several approaches and solutions in the technical literature:

1. The first and easiest approach to cope with the problem consists of supplying the dc link of the converter with four separate dc sources, one per dc-link capacitor [25].

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