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A single-phase nine-level inverter for renewable energy systems employing model predictive control

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ABSTRACT

In this paper a single-phase cascaded Multilevel Inverter (MI) consisting of full NPC bridges for renewable energy systems is investigated. The development of the introduced control strategy is based on the application of Model Predictive Control (MPC) technique meeting the required specifications of the individual voltage level regulation of each separate DC source and neutral point potential balance under unity power factor. Illustrating the effectiveness of the developed controller, two separate PV strings are controlled while being subject to transient phenomena related to asymmetric string conditions in terms of solar radiation and reference voltage variation. The inverter topology of full NPC bridges in cascade allows low current THD factor to be achieved using a simple inductor instead of complicated LCL filters benefiting also from low capacitor banks in the DC-link bus. The proposed MPC performance has been validated by experiments carried out on a cascaded MI topology delivering power from two separate PV system strings.

1. Introduction

The ever-growing demand for electric energy partially constitutes an implicit result of the world-wide effort towards greenhouse effects diminution and quality of life enhancement [1]. Almost every contemporary technological achievement incorporates environmentally friendly practices, while conventional applications that are usually of high consumption are now electrified from renewable energy (RE) sources. Electricity generation, distribution and transmission needs constantly increase confirming future projections that claim a persistence of this tendency [2]. In the realm of RE applications, where the global capacity has nearly doubled in the previous decade, power plants' capacity is also significantly boosted at high levels without being present any apparent factor that seems to interrupt this trend. The standards are regularly updated ensuring that safe practices are being followed by grid operators and manufacturers. For instance, in Photovoltaic (PV) systems, the maximum applicable DC-voltage rises, necessitating modules and converters capable of higher voltage withstand. However, this trend is not only intense at RE systems, but also at medium power electric drives commonly used in industry that become of larger power and voltage capacity.

Power inverters act as the connection link between energy sources and consumptions having the responsibility to efficiently utilize and distribute energy. Such an enhanced role demands flexible converter topologies featuring not only increased power capability but also beneficial operational characteristics. Strict code regulations and energy efficiency considerations gave rise to the development of novel converter topologies and fostered progress toward advanced control techniques [3–7]. Thanks to this oriented effort, several Multilevel Inverters (MIs) topologies have already been proposed in literature [8–12]. MIs gather numerous attractive and advantageous characteristics over the conventional converters in terms of efficiency, power capacity and quality [13,14]. Terminal voltage is characterized by significantly lower Total Harmonic Distortion (THD) simplifying how the inverter is interfaced to grid or the load [15,16].

Significant endeavor has been devoted into the modular Cascaded H-bridges (CHBs) with numerous contributions and several variants found in bibliography [17–20]. Due to the arisen difficulties from their complex nature, CHBs are effectively employed to medium or high power applications [21–23]. Nevertheless, topologies in cascade connection face the acknowledged issue of high frequency leakage currents flowing to earth when used for example in PV applications, where parasitic capacitances exist. High (HF) or low frequency (LF) transformers are employed at DC- or grid-side, respectively, eliminating such phenomena. Since the absence of a LF transformer is one of the critical benefits that

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derive from MI operation in technical/economic terms, the latter option is not considered as cost effective. In literature, several techniques are suggested in order to cope with leakage currents; however, it is a common practice in RE applications, such as PV or Wind Turbine (WT) systems to use an additional DC stage isolating and independently controlling the energy sources.

Furthermore, the complexity of the control process of cascaded topologies is closely dependent on the specific application; while it is exponentially increased with the number of cells in cascade. In literature, several control strategies have been proposed for cascaded topologies involving both linear and non-linear strategies utilizing either analog or digital control platforms [19,24]. In cases that the converter model can be easily expressed as a function of the switching combinations, then the state variables' values can be predicted for the next sampling time [25,26]. Model Predictive Control (MPC) arises in that circumstances as an advantageous choice by appropriately involving constraints in a cost function to be minimized. MPC features the capability of sophisticated control requirements, and several constraints involvement combined into a relatively easy-to-implement algorithm [27,28]. The absence of multiple Proportional Integral (PI) compensators within control loops facilitates the control response rendering the process as independent from the point of operation.

In this paper, a MPC strategy for a MI topology applicable to RE systems is introduced. The examined MI topology consists of full Neutral Point Clamped (NPC) bridges in cascade connection instead of the conventional H-bridges resulting in significantly improved current THD factor. Controller features several significant characteristics such as individual regulation of each separate DC-link voltage enabling the control scheme to satisfy RE systems' need of interfacing various and different power sources into the grid as well as unity power factor. Furthermore, special emphasis is given on neutral point potential keeping each cell's capacitor voltages balanced. MPC involving state space equations in the cost function enables the system to completely meet the aforementioned requirements by deciding proper control actions considering constraints and several control objectives. The developed control strategy is subject to transient phenomena affecting both DC and AC side as well as the system response is also investigated under abrupt reference variations. The effectiveness of the developed control scheme is experimentally demonstrated on a single-phase MI topology delivering power from separate PV system strings.

2. Overall system description and considerations

The generalized block scheme of a cascaded topology comprises n DC input sources, v_{dn}, as shown in Fig. 1. Regarding grid-tied systems, the energy source may be coupled to earth ground through a parasitic capacitance. Such phenomena are common in PV systems where parasitic capacitances exist. Any AC component of the voltage across this capacitor generates current flow to the ground. HF components produce excessive ground currents necessitating further attention even in the case of conventional converters. However, cascaded topologies demand special care because of the voltage potential among separate cells' ground. Furthermore, some standards necessarily require galvanic isolation between the energy source and earth. In the aforesaid cases, a HF or LF transformer at the DC- or grid-side, respectively, is added to the scheme. Instead of the use of LF transformers that negates the significant advantage of MIs, the first option is adopted in this study.

The series connection of the output voltage of each individual cell, v_{anbn}, synthesizes the total output voltage of the cascaded inverter topology, v_{a1bn}, interfaced to the grid through a series connected inductor, L_s, and its parasitic resistance, R_s. Particularly, in order to realize the 9-level output voltage, v_{a1bn}, shown in Fig. 1, the 5-level voltage, v_{anbn}, of two series connected full NPC bridges is necessary to be combined. Employing the CHB topology, it is necessary to combine four H-bridges in series in order to achieve the same output voltage levels under symmetrical operation for both topologies. In this case, the number of power switches, without considering clamping diodes, is the same for both topologies, whereas CHB inverter demands more DC sources and thus more complicated control. Comparing the voltage levels for both topologies derives that the proposed topology presents significantly increased complexity but also the output voltage levels are increased. Considering the investigated topology of two cascaded bridges ($n = 2$) the output voltage consists of 9 ($=4 \cdot n + 1$) distinctive levels, while the connection of two conventional H-bridges yields 5 ($=2 \cdot n + 1$) voltage levels. The greater number of power switches,

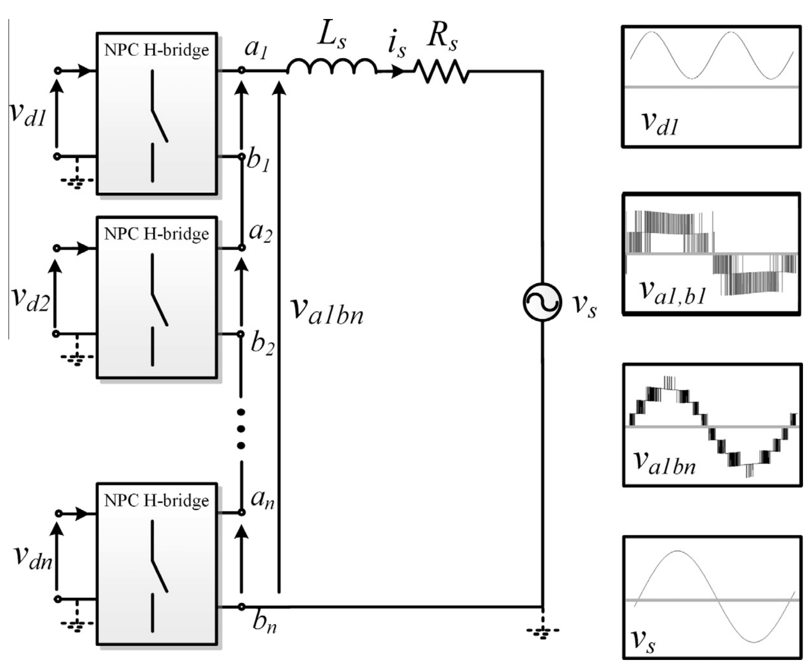

Fig. 1. Single-phase grid-tied cascaded full NPC bridges comprising n separate DC input sources.