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Operational limits of a three level neutral point clamped converter used for controlling a hybrid energy storage system

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ABSTRACT

This work analyses the use of a Three-Level Neutral Point Clamped (3LNPC) converter to control the power flow of a Hybrid Energy Storage System (HESS) and at the same time interconnect it with the common AC bus of a microgrid.

Nowadays there is not any storage technology capable of offering a high energy storage capacity, a high power capacity and a fast response at the same time. Therefore, the necessity of hybridising more than one storage technology is a widely accepted idea in order to satisfy the mentioned requirements.

This work shows how the operational limits of the 3LNPC converter can be calculated and integrated in a control structure to facilitate an optimal use of the HESS according to the rules fixed by the user.

1. Introduction

The Three-Level Neutral Point Clamped (3LNPC) converter is a type of DC–AC power conversion system that uses three DC bus voltage levels. A 3LNPC converter is considered especially interesting for medium-voltage high power applications due to its ability to reduce the voltage ratings of the semiconductor devices to the half in comparison to a typical two-level converter. Therefore, if the same power semiconductors are used in the three-level and two-level converters the DC bus voltage can be doubled in the three-level case, due to the reduction of the voltage applied to each semiconductor device. Assuming that the current is the same in both cases, the power of the three-level converter is thus doubled in comparison to the two-level converter's case [1–3].

A 3LNPC converter has many other advantages in comparison to the common two-level converter, namely a less distorted AC voltage generation, a reduced dv/dt of the output voltage due to the higher amount of DC levels, a smaller DC side current distortion and lower electromagnetic interference problems [1,4–6].

Nevertheless, the high amount of switches requires a more complicated control, and the use of more than one DC bus voltage level creates the well known neutral point voltage balancing issue [7,8].

The 3LNPC converters have been used in large motor drives like conveyors, pumps, fans, and mills, as well as in back-to-back configurations for regenerative applications like grid interfacing of Renewable Energy Sources (RES) [1,6,9].

However, in this work the use of a 3LNPC converter to control the power flow of a Hybrid Energy Storage System (HESS), topology that has been used in other works like [10–14], has been deeply analysed. The structure of the analysed system is shown in Fig. 1.

The use of a HESS is widely accepted as nowadays there is not any storage technology capable of offering a high specific energy, high specific power and a fast response capacity at the same time [15,16]. Therefore, it is common to associate a high specific power storage device with a fast response time and a high specific energy storage device. The power should be divided between both storage systems according to its frequency. The high frequency part should be faced by the high specific power storage device and the low frequency part by the high specific energy storage device. In this work a 3LNPC converter has been used to carry out this power division between a SuperCapacitor (SC) bank and a Vanadium Redox Battery (VRB), as shown in Fig. 1.

The VRB is a flow battery which has independent energy and power densities. It has a long life-cycle, up to 10000 charge/discharge cycles [17]. The VRB has theoretically no depth-of-discharge limitation and a good efficiency, between 75% and 85% [18,19]. Although the electrochemical response time of the VRB is under 0.5 ms [20], the response time of the VRB is limited by the flow of the electrolyte, which is controlled by pumps. As the electrochemical reaction occurs, it is necessary to introduce new

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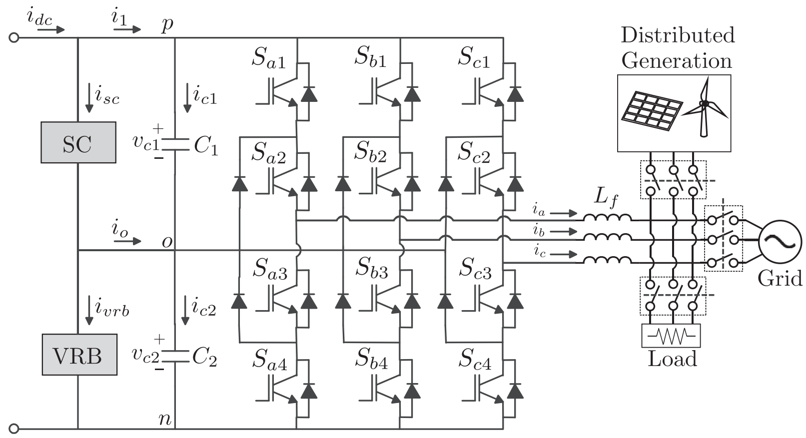

Fig. 1. Structure of a 3LNPC converter.

active species in the stack, and therefore the flow rate must be adapted to each reaction rate [21].

The use of a supercapacitor in parallel with the battery allows reducing the power rating of the VRB and thus also the cost. The supercapacitor stores the energy in electrical form, without converting it into any other kind of energy in order to save it. The most important advantages of a supercapacitor are its very high efficiency (95%), very high power density (up to 10000 W/kg), its tolerance to have deep discharges, and its very long life-cycle (500000 cycles at 100% depth-of-discharge) [22]. However, its energy density is very low and it has a high self-discharge rate (5% per day [23]). Thus, its use is not oriented for long-term applications.

The association of a SC and a VRB permits to take advantage of the characteristics of both ESSs obtaining a high energy density, high power density, high life-cycle and high efficiency HESS.

The novelty of this work in comparison to other research works that use the same topology [10–14] comes from the calculation of the operational limits of the 3LNPC converter and the integration of these limits in a control structure to facilitate an optimal use of the selected HESS according to the rules fixed by the user.

The work is divided as follows: Section 2 presents the effects of the DC voltage unbalances on the switching diagram of the 3LNPC converter. Section 3 presents first the average model of the 3LNPC converter and then, using this model, the operational limits of the selected topology are calculated and analysed. Finally, Section 4 presents the conclusions obtained from the present work.

2. Effect of neutral point voltage unbalances

Fig. 2 shows in the $\alpha\beta$ reference frame the 27 different vectors that a 3LNPC converter is able to generate. They are shown using black points. These vectors can be classified in five main groups: null (only *p*, *n* or *o* connections, 1, 14, 27), small upper redundant (no *p* connection, 2, 4, 5, 10, 11, 13), small lower redundant (no *n* connection, 15, 17, 18, 23, 24, 26) medium (*p*, *n*, *o* connections, 6, 8, 12, 16, 20, 22) and large vectors (no *0* connection, 3, 7, 9, 19, 21, 25) [24].

When the neutral point voltage is balanced, i.e. the two input sources have the same voltage value, the redundant upper and lower vectors are located in the same position, shown using black points in Fig. 2. However, when a voltage unbalance appears, the position of the redundant vectors changes. If $v_{c1} > v_{c2}$, the upper vectors move towards the large vectors in the direction of the red arrows,[1] while the lower vectors move towards the null vectors in the direction of the green arrows. The change of position of the switching vectors is the opposite when $v_{c1} < v_{c2}$.

Fig. 3 shows the configuration of the three-level converter in the case of small upper/lower redundant, medium and large vectors. In this configuration the AC loads have been represented by a three-phase balanced ideal current source system. Fig. 3a corresponds to a small upper redundant vector, Fig. 3b to a small lower redundant vector, Fig. 3c to a medium vector and Fig. 3d to a large vector.

A neutral point voltage unbalance will appear if the neutral point current i_o is different from zero. It can be seen from Fig. 3 that the configurations that can affect the neutral point voltage are the small redundant and medium vectors. Large vectors will not affect the neutral point unbalance, as the same current will flow through both storage devices charging or discharging them at the same rate.

Using the values of the load current i_{abc} of each configuration shown in Fig. 3, the DC side currents i_o, i_{sc} and i_{vrb} can be readily obtained (see Table 1).

The small redundant vectors affect the neutral point voltage. Nevertheless, they can be used in such a way that the average neutral point unbalance is null. For example, in the case of the *nno* (small upper redundant vector, 2) and *oop* (small lower redundant vector, 15) vectors, it can be seen from Fig. 2 that both create the same AC side voltage, as they are located in the same location in the space vector diagram. However, the configuration of the DC side is different in each case, as it is shown in Fig. 3a and b. From Table 1 it can be seen that the vector *nno* and *oop* create opposite i_o currents. Consequently, instead of using only one of them, if both are successively used during the same time, the average effect on the neutral point voltage will be null.

In the case of the medium vectors there is no possibility of controlling their effect on the neutral point voltage. Therefore, small redundant vectors must be used to compensate their effect [25,26].

In this work the redundant vectors have been used to control the power flow of the input storage devices. It can be seen from Table 1 that using the redundant vectors it is possible to control the i_o current. As the currents of the storage systems are related to this current, the control of i_o leads to the control of the currents of the storage devices as well.

2.1. Variation of the modulating signals

When the DC voltages are not equal, the modulating signals are modified in order to ensure a three-phase balanced and null zero-component AC voltage supply. In a sinusoidal PWM strategy this is satisfied changing the amplitude of the carrier signals following Eq. (1) [5].

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.