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New control method of a robust NPC converter for renewable energy sources grid connection

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ABSTRACT

This paper presents a new control strategy for the three-level, neutral point clamped (NPC), voltage source converter. The converter can be used in many high-power renewable energy systems such as direct drive wind turbines and hybrid generating units. The developed control algorithm proposes an improved solution to balance DC bus intermediate voltages using space vector modulation (SVM) techniques. It aims to guarantee fault ride-through (FRT) capabilities of renewable energy plants equipped with multilevel converters. Since the main attention of this paper is the grid side converter control, the energy generating system was simplified to an equivalent variable current source. The grid side converter is connected to the grid through an LCL filter. Two controllers were developed to achieve grid currents regulation. The first controller is based on PI-regulation. In the second case, linear quadratic Gaussian (LQG) control is investigated. The control of DC bus voltage is achieved by PI-regulation. Performances of the two controllers and the improved modulation technique are compared and evaluated in terms of accordance with the grid connection requirements (GCR) including, low voltage ride-through capabilities, frequency variation and reactive power control.

1. Introduction

In the last decades, renewable electricity sources have been one of the most growing industry in the field of electricity production [1]. Many countries worldwide have paid much more attention to these emerging renewable resources thanks to their economical and environmental benefits. In recent years, wind power accounts for around 40% of all new generation capacity across the EU and USA [2,3]. Actually, most of countries use high power class wind turbines to equip their new erected wind parks. This increased capacity production has presented more challenges for manufacturers to guarantee efficiency and reliability of their modern generating units. Indeed, adoption of flexible control strategies along with innovative configurations of power converters, make it possible to increase nameplate capacity of wind turbines. Among converter topologies, multilevel converters were one of the most successful configurations in wind industry. These converters constitute an alternative solution to extend the power and the voltage ranges of the classical two-level technology. They are suitable for high power applications since semiconductors are operated at a voltage level lower than the DC link voltage. Besides, as the amount of wind power feeding AC grids is increasing, more stringent interconnexion demands are required by the transmission system operators (TSOs). These requirements have mainly focused on power quality, low voltage ride-through capabilities and reactive power control. Different control strategies were designed in order to overcome technical challenges imposed by the GCR. The most common strategies are the vector current controllers with PI-regulators [4,5], the proportional-resonant (PR) controllers [4,6] and the deadbeat (DB) controller implemented in the abc abc frame [7]. Currently, these strategies are used in many distributed power generation systems and their capability to ride-through voltage dips was proven. However, these current controllers present necessarily an overshoot in their response when a voltage dips takes place in the grid. Therefore, power semiconductors are generally oversized to prevent the activation of current protections. For high power applications, it may be very expensive to oversize power converters. Therefore, this study proposes a new control algorithm for the three-level NPC converter. Based on LQG control, it aims to improve the transient response of grid connected converter during voltage dips. Its performances are compared with the classical PI-regulation strategy. A robust SVM scheme is used in order to ensure an effective control of DC bus intermediate voltages. SVM technique was adopted because it has a relatively easy hardware implementation and it aloows higher utilization of the DC-link voltage. Section 2 presents the converter and grid interface models. Section 3 is devoted to the design procedure of the LCL filter. PI-regulation method and LQG

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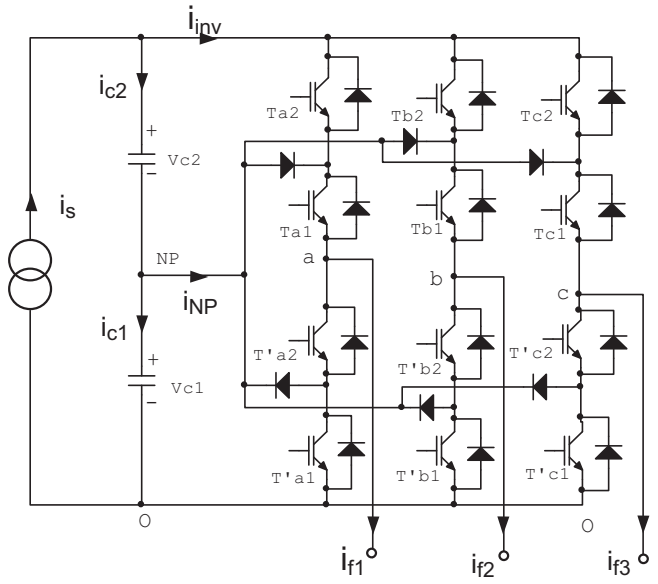

Fig. 1. Three level NPC inverter topology.

Table 1
Relationships in the three level NPC converter.

S_a	T_{a2}	T_{a1}	v_{ao}	$i_{NP,a}$
0	0	0	0	0
1	0	1	v_{c1}	i_{f1}
2	1	1	$v_{c1}+v_{c2}$	0

controller are respectively studied in the forth and fifth sections. Performances of the two controller are investigated in the sixth section. Section 7 presents the basics of the modified SVM technique. Finally, in the last section, the control algorithm behaviour is investigated during voltage dips and reactive power generation. The overall performances are evaluated in term of accordance with the GCR of the German TSO, E. ON NEtz.

2. System modelling

This section presents the grid side converter modelling, carried out in the three-phase system. Fig. 1 depicts the diode clamped inverter topology.

Table 1 gives for each state of the switching signals T_{a1} and T_{a2}, the corresponding output voltage v_{ao} for phase a and the corresponding neutral point current.

According to Table 1, output voltages $v_{(a,b,c)o}$ can be expressed by ($k \in \{a, b, c\}$):

$$v_{ko} = \sum_{j=1}^{j=2} T_{kj} v_{cj} \tag{1}$$

The phase-to-line inverter voltages are given by:

$$\begin{pmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{pmatrix} \tag{2}$$

Then, these voltages $V_i = [\, v_{an} \quad v_{bn} \quad v_{cn} \,]^T$ are related to the switching signals $T_1 = \begin{bmatrix} T_{a1} & T_{b1} & T_{c1} \end{bmatrix}^T$ and $T_2 = \begin{bmatrix} T_{a2} & T_{b2} & T_{c2} \end{bmatrix}^T$ by:

$$\begin{pmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} \sum_{j=1}^{j=2} T_{aj} v_{cj} \\ \sum_{j=1}^{j=2} T_{bj} v_{cj} \\ \sum_{j=1}^{j=2} T_{bj} v_{cj} \end{pmatrix} \tag{3}$$

Expression (3) can also be written as:

$$V_i = v_{c1} M_i T_1 + v_{c2} M_i T_2 \tag{4}$$

Here M_i is a matrix given by:

$$M_i = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}$$

Furthermore, Fig. 2 represents the control strategy of this converter. According to this figure, differential equations describing the LCL filter model are given by:

$$\begin{cases} L_1 \dot{I}_f = v_{c1} M_i T_{i1} + v_{c2} M_i T_{i2} - R_1 I_f - V_f \\ C_f \dot{V}_f = I_f - I_{gr} \\ (L_2 + L_{gr}) \dot{I}_{gr} = V_f - (R_{gr} + R_2) I_{gr} - E_{gr} \end{cases} \tag{5}$$

In relation (5), $I_f = \begin{bmatrix} i_{f1} & i_{f2} & i_{f3} \end{bmatrix}^T$ stands for the converter output currents, $V_f = \begin{bmatrix} v_{f1} & v_{f2} & v_{f3} \end{bmatrix}^T$ are the LCL filter capacitor voltages and $I_{gr} = \begin{bmatrix} i_{gr1} & i_{gr2} & i_{gr3} \end{bmatrix}^T$ are the grid currents. $E_{gr} = \begin{bmatrix} e_{gr1} & e_{gr2} & e_{gr3} \end{bmatrix}^T$ are the grid e.m.f. R_1 and R_2 represent the resistances of the filter inductances.

Moreover, according to Fig. 1 and Table 1, voltage ripples in the DC bus capacitors, v_{c1} and v_{c2}, are given by:

$$\begin{cases} C_{dc1} \dot{v}_{c1} = i_s - I_f^T T_1 \\ C_{dc2} \dot{v}_{c2} = i_s - I_f^T T_2 \end{cases} \tag{6}$$

Here i_s is the output current of the power source. C_{dc1} and C_{dc2} are the DC bus capacitors which are assumed equal and constant ($C_{dc1} = C_{dc2} = 2C_{dc}$).

3. LCL filter design

In order to attain power quality standards, grid current harmonics are reduced using an LCL filter. The design procedure for this filter is the same presented in [8]. Assuming lossless components and pure sinusoidal grid voltage, the harmonic model of this filter is depicted in Fig. 3.

X'_2 is the total impedance of the grid and the filter ($X'_2 = L'_2\omega = (L_2 + L_{gr})\omega$). According to this model, the transfer function from i_{gr} to v_i is obtained as:

$$\frac{i_{gr}(jh\omega)}{v_i(jh\omega)} = \frac{-j}{h\omega(-h^2\omega^2 L_1 L'_2 C_f + L_1 + L'_2)} \tag{7}$$

Based on (7), the resonant frequency is:

$$\omega_{res}^2 = \frac{1}{C_f} \frac{L_1 + L'_2}{L_1 \times L'_2} \tag{8}$$

This filter is used to reduce high frequency harmonics due to the switching of transistors. Assuming that the inverter is controlled by a SVM technique, voltage harmonics are centred around the switching frequency and its multiples. Hence, as a first design criterion, the