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Low-Voltage Ride-Through Capability of Cascaded H-Bridge Multilevel Converters for Large-Scale Photovoltaic Power Plants

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Abstract—Multilevel cascade H-bridge (CHB) converters are increasingly applied for large-scale grid-connected photovoltaic power plants (GCPVPPs) because of their improved quality of output voltage waveforms, high efficiency due to the elimination of the line frequency transformer and modular structure. On the other hand, due to the high penetration of the installed distributed generation units in the power system, low-voltage ride-through (LVRT) capability and injection of reactive power during voltage sags are becoming necessary for large-scale GCPVPPs. This paper studies the LVRT capability of the grid-connected CHB inverter of a GCPVPP during various voltage sag conditions. Active/reactive power injection to the grid is also considered according to grid codes. The performance of the grid-connected seven-level CHB with LVRT capability is investigated on a 10-MVA GCPVPP, connected to the 6.6 kV medium-voltage grid simulation model during various voltage sag conditions.

Index Terms—Photovoltaic systems, multilevel converter, cascaded H-bridge (CHB) converter, low-voltage ride-through (LVRT), active/reactive power injection, unbalanced voltage sag

I. INTRODUCTION

Renewable energy sources are occupying an increasing share in the global power generation market. Among various renewable energy sources, the photovoltaic (PV) technology has been in the focus of many governments and, supported substantial subsidies has resulted a steep increase in the installed capacity [1]. Due to the increasing tendency of installed grid-connected photovoltaic power plants (GCPVPPs), there is a requirement to use advanced converter topologies in combination with optimized control structures in order to maximize the extracted power and reduce the losses and complying with grid code and standards [2]–[4].

Among various converter topologies, the cascaded H-bridge (CHB) converter, shown in Fig. 1, is utilized for large-scale GCPVPPs in several studies [4]–[9], because:

- Switching frequency of each semiconductor can be decreased close to the fundamental frequency while the quality of the output voltage remains good. Therefore, semiconductor losses can be reduced, which leads to a higher power conversion efficiency.
- The bulky and expensive line-frequency transformer can be eliminated by increasing the number of levels and generating medium voltage level output which also eliminates the losses of the line-frequency transformer.

Fig. 1. Circuit configuration for a grid-connected PV power plant with CHB converter and isolated dc/dc converters.

- The use of multiple dc-links allows the implementation of multiple instances of maximum power point tracking algorithms in order to maximize the extracted power from all PV strings.

As depicted in Fig. 1, a dc/dc converter is used to connect the PV string to the dc-link. The dc/dc converter extracts the maximum power from the PV string to the dc-link. It should be mentioned that due to the second harmonic oscillation of the dc-link, the direct connection of the PV string to the dc-link, results to an oscillation in the extracted power from PV string. Additionally, the existed parasitic capacitance between each PV module and ground, results in a leakage current due to the common mode voltage and can cause safety and protection issues. In order to get rid of the leakage current, isolated dc/dc converters with various topologies considered in CHB [2], [10]–[12].

Several investigations on the power balance [13], [14] and bridge failure [8] of GCPVPPs with CHB have been performed in the literature. However, due to the drastic increase of the installed GCPVPPs in the power system, new standards and

grid-codes regulate low-voltage ride-through (LVRT) requirement in order to withstand voltage sags and maintain the connection to the grid and avoid loss of power generation [15]. Additionally, reactive power injection during voltage sags is also required to enhance the voltage of point of common coupling (PCC). Several studies have been performed on LVRT capability of single- and two-stage GCPVPPs considering the injection of balanced active/reactive currents to the grid during voltage sags [16]–[18]. The injection of balanced currents during unbalanced voltage sags results in the oscillation of injected active/reactive power which leads to the oscillation of the dc-link voltage. Accordingly, unbalanced current injection is introduced with the aim of peak current limitation [19] and oscillating power control [20]–[22].

Several algorithms are introduced for calculation of balanced/unbalanced current references during voltage sags [16], [17], [19]–[24]. However, the implementation of the injection of such balanced/unbalanced currents on the grid-connected CHB inverters is challenging during voltage sags and has not been investigated in the literature. The purpose of this paper is to study the LVRT capability of the grid-connected CHB inverter of a GCPVPP. An algorithm for the calculation of the balanced/unbalanced current references is implemented which complies with grid codes and inverter current limitations. Also, the performance of the GCPVPP under balanced and unbalanced current injection algorithms is investigated and the results are compared with each other.

The rest of the paper is organized as follows. Section II provides an overview of the requirements of grid codes during voltage sags for active/reactive power injection during voltage sags. The detailed implementations of the proposed active/reactive power controller of the grid-connected CHB during voltage sags is described in Section III. Simulation results of the performance of the proposed controller for balanced/unbalanced current injection during various voltage sag conditions on a 10-MVA GCPVPP with CHB are illustrated in Section IV and the conclusions of the work are summarized in Section V.

II. GRID-CODE REQUIREMENTS AND ACTIVE/REACTIVE POWER INJECTION DURING GRID VOLTAGE SAGS

Grid codes regulate reactive power injection to the grid during voltage sags in order to enhance the voltage of the point of common coupling (PCC) during these events. The requirement of grid codes for reactive current (I_q) is [15]:

$$I_q^* = \begin{cases} 0, & 0.9 \text{ pu} \leq \hat{V}_{min} < 1.1 \text{ pu} \\ k \frac{\Delta V}{\hat{V}_N} I_{N_{dq}} + I_{q0}, & 0.5 \text{ pu} \leq \hat{V}_{min} < 0.9 \text{ pu} \\ -I_N + I_{q0}, & \hat{V}_{min} < 0.5 \text{ pu}, \end{cases} \quad (1)$$

where $\hat{V}_N$ is the nominal amplitude of the PCC phase voltage and $\Delta V = \hat{V}_{min} - \hat{V}_N$. It should be noted that $\hat{V}_{min}$ is calculated instantaneously over time through the controller. $I_{N_{dq}}$ denotes the transformed nominal inverter current to dq-coordinate ($I_{N_{dq}} = \sqrt{3}I_N$, where I_N is the nominal rms

Fig. 2. Proposed active/reactive power control of the grid-connected CHB during voltage sags

current of the inverter). I_{q0} is the initial reactive current of the inverter before the voltage sag. k is a constant value defined according to the agreement between power system operator and power producer and is usually larger or equal to 2 [15]. In this study, k is considered to be 2.

According to (1), for voltage sags with amplitude smaller than 0.5 pu (referred as *Sag II* in this paper), the injected reactive current is equal to the nominal current of the inverter. Therefore, no active current can be injected to the grid and the extracted power from PV strings should be reduced to zero. During voltage sags with amplitude between 0.5 pu and 0.9 pu (*Sag I*), I_q is smaller than $I_{N_{dq}}$. Therefore, the inverter is able to simultaneously inject active and reactive powers to the grid. The possible injected active current is computed based on the nominal current rating of the converter as:

$$I_d^* = \sqrt{I_{N_{dq}}^2 - I_q^{*2}}. \quad (2)$$

where I_d^* is the amplitude of d-axis current of the inverter which is related to the active power of the inverter.

According to the instantaneous power theory, the injected positive and negative sequence voltage currents to the grid for GCPVPP during unbalanced voltage sags are [25]:

$$i_{abc}^{+*} = \frac{k_1 P^* - j k_2 Q^*}{|v_{pcc}^+|^2} v_{pcc}^+ \quad (3)$$

$$i_{abc}^{-*} = \frac{(1 - k_1) P^* + j(1 - k_2) Q^*}{|v_{pcc}^-|^2} v_{pcc}^-, \quad (4)$$

where v_{pcc}^+ and v_{pcc}^- are the three-phase PCC positive- and negative-sequence voltage vectors, while i_{abc}^+ and i_{abc}^- are the inverter positive- and negative-sequence current vectors. k_1 and k_2 are the ratios of the positive-sequence active or reactive power to the total active or reactive power ($k_1 = \frac{P^+}{P}$ and $k_2 = \frac{Q^+}{Q}$), where Q is the average reactive power and Q^+ is

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value
Three phase nominal power	P_{nom}	10 MW
Grid voltage	v_{pcc-ll}	6.6 kV _{rms}
Inductor filter	L_f	5 mF
dc-link voltage	V_{dc}	2.2kV
dc-link capacitor	C	10mF
Carrier frequency	f_{car}	600 Hz
Switching frequency	f_{sw}	3600 Hz

its positive-sequence. P^* and Q^* are the average active and reactive power references and can be calculated from dq-axis current references.

By setting $k_1 = 1$ and $k_2 = 1$ in (4), the negative sequence current reference is equal to zero which results in the injection of the balanced current to the grid during unbalanced voltage sags. The values of k_1 and k_2 can be computed in order to achieve zero active or reactive power oscillation. In this paper, zero active power oscillation during unbalanced voltages sags is considered in order to reduce the dc-link voltage oscillation of the CHB inverter.

III. PROPOSED CONTROLLER FOR GRID-CONNECTED CHB DURING VOLTAGE SAGS

A comprehensive schematic of the proposed current controller is illustrated in Fig. 2. During grid normal operation ($0.9 \text{ pu} \leq \hat{V}_{min} < 1.1 \text{ pu}$), referred as *Normal*, the inverter should inject active power to the grid under unity power factor operation. Therefore, I_q^* is set to zero and I_d^* is realized by controlling the dc-link voltages. In this condition, the calculated P^* is adjusted to the total extracted power from PV strings. During voltage sags, the dq-axis current references are calculated according to the grid code requirements (1) and current limitation of the inverter (2). Subsequently, the active and reactive power references are calculated based on the instantaneous PCC voltages.

As depicted in Fig. 2, the values of k_1 and k_2 are calculated based on the PCC voltage positive and negative sequences. Two different methods for setting the values of k_1 and k_2 are considered in this study:

Balanced current injection: In order to achieve balanced current injection during all different types of voltage sags, the current negative sequence is set to zero by setting $k_1 = 1$ and $k_2 = 1$. It should be considered that since the full current capacity of the inverter is utilized in this study, the amplitude of the injected currents in all three phases, during voltage sags, are equal to the amplitude of the nominal current of the inverter.

Zero active power oscillation: In order to reduce the dc-link voltage oscillation, the values of k_1 and k_2 are calculated dynamically based on the PCC voltage positive and negative sequences with the aim of zero active power oscillation.

Fig. 3. Normal operation of grid-connected CHB: (a) inverter output phase voltage (v_{inv-a}) and (b) fast fourier transformation of v_{inv-a}

Subsequently, the current positive and negative sequence references are calculated according to (3) and (4) and converted to their equivalent values in abc coordinate. Since the unbalanced current injection during voltage sags is intended in this study, individual proportional resonant (PR) current controllers with anti-windup are implemented on each phase. Although, the implementation of the conventional PI controller for balanced current injection is simple, it requires multiple frame transformation and results in slow performance. On the other hand, for injection of proper unbalanced currents under unbalanced voltage sags, the calculation of both positive- and negative-sequence voltages in dq frame is required which increases the computational complexity [26], [27]. The PR controller with anti-windup shows faster dynamic response and zero steady-state error [28], [29]. Finally, phase-shifted pulse-width modulation is applied for generating the switching signals of the CHB inverter, based on [13].

IV. EVALUATION RESULTS

The GCPVPP with CHB inverter (Fig. 1) is modelled and developed using Matlab/Simulink© and PLECS toolbox. The parameters of the simulated three-phase, seven-level CHB converter are listed in Table I. Based on [13], [14], the capacitor voltage of each H-bridge was regulated to be constant at 2200 V with a capacitance value of 10 mF. With three bridges in each phase, the converter is able to connect to the 6.6 kV distribution network directly, without a line-frequency power transformer. In real applications the capacitor voltage could be lower if more H-bridges were introduced. The multilevel waveform synthesis allows the switching frequency to be as

Fig. 4. Operation of grid-connected CHB during *Sag I* with *Balanced current injection*: (a) Three-phase grid voltages, (b) inverter three-phase currents and (c) injected active/reactive power

Fig. 5. Operation of grid-connected CHB during *Sag I* with *Zero active power oscillation*: (a) Three-phase grid voltages, (b) inverter three-phase currents and (c) injected active/reactive power

low as 600 Hz, thus greatly reducing the switching losses. Initially the steady state performance of the CHB is evaluated and subsequently, the proposed controller has been evaluated under two different cases corresponding to *Sag I* and *Sag II* of Section II.

Steady state: The output phase to neutral voltage of the seven-level CHB (v_{inv-a}) is depicted in Fig. 3(a). It can be seen that the output voltage includes seven voltage levels. The amplitudes of Fast fourier transform (FFT) are shown in Fig. 3(b). It can be easily seen the amplitudes of FFT are significant around frequency of 3600 Hz which shows the overall switching frequency of the converter is equal to 3600 Hz. It should be mentioned that switching frequency of each semiconductor switch is kept at 600 Hz which reduces the overall switching losses of the grid-connected CHB.

Sag I: It includes 27% single-phase voltage sag for a duration of 150 ms, between $t = 0.05$ s and $t = 0.2$ s, as shown in Fig. 4(a). Initially, the performance of *Balanced current injection* strategy is investigated and results are presented in Fig. 4. It can be seen that before $t = 0.05$ s, the CHB inverter operates at *Normal* condition and there is no phase-shift between the PCC three phase voltages and injected current of

the inverter. Consequently, as shown depicted in Fig. 4(c), the inverter injects purely active power to the grid and the amount of the injected reactive power is zero in this condition. At $t = 0.05$ s, due to the occurrence of the voltage sag in the grid, the operation mode of the inverter is changed to *Sag I*. According to (1), the GCPVPP injects both active and reactive powers to the grid. Since the aim of the controller is *Balanced current injection*, the injected currents are remained balanced under this condition. There is an oscillation in the injected active power to the grid in this condition. Also it should be noted that due to the current limitation of the inverter, the average amount of injected active power is reduced during *Sag I*.

The performance of the proposed controller with *Zero active power oscillation* during *Sag I* is presented in Fig. 5. The amplitude of the injected current to phase a, which is under voltage sag, is kept as nominal inverter current. However, in order to achieve zero active power oscillation, the value of k_1 is increased to 1.011 and the value of k_2 is reduced to 0.989. It can be seen that as a result of negative sequence injection, no oscillation exists in the injected active power to the grid. After the clearance of voltage sag in the grid, the inverter is

Fig. 6. Operation of grid-connected CHB during *Sag II* with *Balanced current injection*: (a) Three-phase grid voltages, (b) inverter three-phase currents and (c) injected active/reactive power

recovered to its *Normal* operation and the injected reactive current is reduced to zero.

Sag II: It consists of a two-phase voltage sag of 60% as shown in Fig. 6(a). Phases b and c experience the voltage amplitude of 40% of the nominal one. The performance of proposed controller with *Balanced current injection* is depicted in Fig. 6. During this voltage sag condition, only reactive power is injected to the grid according to (1). Therefore, the average amount of the injected active power is reduced to zero. However, due to the balanced current injection of the inverter during unbalanced voltage sag, there is an oscillation in the active power.

The performance of the proposed controller with *Zero active power oscillation* during *Sag II* is depicted in Fig. 7. The amounts of k_1 and k_2 , which are equal to 1 during *Normal* operation mode, are changed to 1.13 and 0.897, respectively. Therefore, unbalanced current, which includes negative sequence is injected to the grid. The injected current to the phase with smaller voltage is larger than other phases. Consequently, no oscillation exists in the active power. It should be noted that due to the fast performance of the PR current controller, no spikes exist in the injected current of the inverter and current

Fig. 7. Operation of grid-connected CHB during *Sag II* with *Zero active power oscillation*: (a) Three-phase grid voltages, (b) inverter three-phase currents and (c) injected active/reactive power

reaches its steady state during voltage sag in a duration smaller than one voltage period.

V. CONCLUSION

This paper studies the low-voltage ride-through (LVRT) capability of the grid-connected cascaded H-bridge (CHB) inverter of a large-scale grid-connected photovoltaic power plant (GCPVPP). Two algorithms for the injection of active and reactive powers to the grid during voltage sags are introduced, which comply with grid codes and inverter current limitations. The full current capacity of the inverter is utilized by injecting balanced currents to the grid during voltage sags, however, there is an oscillation in the injected active power which results in the dc-link voltage oscillation. Zero active power oscillation is achieved by the injection of proper unbalanced currents to the grid. In this control strategy, the current of the phase with smallest voltage is kept as the nominal inverter current and the current of other phases are smaller. Detailed implementation of the proposed control schemes for the grid-connected CHB has been presented, and their effectiveness are demonstrated and compared through simulation results on a seven-level CHB of a 10-MVA GCPVPP. The results show the LVRT capability of

the grid-connected CHB with the proposed controller, which makes it interesting for large-scale GCPVPPs.

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