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Study on the Unbalanced Current Injection Capability of Grid-Connected Photovoltaic Neutral-Point-Clamped Inverter

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Abstract—Due to high penetration of distributed generation units in power system, fault ride through (FRT) capability is one of the new requirements of the medium-scale grid-tied photovoltaic power plants (PVPPs). This paper proposes and investigates a control strategy for the neutral-point-clamped (NPC) inverter in order to inject proper unbalanced reactive currents to the grid during unbalanced grid faults. The proper unbalanced current injection reduces negative sequence of grid voltages and currents. The current references are scaled up/down individually, based on the grid phase rms voltages and inverter nominal current. The performance of the implemented control algorithm is investigated on a 150-kVA PVPP connected to 12.47-kV medium-voltage grid simulation model under various voltage sag conditions. Results from an experimental setup of grid-tied NPC inverter are presented in order to demonstrate the effectiveness of the proposed unbalanced current injection algorithm.

Index Terms—Fault-ride-through capability, photovoltaic power plant, three-leg four-wire grid connected neutral-point-clamped inverter, unbalanced reactive current injection, proportional resonant controller, three-dimensional space vector modulation.

I. INTRODUCTION

With high penetration of distributed generation (DG) units, the power system operators (PSOs) are facing new challenges such as reliability, availability and power quality. Among various DG units, photovoltaic power plants (PVPPs) have recently achieved a drastic increase in the installed capacity, due to the governments policies and low photovoltaic (PV) manufacturer costs [1]. PSOs have regulated new and stricter standards and grid codes in order to maintain the power quality and reliability of the grid. Fault ride through (FRT) capability is one of the main requirements of the new grid codes and standards for medium- and large-scale PVPPs. Also, DG units connected to the medium-voltage (MV) grid are required to inject reactive power to the grid during voltage sags [2]–[4].

The FRT capabilities of single- or two-stage PVPPs are investigated in several studies [5]–[8]. In most cases, a balanced current injection scheme is considered for the grid-tied inverter under all voltage sag conditions (balanced or unbalanced). However, unbalanced voltage sags, which are more common in power systems, result in voltage and current

negative sequences in the grid. Therefore, the injection of proper unbalanced currents (with negative sequence) to the grid can result in a better grid voltage enhancement, compared to the injection of balanced currents. Negative sequence current injection control could be implemented for the next generation of grid-tied PVPPs in order to reduce the grid negative sequence voltages/currents and maintain the phase voltages within standard ranges [9]–[14].

A multi-string PVPP structure consisting of a single dc-link and a three-level neutral-point-clamped (NPC) inverter is implemented for medium-scale PVPPs [15]. The FRT capability of the multi-string PVPP with NPC inverter is studied considering balanced reactive current injection during voltage sags [16]. A proportional-resonant (PR) controller in combination with adaptive space-vector modulation (ASVM) has been applied for the grid-tied three-leg three-wire NPC inverter [17]. In the three-wire structure, the phase currents depend of each other and it is not suitable for the independent unbalanced current injection. In this paper, a three-leg four-wire (3-leg 4-wire) NPC inverter is considered for the grid-connected medium-scale PVPP. This structure is able to inject suitable unbalanced currents to the grid, which reduces the grid voltage and current negative sequences.

Three-dimensional space-vector modulation (3-D SVM) is required for the three-leg four-wire NPC inverter. Various methods for the implementation of the 3-D SVM are reported in the literature, where most of them are implemented in $\alpha\beta$ frame [18], [19]. In this paper, the 3-D SVM, implemented in abc frame, is employed for the 3-leg 4-wire NPC inverter. The proportional resonant (PR) current controller is also implemented in the abc frame in order to obtain the independent unbalanced current control ability of the inverter. The application of the PR controller results in faster dynamic performance and lower steady state error compared to the conventional PI controller [20], [21]. The abc frame current references are scaled up/down in order to calculate the proper unbalanced current references. Additionally, the calculated reference voltages from the PR controllers can be fed into the 3-D SVM directly, without the need of an additional frame transformation.

Fig. 1. (a) Circuit diagram of the four-wire multi-string PVPP with NPC inverter and (b) proposed unbalanced current injection control algorithm with 3-D SVM in abc frame

The rest of the paper is organized as follows. Section II provides an overview of the GCPVPP structure, while the implementation details of the proposed unbalanced current injection algorithm are discussed in Section III. The performance of the proposed controller is simulated on the 150-kVA PVPP connected to a 12.47-kV medium-voltage grid during various unbalanced grid faults, and results are presented in Section IV. An experimental setup of the grid-tied NPC inverter was constructed and the results are provided in Section V to demonstrate the effectiveness of the proposed control structure. Finally, the conclusions of the work are summarized in Section VI.

II. PHOTOVOLTAIC POWER PLANT STRUCTURE

A comprehensive representation of the multi-string PVPP structure, having the unbalanced current injection capability, is depicted in Fig. 1(a). It consists of PV strings, dc/dc converters, a central grid-tied NPC inverter and a step-up YY transformer. The detailed configuration of the PV strings and dc/dc converters has been presented in [16]. The neutral point of the transformer is connected to the midpoint of the dc-link in order to achieve the unbalanced current injection capability to the point of common coupling (PCC). The transformer

also provides the electrical isolation between the grid and PVPP, which eliminates the possible earth leakage current and ensures standard safety requirements. The LCL filter is designed based on the switching frequency, dc-link voltage and modulation index according to the procedure introduced in [22].

III. CONTROL ALGORITHM FOR UNBALANCED CURRENT INJECTION OF THE GRID-TIED NPC INVERTER

The schematic of the implemented control algorithm with unbalanced current injection ability is depicted in Fig. 1(b). The stationary frame current references (I_a^* and I_b^*) are calculated based on the grid condition (normal or fault), PCC voltages (v_{an} , v_{bn} and v_{cn}) and dc-link capacitor voltages (v_{c-u} and v_{c-l}). During normal operation, the inverter output power (P_{inv}) is adjusted to the total power extracted from PV strings, while the dc/dc converters extract maximum available power from all PV strings. After detecting the voltage sag by monitoring the grid voltage amplitude, the NPC controller should be modified in order to inject the required reactive current according to the voltage sag level and grid code. The details of the active/reactive power reference calculation method are presented in [16]. During the voltage sag, the dc/dc

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value
Apparent power	S	150 kVA
PCC line-line voltage	v_{pcc-ll}	12.47 kV _{rms}
dc-link voltage	V_{dc}	700 V _{dc}
dc-link capacitor	C_u / C_l	2.2 mF
Fundamental frequency	f_0	50 Hz
3L-NPC switching frequency	f_s	3.6 kHz
dc/dc converter switching frequency	$f_{s-boost}$	10 kHz
dc/dc converter inductor	L	1 mH
LCL filter inverter-side inductor	L_{f-1}	1 mH
LCL filter grid-side inductor	L_{f-2}	0.5 mH
LCL filter capacitor	C_f	30 μ F

converters adjust the dc-link voltage to its nominal reference by adjusting the total extracted power from PV strings to the injected active power to the grid.

Subsequently, the calculated current references (I_α^* and I_β^*) are transformed to the abc frame through the inverse Clark transformation. In order to inject the proper unbalanced current to the grid during unbalanced voltage sags, the abc frame current references (I_{a0}^* , I_{b0}^* and I_{c0}^*) are scaled up/down based on the rms amount of their voltages. The current reference of the phase with smallest voltage is scaled up to the inverter nominal current. If other phases are also experiencing voltage sag, their current references are scaled up based on their voltage amplitude. On the other hand, current reference of the healthy phases are scaled down by the inverse factor of the phase with smallest voltage. For instance if there is a single-phase voltage sag in phase a , while phases b and c are operating at normal condition, the reactive current reference of phase a (I_{a0}^*) is scaled up by a factor (K_s) to the nominal inverter current. Accordingly, the current reference of phases b and c are scaled down by factor of $1/K_s$. This method results in zero active power oscillation in the output of the inverter during unbalanced voltage sags. Also, it prevents the healthy phases from over voltage, which can occur due to the injection of reactive current into healthy phases.

The abc current errors are obtained by subtracting the scaled current references (I_a^* , I_b^* and I_c^*) with the phase currents (i_a , i_b and i_c). Finally, the abc frame voltage references (V_a^* , V_b^* and V_c^*) are derived from three independent PR controllers. The calculated abc reference voltages are then fed into the 3D-SVM technique, which the details of its implementation are presented in [23].

IV. SIMULATION RESULTS

A 150-kVA multi-string PVPP, shown in Fig. 1(a), is modelled using Matlab/Simulink© and PSIM software. Three parallel PV strings are connected to the dc-link of the grid-connected NPC inverter to investigate the FRT capability of the proposed unbalanced current injection algorithm under various irradiances and temperatures. Different amounts of irradiation and temperature are induced for the PV strings where String I ($I_r = 1 \text{ kW/m}^2$, $T = 25^\circ\text{C}$), String II ($I_r = 0.5 \text{ kW/m}^2$,

Fig. 2. Simulation results. *Cond I* – single-phase voltage sag (45%): (a) PCC three phase voltages at the beginning of the voltage sag, (b) injected currents to the grid at the beginning of the voltage sag, (c) injected active/reactive power to the grid, and (d) extracted power from PV strings.

$T = 25^\circ\text{C}$) and String III ($I_r = 1.1 \text{ kW/m}^2$, $T = 35^\circ\text{C}$). The PVPP is connected to a medium voltage grid test case, adopted from the network model that was introduced in [24]. The grid voltage is 12.47 kV and the PVPP is connected to Bus 3. The parameters of the simulation setup are listed in Table I.

The behavior of the multi-string PVPP is examined under single-phase fault (45% voltage reduction in phase a), referred as *Cond I*, and results are depicted in Fig. 2. Before $t = 0.5 \text{ s}$, the grid is operating at normal condition. During this period,

Fig. 3. Simulation results. *Cond II* – two-phase voltage sag (32%): (a) PCC three phase voltages at the beginning of the voltage sag, (b) injected currents to the grid at the beginning of the voltage sag, (c) PCC three phase voltages after the clearance of the voltage sag, (d) injected currents to the grid after the clearance of the voltage sag,

the injected inverter currents have the same phase than their respective phase voltages. After $t = 0.5$ s, there is a single phase fault in Bus 11, which results in a single-phase voltage sag in phase a at the PCC. The inverter injects reactive current to the grid and it can be seen that there is a phase shift between phase currents and voltages ($\phi \approx \pi/2$). On top of that, due to the proper operation of the unbalanced current controller, the currents of phase b and c (i_b and i_c) are smaller than i_a . The injected active and reactive powers are shown in Fig.

Fig. 4. Experimental setup of the grid-connected NPC inverter

TABLE II
EXPERIMENTAL PARAMETERS

Parameter	Symbol	Value
PCC phase-neutral voltage	$v_{pcc-abc}$	50V _{rms}
dc-link voltage	V_{dc}	130 V _{dc}
dc-link capacitor	C_u/C_l	2.2 mF
Fundamental frequency	f_0	50 Hz
NPC switching frequency	f_s	1.5 kHz
LCL filter inverter-side inductor	L_{f-1}	12 mH
LCL filter grid-side inductor	L_{f-2}	6 mH
LCL filter capacitor	C_f	18 μ F

2(c). The amount of injected reactive power is zero during the grid normal operation, however during *Cond I*, the inverter injects reactive power to the grid. The extracted power from PV strings is reduced to zero during the grid fault through the dc/dc converters in order to maintain the dc-link voltage within its nominal range.

A two-phase to ground fault occurs in Bus 8 in *Cond II* simulation setup. This fault results in a 32% voltage sag in phases b and c at the PCC, as illustrated in Fig. 3(a). The injected current to phases b and c are larger than phase a , which demonstrates the unbalanced current injection capability of grid-connected NPC inverter through the proposed unbalanced current injection algorithm. The behavior of the implemented controller after the fault clearance is depicted in Fig. 3(c) and (d). The fault is cleared at $t = 1.5$ s and currents are recovered to the balanced condition in less than two voltage periods.

V. EXPERIMENTAL EVALUATION

The performance of the implemented control algorithm is experimentally evaluated on a three-phase NPC converter setup, shown in Fig. 4. A programmable AC power supply (Chroma 61511) is employed to emulate the grid, including various voltage sags. The Chroma programmable DC source (62024P-600-8) is employed to emulate the PVPP structure

Fig. 5. Experimental results. *Case study I* – two-phase voltage sag (25%): (a) PCC three phase voltages, (b) PCC phase *a* voltage and three phase currents with balanced current injection and (c) PCC phase *a* voltage and three phase currents under unbalanced current injection.

and generate the required voltage and current in the dc-link. The controller and protection functions are implemented in a dSPACE RT1103 platform. The parameters of the laboratory setup are listed in Table II.

A two-phase voltage sag in phases *b* and *c* is implemented in *Case study I*, shown in Fig. 5(a). Firstly, the controller is adjusted to inject balanced reactive currents to all phases, as shown in Fig. 5(b). This is realized by deactivating the rescaling function in the algorithm. The rms values of three phase currents are approximately equal, with a phase shift of $\phi \approx \pi/2$ between the current and voltage of each phase.

Fig. 6. Experimental results. *Case study II* – single-phase voltage sag (25%): (a) PCC phase *a* and *b* voltages and currents under balanced current injection, (b) PCC phase *a* and *b* voltages and currents under unbalanced current injection.

Subsequently, the controller is modified in order to inject the proper unbalanced currents to the grid, as presented in Fig. 5(c). The injected reactive currents to phases *b* and *c* (with voltage sag) are smaller than the injected current to phase *a* (without voltage sag).

A 25% single-phase voltage sag occurs in phase *a*, as demonstrated in Fig. 6. Firstly, the controller is implemented to inject the balanced reactive currents to the grid and the rms values of the injected currents are approximately equal, as shown in Fig. 6(a). Secondly, the controller is adjusted to inject the unbalanced reactive currents to the PCC. From Fig. 6(b), it is evident that the injected reactive current in phase *a* (with voltage sag) is higher than the injected current to phase *b* (without voltage sag). Experimental results show the validity of the proposed unbalanced current injection algorithm under various unbalanced grid faults.

VI. CONCLUSION

The unbalanced current injection capability of the grid-connected three-leg four-wire neutral-point-clamped (NPC) inverter of photovoltaic power plant (PVPP) has been studied in this paper. A voltage oriented control using the proportional-resonant controller in conjunction with the three-dimensional space vector modulation technique is implemented. In order to inject the proper unbalanced reactive currents to the grid

during unbalanced faults, the abc current references have been scaled up/down according to the rms value of the voltage of the respective phases. The effectiveness of the unbalanced current injection algorithm is demonstrated through simulation results on a 150-kVA PVPP connected to 12.47-kV medium-voltage test-case system under various voltage sag conditions. Experimental results on a laboratory NPC setup have been presented, showing the validity of the proposed control strategy.

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