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Study on the Low-Voltage Ride-Thorough Capability of Photovoltaic Grid-Connected Neutral-Point-Clamped Inverters with Active/Reactive Power Injection

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Abstract: Low-voltage ride-through capability is among the challenges in the operation of medium- and large-scale grid-connected photovoltaic power plants (PVPPs). Additionally, reactive power injection during voltage sags is required by power system operators in order to enhance the voltage of the point of common coupling (PCC). This paper studies the performance of medium- and large-scale grid-connected PVPPs during these events. An algorithm for the calculation of current references, in the dq-frame, during voltage sags is introduced, which considers the inverter current limitation, grid code requirements and the amount of extracted power from photovoltaic strings. The proposed algorithm uses the full current capacity of the inverter in injecting active or reactive powers to the grid during voltage sags, which leads in a better grid voltage enhancement. The performance of proposed control strategies is investigated on a 150-kVA PVPP connected to the 12.47-kV medium-voltage test-case system simulation model during different fault conditions. An experimental setup of the 3.3-kVA grid-connected three-level neutral-point-clamped inverter with a dc/dc converter illustrates and validates the performance of the controller in injecting required active/reactive power and supporting the network voltage.

1. Introduction

Renewable energy sources are occupying an increasing share in the global power generation market. Among various renewable energy sources, photovoltaic (PV) technology has been in the focus of many governments and, supported substantial subsidies has resulted a steep increase in the installed capacity. Moreover, with the decreasing trend in the PV panel costs from \$4.90/ W_{pk} in 1998 to \$0.3/ W_{pk} in 2015, the rate of growth of new PV installations is expected to remain on a high level. Predictions indicate that the rate of growth of solar energy will be 7 to 8 times more than that of wind energy by 2030 [1–3]. With high penetration of installed distributed generation (DG) units, power system operators (PSOs) are facing new challenges such as reliability, availability and power quality. In order to maintain power quality and reliability of the power system, medium- and large-scale photovoltaic power plants (PVPPs) should possess low-voltage ride-through (LVRT) capability, as regulated by new standards and grid codes. Therefore, improved PVPP structures with LVRT capabilities in combination with efficient control strategies are necessary.

A typical two-stage multi-string PVPP consists of a dc/dc converter in each PV string and one central inverter. It is commonly recognized as one of state of the art configurations for medium- and large-scale PVPPs, due to its inherent advantages [4–12].

Multilevel converters have emerged as the most viable solutions for high power energy conversion applications due to their capability of delivering excellent power quality with low harmonic contents and better efficiency, compared to the two-level converters. Therefore, multilevel converters have been proposed and discussed for multi-string PVPPs [13, 14]. A multi-string PVPP structure with combination of a single dc-link and three-level neutral-point-clamped (3L-NPC) inverter was introduced [15, 16], which is suitable for extraction of maximum power from PV strings during various partial shading of PV strings because of its single dc-link and paralleled connection of PV strings.

Several studies have been performed on LVRT capability of single- and two-stage PVPPs considering the injection of balanced active/reactive currents to the grid during voltage sags [17–19]. Moreover, various methods are presented for the injection of unbalanced currents to the grid during unbalanced voltage sags [20–23]. These studies have proposed different algorithms for calculating the current references (balanced or unbalanced) according to a certain amount of active/reactive power references, which are empirically determined only based on the rated apparent power of the inverter [17–23]. However, if the nominal apparent power of the inverter is considered during voltage sags, due to the smaller voltage amplitude of the grid, the amplitude of the calculated current references will be larger than the nominal current of the inverter. On the other hand, by setting the active/reactive power references to a fixed value which is smaller than the nominal apparent power of the inverter, during voltage sags, the full current capacity of the inverter is not utilized in enhancing the grid voltage.

Based on the scenario described above, this paper proposes an algorithm for calculating dq-axis current references during voltage sags based on inverter current limitation, grid code requirements and the amount of extracted power from PV strings. The proposed method ensures that the full current capacity of the inverter is used in injecting active/reactive power to the grid during voltage sag in order to enhance the grid voltage during voltage sags. In order to obtain a constant dc-link voltage and maintain the active and reactive power injection during voltage sags, a coordinated maximum power point tracking (MPPT) algorithm is also implemented for the dc/dc converters of the multi-string PVPP, which reduces the extracted power from PV strings to the amount of active power that can be injected to the grid according to the inverter nominal current and the injected reactive current.

The rest of the paper is organized as follows. The multi-string PVPP structure is explained in Section 2. A brief description of the grid code requirements along with the detailed implementations of the proposed dq-coordinate current reference calculation, current controller and implemented method for controlling the dc-link voltage during grid voltage sags are presented in Section 3. Simulation results of the performance of the proposed controller on a 150-kVA multi-string PVPP during various voltage sag conditions along with the obtained voltage enhancements of the point of common coupling (PCC) are illustrated in Section 4. Experimental results on a 3.3-kVA laboratory grid-connected 3L-NPC are provided in Section 5 and the conclusions are summarized in Section 6.

Fig. 1. Grid-connected multi-string PV power plant

2. Multi-string PV power plant structure

A schematic representation of the proposed multi-string PVPP structure having LVRT capabilities is depicted in Fig. 1. It consists of multiple PV strings, dc/dc converters and a central grid-connected 3L-NPC inverter. Due to its inherent advantages, as follows, the multi-string PVPP structure is considered in this study for medium- and large-scale PVPPs [4–12].

- The maximum power from all PV strings can be extracted during all environmental conditions. In the single-stage power conversion topology with a central inverter, the mismatch between PV strings, resulted from clouds or shadows, dust covering and also temperature differences, aging, or manufacturing imperfections, reduces the extracted power from all of the PV strings. The PV module with lowest output current limits the current of all of the PV modules in that string. Also, the voltage of maximum power point can be different in various PV strings, however all of the parallel PV strings experience the same voltage and hence maximum power cannot be extracted from all of the PV strings.
- Due to the low irradiation during the sunrise/sunset or cloudy sky, the voltage of maximum power point of the PV panels is small. In the single-stage topology, since the dc-link voltage is equal to the voltage of the PV arrays, the grid-connected inverter cannot produce the required voltage for grid connection during such conditions. Consequently, it disconnects from the grid and the available power from PV panels during sunset/sunrise or cloudy sky, cannot be extracted. However, in the double-stage multi-string topology, the dc/dc converters can step up the voltage of PV strings to the dc-link nominal voltage. Hence, the available power from PV panels during sunset/sunrise or cloudy sky can be injected to the grid.
- The modular structure of the multi-string topology, allows the PVPP to be scaled up without the need of changing the installed PV panels. Furthermore, various types of PV panels can be installed due to independent operation of dc/dc converters in each PV string.
- The low frequency bulky transformer can be eliminated by applying isolated dc/dc converters with high frequency transformers. As a result, the required voltage boost can be achieved besides providing isolation required by some standards.

The 3L-NPC inverter is connected to the grid through a LCL filter and a YΔ step-up transformer. The transformer also provides electrical isolation between the grid and PVPP, which eliminates the possible earth leakage current and ensures compliance with standard safety requirements.

3. Proposed control strategy for PVPP during voltage sags

Two controllers, one for the dc/dc stage and one for the grid-connected 3L-NPC inverter, are required for the operation of the PVPP. Each of these controllers require separate control strategies, which are specific for the grid operating condition be it during its normal operation or during network disturbances (voltage sag). Therefore, a fast and precise voltage sag detection strategy is required to determine the operating mode of the controllers. Several voltage disturbance identification and classification strategies have been reported in the literature [24, 25]. In this study, a sag detection second order generalized integrator (SOGI) based orthogonal system is applied for the calculation of the amplitude of phase voltages and determination of the minimum phase voltage amplitude ($\hat{V}_{min}$). The detailed description on the SOGI implementation can be found in [26, 30]. Since the phase voltage amplitudes are required to detect the single- or two-phase voltage sags, the orthogonal voltages ($v_{x-\alpha}$ and $v_{x-\beta}$, where x is referred to phase a , b or c) are calculated by independent SOGI blocks for each phase. The amplitude of the phase voltage ($\hat{V}_x$) is calculated as follows. Subsequently, the minimum voltage amplitude ($\hat{V}_{min}$) is determined, which is utilized for the detection of the voltage sag and operation mode of the controller.

$$\hat{V}_x = \sqrt{v_{x-\alpha}^2 + v_{x-\beta}^2}. \quad (1)$$

The operation of grid-connected PVPPs should comply with grid codes. Therefore, grid code requirements should be considered in the design of the proposed controller of the PVPP. A brief description of the relevant grid codes is presented in the following subsection. Afterwards, the detailed implementation of proposed controller for the grid-connected inverter is provided.

3.1. Medium-voltage grid codes

Dynamic voltage support and LVRT capability is necessary for PVPPs connected to the medium-voltage (MV) grid. PVPPs are required to stay connected to the grid during voltage sags for a specific period of time, and also inject reactive power for grid support. Moreover, PVPPs should be able to restore the active power injection with limited ramp after grid voltage sag clearance [27].

The reactive current requirement of MV grid-connected DGs according to the German grid codes is depicted in Fig. 2 [28]. The shaded area in which $-10\% < \Delta V_g/V_n < 10\%$, relates to the voltage amplitude between 0.9 pu and 1.1 pu, which is considered as the normal grid condition, and active power is only required to be injected to the grid. During this operation mode, the amount of injected reactive power to the grid is zero and the grid-connected inverter operates at unity power factor. However, during any abnormal grid conditions, the PVPPs are required to support the grid voltage by injecting reactive power, as depicted in Fig. 2.

$$I_q^* = \begin{cases} 0, & 0.9 \text{ pu} \leq \hat{V}_{min} < 1.1 \text{ pu} \\ k \frac{\Delta V}{\hat{V}_N} I_{Ndq} + I_{q0}, & 0.5 \text{ pu} \leq \hat{V}_{min} < 0.9 \text{ pu} \\ -I_{Ndq} + I_{q0}, & \hat{V}_{min} < 0.5 \text{ pu}, \end{cases} \quad (2)$$

where $\hat{V}_N$ is the nominal amplitude of the PCC phase voltage and $\Delta V = \hat{V}_{min} - \hat{V}_N$, while $\hat{V}_{min}$ is the minimum phase voltage amplitude. It should be noted that $\hat{V}_{min}$ is calculated instantaneously. I_{Ndq} denotes the transformed nominal inverter current to dq-coordinates ($I_{Ndq} = \sqrt{3}I_N$, where I_N

Fig. 2. Grid reactive current requirement for PVPPs connected to medium-voltage grid [28]

is the nominal rms 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 PSO and PVPP operator and is usually larger or equal to 2 [29]. In this study, k is considered to be equal to 2.

Since three different operation conditions are defined by grid codes, the proposed controller also is divided into three operation modes. If $\hat{V}_{min}$ is between 0.9 pu and 1.1 pu, the controller operates normally (*Normal*). If $\hat{V}_{min}$ is between 0.5 pu and 0.9 pu, the inverter is required to inject both active and reactive power to the grid simultaneously (*Sag I*). Finally, when $\hat{V}_{min}$ is smaller than 0.5 pu, the inverter should inject only reactive current to the grid (*Sag II*).

3.2. Proposed dq-axis current reference calculation algorithm

A comprehensive structure of the proposed controller of the 3L-NPC inverter during voltage sags is presented in Fig. 3.

The main contribution of this study is the proposed method for calculation of dq-coordinate current references during various operation modes of the PVPP. The proposed method ensures that the full current capacity of the grid-connected inverter of the PVPP is utilized for injecting active/reactive power during voltage sags. The q-axis current reference (I_q^*) can be calculated from the grid code, as per (2). During *Normal* condition, the inverter should inject purely active power to the grid and consequently, I_q^* equals to zero. During *Sag I* operation, the amount of the reference reactive current, depends on the minimum voltage amplitude ($\hat{V}_{min}$), while the inverter should purely inject the reactive current to the grid ($I_q^* = -I_{N_{dq}}$) during *Sag II* condition,.

The calculation of d-axis current reference (I_d^*) is more challenging because it relates on the injected active power to the grid (p) and extracted power from PV strings. This paper proposes the following algorithm for calculating I_d^* during various operation conditions in order to utilize the maximum capability of the 3L-NPC inverter in injecting active/reactive power to the grid during

Fig. 3. Proposed current controller for multi-string PVPP

voltage sags.

$$I_d^* = \begin{cases} I_{d-m}^*, & \text{Grid : Normal} \\ I_{d-n}^*, & \text{Grid : Sag I} \\ I_{d-m}^*, & \text{Grid : Sag II} \end{cases} \quad (3)$$

where the proposed algorithms for calculating I_{d-m}^* and I_{d-n}^* under three different operation modes are as follows.

Normal: During *Normal* operation, the dc/dc converters extract the maximum power from PV strings, while the 3L-NPC inverter controller is used to maintain the dc-link voltage (V_{dc}) by controlling the injected active power into the grid. It is realized by manipulating the active current reference I_{d-m}^* , as shown in Fig. 3. Due to the objective of the dc-link voltage controller, the injected active power to the grid is adjusted to the extracted power from PV strings.

Sag I: As mentioned in Section 3.1, in this operation mode, I_q^* is a fraction of the inverter nominal current. Therefore, the inverter is also able to inject active power to the grid, simultaneously. Since, the priority should be given to the reactive power, first I_q^* is calculated from grid code and then the amount of d-axis current reference I_{d-n}^* is calculated as per:

$$I_{d-n}^* = \min \left[\sqrt{I_{N_{dq}}^2 - I_q^{*2}}, \frac{P_{Tot}}{|v_{pcc}^+|} \right], \quad (4)$$

Fig. 4. Power reduction strategy from PV strings during Sag I
a Power-voltage curve of the PV string
b dc/dc converter controller

where, P_{Tot} is the instantaneous total extracted power from all PV strings (P_{Str1} , P_{Str2} , ...), as shown in Fig. 3. Also $|v_{pcc}^+|$ is the amplitude of PCC voltage positive-sequence which is calculated dynamically through the controller.

$I_{N_{dq}}$ is related to the inverter nominal current, which usually is chosen based on the nominal maximum power of PV strings. However, during voltage sags, the nominal maximum power of PV strings might not be available. Therefore, by injection of d-axis current of $\sqrt{I_{N_{dq}}^2 - I_q^{*2}}$ to the grid, the injected active power to the grid is larger than the extracted power from PV strings, which results in discharging of dc-link capacitors and decreasing the dc-link voltage lower than the nominal range. In order to avoid this problem, the instantaneous amount of the extracted power from PV strings should be considered in the calculation of I_d^* , as in (4). The amount of $P_{Tot} / |v_{pcc}^+|$ refers to the available d-axis current which can be injected to the grid based on the instantaneous extracted power from PV strings.

On the other hand, if the total extracted power from PV strings is higher than the injected active power to the grid, the excessive energy between the extracted power from PV strings and the injected active power to the grid ($P_{Tot} - p$, where p is the instantaneous injected active power to the grid), will be stored in the dc-link capacitors, which may lead to overvoltage. Hence, the extracted power from PV strings should be reduced during Sag I. Thus, a power reduction algorithm is implemented by controlling the dc-link voltage through the dc/dc converters as shown in Fig. 4. In order to reduce the extracted power from the PV string, a reduced power (RP) signal is defined. This signal is set to 1 for all PV strings during Sag I, while it is set to 0 for all PV strings during Normal condition. As illustrated in Fig. 4(a), while $RP = 1$ the voltage (ΔV_{st}) is added to V_{mpp} ,

which results in moving the operation point from A to B .

It should be mentioned that according to Fig. 4(a), moving the operation point to points B or C can result in the reduction of the extracted power from the PV string. In this paper, the operation point of the PV string during *Sag I* is moved to point B (in the right-side of the *MPP*), because:

- The difference between v_B and v_{mpp} ($|v_{mpp} - v_B|$) is smaller than $|v_{mpp} - v_C|$ and therefore moving the operation point from A to point B can be executed faster than to point C , which results in a faster response.
- For small power references, the operation of the PV string in the left-side of *MPP* (point C) necessitates the PV string voltage to be close to the short-circuit voltage. This imposes the dc/dc converter duty cycle to be close to one. As a result, controlling the dc/dc converter becomes more difficult and large oscillations may appear in the input/output voltages. This issue is avoided by moving the operation point to the right-side of the *MPP* (B), where the PV string voltage becomes closer to its open-circuit voltage resulting in a decrease of the duty cycle.

In order to control the dc-link voltage during *Sag I*, the stored energy of the dc-link ($0.5CV_{dc}^2$, where C is the equivalent value of all dc-link capacitors) is manipulated. Therefore, ΔV_{st} is calculated with the aim of controlling the dc-link energy. Accordingly, the square of the dc-link voltage reference (V_{dc}^{*2}) is compared with the instantaneous dc-link voltage square (V_{dc}^2) and is multiplied with $0.5C$. This error is fed into the PI controller in order to calculate the required ΔV_{st} . As shown in Fig. 4(b), various types of MPPT algorithms, like perturb and observe (P&O) or incremental conductance (INC), can be implemented in the proposed controller. Partial shading has been extensively addressed in several research articles and can also be implemented in the MPPT algorithm, however, since the main focus of this paper is study of the LVRT of the grid-connected PVPP, partial shading is not investigated in this study. Accordingly, the well-known P&O algorithm, as introduced in [31], is implemented. As shown in Fig. 4(b), the calculated reference voltage, is then compared with the instantaneous voltage of the PV string (V_{st}) and the difference is fed to a PI controller in order to generate the duty cycle of the boost converter.

Sag II: Grid codes require PVPPs to inject the maximum possible reactive current of the inverter to the grid, during *Sag II*. Therefore, due to the current limitation of the grid-connected inverter, the active power injection is maintained to zero in order to inject maximum possible reactive current to compensate for the voltage sag. Accordingly, PV strings are open-circuited (*O.C.*) in order to reduce the extracted power from all of the PV strings to zero. The operation point of the PV string is moved to point C in Fig. 4(b) which results in zero power extraction from the PV string. During this operation mode, I_d^* is considered to be I_{d-m} , which is calculated from the dc-link voltage controller, as shown in Fig. 3. Since, no power is injected to the dc-link from PV strings during *Sag II*, the amount of I_{d-m} is almost zero. However, it can help to keep the dc-link voltage at its reference value, especially during unbalanced voltage sags which result in the oscillation of the dc-link voltage.

As shown in Fig. 3, the computed dq-axis current references (I_d^* and I_q^*), from (2) and (4), are converted to their equivalent reference stationary frame currents (I_α^* and I_β^*) using the inverse park transformation. An adaptive phase locked loop (PLL) is applied for extracting the angle of the voltage positive sequence, as shown in Fig. 3. The PCC voltages are first converted into the dq-frame using an arbitrary angle that rotates at $2\pi f$. In order to remove the voltage negative sequence, a moving average filter (MAF) is applied to calculate $\bar{e}_d$ and $\bar{e}_q$. Subsequently, the voltage positive sequence in abc frame (e_{abc}^+) is calculated using the inverse park transformation. e_{abc}^+ is then fed

Table 1 Simulation parameters

Parameter	Symbol	Value
Grid line-line voltage	v_{g-ab}	12.47kV _{rms}
PCC phase-neutral voltage	$v_{PCC-abc}$	230V _{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

into the conventional PLL to calculate the angle of voltage positive sequence (θ^+). The detailed implementation of the adaptive PLL can be found in [32].

The respective $\alpha\beta$ current errors are then obtained by subtracting the stationary frame current references with the stationary frame currents (I_α and I_β) obtained from the measured three-phase output inverter currents through inverse Clarke transformation. The errors between the calculated current references and instantaneous phase currents are fed into the proportional resonant (PR) with anti-windup controller, which is implemented in $\alpha\beta$ -coordinate. Although, the implementation of the conventional PI controller for balanced current injection is simple, it requires multiple frame transformation and results in slow performance. The PR controller with anti-windup shows faster dynamic response and zero steady-state error [33]. Finally, an adaptive space vector modulation (ASVM) technique is applied for generating the switching signals of the 3-wire 3L-NPC inverter by considering dc capacitor voltage balancing, based on [34].

4. Simulation validation

The multi-string PVPP (Fig. 1) is modelled and developed using Matlab/Simulink and PLECS toolbox. Three parallel PV strings are connected to the dc-link of the grid-connected 3L-NPC inverter. Each PV string is constructed with 15 paralleled PV branches with each branch having 14 series connected PV panels. The PV panel is modelled according to the parameters of the SHARP NU-U235FI, which produces the maximum power of 235 W (30 V and 7.84 A) at 25°C and 1 kW/m².

Consequently, the maximum output power of each PV string is 50 kW and the maximum total power of PVPP equals to 150 kW. The detailed parameters of the simulated PVPP are presented in Table 1. In order to validate the performance of the proposed controller, under various irradiation and temperature values, different amounts of irradiance 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 ($I_r = 0.5 \text{ kW/m}^2$, $T = 25^\circ\text{C}$) and String III ($I_r = 1.1 \text{ kW/m}^2$, $T = 35^\circ\text{C}$).

It is necessary to perform a comprehensive power system test case simulation in order to investigate the performance of the designed PVPPs in terms of the control and dynamic performance. Accordingly, a medium voltage grid test case, based on North American Network, depicted in Fig. 5, is introduced in [35]. The grid voltage is 12.47 kV and the PVPP is connected to Bus 3 (PCC) using a step up transformer (0.4 kV/12.47 kV). The test case system consists of both single-phase and three-phase loads. Single-phase loads are connected to Bus 2 and Bus 5. The

Fig. 5. Schematic diagram of the medium-voltage test-case network [35]

X/R ratio of lines equals to 6 and the medium voltage grid is connected to the 115 kV line through a 12.47 kV/115 kV transformer. The total load of Sub-network 1, shown in Fig. 5, is 200 kVA, while 150 kVA of this capacity, can be supplied by the only DG unit in this network, which is the PVPP connected to Bus 3.

Two different study sets are performed on the modelled grid-connected PVPP and results are presented in the following subsections. Firstly, the dynamic performance of the proposed controller is investigated during the different voltage sag conditions. Subsequently, the effect of the proposed active/reactive power injection method in enhancing the PCC voltage during various fault conditions at different buses of the system is evaluated.

4.1. Dynamic performance of the proposed controller

In order to validate the applicability of the proposed controller, the operation of PVPP is examined under two different voltage sags:

- *Sag I*: It includes a single phase to ground fault at Bus 4 which results in a 27% two-phase voltage sag between $t = 0.15$ s and $t = 0.3$ s in the PCC, as shown in Fig. 6(a).
- *Sag II*: It consist of a two-phase fault at Bus 4 which leads to a 64% three-phase voltage sag between $t = 0.45$ s and $t = 0.6$ s in the PCC, as shown in Fig. 6(a).

Fig. 6. Dynamic performance of the multi-string PVPP with three PV strings during various operation modes

a PCC voltages

b Injected active and reactive power to the grid

f dc-link and dc capacitors voltages

c PV string voltages

d PV string currents

e Extracted power from PV strings

The amounts of injected active and reactive power to the grid are shown in Fig. 6(b). It can be observed that the 3L-NPC inverter injects maximum active power to the grid during *Normal* operation, however, the amount of active power is reduced during *Sag I*, due to the injection of the reactive power in this period. After $t = 0.3$ s, the grid recovers to *Normal* condition and hence the inverter output active power is increased while the injected reactive power becomes zero. The injection of reactive power increases to its maximum possible value at $t = 0.45$ s due to *Sag II*, while the injected active power is zero. It should be mentioned that the oscillation of injected active and reactive power during *Sag I* and *Sag II*, is as a consequence of the injection of balanced currents to the grid during unbalanced grid voltages. Besides, the proposed control method maintains V_{dc} at its reference value during all of the operation modes, as represented in Fig. 6(c). The dc-link capacitor voltages remains balanced due to the implementation of the ASVM with voltage balancing capability.

Fig. 7. Dynamic current controller performance of the grid-connected 3L-NPC inverter

- a Starting of Sag I - PCC voltages
- b Starting of Sag I - injected currents
- c Ending of Sag II - PCC voltages
- d Ending of Sag II - injected currents

The dynamic performance of PV strings is presented in Fig. 6(d). Since the PV strings are exposed to different amounts of irradiation and temperature, they have different maximum power values, voltages and currents during *Normal* condition. During *Sag I*, the extracted power from PV strings reduces to a certain value which is calculated by the dc-link voltage controller. Accordingly, the voltage of PV strings increases. This moves PV strings operation point to the right-side of *MPP* point. Moreover, the current of PV strings reduces during *Sag I*, as depicted in Fig. 6(e). The total extracted PV power is decreased to zero in order to deliver pure reactive power to the grid during *Sag II*. During this condition the current reduces to zero and PV string voltages increase to their open-circuit value.

The dynamic performance of the current controller of the 3L-NPC inverter at the beginning and end of the voltage sag are depicted in Fig. 7. During *Normal* operation, the 3L-NPC inverter delivers only active power to the grid under unity power factor operation and no phase-shift exists between the PCC phase voltages and the injected currents, as shown in Fig. 7(b). However, there is a phase-shift (ϕ_1) between the voltage and currents, during *Sag I*, which shows the simultaneous injection of active and reactive powers to the grid. Fig. 7(d) shows the injected currents during *Sag II*. A phase-shift of $\phi_2 = \pi/2$ exists between the PCC voltage and injected currents, which implies the pure reactive power injection, during *Sag II*. Moreover, the currents of the inverter recover to *Normal* mode with unity power factor operation quickly, due to the fast performance of the PR current controller. It should be noticed that the amplitude of the inverter current remains at its nominal current amplitude during all sag conditions, which shows the effectiveness of the proposed dq-axis current reference calculation in using the full current capacity of the inverter when injecting active/reactive power to the grid during voltage sags.

Fig. 8. Voltage enhancement of the proposed active/reactive power injection strategy during different fault cases

a *Fault case 1:* Single-phase to ground fault at Bus 4 - injected active and reactive powers

b *Fault case 1:* Single-phase to ground fault at Bus 4 - PCC rms voltages

c *Fault case 2:* Two-phase to ground fault at Bus 7 - PCC rms voltages

d *Fault case 2:* Three-phase to ground fault at Bus 2 - PCC rms voltages

Table 2 PCC voltage enhancement under various fault conditions

Case Study	$\hat{V}_{min}$ during <i>Disconnect</i> mode	$\hat{V}_{min}$ during <i>PQ-inject</i> mode
<i>Fault Case 1</i>	151 V (0.65 pu)	182 V (0.79 pu)
<i>Fault Case 2</i>	122 V (0.53 pu)	152 V (0.66 pu)
<i>Fault Case 3</i>	75 V (0.32 pu)	100 V (0.43 pu)

4.2. Grid voltage support during voltage sags

Since the main objective of this paper is to utilize the full current capacity of the grid-connected inverter in enhancing the PCC voltage during voltage sags, the obtained voltage enhancements under three different fault conditions are investigated and results are shown in Fig. 8.

Fault Case 1: A single-phase to ground fault in Bus 4 results in the 40% voltage sag in PCC. As shown in Fig. 8, between $t = 0.15$ s and $t = 0.3$ s, the PVPP is disconnected from the grid (*Disconnect*). During this period, $\hat{V}_{min}$ equals to 151 V (0.65 pu). The same fault situation is repeated between $t = 0.45$ s and $t = 0.6$ s at Bus 4, however in this period, the PVPP stays connected to the grid and injects both active and reactive power simultaneously to the grid (*PQ-inject*), as depicted in Fig. 8(a). It can be observed that due to the injection of the active/reactive powers with PVPP, $\hat{V}_{min}$ is increased to 182 V (0.79 pu).

Fig. 9. Experimental setup of the grid-connected 3L-NPC inverter

Table 3 Experimental parameters

Parameter	Symbol	Value
PV panel and dc/dc converter parameters		
PV panel maximum power	p_{mpp}	3.3 kW
PV panel maximum power point voltage	v_{mpp}	480 V
PV panel maximum power point current	i_{mpp}	7 A
PV panel filling factor	FF	0.8
PV panel capacitor	C_{pv}	200 μ F
dc/dc converter switching frequency	f_{sw}	10 kHz
3L-NPC inverter parameters		
Apparent power	S	3.3 kVA
PCC phase-neutral voltage	$v_{pcc-abc}$	320 V _{rms}
dc-link voltage	V_{dc}	560 V _{dc}
dc-link capacitor	C_u / C_l	4.9 mF
Fundamental frequency	f_0	50 Hz
3L-NPC switching frequency	f_s	1.5 kHz
Inductor filter	L_f	4 mH

Fault Case 2: A two-phase to ground fault is modeled at Bus 7 in this case study. The operation of the PVPP is kept same as before and the amount of $\hat{V}_{min}$ during both *Disconnect* and *PQ-inject* operation modes are simulated and results are shown in Fig. 8(c) and quantified in Table 2. It can be seen that the PCC voltage is enhanced from 122 V (0.53 pu) during *Disconnect* operation of the PVPP, to 152 V (0.66 pu) during *PQ-inject* operation mode of the PVPP, which shows a 13% improvement in the PCC voltage during the voltage sag, due to the implementation of the proposed

controller.

Fault Case 3: In this case study, a balanced fault occurs at Bus 2 which results in 68% voltage sag in PCC. As a result, the PVPP injects reactive power to the grid (shown in Fig. 8(d) between 0.45 s and 0.6 s) as per the grid code requirements of (2). The comparison between the case where the PVPP disconnects and stays connected to the grid is also shown in Table 2, where an 11% improvement in the PCC voltage is attained.

It can be seen from Table 2 that the injection of the active/reactive power to the grid through the proposed controller enhances the PCC voltage compared to disconnection of the PVPP. This shows the effectiveness of the proposed active/reactive power control strategy in enhancing the grid voltage during voltage sags.

5. Experimental validation

A three-phase 3L-NPC converter setup (Fig. 9) has been utilized in order to experimentally validate the effectiveness of the proposed controller under unbalanced voltage sags. The 3L-NPC setup consists of Semikron SKM145GB176D 1700V IGBT modules. The grid is generated using a TopCon TC.ACS 4-quadrant grid simulator, while the PV side is emulated using an ETS600/8 Terra SAS photovoltaic simulator. A dc/dc boost converter is connected between the PV panel and dc-link, which extracts the maximum power for the PV panel during normal operation mode. The proposed controller and protection functions of the converter are implemented in a dSPACE 1006 platform. The parameters of the experimental setup are given in Table 3. The proposed controller has been evaluated under two different cases corresponding to *Sag I* and *Sag II* of Section 3.1.

Sag I This case study includes a 36% two-phase voltage sag for a duration of 150 ms. The three-phase grid voltages (v_{pcc}) and injected currents (i_{abc}) are depicted in Fig. 10(a). Due to the implementation of the proposed control algorithm, the injected three-phase currents are balanced during such unbalanced voltage sag. Additionally, because the injected currents are equal to the inverter nominal current, maximum current capacity of the inverter is applied for enhancing the grid voltages during the voltage sag. A delay of maximum $T/4$, where T is the grid voltage period, is introduced by the SOGI due to the single-phase quadrature signal generation. It should be noted that this delay also depends on the amplitude of the voltage sag. During voltage sags with smaller amplitude (for instance between 10% and 30%), the sag can be detected faster compared to voltage sags with larger amplitudes (for instance between 70% and 90%).

The dc-link voltage and capacitor voltages are depicted in Fig. 10(b). The dc-link voltage during *Normal* operation is 560 V_{dc} and remains constant during *Sag I*. Additionally, dc-link capacitors remain balanced during all operation modes. The PV voltage (V_{st}) is equal to 480 V_{dc} during *Normal* mode, which shows the operation of the PV string at *MPPT*. During *Sag I*, V_{st} increases to 555 V_{dc} with the proposed controller in Fig. 4 in order to decrease the extracted power. The extracted power from PV string (P_{st}) and output current of the PV string (I_{st}) are reduced during *Sag I*.

The quantities of the injected active and reactive powers (p and q) during *Sag I* are illustrated in Fig. 10(c). During *Normal* operation, the 3L-NPC inverter injects purely active power to the grid equal to 3.1 kW. The average active power is reduced to 1.3 kW for the duration of *Sag I*. As expected, second harmonic oscillation exists in the injected active power, due to the injection of

Fig. 10. Experimental results: Sag I - 36% two-phase voltage sag

- a Three-phase voltages and currents
- b dc-link voltage, PV string voltage, current and power
- c Injected active/reactive power

balanced currents during the unbalanced voltage sag. On the other hand, the average of reactive power Q is increased to 2 kVAR. Consequently, the average injected apparent power is equal to 2.4 kVA ($S = \sqrt{1.3^2 + 2^2}$), which is 77% of the apparent power during Normal operation ($S_N = 3.1 \text{ kVA}$). The reduction of the injected apparent power is due to the decrease of the grid voltages during the voltage sag, while the injected currents remain at the nominal value.

Sag II This case study consists of a three-phase voltage sag of 70% as shown in Fig. 11(a). Phase a experiences the smallest voltage amplitude at 30% of the nominal value, however due to the implementation of the proposed controller, the injected currents remain balanced and the

Fig. 11. Experimental results: Sag II - 70% three-phase voltage sag

- a Three-phase voltages and currents
- b dc-link voltage, PV string voltage, current and power
- c Injected active/reactive power

maximum current capacity of the inverter is utilized during the voltage sag. The dc-link voltage, shown in Fig. 11(b), remains at its nominal value during *Sag II*, while V_{st} increases to $165 V_{dc}$, which is equal to the PV panel open-circuit voltage. Accordingly, P_{st} and I_{st} are also reduced to zero in this condition. The injected active and reactive powers are depicted in Fig. 11(c). It can be seen that the average active power is reduced to zero. The average reactive power (Q) is increased to 1.3 kVAR during the voltage sag, i.e. (45%) of S_N . It should be noted that in this case study the delay of the voltage sag detection algorithm is smaller than *Sag I*, because of the smaller voltage

amplitude of the voltage sag.

6. Conclusion

This paper studies the performance of the grid-connected three-level neutral-point-clamped (3L-NPC) inverter of the medium-scale multi-string grid-connected photovoltaic power plants (PVPPs) during voltage sags. An algorithm for calculating the dq-axis current references is presented. Based on the grid requirements, the 3L-NPC inverter injects the required active/reactive power to the grid during voltage sags. The proposed control strategy employs the full current capacity of the grid-connected inverter resulting in a better grid voltage enhancement. Detailed implementation of the proposed control scheme has been presented, and its effectiveness are demonstrated through simulation results on a 150-kVA PVPP connected to the 12.47-kV medium-voltage test-case system under various voltage sag conditions. Experimental results on a laboratory 3.3-kVA 3L-NPC setup have been presented showing the effectiveness of the proposed control strategy in injecting active/reactive power to the grid during voltage sags.

7. References

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