A review of active/reactive power control strategies for PV power plants under unbalanced grid faults

Dehghani Tafti, Hossein; Maswood, Ali Iftekhar; Lim, Ziyou; Ooi, Gabriel Heo Peng; Harikrishna Raj, Pinkymol

2015

Dehghani Tafti, H., Maswood, A. I., Lim, Z., Ooi, G. H. P., & Harikrishna Raj, P. (2015). A review of active/reactive power control strategies for PV power plants under unbalanced grid faults. 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA).

<https://hdl.handle.net/10356/82231>

<https://doi.org/10.1109/ISGT-Asia.2015.7387144>

© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: [<http://dx.doi.org/10.1109/ISGT-Asia.2015.7387144>].

Downloaded on 26 Apr 2023 18:19:00 SGT

A Review of Active/Reactive Power Control Strategies for PV Power Plants under Unbalanced Grid Faults

Hossein Dehghani Tafti¹, *Student Member, IEEE*, Ali I. Maswood¹, *Senior Member, IEEE*, Ziyou Lim², *Student Member, IEEE*, Gabriel H. P. Ooi¹, *Member, IEEE* and Pinkymol Harikrishna Raj¹, *Student Member, IEEE*

¹School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

²Energy Research Institute @ NTU (ERI@N), Interdisciplinary Graduate School, Nanyang Technological University, Singapore

Email: *hossein002@e.ntu.edu.sg, eamaswood@ntu.edu.sg

Abstract—Fault ride through (FRT) capability is one of the challenges faced in the medium to high voltage large-scale grid-tied photovoltaic power plants (PVPPs). Besides that, due to the high penetration of installed distributed generation (DG) units, the grid voltage enhancement under unbalanced faults is a requirement of several standards and grid codes. The controller of the grid-connected inverter consists mainly of two parts: the selection of the reference active/reactive power and the calculation of the reference currents under faults. This paper reviews various strategies which are proposed in the reported literature for calculating the reference current as well as selecting the reference active/reactive power based on the grid voltage. The performances of these control strategies are investigated on the 150 kW NPC grid-connected multi-string PVPP, which is considered as the state of the art for medium power PVPPs. The PVPP is connected to the 12.47 kV medium voltage distribution system where different fault situations is simulated.

Index Terms—Photovoltaic systems, Unbalanced Voltage sag, Fault Ride-Through capability, Active power control, Reactive power control, NPC inverter.

NOMENCULCTURE

PVPP	PV Power Plant
FRT	Fault-Ride-Trough capability
DG	Distributed Generation unit
NPC	Neutral-Point-Clamped inverter
PR	Proportional-Resonant Controller
ASVM	Adaptive Space Vector Modulation
PSO	Power System Operator

I. INTRODUCTION

Photovoltaic power plants (PVPPs) are one of the most promising renewable sources for electricity generation nowadays which have gained significant growth over the recent years. Such rapid pace for the total installed PV capacity growth is initiated due to the drastic decrease of the PV panel production cost and is expected to remain high in the upcoming years [1]. On the other hand, the inclusion of distributed generation (DG) units is changing the paradigm of energy generation. Microgrids and smart energy networks are receiving higher interest as a reason of their potential advantages over conventional centralized systems. One of these advantages is that the energy is produced much closer to the consumer, thus experiencing lower active and reactive losses in the system [2].

High penetration of the installed distributed generation (DG) units lead to new challenges for power system operators

(PSOs) in various aspects such as power quality and reliability. In order to maintain both excellent power quality and high grid reliability, new standards and grid codes are regulated by the PSOs. One of the main requirements in the new grid codes and standards for medium power PVPPs is the fault ride through (FRT) capability. Additionally, the DGs are required to inject the reactive power to the grid under faults [3].

Several studies have been done on the FRT capability of the single or two stage PVPPs. However, most of the studies only considered injecting the same amount of reactive power to three-phases. In most cases, the unbalanced voltage sags are more likely to be experienced as compared to the balanced voltage sags. As a result, there are negative sequence voltage and current in the grid. Therefore, negative sequence current injection control could be greatly implemented for the next generation of grid codes in order to reduce the negative sequence voltage while maintain the phase voltages within the standard ranges. On top of that, the future standards will require DGs to properly operate with specific limits on the active or reactive power ripple and current harmonics under grid faults.

This paper reviews various strategies for determining the reference current of the inverter based on the reference active/reactive power during the unbalanced faults condition. There are also many different methods to calculate the reference active and reactive power under unbalanced faults which are presented here as well. The performance of these control methodologies is investigated using the state of the art multi-string (two-stage) PVPPs that is popularly installed for the medium and high power. The grid connected three-level neutral-point-clamped (NPC) inverter is implemented in this PVPP. Hence, the performances of the respective controllers are evaluated and compared based on the simulation results under different unbalanced voltage conditions.

II. PROBLEM DEFINITION

Addressing effectively the issue of unbalanced grid faults for the grid connected PVPPs while delivering excellent power quality and maintaining high grid reliability is the main focus of this study. Therefore, it is divided mainly into four different parts in this section. Firstly, the structure of the PVPP that is connected to a medium voltage (MV) distribution system is presented and followed by a description of the proposed

Fig. 1. Schematic diagram of the benchmark medium voltage distribution system.

controller under unbalanced grid faults. The characteristics of the unbalanced faults in the power system are also briefly explained in the latter. Lastly, the new grid codes regulated by the PSOs for PVPPs are introduced.

A. Grid Connected Multi-String PVPP

The proposed structure for the multi-string PVPP is shown in the Fig. 1 which consists of multiple PV strings, DC/DC converters and NPC inverter. The DC/DC converters here extract the maximum power from the respective PV strings to the DC-link. In the event of partial shading, the PVPP operation will not be disrupted and maximum power can still be extracted at all times since these PV strings are working independently. The three-level NPC inverter is considered in this structure because of its higher power rating compared to two-level inverters. Higher power conversion efficiency is achieved as well due to the lower switching frequency operation. Besides that, the filter inductors are connected in between the inverter and the grid to guarantee low current total harmonic distortion (THD) performance at all times which strictly comply to both grid codes and IEEE standards [4]. A detailed description of the proposed structure with its controller is presented in [5].

The PVPP is connected to the grid of the MV distribution system using a YΔ step-up transformer which boosts the voltage from 0.4 kV to 12.47 kV. The transformer also provides the electrical isolation between the grid and the PVPP

Fig. 2. Proposed controller with voltage enhancement under grid faults.

to eliminate the possible earth leakage current and fulfil the standards safety requirements.

With such a high penetration of PVPPs in the power system, it is necessarily to perform a comprehensive benchmark power system simulation in order to investigate the dynamic performance of the designed PVPPs using different control methods. According to the MV benchmark grid based on the North American Network introduced in [5], the single-line schematic diagram is depicted in Fig. 1.

B. Proposed PVPP Controller under Unbalanced Grid Faults

The proposed controller for the grid-connected NPC inverter with voltage enhancement capability under grid faults is shown in Fig. 2. The positive and negative sequences of the grid voltages are extracted in the $\alpha\beta$ frame with the voltage sequence extractor. Subsequently, the reference active or reactive power are calculated based on the obtained voltage sequences, the fault type, the grid impedance and the amount of extracted power from PV strings. Based on the control strategy, the positive/negative sequence active/reactive powers can be injected to the grid. There are various active/reactive power calculation strategies which will be introduced in the Section III.

The current reference generator block will calculate the stationary domain reference currents (I_{α}^* and I_{β}^*) based on the grid voltages and reference active and reactive powers. There are different methods reported in the literature to determine the current, which will be briefly explained in Section IV. The inverter current is controlled using the proportional resonant (PR) controller which results faster dynamic response, achieves smaller steady state error and requires lesser computational complexity. Lastly, the switching signals are generated through the adaptive space vector modulation (ASVM) which balances the DC-link capacitor voltages [7].

C. Unbalanced Voltage Sag

The voltage sag is an abnormal condition with a short-time reduction in the amplitude of one or various phases. Different types of voltage sags can occur in the grid and are generally classified in [8].

Using Fortescue theorem, the unbalanced voltage sags can be synthesized to three instantaneous symmetric components: positive v^+ , negative v^- and zero v^0 . The voltage and current vectors are defined accordingly as follows:

$$\mathbf{i} = \mathbf{i}^+ + \mathbf{i}^- + \mathbf{i}^0 \quad (1)$$

$$\mathbf{v} = \mathbf{v}^+ + \mathbf{v}^- + \mathbf{v}^0 \quad (2)$$

It should be mentioned that the zero sequence currents and voltages do not exist in the three-phase three-wire systems. Instead of using a natural frame for characterizing the grid voltage, the Clarke transformation is applied to express the measured voltages in the stationary reference ($\alpha\beta$) frame.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3)$$

Using this transformation in the three-wire system, the $\alpha\beta$ frame voltages can be written as below:

$$v_\alpha = v_\alpha^+ + v_\alpha^- \quad (4)$$

$$v_\beta = v_\beta^+ + v_\beta^- \quad (5)$$

where v_α^+ and v_β^+ are the positive sequence voltages in $\alpha\beta$ frame and v_α^- and v_β^- are the negative sequence voltages. These voltages can be written as functions of time as below:

$$v_\alpha^+ = V^+ \cos(\omega t + \varphi^+) \quad (6)$$

$$v_\beta^+ = V^+ \sin(\omega t + \varphi^+) \quad (7)$$

$$v_\alpha^- = V^- \cos(\omega t - \varphi^-) \quad (8)$$

$$v_\beta^- = -V^- \sin(\omega t - \varphi^-) \quad (9)$$

where V^+ and V^- are the amplitudes of the positive and negative sequences respectively, ω is the angular frequency of the grid and φ^+ and φ^- are the initial phase angles of positive and negative sequences [9]. A measurement factor which is used in several studies is the voltage unbalance factor (n). This factor shows the ratio between negative-sequence voltage and positive-sequence factor as below:

$$n = \frac{V^-}{V^+} = \frac{\sqrt{(v_\alpha^-)^2 + (v_\beta^-)^2}}{\sqrt{(v_\alpha^+)^2 + (v_\beta^+)^2}} \quad (10)$$

It should be taken note that voltage unbalanced factor does not contain information about the depth of the voltage sag and different depths can result in the same unbalanced factor [10].

TABLE I. ACTIVE-REACTIVE POWER CONTROL STRATEGIES

Control Strategy	Characteristics
Disconnection of PVPP $P^*=0, Q^*=0$ [13]	- Avoid islanding operation - No effect in grid voltage enhancement
Positive Sequence Active Power Injection $Q^*=0, P^*=0$ [14]	- Suitable for power systems with higher resistive loads and lines. - A current limitation strategy is considered to avoid the over current problem of the inverter. - The extracted power of PV strings is decreased according to the injected power to the grid.
Positive Sequence Reactive Power Injection $P^*=0, Q^*=0$ [15]	- Suitable for power system with higher inductive loads and lines. - The extracted power from PV string becomes zero during fault. - The maximum amount of injected reactive power is limited to the inverter nominal current.
Positive/Negative Sequence Active Power Injection $Q^*=0$ [16]	- The amount of positive/negative sequence active power is calculated according the grid unbalanced voltage amplitudes. - The extracted power from PV strings should be adjusted to the injected power to the grid.
Positive / Negative Sequence Reactive Power Injection $P^*=0$ [17], [18]	- The extracted power from PV strings becomes zero during fault. - Capable of reducing the grid negative sequence voltage.
Positive/Negative Sequence Active/Reactive Power Injection [9], [10], [19]	- Voltage Support control can be performed. - Flexible control capability according the grid impedance and lines. - Nominal current of the inverter in the calculation of the referenced active or reactive power.

However, this factor is an important for several current control strategies.

D. Grid Code Requirements

The rapid increase of the installation of DG units in MV and low voltage (LV) networks, the PSOs supported the grid only through the conventional power plants. This policy is changed when many more wind and PV power plants are connected to the grid. As a result, the PSOs started to consider these power plants in planning and supporting the grid. These regulations were first adopted in those high voltage (HV) grid-connected large wind power plants where significant amounts of power are installed. However, the focus is being moved recently down to MV and LV networks where more and more PV power is installed [3].

The basic idea of the grid codes for LV PVPPs is that the services provided by them are applied only for normal operation. The PV system should cease the energy production and immediately disconnect from the grid when voltage disturbances are experienced in order to avoid islanding operation. In contrast to the LV grid codes, the PVPPs that are connected to the MV grid require dynamic voltage support and should have FRT capability. The PVPPs must stay connected even under grid fault and inject the adequate amount of reactive power to the grid. On top of that, they should be also able to restore active power injection with limited ramp after the fault clearance [9].

On the other hand, different PSOs regulate the limits on the disconnection time differently according to the voltage sag depth and the duration. During the short-interval faults (less than 0.15 s), the PVPP should stay connected even with a very deep sag amplitude of 0.2 p.u. During the moderate voltage sags (less than 0.8 p.u.), the PVPP remains connected for longer time (2 s) [11]. Based on this regulation, the grid voltage performance under fault conditions is greatly enhanced with the support of PVPPs and reaches to its nominal range within a shorter period of time as compared to the mentioned disconnection times.

III. ACTIVE/REACTIVE POWER CONTROL STRATEGIES UNDER UNBALANCED GRID FAULTS

As mentioned in Section II, the active/reactive reference calculation is essentially important in the grid-connected inverter controller. The main purpose of the controller is to enhance the grid voltage quality during faults so that disconnecting the grid can be avoided. In the past decades, the PSOs controlled the power grid using conventional power plants. In the case of any grid faults occurred, all the DGs should be disconnected to prevent islanding operation. In the latter, some standards are implemented which require the reactive power injection during fault conditions. However, some studies only considered the active power injection. While other researchers considered injecting active and reactive power simultaneously to achieve higher flexibility in improving the grid voltages.

Distinct strategies of active/reactive power control are presented in Table I with their advantages and disadvantages. In this study, only shunt power compensation methods are investigated. However, several series connected voltage restorers are also proposed in some studies to increase the phase voltages during voltage sags [12]. The performance of these control strategies on the grid voltage enhancement in various conditions is compared in Section V.

IV. CURRENT CONTROL STRATEGIES UNDER UNBALANCED GRID FAULTS

In a three phase grid-connected PV inverter, the instantaneous active and reactive powers delivered to the grid depend on the instantaneous output inverter current $\mathbf{i} = [i_a, i_b, i_c]^T$ and the PCC voltage $\mathbf{v} = [v_a, v_b, v_c]^T$:

TABLE II. CURRENT CONTROL STRATEGIES UNDER GRID FAULTS

Control Strategy	$\mathbf{I}^*$
Instantaneous active reactive control [20]	$\begin{bmatrix} p \\ \mathbf{v} ^2 \end{bmatrix} \mathbf{v}$
Instantaneously controlled positive-sequence [16]	$\begin{bmatrix} p \\ \mathbf{v}^+ ^2 + \mathbf{v}^+ \cdot \mathbf{v}^- \end{bmatrix} \mathbf{v}^+$
Positive-negative sequence compensation [21]	$\begin{bmatrix} p \\ \mathbf{v}^+ ^2 - \mathbf{v}^- ^2 \end{bmatrix} (\mathbf{v}^+ - \mathbf{v}^-)$
Average active-reactive control [21]	$\begin{bmatrix} p \\ \mathbf{v}^+ ^2 + \mathbf{v}^- ^2 \end{bmatrix} \mathbf{v}$
Balanced positive sequence control [16]	$\begin{bmatrix} p \\ \mathbf{v}^+ ^2 \end{bmatrix} \mathbf{v}^+$
Controllable oscillating active/reactive power [22]	$\begin{bmatrix} q \\ \mathbf{v}^+ ^2 - k_p \mathbf{v}^- ^2 \end{bmatrix} \times (\mathbf{v}_\perp^+ - k_p \mathbf{v}_\perp^-) \quad -1 \leq k_p \leq 1$
Controllable oscillating reactive power [22]	$\begin{bmatrix} q \\ \mathbf{v}^+ ^2 - k_q \mathbf{v}^- ^2 \end{bmatrix} \times (\mathbf{v}_\perp^+ - k_q \mathbf{v}_\perp^-) \quad 0 \leq k_q \leq 1$
Controllable oscillating active power [22]	$\begin{bmatrix} q \\ \mathbf{v}^+ ^2 + k_q \mathbf{v}^- ^2 \end{bmatrix} \times (\mathbf{v}_\perp^+ + k_q \mathbf{v}_\perp^-) \quad -1 \leq k_q \leq 1$
Combined PQ control [22]	$\begin{bmatrix} S \cos \varphi \\ \mathbf{v}^+ ^2 + k_{pq} \mathbf{v}^- ^2 \end{bmatrix} (\mathbf{v}^+ + k_{pq} \mathbf{v}^-) + \begin{bmatrix} S \sin \varphi \\ \mathbf{v}^+ ^2 - k_{pq} \mathbf{v}^- ^2 \end{bmatrix} \times (\mathbf{v}_\perp^+ - k_{pq} \mathbf{v}_\perp^-) \quad -1 \leq k_{pq} \leq 1$

$$p = \mathbf{v} \cdot \mathbf{i} \quad (11)$$

$$q = \mathbf{v}_\perp \cdot \mathbf{i} \quad (12)$$

where $\cdot$ represents the dot product and $\mathbf{v}_\perp$ is defined as below:

TABLE III. SIMULATION PARAMETERS

Parameter	Symbol	Value
Grid Frequency	f	50Hz
Line Inductor	L_f	1mH
DC-link Capacitor	C_1, C_2	2200 μ F
DC-link Voltage	V_{dc}	770 V _{dc}
NPC Switching Frequency	$f_{s,inv.}$	7.2kHz
Boost Switching Frequency	$f_{s,boost.}$	10kHz

$$\mathbf{v}_\perp = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} \mathbf{v}^T \quad (13)$$

It should be observed that the current vectors can be varied to inject the same amount of active power to the grid [20]. Therefore, several current control strategies with different control purposes are introduced in the literature. During the grid fault conditions, ripples are found in the injected active/reactive power as well as an increase in the current harmonic distortion. Therefore, several current calculation strategies have been developed to reduce the oscillation of the injected active or reactive power into the grid and improve the current harmonic profile. It is possible to obtain zero active or reactive power oscillation only by accepting highly distorted currents in the grid [14].

On the other hand, the intermediate solutions enable to have sinusoidal grid currents while compensating the oscillation of the active/reactive power. These solutions have been proposed with different purposes which are shown in the Table II. The current references are formulated based on the objectives of the controller. Each of these strategies has different effect on the grid voltage and current harmonic distortion. The proposed strategies in [22] have used a variable k_p or k_q or k_{pq} to achieve an intermediate solution between the current THD and the power oscillation. Based on the system characteristics and the required grid codes, one can select the current calculation strategy adequately for the PVPP.

V. EVALUATION RESULTS

The performance of the proposed controller is investigated through the 150 kW PVPP which is connected to the MV 12.47 kV grid by using a step up transformer. The detailed setting of the system is presented in Table III. In this study, four different active/reactive power injection strategies are being investigated based on Case I – single phase fault and Case II – two phases fault:

- Control I: $P^*=0, Q^*=0$,
- Control II: $P^*=S_{max}, Q^*=0$,
- Control III: $P^*=S_{max}/2, Q^*=S_{max}/2$,
- Control IV: $P^*=0, Q^*=S_{max}$.

where S_{max} is the maximum apparent power of the inverter.

The performance of the controller under the four mentioned control strategies is shown in Fig. 3. The X/R ratio of MV lines

Fig. 3. Case I - Comparison of the performance of the controllers under single phase fault: (a) Injected active and reactive power by PVPP;

(b) PCC Phase voltages

Fig. 4. Case I - Three phase voltages and current under single phase fault with Control I and Control II

is 6 in this study. A single phase fault is occurred at Bus 4 which caused a voltage sag of 84% at Bus 3 (PCC) where the PVPP is being connected. During normal operation, the rms values of all phase voltages ($V_{ph,rms}$) are 7.1 kV. The single phase fault at the Bus 4 happened at $t = 6s$.

During $t = 6s$ and $t = 7s$, the PVPP is operated using the control strategy I and the $V_{phB,rms}$ is 6.03kV. The controller is then changed to Control II method at $t = 7s$ when only the active power is injected to the grid. The result shows that there is an increase in the phase voltages as shown in Fig. 3(b). The inverter currents and voltages under Control I and Control II are depicted in Fig. 4. Since the reference P^* and Q^* are zero before $t = 7s$, the inverter current is zero. However, by increasing the P^* from zero to S_{max} (Control II), the inverter current is also increased within one cycle period. The unity power factor performance is achieved during this period since only the active power is being injected to the grid.

However, when the reactive power is injected to the grid during control strategies III and IV, better enhancement is achieved for the phase voltages. It is clearly observed that the $V_{phB,rms}$ is 3.5% higher when under control strategy IV as compared to the control strategy I.

Fig. 5. Case II - Performance of the controllers under two phase fault at Bus 4 with grid lines of X/R=25

On top of that, various control strategies have different effect on the grid voltage depending on the grid line impedances and loads. The mentioned relationship between the controls and the grid characteristics is validated in Case II of this study where the impedance of the MV benchmark grid is changed to $X/R = 25$. On top of that, a two phase fault is occurred at Bus 4 this time which caused a 68% voltage sag at PCC. The performances of the controllers in the Case II are shown in Fig. 5. The results have clearly evident that the phase voltage is effectively improved by 5% by injecting only reactive power to the grid using Control IV. Therefore, it is important to know the grid characteristics for selecting the proper control strategy to achieve better grid voltage enhancement during faults.

VI. CONCLUSION

The performance of the medium and large-scale PVPPs under grid faults is investigated in this study. Several studies on the determination of the reference active and reactive power as well as the calculation of the reference currents under unbalanced grid faults are reviewed along with their characteristics. Four different active/reactive power injection strategies are implemented on the 150 kW NPC grid-connected multi-string PVPP which is connected to the 12.47 kV power distribution system. It is clearly shown that once the grid impedances and loads are more inductive, the injection of reactive power results in better voltage enhancement on the phase voltages. Therefore the grid characteristics should be considered in selecting the proper control strategy to achieve better voltage enhancement under unbalanced grid faults.

VII. REFERENCES

- [1] P. I. Muoka, M. E. Haque, A. Gargoom, and M. Negnevitsky, "Modeling, simulation and hardware implementation of a PV power plant in a distributed energy generation system," in *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, 2013, pp. 1–6.
- [2] G. Dehnavi and H. L. Ginn, "Load sharing among converters in an autonomous microgrid in presence of wind and PV sources," in *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, 2013, pp. 1–6.
- [3] B.-I. Craciun, T. Kerekes, D. Sera, and R. Teodorescu, "Overview of recent Grid Codes for PV power integration," in *2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, 2012, pp. 959–965.
- [4] "IEEE standard for interconnecting distributed resources with electric power systems," IEEE Std 1547-2003, July 2003.
- [5] Dehghani Tafti, Hossein; Maswood, Ali I.; Ukil, Abhisek; Gabriel, Ooi H.P.; Ziyoun, Lim, "NPC photovoltaic grid-connected inverter using proportional-resonant controller," *Power and Energy Engineering Conference (APPEEC)*, 2014 *IEEE PES Asia-Pacific*, pp.1-6.
- [6] A. Yazdani, A. R. Di Fazio, H. Ghoddami, M. Russo, M. Kazerani, J. Jatskevich, et al., "Modeling Guidelines and a Benchmark for Power System Simulation Studies of Three-Phase Single-Stage Photovoltaic Systems," *IEEE Trans. Power Del.*, vol. 26, pp. 1247–1264, 2011.
- [7] H. Pinkymol, A. Maswood, O. Gabriel, and L. Ziyoun, "Analysis of 3-level inverter scheme with dc-link voltage balancing using ls-pwm and svm techniques," in *Renewable Energy Research and Applications (ICRERA)*, 2013 *International Conference on*, pp. 1036–1041.
- [8] M. Bollen, "Characterisation of voltage sags experienced by three-phase adjustable-speed drives," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1666–1671, 1997.
- [9] A. Camacho, M. Castilla, J. Miret, J. C. Vasquez, and E. Alarcon-Gallo, "Flexible voltage support control for three-phase distributed generation inverters under grid fault," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1429–1441, 2013.
- [10] J. Miret, M. Castilla, A. Camacho, L. G. De Vicuña, and J. Matas, "Control scheme for photovoltaic three-phase inverters to minimize peak currents during unbalanced grid-voltage sags," *IEEE Trans. Power Electron.*, vol. 27, no. 10, pp. 4262–4271, 2012.
- [11] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1398–1409, 2006.
- [12] N. Saadat, S. S. Choi, and D. M. Vilathgamuwa, "A series-connected photovoltaic distributed generator capable of enhancing power quality," *IEEE Trans. Energy Convers.*, vol. 28, no. 4, pp. 1026–1035, 2013.
- [13] M. Mirhosseini, J. Pou, and V. G. Agelidis, "Single- and Two-Stage Inverter-Based Grid-Connected Photovoltaic Power Plants With Ride-Through Capability Under Grid Faults," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1150–1159, Jul. 2015.
- [14] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Design and analysis of active power control strategies for distributed generation inverters under unbalanced grid faults," *IET Gener. Transm. Distrib.*, vol. 4, no. 8, p. 905, 2010.
- [15] Y. Yongheng, F. Blaabjerg, and W. Huai, "Low-Voltage Ride-Through of Single-Phase Transformerless Photovoltaic Inverters," *IEEE Trans. Ind. Electron.*, vol. 50, no. 3, pp. 1942–1952, 2014.
- [16] P. . Rodriguez, a. V. Timbus, R. . Teodorescu, M. . Liserre, and F. . Blaabjerg, "Flexible Active Power Control of Distributed Power Generation Systems During Grid Faults," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2583–2592, 2007.
- [17] A. Camacho Santiago, M. Castilla Fernandez, J. Miret Tomas, R. Guzman Sola, and A. Borrell Sanz, "Reactive power control for distributed generation power plants to comply with voltage limits during grid faults," *IEEE Trans. power Electron.*, vol. PP, no. 99, pp. 6224–6234, 2014.
- [18] M. Castilla, J. Miret, A. Camacho, J. Matas, and L. G. De Vicuña, "Voltage support control strategies for static synchronous compensators under unbalanced voltage sags," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 808–820, 2014.
- [19] A. Camacho, M. Castilla, J. Miret, A. Borrell, and L. G. de Vicuña, "Active and Reactive Power Strategies With Peak Current Limitation for Distributed Generation Inverters During Unbalanced Grid Faults," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1515–1525, Mar. 2015.
- [20] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components," *IEEE Trans. Ind. Appl.*, vol. IA-20, no. 3, pp. 625–630, 1984.
- [21] P. Rodríguez, A. V. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg, "Independent PQ control for distributed power generation systems under grid faults," in *IECON Proceedings (Industrial Electronics Conference)*, 2006, no. 2, pp. 5185–5190.
- [22] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Pliant active and reactive power control for grid-interactive converters under unbalanced voltage dips," *IEEE Trans. Power Electron.*, vol. 26, no. 5, pp. 1511–1521, 2011.