

PAPER • OPEN ACCESS

## Reactive Power Control of a 3-phase Grid-Connected Building Integrated Photovoltaic System

To cite this article: M J M A Rasul and Mohan Kolhe 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **605** 012012

View the [article online](#) for updates and enhancements.

# Reactive Power Control of a 3-phase Grid-Connected Building Integrated Photovoltaic System

**M J M A Rasul and Mohan Kolhe**

Dept. of Engineering Sciences, Faculty of Engineering and Science,

University of Agder (UiA), N-4898 Grimstad, Norway

[ashikmar@gmail.com](mailto:ashikmar@gmail.com), [mohan.l.kolhe@uia.no](mailto:mohan.l.kolhe@uia.no)

**Abstract.** Recently, a tendency in the growing of grid-connected building integrated photovoltaic (BIPV) systems has been noticed in most countries. Hence, high penetration of PV power into the system network can be observed in many points in the network. This may cause severe problems in the distribution network originated by the intermittent behaviour of PV systems. As a feasible solution, the reactive power capability of voltage source inverter in PV systems can be employed rather than approaching expensive grid infrastructures in the distribution network. The purpose of this study is to implement a 3-phase grid-connected BIPV system with reactive power control to regulate the system voltage and improve the system power factor. Subsequent to this, the system model is designed and developed in MATLAB Simulink application. The inverter control system along with the reactive power control is developed for the proper system operation at different system conditions to reduce the var compensation on the utility grid. A better system accuracy of the developed system model is verified by validating with real system data.

## 1. Introduction

Presently, a tendency in the rapid growth of energy has been noticed in the world. Hence in most of the countries, renewable energy resources (RES) have been utilized in electricity production. The main available RESs are hydroelectric, biomass, photovoltaic, wind, geothermal and tidal systems and also called the alternative source of energy which can be used again and again. Consequently, this increase in renewable energy generation systems combined with power electronic systems, the microgrid concept has been developed. The capability of operating in an uninterruptible way either grid-connected or islanding mode is the main benefit of a microgrid.

Integrating RESs such as wind and solar, into the utility grid at the distribution level, is a trending fact. These distributed energy resources (DERs) supply power directly to the grid via power electronic converters where the final stage is a DC-AC inverter between the DERs and the grid. In recent in years, Photovoltaic (PV) system has been the fastest growing power generation system worldwide, has a total capacity of 228 GW at the end 2015 [1]. Generally, the available types of PV systems are residential scale, commercial scale and utility scale in which capacities range from few kilowatts to hundreds of megawatts.

These PV systems inject real power to the grid via at many points in the distribution network. Since this is an effective solution for rapid growing energy demand, but this will bring adverse consequences on the entire distribution network. This is because of the intermittent behavior of the PV energy which accordingly have an impact on the availability, reliability, and quality of the distributed grid. Due to



this intermittent nature and cumulative real power injections at different points, it is a very much complex process of making reliable estimations of the power circulations throughout the distribution network employing a few readings at a few different locations. In case of high PV production level, the whole power system will be out of control and there is a potential risk of significant reverse power circulation, and accordingly causing unacceptable voltage hike in the network voltage [2]-[4].

To overcome this abnormal voltage over-limits situations, the expensive grid infrastructures such as under-load tap changing transformers (ULTC), step voltage regulators (SVR), and fixed and switchable capacitors (FC and SC), can be deployed or the reactive power control ability of voltage source inverter (VSI) in PV systems can be utilized for injecting or absorbing reactive power for voltage compensation as an ancillary service [5],[6]. The advantages of utilizing PV inverters over expensive grid infrastructures are the capability of providing continuous variable reactive power which enables to manage the voltage more closely, and inverter quick response in comparison with switched capacitors [7].

Previously the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems (IEEE Std 1547, 2003) [8] states that the DERs are not permitted to regulate the voltage at the point of common coupling (PCC). Due to some technical problems arise with high PV penetration level after rapid growth in PV energy production, the amendment IEEE Std 1547a-2014 [9] unleashes the restrictions that the DERs are allowed to actively engage in regulating the grid voltage by making alterations to the active and reactive power productions of the DERs coupled with mutual agreements with the distribution grid operators and the DERs.

Hence, the PV inverters can be utilized as the fast acting local var compensators in the areas with significant levels of PV penetration, providing reactive power absorbed by local loads as measured at their point of common coupling (PCC) and subsequently help to enhance the power factor (PF) at PCC. This will assist to attenuate the voltage regulation problems along with the PF improvement while enhancing the grid stability and maximizing the power transmission capability by reducing transmission loss. In the meantime, this will be a significant economic benefit for consumers to avoid the cost of the equipment required to control the PF.

With the rapid growth in the penetration level of PV power on the distribution system, voltage fluctuations issues can be arisen around the location of the interconnection of PV systems due to the real power injection of PV systems. The reactive power control functionality of PV inverter has been utilized to support the voltage regulation at the distribution level. In recent years, most of the researches have been focused on the reactive power control strategies for grid-connected PV inverters for active contribution on the voltage regulation.

Different techniques have been discussed for the voltage support, based on the reactive power compensation of the PV inverter in literature. Those can be grouped as fixed PF (fixed  $\cos\phi$ ), PF as a function of the active power ( $\cos\phi(P)$ ) fed into the network, fixed reactive power (fixed  $Q$ ), reactive power as a function of the voltage at the point of common coupling ( $Q(V)$ ) [10],[11] and reactive power as a function the active power ( $Q(P)$ ) [12]. Besides these technologies, several studies have been presented based on the reactive power control along with the active power curtailment for voltage regulation problem [13]-[15].

Reference [16] presented a three-phase grid interactive PV inverter with reactive power ability to support the grid voltage regulation. The proposed system was enabled to operate in unity PF, variable PF, and zero PF to meet the grid requirements. In [17], an adaptive decentralized voltage restriction control by the autonomous reactive power control of grid-connected PV inverters was presented and tested on different LV grids to reduce the necessity of additional grid reinforcement measures. The proposed strategy based on the V-Q characteristics with a dead band where the reactive power injection or consumption by the inverter was initialized when the voltage limitations exceed. The work in [18] addressed a reactive power control ( $Q(V)$ ) relying on voltage for an inverter with a PF of 0.9 for compensating the voltage rise due to the PV power feed in an MV network located in Belgium.

A power control approach based on the single-phase active-reactive power theory which was controlled by system conditions and specific demands from both system operators and customers was

presented in [19] to enable the PV inverters to perform the multi-functional ancillary services such as “low voltage ride through (LVRT), reactive power compensation and reliability-oriented thermal management” on PV inverters. The prescribed power control strategy was developed and utilized under the limitation of the PV inverter ratings. Similarly, in [20], an inverter control strategy was based on the PQ theory which facilitates to produce the active power and compensate the reactive power of the loads during daytime while only compensating the reactive power of the loads during night time.

Utilizing analysis of voltage sensitivity by setting a location dependent PF to each PV inverter units for the grid voltage support control was presented in [21] as a decentralized reactive power. In this work, the combination of aforementioned strategies,  $\cos\phi(P)$  and  $Q(V)$ , was employed to avoid the unnecessary absorption or injection of reactive power during over-voltage conditions. A similar approach using the voltage sensitivity analysis was discussed in [22] for the reactive power control of the PV systems, to attenuate the voltage fluctuations due to the active power variations of the PV systems. The effect on the inverter efficiency was discussed for three different modes of reactive power control to investigate the inverter performance.

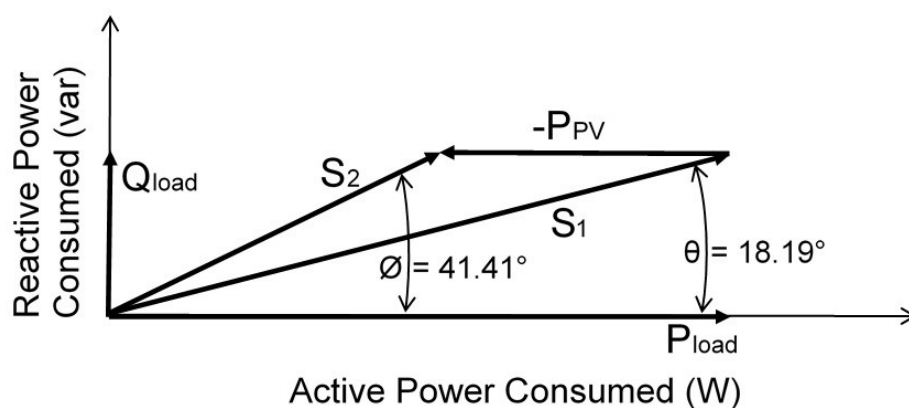
In [23], an inverter reactive power injection control was designed, based on the volt/var control as a “radial optimal power flow (OPF) problem”, subjected to the constraints of voltage and PV inverter reactive power limit where the objective was to reduce the line losses, the energy consumptions and the cost of inverter losses when not operating at unity PF. Reference [24] discussed a method, based on the absorption and injection of uneven reactive power by three-phase PV inverters, to avoid the voltage unbalance due to the high penetration of single-phase inverters in the LV grid. In this proposed method, the average values of the phase voltages at the PCC of the PV inverters were employed as the references for the balancing algorithm for controlling each phase independently to achieve uneven compensation and also reducing the over-voltage conditions.

An active power dependent (APD) ( $Q(P)$ ) voltage regulation method was proposed in [25] in which the required reactive power to manage the voltage was calculated in terms of the penetrated real power of a PV system. In this proposed method, an active power threshold, based on the investigation of the “voltage sensitivity matrix”, was employed as a start point above which the PV system was ready to consume reactive power to regulate the voltage. Reference [26] discussed an active power dependent reactive power compensation method without utilizing a threshold into the system where the aim was to optimally dispatch the inverter reactive power while maintaining the voltage within an admissible range and minimizing the resistive losses over the entire network. An “optimal inverter dispatch (OID)” framework was proposed in [27] where the task was to determine both the real and reactive power set points of the PV inverter so that to optimize the network operation by minimizing the power losses while assuring the voltage regulation and adhering to other electrical network constraints. The proposed OID framework increased the adaptability over the volt/var support and the active power restriction, by invoking a combination control of active and reactive powers generated by the PV inverters.

The work in [28] proposed a control strategy for the PV inverters to enhance the operational performance of the unbalanced four-wire distribution networks with high PV production, based on the optimal generation capability of reactive power and the real power restriction. An optimization problem with the objectives of voltage magnitude, network losses, PV production and active power restriction costs was addressed in previous work to find the optimum control values. In [29], a combination of droop-based inverter reactive power control technique with the active power curtailment (APC) technique was addressed to maintain the local voltage profile within pre-defined limits, in the case of large-scale PV implementation in a specific location. In this approach, the APC was employed only to improve the inductive reactive power generation at the maximum PV generation time.

Based on the literature reviews, the inverter reactive power compensation on both voltage regulation and PF improvement on building integrated PV (BIPV) systems have not been considered together. Hence, this research work is mostly focused on enabling reactive power control of a grid-

connected BIPV system for automatic voltage regulation and PF improvement based on PCC load conditions. The reactive power control system is mainly subjected to the inverter capacity with the instantaneous PV power without any active power curtailment injecting to the grid. Most BIPV systems operate at unity PF where the systems inject only real power to the grid. This may have the effect of lowering the PF at the PCC of a lagging power system. Figure 1 indicates an example of this effect. The power relationship of the relevant load is given as  $S_1$  at a PF of 0.95 ( $18.15^\circ$ ) lagging. If a PV system that injects only active power at a unity PF, is installed at the PCC, the PF of the power combination  $S_2$  that is seen at the PCC will reduce to 0.75 ( $41.41^\circ$ ) lagging. Even though for a small-scale residential PV system, this cannot be neglected. Hence, it would be financially favourable to the electrical power system as well as to the consumers if the PV systems could operate with the facility of reactive power compensation at a local level.



**Figure 1.** Active and reactive power relationship for a unity power factor PV system.

## 2. Modeling of PV system components

In grid-connected PV systems, the power electronic devices are used to connect the PV model into the grid because of its stochastic nature. The different PV system configurations are concerned to connect the PV modules into the grid.

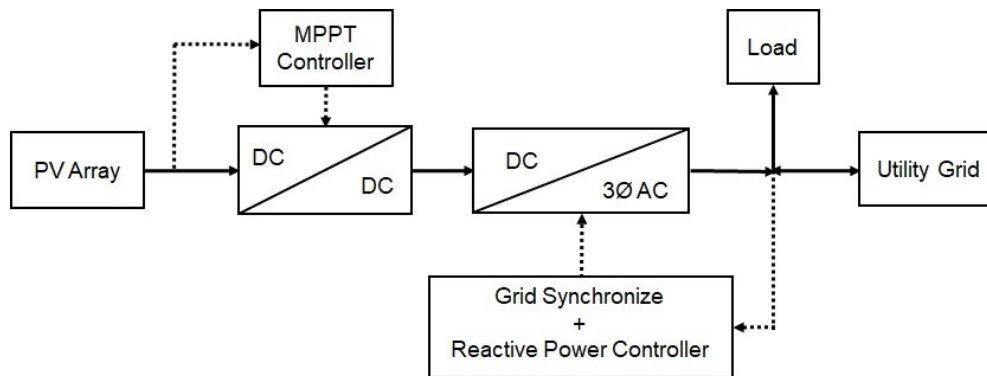
Usually, the configurations can be divided into two categories, such as the PV inverters with DC/DC converter (Double-Stage) and the PV inverters without DC/DC converter (Single-Stage) [30], [31].

The double-stage PV system with a boost converter is used for this research study for boosting the PV voltage to a higher level. In this case, the maximum power point tracking (MPPT) is controlled by the boost DC-DC converter. The boost DC-DC converter is connected to the grid through a DC/AC inverter, which takes care of the grid current control and the grid synchronization [32].

Figure 2 represents the overall system configuration diagram of the grid-connected BIPV system. The system components are connected by the solid lines to represent the power flow while the control systems are connected by the dotted lines to represent the signal flow.

### 2.1. PV array model

The PV array block which is included in the MATLAB Simulink library is used as the PV array model. The PV array block enables to select the inbuilt preset PV model from the National Renewable Energy Laboratory (NREL) System Advisor Model. The PV array model is implemented as strings of the module connected in parallel. The string module is built up with series connected modules. As the main inputs of the PV array module, the solar intensity and the cell temperature values are considered. The SunPower PV panel is considered in the modeling and the PV model specifications are given in table 1.



**Figure 2.** Overall system configuration diagram of the grid-connected BIPV system.

**Table 1.** PV module specifications (SUNPOWER SPR-305E-WHT-U).

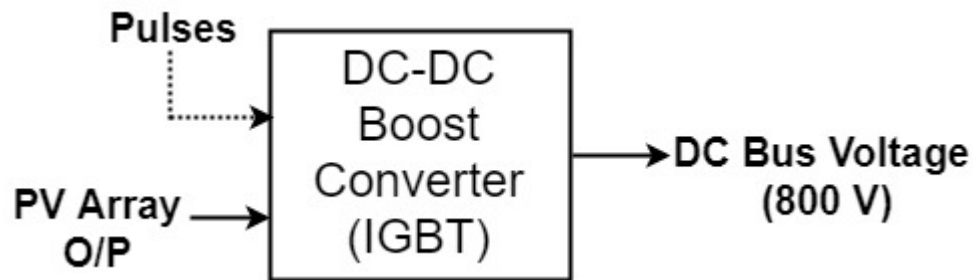
PV Module	
Maximum Power (W)	305.226
Open Circuit Voltage (V)	64.2
Short Circuit Current (A)	5.96
Voltage at MPP (V)	54.7
Current at MPP (A)	5.58
Cells per module	96
PV Array Module	
Modules in series	5
Modules in parallel	5
Maximum Power (kW)	7.63

### 2.2. DC-DC boost converter model

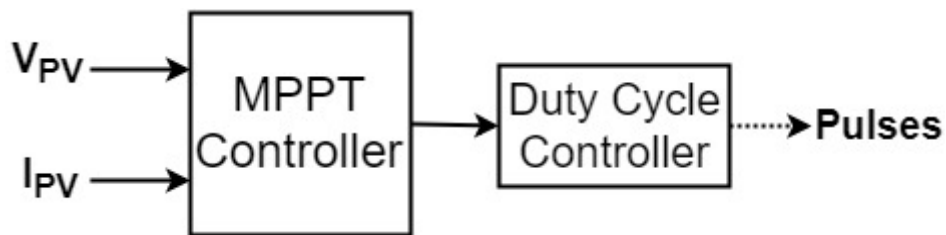
To efficiently track the MPP of the PV array, the duty cycle of the converter is varied by the boost converter under all conditions. The DC bus voltage of the system is kept at 800 V. When PV array is in MPP operating condition under  $1000 \text{ W/m}^2$  of solar irradiance and  $25^\circ\text{C}$  of cell temperature, its output voltage is 273.1 V. Hence, a DC-DC boost converter is deployed to step up the PV array output voltage. The model of the boost converter is shown in figure 3. The IGBT is utilized as the power switching device in the converter.

### 2.3. Boost converter controller model

The gate pulse for the IGBT is generated accordingly by varying the duty ratio in order to track the MPP of the PV panel. The incremental conductance algorithm is utilized to follow the MPP voltage of the PV panel and the duty cycle is continuously changed accordingly to produce the pulses for the boost converter. The model of the boost converter controller with MPPT function is illustrated in figure 4. The initial duty cycle is set as 0.5 in the controller.



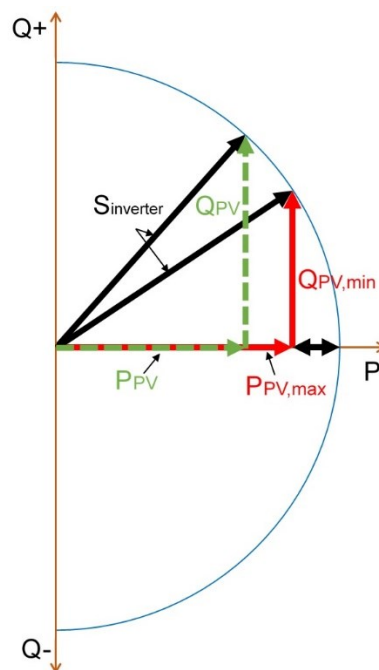
**Figure 3.** DC-DC boost converter model.



**Figure 4.** MPPT controller model

#### 2.4. Voltage source inverter (VSI) model

In grid-connected PV systems, the main task of the DC-AC inverter or VSI is to convert the PV array DC power to the AC power with grid synchronization, while managing the boost converter DC output voltage in double-stage configurations. In this research study, the inverter offers the reactive power compensation service as an additional service. Hence, the two-quadrant operation of the VSI is available as shown in figure 5.



**Figure 5.** VSI 2-quadrant operation

The selected inverter capacity of 9.5 kVA is larger than the maximum PV capacity of 7.63 kW where the inverter maximum operating PF is 0.8 at the maximum PV capacity. Consequently, the inverter has the ability to produce reactive power at the maximum PV system operation as indicated in figure 5. The P-Q relationship of the inverter is given in equation (1).

$$Q = \begin{cases} S \times \sin \left[ \cos^{-1} \left( \frac{S}{P_{PV,max}} \right) \right]; & P = P_{PV,max} \\ \sqrt{S^2 - P^2} & ; P = P_{PV,max} \end{cases} \quad (1)$$

Where S is the Inverter capacity, P is the instantaneous PV Power of the PV array,  $P_{PV,max}$  is the maximum PV power of the PV array and Q is the reactive power of the inverter.

A three phase PWM generator is used to drive the IGBTs in the inverter. The VSI sets the input DC voltage at 800 V and transforms into a three-phase AC voltage of 400 Vrms with a frequency of 50 Hz. The harmonics caused by the inverter is filtered out by deploying an LC filter. The VSI model is depicted in figure 6.

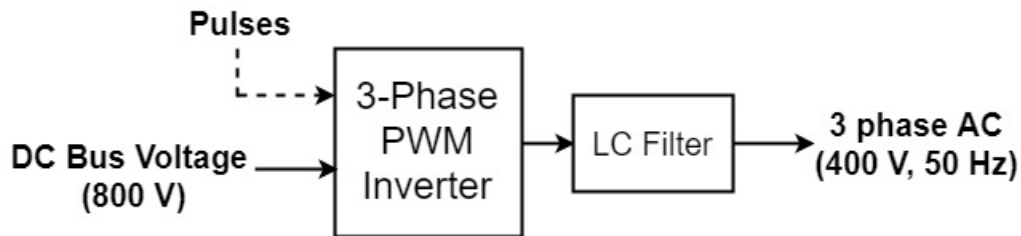


Figure 6. VSI model

### 2.5. VSI controller model

The inverter controller system shown in figure 7 is responsible for generating the PWM signals in the way to synchronize the PV system with the grid. The control system consists of a DC voltage regulator, a phase lockup loop (PLL) block, a current controller block, and a PWM signal generation block. The PLL converts the three-phase time varying system into DC system components ( $[V_d, V_q]$  are voltage components and  $[I_d, I_q]$  are current components) and measures these DC components along with the phase angle of the grid which are to be used for the grid synchronization purpose.

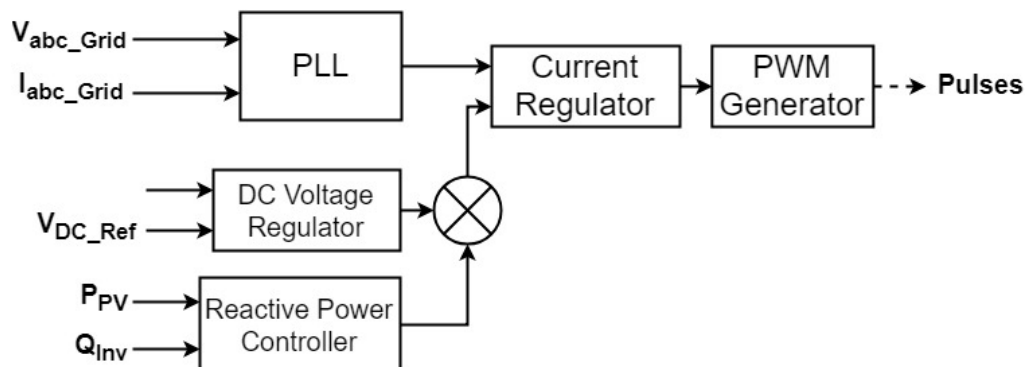


Figure 7. VSI controller model

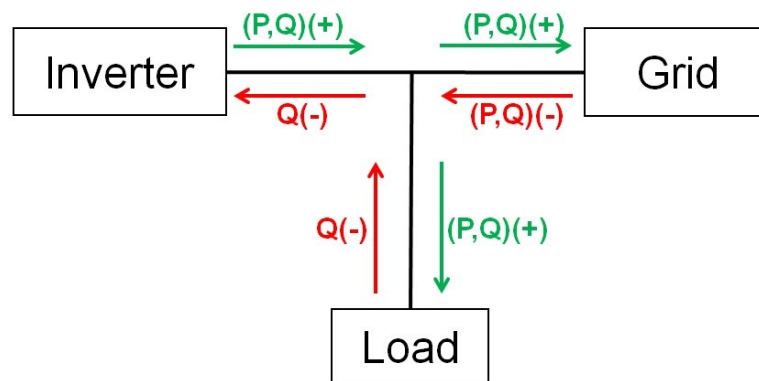
The DC voltage regulator generates the  $I_d$  current reference which is to produce the instantaneous PV power from the inverter as an active power. The  $I_q$  current reference is generated from reactive power controller to maintain the inverter output voltage within the range of  $\pm 5\%$  of 400 V by producing relevant reactive power from the inverter. The current controller output gives the references



of  $V_d$  and  $V_q$  based on the  $I_d$  and  $I_q$  references with the measured  $I_d$ ,  $I_q$  and  $V_d$ ,  $V_q$  values from the PLL. The PWM signal is generated based on the three modulating signals which are generated from  $V_d$  and  $V_q$ . The reactive power controller is responsible for regulating the voltage at the PCC within the admissible limits while improving the PF. Thus, the controller guides the inverter to absorb or provide reactive power related to the required conditions. It is achieved by generating the required  $I_q$  reference to the current controller. The reactive power control is based on the voltage behavior at the PCC and subjected to the inverter limitation. The voltage at the PCC is continuously measured and determined the proper  $I_q$  reference relevant to the instantaneous PV power to manage the voltage and improve the PF at the PCC.

### 3. Results and Discussions

The system power flow relationship with the sign convention as represented in figure 8 is very important fact in the process of system analyzing. The general rule for the sign convention is referenced to the inverter operation. If the inverter feeds, the sign is positive and if the inverter consumes, the sign is negative. Based on this, the opposite sign is assigned for injection and consumption for both the grid and the load.



**Figure 8.** Relationship of the system power flow characteristic

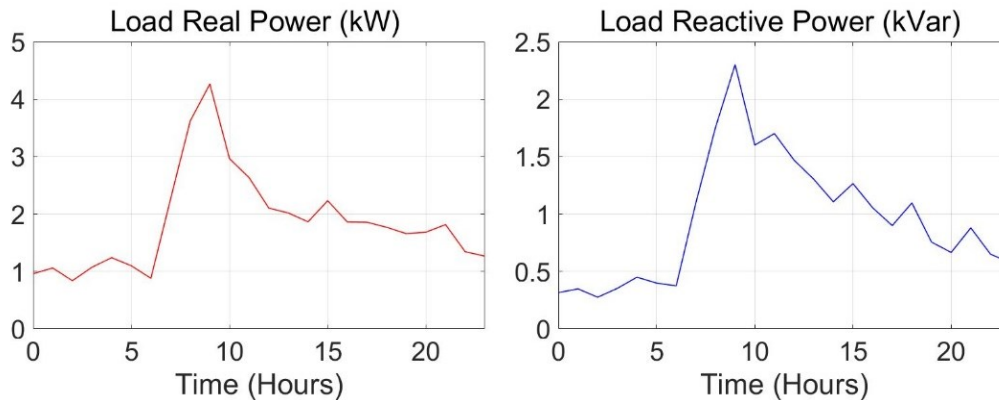
To analyze the effectiveness of the inverter reactive power control, the implemented system is numerically investigated under real data profiles for solar and loading.

In this study, the actual solar radiation along with the cell temperature data which are measured from a Zero Energy Building (ZEB) system is utilized. The ZEB system's load profile is considered as the dynamic load condition at the PCC, where the load PF varies in the range of 0.8 - 0.95.

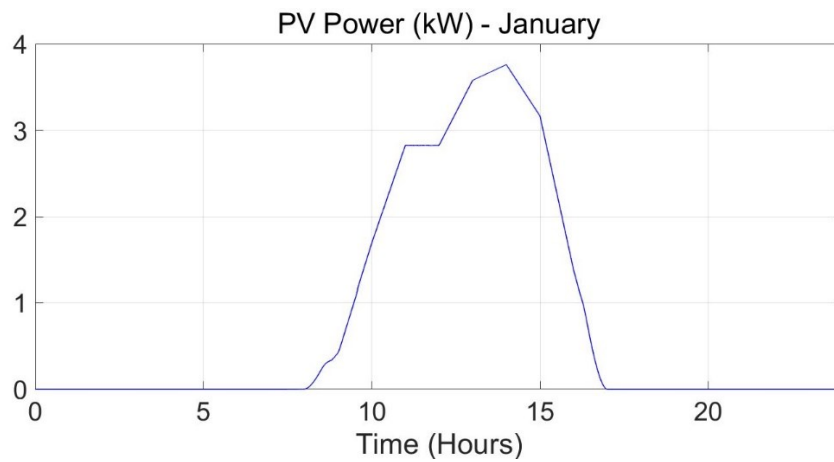
The system is simulated considering the solar radiation and the cell temperature profiles of the midday in the months of January and June.

#### 3.1. System Performance Evaluation in January

The related load profile of the day is depicted in figure 9. The maximum real load of the day is more than 4 kW and the reactive power varies with respect to the load PF. Figure 10 represents the PV power characteristic of the midday in January. The peak PV power is less than 4 kW.

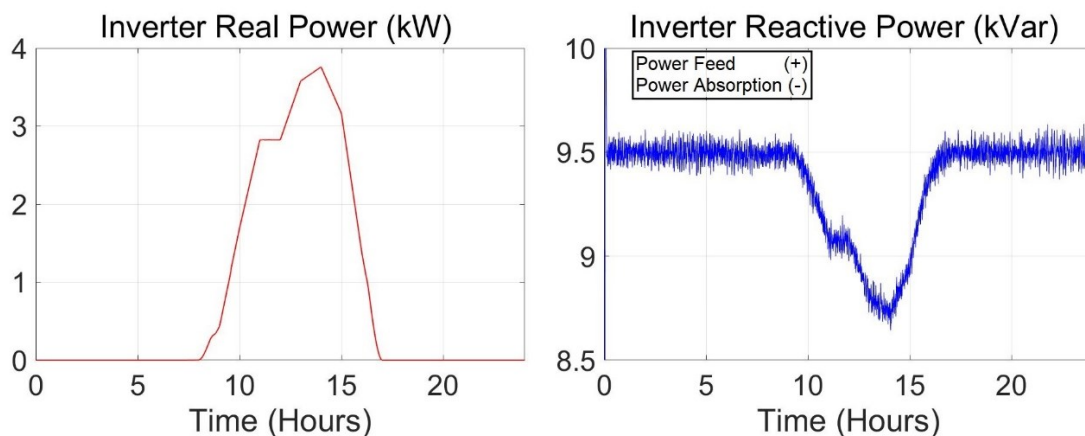


**Figure 9.** Load power flow characteristic

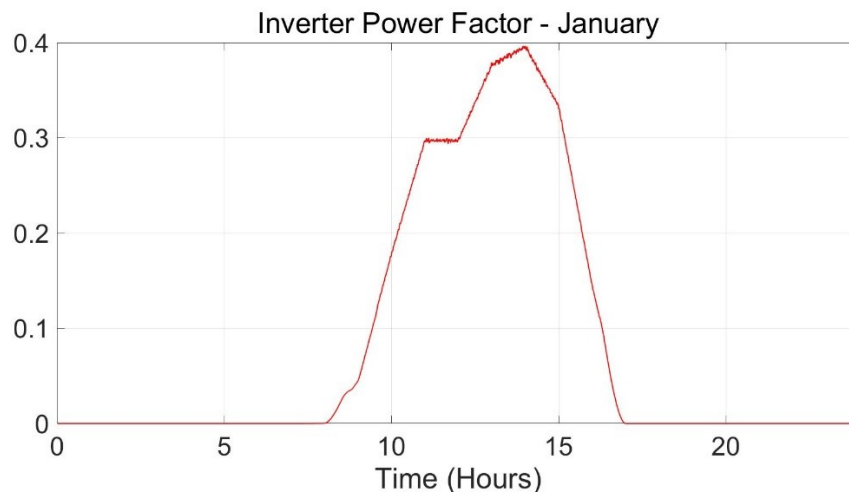


**Figure 10.** PV power characteristic.

The inverter power flow characteristic and the PF variation are illustrated in figure 11 and figure 12 respectively. It can be observed that the inverter var compensation is high when there is no PV power. It gradually decreases with the PV power. The inverter operating PF is in the range of 0 - 0.4.

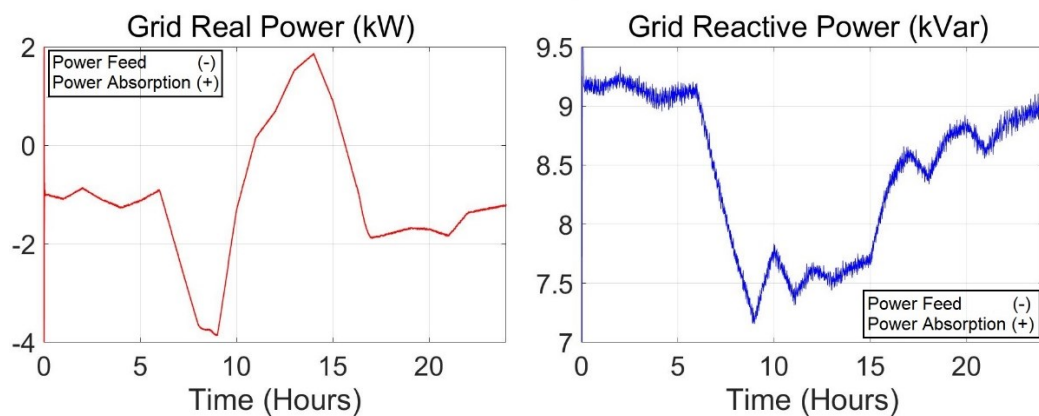


**Figure 11.** Inverter power flow characteristic

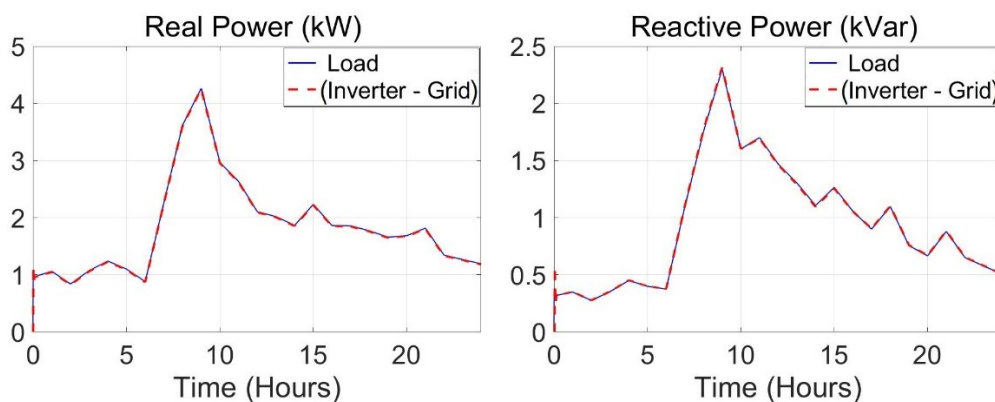


**Figure 12.** Inverter PF characteristic

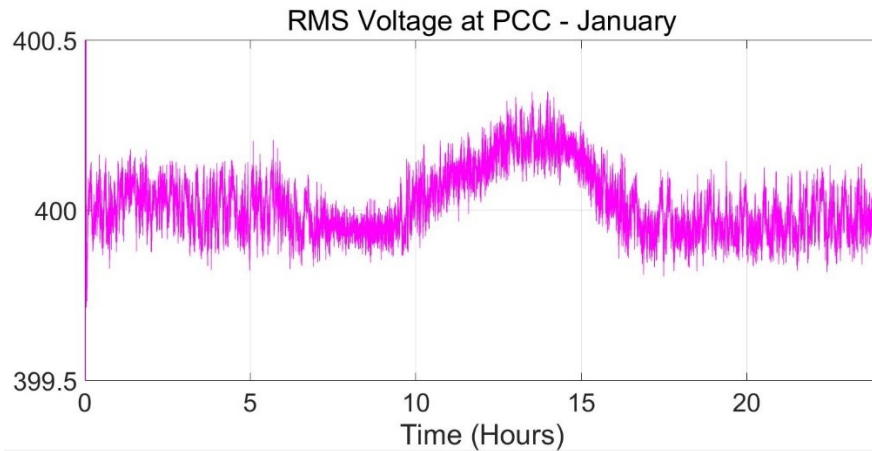
It is observed that the grid is responsible for serving the load when there is no PV power and absorbs the excess reactive power from the inverter as can be illustrated in figure 13. The illustration of the overall system power flow characteristic is given in figure 14. The RMS voltage characteristic at the PCC is shown in figure 15.



**Figure 13.** Grid power flow characteristic



**Figure 14.** System power flow characteristic

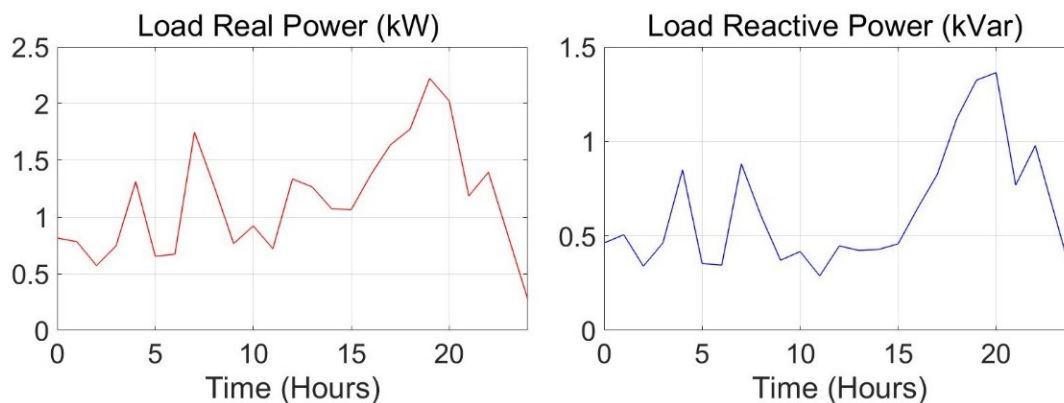


**Figure 15.** RMS voltage characteristic at the PCC

A slight increment is noticed in the RMS voltage when the inverter var compensation is gradually decreasing.

### 3.2. System Performance Evaluation in June

Generally, June is one of the months in the summer season. The system performance is explored using solar radiation and cell temperature profile of the midday in the month of June. The related load profile of the day is shown in figure 16.



**Figure 16.** Load power flow characteristic

The power characteristics of the PV module and the inverter are illustrated in figure 17 and figure 18 respectively. High PV penetrations can be observed throughout the day. The inverter PF characteristic is shown in Figure 19. The inverter operates in maximum operating PF during the mid-hours while lowering the inverter var compensation.

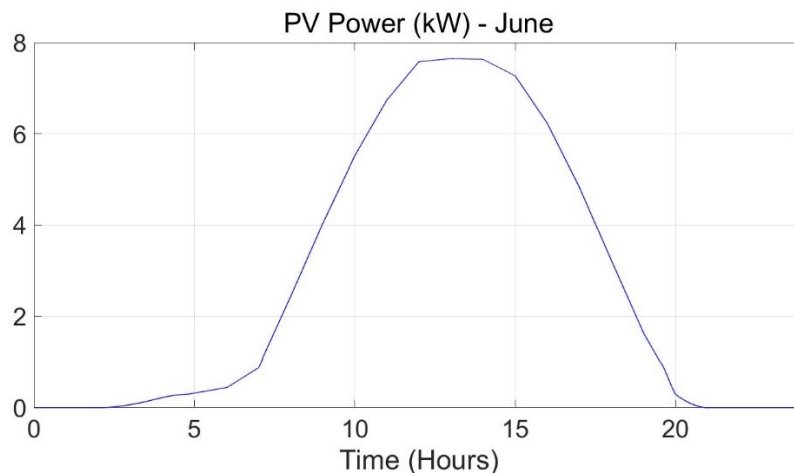


Figure 17. PV power characteristic.

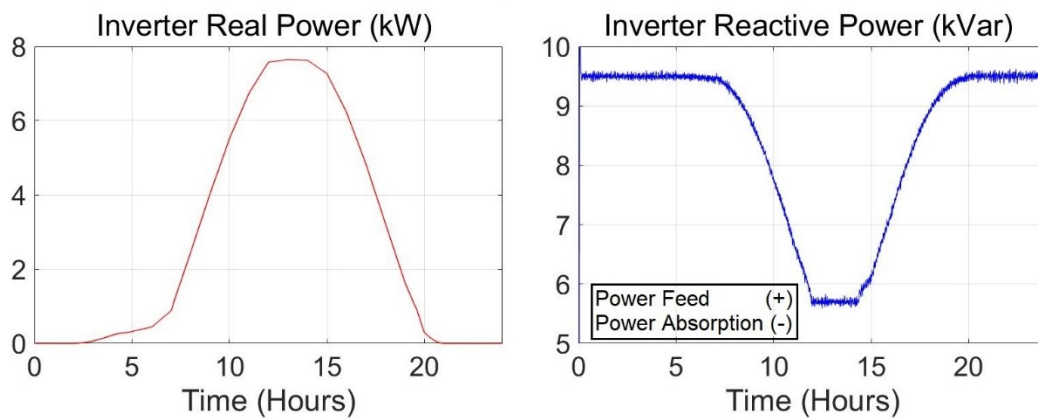


Figure 18. Inverter power flow characteristic

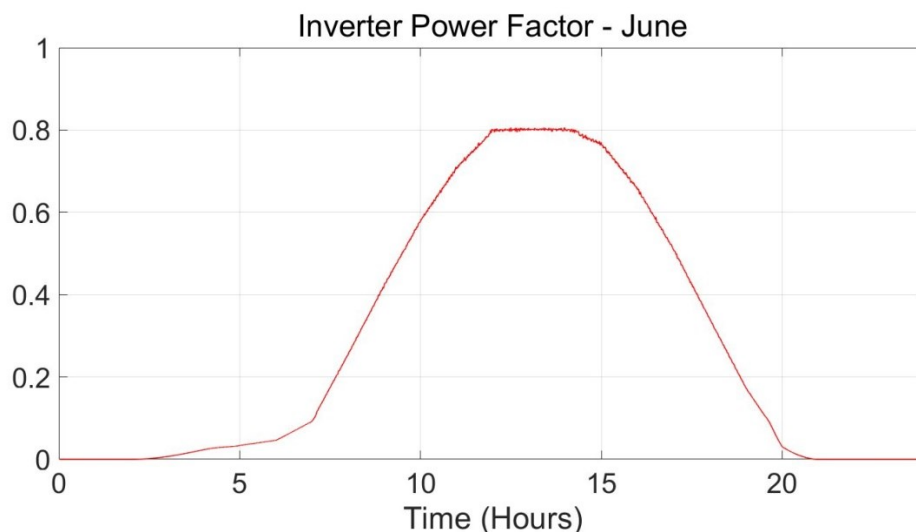
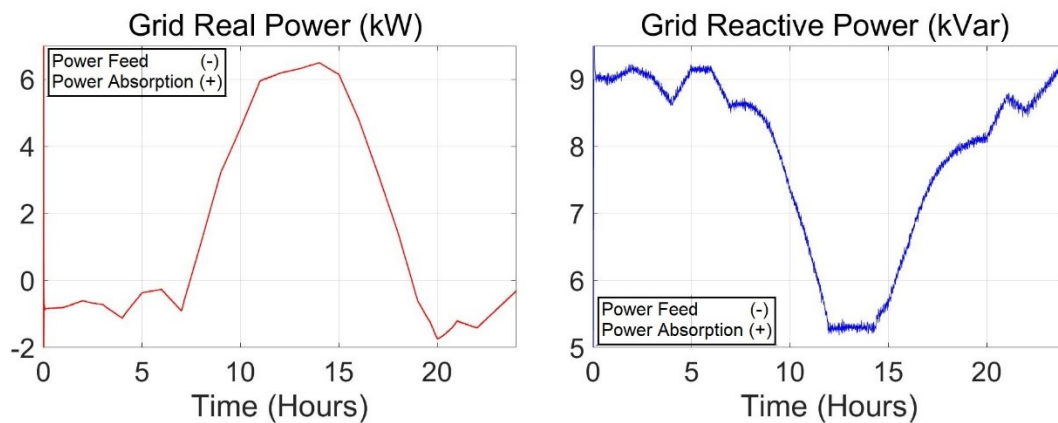
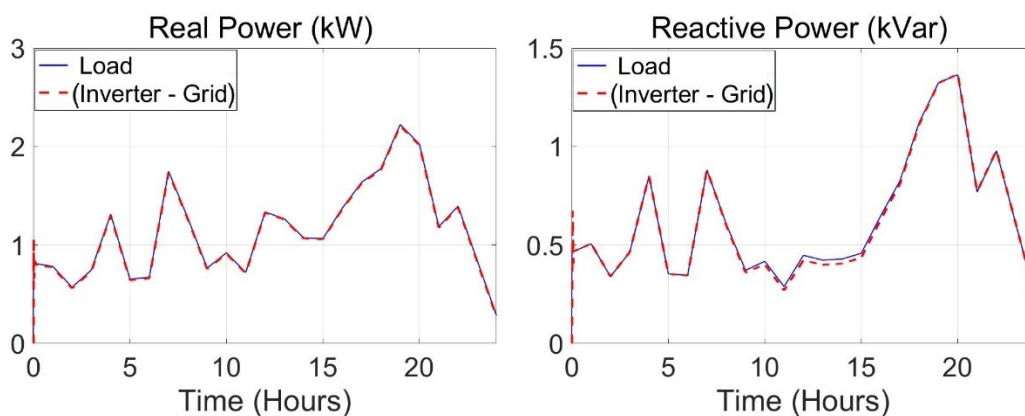


Figure 19. Inverter PF characteristic.

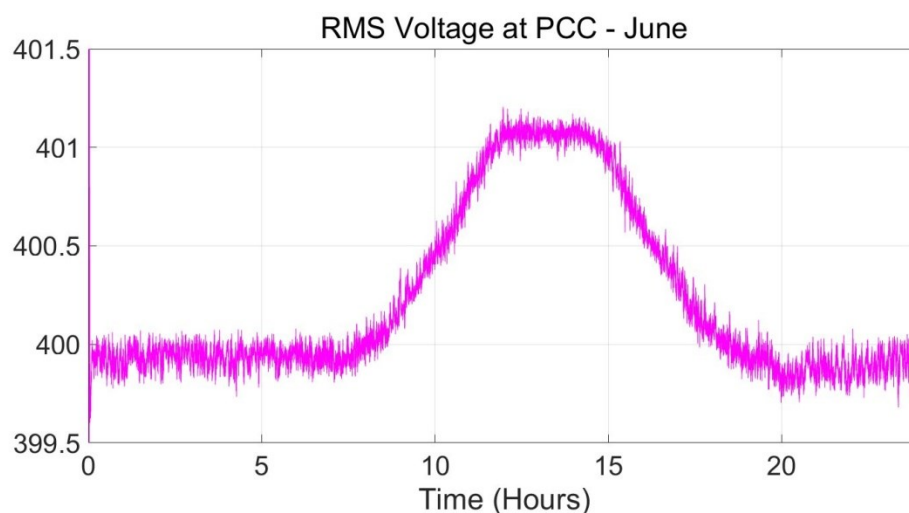
The grid power flow characteristic is indicated in figure 20. The overall system power flow and the RMS voltage characteristic at the PCC are represented in figure 21 and figure 22 respectively.



**Figure 20.** Grid power flow characteristic



**Figure 21.** System power flow characteristic



**Figure 22.** RMS voltage characteristic at the PCC

It can be noticed that the RMS voltage at the PCC escalates above 401 V during the mid-hours of the day when the inverter PF is high. But the overall system manages to operate subject to the limitations.

The simulation result of the overall system performance for real data indicate that the system is ready to feed maximum available power from the PV module and the reactive power subjected to the

inverter capacity regardless of any loading conditions to regulate the system voltage and improve the system PF at low or high PV penetration situations where the grid fulfills the load demand when there is no PV power and absorbs excess reactive power from the inverter. This implies that the system functions with its duties where it leads to a better BIPV system operation by reducing the burden on the utility grid.

#### 4. Conclusions

This research work presents an overall implementation of a 3-phase grid connected BIPV system with the reactive power control capability. The system model includes a PV array module with 7.63 kW capacity, a 3-phase VSI with 9.5 kVA capacity, a boost converter, a 3-phase dynamic load and a utility grid. The main aim of this work is to utilize the reactive power ability of the VSI to regulate the system voltage and improve the system PF by enabling the inverter var compensation while reducing the var compensation from the utility grid. The reactive power control is designed and implemented based on the voltage behavior at the PCC with the inverter limitations and embedded into the inverter control system. Hence, the VSI is responsible for regulating and converting the PV DC power to the AC power while producing and absorbing reactive power as an ancillary service. The boost converter ensures the operation of the PV system at MPP.

The validity and the accuracy of the implemented model were verified by comparing the system performance results with a real system. A better system accuracy was demonstrated from the results. Hence, this research study suggests that more focuses on effective utilization of the reactive power capability of a 3-phase grid-connected BIPV system capitalize on the utility grid to minimize the complexity of the control operation for mitigating the PV system effects on the system network.

#### References

- [1] "International Energy Agency Photovoltaic Power Systems Programme", 2017.[Online]. Available: <http://www.iaa-pvps.org>. [Accessed: 15- Apr- 2018].
- [2] R. Tonkoski, L. A. C. Lopes, "Voltage regulation in radial distribution feeders with high penetration of photovoltaic", Proc. IEEE Energy 2030 Conf., pp. 1-7, 2008.
- [3] Y. Ueda, T. Oozeki, K. Kurokawa, T. Itou, K. Kitamura, Y. Miyamoto, M. Yokota, H. Sugihara, S. Nishikawa, "Analytical results of output restriction due to the voltage increasing of power distribution line in grid-connected clustered PV systems", Conf. Rec. 31st IEEE Photovoltaic Specialists, pp. 1631-1634, 2005.
- [4] Y. Ueda, K. Kurokawa, T. Tanabe, K. Kitamura and H. Sugihara, "Analysis Results of Output Power Loss Due to the Grid Voltage Rise in Grid-Connected Photovoltaic Power Generation Systems", IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 2744-2751, 2008.
- [5] P. Jahangiri and D. Aliprantis, "Distributed Volt/VAr Control by PV Inverters", IEEE Transactions on Power Systems, vol. 28, no. 3, pp. 3429-3439, 2013.
- [6] C. Chang, Y. Lin, Y. Chen and Y. Chang, "Simplified Reactive Power Control for Single-Phase Grid-Connected Photovoltaic Inverters", IEEE Transactions on Industrial Electronics, vol. 61, no. 5, pp. 2286-2296, 2014.
- [7] W. Peng, Y. Baghzouz, S. Haddad, "Local Load Power Factor Correction by a Grid-Interactive PV Inverter" in IEEE-PowerTech, Grenoble, France:, June 2013.
- [8] IEEE Std. 1547-2003, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE, 2003.
- [9] IEEE Std. 1547a-2014, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems - Amendment 1, IEEE, 2014.
- [10] T. Fawzy, D. Premm, B. Bletterie, A. Gorsek, "Active contribution of PV inverters to voltage control - from a smart grid vision to fullscale implementation", Elektrotechnik und Informationstechnik, vol. 128, pp. 110-115, 2011.
- [11] B. Bletterie, S. Kadam, R. Bolgarny and A. Zegers, "Voltage Control with PV Inverters in Low Voltage Networks - In Depth Analysis of Different Concepts and Parameterization

- Criteria", IEEE Transactions on Power Systems, vol. 32, no. 1, pp. 177-185, 2017.
- [12] "VDE-AR-N 4105:2011-08 Forum Netztechnik/Netzbetrieb im VDE (FNN)", Power Generation Systems Connected to the Low/Voltage Distribution Network, 2011.
  - [13] S. Weckx, C. Gonzalez and J. Driesen, "Combined Central and Local Active and Reactive Power Control of PV Inverters", IEEE Transactions on Sustainable Energy, vol. 5, no. 3, pp. 776-784, 2014.
  - [14] M. Ghasemi and M. Parniani, "Prevention of distribution network overvoltage by adaptive droop-based active and reactive power control of PV systems", Electric Power Systems Research, vol. 133, pp. 313-327, 2016.
  - [15] G. Nguyen and K. Uchida, "Active and Reactive Power Control Techniques Based on Feedback Linearization and Fuzzy Logic for Three-Phase Grid Connected Photovoltaic Inverters", Asian Journal of Control, vol. 17, no. 5, pp. 1522-1546, 2014.
  - [16] S. Ozdemir, S. Bayhan, I. Sefa, N. Altin, "Three-phase multilevel grid interactive inverter for pv systems with reactive power support capability", Smart Grid and Renewable Energy (SGRE) 2015 First Workshop on, pp. 1-6, 2015.
  - [17] G. Kerber, R. Witzmann, H. Sappl, "Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters", Proc. Int. Conf. Compatibility and Power Electronics, pp. 129-133, 2009.
  - [18] B. Bletterie, A. Gorsek, T. Fawzy, D. Premm, W. Deprez, F. Truyens, A. Woyte, B. Blazic, B. Uljanic, "Development of innovative voltage control for distribution networks with high photovoltaic penetration: Voltage control in high PV penetration networks", Prog. Photovolt. Res. Appl., vol. 20, no. 6, pp. 747-759, Sep. 2012.
  - [19] Y. Yang, H. Wang, F. Blaabjerg and M. Simes, "Power control exibilities for grid-connected multi-functional photovoltaic inverters", IET Renewable Power Generation, vol. 10, no. 4, pp. 504-513, 2016.
  - [20] G. Tsengenes and G. Adamidis, "Investigation of the behavior of a three phase grid-connected photovoltaic system to control active and reactive power", Electric Power Systems Research, vol. 81, no. 1, pp. 177-184, 2011.
  - [21] E. Demirok, P. Gonzalez, K. Frederiksen, D. Sera, P. Rodriguez and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids", IEEE Journal of Photovoltaics, vol. 1, no. 2, pp. 174-182, 2011.
  - [22] R. Aghatehrani and A. Golnas, "Reactive power control of photovoltaic systems based on the voltage sensitivity analysis", in Proc. IEEE PES Gen. Meet., pp. 1-5, 2012.
  - [23] M. Farivar, R. Neal, C. Clarke, and S. Low, "Optimal inverter VAR control in distribution systems with high PV penetration", in Proc. IEEE PES General Meet., pp. 1-7, 2012.
  - [24] C. Garcia Bajo, S. Hashemi, S.B. Kjsar, Guangya Yang, J. stergaard, "Voltage unbalance mitigation in LV networks using three-phase PV systems", Industrial Technology (ICIT) 2015 IEEE International Conference on, pp. 2875-2879, 17-19 March 2015.
  - [25] A. Samadi, R. Eriksson, L. Soder, B. Rawn and J. Boemer, "Coordinated Active Power-Dependent Voltage Regulation in Distribution Grids With PV Systems", IEEE Transactions on Power Delivery, vol. 29, no. 3, pp. 1454-1464, 2014.
  - [26] K. Turitsyn, P. Sulc, S. Backhaus, M. Chertkov, "Distributed control of reactive power flow in a radial distribution circuit with high photovoltaic penetration", Proc. IEEE Power and Energy Society General Meeting, pp. 1-6, 2010-Jul.
  - [27] E. Dall'Anese, S. Dhople and G. Giannakis, "Optimal Dispatch of Photovoltaic Inverters in Residential Distribution Systems", IEEE Transactions on Sustainable Energy, vol. 5, no. 2, pp. 487-497, 2014.
  - [28] X. Su, M. Masoum and P. Wolfs, "Optimal PV Inverter Reactive Power Control and Real Power Curtailment to Improve Performance of Unbalanced Four-Wire LV Distribution Networks", IEEE Transactions on Sustainable Energy, vol. 5, no. 3, pp. 967-977, 2014.
  - [29] S. Ghosh, S. Rahman, M. Pipattanasomporn, "Local distribution voltage control by reactive



- power injection from PV inverters enhanced with active power curtailment", 2014 IEEE PES General Meeting, pp. 1-5, 2014.
- [30] F. Balaabjerg, R. Teodorescu, Z. Chen, M. Liserre, "Power converters and control of renewable energy systems", In: Proc. 6th Int. Conf. Power Electron, pp1-20. 2004.
- [31] H. Haeberlin, "Evolution of inverters for grid connected PV-systems from 1989 to 2000", in Proc. 17th Eur. Photovoltaic Solar Energy Conf., Munich, Germany, Oct. 22-26, 2001, pp. 426-430.
- [32] J. M. Carrasco et al., "Power-electronic systems for the grid integration of renewable energy sources: A survey", IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1002-1016, Jun. 2006.