IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 29 October 2023, accepted 26 November 2023, date of publication 5 December 2023,
date of current version 15 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3340035

RESEARCH ARTICLE

Improved Inverter Control Techniques in Terms of Hosting Capacity for Solar Photovoltaic Energy With Battery Energy Storage System

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This work was supported by the Deanship of Scientific Research at King Khalid University through Large Group Research Project under Grant RGP.2/179/44.

ABSTRACT The integration of solar photovoltaic systems into low-voltage distribution networks is witnessing significant global growth. While solar photovoltaic generation offers numerous benefits, exceeding the hosting capacity limits in these networks remains a major technical challenge for network operation, particularly in terms of voltage management. Modern smart inverters are equipped with reactive power, active power, and Power Factor (PF) control features, which can assist in regulating network voltage levels. This paper presents a comparative evaluation of smart inverter control methods (reactive power and PF) to achieve maximum solar PV system penetration without impacting the voltage profile at the Point of Common Coupling (PCC). Additionally, a Battery Energy Storage System (BESS) is employed to enhance the system's hosting capacity. The active power, reactive power, and bus voltage of the system are analyzed under different control methods using MATLAB/Simulink to determine the most effective approach for achieving maximum hosting capacity without compromising bus voltage. The modeling includes a PV system connected to the grid with various control strategies. The results demonstrate an increase in the Hosting Capacity (HC) of the network, thereby improving grid characteristics. The integration of smart inverter functionalities will greatly facilitate the integration of PV solar installations into electricity grids.

INDEX TERMS Battery energy storage system, hosting capacity, photovoltaic energy, distribution system, inverter control techniques.

NOMENCLATURE

PV	Photovoltaic.
LV	Low- voltage.
HC	Hosting Capacity.
PCC	Point of Common Coupling.
PQ	Power Quality.
DG	Distributed Generation.
SLD	Single Line Diagram.
DC	Direct Current.
D	A duty cycle of the boost converter.
I_O	Diode's leakage current presents (A).
I_{PV}	The Output current of the PV module
	Input voltage of the boost converter.
v_{in}	Active power from PV system.
P_{PV}	Reference Active Voltage.
V_{d-ref}	Rated apparent power at PCC.
S_{rated}	
DER	Distributed Energy Resources.
PF	Power Factor.
DN	Distribution Network.
DSR	Distribution System Reconfiguration.
MPPT	Maximum Power-Point Tracking.
PQE	Power Quality Enhancement.
AC	Alternating Current.

The associate editor coordinating the review of this manuscript and approving it for publication was Diego Bellan.

ES	Energy Storage.
I_{d-ref}	Reference active current of the PV smart inverter.
I_{q-ref}	Reference reactive current of PV smart inverter.
v_o	Output voltage from the boost converter.
V_a	Applied voltage of the Volt-Var control.
V_{q-ref}	Reference Reactive Voltage.

I. INTRODUCTION

The rising energy demand has prompted the consideration of alternative and renewable sources that do not get depleted over time. Such sources also offer the benefit of reducing carbon emissions, thereby promoting environmental preservation. According to projections, by the year 2050, renewable energy sources are expected to contribute 86% of power production and meet two-thirds of the world's energy consumption [1], [2]. Distributed generation resources, such as photovoltaic (PV) systems, are becoming increasingly popular as renewable energy sources. Multiple photovoltaic panels in solar power stations have been successfully connected to various distribution networks, and they can also be linked to high-voltage networks using different power transformers. Additionally, as traditional fossil-fuel-powered turbines are retired, similar amounts of power are being generated using renewable resources instead [3]. The installation of PV arrays within a low-voltage distribution grid can result in voltage rise problems at the connection feeder and low-voltage infrastructure, leading to efficiency constraints and reduced system reliability [4]. To avoid exceeding the capability of hosting solar panels in a feeder, the allowable limit of such violations needs to be established and adhered to [5] and [6].

The PV hosting capacity has generally defined a maximum connectable solar power output to the grid without impact on the system's regular operation [7]. This definition depends on several factors, including voltage rises that cause the system's power flow to reverse, thermal overloads of conductors and transformers, and unbalanced voltage. Solar PV system evaluation of an actual network due to the impact of several elements, like the topology, feeder characteristics, degree of network loading, and location of PV have been installed [8]. The most frequent problems that restrict the maximum connected PV array capacity are a voltage increase in realistic LV distribution systems and the ensuing violation of statutory limits [9].

Smart inverters, formerly referred to as sophisticated inverters, have caused a fundamental change when it comes to the implementation of Distributed Energy Resources (DER) [10]. These inverters can carry out several tasks including both reactive (Volt-Var) and active power (Volt-Watt) regulation, moreover, voltage regulation, PF control, real power limits, ramp-rate regulation, fault ride-through, and frequency control are some of the processes involved in converting electricity from DC to AC. Various grid support services are currently being demonstrated using smart inverters on actual distribution and transmission systems in several nations [11].

Three distinct hosting capacity methods are available: deterministic, stochastic, and time series. These methods are investigated in the research paper "Methods for calculating photovoltaic capacity in low-voltage distribution networks." They analyze the impact of a considerable proportion of solar PV on the voltage levels and the load on lines, cables, and transformers within these grids. However, they give less attention to other grid abnormalities. The deterministic, stochastic, and time series approaches aim to assess and explore the consequences of higher penetration of PV output power on voltage levels and load distribution [12]. When considering control methods, there are various choices to consider, such as active power control, reactive power control, and combined active and reactive control. Comparing strategies to enhance solar PV hosting capacity based on these control options reveals that Volt-Var control demonstrates superior performance and is more cost-effective than the combined Volt-Var and Volt-Watt control [4]. The smart inverter holds significant importance in hosting capacity control as it assesses the increase in hosting capacity through the control mechanisms present in both the smart inverter and Battery Energy Storage System (BESS). Although the system is the most effective means to enhance hosting capacity, it incurs higher costs due to issues associated with the battery system [13]. Moreover, the improving of HC of PV system by using a harmonic filter, a passive harmonic filter has been designed to enhance the PVHC in low-voltage distribution systems depending on optimization problems by considering over and under-voltage issues, transmission line losses, harmonic distortion produced by non-linear load (six-pulse rectifier), and the capability currents of the line. The results enhance the PVHC and increase the system's power factor by reducing Total Harmonic Distortion (THD) and Total Demand Distortion (TDD) [14]. In [15], a novel approach to harmonic filtering, specifically the implementation of the C-type passive filter, to improve Hosting Capacity (HC) within low-voltage electricity distribution grids. The method proposed in this reference focuses on reducing distortion levels in both current and voltage signals at a bus connected to renewable energy sources, aiming to achieve the highest possible HC through a new optimization process. This comprehensive review covers all aspects related to HC, including its various terms, references, limiting constraints within the networks under study, geographical divisions, and the methods used to determine them. Furthermore, the review study briefly outlines the factors that define hosting capacity in different networks and describes the architectures employed to enhance it [16]. Assessing the ideal configuration of a distribution network in terms of its capacity to accommodate solar energy generation [17]. This text summarizes investigations carried out concerning the assessment of hosting capacity (HC) for solar PV in Low-Voltage (LV) networks. It outlines a feeder-based approach developed to assess solar

PV hosting capacity, particularly when constrained by over-voltage conditions in LV networks [18].

Previous research in this area has primarily emphasized the utilization of Volt-Var control and Volt-Watt control to ascertain the hosting capacity of a low-voltage distribution grid with PV systems. However, this prior work did not incorporate power factor control to enhance the grid's hosting capacity when integrating PV systems, nor did it compare various control strategies to identify the most effective one for maintaining voltage stability at the Point of Common Coupling (PCC).

The integration of renewable energy sources like PV systems, wind turbines, and other systems into the power grid gives rise to several issues. These problems include voltage rise, thermal overload, protection failure, reverse power flow, potential grid upgrades, and increased harmonic distortion. There are various solutions available to tackle these problems, such as smart inverter control (reactive power, power factor, active power, combined active and reactive control), Model Predictive Controller (MPC), and harmonic filter mitigation. This paper introduces and examines the utilization of Volt-Var control, Power Factor (PF) control, and Battery Energy Storage System (BESS) to determine good control to improve the voltage stability at PCC and increase the HC of the grid. In addition, the article aims to conduct a comparative study to determine the most effective control method for maximizing the hosting capacity of solar energy in low-voltage distribution grids, while adhering to standard limit conditions.

The remaining sections of this study can be structured as follows: Following the introduction, Section II presents an overview of the construction of a PV solar system connected to a grid. Section III discusses the implementation of smart inverter control and battery energy storage systems (BESS) to ensure optimal connectivity of the PV system without disrupting normal system operation. Section IV focuses on hosting capacity calculation. In Section V, the results of the hosting capacity assessment for the PV system are presented, comparing the effectiveness of Volt-Var control, power factor (PF) control, and BESS. Finally, Section VI concludes the study and discusses potential avenues for future research.

II. PV SOLAR SYSTEM

The essential components of a PV generation system include the inverter and PV arrays. To generate a solar cell that can supply the required voltage and current for practical applications, the cells are connected in series, parallel, or a combination of both configurations. The electrical model of the PV cell is given in Fig.1. This model consists of a current source in parallel with a diode and two resistors [19].

The e equations describing the behavior of PV panels have been presented in [19]. The output current *Ipv* of a PV module is identified as:

$$I_{PV} = I_{Ph} - I_O\left[\exp\left(\frac{V_{PV} + I_{PV}R_S}{a}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_S}{R_{Sh}} \tag{1}$$

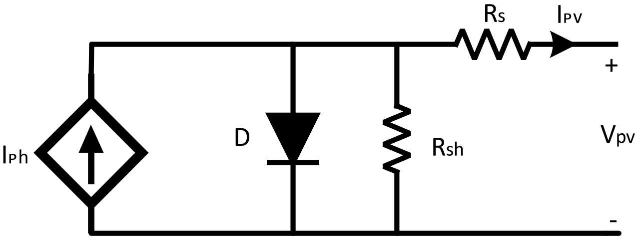


FIGURE 1. Single diode PV cell circuit [19].

where, I_{PV} Output Current (A), I_O diode reverse saturation current (A), V_{pv} terminal voltage (V), R_{Sh} Shunt Resistance, and R_s Series Resistance, a is a constant.

The boost converter which is shown in Fig.2 is a chopper topology that boosts the input DC to a large value of DC depending on the duty cycle value, the duty cycle can be varied from zero to less than unity deters the equation describing the relationship between the input and output has been presented in equation (2) according to [20].

$$v_o = \frac{1}{1 - D} * v_{in} \tag{2}$$

where, v_o is the output voltage from the boost converter, D id duty cycle, and v_{in} is the input voltage of the boost converter.

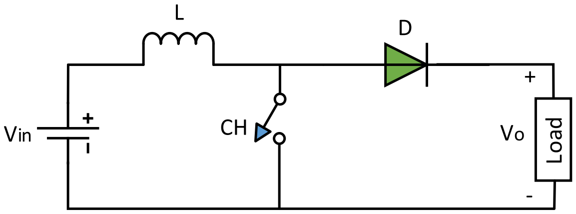


FIGURE 2. Boost converter.

The main interphase units between the PV system and the grid are a DC/DC converter and a DC/AC inverter. The perturbation and observation (P&O) MPPT algorithm is used to control the DC/DC converter to guarantee optimum power generation from the PV source. The produced electricity is transferred to the AC side with the help of an inverter. A few instances of inverter control include grid synchronization, DC connection voltage balancing, and active/reactive power regulation. It is common practice to modify the inverter current for the control of both active and reactive power [19].

The proposed control method will be validated based on the system illustrated in Fig.3. The system consists of a simple low voltage (LV) distribution network that supplies a 100 kVA PV system and a 100 kVA lumped load located 5 km away from the feeder. The detailed specifications of the PV system, which operates at its maximum capacity, are summarized in Table 1. It includes an appropriate number of series and parallel PV arrays with the required PV capacity. The operating conditions for the PV system are set to standard conditions of 1000W/m2 for irradiation level and 25°C for temperature. The temperature and irradiance are fixed at a certain value depending the on deterministic method.

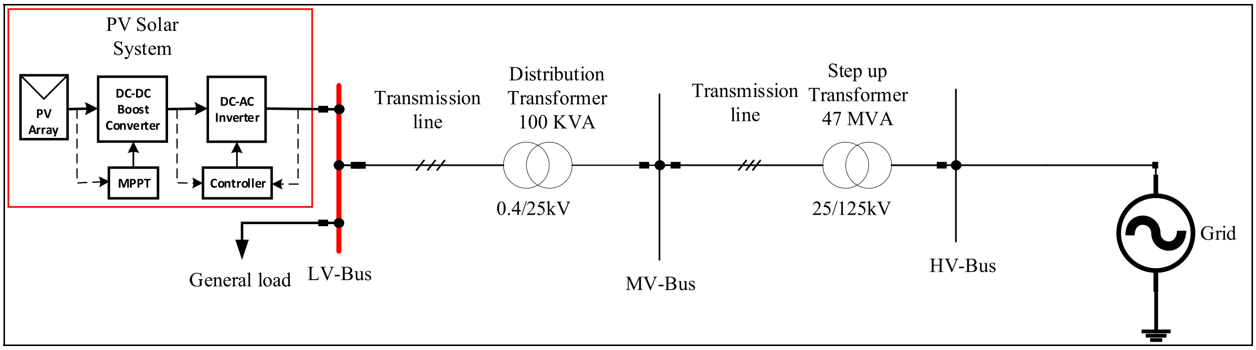


FIGURE 3. A single-line schematic of the test system [21].

TABLE 1. PV solar system parameters.

Parameters	Value
PV Energy Rating	100 KW
Solar Energy Panel	305 W sun power
Current Models at MPP	5.58 A
Voltage Models at MPP	54.7 V
Radiance Restrictions	1000 W/m2
Number of Series Modules	5
Number of Parallel Strings	66
Temperature	25^0C
Distribution Transformer	100KVA(0.26/25)kV
Feeder Length	5 km
Step up transformer	47 MVA (25/125)kV
Resistance of the Line	0.754Ω/km
Inductance of the Line	0.25 mH/km
General Load	10 kVA

III. TYPES OF CONTROL

Various control methods exist to enhance the hosting capacity of solar systems in low-voltage distribution networks. This section demonstrates the implementation of Volt-Var control, PF control, and battery energy storage systems (BESS) to improve the HC.

A. REACTIVE POWER CONTROLLER

The defining characteristic of the reactive power controller is its ability to establish a relationship between the voltage level and the amount of reactive power necessary to keep the electrical potential difference within acceptable limits. Capacitive reactive power is operated at low voltage condition, while inductive reactive is operated at over-voltage condition. When the voltage at PCC reaches the electricity limit, the reactive power regulation operates the PV in various locations at a power factor of one [12].

The reactive power concept is a useful tool for managing the available controllable reactive power of distributed generation resources. It is a function that can be programmed into a PV inverter, which determines the reactive power output based on the voltage at the bus.

The Volt-Var concept is an example of decentralized and autonomous voltage control that establishes the correlation between an inverter's reactive power output and the local voltage at the point of connection [22].

As a result, the reactive power computes the necessary insertion or uptake of reactive power; Q (also known as i_q) at a voltage value, V_o, using (3) [4].

$$Q = \begin{cases} \frac{Vo}{|Vo|} * (|Vo| - db) * K_{iq} & if\ |Vo| > db \\ 0 & Otherwise \end{cases} \tag{3}$$

where V_o ($V_o = V_{ac\_ref} - V_{ac\_mes}$) is the voltage applied, and K_q is the reactive current droop gain. The inverters are large while using their rated capacity, as indicated by [23] and [24], Consequently, they can generate 44% reactive power. The I_{qref} is restricted to avoid violating the inverter's current restriction [24].

The architecture of the PV solar inverter controller and its functionality is presented in Fig. 4. The measured DC voltage is compared to the DC reference and the resulting error signal is amplified by the gain. The PI Controller is used to correct the error signal and generate the I_{d-ref}. The reactive power control is implemented by comparing the measured voltage at the busbar (Bus) with the reference AC voltage. An appropriate controller is employed to correct the error signal and produce I_{q-ref}. The control system is limited by maximum and minimum values. The developed reactive power control method's efficacy in enhancing the hosting capacity is tested by running simulation experiments using MATLAB/Simulink

The PI controller for AC voltage regulation employs the following equation [25].

$$F_{ac}(s) = K_{ac}(1 + \frac{1}{T_{ac}(s)}) \tag{4}$$

where, K_{ac} is the gain of the DC voltage regulator, and T_{ac} is the time constant of the DC voltage regulator in sec.

Grid restrictions that influence PV inverters include factors like over and under-voltage, solar PV placement, feeder length/loading levels, conductor types, and specified voltage limits. These limitations according to

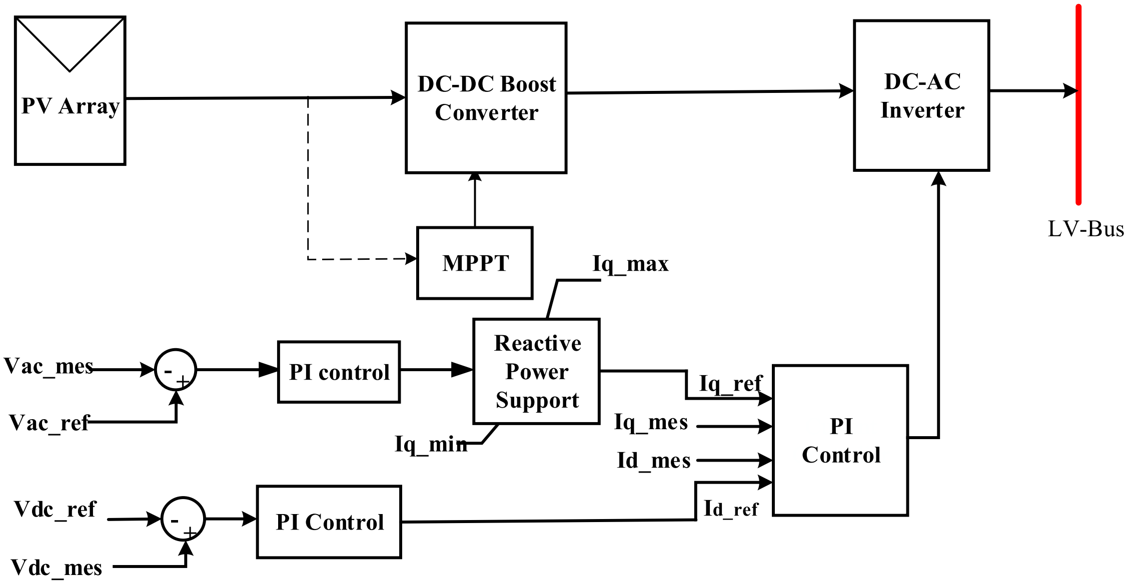


FIGURE 4. The control loop for reactive power regulation in a solar PV inverter system.

IEEE Std.1547-2018 [24], AS/ NZS 4777.2-2015 [26], California Rule 21-2018 [27], and Hawaii Rule 14-2018 (Revised Sheet No. 34B-21) [28].

B. ACTIVE POWER CONTROLLER

Active power control is the ability to modify and control the active power produced by a power generation system. It entails actively managing the amount of power generated or absorbed within the system to uphold stability, specific needs, and adapt to fluctuations in demand or operational circumstances. Active power control is frequently utilized in different energy systems, including renewable energy systems like PV systems, to guarantee effective and dependable power generation and distribution. It enables the alteration of active power output by considering factors such as voltage regulation, frequency control, grid limitations, or specific control strategies [29].

The active power feature is utilized to restrict the real energy output of each PV system separately to mitigate over-voltages that may occur when traditional voltage regulation systems fail to prevent them [30]. This capability can be particularly crucial during the integration of PV systems.

The active power support computes real power insertion from the inverter; P (known as id) is an observed voltage, V_o, by expression (5) [4].

$$P = \begin{cases} P_{max} & if\ V_o \leq IB \\ P_{max} + (V_o - IB) * K_d & if\ IB < V_o \leq IB + AB \\ P_{min} & Otherwise \end{cases} \tag{5}$$

where, V_o ($V_o = V_{ac\_ref} - V_{ac\_mes}$) is the voltage applied, id max is the PV system's greatest actual current available, and K_d is the active current gain.

Fig.5 illustrates the configuration of the PV inverter processor, showcasing the DC voltage measurement in relation to the DC reference. This measurement leads to an error that is subsequently corrected by applying gain, which is then compensated by the PI Controller to produce I_{d_ref}. Additionally, the controller is governed by maximum and minimum values. The efficacy of the developed Active power controller in improving the hosting capacity is assessed through simulation results carried out in MATLAB Simulink.

C. POWER FACTOR CONTROLLER

The power factor is one of the most important factors affecting energy production systems. The smaller the power factor becomes, the higher the reactive power, and this leads to low efficiency and greater fuel consumption in thermal plants. Therefore several methods have emerged to improve the power factor such as capacitor banks, synchronous generators, static VAr compensators, and phase advances [31].

The equations of power factor are used in this paper [32]. Equation (6) expresses the reference active power obtained by the product of the direct axis for reference voltage and the current from the PV system. Also, equation (7) describes the reference reactive power that is absorbed or injected from the PV inverter to maintain the bus voltage and it is obtained by product quadrature axis reference reactive voltage and current. Moreover, equation (8) presents the apparent reference power, which is the product of actual voltage and actual current. Dividing the reference active power by apparent reference power led to obtaining the reference power factor as presented in equation (9). Also, equations (10, 11, 12, and 13) describe the active power, reactive power, apparent power, and power factor measured

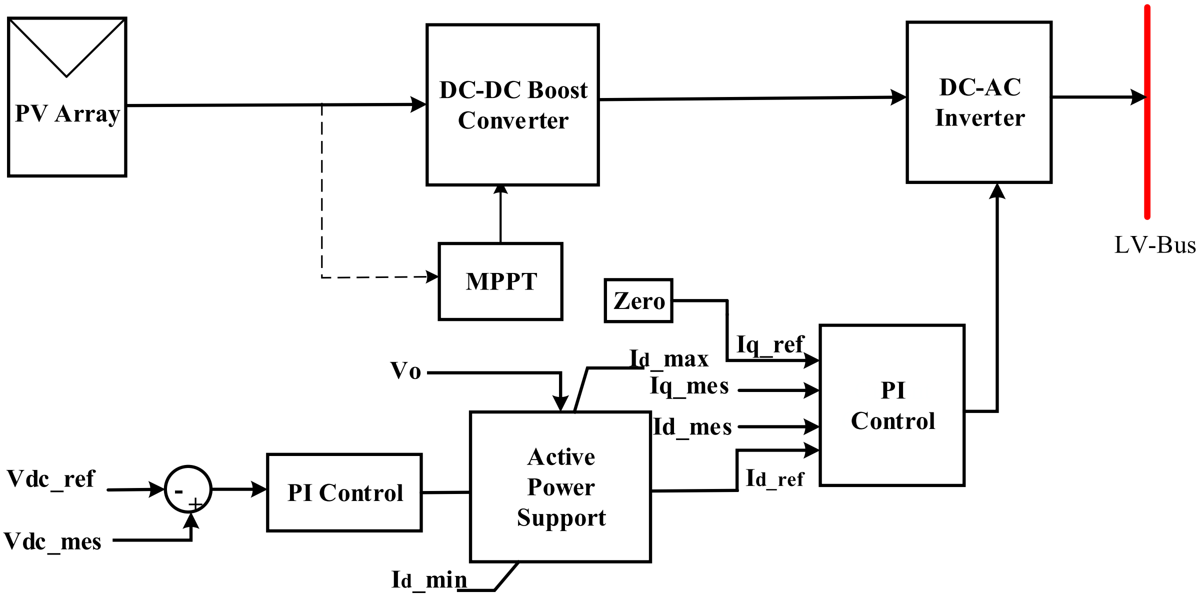


FIGURE 5. The control loop for active power regulation in a solar PV inverter system.

at the point of connection PV solar system.

$$P_{ref} = V_{d-ref} * I_{d-ref} \tag{6}$$

$$Q_{ref} = V_{q-ref} * I_{q-ref} \tag{7}$$

$$S_{ref} = \sqrt{{P_{ref}}^2 + {Q_{ref}}^2} \tag{8}$$

$$PF_{ref} = \frac{P_{ref}}{S_{ref}} \tag{9}$$

$$P_{mes} = V_{d-mes} * I_{d-mes} \tag{10}$$

$$Q_{mes} = V_{q-mes} * I_{q-mes} \tag{11}$$

$$S_{mes} = \sqrt{{P_{mes}}^2 + {Q_{mes}}^2} \tag{12}$$

$$PF_{mes} = \frac{P_{mes}}{S_{mes}} \tag{13}$$

where, $P_{ref}, Q_{ref}, and\ S_{ref}$ are the references active, reactive, and apparent power of the system, also, $P_{mes}, Q_{mes}, and\ S_{mes}$ are the measurements active, reactive, and apparent power of the system. $V_{d-ref}, I_{d-ref}, V_{q-ref}\ and, I_{q-ref}$ are references to the direct axis and quadrature axis voltage and current respectively. $V_{d-mes}, I_{d-mes}, V_{q-mes}, \ and, I_{q-mes}$, are measurements of direct axis and quadrature axis voltage and current respectively, PF_{ref}, PF_{mes} are reference and measurement power factors respectively.

By using equations (6) to (13), the controller for PV solar inverters is created with power factor control as shown in Fig.6.

D. BATTERY ENERGY STORAGE SYSTEM

A Battery Energy Storage System (BESS) is a type of energy storage system that employs batteries to store electrical energy for future use. It has various applications, including load leveling, frequency regulation, and peak shaving. Moreover, BESS can facilitate the integration of renewable energy sources into the power grid, which can be inconsistent and unpredictable. The system can store excess power generated by renewable sources and release it during power shortages, thereby contributing to grid stability and enhancing the reliability of the power supply. BESS finds utility in both residential and commercial environments.

The battery block simulates a charge-dependent voltage source with a finite capacity, along with a series resistance. This voltage source exhibits a reciprocal relationship with charge, as defined by the equation [33].

$$V = V_O \left(1 - \frac{\alpha(1-x)}{1-\beta(1-x)}\right) \tag{14}$$

where:

x is the ratio of the charge left to the rated or full charge for the battery. V_0 is the voltage when the battery is fully charged, which you specify using the Nominal Voltage. α and β are curve-fitting constants.

Fig. 7(a). illustrates the benefits of incorporating a storage system in the low-voltage distribution grid to improve the HC. This figure indicates that the incorporation of a storage system increases the amount of hosting capacity, as compared to when there is no storage system. Additionally, the implementation of a storage system also leads to improved system stability, reduced gas emissions, decreased global warming, and enhanced power quality. Energy storage (ES) technologies will play an important role as a promising HC enhancement tool shortly. ES systems aid in overcoming overvoltage caused by high DG penetration, allowing the system's HC to be increased. Electricity demand and generation can be decoupled using ES systems. Even though ES is still expensive [34]. Fig. 7(b) demonstrated the BESS used in the system.

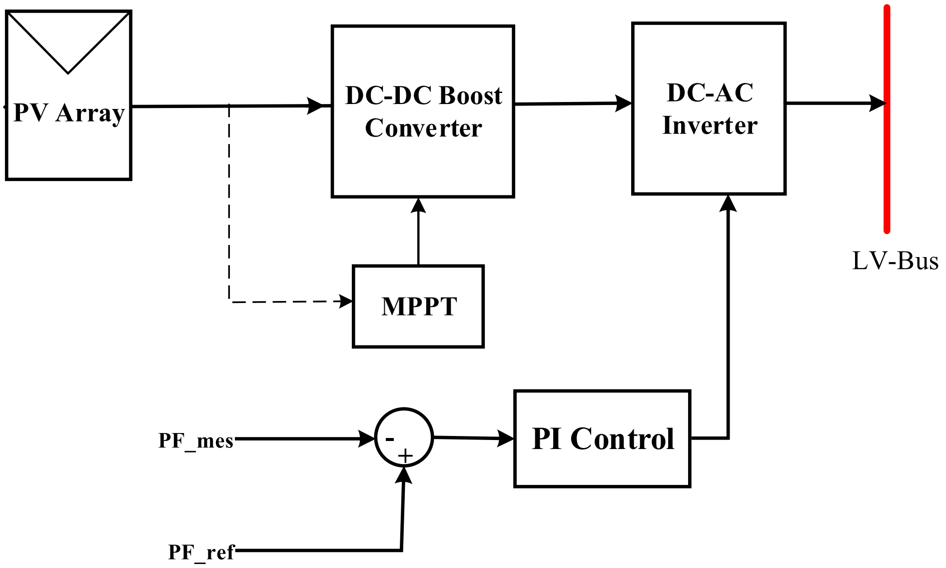


FIGURE 6. The control loop for power factor regulation in a solar PV inverter system.

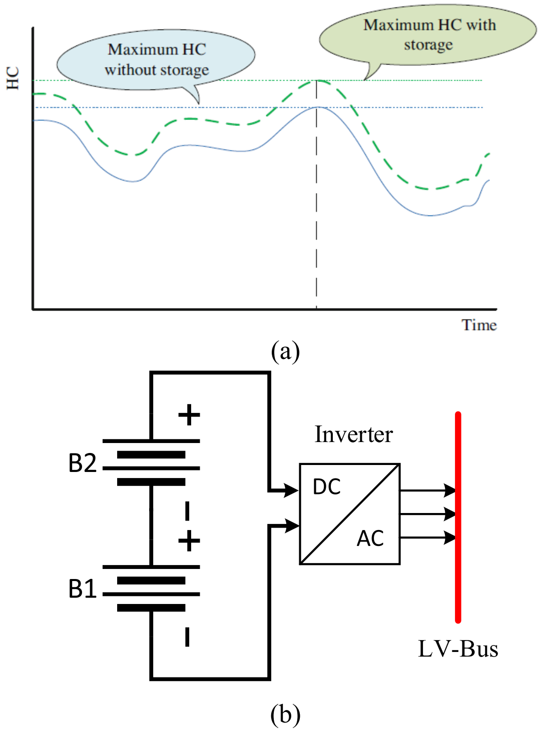


FIGURE 7. (a). Hosting capacity with and without a storage system [34]. (b). Battery energy storage system.

IV. HOSTING CAPACITY CALCULATION

The addition of a new generator or load in a distribution network can impact the power flow. Such a change can lead to an improvement or degradation of network performance for consumers already connected to the network. Thus, it becomes necessary to define the hosting capacity, which is the amount of production or consumption that can be introduced into the network without jeopardizing the quality or reliability of the system for consumers [35].

The excess local generation that a system can handle is often restricted by the distribution networks and their components. This limit is referred to as the hosting capacity and exceeding it can result in the overloading of components, leading to reduced lifespan or system failure.

To assess the hosting capacity, it is necessary to establish appropriate performance indices, which will vary depending on the analysis conducted. These indices will determine whether the network's operational conditions are acceptable or not. The maximum value that a performance index can reach without compromising the system's reliability and adherence to design standards is referred to as the hosting capacity limit. Once this limit is reached, the network will be operating under unacceptable conditions, which can lead to components being overloaded, shortening their lifespan, or even resulting in system failure.

The hosting capacity of the system in a low-voltage distribution grid can be calculated by the following equation [36]

$$HC(\%) = \frac{P_{PV}}{S_{rated}} * 100 \tag{15}$$

where, P_{PV} is the amount of solar PV generation, and S_{rated} is the rated apparent power of the load bus.

The equation of hosting capacity when compared with two controls or compared with control [4].

$$\begin{aligned}&\mathit{Hosting\ Capacity\ Equation}\%\\&\quad=\frac{HC\ (with) - HC\ (without)}{HC\ (without)}\end{aligned} \tag{16}$$

From equation (15) HC (with) is the value of watt when using control and HC (without) is the value of watt when without control.

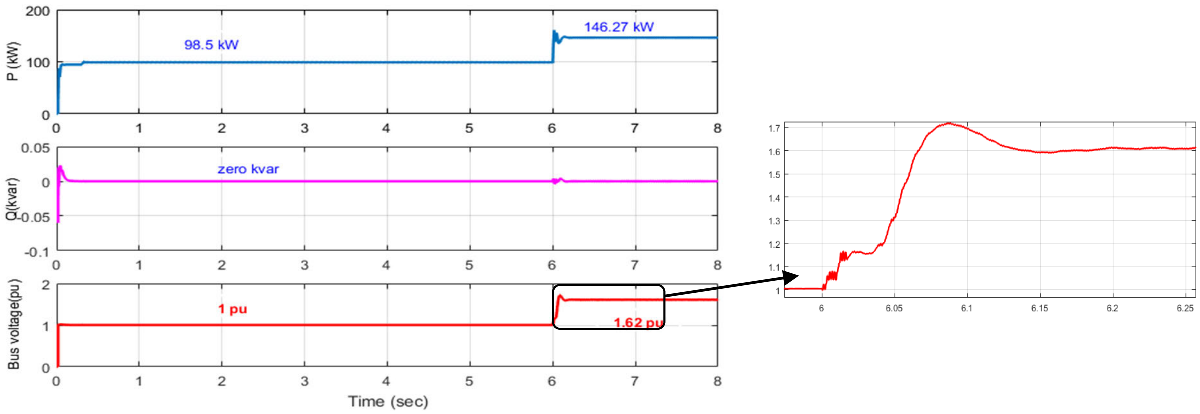


FIGURE 8. **The results of a PV system with a connection to a grid with classic control.**

Increasing a solar system's capacity has the advantage of stabilizing the system by reducing voltage drops and power losses in the grid. Although a battery system provides better hosting performance, there are still several drawbacks, such as the battery's maintenance and cost.

The conventional power system design was unique in that power flow was unidirectional from generation to transmission to distribution. Due to the increasing demand for electrical energy, there is a need for dependable, consistent power; however, the issue with hosting capacity is the reversal of the energy flow.

Smart inverters can mitigate the effects of increased PV penetration by performing active power curtailment and/or reactive compensation. Depending on the voltage level, these devices can provide variable control by acting on the injected active power limit (Volt–Watt control) or reactive compensation (Volt–VAr control). The battery system also contributes to grid integrity and can be programmed to absorb excess PV energy generated.

V. SIMULATION RESULTS

The results of the hosting capacity analysis for PV systems can be divided into three parts. The first part considers the scenario where the PV system is connected to the grid without any controls. The second part examines the implementation of reactive power (Volt-Var) control to address voltage rise issues at the Point of Common Coupling (PCC). Lastly, the third part explores the utilization of Power Factor (PF) control to improve the voltage profile of the system.

A. PERFORMANCE OF STUDIED SYSTEM WITH CLASSIC CONTROL

The outcomes of this operation are depicted in Fig. 8, which showcases the active power, reactive power, and voltage at the bus. The active power generated by the PV system remains constant at 98.5 kW until the solar system's penetration increases at t=6 seconds, reaching 146.27 kW. However, due to the utilization of a traditional inverter, the reactive power of the system remains unchanged. Nevertheless, this increase in solar penetration causes a voltage rise at the Point of Common Coupling (PCC), resulting in the voltage reaching 1.62 pu, which signifies a 62% increase compared to the normal voltage. If this problem persists over an extended period, it can adversely impact the system's quality, equipment performance, line losses, harmonic distortion, and reverse power flow. The penetration level of PV system increases by 50%

B. PERFORMANCE OF STUDIED SYSTEM WITH BESS

The outcomes of this operation are depicted in Fig. 9, which showcases the active power, reactive power, and voltage at the bus. The active power generated by the PV system remains constant at 98.5 kW until the solar system's penetration increases at t=6 seconds, reaching 108.07 kW. However, due to the utilization of a traditional inverter, the reactive power of the system remains unchanged. To address the issue of voltage rise at the Point of Common Coupling (PCC), a battery system is employed. The battery system ensures voltage stability at the PCC by storing excess energy when power generation exceeds the load demand and discharging stored energy when the load demand exceeds power generation from Distributed Generators (DGs). The voltage at the bus is regulated to a maximum of 1.03 per unit (pu) within the defined voltage bus standards. By utilizing control mechanisms, the voltage profile can be significantly improved by 57.3% compared to the scenario without any control measures in place. This enhancement allows for better regulation and stability of the voltage levels. The HC of the system enhanced by 9.7%

C. PERFORMANCE OF STUDIED SYSTEM WITH ACTIVE POWER CONTROL

The Volt-Watt control mechanism involves comparing the reference DC voltage with the measured DC voltage of the PV inverter. The resulting error signal is then inputted to the PI controller to provide active power support. The outcomes of the PV system connected to the grid using Volt-Watt control can be observed in Fig.10. The active power generated by the PV system remains steady at 98.84 kW until the solar system's penetration increases at t=6 seconds,

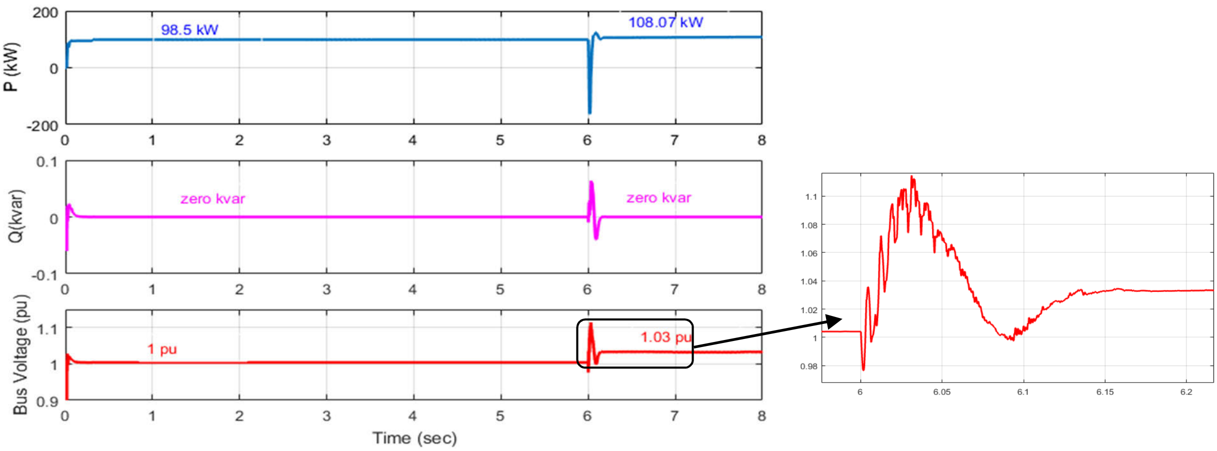


FIGURE 9. The results of a PV system with a connection to a grid with BESS.

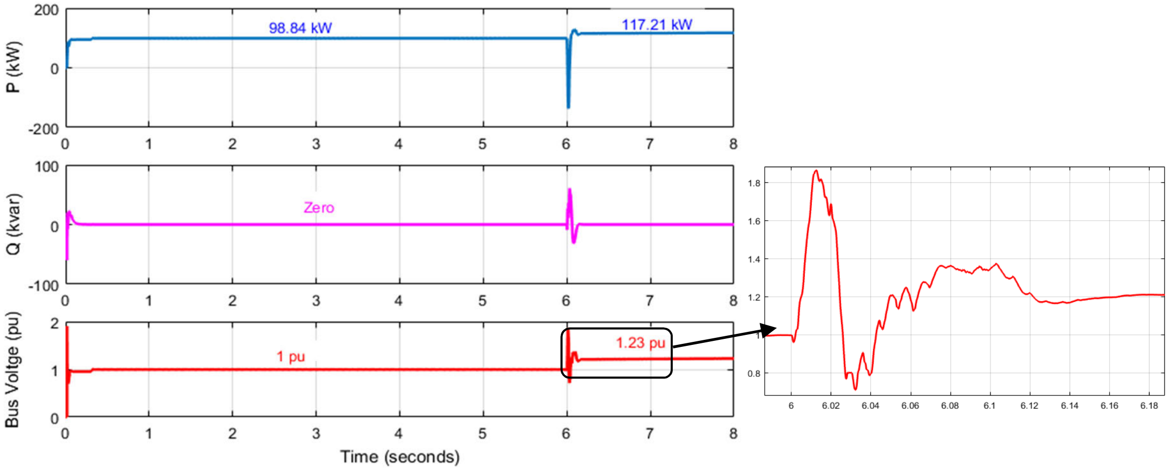


FIGURE 10. The results of a PV system with a connection to a grid with Volt-Watt control.

reaching 117.21 kW. However, the utilization of a traditional inverter keeps the reactive power of the system unaltered. To mitigate the issue of voltage rise at the point of common coupling (PCC), the active power control adjusts the voltage at PCC from 1.62 pu under traditional control to 1.23 pu with Volt-Watt control. As a result, the system's hosting capacity is enhanced by 19% compared to traditional control.

D. PERFORMANCE OF STUDIED SYSTEM WITH REACTIVE POWER CONTROL

The Volt-Var control compared with the reference voltage bus and measured voltage at PCC, the error signal insert to the pi controller, and reactive power limitation. The outcomes of this operation are depicted in Fig. 11, which showcases the active power, reactive power, and voltage at the bus.

The active power generated by the PV system remains constant at 98.5 kW until the solar system's penetration increases at t=6 seconds, reaching 146.27 kW. Moreover, this time the smart inverter (Volt-Var) absorbs the reactive power by equal (53.57) kVAR to limit the voltage rise problem at PCC to reach 1.10 pu by enhancing 47.27% by comparing the connected PV system without using control and Diminishing voltage value by 6.36% when using the storage system. The power factor of the system is equal to .939 lagging. The hosting capacity of the system is enhanced by 94% according to equation (16).

E. PERFORMANCE OF STUDIED SYSTEM WITH POWER FACTOR CONTROL

The PF control compares with the reference power factor at the connection bus and measured power factor at PCC, the error signal inserted to the pi controller. The outcomes of this operation are depicted in Fig. 12, which showcases the active power, reactive power, and voltage at the bus. The active power generated by the PV system remains constant at 98.5 kW until the solar system's penetration increases at t=6 seconds, reaching 146.27 kW. Moreover, in this instance, the smart inverter with PF-Control functionality is employed to address the issue of voltage rise at the point of common coupling (PCC). It accomplishes this by absorbing

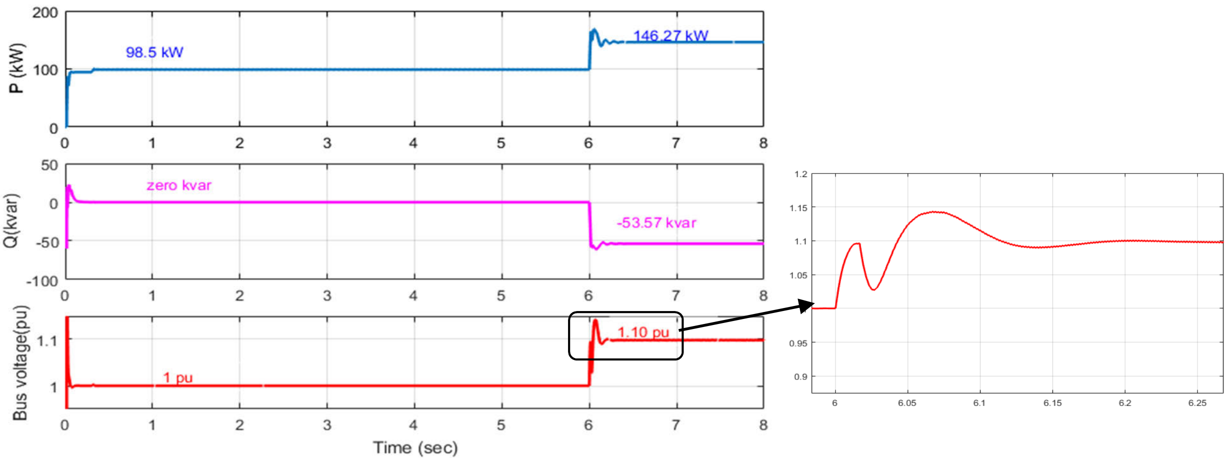


FIGURE 11. The results of a PV system with a connection to a grid with Volt-Var control.

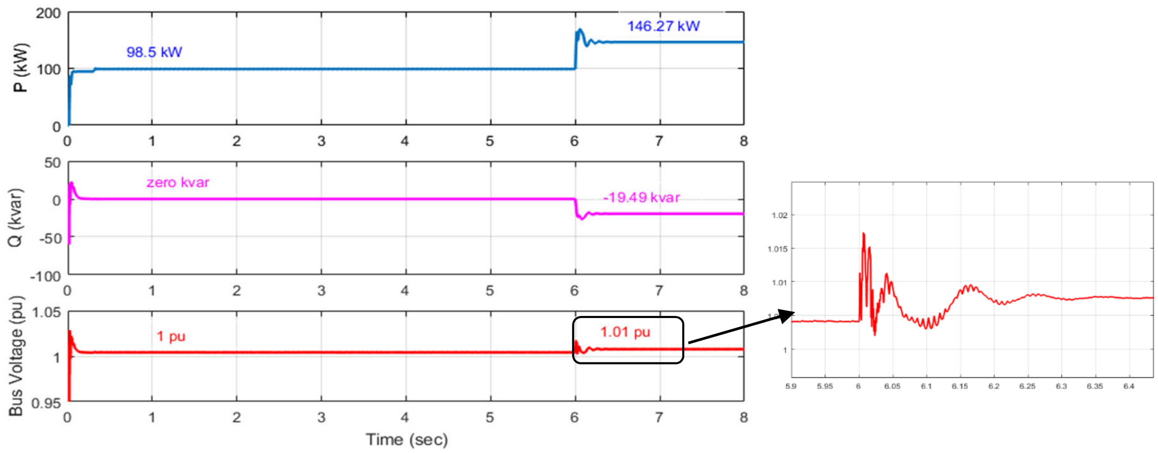


FIGURE 12. The results of a PV system with a connection to a grid with PF control.

reactive power in equal amounts of 19.49 kVAR, effectively limiting the voltage rise problem at the PCC to reach a maximum of 1.01 per unit (pu). This implementation results in a remarkable improvement of 60.4% when compared to the connected PV system without any control measures. Furthermore, it showcases an improvement of 8.91% compared to reactive power control, and a 1.95% improvement when compared to a storage system. The power factor of the system stands at 0.991, indicating a lagging power factor. The hosting capacity of the system is enhanced by 99.1% according to equation (16).

F. THE STUDY OF REACTIVE POWER CONTROL WITH BESS

Reactive power control with a battery energy storage system (BESS) is employed to improve the harmonic content (HC) of the system. Reactive power control enables the provision of reactive power support by injecting or absorbing reactive power into the electrical grid. When the grid voltage is low, the Volt-Var control can inject reactive power to raise the voltage. Conversely, when the voltage is high, the Volt-Var control can absorb reactive power to lower the voltage. Therefore, the Volt-Var control is utilized to enhance the voltage bus while adhering to specified limits. The battery energy storage system is utilized to store active power from the PV system during periods of increased total loads connected to the bus. As a result, the Volt-Var control, in conjunction with BESS, maintains the voltage bus within limits and stores power for future use. Figure 13 depicts the active power, reactive power, and bus voltage. At 6 seconds, the PV solar system's capacity increases by 50 kW. However, the battery system stores the excess active power for future or night-time usage, resulting in an active power value of 130.83 kW. To enhance the voltage bus to approximately 1 per unit (pu) or a value close to it, the inverter control absorbs a reactive power value of 53.57 kVAR. The HC of the system is reaching 92.5%.

G. THE STUDY OF PF CONTROL WITH BESS

Power factor control with a Battery Energy Storage System (BESS) involves managing the reactive power flow to improve the power factor of an electrical system. The power

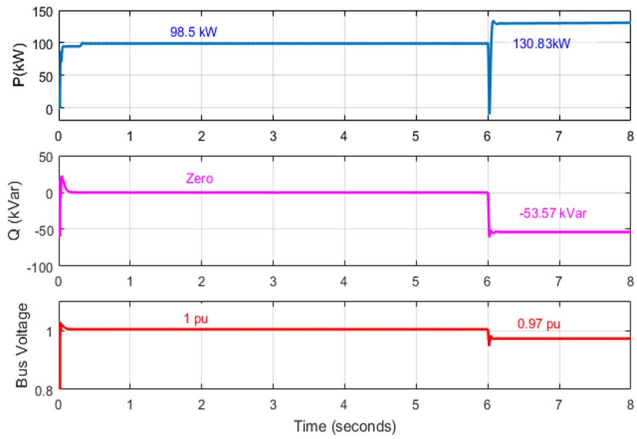


FIGURE 13. The results of a PV system with a connection to a grid with Volt-Var & BESS.

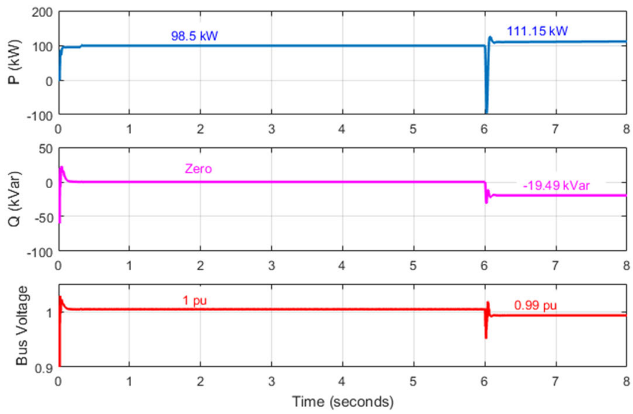
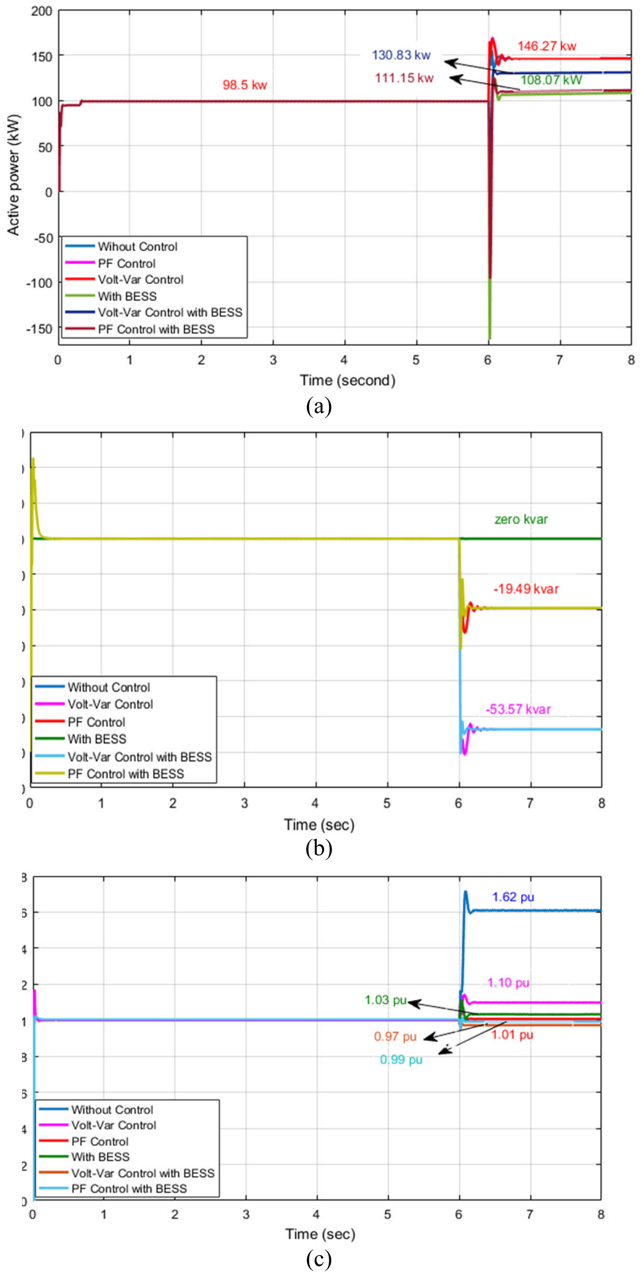


FIGURE 14. The results of a PV system with a connection to a grid with PF control & BESS.

factor is a measure of how effectively electrical power is being utilized and is determined by the ratio of real power (measured in kilowatts, kW) to apparent power (measured in kilovolt-amperes, kVA). Figure 14 illustrates the active power, reactive power, and bus voltage. At the 6-second mark, the capacity of the PV solar system rises by 50 kW. Nevertheless, the battery system stores the surplus active power for future utilization, including night-time, leading to an active power value of 111.15 kW. To enhance the voltage bus to around 1 per unit (pu) or a value in proximity, the inverter control absorbs a reactive power amounting to 19.49 kVAR. The (HC) of the system reaches 98.5%.

H. THE COMPARATIVE STUDY

The results of comparing Volt-Var control and Power Factor (PF) control are presented in Figure 15. Figure 15(a) shows the active power of the system. Notably, the active power remains consistent across different control methods but reduces the usage of the battery system to maintain the voltage at the Point of Common Coupling (PCC). Moreover, the active power also decreases when employing Volt-Var control with BESS and PF control with BESS. This indicates that the system can accommodate additional solar energy without encountering any issues. However, at t=6 seconds, when the penetration level increases, the response of PF control is slower compared to Volt-Var control. In Figure 15(b), the reactive power of the system at the connection bus is depicted. It is observed that PF control absorbs a lower amount of reactive power from the grid compared to Volt-Var control. This implies that employing PF control in the smart inverter reduces the cost of the capacitor bank. Figure 15(c) demonstrates the voltage bus at the Point of Common Coupling (PCC). The voltage bus experiences an 8.91% increase when PF control is utilized, as compared to Volt-Var control, and



(a)

(b)

(c)

FIGURE 15. Comparative study between Volt-Var & PF control (a) active power (b) reactive power (c) bus voltage.

shows a 1.95% enhancement compared to the battery system. The voltage bus plays a crucial role in determining the hosting capacity of the system.

VI. CONCLUSION

The hosting capacity of a photovoltaic (PV) system in a low-voltage distribution grid can be managed through various control mechanisms such as smart inverter control, battery system, reactive power control, and power factor control. Reactive power control is responsible for regulating the bus voltage within specified limits by either absorbing or injecting reactive power from the grid. When employing Volt-Var control for a PV system connected to the grid, the bus voltage increases by 32.1% and decreases by 6.8% compared to a system without any control mechanism or a system solely relying on the battery system. Similarly, power factor (PF) control results in bus voltage increases of 37.65%, 8.2%, and 1.94% when compared to a system without control, Volt-Var control, and a battery system, respectively.

The system's HC experiences a 9.7% increase when Battery Energy Storage Systems (BESS) are utilized. Furthermore, HC is enhanced by 19%, 94%, and 99.1% when employing Volt-Var, Volt-Watt, and Power Factor (PF) control. This comparative study clearly highlights that PF control is the most effective method for ensuring voltage stability at the Point of Common Coupling (PCC).

In the comparative study involving BESS with reactive power control and PF control, it is observed that BESS effectively mitigates voltage profile instability. HC is enhanced by 92.5% and 98.5% when BESS is combined with reactive power control and PF control, respectively.

REFERENCES

[1] IEA Renewables. (2019). *Renewables 2019—Analysis—IEA*. International Energy Agency. [Online]. Available: https://www.iea.org/reports/renewables-2019

[2] M. Bajaj and A. K. Singh, "Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques," *Int. J. Energy Res.*, vol. 44, no. 1, pp. 26–69, 2020, doi: 10.1002/er.4847.

[3] N. Upadhayay, M. Nadarajah, and A. Ghosh, "System strength improvement using reactive compensation for enhanced PV hosting capacity," in *Proc. 29th Australas. Universities Power Eng. Conf. (AUPEC)*, Nov. 2019, pp. 1–6, doi: 10.1109/AUPEC48547.2019.211910.

[4] D. Chathurangi, U. Jayatunga, S. Perera, A. P. Agalgaonkar, and T. Siyambalapitiya, "Comparative evaluation of solar PV hosting capacity enhancement using Volt-Var and volt-watt control strategies," *Renew. Energy*, vol. 177, pp. 1063–1075, Nov. 2021, doi: 10.1016/j.renene.2021.06.037.

[5] M. Bajaj, A. K. Singh, M. Alowaidi, N. K. Sharma, S. K. Sharma, and S. Mishra, "Power quality assessment of distorted distribution networks incorporating renewable distributed generation systems based on the analytic hierarchy process," *IEEE Access*, vol. 8, pp. 145713–145737, 2020, doi: 10.1109/ACCESS.2020.3014288.

[6] M. A. Ismeil, A. Alfouly, H. S. Hussein, and I. Hamdan, "Hardware in the loop real-time simulation of improving hosting capacity in photovoltaic systems distribution grid with passive filtering using OPAL-RT," *IEEE Access*, vol. 11, pp. 78119–78134, 2023, doi: 10.1109/access.2023.3298547.

[7] M. Bollen and S. Rönnberg, "Hosting capacity of the power grid for renewable electricity production and new large consumption equipment," *Energies*, vol. 10, no. 9, p. 1325, Sep. 2017, doi: 10.3390/en10091325.

[8] I. Hamdan, A. Alfouly, and M. A. Ismeil, "Hosting capacity enhancement for photovoltaic systems at various conditions based on Volt-Var control," in *Proc. 23rd Int. Middle East Power Syst. Conf. (MEPCON)*, Cairo, Egypt, 2022, pp. 1–8, doi: 10.1109/MEPCON55441.2022.10021815.

[9] E. Mulenga, M. H. J. Bollen, and N. Etherden, "A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids," *Int. J. Electr. Power Energy Syst.*, vol. 115, Feb. 2020, Art. no. 105445, doi: 10.1016/j.ijepes.2019.105445.

[10] X. Y. Lee, S. Sarkar, and Y. Wang, "A graph policy network approach for Volt-Var control in power distribution systems," *Appl. Energy*, vol. 323, Oct. 2022, Art. no. 119530, doi: 10.1016/j.apenergy.2022.119530.

[11] R. K. Varma and V. Singh, "Review of studies and operational experiences of PV hosting capacity improvement by smart inverters," in *Proc. IEEE Electric Power Energy Conf. (EPEC)*, Nov. 2020, pp. 1–6, doi: 10.1109/EPEC48502.2020.9320116.

[12] I. Hamdan, A. Alfouly, and M. A. Ismeil, "A literature review on hosting capacity methodologies and inverter control technologies for photovoltaic system," in *Proc. IEEE Conf. Power Electron. Renew. Energy (CPERE)*, Feb. 2023, pp. 1–7, doi: 10.1109/CPERE56564.2023.10119630.

[13] J. F. B. Sousa, C. L. T. Borges, and J. Mitra, "PV hosting capacity of LV distribution networks using smart inverters and storage systems: A practical margin," *IET Renew. Power Gener.*, vol. 14, no. 8, pp. 1332–1339, Jun. 2020, doi: 10.1049/iet-rpg.2019.1054.

[14] M. Bajaj and A. Kumar Singh, "Hosting capacity enhancement of renewable-based distributed generation in harmonically polluted distribution systems using passive harmonic filtering," *Sustain. Energy Technol. Assessments*, vol. 44, Apr. 2021, Art. no. 101030, doi: 10.1016/j.seta.2021.101030.

[15] E. Kazemi-Robati, M. S. Sepasian, H. Hafezi, and H. Arasteh, "PV-hosting-capacity enhancement and power-quality improvement through multiobjective reconfiguration of harmonic-polluted distribution systems," *Int. J. Electr. Power Energy Syst.*, vol. 140, Sep. 2022, Art. no. 107972, doi: 10.1016/j.ijepes.2022.107972.

[16] N. Qamar, A. Arshad, K. Mahmoud, and M. Lehtonen, "Hosting capacity in distribution grids: A review of definitions, performance indices, determination methodologies, and enhancement techniques," *Energy Sci. Eng.*, vol. 11, no. 4, pp. 1536–1559, Apr. 2023.

[17] V. Puvi and M. Lehtonen, "Evaluating distribution network optimal structure with respect to solar hosting capacity," *Electric Power Syst. Res.*, vol. 216, Mar. 2023, Art. no. 109019, doi: 10.1016/j.epsr.2022.109019.

[18] D. Chathurangi, U. Jayatunga, and S. Perera, "Recent investigations on the evaluation of solar PV hosting capacity in LV distribution networks constrained by voltage rise," *Renew. Energy*, vol. 199, pp. 11–20, Nov. 2022, doi: 10.1016/j.renene.2022.08.120.

[19] S. Shamraiz. (May 2021). *Optimal Volt Var Control in Smart Distribution Networks*. [Online]. Available: https://munin.uit.no/handle/10037/23367

[20] M. H. Rashid, *Power Electronics: Circuits, Devices, and Applications*, 3rd Ed. Englewood Cliffs, NJ, USA: Prentice-Hall, 2003, doi: 10.1080/02286203.2023.2237400.

[21] I. Hamdan, A. Alfouly, and M. A. Ismeil, "Hosting capacity improvement for solar systems based on model predictive controller of Volt-Watt-Var smart inverter functions," *Int. J. Model. Simul.*, pp. 1–15, Jul. 2023, doi: 10.1080/02286203.2023.2237400.

[22] A. O'Connell and A. Keane, "Volt-Var curves for photovoltaic inverters in distribution systems," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 3, pp. 730–739, Feb. 2017, doi: 10.1049/iet-gtd.2016.0409.

[23] S. Mohan, S. Hasan, Y. Gebremariam, and R. K. Varma, "Increasing hosting capacity of PV solar systems using smart inverter Volt-Var control," in *Proc. 20th Nat. Power Syst. Conf. (NPSC)*, Dec. 2018, pp. 1–6, doi: 10.1109/NPSC.2018.8771749.

[24] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*, IEEE Standard 1547, 2018.

[25] A. Alfouly, I. Hamdan, and M. Ismeil, "Voltage profile of hosting capacity enhancement based on smart inverter reactive power control for PV grid connected system," *SVU-Int. J. Eng. Sci. Appl.*, vol. 4, no. 2, pp. 234–242, Dec. 2023, doi: 10.21608/svusrc.2023.194712.1106.

[26] *Grid Connection of Energy Systems Via Inverters*, Standards Australia, AS/NZS 4777.2, 2015.

[27] C-Smart, I-Implementation, and W-Group, *Common California IOU Rule 21 Implementation Guide for Smart Inverters*, IEEE Standard 2030, Inst. Electr. Electron. Eng., 2016.

[28] *Distributed Generating Facility Interconnection Standards Technical Requirements*, Revis. Sheet No. 34B-1, Hawaii Electr. Company, Honolulu, HI, USA, 2018.

[29] I. Hamdan, A. Alfouly, and M. A. Ismeil, "Impact of active power control for hosting capacity grid-connected PV systems," *J. Electr. Power Syst. Eng.*, vol. 9, no. 2, pp. 32–43, 2023. [Online]. Available: https://matjournals.co.in/index.php/JEPSE/article/view/2716/3537

[30] W. Sunderman, R. C. Dugan, and J. Smith, "Open source modeling of advanced inverter functions for solar photovoltaic installations," in *Proc. IEEE PES TD Conf. Exposit.*, Apr. 2014, pp. 1–5, doi: 10.1109/TDC.2014.6863399.

[31] Electrical4U. (2022). *Power Factor: Improvement, Formula and Definition*. [Online]. Available: https://www.electrical4u.com/electrical-power-factor/

[32] D. Povh, *HVDC Transmission*, vol. 3, 4th ed. Amsterdam, The Netherlands: Elsevier, 1981, doi: 10.1016/b978-0-7506-1202-9.50033-x.

[33] S. Das, "Modeling for hybrid and electric vehicles using simscape," *Synth. Lectures Adv. Automot. Technol.*, vol. 5, no. 1, pp. 1–217, May 2021, doi: 10.2200/s01088ed1v01y202104aat014.

[34] A. F. Zobaa, S. H. E. A. Aleem, S. M. Ismael, and P. F. Ribeiro, *Hosting Capacity for Smart Power Grids*. Berlin, Germany: Springer, Apr. 2020, doi: 10.1007/978-3-030-40029-3.

[35] M. T. Alturki. (2014). *Digital Commons @ DU Hosting Capacity Calculations in Power Systems Recommended Citation*. [Online]. Available: https://digitalcommons.du.edu/etd/28

[36] N. Qamar, A. Arshad, K. Mahmoud, and M. Lehtonen, "Hosting capacity in distribution grids: A review of definitions, performance indices, determination methodologies, and enhancement teqiques," *Energy Sci. Eng.*, vol. 11, no. 4, pp.1536–1559, 2022, doi: 10.1002/ese3.1389.

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