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DESIGN OF A NOVEL CONTROLLER FOR ENHANCING THE PERFORMANCE OF ON GRID WITH PV AND BATTERY BASED MICROGRID

GARIMILLA INDUJA[1], Dr. SADANANDAM PERUMANDLA[2]
1, PG Scholar, Department of Electrical and Electronics Engineering
2, Professor, Department of Electrical and Electronics Engineering
Vaagdevi College Of Engineering, Bollikunta, Warangal, Telangana, India.
indujagarimilla@gmail.com

ABSTRACT

The integration of solar photovoltaic systems into low-voltage distribution networks is wit- nessing 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.

Key words: photovoltaic systems, reactive power, active power, Power Factor, PCC, BESS and Hosting Capacity.

I INTRODUCTION

Amidst the resource limitations, the incessant quest for energy has shifted the concentration towards the development of environmentally friendly and non exhaustible energy sources. It is expected that by the year 2050, eighty six percent of the total global power will come from renewable sources of energy, while two thirds of the total energy requirements will be fulfilled【1】【2】. The deployment of photovoltaics (PV) systems in various users is gaining a lot of traction, and in turn helps to eliminate the use of conventional fossil fuel sources of energy【3】. The downside, however, is that if PV arrays are connected to the low voltage distribution grid directly without any precaution, it will lead to voltage rise problems and thus affect the reliability and efficiency of the system.【4】.

Thanks to the intellectual inverters, the integration of DER has advanced intensely, where for example reactive and active power regulation, voltage regulation, and other grid services can be performed【10】【11】. Other recent works have also reported advances in PV hosting capacity HC in combination with harmonic filtering methods passive filters and novelty C-type filters to minimize Total Harmonic Distortion THD and improve the grid performance as a whole【14】【15】【16】.

This paper considers the improvement of control methods such as Volt-Var control, Power Factor (PF) control and deployment of Battery Energy Storage Systems (BESS) to ensure voltage stability at the Point of Common Coupling (PCC) given the limits of solar energy integration within low-voltage distribution grids. Addressing these problems strives to keep standard limits【18】.

II DESIGN OF A PROPOSED SYSTEM

The essential components of a PV generation system includethe inverter and PV arrays. To generate a solar cell thatcan supply the required voltage and current for practical applications, the cells are connected in series, parallel, or a combination of both configurations.

a) Renewable power (PV) mode used

The electrical model ofthe PV cell is given in Fig.1. This model consists of a currentsource in parallel with a diode and two resistors [19].

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

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

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.

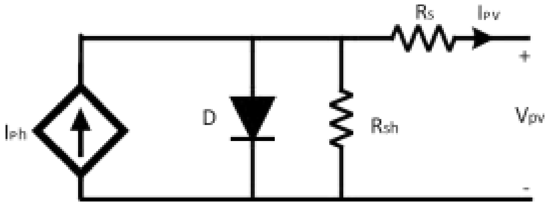


Figure 1 Single diode PV cell circuit

The boost converter which is shown in Fig.2 is a chop- per topology that boosts the input DC to a large value ofDC depending on the duty cycle value, the duty cycle canbe varied from zero to less than unity deters the equation describing the relationship between the input and output hasbeen presented.

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

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

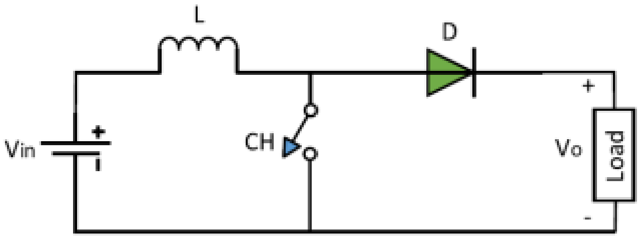


Figure 2 Boost converter used in Proposed system.

The main interphase units between the PV system andthe grid are a DC/DC converter and a DC/AC inverter. The perturbation and observation (P&O) MPPT algorithm is usedto control the DC/DC converter to guarantee optimum powergeneration from the PV source. The produced electricity is transferred to the AC side with the help of an inverter. A fewinstances of inverter control include grid synchronization, DC connection voltage balancing, and active/reactive powerregulation. It is common practice to modify the inverter cur-rent 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 suppliesa 100 kVA PV system and a 100 kVA lumped load located5 km away from the feeder. The detailed specifications of the PV system, which operates at its maximum capacity, aresummarized in Table 1. It includes an appropriate number ofseries 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 acertain value depending the on deterministic method.

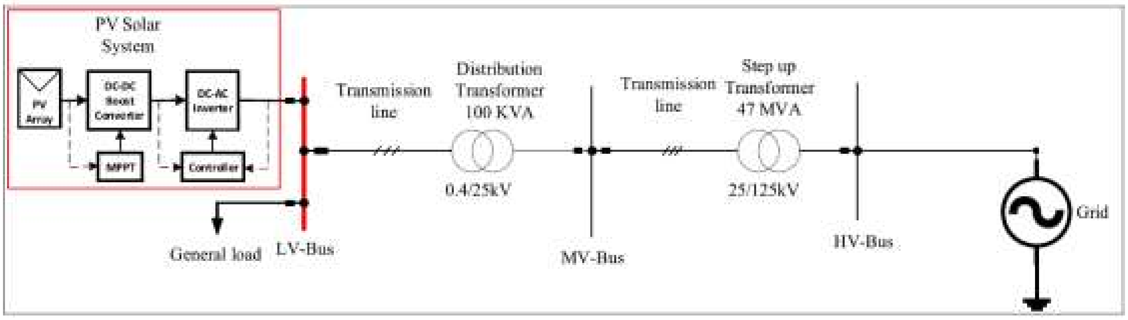


Figure 3 single-line representation of the test system.

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

b) 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.

i)Reactive power control

The defining characteristic of the reactive power controller isits ability to establish a relationship between the voltage leveland the amount of reactive power necessary to keep the elec-trical 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].

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

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

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 invert- ers are large while using their rated capacity, as indicatedby [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 andits 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 ACvoltage. An appropriate controller is employed to correct theerror signal and produce $I_{q\ ref}$. The control system is limitedby 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].

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

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

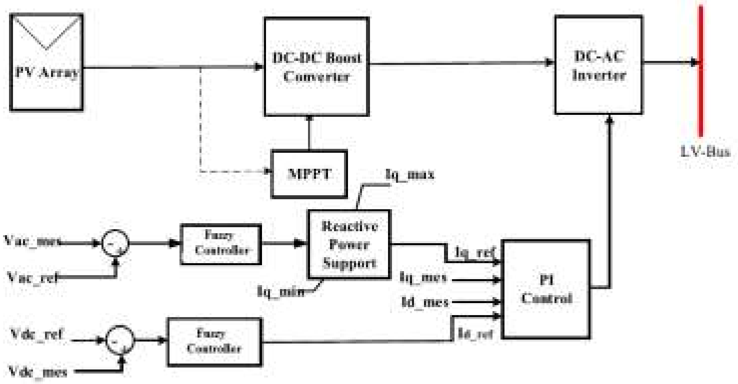


Figure 4 Proposed fuzzy control loop for reactive power regulation.

Grid restrictions that influence PV inverters include factors like over and under-voltage, solar PV place-ment, feeder length/loading levels, conductor types, andspecified voltage limits.

ii)Active Power Control

Active power control is the ability to modify and controlthe 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 indifferent energy systems, including renewable energy sys- tems like PV systems, to guarantee effective and dependablepower generation and distribution. It enables the alteration ofactive 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 realenergy output of each PV system separately to mitigateover-voltages that may occur when traditional voltage reg-ulation systems fail to prevent them [30]. This capability canbe 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].

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

where, Vo ($Vo = Vac\_ref - Vac\_mes$) is the voltage applied, id max is the PV system's greatest actual current available, and Kd is the active current gain.

The configuration of the PV inverter pro- cessor, 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.

iii)Power Factor Control

The power factor is one of the most important factors affect-ing 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 genera- tors, static VAr compensators, and phase advances.

The reference active power obtained by the product of the direct axis for reference voltage and the current from the PV systemThe 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 reac-tive voltage and current. Moreover, Theapparent reference power, which is the product of actual voltage and actual current. Dividing the reference activepower by apparent reference power led to obtaining the Dividing the reference active power by apparent reference power led to obtaining the reference power factor.

$$P_{ref} = V_{d-ref} * I_{d-ref}$$
$$Q_{ref} = V_{q-ref} * I_{q-ref}$$
$$S_{ref} = \sqrt{P_{ref}{}^2 + Q_{ref}{}^2}$$
$$PF_{ref} = \frac{P_{ref}}{S_{ref}}$$
$$P_{mes} = V_{d-mes} * I_{d-mes}$$
$$Q_{mes} = V_{q-mes} * I_{q-mes}$$
$$S_{mes} = \sqrt{P_{mes}{}^2 + Q_{mes}{}^2}$$
$$PF_{mes} = \frac{P_{mes}}{S_{mes}}$$

where, *Pref , Qref , and Sref* are the references active, reactive, and apparent power of the system, also, *Pmes, Qmes, and Smes* are the measurements active, reactive, and apparent power of the system. *Vd−ref* , *Id−ref* , *Vq−ref and*, *Iq−ref* are references to the direct axis and quadrature axis voltage and current respectively. *Vd−mes*, *Id−mes*, *Vq−mes*, *and*, *Iq−mes*, are measurements of direct axis and quadrature axis voltage and current respectively, *PFref* , *PFmes* are reference and measurement power factors respectively.

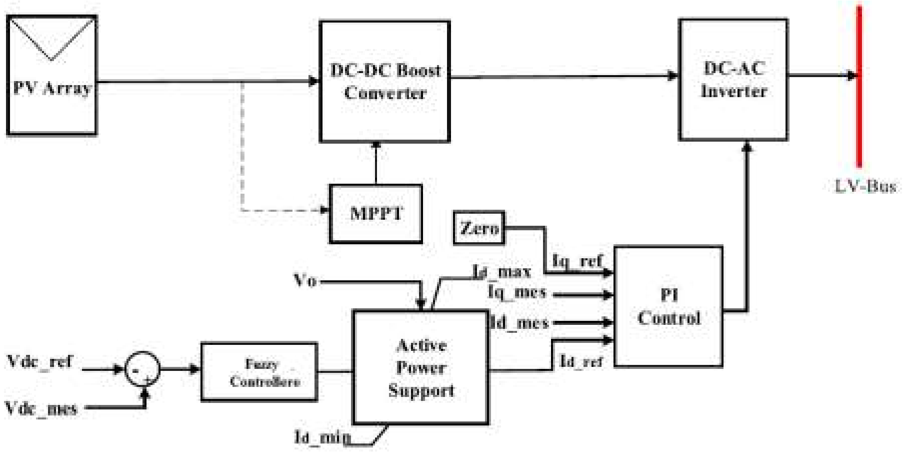


Figure 5 Proposed fuzzy control loop for active power regulation

C. BATTERY ENERGY STORAGE SYSTEM

A Battery Energy Storage System (BESS) is a type of energystorage system that employs batteries to store electrical energy for future use. It has various applications, including load leveling, frequency regulation, and peak shaving. More-over, 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 generatedby renewable sources and release it during power short- ages, thereby contributing to grid stability and enhancing thereliability of the power supply. BESS finds utility in both residential and commercial environments.

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

Where, x is the ratio of the charge left to the rated or full charge forthe 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. 4. 7(a). illustrates the benefits of incorporating a storagesystem 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 com- pared 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 sys- tem's HC to be increased. Electricity demand and generation can be decoupled using ES systems. Even though ES is still expensive [34]. Fig. 4.7(b) demonstrated the BESS used in thesystem.

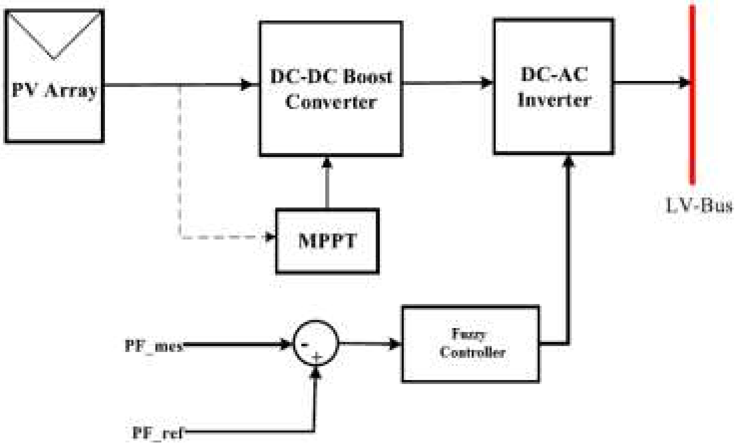


Figure 6 Proposed Fuzzy control loop for power factor regulation

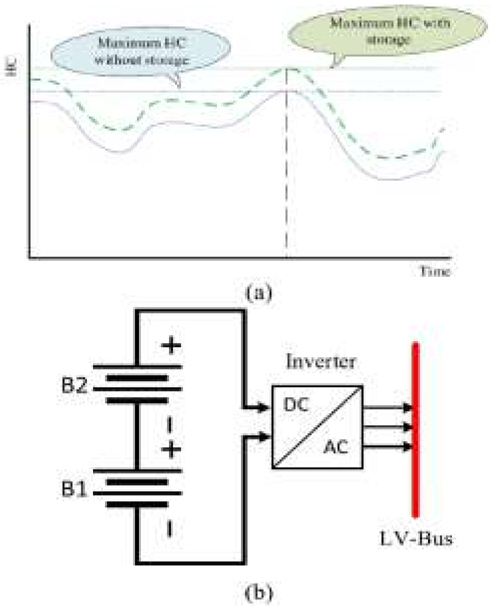


Figure 7 (a). Hosting capacity with and without a storage system (b). Battery energy storage system

d)HOSTING CAPACITY CALICULATION

The addition of a new generator or load in a distribution net-work can impact the power flow. Such a change can lead to an improvement or degradation of network performance for con-sumers 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 thesystem for consumers.

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

To assess the hosting capacity, it is necessary to establishappropriate performance indices, which will vary depend- ing on the analysis conducted. These indices will determine whether the network's operational conditions are accept- able or not. The maximum value that a performance index can reach without compromising the system's reliability andadherence 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 distri-bution grid can be calculated by the following equation [36]

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

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 twocontrols or compared with control [4].

Hosting Capacity Equation%

$$= \frac{HC\ (with) - HC\ (without)}{HC\ (without)}$$

From equation (15) HC (with) is the value of watt when using control and HC (without) is the value of watt when without 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 betterhosting performance, there are still several drawbacks, suchas the battery's maintenance and cost.

The conventional power system design was unique in thatpower flow was unidirectional from generation to trans- mission 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.

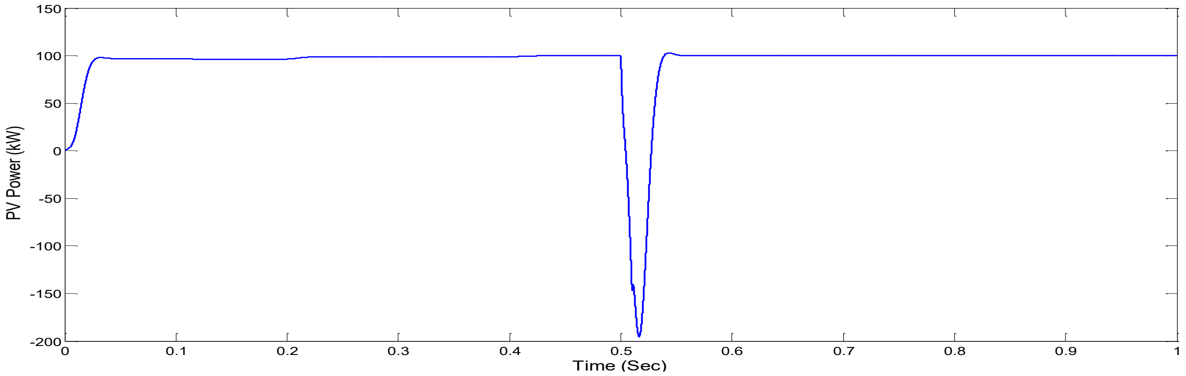
Smart inverters can mitigate the effects of increased PV penetration by performing active power curtailment and/or reactive compensation. Depending on the voltage level, thesedevices can provide variable control by acting on the injectedactive power limit (Volt–Watt control) or reactive compensa-tion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

III SIMULATION RESULTS

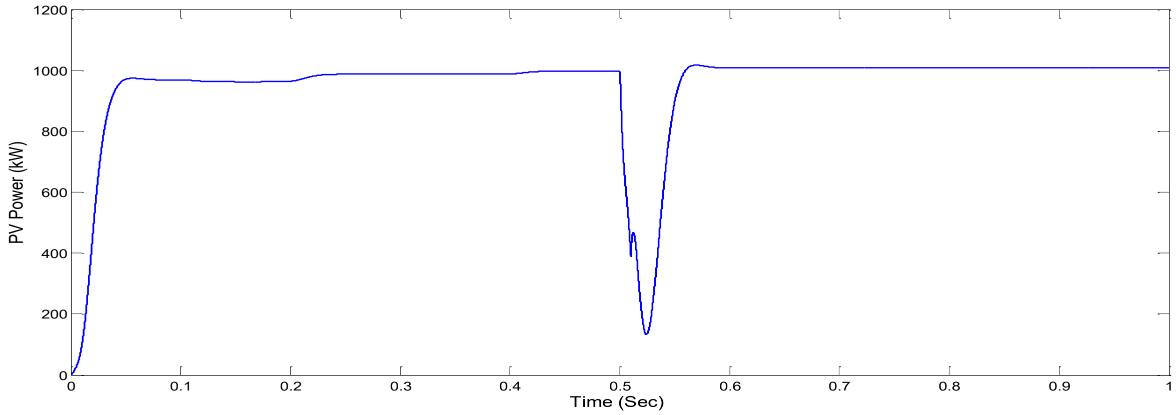
The results of the hosting capacity analysis for PV systems can be divided into three parts. The first part considers the scenario where the PV system is connected to the grid without any controls. The second part examines the implementation of reactive power (Volt-Var) control to address voltage rise 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 Fuzzy based active power Control

The outcomes of this operation are depicted in Fig. 5.1,2&3, 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 132.5 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 1.55 pu, which signifies a 62% increase compared to the nor- mal voltage. If this problem persists over an extended period, it can adversely impact the system's quality, equipment per- formance, line losses, harmonic distortion, and reverse power flow. The penetration level of PV system increases by 50%

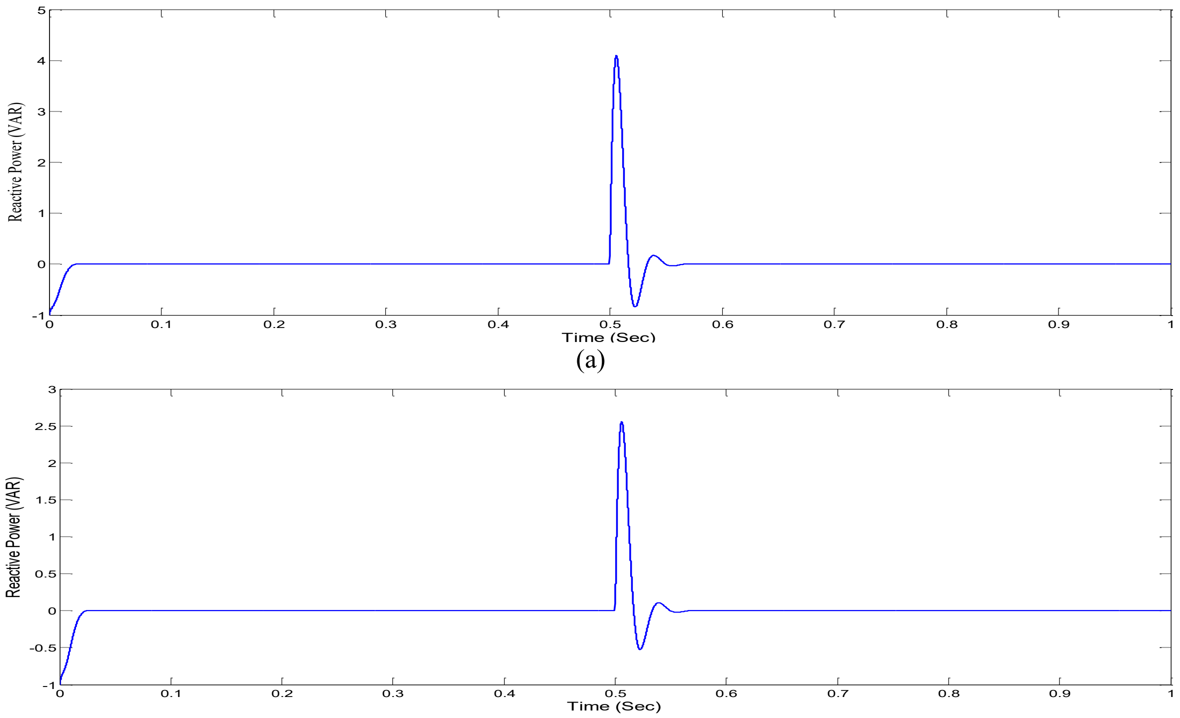


(a)



(b)

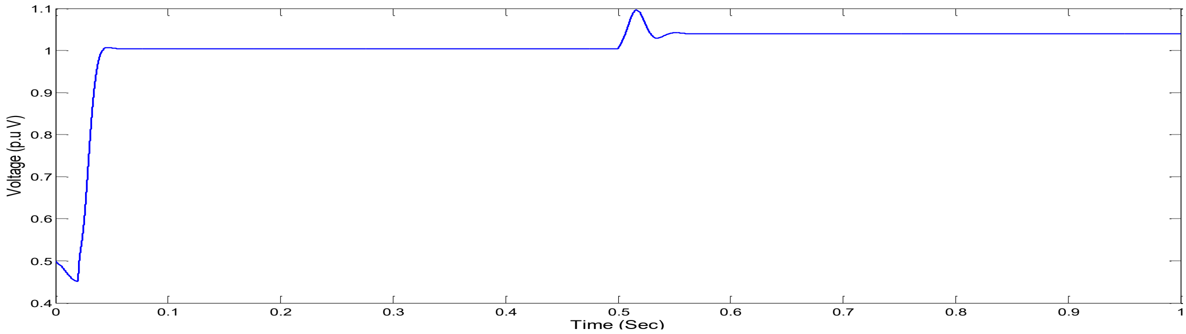
Figure 8 PV power output (a) Conventional (b) proposed Fuzzy based active power control



(a)

(b)

Figure 9 Reactive power absorption with (a) Conventional and (b) proposed Fuzzy based active power control



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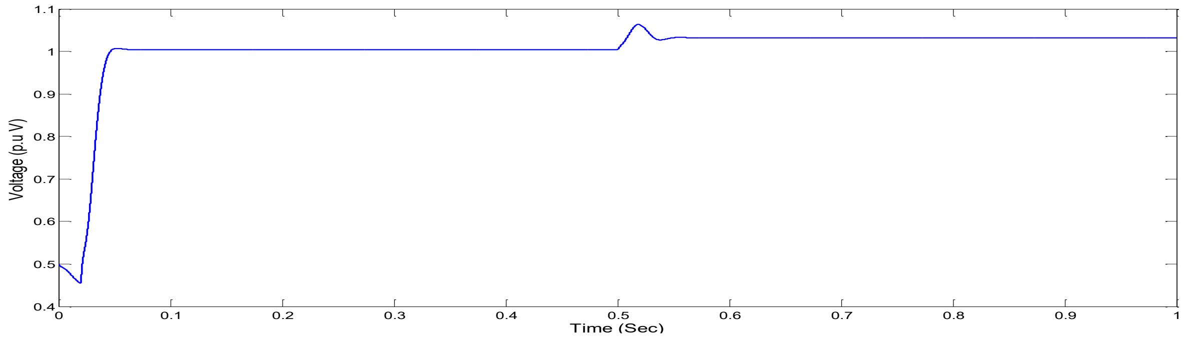
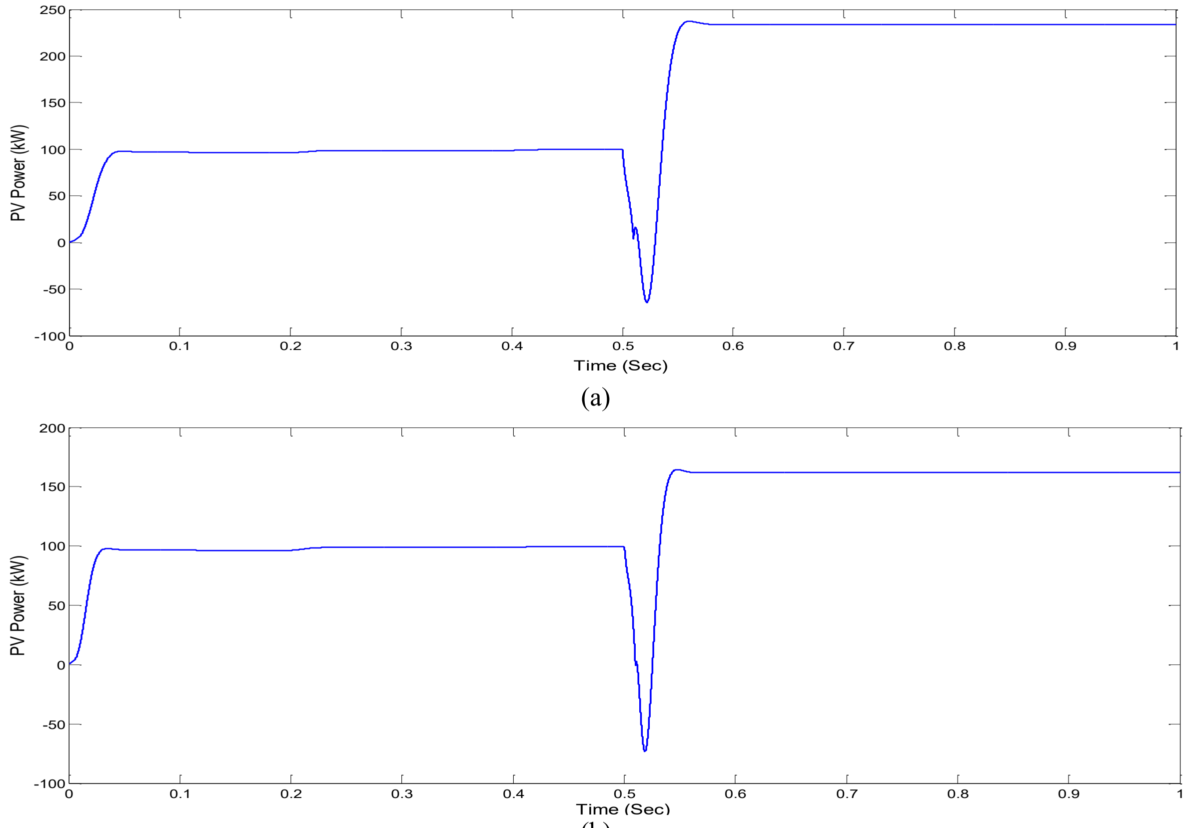


(b)

Figure 10 PCC Voltage in p.u with (a) Conventional and (b) proposed Fuzzy based active power control

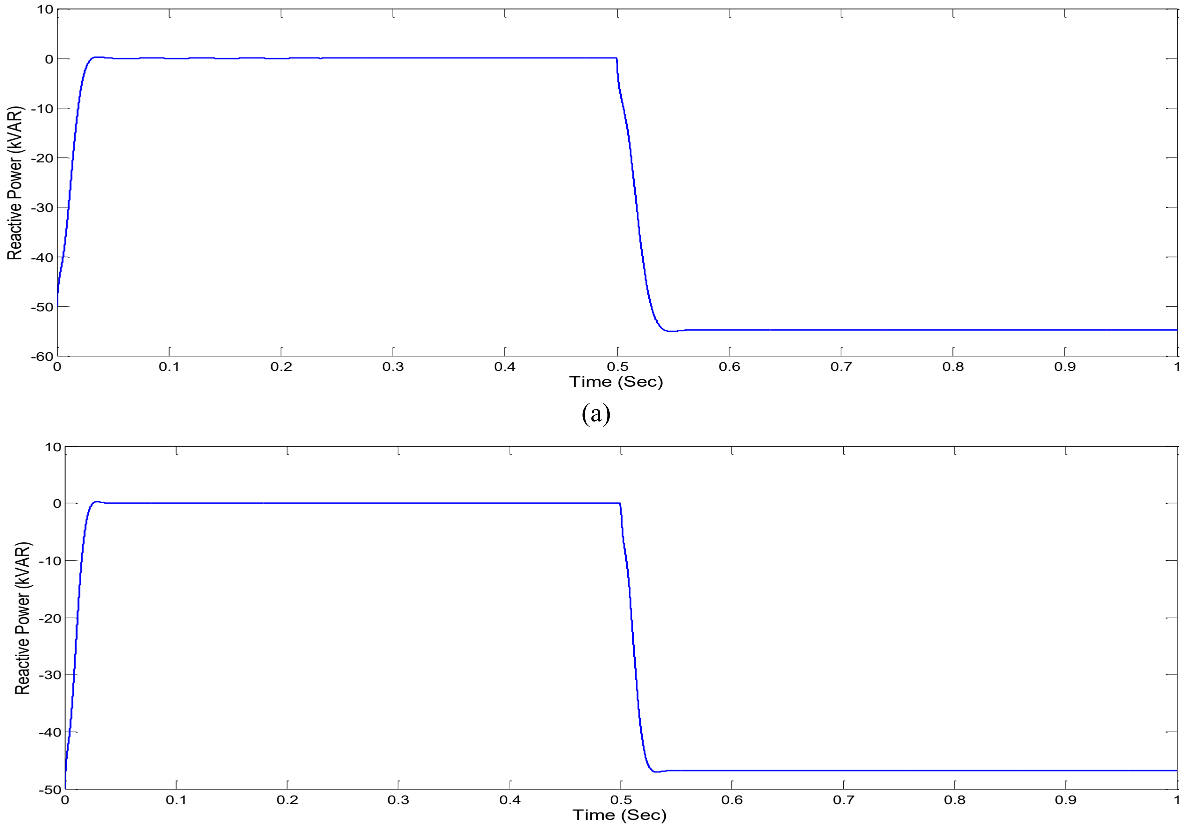
b) Performance of Studied System with Fuzzy based volt-watt Control

The Volt-Watt control mechanism involves comparing the reference DC voltage with the measured DC voltage ofthe PV inverter. The resulting error signal is then inputtedto 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 98.88 kW until the solar system's penetration increases at t=6 seconds.



(b)

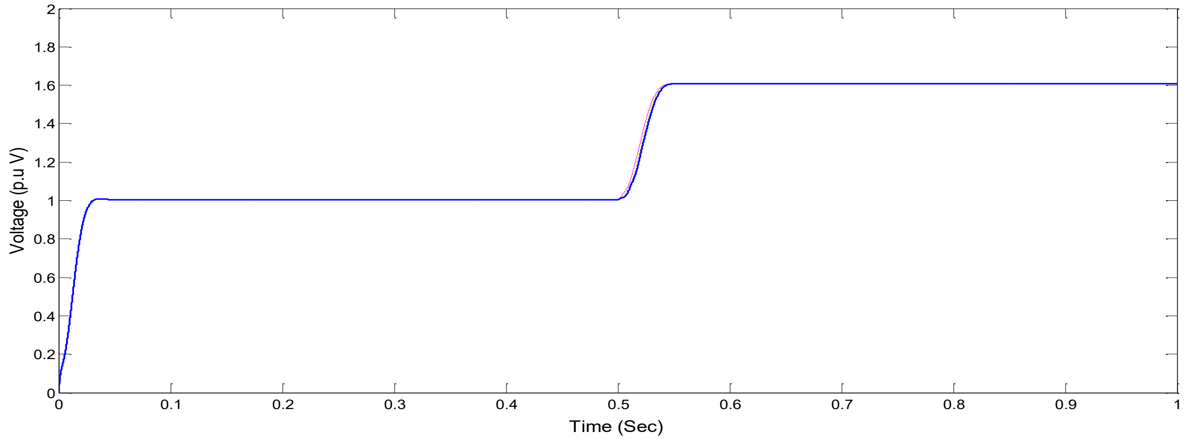
Figure 11 PV power output with (a) Conventional and (b) proposed Fuzzy based volt control



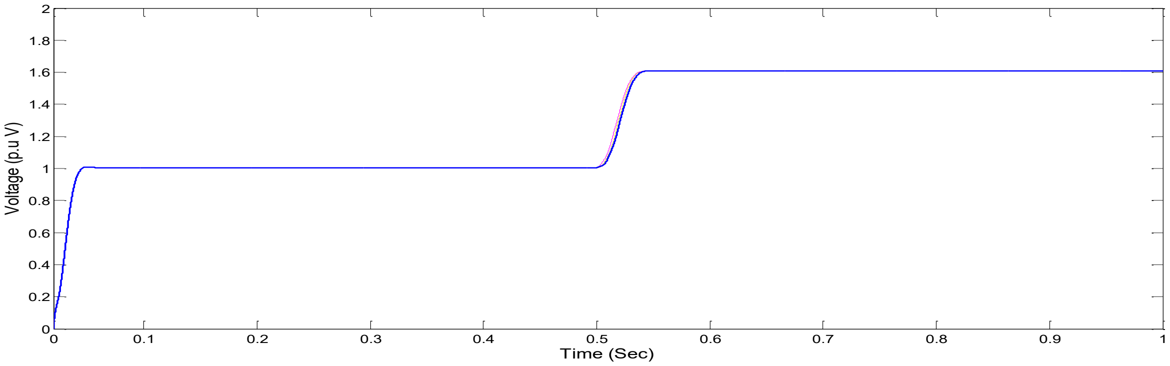
(a)

(b)

Figure 12 Reactive power absorption with (a) Conventional and (b) proposed Fuzzy based volt control



(a)

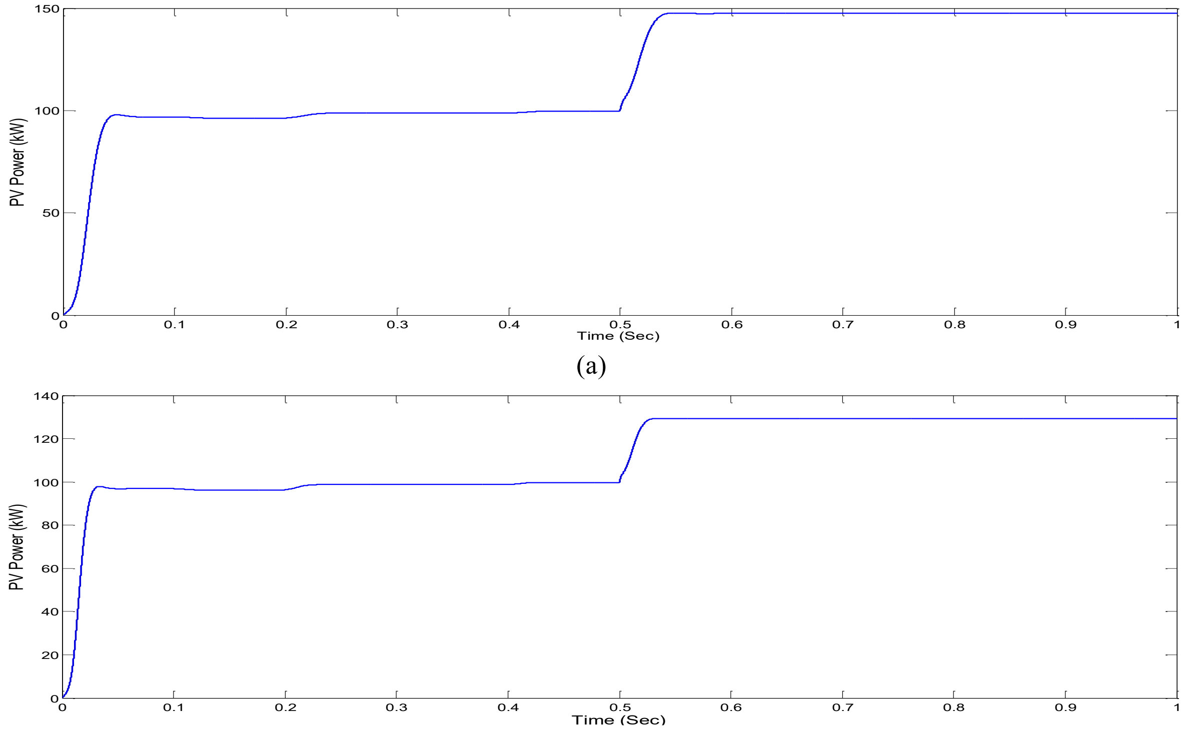


(b)

Figure 13 PCC Voltage in p.u with (a) Conventional and (b) proposed Fuzzy based volt control

c) Performance of Studied System with fuzzy based PowerFactor Control

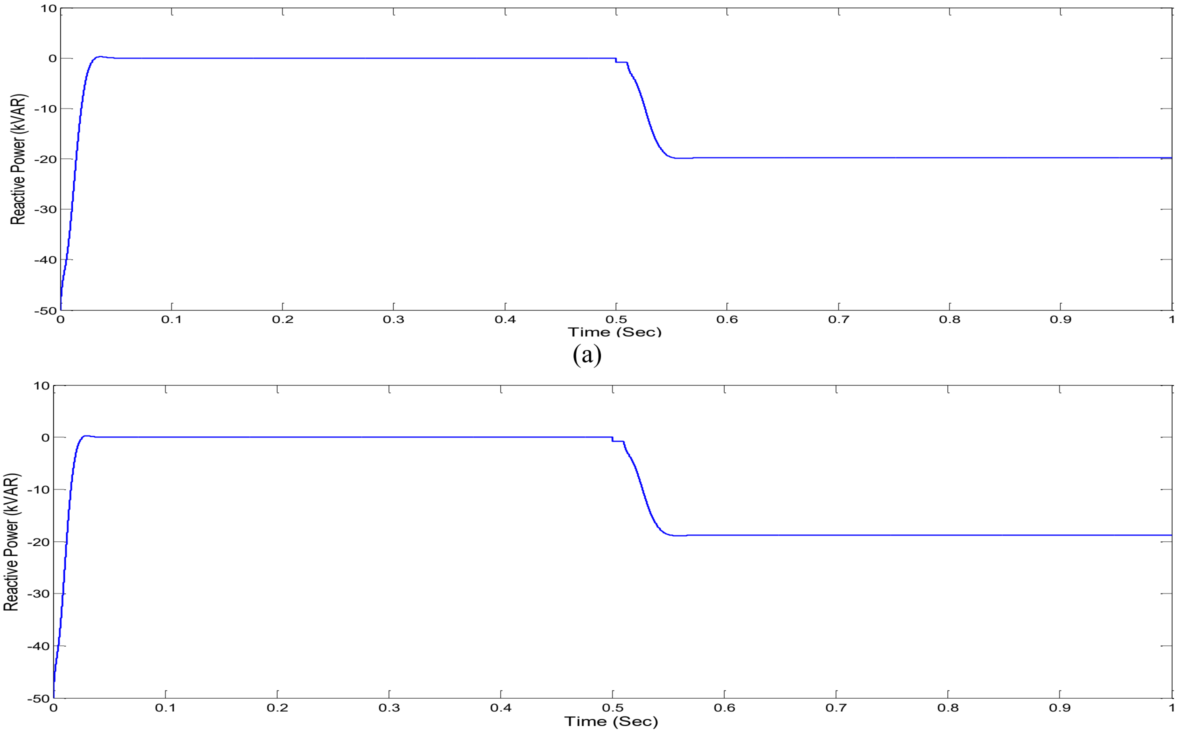
The PF control compares with the reference power factorat the connection bus and measured power factor at PCC, the error signal inserted to the pi controller. The outcomesof this operation are depicted in Fig. 12, which showcases the active power, reactive power, and voltage at the bus. Theactive power generated by the PV system remains constant at 98.7 kW until the solar system's penetration increasesat t 6 seconds, reaching 130.5 kW.



(a)

(b)

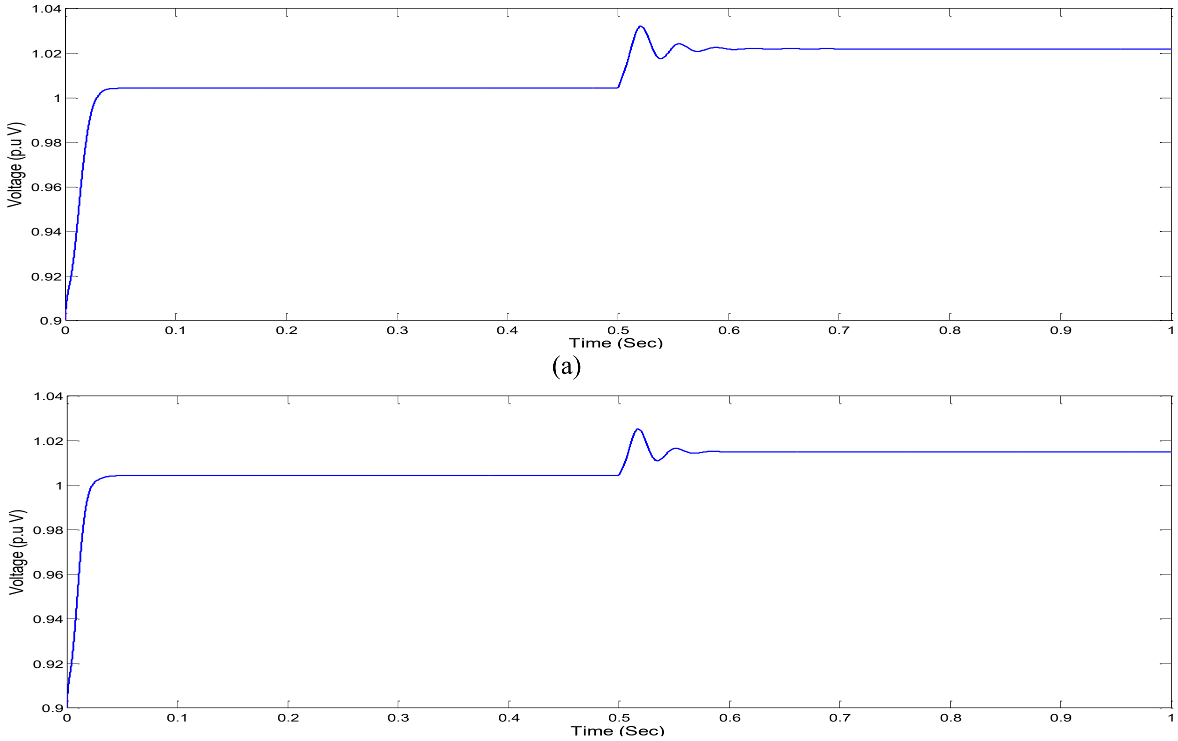
Figure 14 PV power output with (a) Conventional and (b) proposed Fuzzy based PF control



(a)

(b)

Figure 15 Reactive power absorption with (a) Conventional and (b) proposed Fuzzy based PF control



(a)

(b)

Figure 16 PCC Voltage in p.u with (a) Conventional and (b) proposed Fuzzy based PF control

It accomplishes this by absorbing reactive power in equal amounts of 17.9 kVAR, effectivelylimiting the voltage rise problem at the PCC to reach a maximum of 1.001 per unit (pu).

The Comparative Study

The results of comparing Volt-Var control and Power Fac- tor (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 volt-age at the Point of Common Coupling (PCC).

IV CONCLUSION

In the context of coordinating the hosting capacity (HC) of photovoltaic (PV) systems in low-voltage grids, smart inverter control, battery energy storage systems (BESS), reactive power control, and power factor (PF) control are the key methods employed. When applying the Volt-Var control in a reactive power control, it is possible to stabilize the voltage at the bus to which the PV-diesel system under control is connected, increasing the bus voltage by 32.1% and reducing it by 6.8% relative to the cases without any control or with only BESS applied. The PF method has been reported to be even more efficient increasing bus voltage by as much as 37.65%, 8.2% and 1.94% above those obtained from systems with no control, with Volt-Var control only and with only BESS respectively.Looking at HC improvement BESS relatively increases HC by 9.7% alone, whereas looking at Volt-Var, Volt-Watt, and PF control these values are respectively 19%, 94%, and 99.1% showing that PF control is the most efficient at the Point of Common Coupling.

The combined effect of BESS together with reactive power and PF control results in HC improvement of 92.5% and 98.5% respectively effectively enhancing the stability of the voltage profile and optimizing the solar capacity in the grid.

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