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

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Abstract –

Electric power systems have been in constant transformation, specifically distribution systems, as the penetration of photovoltaic (PV) distributed energy resources (DER) has increased in recent years. 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 project 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.

Keywords – Battery energy storage system, hosting capacity, photovoltaic energy, distribution system, inverter control techniques.

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. 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. 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. To avoid exceeding the capability of hosting solar panels in a feeder, the allowable limit of such violations needs to be established and adhered. The PV hosting capacity has generally defined a maximum connectable solar power output to the grid without impact on the system's regular operation. 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. 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. Smart inverters, formerly referred to as sophisticated inverters, have caused a fundamental change when it comes to the implementation of Distributed Energy Resources (DER). 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.

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. 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. 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. 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). In 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. Assessing the ideal configuration of a distribution network in terms of its capacity to accommodate solar energy generation. 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. 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, and combined active and reactive control), Model Predictive Controller (MPC), and harmonic filter mitigation. This project 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, this project 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.

II. DISTRIBUTION NETWORK

In order to provide reliable electrical energy given these increasing energy usage trends, integration of renewable energy into the power grid and enabling end-users to actively participate in the energy management of the system are two possible solutions. Focus of this dissertation would be on integration and coordination of renewable energy and demand response into distribution power systems. Distribution power systems management and control will face many challenges with increasing penetration of intermittent distributed energy resources requiring appropriate strategies to deal with these. A multi-layer management and control architecture is proposed at building layer and system layer for active distribution systems (ADS). Active distribution system is defined as distribution system including distributed energy resources (DERs). In order to increase the participation of end-user, a demand response (DR) control algorithm has been developed to control the inside temperature of building with given constraint and with different goals such as maintaining inside temperature at acceptable range, minimizing energy consumption of heat-ventilation air conditioning (HVAC) and maximizing the consumption of photovoltaic (PV) generations inside the building to minimize energy exchange between building and distribution system.

Advanced distribution automation (ADA) is the cornerstone for evolving the distribution systems of the future. ADA is revolutionary approach to traditional distribution

automation (DA). DA has been defined as “a system that enables an electric utility to monitor, coordinate, control, protect and operate distribution components in a real-time mode from remote locations”. Traditional distribution systems were designed to distribute electrical energy based on end-users requirements while ADA systems will facilitate the exchange of electrical energy and information between participants and system components. The distinction between supplier and consumer will blur because many of participants will assume both roles and will need to switch effortlessly between these roles, possibly several times a day. The exchange of data and information will facilitate the “*supplying*” or “*consuming*” electrical energy based on dynamic rather than static prices. A flexible electrical architecture is needed that will allow interoperability of a multitude of controllable electrical and electronic devices within the distribution system in an organized strategic manner that provides improved functionality, performance, reliability, efficiency and sustainability from the system. Figure (1) represents conceptual view of ADA and next generation of distribution systems.

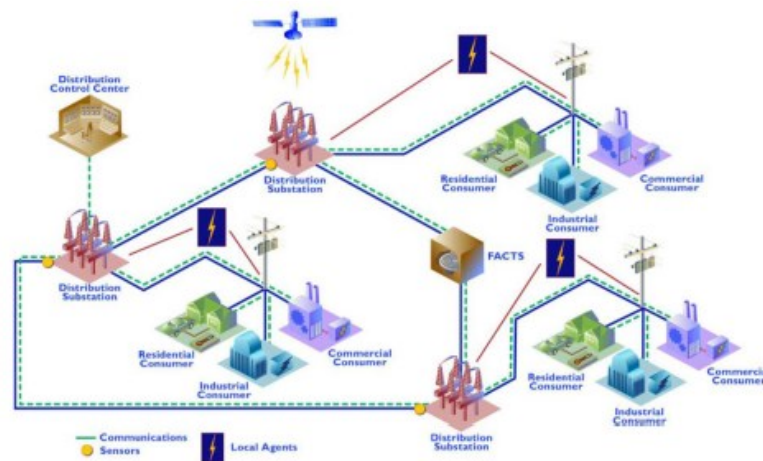


Fig:1. Conceptual view of Advanced Distribution Automation.

III. SYSTEM MODELLING

The proposed control method will be validated based on the system illustrated in Fig.2. 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. 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/m^2 for irradiation level and 25°C for temperature. The temperature and irradiance are fixed at a certain value depending the on deterministic method.

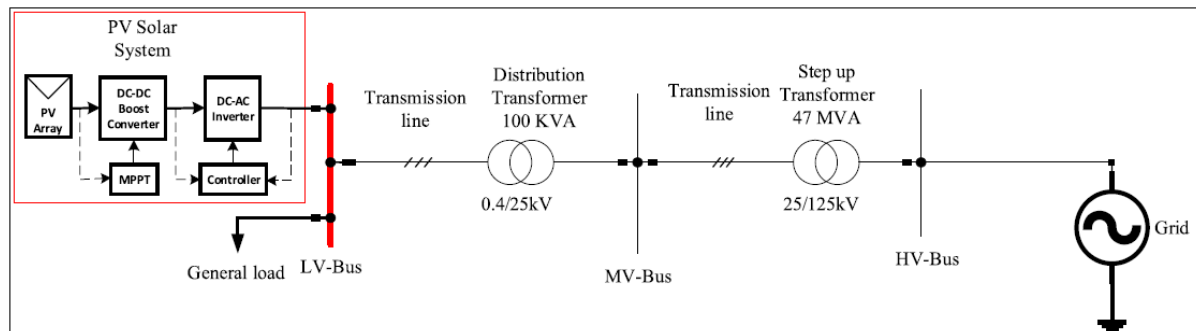


Fig.2: A single-line schematic of the test system.

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. 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. The architecture of the PV solar inverter controller and its functionality is presented in Fig. 3. 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 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 IEEE Std.1547-2018, AS/ NZS 4777.2-2015, California Rule 21-2018, and Hawaii Rule 14-2018 (Revised Sheet No. 34B-21).

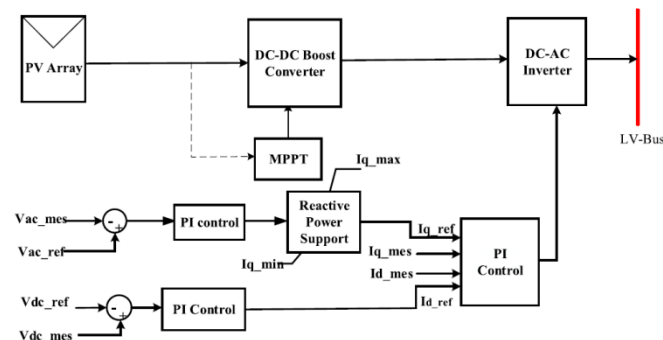


Fig.3: The control loop for reactive power regulation in a solar PV inverter system.

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.

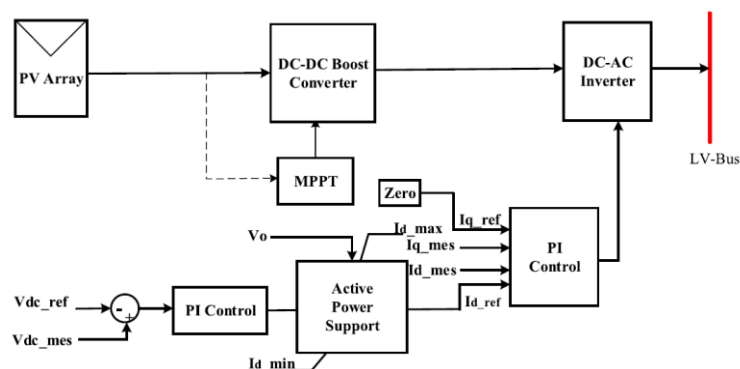


Fig.4: The control loop for active power regulation in a solar PV inverter system.

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. 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. This capability can be particularly crucial during the integration of PV systems. Fig.4 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.

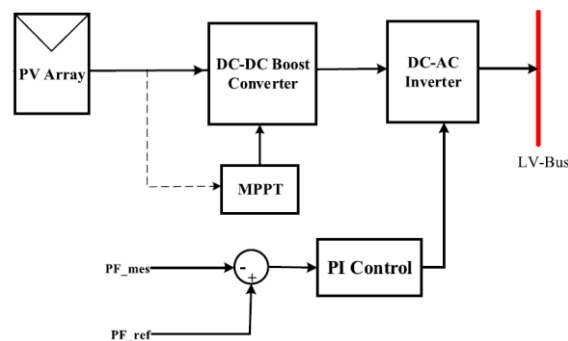


Fig.5: The control loop for power factor regulation in a solar PV inverter system.

Therefore several methods have emerged to improve the power factor such as capacitor banks, synchronous generators, static VAR compensators, and phase advances. The equations of power factor are used in this paper. Equation 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 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 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. Also, equations describe the active power, reactive power, apparent power, and power factor measured at the point of connection PV solar system.

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. Fig. 6(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. Fig. 6(b) demonstrated the BESS used in the system.

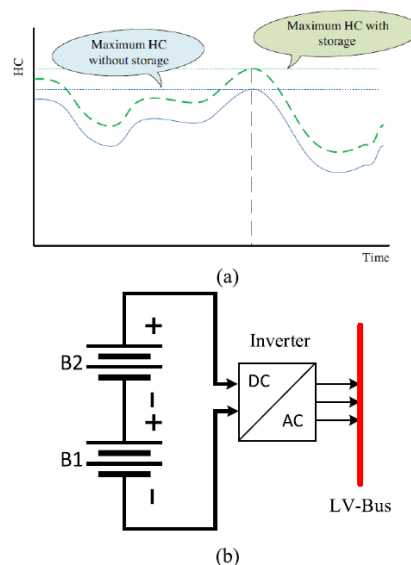


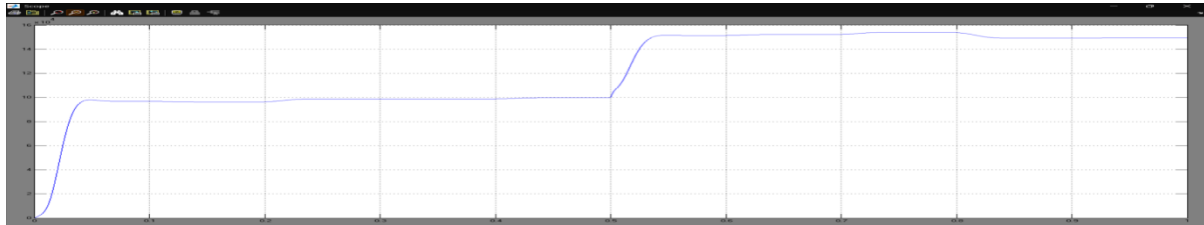
Fig.6: (a). Hosting capacity with and without a storage system. (b). Battery energy storage system.

IV. SIMULATION RESULTS

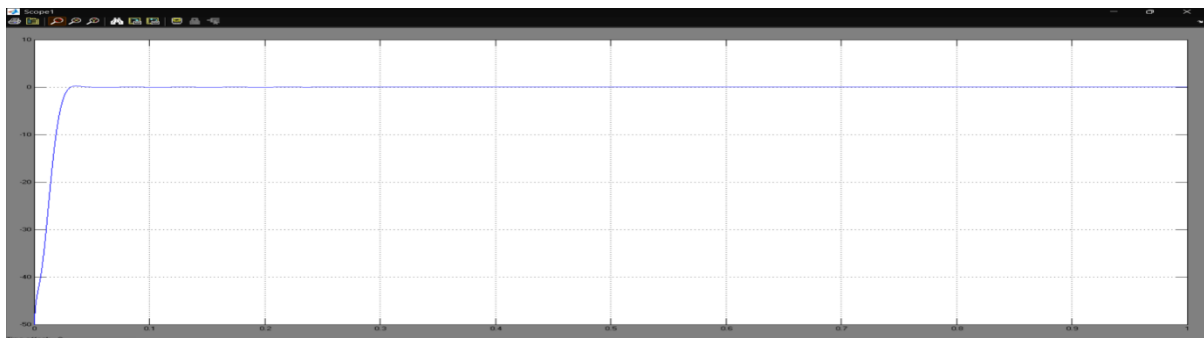
The results of the hosting capacity analysis for PV systems can be divided into three parts. The first part considers the scenario where the PV system is connected to the grid without any controls. The second part examines the implementation of reactive power (Volt-

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.

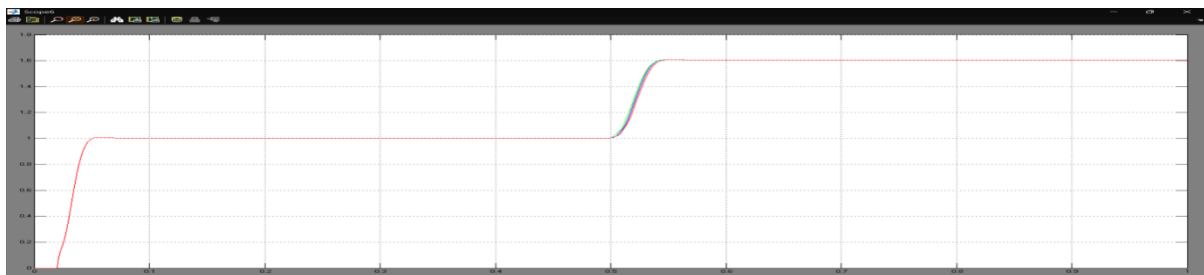
CASE A: PERFORMANCE OF STUDIED SYSTEM WITH CLASSIC CONTROL



(a) Active power



(b) Reactive power



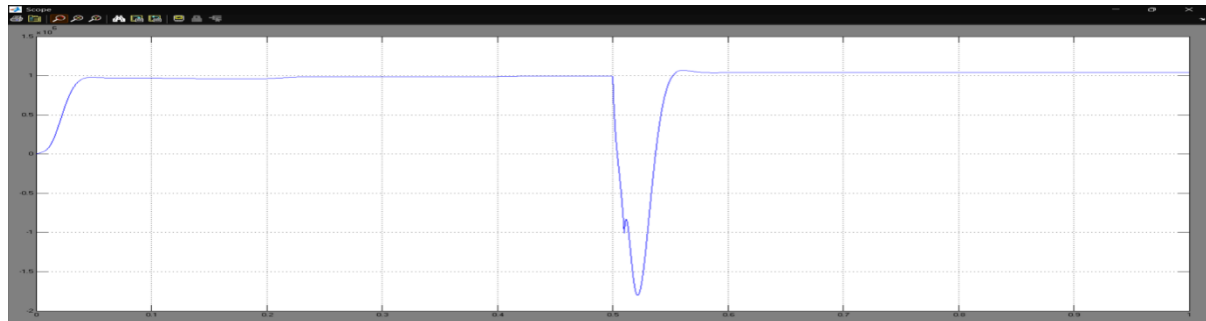
(c) Bus voltage

Fig. 7. The results of a PV system with a connection to a grid with classic control.

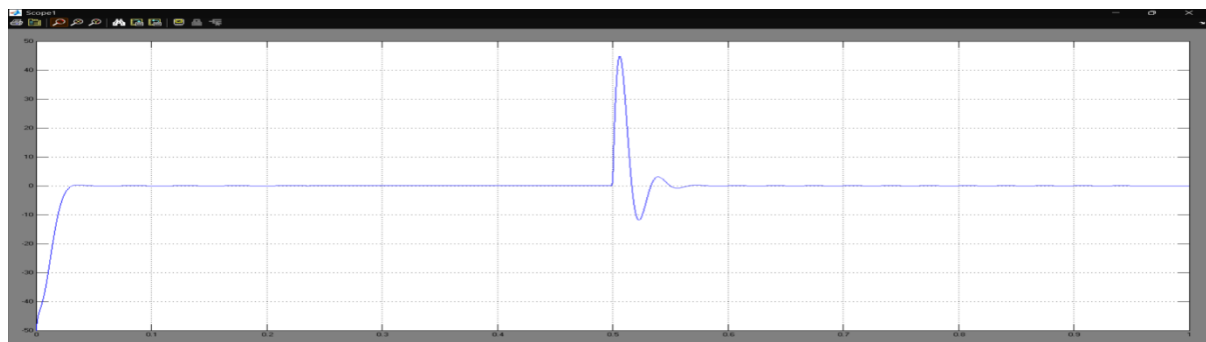
The outcomes of this operation are depicted in Fig. 7, which showcases the active power, reactive power, and voltage at the bus. The active power generated by the PV system remains constant at 98.5 kW until the solar system's penetration increases at $t=0.5$ seconds, reaching 146.27 kW. However, due 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%.

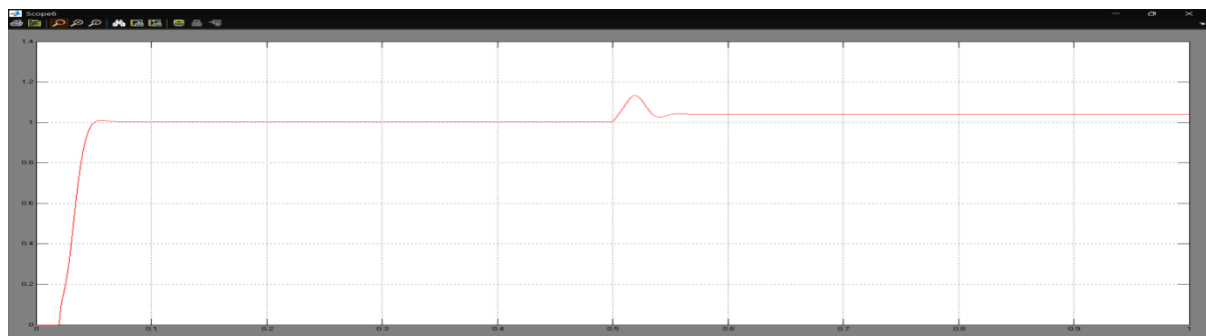
CASE B: PERFORMANCE OF STUDIED SYSTEM WITH BESS



(a) Active power



(b) Reactive power



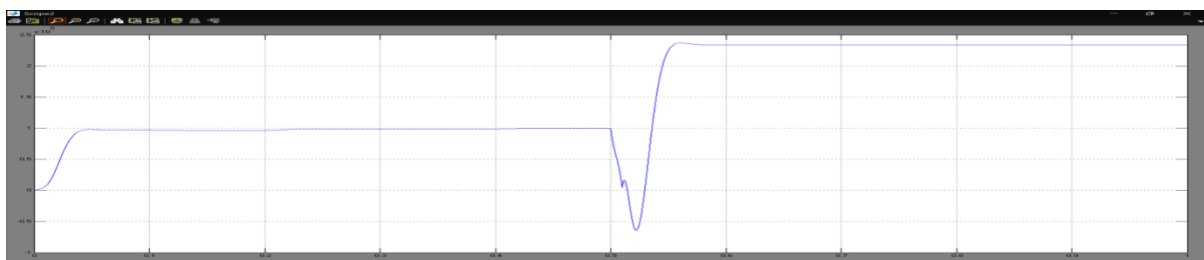
(c) Bus voltage

Fig. 8: The results of a PV system with a connection to a grid with BESS.

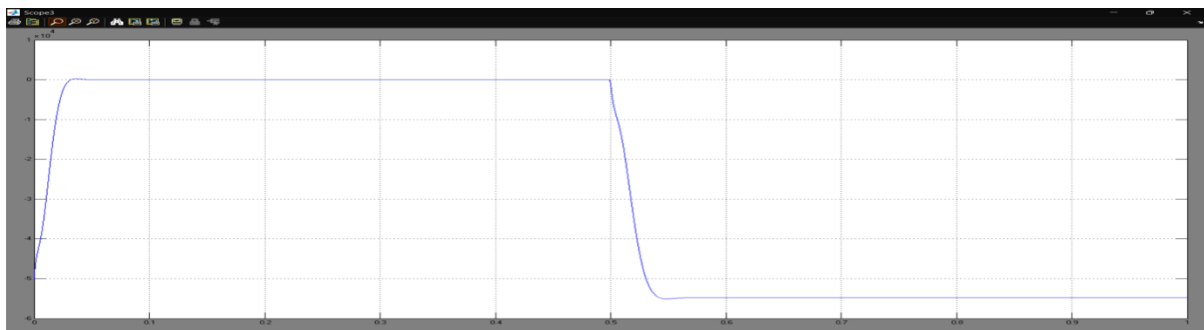
The outcomes of this operation are depicted in Fig. 8, which showcases the active power, reactive power, and voltage at the bus. The active power generated by the PV system remains constant at 98.5 kW until the solar system's penetration increases at $t=0.5$ seconds, reaching 108.07 kW. However, due 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%.

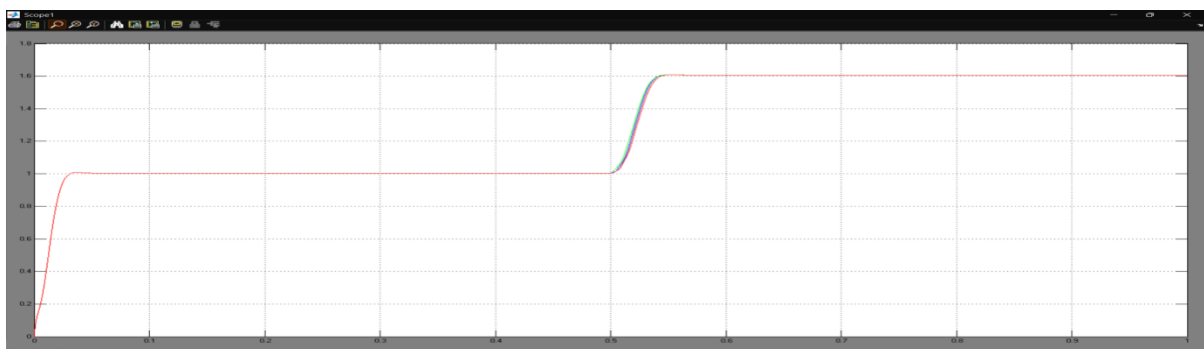
CASE C: PERFORMANCE OF STUDIED SYSTEM WITH REACTIVE POWER CONTROL



(a) Active power



(b) Reactive power

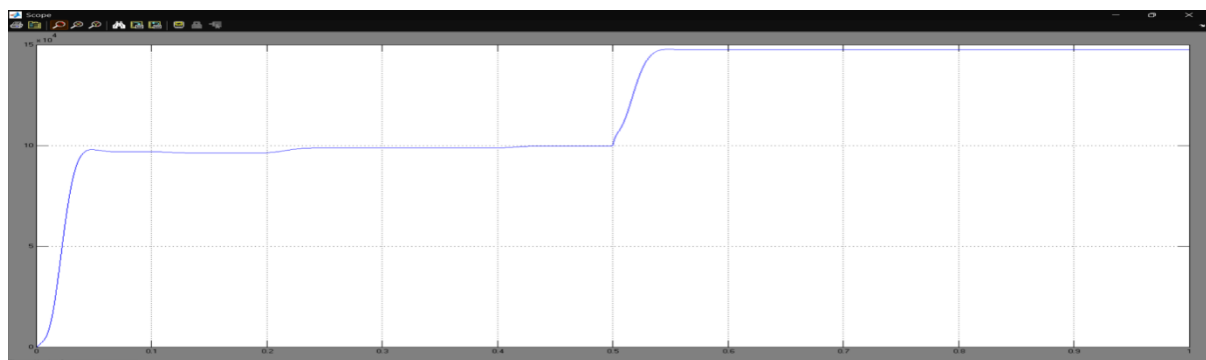


(c) Bus voltage

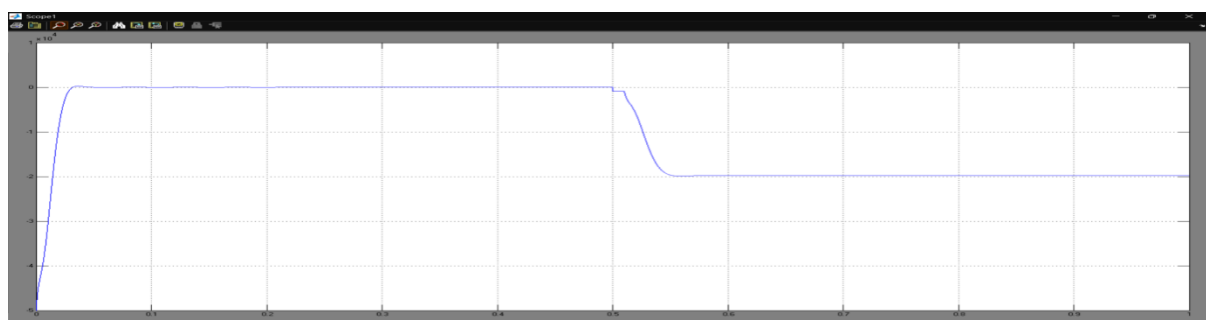
Fig.9: The results of a PV system with a connection to a grid with Volt-Var control.

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. 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 $t=0.5$ 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.

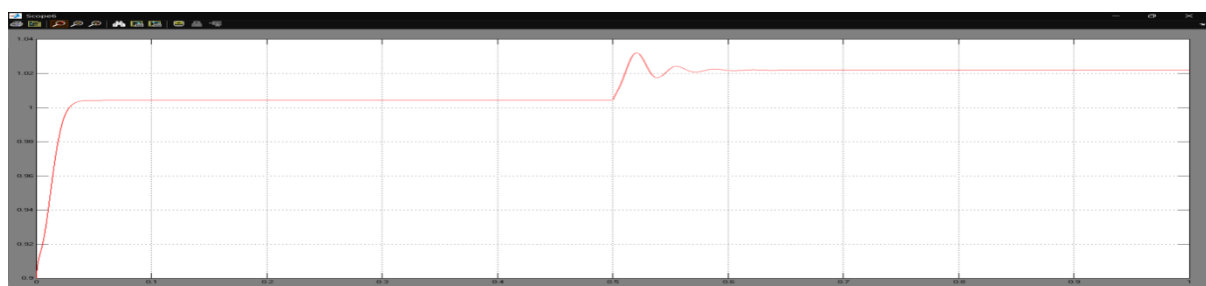
CASE D: PERFORMANCE OF STUDIED SYSTEM WITH POWER FACTOR CONTROL



(a) Active power



(b) Reactive power

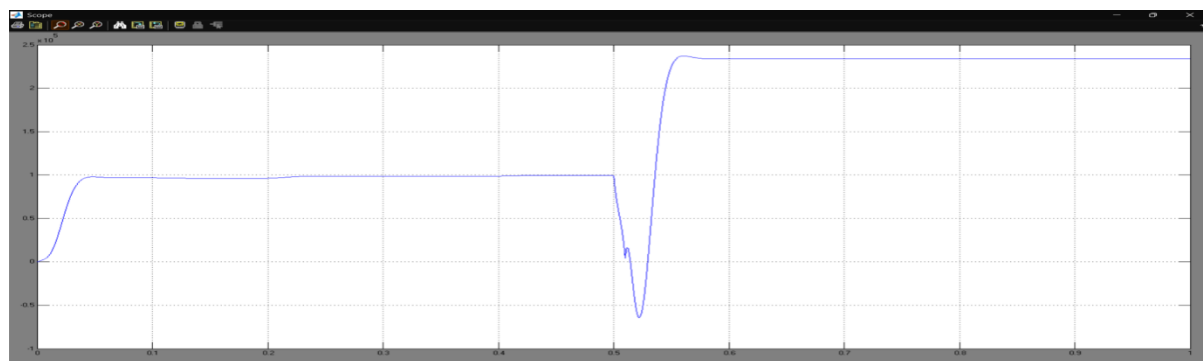


(c) Bus voltage

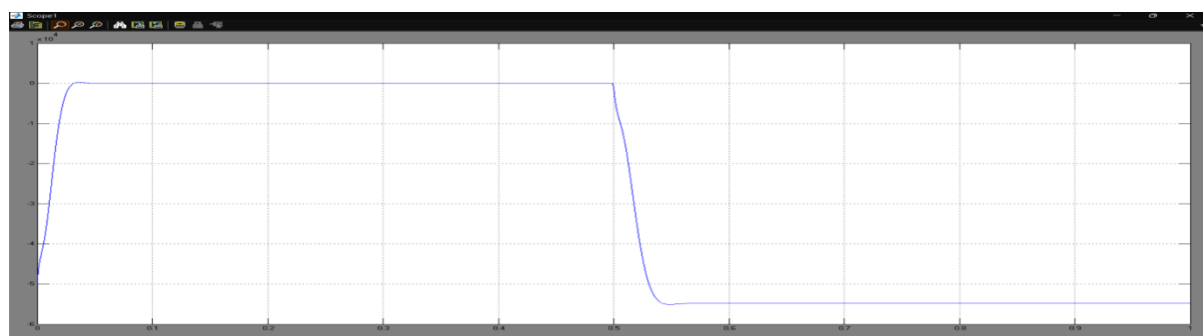
Fig.10: The results of a PV system with a connection to a grid with PF control.

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. 10, 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 $t=0.5$ 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 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.

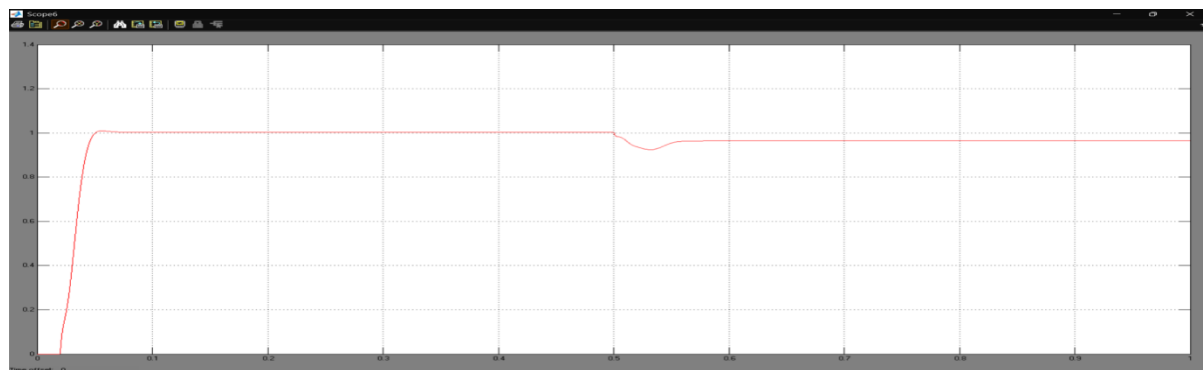
CASE E: THE STUDY OF REACTIVE POWER CONTROL WITH BESS



(a) Active power



(b) Reactive power

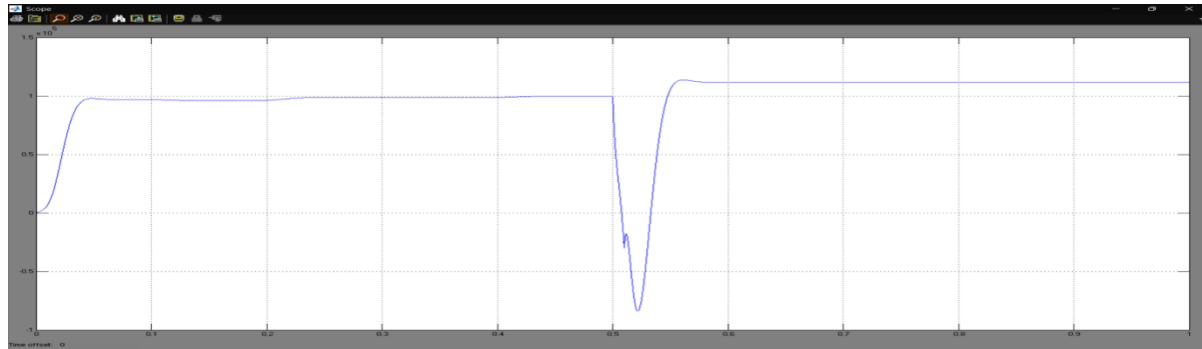


(c) Bus voltage

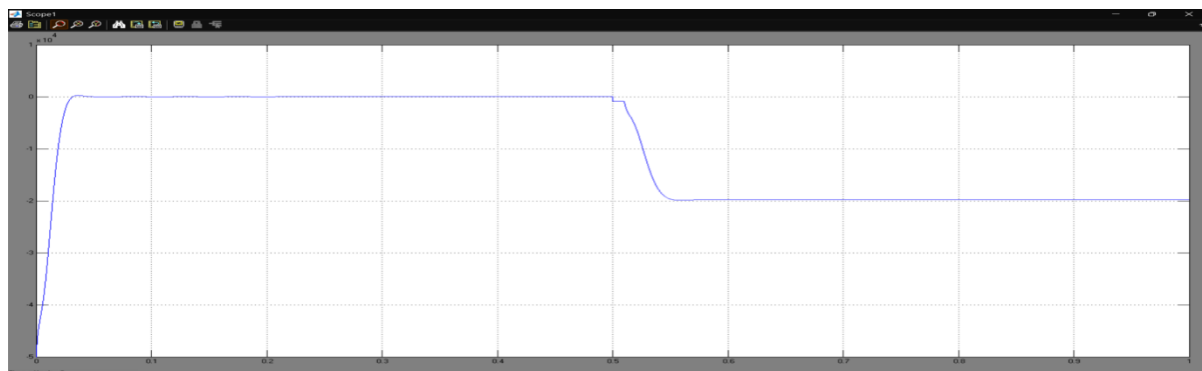
Fig.11: The results of a PV system with a connection to a grid with Volt-Var & BESS.

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 11 depicts the active power, reactive power, and bus voltage. At 0.5 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%.

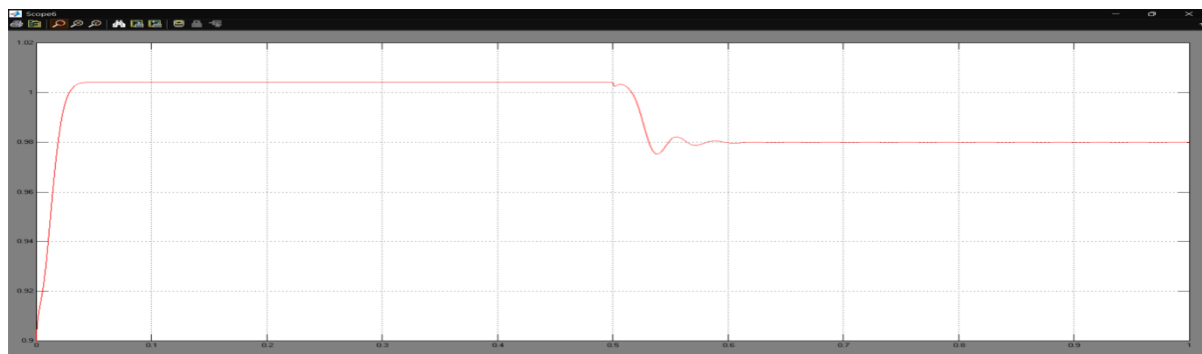
CASE F: THE STUDY OF PF CONTROL WITH BESS



(a) Active power



(b) Reactive power



(c) Bus voltage

Fig.12: The results of a PV system with a connection to a grid with PF control & BESS.

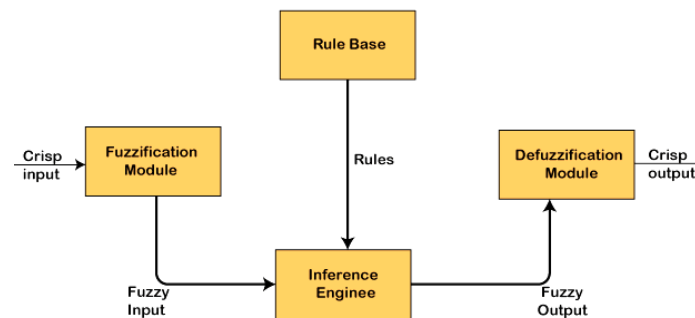
Power factor control with a Battery Energy Storage System (BESS) involves managing the reactive power flow to improve the power factor of an electrical system. The power factor is a measure of how effectively electrical power is being utilized and is determined by the ratio of real power (measured in kilowatts, kW) to apparent power (measured in kilovolt-amperes, kVA). Figure 12 illustrates the active power, reactive power, and bus voltage. At the 0.5-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%.

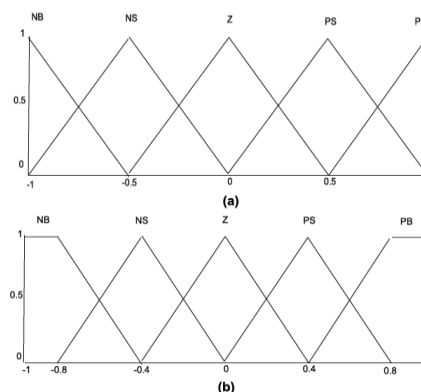
COMPARISION RESULTS:

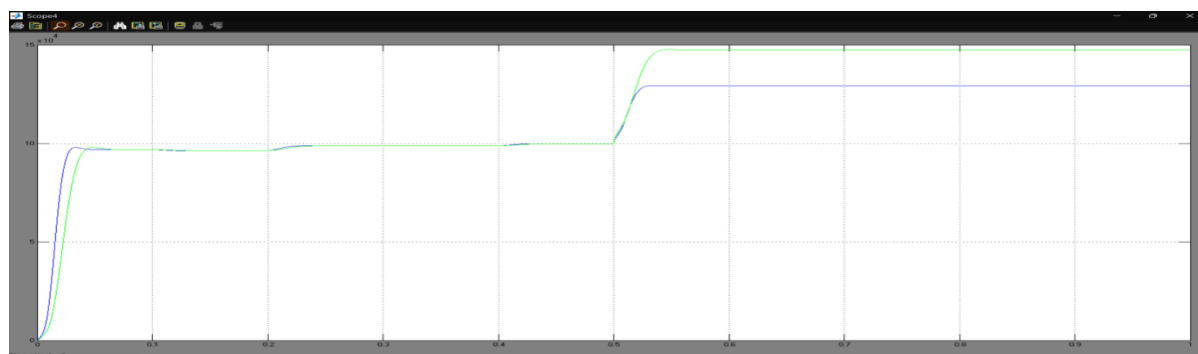
Fuzzy Controller Design:

Fuzzy logic is a technique that uses degrees of truth and is computer-based. The output of a fuzzy logic framework is determined by the extent of truth & linguistic elements that are taken into account. Whatever this input is in; it will dictate the output type.

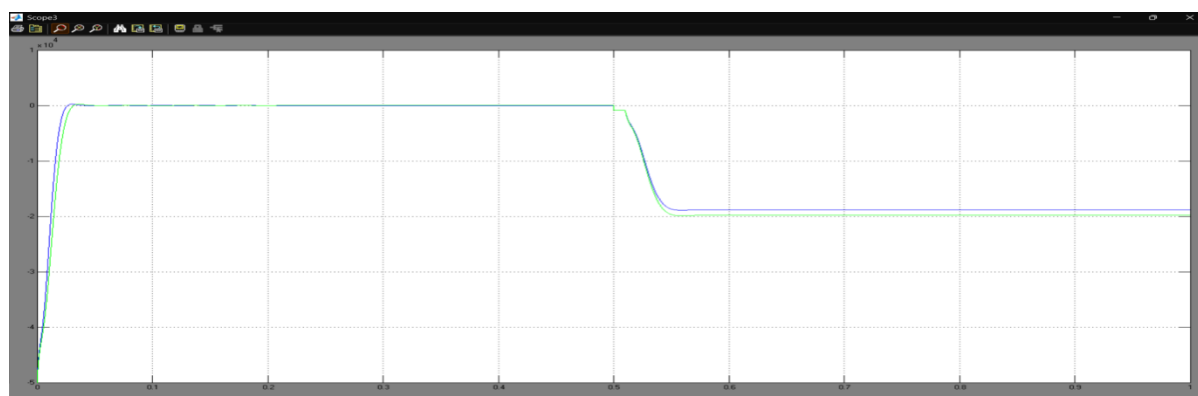


In fuzzy logic, solutions are designated and put into action by applying rules that connect expert inputs with the intended outputs. Significant influences on fuzzy logic come from fuzzy sets, membership functions, language variables, and fuzzy rules. Estimating or computing the degree to which an input unit belongs to a general set, such a fuzzy set, is the purpose of this function. On one side, we see the cosmos, and on the other, we see different levels of membership within that structure. See below for a visual representation of a membership function. Figure shows as, (a) Inputs membership function, (b) Outputs membership function.

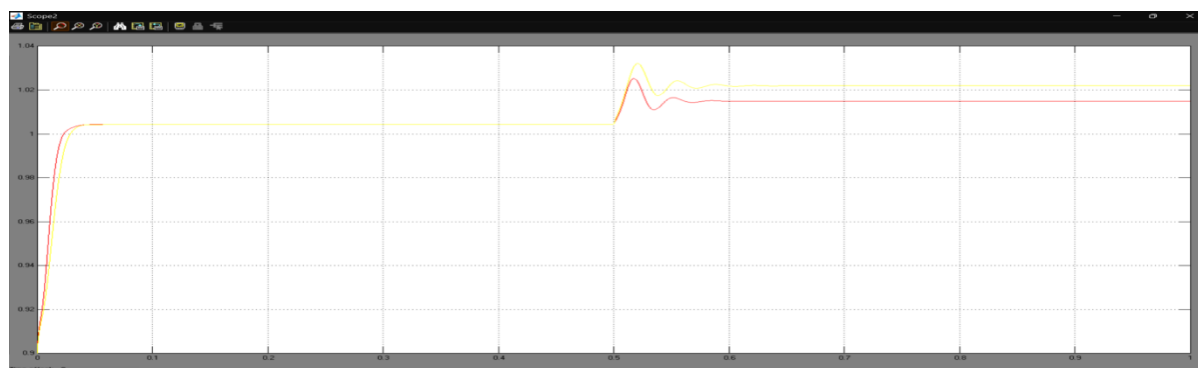




(a) Active power

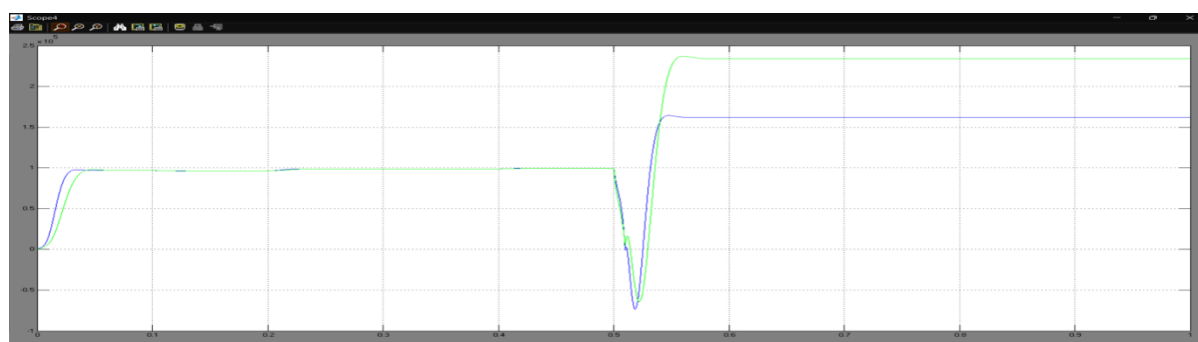


(b) Reactive power

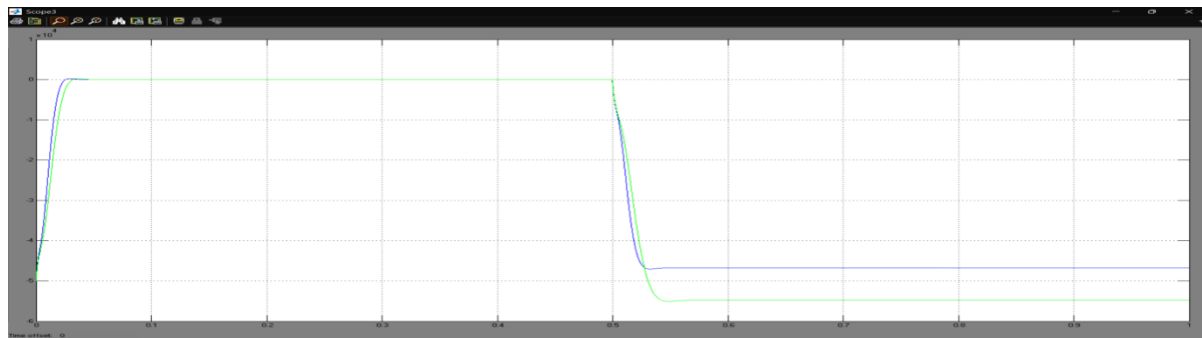


(c) Bus voltage

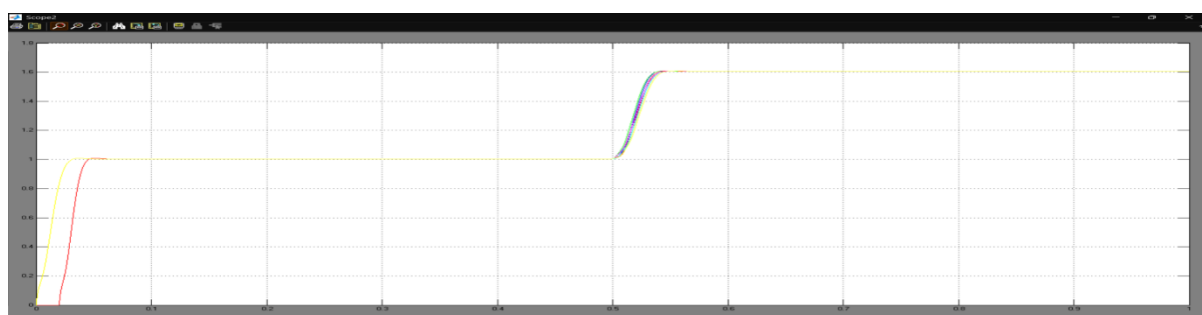
Fig.13: The results of a PV system with a connection to a grid with PF control.



(a) Active power



(b) Reactive power



(c) Bus voltage

Fig.14: The results of a PV system with a connection to a grid with Volt-Var control.

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.

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