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An Uninterrupted Fuzzy-Based PV-BES System for Improving Power Quality in Grid-Connected Systems

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A B S T R A C T

This article proposes a technique to improve power quality and eliminate current and voltage harmonics. The robustness of the system functioning in various operating modes is the key contribution of this research. Research findings demonstrating the PV array insulation, load variation, and grid unavailability are employed for transitioning between modes and are used to assess the performance of a grid-interfaced PV-BES (Battery Energy Storage) system. The system also operates in constant and variable power modes to provide power smoothening and reduce the load on the distribution grid during peak demand. This system also turns out to be capable of operating in an islanding mode to provide the load with uninterrupted power. For this, a grid-tied voltage source converter (VSC) with effective control logic is designed. A PI controller was used in the existing model to enhance the system's performance, but due to various disadvantages, a fuzzy logic controller has been implemented in the proposed system, which has more advantages and aids in suppressing harmonics and enhancing the reliability of the power. Consequently, a comparison of the controller is done in this article. For implementing the performance of this system, MATLAB/Simulink software is used.

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1. Introduction

Abozaed et al. [1] propose the application of controllers that monitor the maximum power point of photovoltaic systems is thought to be the ideal solution to boost their efficiency and enhance the quality of the resulting electrical power, so as to extract the maximum productive capacity from such systems. Panigrahi et al. [2] described the outcome of lower solar panel costs, higher panel efficiencies, and improvements in the related power electronics. Small-scale rooftop PV installation is one of the numerous types of PV plants. In order to integrate PVs and other distributed generation (DG) sources into the grid, numerous standards have been developed.

Myneni et al. [3] proposed a single-stage transformation that grows in popularity, in which MPPT of SPV and actual power injection are accomplished with VSC alone. Bendedia et al. [4] proposed a thorough analysis of a hybrid system that uses batteries as an additional source and a PV generator as the main power source. In order to maximize the PV efficiency at the load and the PV generator, the MPPT algorithm has been used to regulate the boost converter.

Establishing a network connecting users and load profiles is referred to in the overall scheme of smart grid systems as network communication. Additionally, used for effective power management includes clustering and cloud computing was proposed in this article by Kumar et al. [5].

Rallabandi et al. [6] proposed a photovoltaic (PV) system that runs at its maximum power point during times of reduced irradiance in an effort to increase capacity factor, while the power output is restricted to a rated value at times of high irradiance. A utility-scale battery energy storage system (BESS) is also included in the planned arrangement, and it is linked to the grid through a separate inverter

Harmonic problems were reduced by using a photovoltaic shunt active harmonic filter and an impedance source converter proposed in this article by Sai Thrinath et al. [7]. Integration of PV systems and energy systems will increase reliability, efficiency, and electricity cost was proposed in this article by Tran et al. [8].

Ravindra et al. [9] proposed an MPPT and current control algorithms are used in single-phase grid-connected systems for efficient performance. A P-Q theory is used to control the power between load and PV generation.

Incorporating machine learning concepts, this research article by Venkatesh et al. [10] provides a novel approach for quickly estimating the line severity and clustering in the distribution grid. Ravindra et al. [11] proposed an energy management system that controls the battery system which helps in the mitigation of voltage fluctuations and constant power can be achieved and also benefits by decreasing cost.

Farook et al. [12] investigated the performance of voltage source converters in grid-connected solar PV systems that use fuzzy controllers to differentiate the essential elements from load current and generate firing pulses. A fuzzy-based controller is used to alter the controller's duty cycle under controlled irradiance and environmental temperature conditions as well as to adjust the DC link voltage in order to fulfil the power demand, need, and reduce power quality issues at the common point of connection.

Rajkumar et al. [13] proposed a fuzzy logic circuit to increase the system's efficiency. The reliability and efficiency of the PV system depend on the FLC's capacity to regulate the converter's output voltage. The results significantly decreased the barriers to entry in designing and improving fuzzy logic controllers, which has significant implications for the development of more reliable and effective energy systems.

Srinivasan et al. [14] proposed an enhanced Archimedes optimisation algorithm for reactive power optimisation in distribution systems in order to obtain an improved solution. The goal of article is to maximize economic gain by lowering power loss and capacitor purchasing costs under three distinct load circumstances while satisfying equality and inequality requirements.

Parimalasundar et al. [15] investigated the performance of a five-level inverter with varying loads is highlighted in this paper. This design cost was less than traditional multilevel inverters for the identical five output levels because it requires less controller circuits. The suggested modular five level design is simulated using both fundamental frequency switching modulation techniques and high frequencies switching PWM techniques.

Komala et al. [16] proposed a distribution method to estimate the photo energy using a deep learning model, a compact flat not only uses less energy, but it also costs less to build. A building that uses little energy and has a pleasant microclimate is said to be energy-efficient.

Srilakshmi et al. [17] proposed an intelligent hybrid controller for an integrated UPQC solar PV system and battery storage (BES) system. The suggested controller incorporates elements of both an integrated sliding mode controller and an artificial neural network. For the best UPQC performance under unbalanced/distorted supply voltage conditions, the self tuning filter (STF) in conjunction with unit vector generation technique (STF-UVG) synchronizes the phases.

Suresh et al. [18] proposed a significant reduction in power loss and the downstream power process of a DC-DC converter. Switching losses in the T-PC can be minimised thanks to multilayer properties. The total bidirectional dc-ac conversion process can be made much more efficient. T-PC-based bidirectional dc-ac conversion concepts were analysed with regard to their circuit model, operation, and modulation control.

The system consists of a PV array, a boost converter with MPPT, and a single phase inverter connected to the utility grid. To operate the IGBT switch of the boost converter, the MPPT uses fuzzy logic. The FLC is more effective at locating the maximum power point than the traditional incremental conductance method proposed in this article by Menniti et al. [19].

Moorthy et al. [20] proposed a conceptual study of a smart grid invention that used an eco-friendly power source and the Internet of Things. This smart grid, which incorporates computerised innovation and information the board approaches, is one of several components in the system that is currently being used to modernise how power is distributed, and it is one of the most important. In order to employ a photovoltaic cell, solar energy is being examined as a viable sustainable power source.

Suresh et al. [21] proposed an approach that can achieve high efficiency and smooth switching grid operation. A prototype model with a 500 W power rating and a voltage range of 20–50 V was used to test the proposed converter's working theory, design process, control scheme, and features. Bialasiewicz et al. [22] mainly focused on PV power generator stand-alone power system operation and modelling. A renewable energy power system modular simulator was used to simulate systems with PV array-inverter assemblies that operate in the slave- and master-modes.

Sai Thrinath et al. [23] proposed an MPPT method to boost the system performance offered by the fuzzy controller (FC) like P&O to draw out as much power as possible and use the new regulators to keep the DC-DC converter's bus voltage constant. This FC with DC-DC converters was evaluated using the fuzzy logic controller (FLC) based MPPT technique.

Singh et al. [24] proposed a solar photovoltaic (PV) array, a BES, the grid, and nearby residential loads that make up this system. A new control was implemented such that the utility grid, a BES unit, and a PV array all will supply the active power requirement of commercial loads. With the integration of BES and extra power from the PV arrays that is sold back to the grid, the power control in this system functions in several power modes to give benefits to the end users.

The novelty of the paper is that the designed system uses a fuzzy logic controller, over than PI controller, which has additional benefits and helps to reduce harmonics and improve power reliability.

2. The Solar Energy Resource

The primary energy source that sustains all life processes on Earth, including photosynthesis in plants, the planet's thermal comfort, and the entire biochemical system, is the sun. The electromagnetic radiation that the sun emits is transformed into other forms of energy once it reaches the earth's surface and is used for a variety of purposes.

The output of the PV cells changes with solar irradiation is

$$V_{oc} = V_{oc} - \frac{KT}{q} \ln\left[\left(\frac{V_{mp} * q}{nKT}\right) + 1\right] \qquad (1)$$

The quality of Cell can be measured by the form factor, which is given by formula

$$FF = \left[\frac{V_{mp} * \mathrm{I}_{mp}}{V_{oc} * I_{sc}}\right] \qquad (2)$$

The quality is greater the closer the level of form factor is near unity. Furthermore, to determine the Photo Voltaic module's efficiency:

$$\%\eta = \left(\frac{FF * V_{oc} * I_{sc}}{P_{in}}\right) \qquad (3)$$

3. Battery Energy Storage System

The electrical energy can be stored by using devices like batteries. The majority of the time, energy storage systems (batteries) are utilized in conjunction with solar power to store extra energy produced during high production periods for usage during low production or times of high demand. Battery storage systems have a number of benefits, including greater grid stability and dependability, decreased dependency on fossil fuels, and increased energy efficiency. They can also assist in lowering energy costs by supplying energy that has been stored during times of high demand when power rates are normally higher.

4. Boost DC-DC Converter

In PV applications for grid-based mode, there are two configurations to choose from; The MPPT process and solar power plants with one or two phases have received the most attention. Because a two-stage PV energy conversion technology gives more operational flexibility than a one- stage system, it is used for this purpose. Because of the minimum output voltage of Photovoltaic cells, minimumvoltage arrays are used.

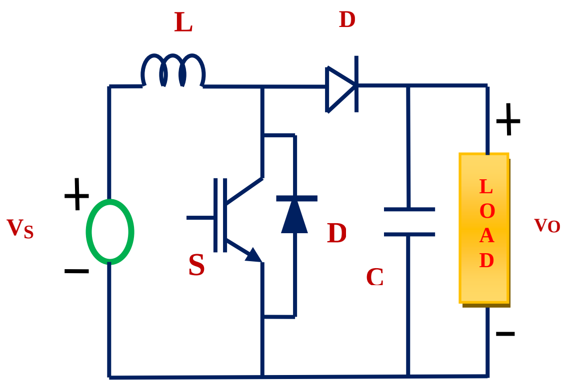

Figure 1. Circuit diagram of the boost converter

The circuit uses a capacitor as a means to lessen errors at higher frequencies. The pulse width of the switch is arranged, and the output voltage, which initiates the switching duration is relative to the complete cycle, it may be changed. The resultant power of the converter increases as the duty cycle is raised; it decreases as the duty cycle is lowered.

5. Modelling of Inverter

An inverter is sometimes referred to as a device that converts DC to AC power. The AC electricity produced by an inverter may power the electrical appliances and devices in homes, offices, and cars.

Usually, the purpose of the inverter is to convert a minimum DC voltage to a maximum AC voltage using the battery or by using other energy sources. Further, the AC voltage will be converted to low-frequency AC as it can be used for electrical devices.

Inverter devices are used in a range of uses, from a tiny computer switching the electric energy is transferred to large Energy utilization to transport vast electricity.

Therefore, if the use of AC power appliances is essential,they are good alternatives.

Power inverters provide three different wave outputs:

- Sinusoidal wave
- Squared wave
- Real sine waves

The converter's two main goals are to maintain balance in the total power supply from photovoltaic modules to the grid and to successfully provide AC current simultaneously with the grid of AC usage.

6. Controlling of PhotovoltaicArray Based on Grid

Energy is generated from solar arrays by a photovoltaic system with the grid-connected and supplied to the electrical grid. This system comprises controlling the electrical flow in the solar cells, as well as the electricity grid, its inverter, and the Photovoltaic system, which is attached to the grid. The main purpose of Controls

1. The MPP tracking rule requires that as much power as feasible be drawn from a Photovoltaic generator.
2. By controlling the inverter, it regulates the DC source voltage; - Adjusts that reactive power and regulates the active power.

The administration system makes sure that power is provided. This reduces the usage of standard power sources, efficiency will be increased and decreases the carbon footprint of the electrical infrastructure.

7. Maximum Power Point Tracking System

Due to the weather and load disturbances, the performance of the photovoltaic system changes rapidly. For the generation of maximum power, a tracing technique is used. A P&O method is used, and by this technique few parameters are observed.

8. Fuzzy Logic Controller

To all other controllers like PI, PID and FLC has more advantages. It can be also used for non-linearity functions and the complexity of the FLC is less when compared to the others. FLC consists of two inputs, they are error E and change in Error ΔE. The manifestation of the FLC will be based on the membership functions Shape of the rule base. This is useful to trace the maximum power. The membership functions are assigned to five fuzzy sets and 25 rules are shown in the below table.

Table1. five fuzzy sets and 25 rules

e / Δe	**NB**	**NS**	**ZO**	**PS**	**PB**
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NB	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

In Fig.2 The error input should be more than the reference voltage and less than the actual voltage, a change in the error is the error in the sampling interval. In Fig.3 The output of the FLC is the reference signal for PWM Unit. Here three steps are present, fuzzification, knowledge base, and defuzzification. In the fuzzification process, the numerical values are converted to a fuzzy set. In Figure4 During the knowledge base, the required output is generated and during the last stage of defuzzification, the fuzzy set is converted to numerical values. Therefore, the membership functions for these variables are shown below Figure 2, change in error is shown in Figure 3 and membership function output is shown in Figure 4.

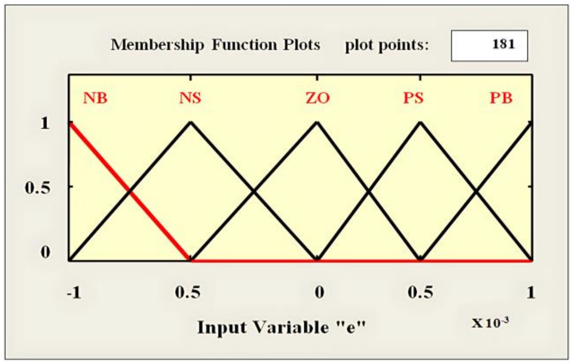

Figure 2: Membership function Error

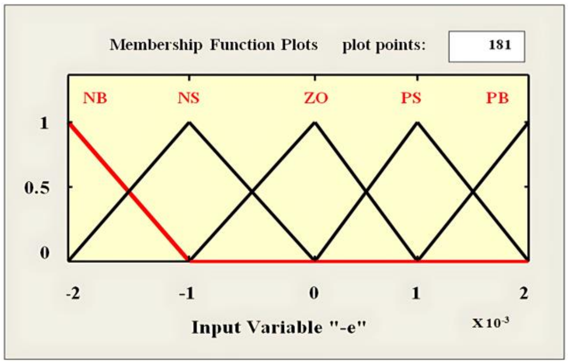

Figure 3. Membership function Change in Error

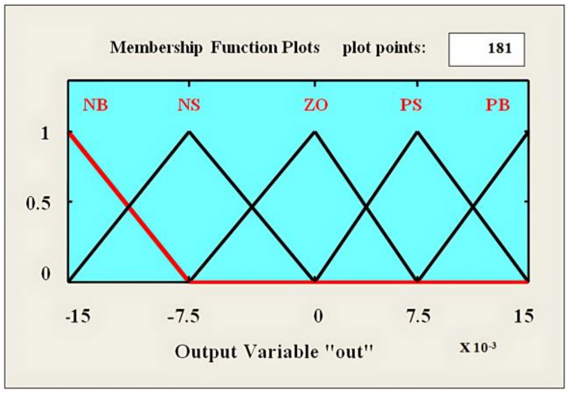

Figure 4. Membership function output

9. System Methodology

This configuration consists of a Photovoltaic array, Battery system (BES), a grid, and non-linear loads. It operates as the power is generated in the solar PV array which consists of irradiance and temperature as inputs and voltage and current as output. The voltage which is generated in Photovoltaic is increased by using the PV boost converter where a small amount of power is not sufficient for the loads. After boosting the voltage, the required power will be sent tothe loads or it will be stored in the battery. The power that is sent to the loads is transferred through a voltage source converter where the power is converted to dc-ac and the power that is sent to loads is first filtered to decrease the voltage distortions using filters and finally, the filtered power will be transferred to the loads. If both the solar Photovoltaic and the battery run out of power, the grid will help to transfer the power to the loads.

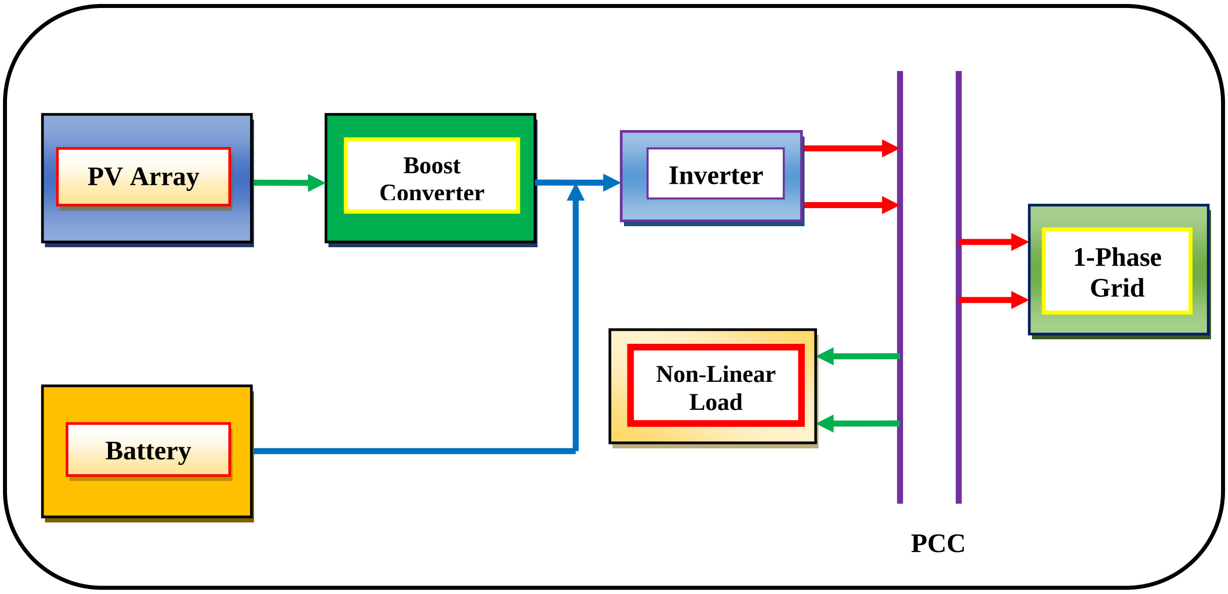

Figure 5. Schematic Layout of Proposed Topology

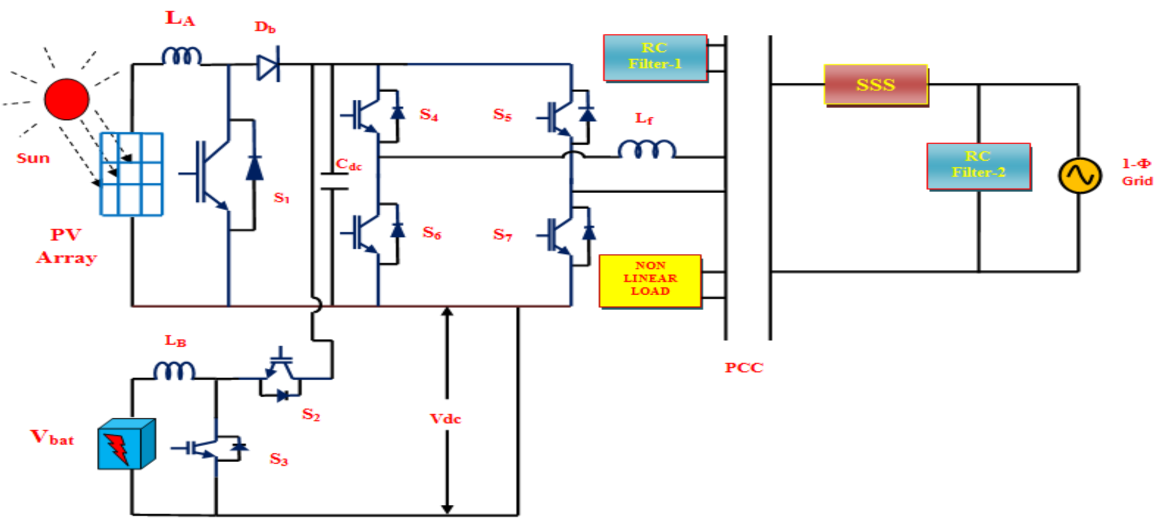

Figure 6. System Configuration

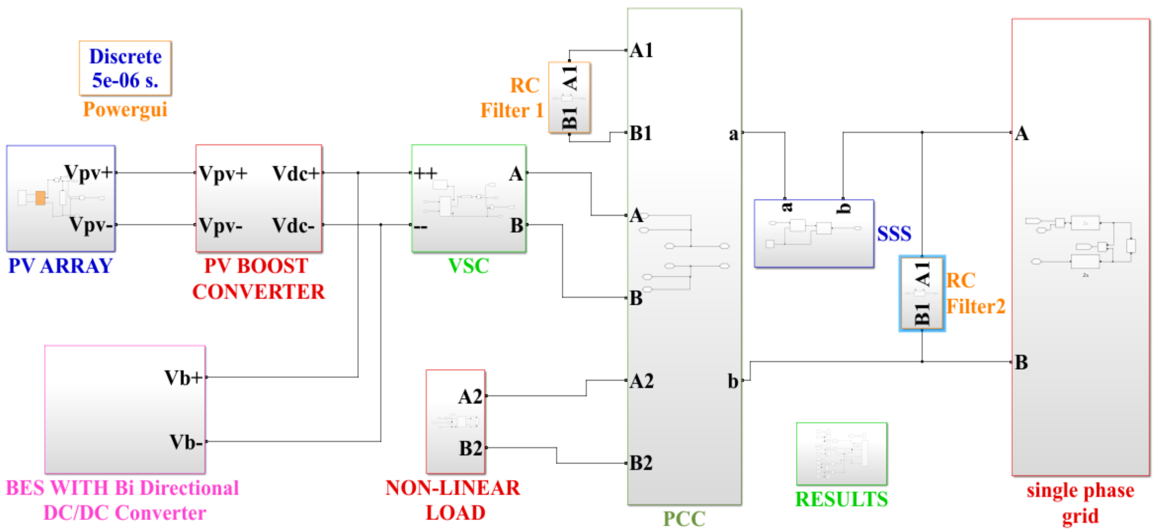

Figure 7. Simulink Diagram of PV-BES Integrated System

10. Simulation Results

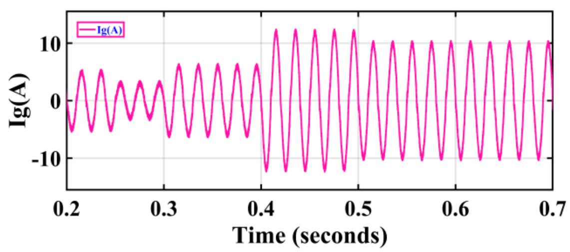

Figure 8. Grid Current(I_g)

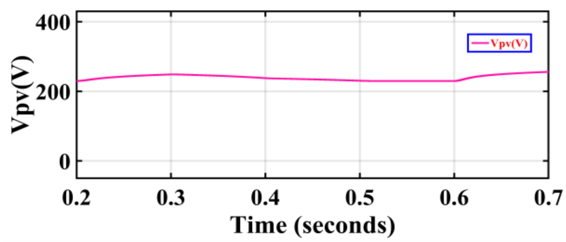

Figure 10. PV Pannel Voltage (V_{pv})

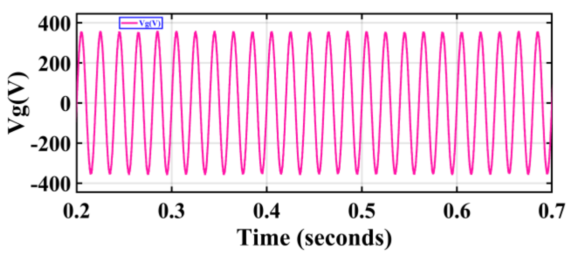

Figure 9. Grid Voltage (V_g)

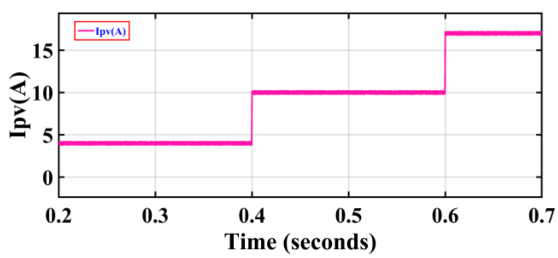

Figure 11. PV panel Current (I_{pv})

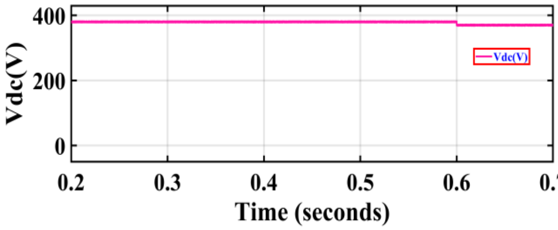

Figure 12. Voltage of boost Converter (Vdc)

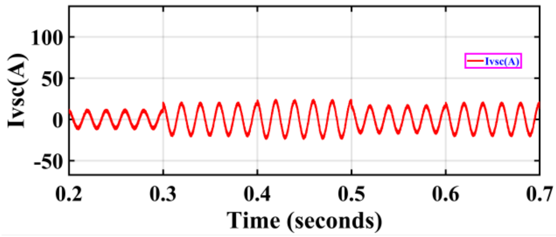

Figure 13. Voltage Source Converter Current (I_{VSC})

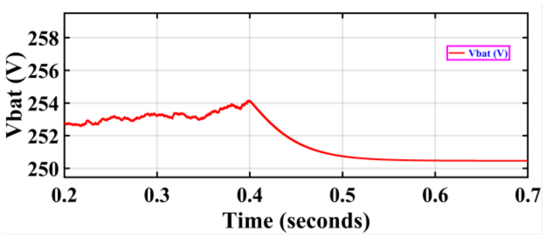

Figure 14. Battery Voltage (V_b)

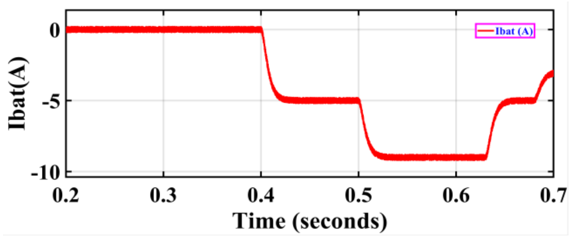

Figure 15. Battery Current (I_b)

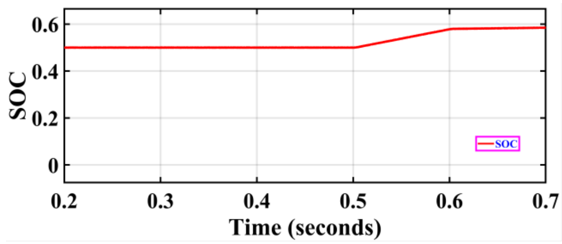

Figure 16. State of Charge (SOC)

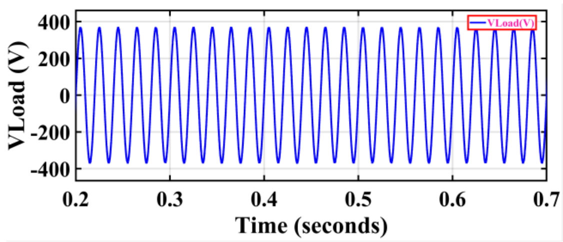

Figure 17. Load Voltage(V_L)

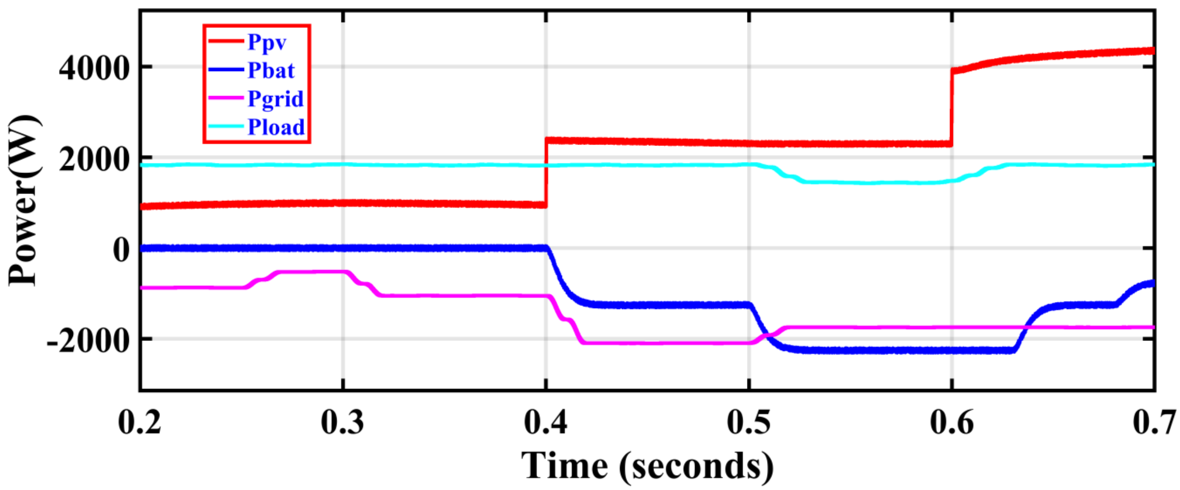

Figure 18 PV Power ,Battery Power , Grid Power and Load Power

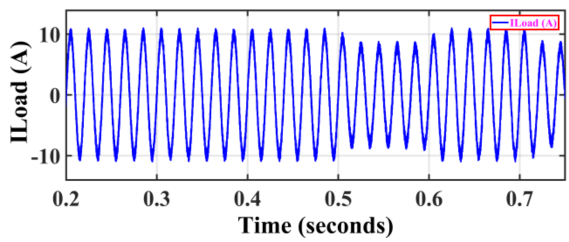

Figure 19. Load current(I_L)

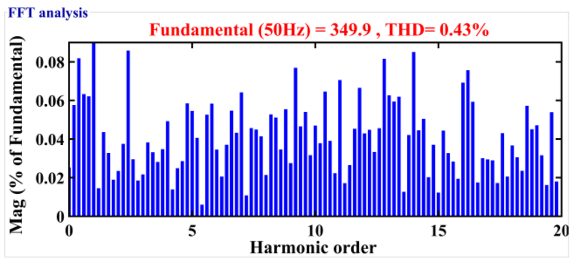

Figure 20. % THD of Grid Voltage

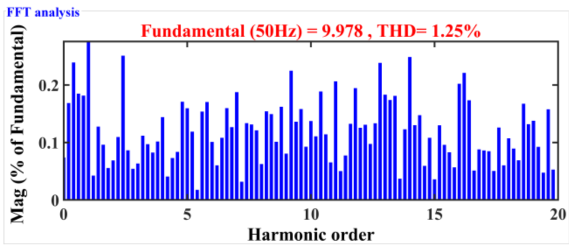

Figure 21. % THD of Grid Current

Figures 5& 6 show the schematic layout of proposed topology and system configuration which describes a grid-interfaced PV-BES system and consists of a solar PV array, a utility grid and a BES unit. The BES unit is coupled to the DC link using a DC-DC bidirectional converter (DBC), and the maximum power extraction (MPE) is accomplished using a boost converter. The VSC is responsible for the actual power transfer between the grid, battery, and PV array. Across the system's point of common coupling (PCC), the ripple filter (R-C) is connected.
By switching VSC, the high switching ripples are removed using an R-C filter. For grid-on and grid-off controls, this system is connected to the main grid through a controlled solid-state switch (SSS). SSS is not accessible during GCM. In contrast, when the grid goes off-grid, the PCC is cut off from the grid by opening SSS. The system's PCC is where the nonlinear loads are coupled and finally figure 7 represents the simulation model diagram from which to get the below simulation results which are elaborated in detail below.
In this simulation, the primary objective is to assess the performance of various parameters when utilizing the FLC (Fuzzy Logic Controller). One of the critical parameters under evaluation is the grid current, which is depicted in Figure 8, exhibiting a steady flow of approximately 9.978 A. Furthermore, in Figure 9, the voltage supplied to the grid starts to show signs of saturation at 349.9 volts, a phenomenon observed at the 0.2-second mark. Turning our attention to the photovoltaic (PV) panel's characteristics, Figures 10 and 11 reveal the generation process of two parallel PV array strings. The voltage output from this setup remains relatively constant at around 254 V, while the current output hovers at 16 A.
Figure 12 represents the voltage output of the boost converter, consistently maintaining a level of approximately 370 V. This voltage source converter is responsible for converting the DC voltage to AC voltage, and Figure 13 showcases this conversion process. Here, the fuzzy logic controller technique is employed to regulate the AC voltage sent to the point of common coupling.
Finally, the current in the voltage source converter, as depicted in Figure 13, remains at a stable level, approximately 16.8 A. These parameters collectively form a comprehensive evaluation of the FLC controller's performance in this simulation, providing valuable insights into the effectiveness of the control system in managing the grid current and voltage within desired operational limits.
Figures 14 and 15 describe about battery. The battery voltage (V_b) is decreasing from 258.5 volts to 250.5 volts over a period of 0.1 seconds and beyond. Simultaneously, the battery current (I_b) remains constant between 0.1 seconds and 0.4 seconds and then starts to discharge at 0.62 seconds. This suggests that the battery is discharging during this time frame.
Figure 16 represents the battery's state of charge in an incremental mode, likely indicating how the battery's capacity or charge level changes over time with the assistance of a boost converter. A boost converter is a device that can increase the voltage output from a power source.
Figures 17 and 19 describe the voltage and current associated with a non-linear electrical load connected to a Point of Common Coupling (PCC).

The load voltage is about 350V, and the load current is approximately 10.2A. Non-linear loads can introduce harmonics and distortions into the electrical system

Figure 20 displays a Fast Fourier Transfom(FFT) analysis of the grid voltage. FFT is a technique used to analyze the frequency components of a signal. In this case, it's applied to the grid voltage. The analysis shows that there are significant changes in distortion at intervals corresponding to the fundamental frequency (likely 60 Hz in the US or 50 Hz in some other regions). The Total Harmonic Distortion (THD) value is reported to be 0.43%, and the voltage value is 349.9V. THD measures the quality of the power supply, and lower values are generally desirable, indicating cleaner power with fewer harmonics.

Figure 18 illustrates the power output of the photovoltaic (PV) panel over time. At the beginning, the PV panel generates a consistent 1010W of power, and this level is maintained for the initial 0.4 seconds.This indicates that stable sunlight conditions or an optimal operating state. However, at 0.4 second, there is a significant increase in power generation, and the output jumps to 4022W by the time 0.7 seconds have elapsed. This sudden increase is due to changes in irradiance on PV panels.

Initially, the battery power level is at zero, indicating that the battery is not actively supplying or receiving power during this period. It remains at zero up to the 0.4-second mark. After this point, the battery starts to discharge power at a rate of 2152W. This discharge suggests that the stored energy in the battery is being used to support the electrical load or to supplement the power from the PV panel. It's important to note that the description does not provide information on when or if the battery starts recharging. The graph represents the power flow to or from the electrical grid. It begins at 100W, indicating a modest power draw or supply. Over a short time, span, from 0.2 seconds to 0.7 seconds, there is a notable increase in grid power, reaching 1950W. This suggests a change in the grid's role in the system, possibly transitioning from supplying power to receiving excess power from the solar system or vice versa.

Finally, Load power represents the electrical energy consumed by devices or appliances within the system. Initially, it remains constant from 0.2 seconds to 0.5 seconds, indicating a consistent power demand. After 0.5 seconds, the load power starts maintaining a constant level of nearly 2KW (2000W), which might imply that a significant load or set of appliances with a constant power demand has been activated.

In Figure 21, a detailed analysis of the grid current using Fast Fourier Transform (FFT) techniques is presented, revealing its harmonic distortion characteristics. Notably, within this analysis, a distinct and significant change in harmonic distortion occurs at intervals corresponding to the fundamental frequency. At this specific interval, the Total Harmonic Distortion (THD) value is reported to be 1.25%, with the grid current magnitude measuring at 9.978 A.

To further evaluate the effectiveness of different control strategies, a comparison Table 2 is provided, contrasting the performance of a Proportional-Integral (PI) controller and a Fuzzy Logic Controller (FLC). The primary metric of interest in this comparison is the reduction in THD for both grid voltage and grid current. It is observed that when the FLC is employed, the THD in grid voltage decreases from 1.46% to a lower and improved value of 0.43%. Similarly, for grid current, the application of the FLC results in a substantial reduction, lowering the THD from 9.09% to a significantly improved level of 1.25%. This demonstrates the superior performance of the Fuzzy Logic Controller in minimizing harmonic distortion in both grid voltage and current, underscoring its effectiveness in improving the quality and stability of the power supply system.

The methodology described in this research article serves several essential purposes. Firstly, it aims to enhance power quality by mitigating issues like voltage fluctuations and harmonics, which can adversely affect electrical equipment and grid stability. Secondly, the development of an islanding-capable PV-BES system, facilitated by a grid-tied voltage source converter (VSC) and advanced control logic, is crucial for ensuring uninterrupted power supply to critical loads, especially in regions prone to grid outages or for applications requiring high reliability. Additionally, the transition from a Proportional-Integral (PI) controller to a fuzzy logic controller is driven by the need to improve system performance, with fuzzy logic controllers being better suited for complex and nonlinear systems, contributing to enhanced stability and harmonics suppression. The adoption of MATLAB/Simulink for performance assessment allows for safe and cost-effective evaluation of the system under various conditions, ultimately advancing the field of power engineering and renewable energy and providing valuable insights for future application

Table 2. Comparison of THD for PI Controller & FLC

S.No	Parameters	PI controller	Proposed Fuzzy Logic Controller
1	THD of Grid Voltage	1.46%	0.43%
2	THD of Grid Current	9.09%	1.25%

Table.3 System Parameters & Ranges

PARAMETERS	RANGE
Parallel strings	02
Series connectedmodules per string	28
Maximum Power	215 W
maximum Voltage V_{max}	29V
maximum Current Imax	7.35A
Temperature Coefficient	$25^{O}C$
Irradiance	1200 W/m^2
Ripple Filter	L_f = 4 mH, R_f =5 Ω and C_f =10 μF
Load	2000W
Grid Voltage	400V

11. Conclusions

The robustness of the system functioning in various operating modes is one of this work's primary contributions. Experimental findings that leverage the most extreme scenarios of PV array isolation, load variation, and grid unavailability for transition between modes serve to validate the performance of a grid interfaced PV-BES system. In order to offer power easing and minimize the strain on the distribution grid during peak demand, the system is also running in constant and variable power modes. By developing this system, an uninterruptable powersupply will be provided to the loads even when the grid is not present. This is capable of working in islanding mode and the harmonics are decreased by using the fuzzy logic controller in the inverter as it increases the performance of the system and the quality of the power will also be increased. In this article, a comparison is done for both PI and FLC. Thus, by implementing this FLC into practice, the system responds faster and has better power quality overall. Fuzzy logic controllers reduce the Total Harmonic Distortion by 4.83% (voltage) and 1.25% (current). Future scope is to Polynomial load modeling using machine learning for hybrid line stability under contingency situations.

The future scope for this research includes exploring improved grid integration, endurance to disturbances, cost-saving strategies, and environ mentally sustainable practices, as well as further enhancing the robustness and efficiency of grid-interfaced PV-BES systems. This work has the potential to be extremely important in decreasing grid stress during peak demand periods, increasing the utilization of renewable energy sources, and assuring a sustainable and stable electricity supply in the future.

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Nomenclature

PLL	Phase Locked Loop
FLC	Fuzzy Logic Controller
BESS	Battery Energy Sotage system
MPPT	Maximum Power Point Tracking
SOC	State of Charge
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Control
STF	Self Tuning Filter
UVG	Unit Vector Generation
Vpp	Voltage at point of common coupling
Vpv	Photo Voltaic Voltage
Ipv	Photo Voltaic Current
Ig	Grid Current

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