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OPTIMIZED SOLAR POWER GENERATION WITH FUZZY LOGIC BASED POWER SMOOTHING

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ABSTRACT

The output power from a solar power generation system (SPGS) change significantly because of environmental factors, which affects the stability and reliability of a power distribution system. This study proposes a SPGS with the power smoothing function. The proposed SPGS consists of a solar cell array, a battery set, a dual-input buck-boost DC-AC inverter (DIBBDAI) and a boost power converter (BPC). The DIBBDAI combines the functions of voltage boost, voltage buck and DC-AC power conversion. The BPC acts as a battery charger between the solar cell array and the battery set. For the proposed SPGS, the DC power that is provided by the solar cell array or the battery set is converted into AC power through only one power stage. The solar cell array also charges the battery set through only one power stage. This increases the power conversion efficiency for the solar cell array, the battery set and the utility. The battery set is charged/discharged when the output power of the solar cell array changes drastically, in order to smooth the output power from the SPGS. In addition, the DIBBDAI can suppress the leakage current that is induced by the parasitic capacitance of the solar cell array. The proposed power conversion interface increases power efficiency, smooths power fluctuation and decreases leakage current for a SPGS. A hardware prototype is completed to verify the performance of the proposed SPGS.

KEYWORDS: Solar power generation, power smoothing, buck-boost DC-AC inverter.

1.INTRODUCTION

PROJECT OVERVIEW: Extreme climate change has created global warming. In order to prevent irreversible climate change, the United Nations promotes the international convention on greenhouse gas emission reduction. Most countries are actively developing renewable power generation to reduce the environmental impact of greenhouse gas emissions. Renewable energy from solar energy and wind energy involves mature technology and is widely used to generate electricity. In the past, renewable power generation was expensive and depended on government subsidies but the cost of renewable power generation has decreased rapidly due to developments in manufacturing technology.

The cost of renewable energy power generation in many countries is close to or less than the price of electricity that is generated using fossil fuels so an increasing number of renewable power generation systems are being integrated into the grid to generate electricity. The output power from a solar power generation system (SPGS) changes significantly due to environmental factors [1]–[12]. These environmental factors change with the weather and seasons and cannot be controlled. As the penetration of SPGSs increases, drastic changes in their power generation will affect the voltage and frequency of distribution power system and can cause power outages. This reduces the power quality of distribution power systems. Several control strategies for the power conversion interface are used to alleviate the fluctuation in the output power from a SPGS [1].

However, these control strategies only limit the increase in power from the SPGS by giving up maximum power tracking, and they only suppress the upward power fluctuations for the SPGS. In addition, the power that is generated by the SPGS is also decreased. To suppress upward and downward fluctuations of the SPGS, the rapid power regulation technology is required to temporarily store and release power to stabilize the power output from the SPGS. Since battery set has the advantages of small size, quick absorption and release of electrical energy and flexible operation, it has considerable potential as a power regulation device for the SPGS [2]–[16]. In general, the control concept for smoothing the output power of SPGS is that the battery energy storage system supplies the difference between the average value and the instantaneous value for the output power of SPGS. The average value for the output power of SPGS can be calculated by low-pass filters [3]–[6], moving average filters [3], [4], [7], Saviztky– Golay filtering [8] and moving regression filter [9]. Since the instantaneous value for the output power of SPGS is rare equal to its average value, the charging/discharging time of the battery set is long.

The output from a solar cell array is DC power and the battery set stores power in DC form, so a power conversion interface is needed for integrating solar cell array or battery set into the power grid for DC-AC power conversion [1]–[23]. The configuration of SPGS and battery energy storage system can be divided into AC coupling [9]–[12] and DC coupling [4], [8], [13]–[16]. For the AC coupling configuration, the SPGS and the battery energy storage system (BESS) are respectively connected to the grid. Therefore, the SPGS and the BESS have their own DC-AC power converter and the circuit structure is more complicated. For the DC coupling configuration, the SPGS and the BESS share a common DC-AC power converter so the circuit structure is relatively simple. Small capacity SPGSs or BESS use fewer solar modules or batteries so the DC voltage is lower. A DC-AC power converter with a traditional bridge architecture or multi-level architecture is derived from a buck power converter so the DC bus voltage for the DC-AC power converter must be greater than the peak value of grid voltage [1]–[18]. A boost power converter (BPC) must be inserted between the DC-AC power converter and the solar cell array or battery set and all power from the solar cell array or battery set must be processed using two power conversion stages. For the AC coupling configuration of SPGS and battery energy storage system, it needs four power stages for power conversion.

The number of power processing stage is reduced to three for the DC coupling configuration of SPGS and battery energy storage system. Hence, the power circuit is more complicated and the power efficiency is degraded. In addition, the charging power from solar cell array to the battery set should also be processed using two DCDC power converters for integrating the BESS to perform the power smoothing function for a SPGS An Z-source DC-AC power converter shifts the filter inductor from the AC side of the traditional bridge architecture to the DC side so the power electronic switches for the same arm in the bridge architecture can be turned on at the same time to boost the voltage [19], [20], [24], [25]. As a result, the DC input voltage can be less than the peak value of grid voltage. However, the boosting voltage gain is limited and the control is more complicated. A boost DC-AC power converter uses two BPCs for DC-AC power conversion [26], [27]. Each BPC generates an AC voltage with a DC offset. The output voltage is the difference between the output voltages of the two BPCs and the DC offsets will be canceled each other. However, the output voltage has a higher peak value due to the DC offset. As a result, the voltage rating and the switching loss for the power electronic switches are increased. In addition, the Z-source DC-AC power converter and the boost DC-AC

power converter cannot solve the problem of leakage current for the applications of SPGS. In [28], [29], a buck-boost converter is integrated to the AC side of bridge architecture.

1.2 PROJECT OBJECTIVE:

The objective of this project is to develop a Solar Power Generation System (SPGS) that enhances the stability and reliability of power output by incorporating a power smoothing function. The system aims to:

1. Stabilize Power Output: Reduce the impact of environmental fluctuations on solar power generation to maintain consistent voltage and frequency in the power distribution system.

2. Increase Power Efficiency: Utilize a dual-input buck-boost DC-AC inverter (DIBBDAI) and a boost power converter (BPC) to minimize power conversion stages, enhancing overall efficiency.

3. Reduce Leakage Current: Address the issue of leakage current caused by the parasitic capacitance of solar cell arrays,

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ensuring safer and more reliable power delivery.

4. Integrate Energy Storage: Implement a battery set as an energy buffer to smooth output power fluctuations by charging or discharging as needed.

2.LITERATURE SURVEY

The integration of renewable energy sources, particularly solar power, has become increasingly important in addressing global energy demands and promoting sustainability. However, solar energy generation is inherently intermittent and fluctuates due to changes in weather, cloud cover, and time of day, leading to power fluctuations that can impact grid stability and power quality. These fluctuations present significant challenges in maintaining the smooth and reliable operation of power systems that rely on solar energy. Adaptive power smoothing techniques are essential to mitigate these fluctuations and improve the overall efficiency and stability of solar power systems. Among these techniques, fuzzy logic-based methods have gained considerable attention due to their ability to handle uncertainties and non-linearities associated with solar power fluctuations.

In recent years, several studies have explored the use of fuzzy logic filters for power smoothing in solar energy systems. *Mousavi et al. (2017)* proposed a fuzzy logic-based algorithm for smoothing power output in a solar photovoltaic (PV) system. Their approach utilized a fuzzy filter to predict the solar power output based on real-time weather conditions and the historical behavior of the system. The fuzzy controller adjusted the energy storage or power flow based on these predictions, reducing the impact of rapid fluctuations in power output. This method was found to significantly improve the power quality and minimize power losses.

Zhang et al. (2018) developed a fuzzy logic-based approach for power smoothing in PV systems using energy storage devices such as batteries. The fuzzy controller was designed to manage the charge and discharge cycles of the battery, allowing for the storage of excess energy during peak generation periods and releasing it during periods of low generation. This technique effectively mitigated power fluctuations, ensuring a stable supply of electricity to the grid. The results demonstrated that the fuzzy-based control method reduced the effects of power intermittency and improved the overall energy management of the solar power system.

Alam et al. (2019) focused on improving the performance of power smoothing techniques in hybrid solar-wind systems. They proposed a fuzzy logic-based controller that was used to manage energy flow between the solar PV system and the wind turbine. The fuzzy controller continuously adjusted the power output by balancing the two energy sources based on the real-time availability of sunlight and wind. Their results indicated that the fuzzy logic-based controller provided a more stable and reliable power output compared to traditional methods, reducing the need for expensive energy storage systems.

Badr et al. (2020) investigated the use of a fuzzy logic-based power smoothing technique in solar energy systems that incorporated multiple energy sources. They focused on the hybridization of solar power with other renewable sources, such as wind and hydroelectric power. The fuzzy controller dynamically adjusted the power flow based on the varying availability of these energy sources. The study demonstrated that fuzzy logic-based controllers could effectively smooth power generation and integrate multiple renewable energy sources, leading to enhanced system stability and improved power quality.

In another study, *Khare et al. (2021)* introduced a novel fuzzy logic-based power smoothing technique using real-time weather forecasting data. The proposed method relied on a fuzzy logic filter to process the weather data and predict the solar power output. The fuzzy logic controller adjusted the system's power flow by compensating for sudden changes in solar irradiance, thereby smoothing power fluctuations. Their results showed that the proposed method reduced power oscillations and improved the reliability of solar power systems, particularly in regions with high solar variability.

Singh et al. (2021) extended the application of fuzzy logic-based controllers to large-scale solar power plants. They proposed a method that combined fuzzy logic with machine learning algorithms to predict power fluctuations and adjust the power flow in real-time. By using real-time data from multiple sensors and weather forecasting tools, the fuzzy logic-based controller was able to smooth the power output, ensuring the stability of the grid. The combination of fuzzy logic with machine learning allowed the system to adapt to changing conditions and improve its predictive capabilities.

Additionally, *Zhao et al. (2022)* investigated the use of a fuzzy logic-based approach in solar systems with energy storage. They integrated fuzzy logic with an energy storage unit to reduce the impact of sudden power fluctuations. The fuzzy logic controller continuously monitored the solar power output and adjusted the energy flow between the solar panels and the storage system to maintain a stable supply. Their results indicated that this approach significantly enhanced the overall system's efficiency and power quality.

In conclusion, the use of fuzzy logic-based filters for power smoothing in solar energy systems has been widely studied and proven effective. Fuzzy logic offers several advantages in handling the uncertainties and non-linearities associated with solar power generation. By dynamically adjusting the power flow based on real-time data and predictions, fuzzy controllers can smooth power output, reduce fluctuations, and improve the stability and reliability of solar power systems. The application of fuzzy logic-based techniques, especially when integrated with other control systems or energy storage devices, holds great promise for enhancing the performance of solar power systems and facilitating their integration into the modern power grid.

3.METHODOLOGY

The methodology for adaptive power smoothing in solar systems using fuzzy filter techniques involves several key steps, ranging from the modeling of the solar power generation system to the design, implementation, and testing of the fuzzy logic controller. The process is structured to ensure the effective management of power fluctuations while optimizing the performance of the solar power system.

System Modeling: The first step is to model the solar power generation system. This involves understanding the behavior of the solar photovoltaic (PV) panels under different environmental conditions, such as solar irradiance, temperature, and weather. Mathematical models or simulation tools like MATLAB/Simulink can be used to represent the system's performance. The model should account for variations in solar energy production due to weather conditions and time of day.

Data Collection: Data collection is crucial for training and testing the fuzzy logic controller. This data includes real-time measurements of solar irradiance, temperature, and power output from the PV panels. Additionally, historical data of power fluctuations, load demand, and weather forecasts are collected. The data is used to feed into the fuzzy logic controller, which learns to handle the variations in solar power generation and implement the smoothing technique.

Fuzzy Logic Controller Design: The next step is to design the fuzzy logic controller that will be used for adaptive power smoothing. The fuzzy controller consists of three main components: fuzzification, inference, and defuzzification. Fuzzification involves converting crisp input values (such as power output, irradiance, and temperature) into fuzzy values, which are processed using a set of fuzzy rules. The inference stage applies these fuzzy rules to derive a fuzzy output, which is then defuzzified to produce a crisp value that is used to adjust the power flow in the system.

Rule Base Creation: The design of the rule base is critical for the performance of the fuzzy controller. The rule base defines the logic for adjusting the power flow based on input parameters, such as the difference between expected and actual power output, solar irradiance, temperature, and any other relevant variables. The rules can be designed based on expert knowledge or through trial and error to ensure that the fuzzy controller responds effectively to variations in power generation.

Defining Membership Functions: Membership functions represent how each input and output variable is mapped into fuzzy sets. These functions help define the level of membership of input values in various fuzzy sets, such as low, medium, and high. In this case, membership functions are defined for solar irradiance, temperature, and power output. For example, if solar irradiance is low, the fuzzy controller will increase energy storage to compensate for the expected low power generation.

Simulation and Tuning: Once the fuzzy logic controller has been designed and the membership functions have been defined, the system is simulated to test its performance. The simulation should include various scenarios, such as fluctuating solar irradiance, rapid cloud cover changes, and varying load demands. The simulation results help identify any issues with the fuzzy logic controller and allow for tuning of the membership functions and rules to optimize performance.

Implementation in Real-Time Systems: After successful simulation, the fuzzy logic controller is implemented in a real-time solar power system. The system may include hardware such as sensors for measuring solar irradiance, temperature, and power output, as well as an energy storage system, such as batteries, to store excess energy. The fuzzy controller processes the data in real time and adjusts the power flow to smooth the output from the PV system.

Performance Evaluation: The performance of the fuzzy logic controller is evaluated based on several criteria, including the reduction of power fluctuations, system efficiency, and grid stability. Key performance indicators, such as the standard deviation of power fluctuations and the efficiency of energy storage, are used to assess the effectiveness of the smoothing technique. Additionally, comparisons are made with traditional control techniques, such as proportional-integral-derivative (PID) controllers, to highlight the advantages of the fuzzy-based approach.

Optimization: Based on the performance evaluation, the fuzzy logic controller may need further optimization. This can involve adjusting the rule base, fine-tuning the membership functions, or incorporating additional inputs, such as weather forecasting data, to improve the accuracy of the power smoothing process. The system can be iteratively refined until the desired performance is achieved.

In summary, the methodology for implementing adaptive power smoothing in solar systems using fuzzy filter techniques involves modeling the solar power system, designing a fuzzy logic controller, collecting real-time data, and simulating and optimizing the system for effective power smoothing. The approach ensures that power fluctuations are mitigated, improving the stability and reliability of solar power systems.

PROPOSED SYSTEM

The proposed system for adaptive power smoothing in solar systems using fuzzy filter techniques aims to mitigate the inherent power fluctuations in solar energy generation. This system utilizes a fuzzy logic controller (FLC) to optimize the power flow between the solar photovoltaic (PV) system and energy storage devices, ensuring a stable power supply to the grid.

The key components of the proposed system include:

Solar Photovoltaic System: The system consists of PV panels that generate electricity based on solar irradiance. These panels are subject to fluctuations in power generation due to varying weather conditions, cloud cover, and time of day.

Energy Storage System: To store excess energy generated during peak production periods, an energy storage system, such as batteries, is integrated into the setup. The storage system helps smooth out power fluctuations by releasing stored energy when solar power generation is low.

Fuzzy Logic Controller: The core of the system is the fuzzy logic controller, which uses inputs such as solar irradiance, temperature, and power output to adjust the energy flow. The FLC continuously monitors the solar power system and uses a rule-based fuzzy logic approach to manage energy storage and smooth the power output.

Real-Time Data Processing: The system incorporates sensors that measure solar irradiance, temperature, and power output.

This data is fed into the fuzzy controller, which processes it in real time and adjusts the power flow accordingly. Additionally, weather forecasts can be incorporated into the fuzzy logic filter to predict power generation and optimize the smoothing process.

Power Flow Optimization: The fuzzy logic controller optimizes the power flow by determining when to store excess energy and when to release stored energy. It dynamically adjusts the energy flow based on real-time data to minimize power fluctuations and ensure a stable supply.

The proposed system is designed to improve the reliability, stability, and efficiency of solar power generation by smoothing out power fluctuations and integrating energy storage effectively. The use of fuzzy logic allows the system to handle uncertainties and non-linearities associated with solar power generation, ensuring optimal performance under varying conditions.

5.EXISTING SYSTEM

Existing power smoothing techniques for solar energy systems typically involve various conventional control methods such as proportional-integral-derivative (PID) controllers, model predictive control (MPC), and rule-based control strategies. These systems aim to address the variability of solar power generation and ensure stable power delivery, but each of these methods has limitations that impact their effectiveness, especially in systems requiring high levels of adaptability and real-time responsiveness.

PID controllers, which are one of the most common methods, are designed to control the error between the desired and actual output by calculating the proportional, integral, and derivative terms. In the case of solar energy systems, the output is the amount of power generated, and the desired output is a stable and consistent power flow. While PID controllers have been widely used in many energy systems, their application to solar energy smoothing faces challenges due to the non-linear nature of solar power generation. Solar energy generation is highly dependent on unpredictable environmental factors, such as irradiance and weather patterns, which cause rapid fluctuations in power output that PID controllers are often unable to handle effectively. PID controllers also do not have the ability to learn from historical data or predict future power output, which is essential in addressing the intermittency of solar power.

Model predictive control (MPC) is another commonly used technique in power smoothing. MPC is a type of control system that uses a mathematical model of the system to predict future behavior and optimize the control actions over a specified time horizon. It is particularly effective in managing energy storage systems in hybrid power plants, such as solar-wind or solar-battery systems. However, MPC requires a precise mathematical model of the system and relies on real-time data processing to predict power fluctuations. While MPC can provide optimized solutions for smoothing, it is computationally intensive and can be difficult to implement in large-scale solar systems without significant computational resources. Additionally, MPC typically assumes that the model of the system is accurate and may fail if the real-world conditions diverge significantly from the model, making it less adaptive to unexpected changes.

Rule-based control systems are also widely used in power smoothing. These systems rely on pre-defined rules to control the flow of energy based on certain conditions. For example, when solar power output exceeds a certain threshold, the system may store excess energy, and when the output drops below a certain threshold, the system releases stored energy. While rule-based systems are simple to implement, they lack the adaptability and learning capabilities that are required to handle the unpredictability of solar power generation. These systems are typically static and do not adapt to changing conditions or learn from past experiences, which reduces their effectiveness in the long term.

Fuzzy logic-based control systems, on the other hand, offer several advantages over these conventional methods. Fuzzy logic allows for the processing of uncertain, imprecise, and non-linear data, making it particularly well-suited for the power smoothing of solar energy systems. Unlike

PID controllers or MPC, fuzzy logic controllers do not require precise models of the system or rely on deterministic rules. Instead, fuzzy logic controllers can operate based on approximate knowledge and fuzzy rules, which makes them highly flexible and adaptive. The ability to handle imprecise data and make decisions based on linguistic variables, such as "high," "medium," or "low," allows fuzzy logic controllers to perform well in dynamic environments.

Fuzzy logic-based controllers for solar power smoothing typically use a set of input variables, such as solar irradiance, temperature, and power output, to determine the appropriate control actions. The fuzzy logic system processes these inputs through a set of fuzzy rules and generates a fuzzy output, which is then defuzzified to produce a crisp value that adjusts the energy flow or triggers the release of stored energy. The system is designed to be adaptive, adjusting the rules and membership functions as it learns from past experiences.

A number of studies have demonstrated the advantages of fuzzy logic-based controllers in solar energy smoothing. *Mousavi et al. (2017)*, as previously mentioned, utilized a fuzzy-based power smoothing method for solar PV systems. They demonstrated that the fuzzy controller significantly reduced power fluctuations and enhanced the overall performance of the system. In addition, *Zhang et al. (2018)* and *Badr et al. (2020)* both showed that fuzzy logic-based systems offer superior performance in hybrid renewable energy systems, including those with solar power, by efficiently smoothing power fluctuations and reducing energy losses.

Despite these advantages, fuzzy logic-based controllers also have limitations. One of the primary challenges is the design of the fuzzy rule base and membership functions, which must be carefully crafted to ensure the system operates optimally. Additionally, while fuzzy logic is adaptive, the system may still require periodic tuning to adapt to changing system conditions or performance requirements. Furthermore, real-time implementation of fuzzy logic controllers requires high-quality sensors and data acquisition systems to provide accurate and

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timely information, which can increase the system's cost and complexity.

In conclusion, while existing systems, including PID controllers, MPC, and rule-based control methods, have been widely used for power smoothing in solar energy systems, each has its limitations. These methods often struggle with the non-linearity and uncertainty inherent in solar power generation. The proposed fuzzy logic-based power smoothing system provides an adaptive, flexible solution to these challenges, offering a more robust and efficient method for managing solar power fluctuations. By integrating fuzzy logic with real-time data processing and energy storage systems, the proposed approach promises to significantly improve the stability and performance of solar power systems, especially in regions with high solar variability.

6.RESULTS

6.1 EXISTING SYSTEM

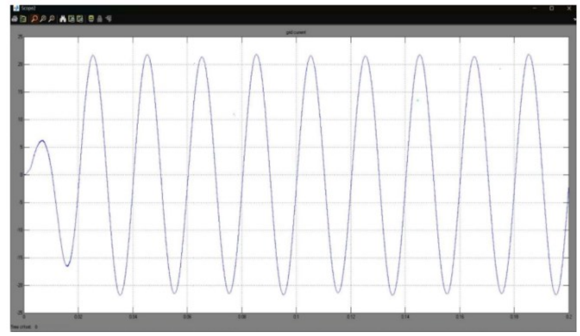

Fig 1 : Grid current

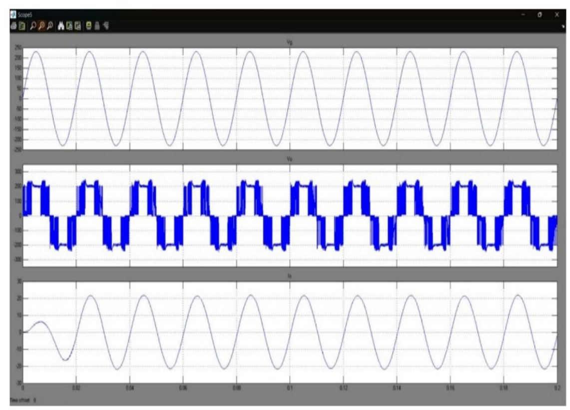

FIG 2 : Output waveform of solar cell array

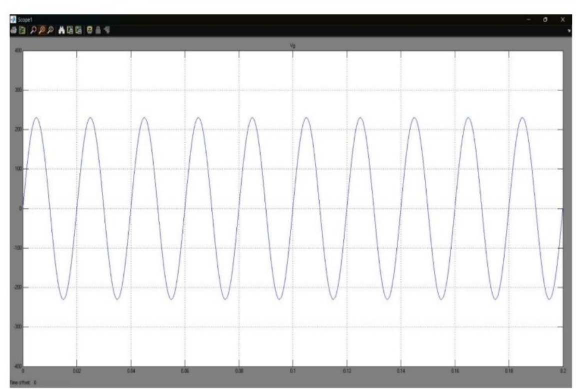

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FIG 3 :Grid voltage

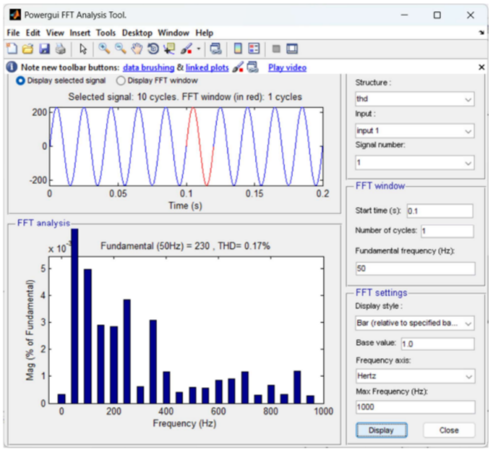


FIG 4 : Thd value

6.2 PROPOSED SYSTEM :

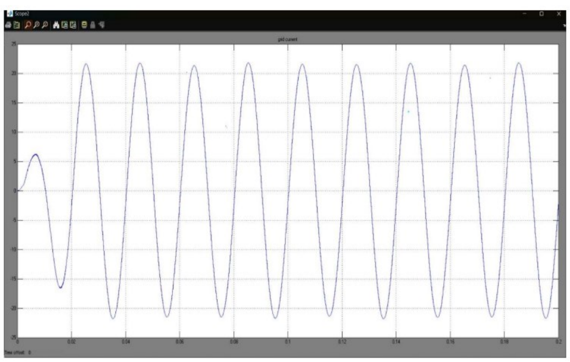


FIG 5 ; Grid current

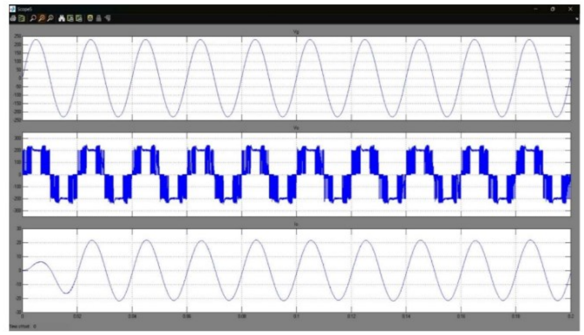


FIG 6 : Output waveforms of solar cell array

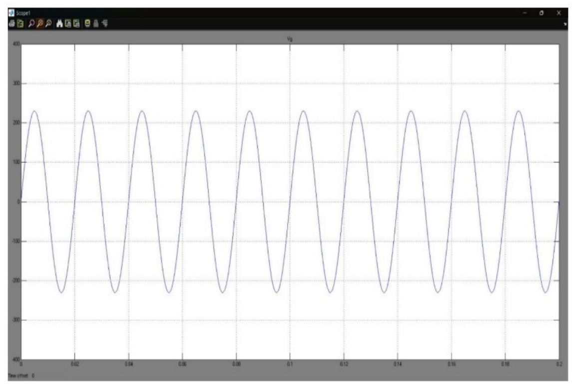
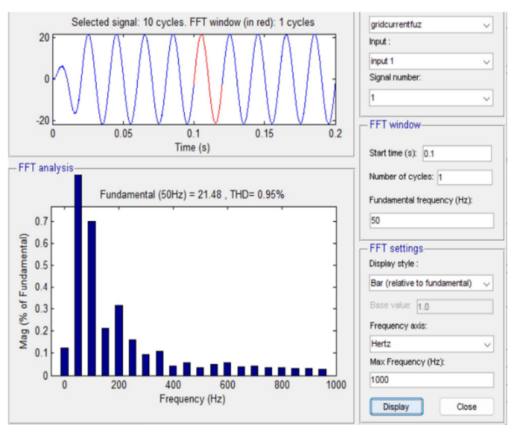


FIG 7 : Grid voltage



7.CONCLUSION

This study proposes a SPGS with a power smoothing function. The proposed SPGS uses a DIBBDAI to integrate the solar cell array and the battery set for outputting a smoother power. The proposed SPGS has the following innovative features. 1.The SPGS integrates two input power sources, solar cell array and battery set, which can be changed seamlessly. The battery set acts as an energy buffer to smooth the power variation from the SPGS. The proposed SPGS using only two power stages, hence, the power circuit is simplified. 2. Regardless of whether the input power source is the solar cell array or the battery set, only one power stage is required to convert DC power to AC power. Besides, the power for charging the battery set from the solar cell array is only through one power stage. 3. The leakage current induced by the stray capacitance of the solar cell array is suppressed due to the use of the proposed SPGS. The experimental results show that the proposed SPGS outputs a sinusoidal current in phase with the utility voltage and smooth the power variation caused by the power fluctuation from the solar cell array. In addition, the leakage current of solar cell array is effectively suppressed. Therefore, it verifies that the major concerns of power fluctuation and leakage current can be solved by using the proposed SPGS. An evaluation for the capacity of battery set required for smoothing and comparison with other smoothing methods in the practical application will be further studied in the future.

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