International Journal of Engineering Research and Science & Technology

IJERST

www.ijerst.org

ISSN : 2319-5991

Vol. 21 No. 4 (2025)

ijerst.editor@gmail.com
editor@ijerst.com

ISSN 2319-5991 www.ijerst.com
Vol. 21, No. 4, 2025

Research Paper

SOLAR POWER GENERATION SYSTEM WITH POWER SMOOTHING FUNCTION USING FUZZY LOGIC CONTROLLER

Teegala Sujay Kumar[1], DR. K. Ranjith Kumar[2]

[1]*M. Tech Student, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Khammam - Warangal Hwy, Road, Bollikunta, Telangana 506005*

[2]*Associate Professor, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Khammam - Warangal Hwy, Road, Bollikunta, Telangana 506005*

Abstract *The main aim of this project is solar power generation system with power smoothing function. 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 paper 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. Between the battery set and the solar cell array, the BPC functions as a battery charger. There is just one power stage involved in the proposed SPGS's conversion of DC power from the solar cell array or battery set to AC power.*

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. To stabilize the output power from the SPGS, the battery set is charged or discharged when the solar cell array's output power fluctuates significantly.

Furthermore, the parasitic capacitance of the solar cell array induces leakage current, which can be suppressed by the DIBBDAI. For an SPGS, the suggested power conversion interface reduces leakage current, evens out power fluctuations, and boosts power efficiency. A simulation study is to verify the performance of the proposed SPGS by using SIMLINK environment.

Received: 03-09-2025 Accepted: 16-10-2025 Published: 23-10-2025

1. INTRODUCTION

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].

The objective of a Solar Power Generation System with a Power Smoothing Function is to ensure a stable and reliable power supply by mitigating fluctuations caused by varying solar irradiance. These fluctuations can be due to changes in weather conditions, cloud cover, and other environmental factors. The key objectives include:

1. Stable Power Output – Reduce power variations and maintain a consistent energy supply to the grid or load.
2. Grid Stability – Prevent voltage and frequency instability in the grid due to sudden changes in solar power generation.
3. Efficient Energy Management – Optimize the integration of solar energy with storage systems (such as batteries or supercapacitors) to balance supply and demand.
4. Improved Power Quality – Reduce issues such as voltage sags, harmonics, and flickers that can affect sensitive electrical equipment.
5. Enhanced Reliability – Ensure a more predictable and dependable energy supply for both standalone and grid-connected applications.
6. Extended Equipment Lifespan – Reduce stress on inverters and other power electronics by smoothing out rapid changes in power flow.
7. Regulatory Compliance – Meet grid codes and regulations that require renewable energy sources to maintain power quality and stability.

This system typically incorporates energy storage, power electronic converters, and control algorithms to achieve effective power smoothing and improve the overall performance of solar power integration.

2. MODELLING OF CASE STUDY

2.1 Circuit configuration

The circuit configuration for the proposed SPGS is shown in Fig.1. The DC coupling configuration is used for the proposed SPGS. As seen in Fig. 1, the proposed SPGS is composed of a solar cell array, a battery set and the power conversion interface. The power conversion interface consists of a DIBBDAI and a BPC. The BPC is connected between the solar cell array and the battery set to control the power from the solar cell array that charges the battery set. In order to reduce the capacity of battery set, the battery set only operates when the power variation for the solar cell array exceeds the specified range. The battery set is only charged by the solar cell array so the power flow of BPC is unidirectional. The DIBBDAI performs the functions of voltage boost, voltage buck and DC-AC power conversion. The DIBBDAI BPC operate at the same time to convert the power from the solar cell array for injecting into the grid and for charging the battery set, respectively.

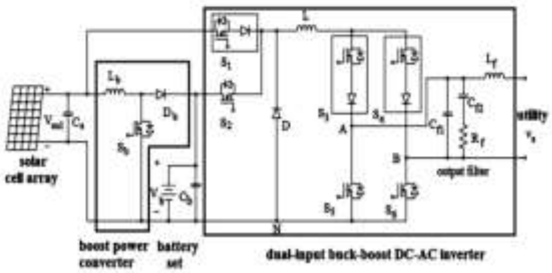


FIGURE 1. Circuit configuration for the proposed SPGS

2.2 OPERATION OF DIBBDAI

The two input terminals of the DIBBDAI are respectively connected to the solar cell array and the battery set. The operation of the DIBBDAI can be divided into the boost mode and the buck mode. The two input terminals of the DIBBDAI are respectively connected to the power electronic switches S1 and S2. Since the voltage of the solar cell array is lower than that of the battery set, S1 should further contain a diode to form a unidirectional switch to prevent the battery voltage from affecting the voltage of the solar cell array. Power electronic switches S1 and S2 are used as switches during the buck mode. For the proposed SPGS, the solar cell array and the battery set will not release the power at the same time; hence, the power electronic switches S1 and S2 will not operate at the same time. The DIBBDAI also includes a bridge structure that is composed of S3-S6 for commutation, in order to generate an AC output current. Among them, S3 and S4 further contain a diode to form a unidirectional switch to avoid short circuit in the grid. S3 or S4 are also used as switches during the boost mode. Cf1, Cf2, Rf and Lf create a damped second-order lowpass filter. If the solar cell array is operating and the battery set is disabled, S1 is activated and S2 is turned off. If the grid has two DC input terminals, which are respectively connected to battery set and the solar cell array, and both the battery set and the solar cell array can directly use the DIBBDAI to convert DC power into AC power for supplying to the grid.

When the output power from the solar cell array is stable, the DIBBDAI converts the power from the solar cell array to the grid, so the BPC is disabled and the battery set is in standby mode. The DIBBDAI converts the power from the battery set to the grid when the power of solar cell array suddenly decreases, and the BPC tracks the maximum power of solar cell array to charge the battery set. When the power of solar cell array suddenly increases, the DIBBDAI and voltage is lower than the voltage of the solar cell array, the DIBBDAI is operated in the buck mode. At this time, S1 is operated in pulse width modulation (PWM) switching and S3-S6 are operated in accordance with the polarity of the grid voltage. The operation of buck mode can be divided into four modes. Mode Bk-1: During the positive half cycle of the grid voltage, S1, S3, and S6 are turned on, and S4, S5 and D are turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = \frac{V_{sol} - v_s}{L}$$

Where vs and Vsol are the grid voltage and the voltage of the solar cell array, respectively. The solar cell array releases energy to the inductor and the grid. Mode Bk-2: During the positive half cycle of the grid voltage, S3, S6 and D are turned on, and S1, S4, and S5 are turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = -\frac{v_s}{L}$$

The inductor releases energy to the grid. Mode Bk-3: During the negative half cycle of the grid voltage, S1, S4 and S5are turned on, and S3, S6 and D are turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = \frac{V_{sol} + v_s}{L}$$

The solar cell array releases energy to the inductor and the grid. Mode Bk-4: During the negative half cycle of the grid voltage, S4, S5 and D are turned on, and S1, S3 and S6 are turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = -\frac{v_S}{L}$$

The inductor releases energy to the grid. The equivalent circuit for the DIBBDAI in the buck mode, where S is S1. The grid voltage is converted to its absolute value by the operation of S3-S6 and then added to the output of conventional buck power converter. As a result, the DIBBDAI operates as a conventional buck power converter, and the inductor current can be controlled by the switching of S. If the grid voltage is higher than the voltage of the solar cell array, the DIBBDAI operates in the boost mode. At this time, S1 is always on, S4 and S3 are respectively operated in PWM switching during the positive and negative half cycles for the grid voltage and S6 and S5 are operated in accordance with the polarity of the grid voltage. The operation of boost mode can also be divided into four modes. Mode Bt-1: When the grid voltage is in the positive half cycle, S3, S4 and S6 are turned on and S5 is turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = \frac{V_{sol}}{L}$$

The solar cell array releases energy to the inductor. Mode Bt-2: When the grid voltage is in the positive half cycle, S3 and S6 are turned on and S4 and S5 are turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = \frac{V_{sol} - v_s}{L}$$

Both the solar cell array and the inductor release energy to the grid. Mode Bt-3: When the grid voltage is in the negative half cycle, S3, S4 and S5 are turned on and S6 is turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = \frac{V_{sol}}{L}$$

The solar cell array releases energy to the inductor.

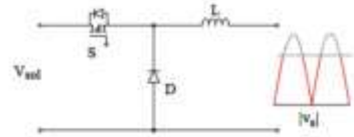


FIGURE 2. Equivalent circuit for the DIBBDAI in the buck mode

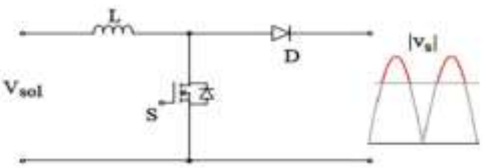


FIGURE 3. Equivalent circuit for the DIBBDAI in the boost mode

Mode Bt-4: When the grid voltage is in the negative half cycle, S4 and S5 are turned on and S3 and S6 are turned off. The change rate for the inductor current is:

$$\frac{di_L}{dt} = \frac{V_{sol} + v_s}{L}$$

Both the solar cell array and the inductor release energy to the grid. The equivalent circuit for the DIBBDAI operating in the boost mode. The grid voltage is converted to its absolute value and then added to the output of conventional BPC by the operation of S3-S6. In Fig. 3, switch S is S4 or S3 and the diode is the body diode of S3 or S4 depending on the polarity of the grid voltage. The DIBBDAI operates as a conventional BPC and the inductor current is controlled by switching S. When the DIBBDAI is powered by the battery set, S2 is activated and S1 is turned off. At this time, the DIBBDAI operates similarly to when the solar cell array is operated, and it is not repeated. The control signals S1-S6 and operation voltage during a grid cycle when the solar cell array supplies power to the DIBBDAI. As can be seen only one power electronic switch is operated in PWM switching at any time, and VAN and VBN are close to the positive cycle voltage and the negative cycle voltage of grid, respectively. The equivalent circuit of the DIBBDAI for the leakage current analysis [33], [34]. Cpv and Rg are the stray capacitor for the solar cell array and ground resistor for the grid, respectively. VAN and VBN are the voltages from terminals A and B to the negative terminal N of the solar cell array, respectively. Since Cf1, Cf2 and Rf are connected across terminals A and B, these components do not affect the leakage current. S5 and S6 are switched synchronously with the grid voltage. S6 is turned on and S5 is turned off when the grid voltage is in the positive half cycle, and:

$$V_{AN} = v_s + v_{Lf}$$
$$V_{BN} = 0$$

where vLf is the voltage of Lf . Since VBN is equal to 0, the voltage across the loop of CPV and Rg is 0 and the leakage current is 0. When the grid voltage is in the negative half cycle, S5 is turned on and S6 is turned off and

$$V_{AN} = 0$$
$$V_{BN} = -(v_s + v_{Lf})$$

The voltage across the loop of CPV and Rg is −(vs + vLf). Since vs is a sinusoidal voltage of 60Hz and the impedance of the stray capacitor is very large at 60Hz, the leakage current induced by vs is very small. vLf contains a switching-frequency component, which is caused by the switching-frequency ripple in the output current.

TABLE 1. Operation of S1 -S6

	power source	voltage range	S_1	S_2	S_3	S_4	S_5	S_6
PHC	solar cell array	$v_s<V_{sol}$	PWM	off	on	off	off	on
		$v_s>V_{sol}$	on	off	on	PWM	off	on
	battery	$v_s<V_b$	off	PWM	on	off	off	on
		$v_s>V_b$	off	on	on	PWM	off	on
NHC	solar cell array	$\|v_s\|<V_{sol}$	PWM	off	off	on	on	off
		$\|v_s\|>V_{sol}$	on	off	PWM	on	on	off
	battery	$\|v_s\|<V_b$	off	PWM	off	on	on	off
		$\|v_s\|>V_b$	off	on	PWM	on	on	off

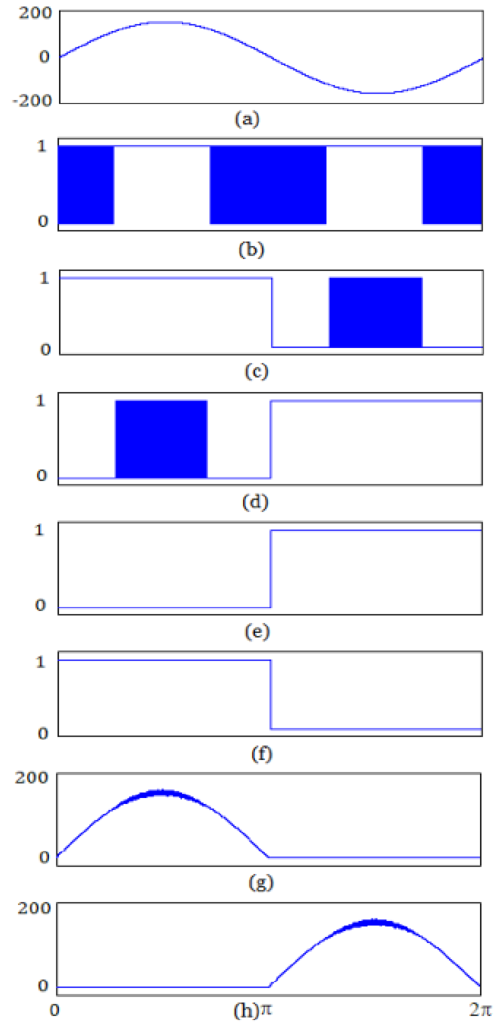


FIGURE 4. Control signals S1 -S6 and operation voltage in a power grid cycle, (a) utility voltage, (b) S1 , (c) S3 , (d) S4 , (e) S5 , (f) S6 , (g) VAN, (h) VBN.

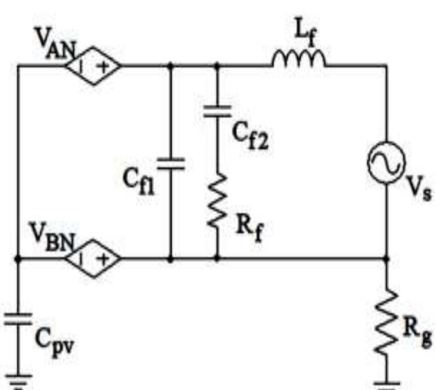


FIGURE 5. Equivalent circuit of the DIBBDAI for the leakage current analysis.

However, the switching-frequency component of vLf is effectively suppressed by Cf1, Cf2 and Rf . As can be seen inFig. 4 (g) and (h), VAN and VBN are respectively close to the positive cycle voltage and the negative cycle voltage of grid, and it is consistent with the analysis. Accordingly, the leakage current induced by vLf is still small even the impedance of the stray capacitor at the switching frequency is small. Therefore, the leakage current contains a small switching-frequency component and a small fundamental component during the negative half cycle.

2.3 OPERATION OF BPC

The BPC is inserted between the solar cell array and the battery set and is used when the battery set is charged by the solar cell array. The BPC is disabled when the power variation for the solar cell array is within the specified range. The BPC performs maximum power tracking (MPPT) for the solar cell array if the power variation for the solar cell array exceeds the specified range. The BPC is designed to be operated in continuous-conduction mode, and the relationship between the voltage of the solar cell array and the voltage of the battery set is:

$$\frac{V_{sol}}{V_{bat}} = \frac{1}{1 - D_{Sb}}$$

where DSb is the duty cycle for Sb.

3 SMOOTHING OPERATION

If the output power of the solar cell array is stable, the output power from the solar cell array is converted into AC power by the DIBBDAI. At this time, the DIBBDAI performs MPPT using the perturbation and observation (P&O) method. The output voltage from the solar cell array is disturbed, and then the change in the power from the solar cell array is observed to determine the direction in which the output voltage from the solar cell array is disturbed until the maximum power point is tracked. The output power smoothing mechanism is activated when the power variation for the solar cell array significantly exceeds the specified range. The state of charge (SOC) of the battery set is specified as between 30% and 90% to avoid over-charging or over-discharging, which decreases the life of the battery set. Considering the upward and downward power fluctuations of SPGS, the desired SOC of the battery set is at 60% when the battery set is in the stand-by mode. Since this study concerns the smoothing operation for the output power from the SPGS, the SOC of the battery set is estimated simply using the terminal voltage. The output power from the SPGS is smoothed when the power variation (1PPV) for the solar cell array exceeds the specified value P1. P1 is determined by the power variation of regulation. The DIBBDAI is still powered by the solarcell array but MPPT is performed by the BPC using the P&O method. Consequently, the output current amplitude of DIBBDAI is controlled to be increased linearly along a specified gradient, driving the output power (Pout) from the SPGS also linearly increases along the specified gradient.

The specified gradient for the output current amplitude depends on the allowable maximum power variation for Pout. At this time, the difference between the PPV and Pout is positive. This power difference is automatically injected into the battery set through the BPC and the SOC of battery set is increased. When Pout exceeds PPV by P2, the DIBBDAI controls the output current amplitude to be a fixed value. The BPC still performs MPPT. At this time, the difference between PPV and Pout becomes negative and the power difference is automatically supplied from the battery set to decrease the SOC of the battery set. If PPV remains stable, the BPC stops operating when the SOC of the battery decreases to 60%.

The DIBBDAI performs MPPT. At this moment, the power variation in Pout is P2. P2 must be less than or equal to P1 to avoid exceeding the power variation of regulation. When the output power Pout is still less than

PPV and the SOC of the battery set has been equal to 90%, the BPC stops and the power smoothing function is disabled, in order to prevent the battery set from over-charging. The output power from the SPGS is also smoothed when 1PPV for the output power from the solar cell array decreases to less than the specified value −P1. At this time, the DIBBDAI is powered by the battery set and the BPC performs MPPT. The solar cell array charges the battery set through the BPC. The DIBBDAI decreases the amplitude of the output along the specified gradient, so Pout also linearly decreases along the specified gradient. At this time, the difference between Pout and PPV is automatically supplied from the battery set and the SOC of the battery set is decreased. When Pout is P1 less than PPV, the DIBBDAI maintains the output current amplitude at a fixed value. The BPC continuously performs MPPT. PPV is greater than Pout so the battery set is charged instead and the SOC of the battery set is increased. If PPV remains stable, the BPC stops operating when the SOC of the battery is increased to 60%. The DIBBDAI is powered by the solar cell array and performs MPPT. At this moment, the power variation in Pout is P2. If Pout is not less than PPV and the SOC of the battery set has been equal to 30%, the BPC stops smoothing the power output of the SPGS, in order to prevent the battery set from over-discharging. The DIBBDAI is powered by the solar cell array and performs MPPT. The operation flowchart for the proposed SPGS with power smoothing function. No matter PPV increases or decreases drastically, Pout increases or decreases linearly along the specified gradient to smooth the output power from the SPGS. Since the battery set is actuated only when the absolute value of power variation (1PPV) for the solar cell array exceeds the specified value P1, the charging/discharging time of the battery set is much less than other smoothing methods [3]–[9]. Moreover, regardless of whether the battery set is charged or discharged to smooth the output power from the solar cell array, the battery set willimmediately discharge or charge to maintain its SOC close to 60% when Pout catches up with PPV. As a result, the capacity of battery set can be reduced.

4. Fuzzy Logic Controller

Fuzzy Logic is a multi-esteemed logic which is like human speculation and elucidation. It has the capability of consolidating human heuristics into PC helped basic leadership. Fuzzy logic controller (FLC) is made of fuzzification; learning and inference unit and defuzzification. The fuzzy logic needs that variable utilized as a part of depicting the control rules ought to be communicated as far as fuzzy set variables with linguistic names. Behind the guidelines have been assessed, the final gait to finish the calculation is to figure the fresh result of the fuzzy calculation by means of de fuzzification.

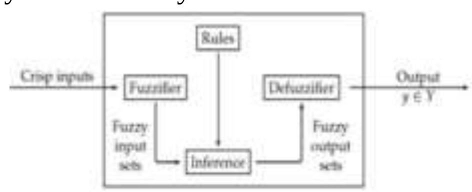
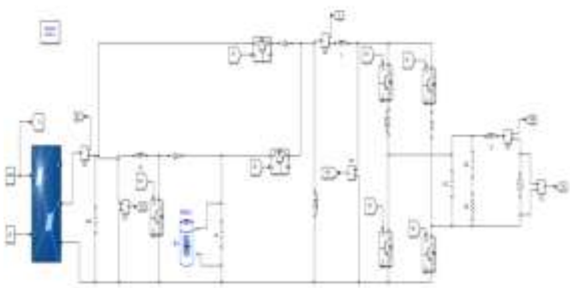


Fig 4: Fuzzy logic structure

The primary favorable position of FLC is that Fuzzy Logic portrays frameworks regarding a mix of numerics and etymology (symbolics). This has points of interest over immaculate scientific (numerical) approaches or unadulterated typical methodologies in light of the fact that all the time framework information is accessible in such a mix and furthermore fuzzy logic some of the time utilizes just

5. SIMULATION RESULTS

Existing System Results



MATLAB/SIMULINK circuit of the SPGS

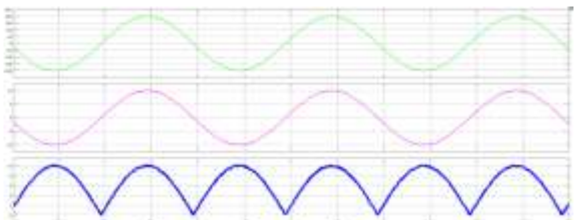


FIGURE 8.2Simulation results of the DIBBDAI under steady state, (a) grid voltage, (b) output current, (c) inductor L current.

FIGURE 10. Simulation results for the leakage current of DIBBDA, (a) output current, (b) leakage current.

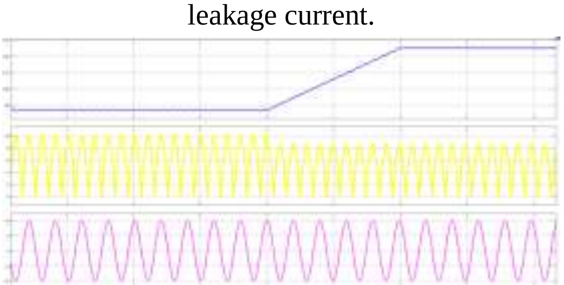


FIGURE 11. Simulation results for the variation of input DC voltage, (a) input DC voltage, (b) inductor L current, (c) output current.

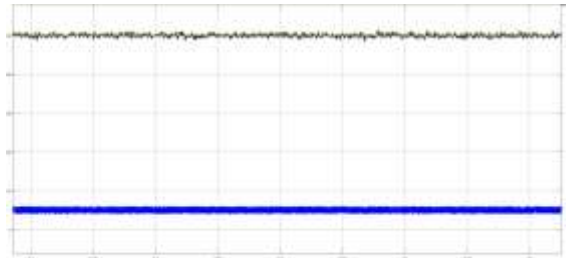


FIGURE 12. Simulation results for the BPC, (a) solar cell array voltage, (b) battery set voltage, (c) inductor Lb current.

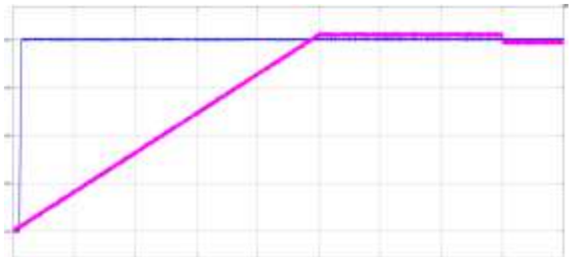


FIGURE 15. Transient result for suddenly increasing the output power from the solar cell array.

FIGURE 16. Transient result for suddenly decreasing the output power from the solar cell array.

Fuzzy logic controller Results

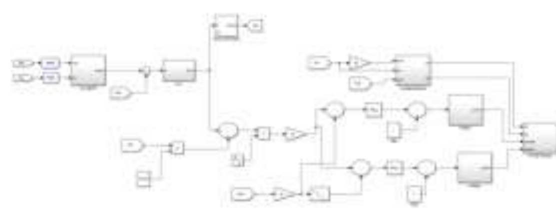


Fig. 17 Control system with Fuzzy Logic controller

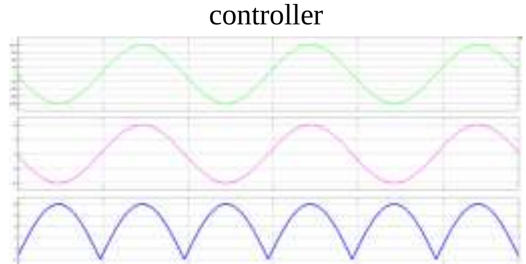


FIGURE 18. Simulation results of the DIBBDAI under steady state, (a) grid voltage, (b) output current, (c) inductor L current.

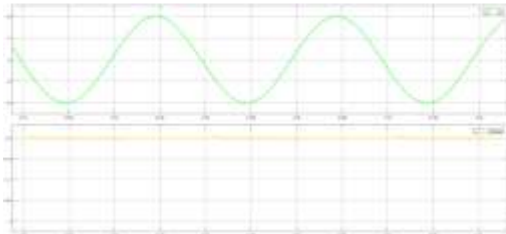


FIGURE 19. Simulation results for the leakage current of DIBBDA, (a) output current, (b) leakage current.

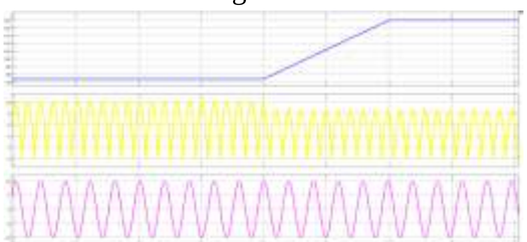


FIGURE 20. Simulation results for the variation of input DC voltage, (a) input DC voltage, (b) inductor L current, (c) output current.

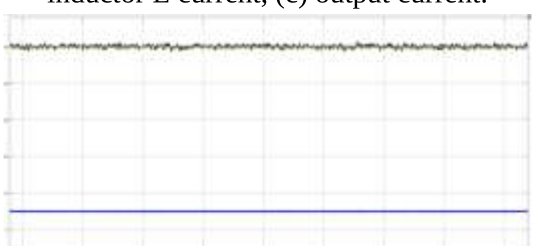


FIGURE 21. Simulation results for the BPC, (a) solar cell array voltage, (b) battery set voltage, (c) inductor Lb current.

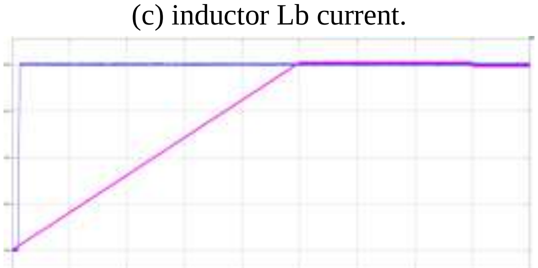


FIGURE 22. Transient result for suddenly increasing the output power from the solar cell array.

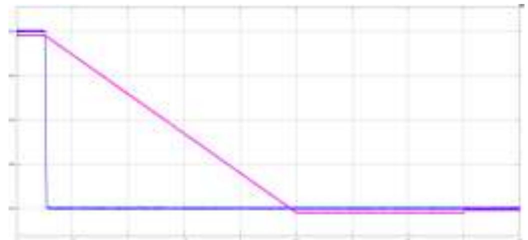


FIGURE 23. Transient result for suddenly decreasing the output power from the solar cell array

5. 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 seam-lessly. 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 simulation 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.

REFERENCES

[1] Q. Peng, A. Sangwongwanich, Y. Yang, and F. Blaabjerg, ‘‘Grid-friendly power control for smart photovoltaic systems,’’ Sol. Energy, vol. 210, pp. 115–127, Nov. 2020.

[2] D. Cheng, B. A. Mather, R. Seguin, J. Hambrick, and R. P. Broadwater, ‘‘Photovoltaic (PV) impact assessment for very high penetration levels,’’ IEEE J. Photovolt., vol. 6, no. 1, pp. 295–300, Jan. 2016.

[3] J. Martins, S. Spataru, D. Sera, D.-I. Stroe, and A. Lashab, ‘‘Comparative study of ramp-rate control algorithms for PV with energy storage systems,’’ Energies, vol. 12, no. 7, p. 1342, Apr. 2019.

[4] D. Lin and N. Normal University, ‘‘Strategy comparison of power ramp rate control for photovoltaic systems,’’ CPSS Trans. Power Electron. Appl., vol. 5, no. 4, pp. 329–341, Dec. 2020.

[5] H. Nazaripouya, C.-C. Chu, H. R. Pota, and R. Gadh, ‘‘Battery energy storage system control for intermittency smoothing using an optimized two-stage filter,’’ IEEE Trans. Sustain. Energy, vol. 9, no. 2, pp. 664–675, Apr. 2018.

[6] K. Koiwa, K.-Z. Liu, and J. Tamura, ‘‘Analysis and design of filters for the energy storage system: Optimal tradeoff between frequency guarantee and energy capacity/power rating,’’ IEEE Trans. Ind. Electron., vol. 65, no. 8, pp. 6560–6570, Aug. 2018.

[7] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, ‘‘A novel approach for ramprate control of solar PV using energy storage to mitigate output fluctuations caused by cloud passing,’’ IEEE Trans. Energy Convers., vol. 29, no. 2, pp. 507–518, Jun. 2014.

[8] A. Atif and M. D. Khalid, ‘‘Saviztky-Golay filtering for solar power smoothing and ramp rate reduction based on controlled battery energy storage,’’ IEEE Access, vol. 8, pp. 33806–33817, 2020.

[9] M. A. Syed and M. Khalid, ‘‘Moving regression filtering with battery state of charge feedback control for solar PV firming and ramp rate curtailment,’’ IEEE Access, vol. 9, pp. 13198–13211, 2021.

[10] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, ‘‘Battery energy storage to mitigate rapid voltage/power fluctuations in power grids due to fast variations of solar/wind outputs,’’ IEEE Access, vol. 9, pp. 12191–12202, 2021.

[11] A. Makibar, L. Narvarte, and E. Lorenzo, ‘‘Contributions to the size reduction of a battery used for PV power ramp rate control,’’ Sol. Energy, vol. 230, pp. 435–448, Dec. 2021.

[12] M. Combe, A. Mahmoudi, M. H. Haque, and R. Khezri, ‘‘Optimal sizing of an AC-coupled hybrid power system considering incentive-based demand response,’’ IET Gener., Transmiss. Distrib., vol. 13, no. 15, pp. 3354–3361, Jul. 2019.

[13] V. T. Tran, M. R. Islam, D. Sutanto, and K. M. Muttaqi, ‘‘Mitigation of solar PV intermittency using ramp-rate control of energy buffer unit,’’ IEEE Trans. Energy Convers., vol. 34, no. 1, pp. 435–449, Mar. 2019

[14] S. Kumar, L. N. Patel, B. Singh, and A. L. Vyas, ‘‘Self-adjustable stepbased control algorithm for grid-interactive multifunctional single-phase PV-battery system under abnormal grid conditions,’’ IEEE Trans. Ind. Appl., vol. 56, no. 3, pp. 2978–2987, May 2020.

[15] R. K. Dhar, A. Merabet, A. Al-Durra, and A. M. Y. M. Ghias, ‘‘Power balance modes and dynamic grid power flow in solar PV and battery storage Simulation DC-link microgrid,’’ IEEE Access, vol. 8, pp. 219847–219858, 2020.

[16] N. Vazquez, S. S. Yu, T. K. Chau, T. Fernando, and H. H.-C. Iu, ‘‘A fully decentralized adaptive droop optimization strategy for power loss minimization in microgrids with PV-BESS,’’ IEEE Trans.

Energy Convers., vol. 34, no. 1, pp. 385–395, Mar. 2019.
[17] C. M. Nirmal Mukundan, P. Jayaprakash, U. Subramaniam, and D. J. Almakhles, ''Binary hybrid multilevel inverter-based grid integrated solar energy conversion system with damped SOGI control,'' IEEE Access, vol. 8, pp. 37214–37228, 2020.
[18] J. Wu, H. Jou, and X. Wu, ''Power conversion interface with harmonic suppression for a DC grid and single-phase utility,'' IET Power Electron., vol. 13, no. 7, pp. 1302–1310, May 2020.
[19] D. Ghaderi, G. Bayrak, and J. M. Guerrero, ''Grid code compatibility and real-time performance analysis of an efficient inverter topology for PVbased microgrid applications,'' Int. J. Electr. Power Energy Syst., vol. 128, Apr. 2021, Art. no. 106712.
[20] E. Kabalcè, ''Review on novel single-phase grid-connected solar inverters: Circuits and control methods,'' Sol. Energy, vol. 198, pp. 247