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Design and Simulation of an Efficient and Controlled Solar Power Electronics Converter in Microgrid and Smart Grid Applications

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Abstract

The solar energy rectifier plays a key role in electric energy conversion from DC power to AC power supply that can be fed directly into on grid. Nowadays, power inverters are being used in power conversion process but these devices face with challenges like inefficiency and insensitivity. This paper, proposed an efficient and controlled solar power electronic converter (ECSPEC) in microgrid and smart grid applications. The two PV arrays with 1000Watts per square meter each, solar generated current of 3.80Amps (A), diode voltage of 0.7Volts (V) and diode saturation current of 3.15e-7A each, drain-source current of 15A of Metal-Oxide Field Effect Transistor (MOSFET), gate-source voltage and threshold value of 10V and 1.7V of MOSFET each respectively, capacitor filter of 1e-6 farad were considered. The MATLAB/Simulink 2019a was used modeling and simulation. The EC-SPEC efficiency was developed in 2 self-regulating approaches. Firstly, AC output power to DC input power ratio was compared within one AC cycle. Secondly, system losses were calculated by single component using SIMSCAPE Logging. The models were used to simulate each full AC cycle for a provided amount of solar irradiance, as well as the effective DC voltage and AC root-mean square current. The results shows that output power control and synchronization were attained through MOSFET control, and optimized parameters such as 348VDC, 20A, 100VAC, and 96.72% efficiency have been ascertained utilizing efficient and integrated single-stage converter characteristics. Finally, the proposed EC-SPEC demonstrated the better performance with compared to the existing devices for efficiency, sensitivity and reliability considerations.

Keywords

MOSFETs, Solar Power Generation, Power Electronics, DC-AC Power Conversion

1. Introduction

Among the most essential items of hardware in a photovoltaic system are the power electronics inverters. It is a system that transforms direct current (DC) electricity generated by a photovoltaic panel to alternating (AC) electricity used by the power grid. In dc current, electricity is carried out at a constant voltage for one direction. As like the voltage in the switch from positive to negative, power streams across both ways. Rectifiers seem to be just one type of power embedded device that controls the flow of electrical power [1]. Due to the utilization of renewable energy sources to satisfy power requirements, the rapid increase in energy demands caused by industrial advancement, environmental concerns, and depletion of natural resources has risen. Solar PV power stations, hybrid renewable energy systems, thermoelectric generators, and the battery systems are used to generate electricity from energy storing devices (ESD) reportedly like battery energy banks or to connect directly to loads via power self-regulatory equipments. Furthermore, solar generators have received the most attention in electricity production between all renewable energy sources due to their accessibility [2]. All renewable energy systems necessitate the use of particular electronic power multilevel inverter to convert produced energy into an electrical energy agency that can be specifically tied to the grid system [3]. The aspects of such rectifier are becoming crucially significant, especially when used during one of the most overpriced electricity generation inputs, such as photovoltaic solar power system source. Because of power conversion system is the power system's interface, a certain fault of this device would make the overall system inoperable and unserviceable, and therefore it must be deliberately selected and chosen carefully. These converter topologies must be efficiently chosen in order to ensure greater energy efficiency and minimal losses while making sure the overall reliability and safety of the microgrid and smart grid required for various applications [4]. Due to the obvious rapid depletion of nonrenewable resources, power system supply in a grid-connected region has come to a complete halt. Solar, wind, and other renewable energy sources are used. Power produced by solar panels, on the other hand, suffers failures. Failures could perhaps occur as a result of extreme meteorological conditions during the rainy period, a significant decline in solar irradiation, a temperature fluctuations, or even other considerations. PV system models should be streamlined in sequence for solar cells to generate maximum output power throughout all where MATLAB/Simulink is best candidate to model and simulate the solar panel. Architecture of a DC-DC power inverter was designed to control the voltage of a solar power output and a Pulse width modulation inverter to convert DC-AC for delivering power demand [5].

2. Literature Review

A HV (high voltage) DC power station that used to power a solar resonant power converter was developed in [6]. A photovoltaic, boost rectifier, full-bridge Coupled inductor tank, power transformer, and rectifier loop with negligible voltage and current switching control systems are used to control switching loss in this type of converter. Moreover, to ensure fair power movement from the tank, all power converters use an overlapping switching cycle. This resonant converter has significant drawbacks, including the inability to control AC voltage and power dissipation. In [7], it has been proposed to use a parallel resonant converter system (PRCS). In this system, an inductor and capacitor with resonance characteristics were interconnected and coupled with power system converter stage. The value of resistance in this converter takes a big influence on its maximum gain that arises at a frequency lower than frequency response which goes some way to amplify its frequency at peak level which was relatively low as long as the power consumption remains stiffer at the end. The main drawbacks of this converter are an unpredictable peak value, an unsteady peak parallel resonant converter frequency, and when the load on the grid increases, the gain and peak frequency decrease, resulting in power outages. A shunt connected power converter (SCPC) was also developed in [8]. This method uses a controlled inductance interconnected in series with a controlled capacitance together with load resistance output. Noticeably, whenever the output power load stays negligible, and their slope was smooth at no-load or zero state situations, this shunt converter are not the top qualified inverting system, trying to prevent them from becoming perfectly controlled in light load level conditions. A further concern of this conducted architecture is power losses during OFF- switching condition whenever the system is working beyond the resonant frequency. As a result, this converter also was unsuitable for wide input voltage and load disturbances. The hybrid renewable energy system comprises a range of rectifier, including current which is alternating to direct state direct to direct state, and direct to alternating conversion systems which are controlled by an embedded intelligent controllers coded with sophisticated manipulation techniques was presented in [9].

The challenges were that the independent power sources in this system may perform poorly to supply energy to the load if their inputs are unreachable. The Dual Power System Converter topology for On-Grid Photovoltaic System was investigated for efficiency in [10].

The system investigated the potential advantages of an innovative three-phase a double power system rectifier over a regular rectifier used in a PV plants, but still has several problems with limited stochastic energy utilization from alternative energy sources. These current solar power conversion systems have very many different drawbacks as mentioned in the literature with additional issues of inefficiency, unreliability, high loss, and limited to small power loads. The proposed efficient and controlled solar power electronics converter (EC-SPEC) can elucidate all of these mentioned drawbacks.

3. Materials and Methods

3.1 Solar Power Electronics Converter (SPEC) design

The two solar PV arrays of 1000W/m^2 each have been considered and connected in parallel. The DC voltage and current sensors were also considered in this paper. The role of DC voltage sensor was to measure the DC voltage and maintain the accuracy and efficiency of the system design whenever temperature raised. This sensing voltage device also begins with internal high voltage resistor network by directly contacting both positive and negative high voltage and voltage signal received, was transmitted to secondary side of the sensor to provide high insulation and DC voltage zero drift amplification. The DC current sensor was needed throughout grid tied system for converter control and optimization of power extraction from the two panels with fault detection mechanism for safety in DC current measurement. The system used a capacitor of 1e-6 Farad assisted to filter DC signals in the system and to improve the efficiency of a Photovoltaic system with on changing the power stage. The proposed power electronics solar converter considered the four MOSFETs for switching operation hooked up to the power converter transformer's primary coil. When switching received the MOSFET driver signal from driver gate circuit, these MOSFETs started switching between ON/OFF states at a rate of 50Hz. The four gate driver circuits have been also proposed. These gate governors may have a poor output power amplitude to reduce power dissipation and an extremely quickly switching operation to mitigate switching losses. These gate drivers were required to provide very equally correlated timing characteristics efficiency in order to reduce dead time whenever one switch of the half bridge ultimately turned off before the second transition turns on for the accuracy and efficiency of the power converter system so that the drivers can be able to reduce power loss during switching by PWM duty cycle application and control large amount of power supplied by the power source to load. Figure 1 demonstrates the driver gate model used in the case study as described.

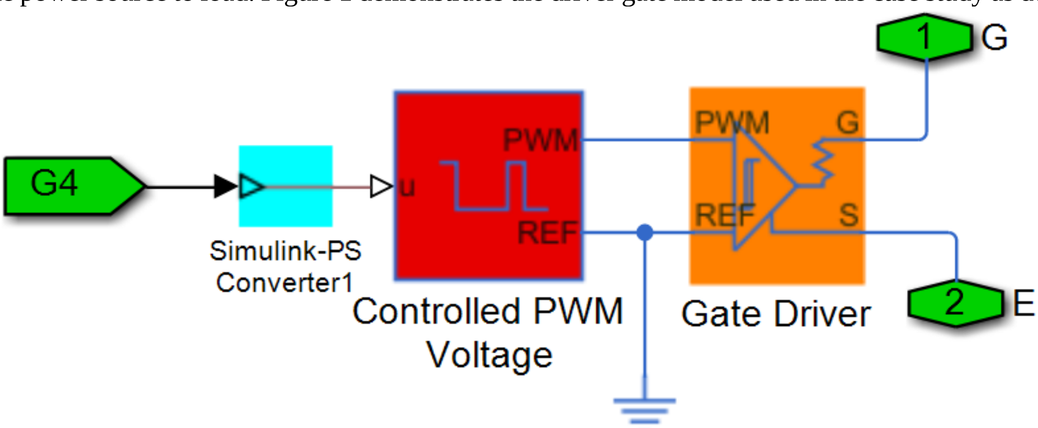

Figure 1. Gate driver circuit.

The D_1, D_2, D_3, and D_4 diodes have been considered and utilized in this SPEC design to as blocking devices, they were used to avoid current reflux (unidirectional flow of current). They were also used as override devices to keep the entire EC-SPEC system running in the event of a PV system failure. The AC voltage and AC current sensors have been connected and installed in the EC-SPEC circuit to measure and analyze the AC voltage and current before supply to the utility grid. MATLAB/Simulink 2019a software environment has been used to compute, model, simulate, and analyze the system. Figure 2 indicates the model of efficient and controlled solar power electronics converter (EC-SPEC) design as discussed in this paper.

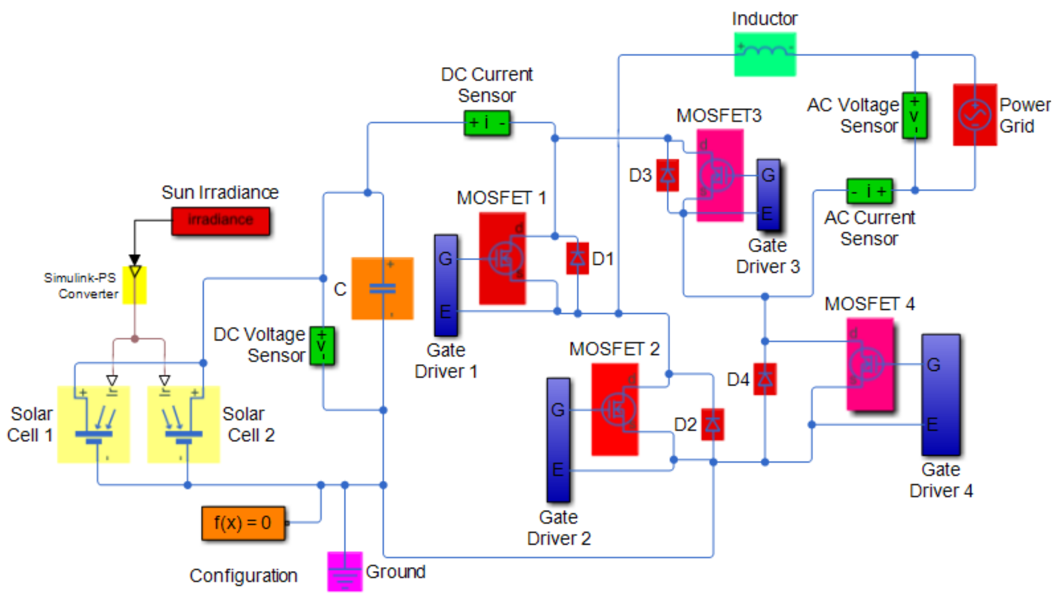

Figure 2. Solar Power Electronics Converter (SPEC) design.

3.2 Parameters and Settings used in simulations

Table 1 below shows the parameters used for diodes during simulations.

Table 1. Diode Parameters

S/N	Parameters	Values
1.	Parameterization	I-V curve Data point
2.	Currents [I_1, I_2]	[0.137, 5.45] A
3.	Voltages [V_1, V_2]	[0.6, 0.7] V
4.	Ohmic Resistance Rs	0.01Ω
5.	Measurement Temperature	25℃
6.	Junction Capacitance	50pF

Table 2 demonstrates the parameters and settings PV cells characteristics that have been considered in this paper during modeling and simulation of SPEC.

Table 2. Solar Cell Parameters Configuration in Ec-Spec

S/N	Parameters	Values
1.	Diode Saturation Current I_s	$3.15 * 10^{-7} A$
2.	Diode Saturation Current I_{s2}	$0A$
3.	Solar generated current	$3.80A$
4.	Irradiance	$1000W * m^{-2}$
5.	Quality factor N	1.4
6.	Quality factor N_2	2
7.	Series Resistance R_s	0.0042Ω
8.	Parallel Resistance R_p	10.1Ω

Table 3 depicts the parameters and simulation settings during testing and validating of MOSFETs.

Table 3. Mosfet Parameters and Settings

S/N	Parameters	Values
1.	Resistance R_D_s (Drain Source)	0.1Ω
2.	Current I_{ds} for Drain Source	15A
3.	V_{gs} (Voltage Gate − Source) for ON R_D_s	10V
4.	V_{th} (Threshold $Voltage_{Gate}$ − source)	1.7V
5.	Temperature	25°C

3.3 EC-SPEC efficiency determination

An converter's efficiency predicts how much DC power is converted to AC power. Most of the power is wasted as heat, as well as some stand-by power is utilized to maintain the converter operating smoothly. The equation 1 below shows the efficiency formula.

$$\eta_{EC-SPEC} = \frac{P_{AC}}{P_{DC}} * 100\% \quad (1)$$

Where P_{AC} is AC power output, P_{DC} is DC power input, and η is efficiency in percentage.

To model and simulate the efficiency in MATLAB environment, fig. 3 depicts the block diagram computed to calculate and simulate the efficiency and DC power in SPEC experiment.

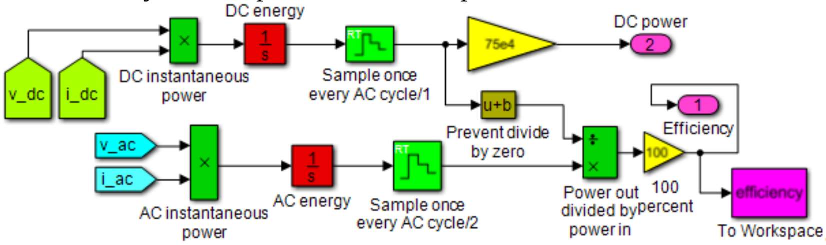

Figure 3. EC-SPEC Efficiency block diagram.

3.4 SPEC Controller circuit design

The SPEC controller was designed and employed in the whole solar power converter system. The AC and DC voltage and current signals were received and integrated to the controller in order to be analyzed and compared to reference signals. The integrated circuit controller sends the output signal normalized by DC voltage and disable it if the DC volts is too low to facilitate switching operation. Fig. 4 illustrates the computed modeling system of internal integrated regulating circuit design. Fig. 5 demonstrates the created subsystem of the EC-SPEC controller that was enabled to control the AC and DC voltage and current with reference signal.

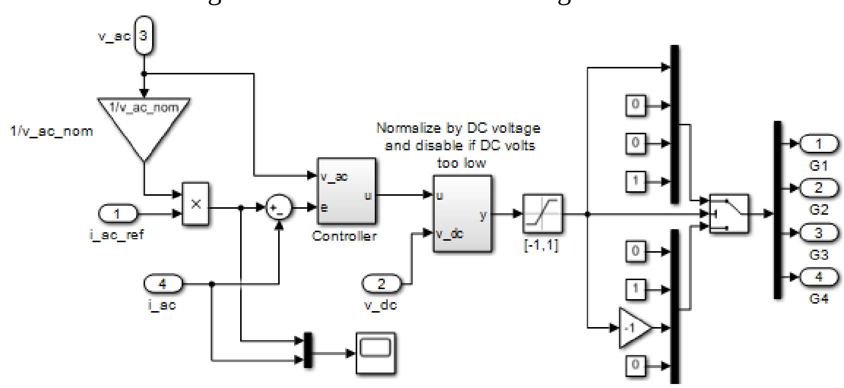

Figure 4. Internal of EC-SPEC controller design.

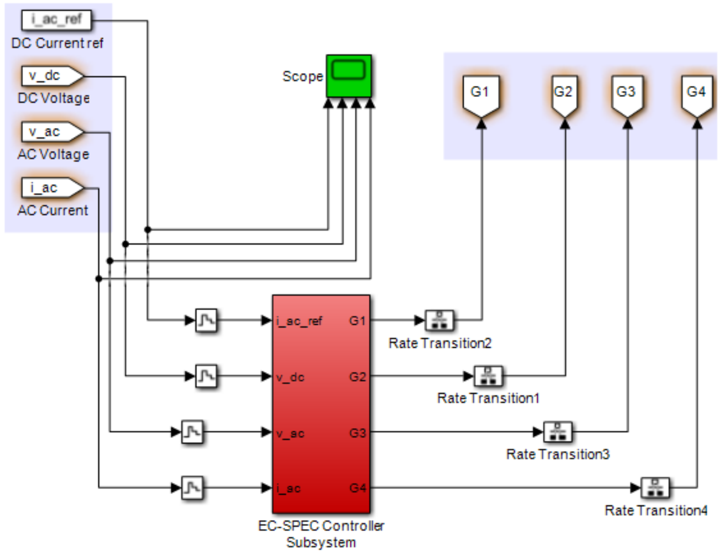

Figure 5. The subsystem of EC-SPEC controller system design.

The efficient and controlled solar power electronic converter (EC-SPEC) has been modeled, connected, and simulated. Fig. 1 was created into subsystem to be able connected with other MATLAB models. Fig. 2 also illustrates the EC-SPEC without controller. Fig. 3 efficiency calculation model which was created as subsystem. Fig. 4 indicates the internal EC-SPEC controller design which was also created as subsystem. Fig. 5 depicts the controller design with AC and DC voltages and currents with display. The above mentioned figures were assembled to produce full EC-SPEC as observed in Figure 6.

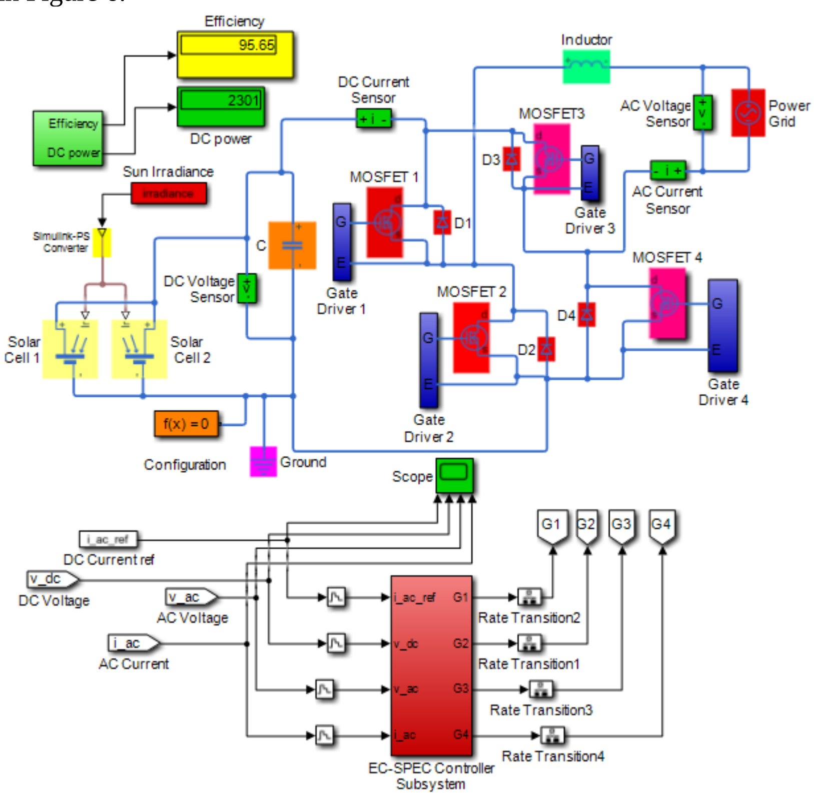

Figure 6. Overall EC-SPEC system design.

4. Results and Discussion

4.1 Output Current and Power Dissipation

The dissipated power and output current of the two MOSFETs were obtained and observed during testing and simulations as shown in fig. 7 below.

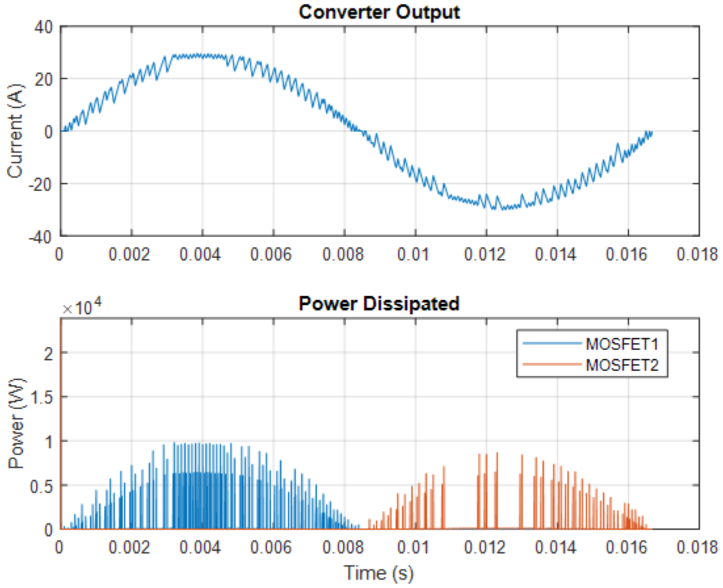

Figure 7. Power Dissipated and Output current of MOSFETs.

4.2 Line Inductance output

Simulation results of current and voltage of transmission line inductance sent to grid as illustrates in fig. 8 below.

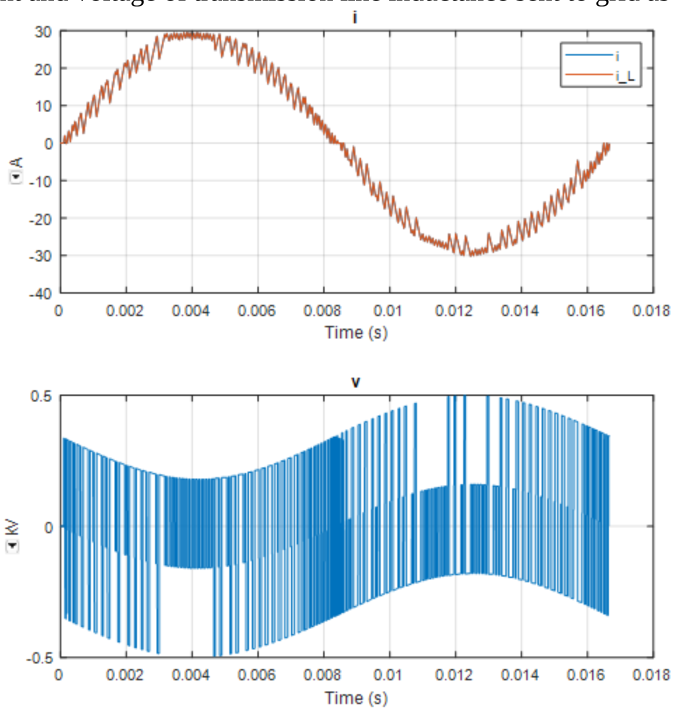

Figure 8. Current and Voltage of inductance in transmission line.

4.3 DC and AC Voltage and Current Sensor outputs

Simulation results of DC voltage sensor measured and sensed from PV solar system where the DC voltage is maximum while DC current is 0A as shown in fig. 9 below.

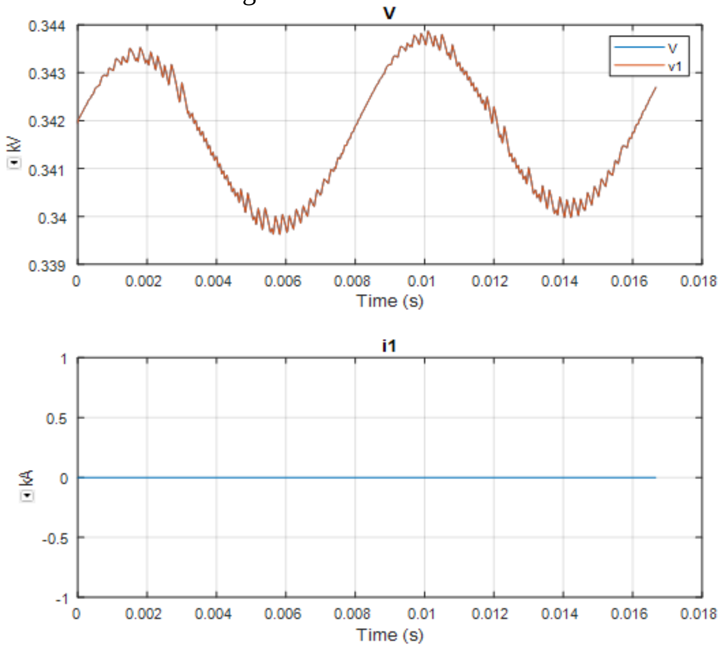

Figure 9. DC voltage and current sensed by DC voltage sensor.

Simulation results measured and sensed by DC current sensor from PV solar where DC current is maximum where 0VDC was indicated as simulated in fig. 10 below.

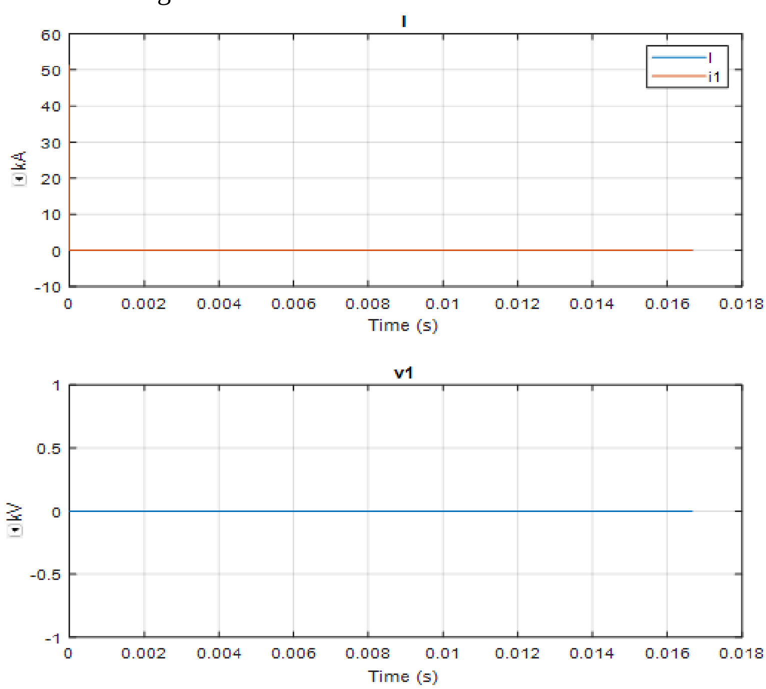

Figure 10. Sensed current and voltage in DC current sensor.

4.4 Simulation results of Diode Outputs

Simulation results of Diode 1(D1) in SPEC. Fig. 11 shows voltage generated by D1 (Diode). Fig. 12 shows current in D1.

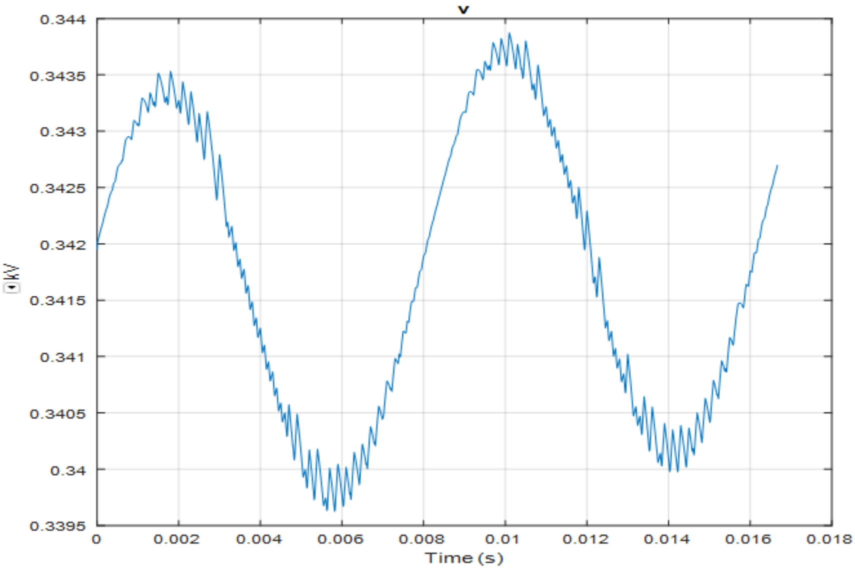

Figure 11. Voltage in diode (D1).

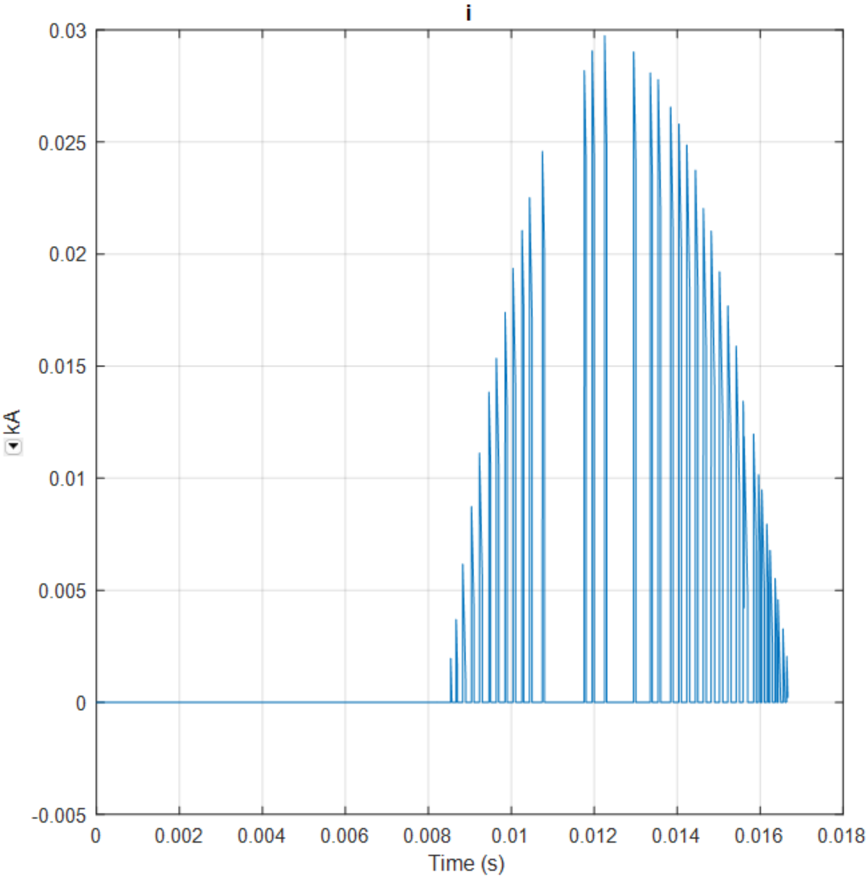

Figure 12. Current in diode (D1).

Diode (D2) was simulated to observe the current, voltage and power dissipated and temperature of measurement that it can hold. Fig. 13 demonstrates the performance of D2 in the converter during switching operation.

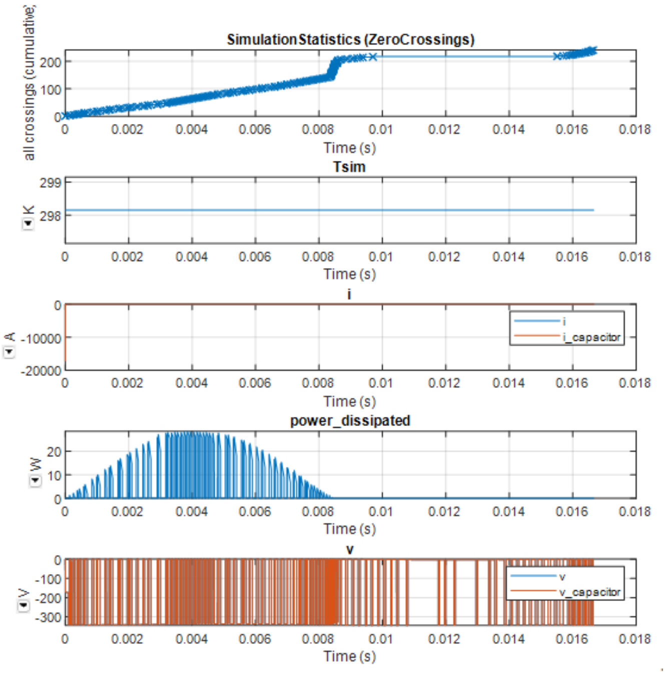

Figure 13. Simulation results of Diode (D2).

The simulation characteristics in Diode (D3) has observed. The temperature measurement is 25℃ with zero amps that can pass through capacitor filter and also power loss became minimum. Fig. 14 indicates the simulation results of D3 in EC-SPEC during testing and simulations.

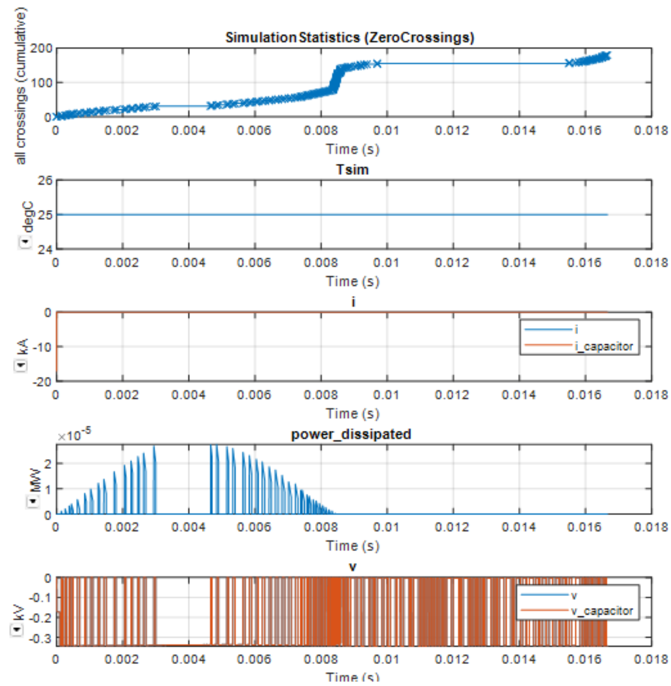

Figure 14. Simulation results of Diode (D3).

Fig. 15 depicts also the Diode (D4) results when testing has been conducted. The simulation statistics looks better as current and voltage through capacitor became 0A and 0V respectively. The temperature measurement of the solar panels remained at 25℃ each with minimum power dissipation in SPEC.

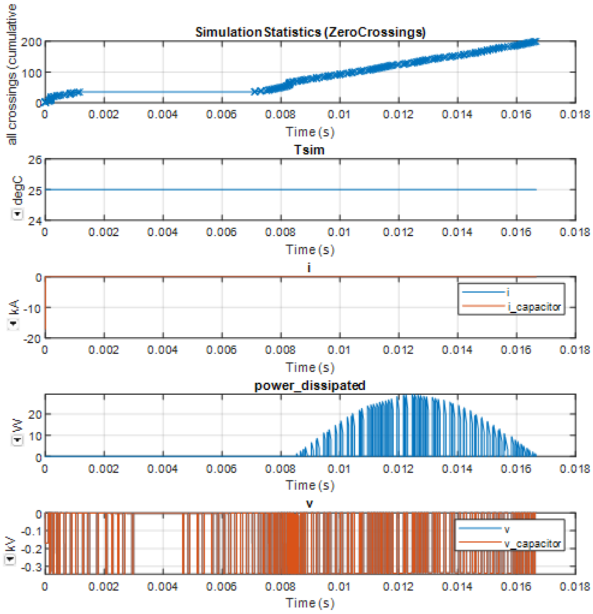

Figure 15. Simulation results of Diode (D4).

4.5 Simulation results of MOSFET Outputs

The MOSFET1, 2, and 3 demonstrate the simulated voltage during experiment with testing of sensitivity compared to existing MOSFETs used in power conversion. The recent research shows the minimum DC voltage that MOSFETs can support as in [11]. Figs. 16, 17, and 18 show the voltage waveforms of the above mentioned MOSFETs.

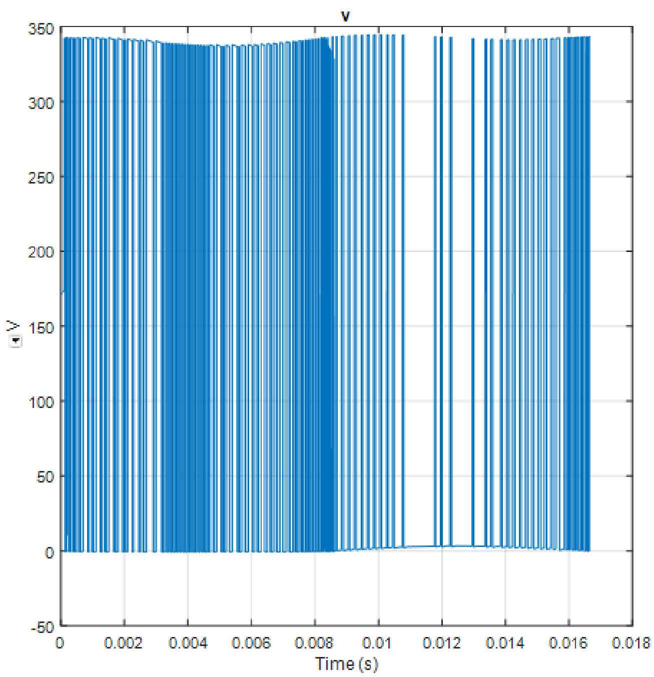

Figure 16. DC voltage for MOSFET 1.

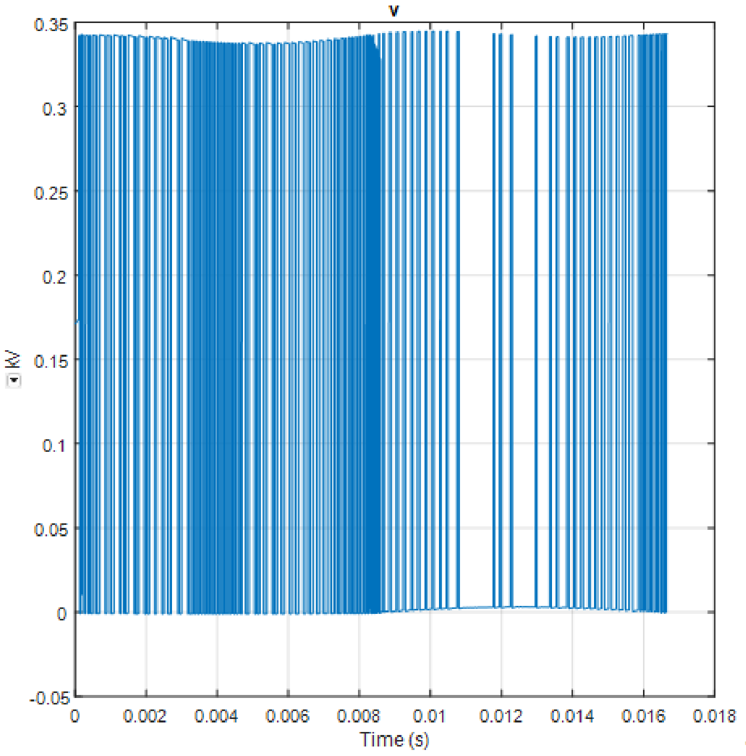

Figure 17. DC voltage for MOSFET 2.

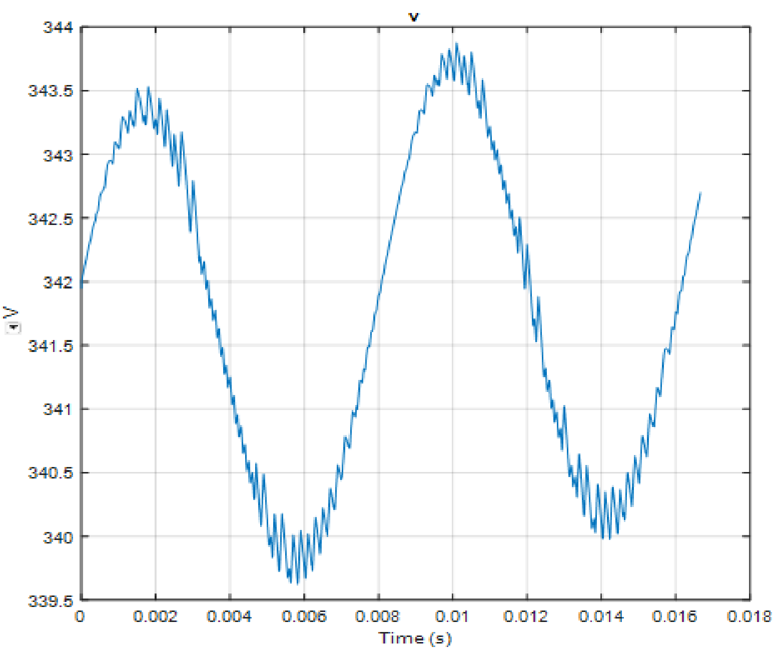

Figure 18. DC Voltage for MOSFET 3.

Fig. 19 indicates the characteristics of MOSFET 4 during simulations. The current and voltage drain-source, voltage and current gate-source, power dissipated and simulation statistics with zero crossings have been observed.

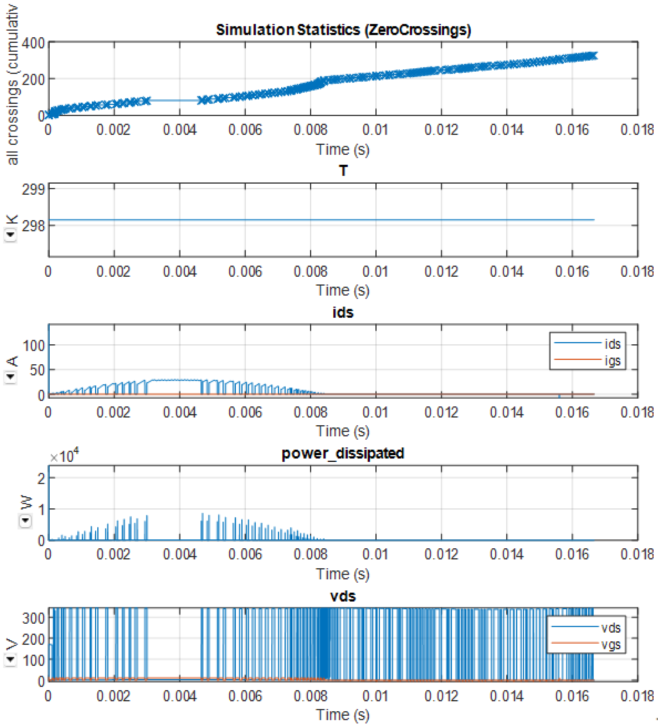

Figure 19. Current and Voltage with power dissipation in EC-SPEC.

4.6 Simulation results of overall SPEC system design

Figure 20 predicts the overall simulation results of DC and AC voltage waveforms, AC and AC RMS current waveforms of the whole SPEC system design performance.

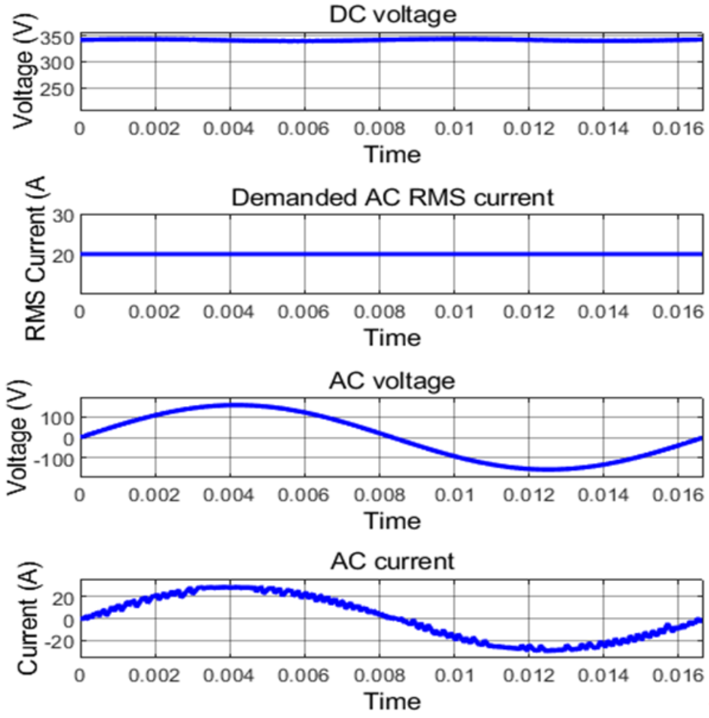

Figure 20. The voltage and Current waveforms of EC-SPEC.

4.7 Comparison results of SPEC individual components using looped Simscape

Table 4 below tabulates the simulation results of the proposed solar power converter that explains how the power in individual component of the EC-SPEC system design was dissipated.

Table 4. Power dissipated of individual component in the power conversion system

S/N	EC-SPEC Components	Power Dissipated(W)
1.	*MOSFET 1*	14.7
2.	*MOSFET 2*	18.0
3.	*MOSFET 3*	14.2
4.	*MOSFET 4*	17.5
5.	*DIODE D1*	1.7
6.	*DIODE D2*	3.0
7.	*DIODE D3*	1.9
8.	*DIODE D 4*	3.2

Fig. 21 below predicts the comparison power dissipated results of SPEC individual component obtained during testing and simulations.

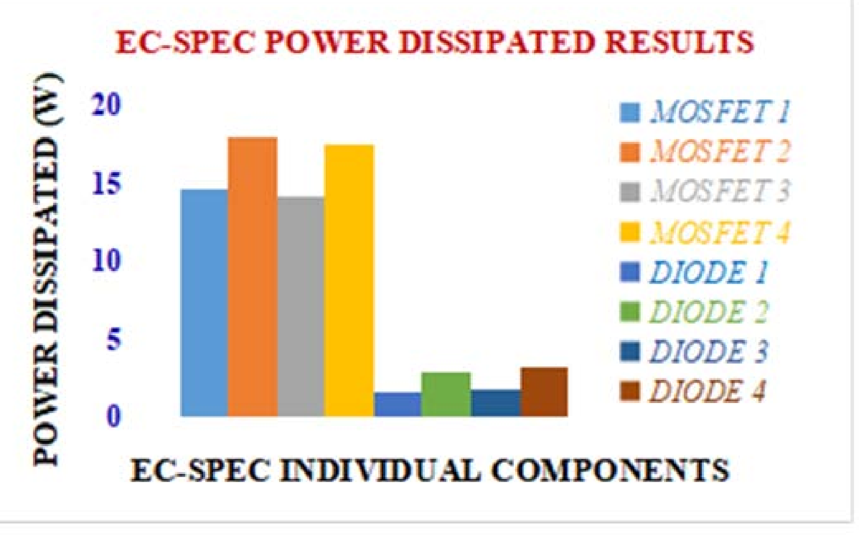

Figure 21. The comparison of power dissipated results of EC-SPEC during testing.

5. Conclusion and Future Works

The efficient and controlled solar power electronic converter in microgrid and smart grid applications was designed, simulated and tested. The DC and AC currents and voltages at DC and AC voltage and current sensors have been sensed, simulated, and measured in the EC-SPEC system design. The power dissipated, DC and AC voltage and current of MOSFET 1, 2, 3, and 4, D1, D2, D3, and D4 were determined using logged simscape within MATLAB/Simulink 2019a. The accurate percentage EC-SPEC efficiency was achieved. The small difference between claculated and simuated efficiency was due to trapezodoically integrated with greatest accuracy achieved by solver step in MATLAB/Simulink.

The proposed EC-SPEC system design demonstrates the lower power dissipated and higher efficiency compared to the existing converters and defended the better performance. The industrial internet of things and cyber physical systems in virtual control are recommended to be considered for future work.

6. Acknowledgment

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7. Data Availability

This research article encompasses all necessary information. Upon request, the corresponding author will provide any additional information.

References

[1] US. Department of Energy. "Solar Integration: Inverters and Grid Services Basics," Energy Efficiency & Renewable Energy, 27 December 2021. [Online]. Available: http://www.energy.gov. [Accessed 03 April 2022].

[2] Sathiyanathan, M., et al. (2019). "Design and Analysis of Universal Power Converter for Hybrid Solar and Thermoelectric Generators," Journal of Power Electronics, vol. 19, no. 1, pp. 220-233, 2019.

[3] M. Gordievsky, et al. (2020). "Simulation Model of Solar Power Installation in Matlab Simulink Program," in 2020 International Ural Conference on Electrical Power Engineering, Moscow, 2020.

[4] Mohanty, Parimita. (2014). "Role of Power Converters in Distributed solar Power Generation," Journal of Automation and Control Engineering, vol. 2, no. 1, pp. 38-43, 2014.

[5] R. Thangam, et al. (2016). "Designing Solar Power Inverter Using MATLAB/Simulink," International Journal of Pharmacy & Technology, vol. 8, no. 4, pp. 19747-19752, 2016.

[6] Muhammad Ajmal, et al. (2022). "Solar Powered Resonant Inverter Fed a High Voltage DC Power Supply," Engineering Proceedings MDPI, vol. 12, no. 70, pp. 1-5, 2022.

[7] B. Lu, W. Liu, Y. Liang, F. Lee, and J. van Wyk. (2006). "Optimal design methodology for LLC resonant converter," In Proceedings of the IEEE Applied Power Electronics Conference and Exposition-APEC, pp. 533-538, 2006.

[8] S. Lee, et al. (2012). "A new ZCS series resonant high-voltage DC power supply," In Proceedings of the PEcon 2012 IEEE International Conference on Power and Energy, pp. 44-48, 2012.

[9] C. H. Huang, C. C. Chen. (2016). "A high-efficiency current mode buck converter with a power-loss-aware switch-on demand modulation technique for multifunction SoCs,," IEEE Transaction of Power Electronics, vol. 31, no. 12, pp. 8303-8316, 2016.

[10] Jonas Vaicys, et al. (2022). "Efficiency Evaluation of the Dual System Power Inverter for On-Grid Photovoltaic System," Energies MDPI, vol. 15, no. 161, pp. 1-14, 2022.

[11] G. Fonte. (2020). "Power MOSFETS," nutsvolts, 20 December 2020. [Online]. Available: https://www.nutsvolts.com/magazine/article/power_mosfets. [Accessed 06 April 2022].