Relative Analysis of Single-Stage and Two-Stage Energy Storage System Interconnected Solar Power System Performance

[1]E. Sreeshobha, [2]R. Lingaswamy

[1,2]Assistant Professor
Department of Electrical Engineering,
University College of Engineering,
Osmania University, Hyderabad, Telangana, India

***Abstract*: Solar power system is self-sustainable, and feed loads independently. Due to this feature of solar power system loads do not rely on the grid. Thus solar power generation is gaining higher priority. The initial investment for establishing the solar power plant is also very high. Obtained solar output power is directly interlinked with irradiance. Numerical efficiency evaluation of solar power systems is the basic requirement to propose schemes to improve the efficiency of the solar power system. Single-stage bidirectional DC-DC converter and Two-stage bidirectional DC-DC converter configurations are examined for higher efficiency operation of the system. Four possible modes of operation of the solar system are thoroughly examined through battery charging and discharging states, power levels at solar panels, energy storage system, inverter, and the load power. To improve the performance and reduce the payback period of the solar system, the key parameters, Total harmonic distortion, and the duty ratio of the Bidirectional DC-DC converters estimated by simulation. The effect of the obtained duty ratio of the energy storage system on the payback period of the system is examined.**

***Index Terms*: Solar power system, Maximum power point tracking, Single stage bidirectional DC-DC converter, Two stage bidirectional DC-DC converter, energy storage system.**

I. INTRODUCTION

Among the available renewable energy sources, solar energy is more popular due to its abundant availability, everywhere. Solar Power Systems (SPS) converts sunlight into electrical energy by the photovoltaic effect. Due to the absence of greenhouse gases emission, during the electrical power generation process from solar energy, the solar power system is eco-friendly [1][2]. Each SPS by supplying power independently to the local loads acts like a small power plant and improves the grid security [3]. Due to these eminent features, SPS is gaining more importance and growing more in number. Hence the thorough analysis of SPS is very much important in the present scenario. For Single-stage and Two-stage bidirectional DC-DC converter configurations, operation of the Energy Storage System interconnected SPS [4] is simulated and analyzed for four different modes of operation, as a function of the irradiance. The analysis presented in this paper will help in identifying the operational parameters which will influence the maximum output power of the system and thereby selecting the essential operating conditions of the system for improved performance[5]-[7].

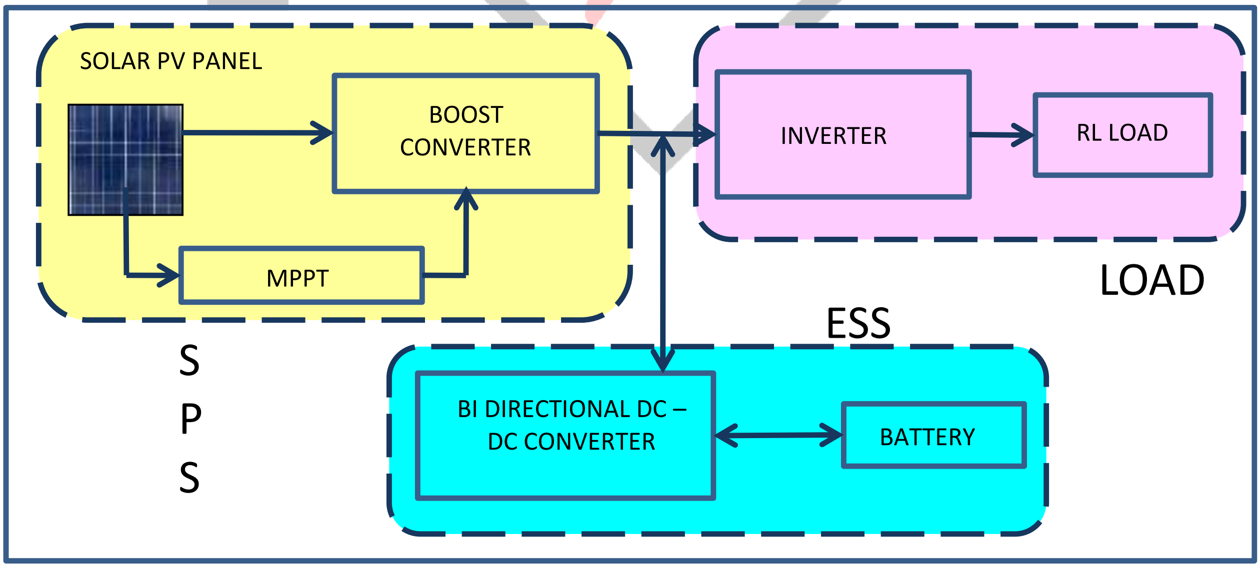

Figure 1: Energy storage system integrated solar power system schematic diagram

Twelve series and four parallel Soltech 1STH-215-P solar module based SPS with 213.15 W maximum power per cell capacity, 36.30 V open-circuit voltage (V_{OC}), 7.87 A short circuit current (I_{SC}), 29.00 V voltage (Vmp), and 7.35 A current (Imp) corresponding to Maximum Power Point (MPP) is considered for the analysis[8]-[10]. Schematic of SPS consisting of solar PV module, boost converter to implement maximum power point tracking (MPPT), and load interfacing inverter is shown in figure 1. An energy storage system (ESS) with 48 V, 1200 Ah lithium-Ion battery-based bidirectional DC-DC Chopper (BDC) is integrated into SPS. As per the load requirement charging and discharging of the ESS battery is facilitated by BDC. The basic operation of the schematic is elaborated in section II. The operational aspects of BDC are discussed in section III. ESS integrated SPS simulated with MATLAB Simulink tool [11]-[13] in section IV. Results and conclusions related to the analysis are presented in sections V and VI respectively.

II. SPS Operation with MPPT

Solar panels separate the charges of incident light energy and establish the current flow and forward biasing voltage for the load by the photovoltaic effect. Hence the equivalent circuit of a solar cell is represented by a current source connected in parallel with a diode as shown in figure 2. R_s is the series resistance offered by the semiconductor layers and contacts. R_{sh} is the leakage resistance. The resultant load current is given by equation 1 and equation 2.

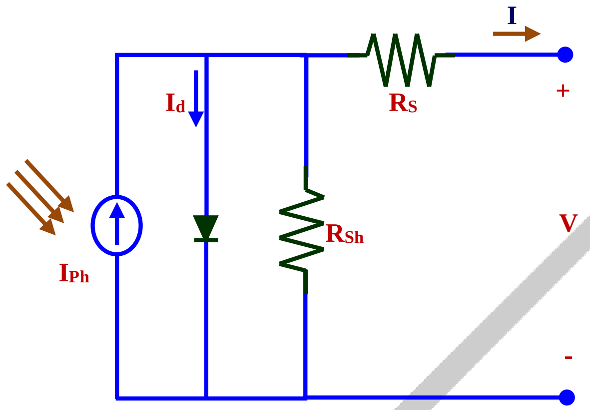

Figure 2. Solar cell equivalent circuit

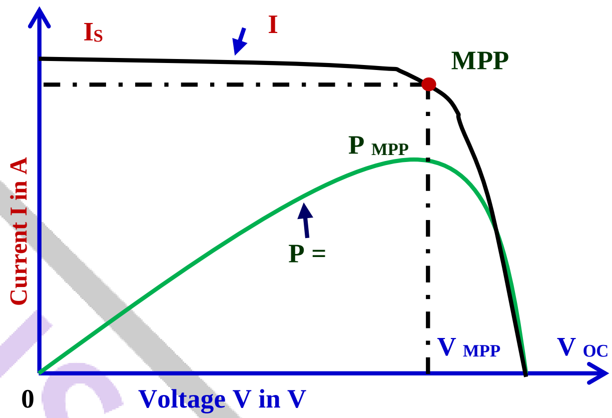

Figure 3. I-V and P-V characteristics of Solar cell

$$I = I_{ph} - I_d - I_{Rsh} \quad \text{.....(1)}$$

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S)}{\eta kT}} - 1\right) - \left(\frac{V+IR_S}{R_{Sh}}\right) \quad \text{.....(2)}$$

Where

- I : load current (Amps)
- I_{ph} : photon current (Amps)
- I_{Rsh} : leakage current (Amps)
- I_D : Diode current
- I_0 : Reverse saturation current (Amps)
- η : Diode ideality factor
- q : Elementary Charge (Columbs) = $1.602176634\times10^{-19}$ C
- k : Boltzmann's constant (1.380649×10^{-23} JK^{-1})
- T : Absolute temperature (K)

I_{SC} and V_{OC} are the maximum magnitudes of the short circuit current and open-circuit voltages that can be obtained by operating the solar panel. The output of the solar panel when operated in the range of I_{SC} and V_{OC} as a function of solar irradiance and ambient temperature, attains a single maximum power point as indicated in figure 3. Implementing control strategies to operate SPS at this maximum power point is maximum power point tracking (MPPT). Perturb and observe (P&O) MPPT tracking control algorithm is implemented in analyzing the present Solar Power System, a related flow chart is shown in figure 4.

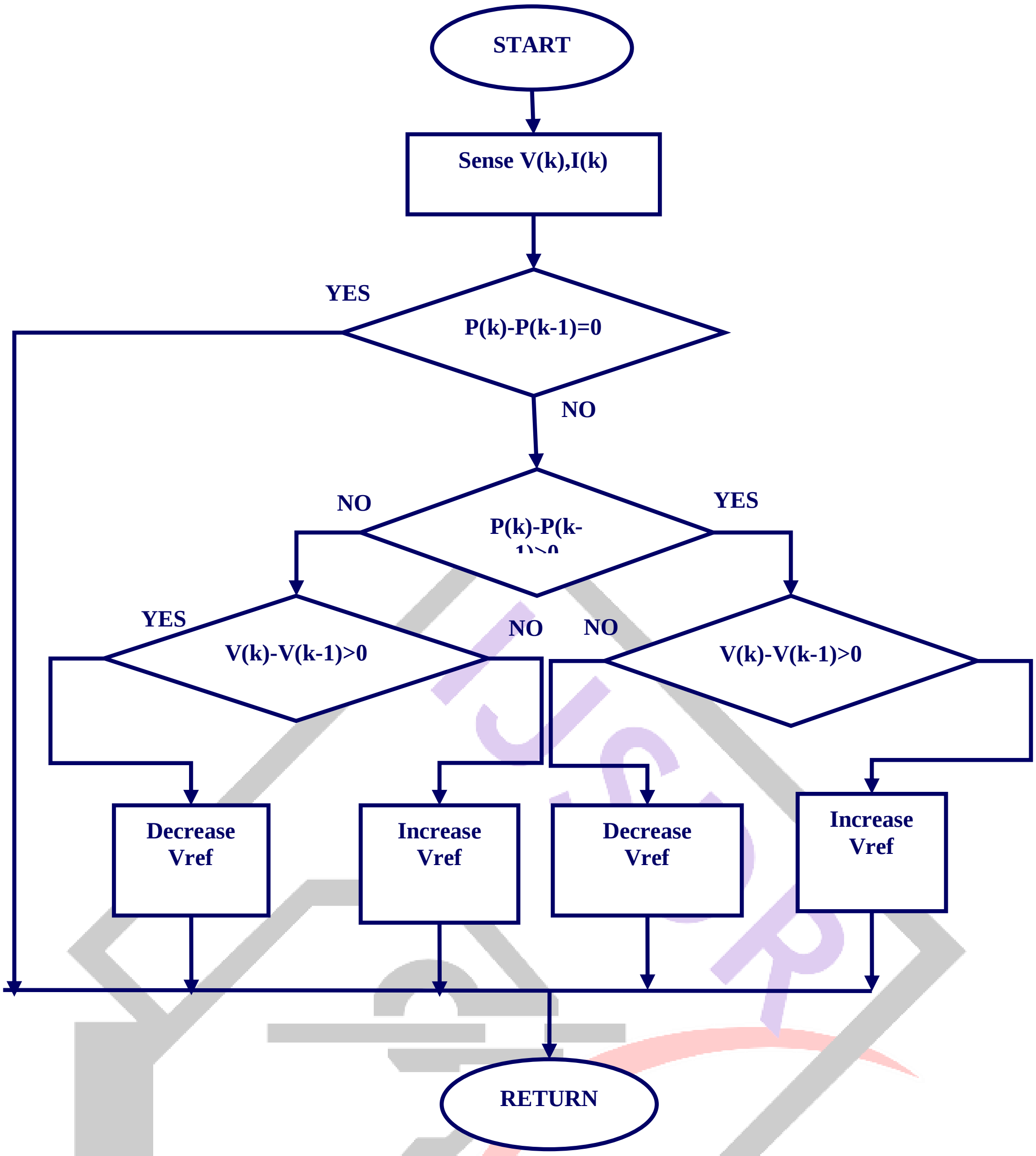

Figure 4. Perturb and observe MPPT controller flowchart

Charging of the ESS and feeding the load (mode 1) when demand is less than the generation - charging mode of operation, feeding the only load (mode 2) as load demand exactly matches with the generation, when load demand is more than the generation supplying the load from ESS along with solar system (mode 3) – discharging mode of operation, supplying the rated load by ESS in the absence of solar power (mode 4) like night time - discharging mode of operation are the various possible operating modes that can prevail in the SPS. BDC operation plays a vital role in charging and discharging modes of operation of the SPS. Hence the charging and discharging modes of operation are considered for the analysis and illustrated in the next section.

III. SINGLE-STAGE AND TWO-STAGE BDC OPERATION

A bidirectional DC-DC converter plays a vital role in interfacing SPS, inverter, and ESS. The anti-parallel connection of buck and boost converters configuration to facilitate the bidirectional power flow as shown in figure 5, results in single-stage BDC (SSBDC). The voltage at the point of common coupling (PCC) of solar panel, inverter, and BDC is 700 V and ESS battery voltage is 54 V. Mode of operation where solar power is more than the load demand, to charge ESS battery, BDC has to operate in buck mode by stepping down the voltage 700 V to 54 V. In the absence of deficit solar power conditions BDC boosts the voltage from 54 V to 700 V by discharging the battery to provide the power supply to the load.

Single Stage Bidirectional DC-DC Converter:

The operating state of power electronic switching devices, during charging and discharging modes are tabulated in Table 1 and figure 6, figure 7, figure 8, and figure 9 are the corresponding operating states of the SSBDC.

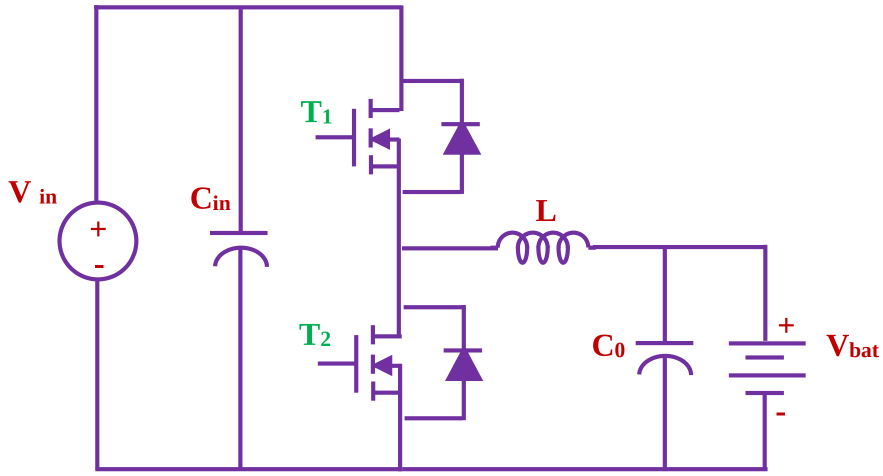

Figure 5. Single Stage Bidirectional DC-DC Converter

Table 1. Operating state of switching devices of SSBDC

	T1	D1	T2	D2
Charging – Interval 1	ON	OFF	OFF	OFF
Interval 2	OFF	OFF	OFF	ON
Discharging – Interval 1	OFF	OFF	ON	OFF
Interval 2	OFF	ON	OFF	OFF

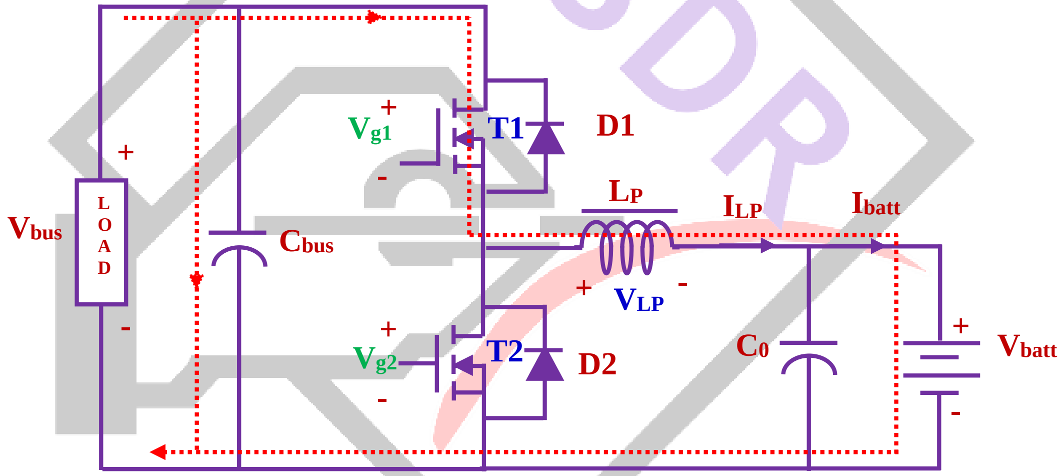

Figure 6. Current flow in SSBDC during charging mode interval 1

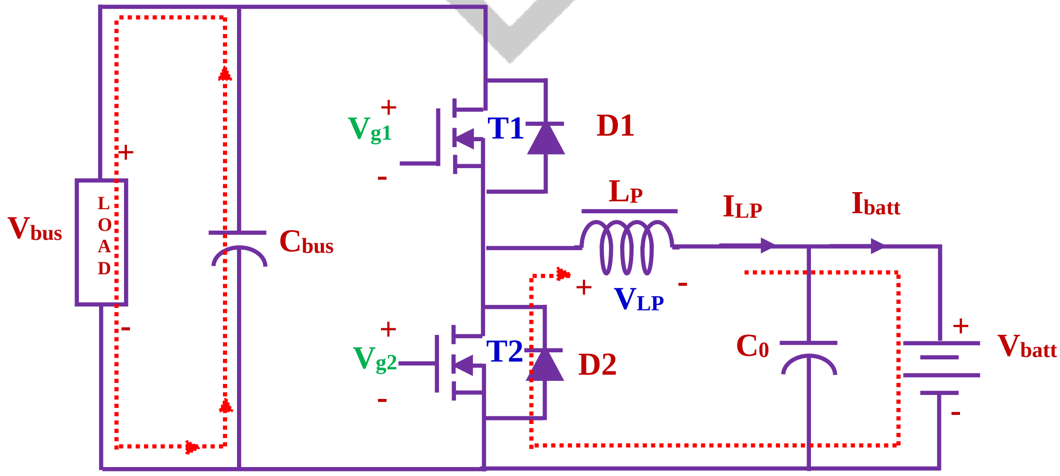

Figure 7. Current flow in SSBDC during charging mode interval 2

For T1-on, D1-off, T2-off, D2-off state interval 1, the filtering inductor Lp, output capacitor, and battery are charged. T1-off, D1-off, T2-off, D2-on state of interval 2, will result in, charging of the inductor via the freewheeling diode D2. During T2-on, D2-off, T1-off, D2-off state interval 1, diode D1 is reversed biased battery discharges via inductor and T2. For T1-off, D1-off, T2-off, D2-on mode interval 2, inherent voltage polarity reversal of the inductor will forward bias the diode D1, and discharging of battery occurs.

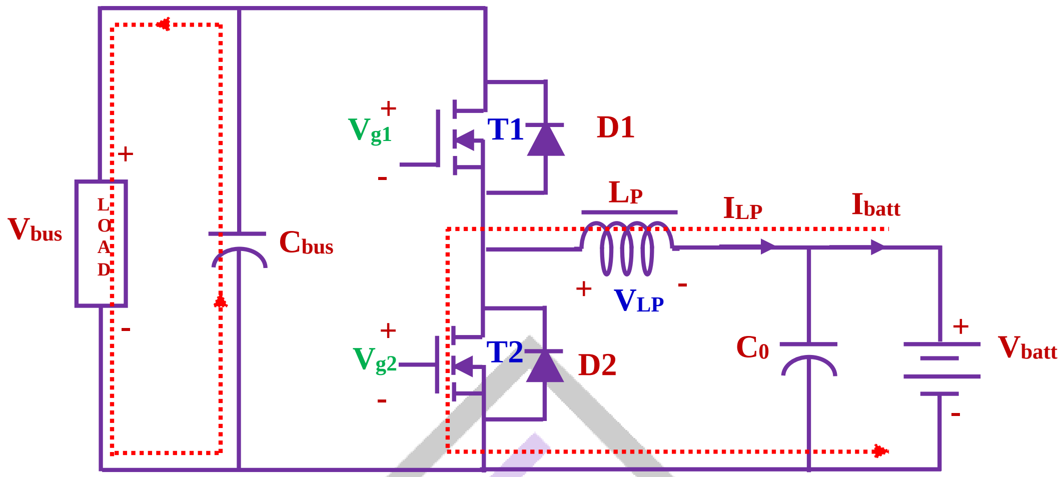

Figure 8. Current flow in SSBDC during discharging mode interval 1

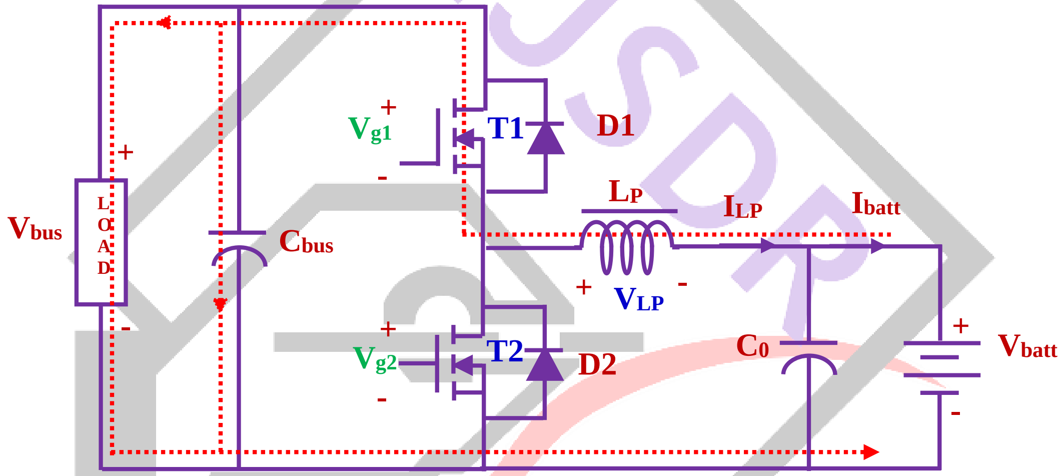

Figure 9. Current flow in SSBDC during discharging mode interval 2

During T2-on, D2-off, T1-off, D2-off state interval 1, diode D1 is reversed biased battery discharges via inductor and T2. For T1-off, D1-off, T2-off, D2-on mode interval 2, inherent voltage polarity reversal of the inductor will forward bias the diode D1, and discharging of battery occurs.

Two-Stage Bidirectional Converter:

Cascaded connection of two, single-stage BDC converters configuration as shown in figure 10, is two-stage BDC (TSBDC). From 700 V PCC voltage to 54 V of battery voltage stepping up and stepping down operation takes place in two stages. At the first stage, voltages are converted into an intermediate voltage of 200 V, between 700 V and 54 V, then at the second stage, the final magnitude of the required voltage is obtained. The operating state of power electronic switching devices, during charging and discharging modes, is tabulated in Table 2.

Table 2. Operating state of switching devices of SSBDC

	Q1	D1	Q2	D2	Q3	D3	Q4	D4
Charging – Interval 1	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF
Interval 2	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON
Discharging – Interval 1	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF
Interval 2	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF

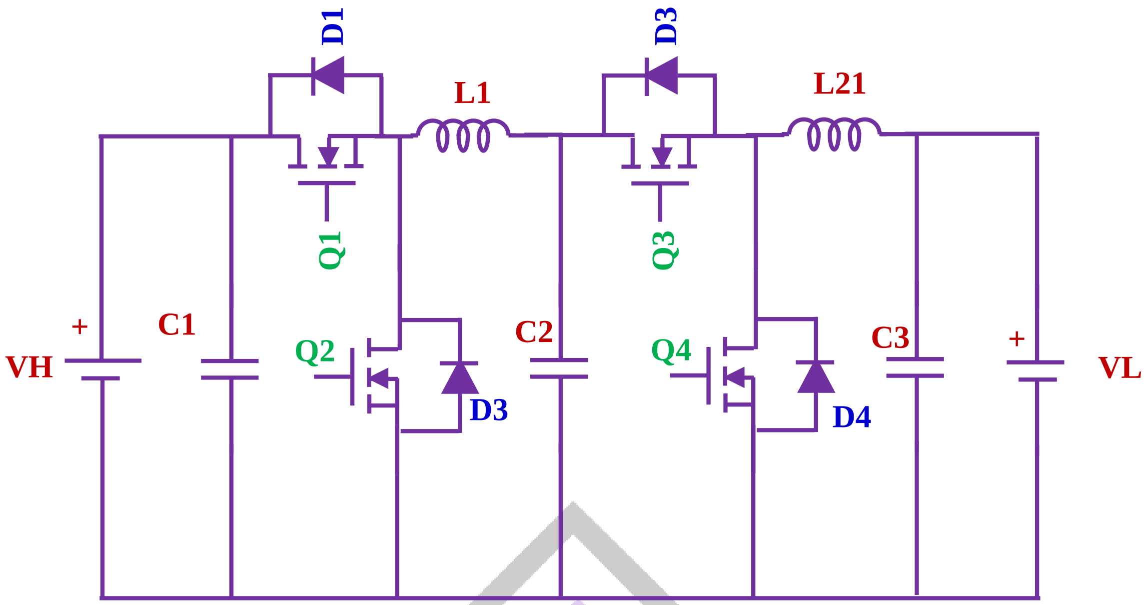

Figure 10. Two-Stage Bidirectional DC-DC Converter

IV. SPS SIMULATION WITH SSBDC AND TSBDC

The simulation block diagram of integrated Solar Power System, Energy Storage System, Inverter, and load is shown in figure 11. The Solar PV panel 10 kW, the output obtained by implementing P&O - MPPT algorithm. The error obtained by comparing the PV output voltage with MPPT reference voltage is fed to the PI controller. 15 kHz carrier wave superimposed with PI controller output signal and generates a pulse signal to switch the boost converter and constant output 10 kW is maintained. The specifications of the solar panel and boost converter are given in Tables 3 and 4.

Table 3. Solar PV 1Soltech 1STH-215-P module configuration

No. of Series cells	12
No. of Parallel cells	4
Short Circuit Current (I_{sc})	7.84 A
Open Circuit Voltage (V_{oc})	36.30 V
Voltage at MPP (Vmp)	29.00 V
Current at MPP (Imp)	7.35 A
Temperature Coefficient of Isc	0.102
Maximum Power	213.15 W
Total Power	10.00kW

Table 4. Boost Converter Configuration

Output Voltage (Vo)	700 V
Switching Frequency (fsw)	15 kHz
Duty cycle (D)	75%
Inductor (L)	500 mH
Capacitor (C)	220 µF
Output Power(Po)	10kW
MOSFET Switch V_{DSS}	800V

DC voltage either from the PV module or from the battery is converted into AC to cater to the load employing a three-phase inverter. 800 V VDSS and 0.01Ω Rd switch operating at 15 kHz with voltage and current PI controller, 400 V load voltage is simulated. Simulink subblocks of Single Stage Bidirectional DC – DC converter and Two Stage Bidirectional DC – DC converter based Energy Storage System are shown in figure 12 and figure 13.

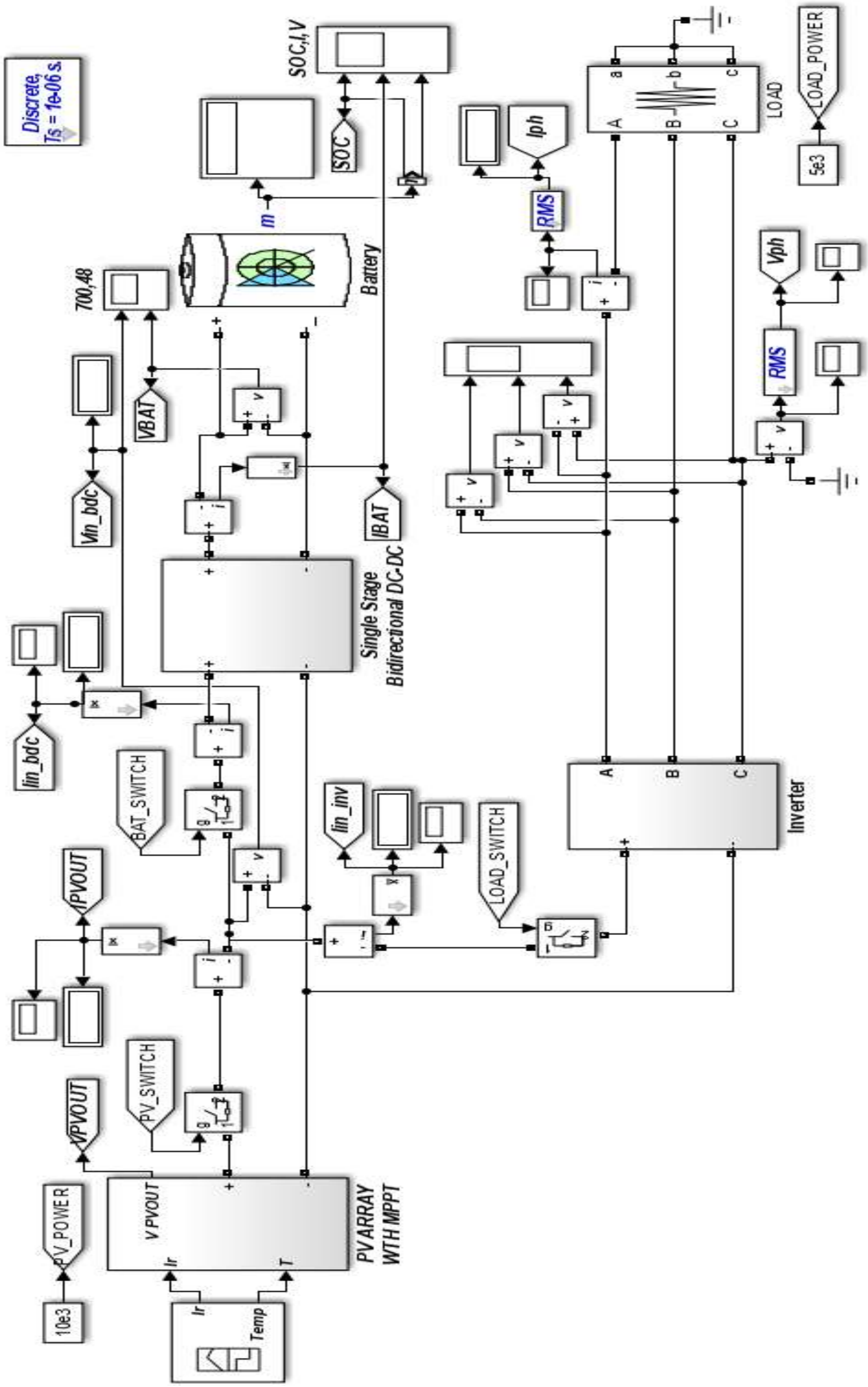

Figure 11. Simulink block diagram of SPS with SSBDC and TSBDC

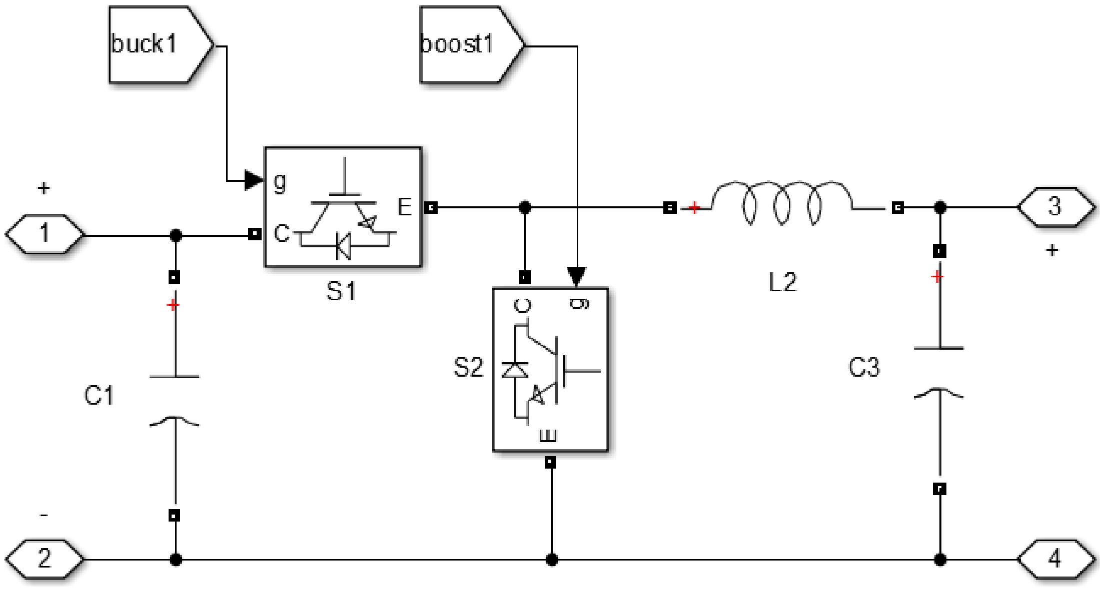

Figure 12. Simulink sub block diagram of SSBDC and TSBDC

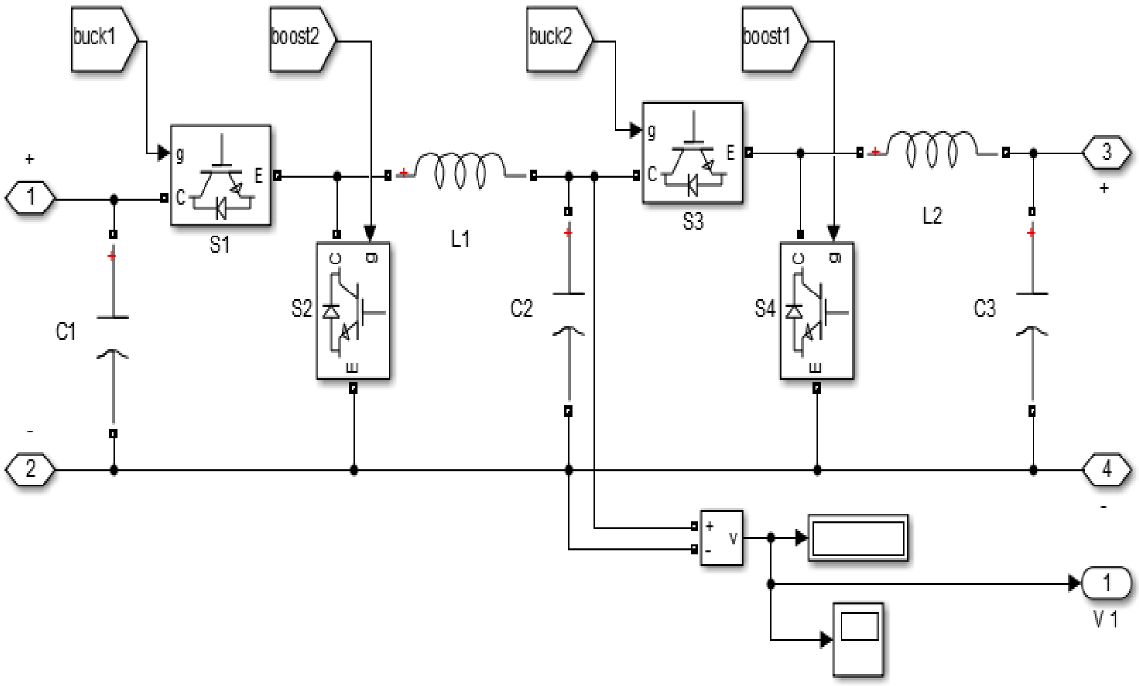

Figure 13. Simulink sub-block diagram of TSBDC

V. RESULTS

Relative analysis of SSBDC and TSBDC based SPS performance is carried out, based on the solar output power, load voltage and THD’s, and overall efficiency of the system which are indicated in Table 5. Effect of irradiance on the overall efficiency of the SPS is verified for all the modes of operation and mode 3 results are tabulated in Table 5. At 1000 W/m2 irradiation overall variation in the efficiency of the system for SSBDC and TSBDC operation is negligible. The minimal reduction in the efficiency is due to an increase in the number of switches in the two-stage BDC configuration. As the irradiance decreases the overall efficiency of the system also decreasing. PV module output power, state of charge of the battery, output voltage of BDC, inverter input current, load voltage, THD, load power, and overall efficiency Parameters which indicate the effectiveness of the SPS operation are shown in figure14 to figure 22 respectively. Relative analysis of the SPS operation is demonstrated by considering mode 3, in which solar PV modules and ESS both are supplying the load.

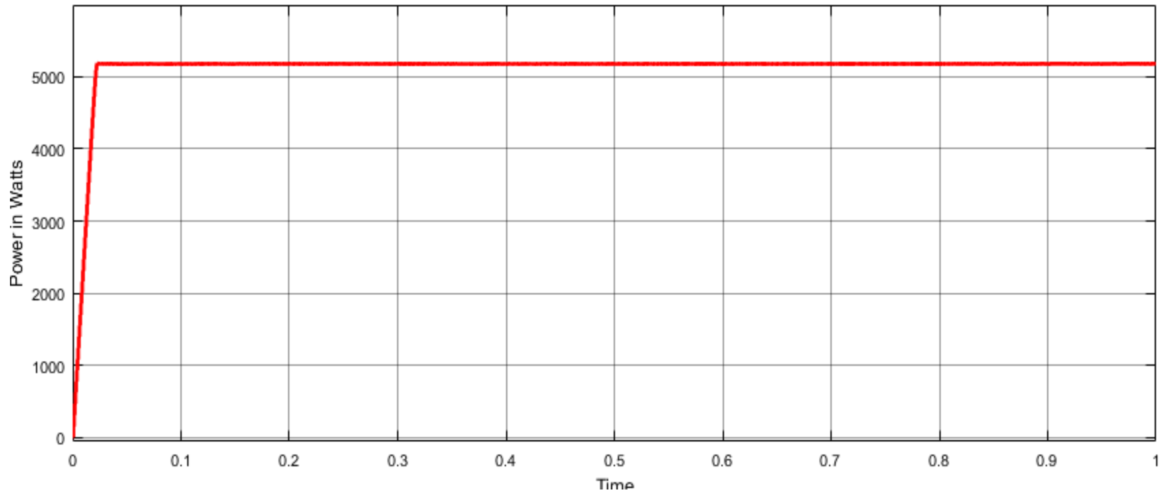

Figure 14. PV module output power for TSBDC operation

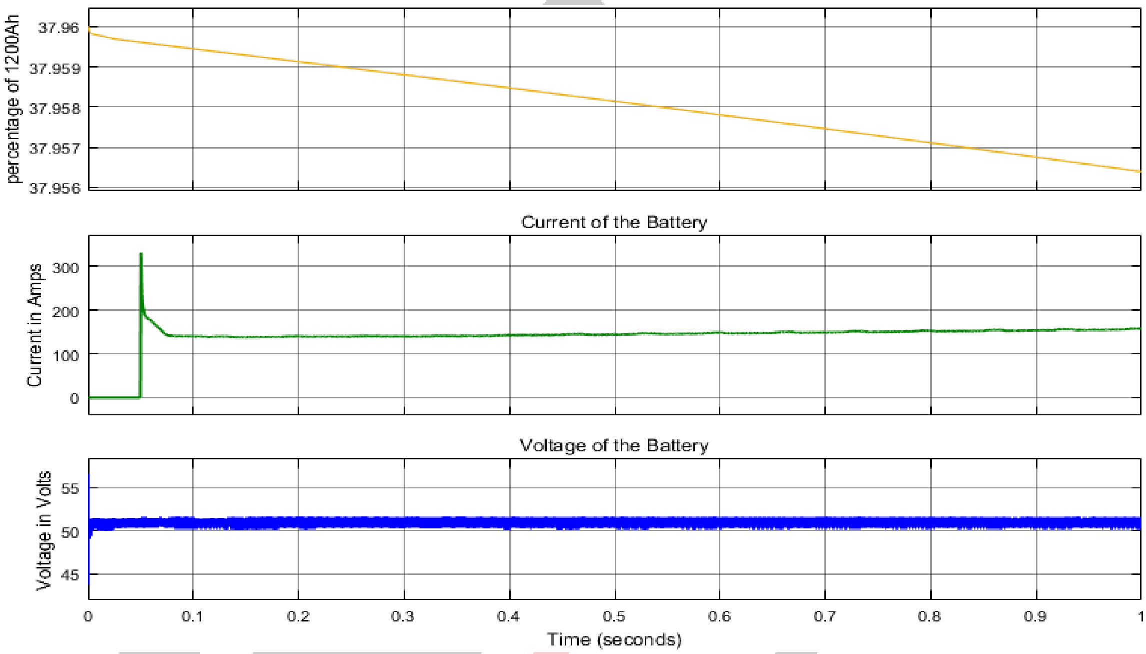

Figure 15. Battery state of charge, current, and voltage for TSBDC operation

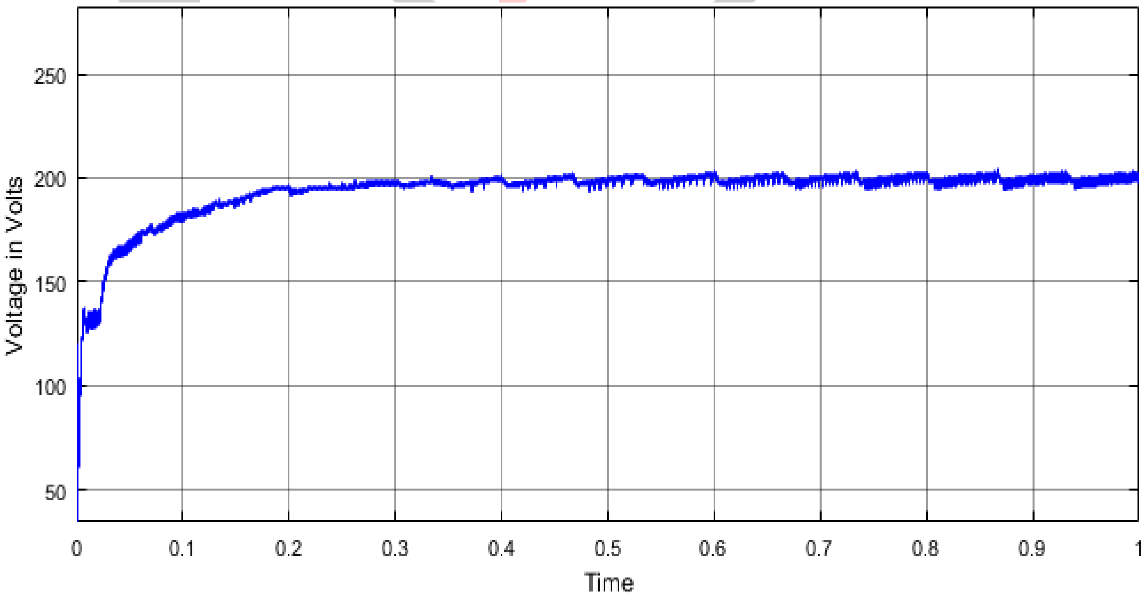

Figure 16. The intermittent output voltage of TSBDC operation

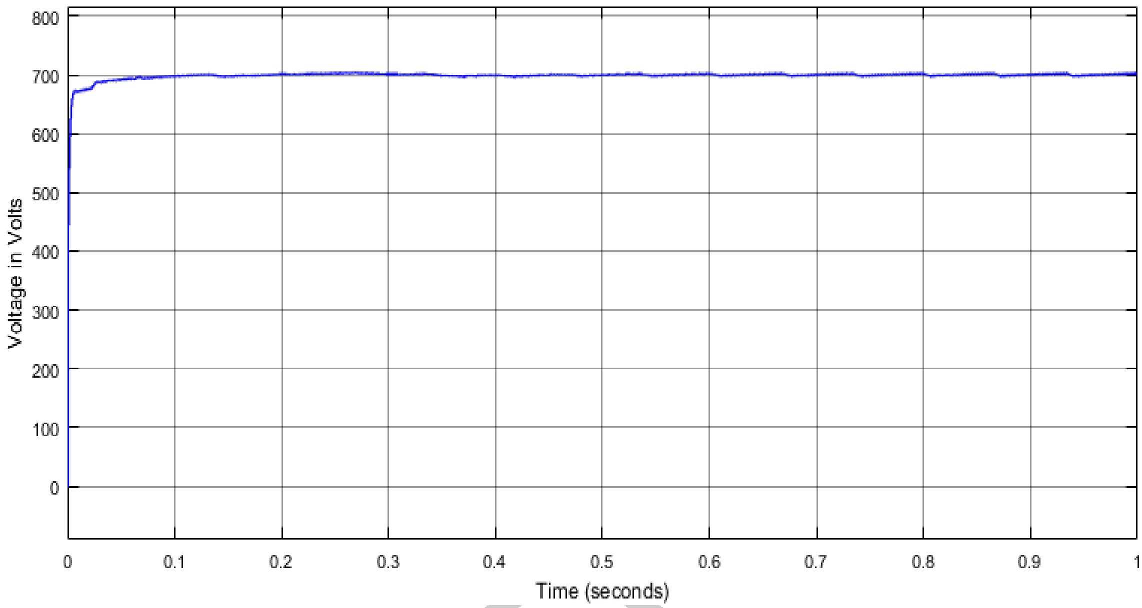

Figure 17. TSBDC output voltage during mode 3 operation

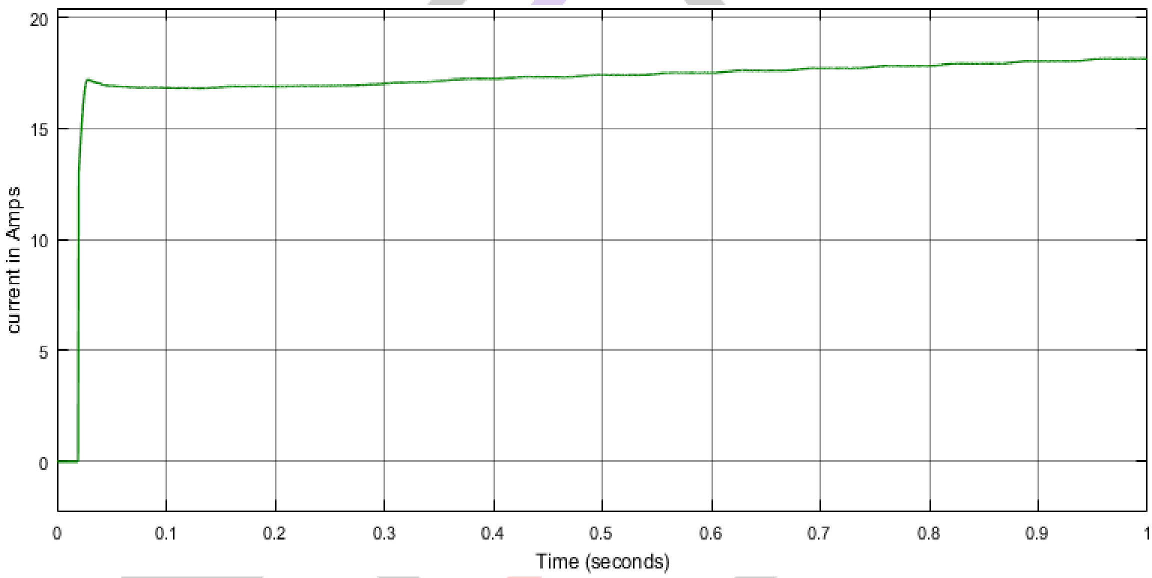

Figure 18. Inverter input current during mode 3 operation

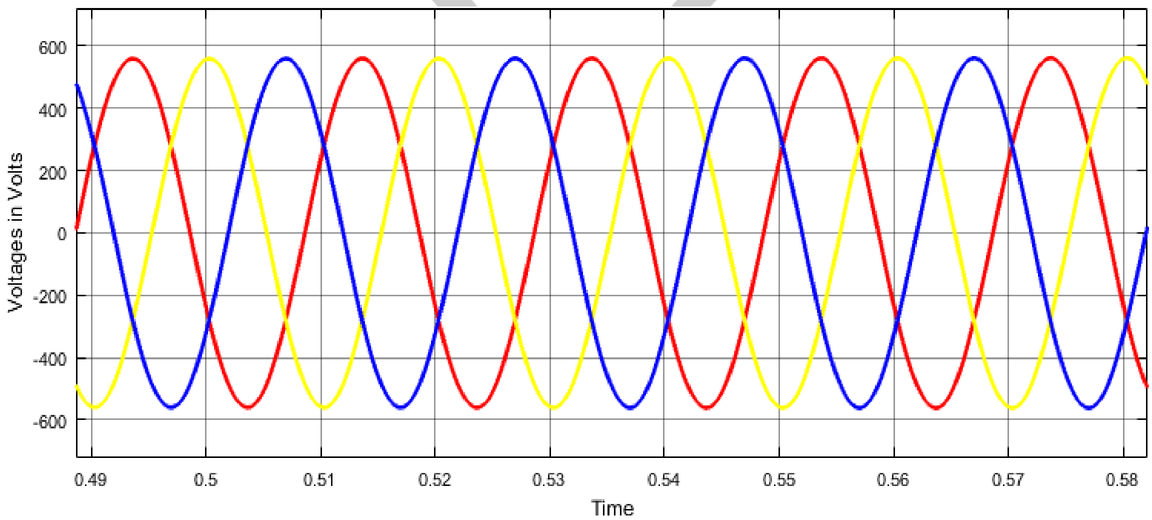

Figure 19. Load voltage during mode 3 operation

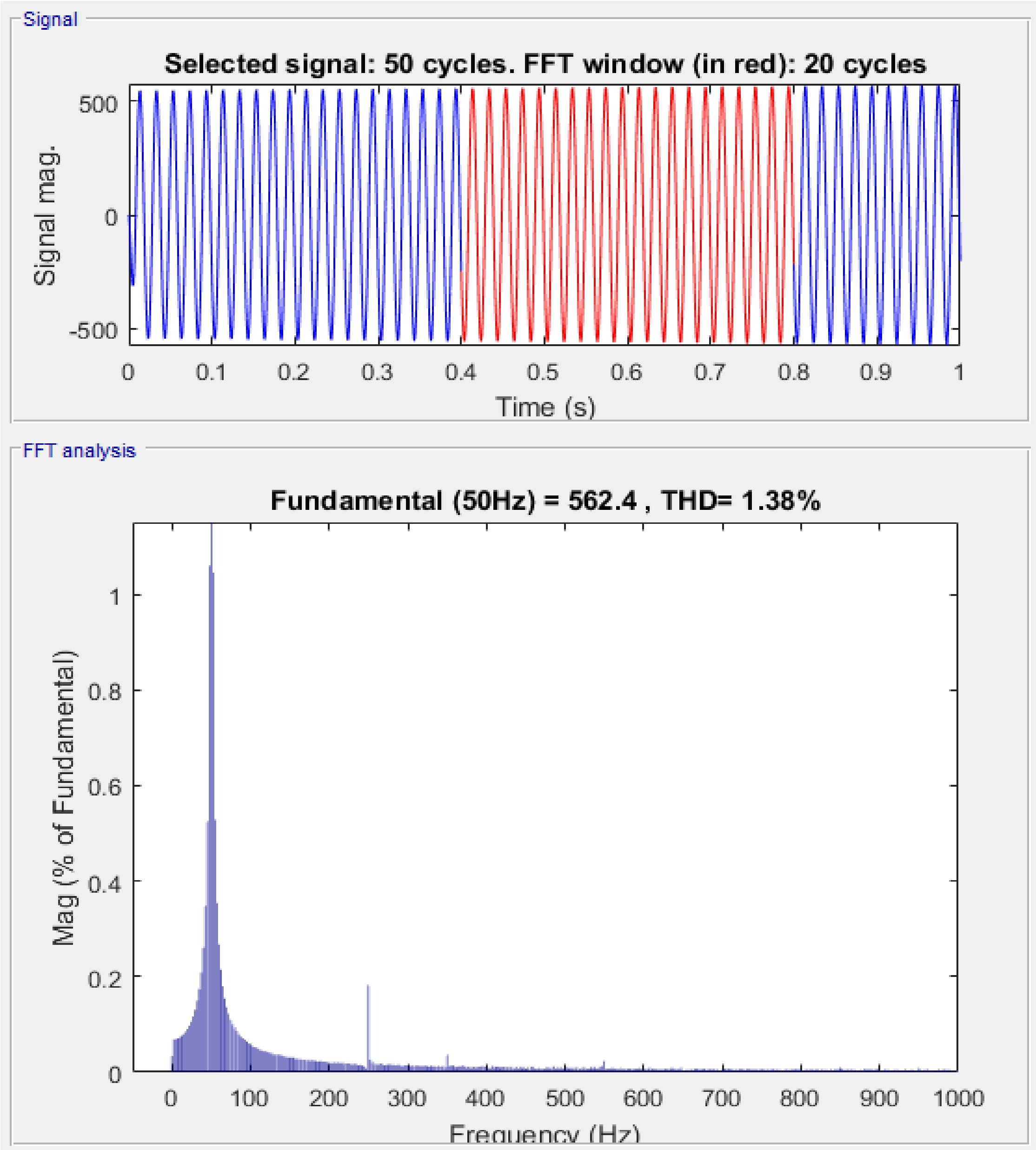

Figure 20. Load voltage THD during mode 3 operation.

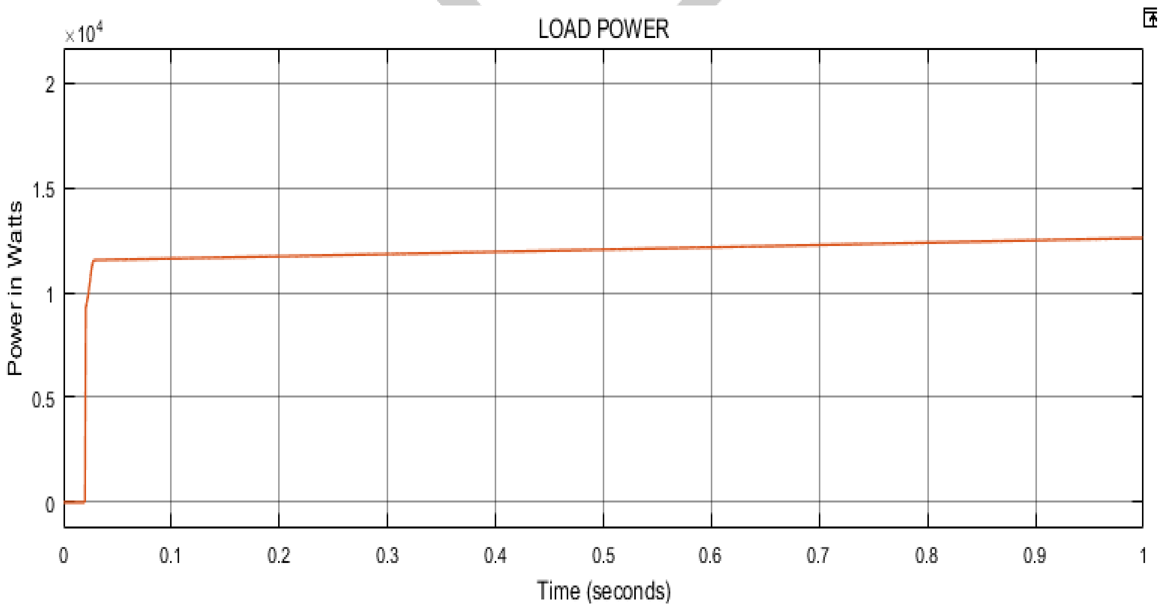

Figure 21. Load power with TSBDC during mode 3 operation

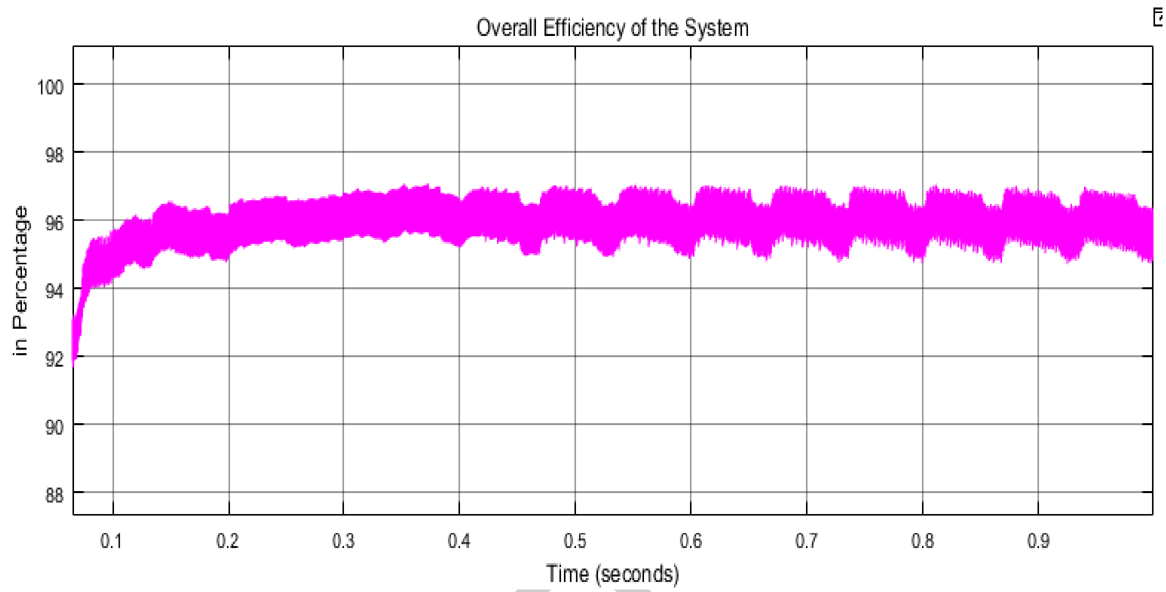

Figure 22. SPS efficiency with TSBDC during mode 3 operation

Table 5. SPS performance indicators as a function of irradiance

PV array with MPPT			Battery			BDC		Inverter		Load				Efficiency
Irradiance W/m^2	Voltage V	Current A	Voltage V	Current A	Mode of operation	Type	Voltage V	Voltage V	Current A	Line Voltage V	THD of line voltage	Current A	Three phase Load Power	
1000	700	13.9	51.44	49	Discharging	SSBDC	700	700	17.3	399.5	1.38%	17.49	12kW	99%
1000	700	14.32	51.44	48.6	Discharging	TSBDC	700	700	17.3	399	1.38%	17.51	12kW	98.50%
500	700	7.1	51.37	150	Discharging	SSBDC	700	700	17.5	400.2	1.38	17.53	12kW	98%
500	700	7.36	51.39	143	Discharging	TSBDC	700	700	17.36	399.5	1.38%	17.51	12kW	96%

PV module output power, battery output voltage, current, inverter input current load voltage, THD, load power, and efficiency of the SPS at 1000 W/m2 irradiance for SSBDC and TSBDC configuration are shown in figure 23 to figure 30 respectively and tabulated in Table 6.

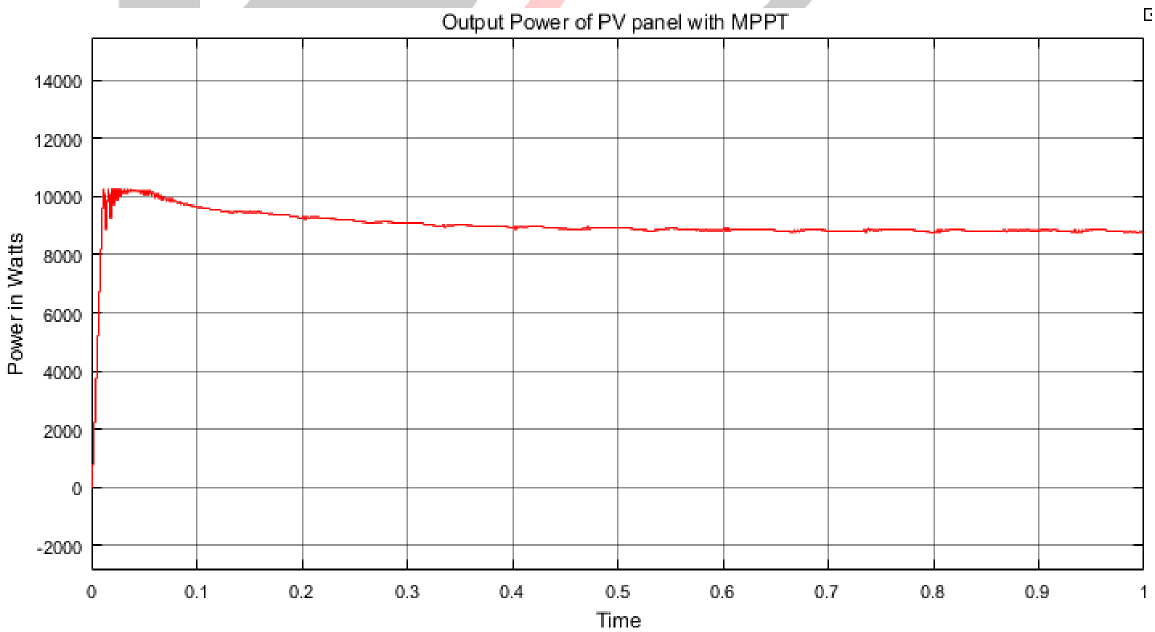

Figure 23. PV module output power for SSBDC operation

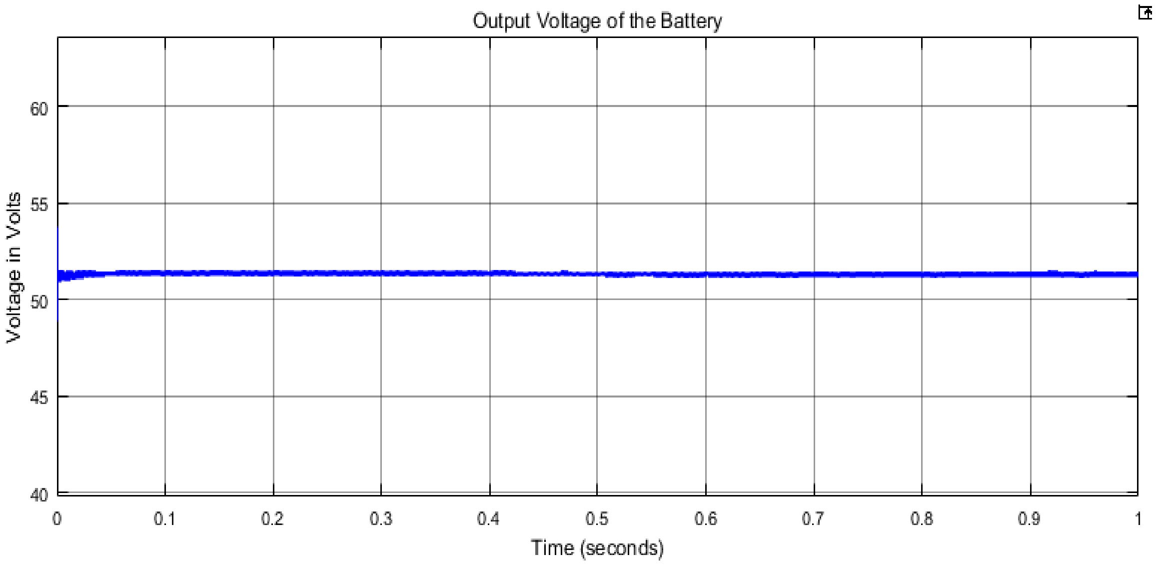

Figure 24. Battery output voltage for SSBDC operation

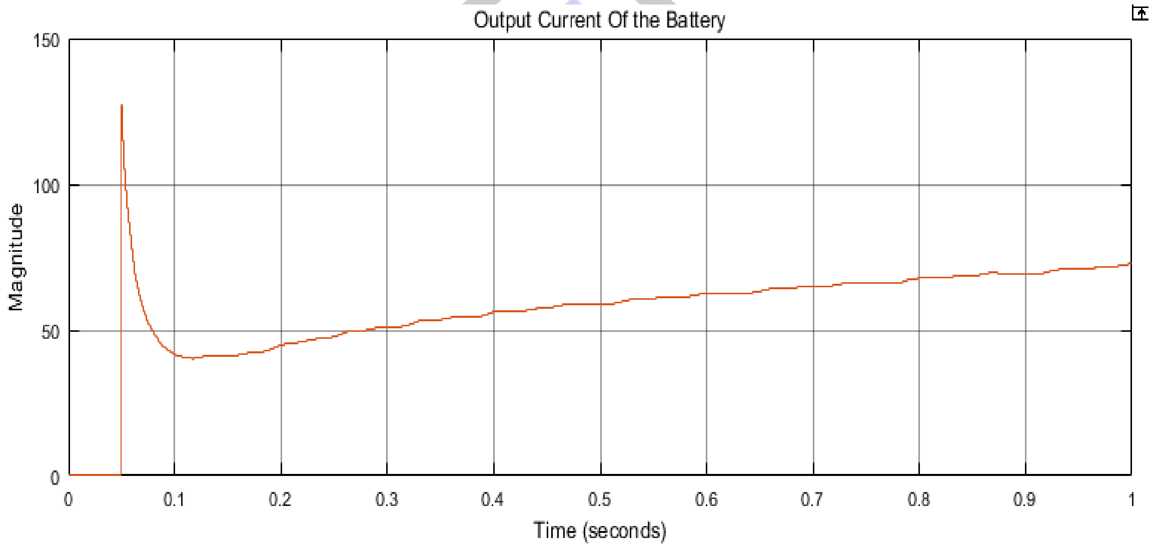

Figure 25. Battery output current for SSBDC operation

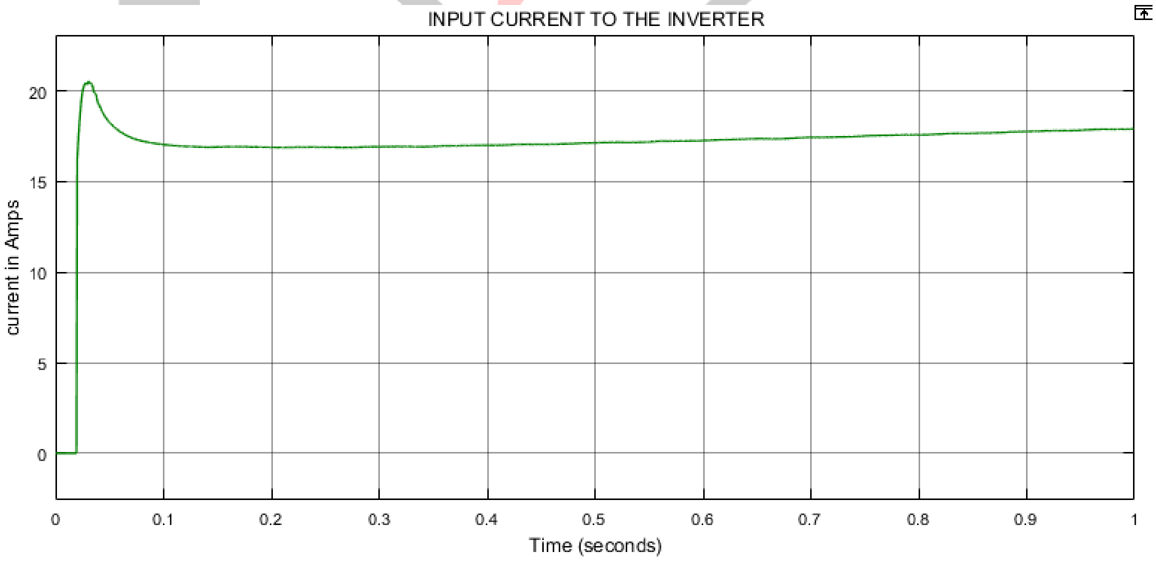

Figure 26. Inverter input current during mode 3- SSBDC operation

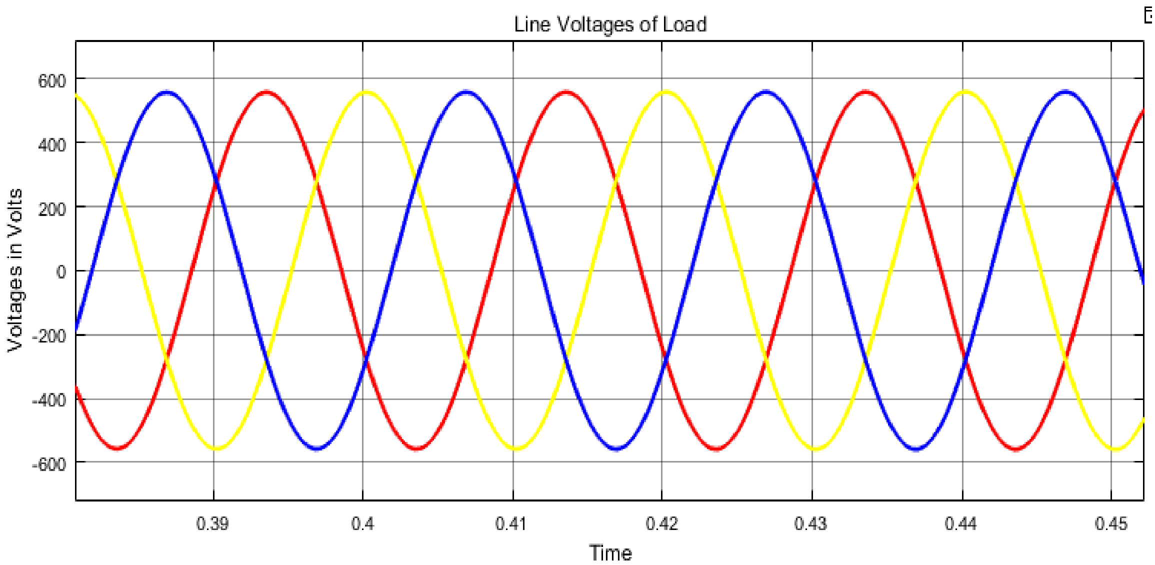

Figure 27. load voltage during mode 3- SSBDC operation

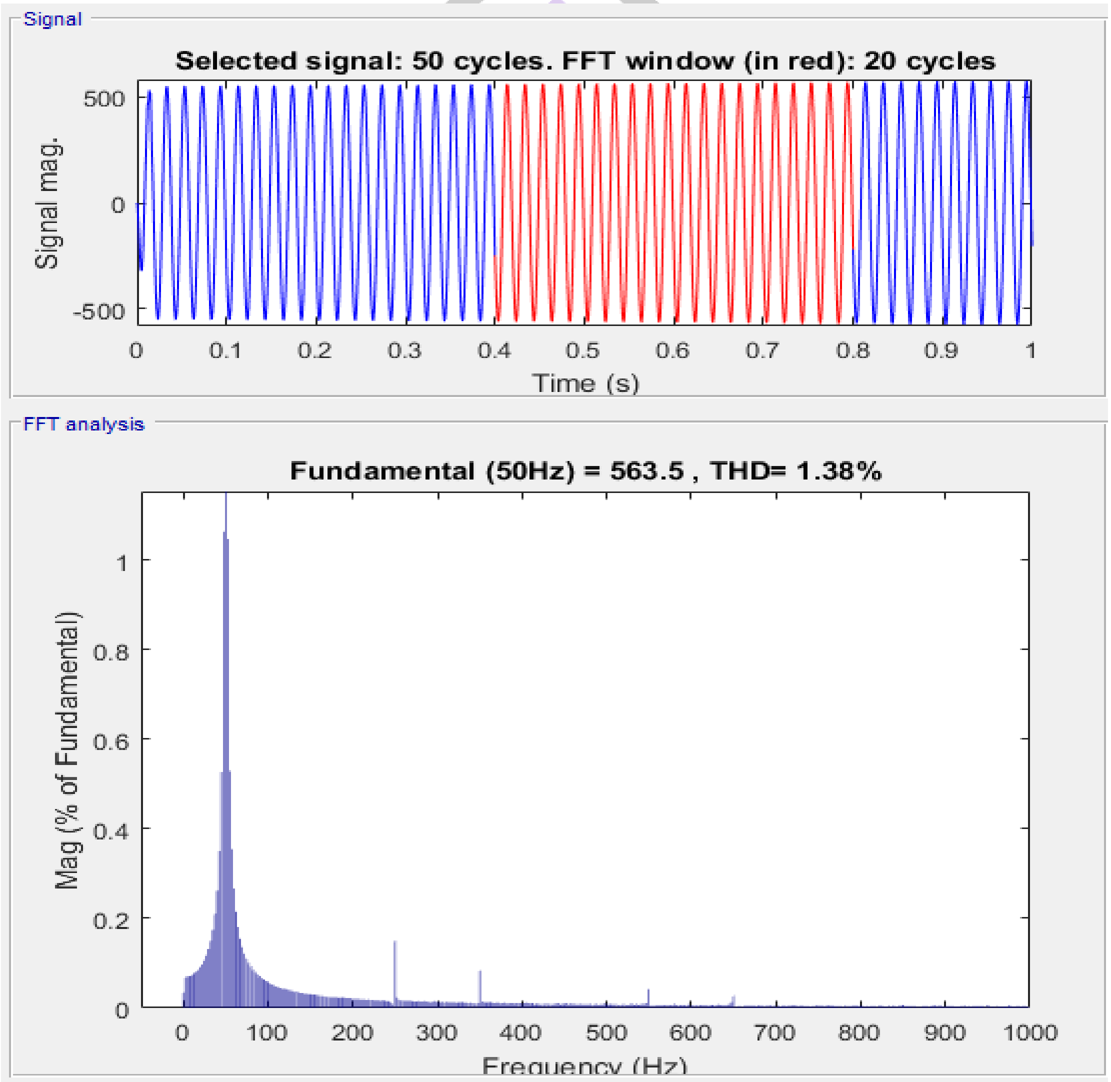

Figure 28. Load voltage THD during mode 3- SSBDC operation

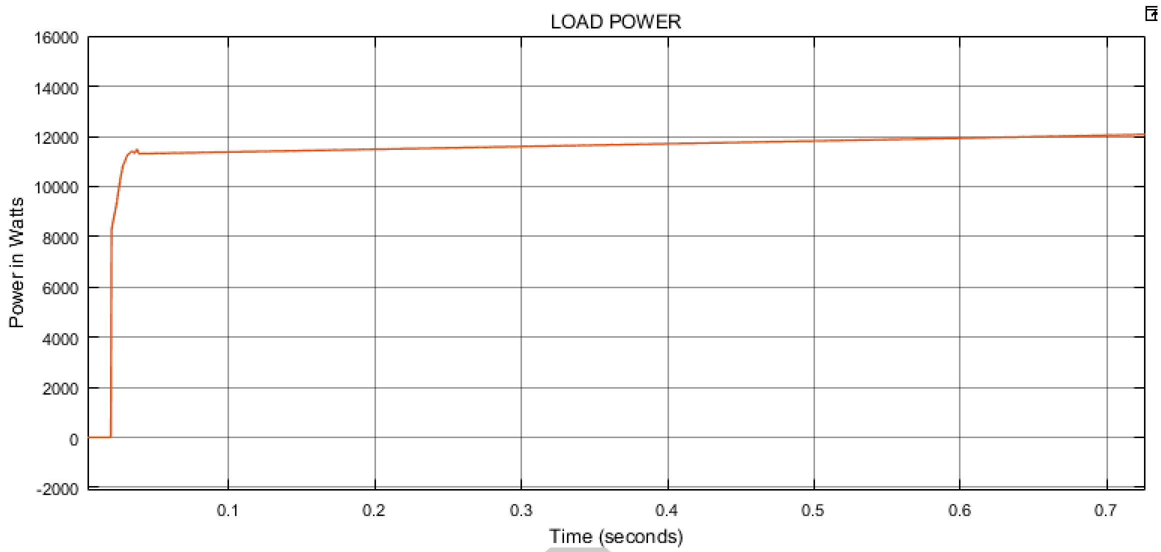

Figure 29. Load power for mode 3- SSBDC operation

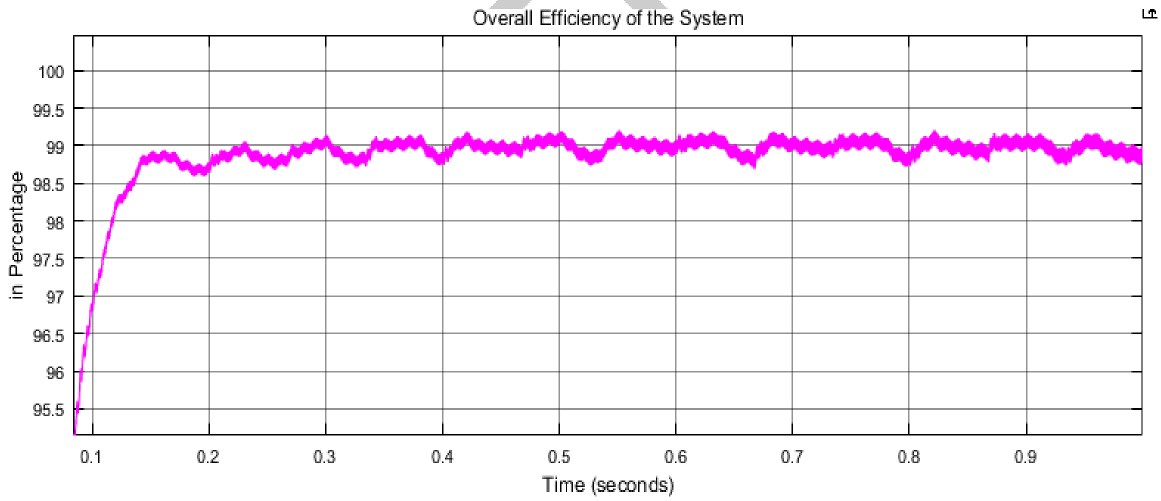

Figure 30. The overall efficiency of SPS for mode 3- SSBDC operation

Table 6. SPS performance indicators for SSBDC and TSBDC operation

	PV output Power (kW)	Battery Voltage	BDC Voltage	Inverter Voltage	Line Voltage THD	Load Power	η
SSBDC	10	51.44	700	17.30	1.38	12	99.00
TSBDC	10	51.44	700	17.30	1.38	12	98.50

The duty ratio of the BDC is another important parameter that indicates the performance of the SPS. Variation in the efficiency and THD values are examined as a function of duty ratio for each mode of operation and tabulated in Table 7.

Table 7. SPS performance indicators for SSBDC and TSBDC operation

	SSBDC				TSBDC			
	δ of BDC	Load Voltages THD (%)	Load Power (kW)	Efficiency (η) (%)	δ of BDC	Load Voltages THD (%)	Load Power (kW)	Efficiency (η) (%)
MODE 1	0.074	1.38	5	99.30	0.25	1.38	5	98.20
MODE 2	-	1.38	10	99.70	-	1.37	10	99.60
MODE 3	0.92	1.58	12	99.00	0.71	1.38	12	99.00
MODE 4	0.92	1.38	5	98.00	0.71	1.38	10	93.00

VI. CONCLUSIONS

Operation of the ESS interconnected SPS is simulated and analyzed for mode 1 to mode 4 different operating conditions, as a function of irradiance. Performance indicators for SSBDC and TSBDC states are obtained with the help of the MATLAB Simulink tool. Reduction in irradiance is reducing the efficiency of the SPS from SSBDC to TSBDC modes of operation. Also, the reduction in efficiency is negligible. When the efficiency of the system is the prime focus, TSBDC also can be opted as the reduction in the efficiency is negligible. Efficiency of the SPS, the duty ratio of the BDC is minimum for TSBDC than SSBDC at a given constant output power. This is also resulting in a reduction in THD. This reduced duty ratio increases the lifetime of the power electronic switches of the BDC. This particular feature is highly significant in the scenario of only 13 to 15 years of the payback period of the SPS. As the duty ratio decreases, thermal stress on the switches decreases, the lifetime of the converter increases, maintenance and repairs of the converter decrease, hence payback period also reduces.

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