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Analysis of Solar Energy Storage System Operating Modes with Bidirectional Buck-Boost DC-DC Converter

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Abstract : Solar energy is a suitable replacement for fossil fuels due to its superabundant availability and lesser cost. As the Photovoltaic (PV) array output is non-linear, applying the concept of Maximum Power Point Tracking (MPPT), the efficiency of the PV system can increase. Due to the faster response advantage of the perturbation and observation (P&O), MPPT algorithm implementation is selected. A bidirectional buck-boost converter operation to establish charging and discharging the battery to feed the power to load is controlled with a PI controller. Battery discharges and acts as a source, and the bidirectional converter operates as a boost converter. During the charging phase of the battery, the bidirectional converter acts as a buck converter and the battery acts as a load. Operation of the inverter with sinusoidal PWM to obtain AC power to the load is realized. Power supply to the load from the solar PV module and/or ESS corresponding to different modes of operation are simulated and analyzed. The method of analyzing the solar PV system is explained. The analysis presented is a prerequisite and will help in identifying the scope of modification of the system for future requirements.

***Index Terms* - Solar Power, Bidirectional Buck-Boost converter, Energy Storage System, MPPT.**

I. INTRODUCTION

The need for power in the world is increasing day by day. The majority of the power generated is from fossil fuel- coal, which pollutes the air and leading to global warming. To overcome these effects, it is possible to integrate renewable energy resources in remote locations, where wind or water, or sunlight resources are available[1]-[3]. Among wind, water, and sunlight, the integration of solar power into the grid has experienced extraordinary progress due to the weather conditions and availability of solar energy. Solar PV panels generate electric power, to feed the load and also charge the battery. Whenever solar power is not available then the energy stored in the batteries will cater to the load. The Solar PV panel is designed to generate the DC power of 10kW at the maximum PowerPoint. The Solar PV panel voltage is enhanced by implementing the Maximum Power Point Tracking (MPPT) technique[4][5] which is perturbed and observe method coupled with a boost converter tending to get a DC output voltage of 700V. Based on the magnitude of available solar power and load demand, solar PV system operates in various modes and are elaborated in section V. A three-phase inverter [6][7] is employed to convert DC voltage into three-phase AC voltage to feed the AC load. A bidirectional buck-boost converter serves the purpose of charging and discharging modes of the battery as per the requirement during the different modes of operation. The complete PV panel, MPPT boost converter, Bidirectional DC-DC Converter, three-phase inverter integration is solar power system and the schematic is shown in figure 1. Bidirectional DC-DC converter and battery jointly form a solar energy storage system (ESS).

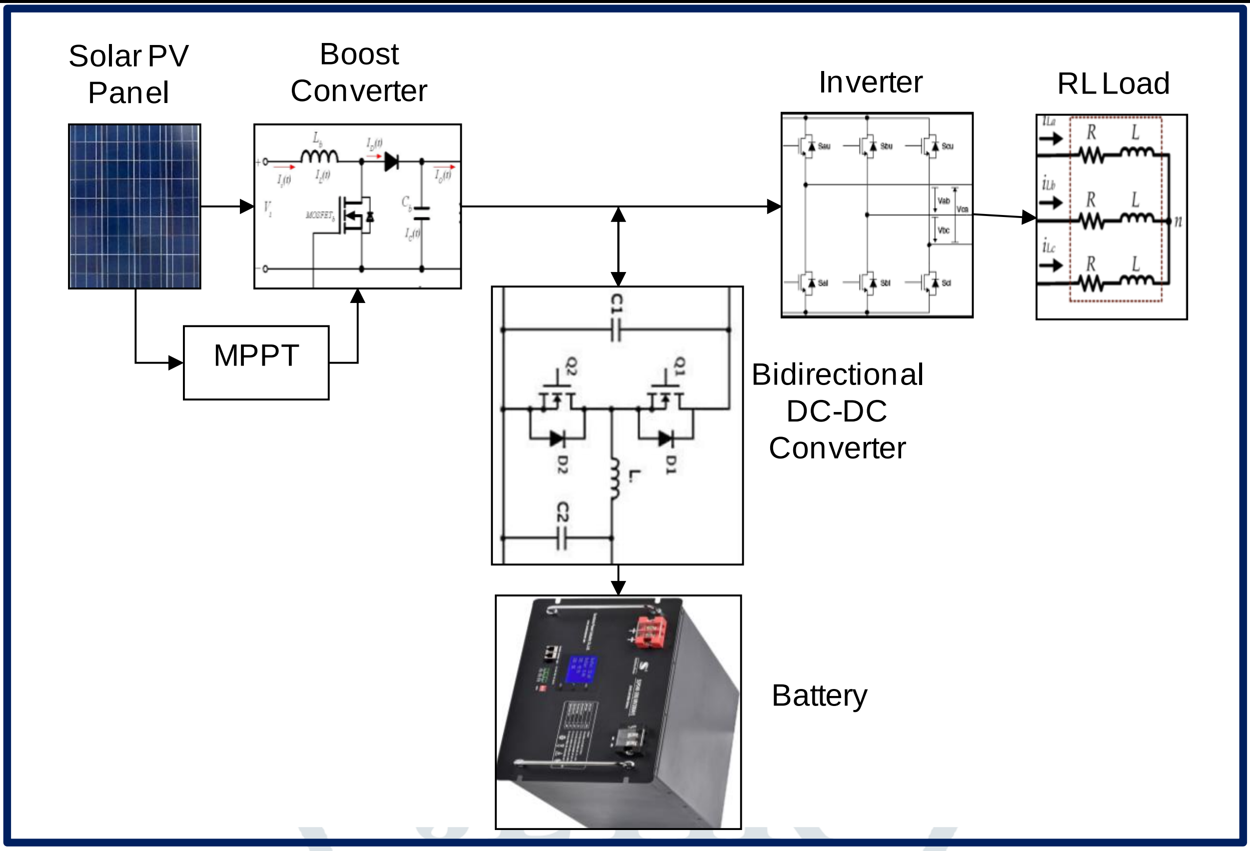

Figure 1. Block Diagram of Solar PV System with Energy Storage System

II. SOLAR PV ARRAY OPERATION WITH MPPT

Solar PhotoVoltaic (PV) has emerged in recent years as a cost-effective, low-emission technology that is changing the scenario of providing power to load all over the world. PV is a versatile and elegant electricity generation technology with the advantages of green energy generation, no rotating machines and related losses, and no sound pollution. PV is modular and can be scaled to meet load requirements ranging from a few watts to utility-scale generation comprising hundreds of megawatts.

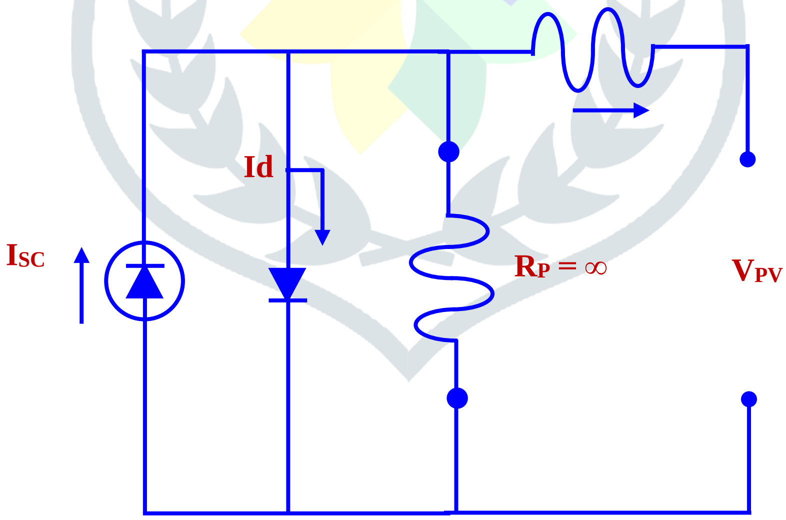

Figure 2. Equivalent Circuit of a Solar Cell

The equivalent circuit of the solar cell is a current source connected in parallel with a diode as shown in Figure 2. The output current is proportional to the solar irradiation falling on the cell. During the night, the solar cell works as a diode in the reverse mode. If light falls on the solar cell, it generates a diode current. The I-V characteristics of the cell are determined by the properties of the diode. The series resistance R_s represents the resistance inside each cell, R_p is very large shunt resistance, so that current through the R_p is negligible. I_{sc} is photocurrent, I_d is diode current, and the net voltage and current of PV cell are represented as V_{PV} and I_{PV} respectively.

The net PV cell current I_{PV} is expressed as $I_{PV} = I_{SC} - I_0\left(e^{\frac{q(V_{PV}+I_{PV}R_S)}{\eta kT}} - 1\right)$

Where

I_0= Reverse saturation current (Amps)
η= Diode factor =1 for ideal diode

q=Elementary Charge (Columbs) = $1.602176634\times10^{-19}$ C
k= Boltzmann's constant (1.380649×10^{-23} JK^{-1})
T= Absolute temperature (K)

Maximum power point tracking (MPPT) plays an important role in renewable energy sources integration. With the changes in solar irradiance level, ambient temperature, and load, the solar energy is intermittent, so the output of the PV array is nonlinear. For continuously determining the efficient PV output, the operating point of the PV array is adjusted around the maximum PowerPoint. This process is called Maximum Powerpoint Tracking. Perturb and observe (P&O) method is modeled for the determination of the efficient operating point of the PV array. This technique could be easily structured. To track the maximum power point, the perturbance step has to be larger, but it will have more fluctuations. The flowchart of perturb and observation technique is shown in figure 3. The reference voltage from the MPPT is compared with the PV output voltage and fed to the PI controller. The signal generated by the PI controller is compared with a carrier wave of 15kHz and generates a pulse signal. This pulse signal is used as a gating signal for the switch in the boost converter. This boost converter boosts the PV output voltage to the required voltage.

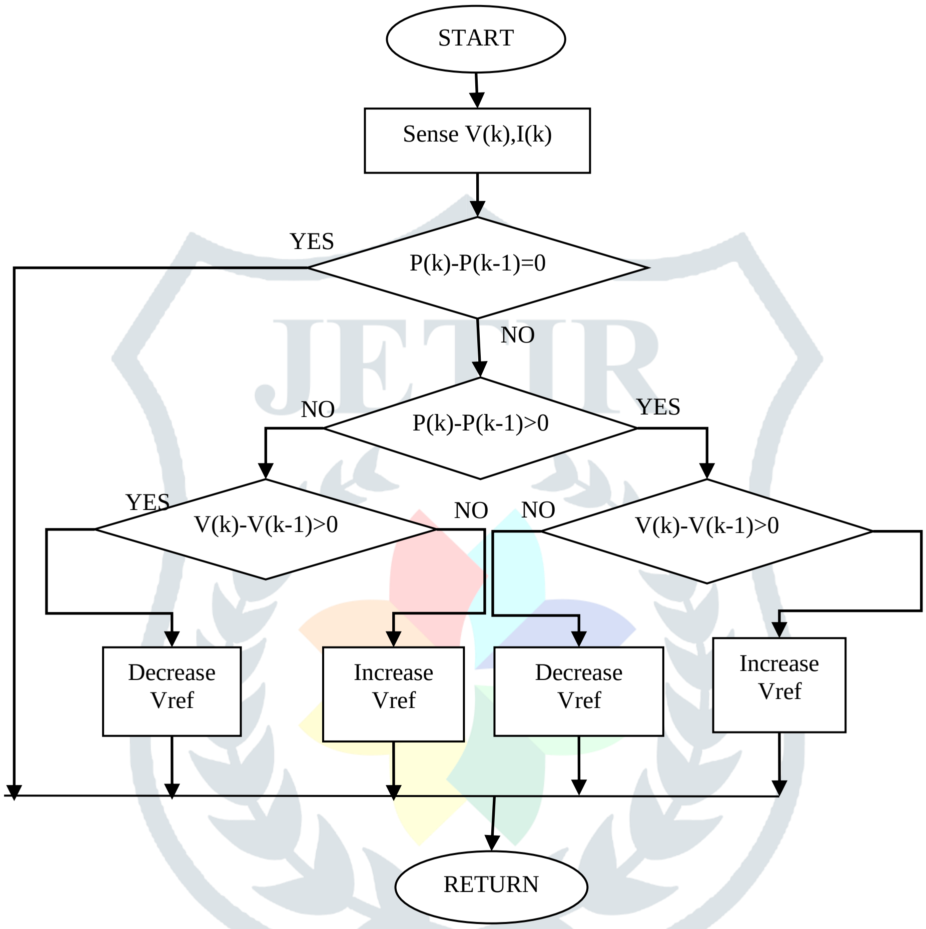

Figure 3. Flow Chart of Perturb & Observe technique for MPPT

III. Bidirectional Dc-Dc Converter And Battery

Bidirectional dc to dc converter is a significant power electronic device for interfacing the ESS, PV module, and load to ensure uninterrupted power to the load [8]-[10]. Due to irradiation variation output power of PV module changes. Under such conditions, bidirectional power flow is required to obtain the uninterrupted power supply to the load. Bidirectional dc to dc converter controls the flow of power in both directions between two dc sources PV module and ESS. The circuit configuration of the bidirectional dc to dc converter is shown in figure 4. The switching scheme for the buck-boost bidirectional converter is decided based on the solar power generated, load demand, and charge in the battery.

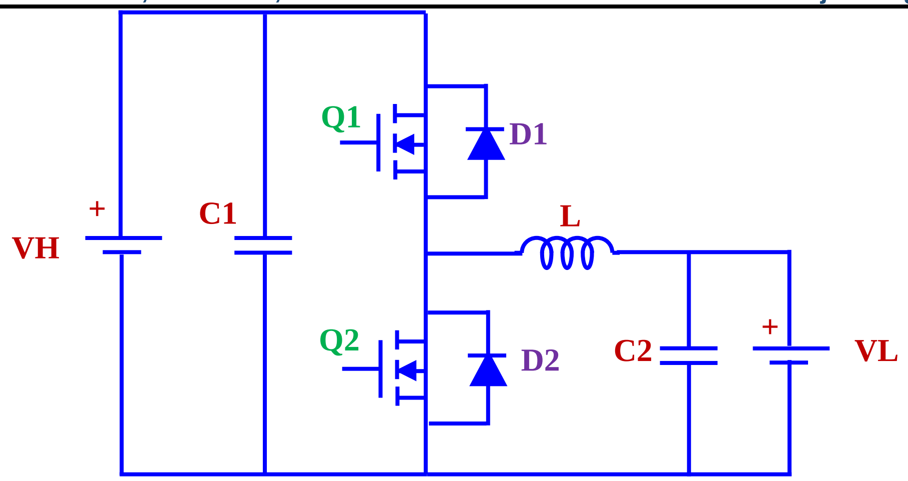

Figure 4. Bidirectional Buck-Boost DC-DC Converter

A battery consists of two electrodes and an electrolyte in which the two electrodes are immersed. Batteries are a form of electrochemical storage that releases energy via an oxidation-reduction reaction involving the transfer of electrons between electrodes. These electrodes are separated in an electrolyte matrix, and then they absorb or release electrons. When connected to the load, this reaction establishes current flow power. Batteries in which, the electrochemical reaction can be reversed by the application of an external electric supply are secondary or rechargeable batteries.

IV. SOLAR PV SYSTEM WITH ENERGY STORAGE SYSTEM

Based on the power generated by the PV module, charge in the battery, and load demand, a solar power system with ESS will operate in four different modes. Simultaneous power supply to the load and charging of the battery from solar PV module is mode 1. The power supply to the load directly from the solar PV module is mode 2. Supplying the load from the solar PV module and ESS is a mode 3 operation. In the absence of solar power meeting, the load from ESS is mode 4 operation. To analyze the different modes of operations, the solar PV module with ESS is simulated in MATLAB Simulink [11] as shown in figure 5. Specifications of PV module and ESS are tabulated in Table 1 and Table 2 respectively.

Table 1: Specifications of Solar PV Panel

Module	**1Soltech 1STH-215-P**
Maximum Power per Cell	213.15 W
Open Circuit Voltage (V_{oc})	36.30V
Short Circuit Current (I_{sc})	7.84 A
Voltage at MPP (V_{mp})	29.00 V
Current at MPP (I_{mp})	7.35 A
Temperature Coefficient of (I_{sc})	0.102
No. of Parallel cells	4
No. of Series cells	12
Total Power (P_o)	10.00 kW

Table 2: Specifications of Battery

Battery Type	**Lithium Ion**
Nominal Voltage (V)	48
Rated Capacity (Ah)	1200
Initial State of Charge	40%
Battery response time (S)	0.1
Cut-off Voltage (V)	55.87

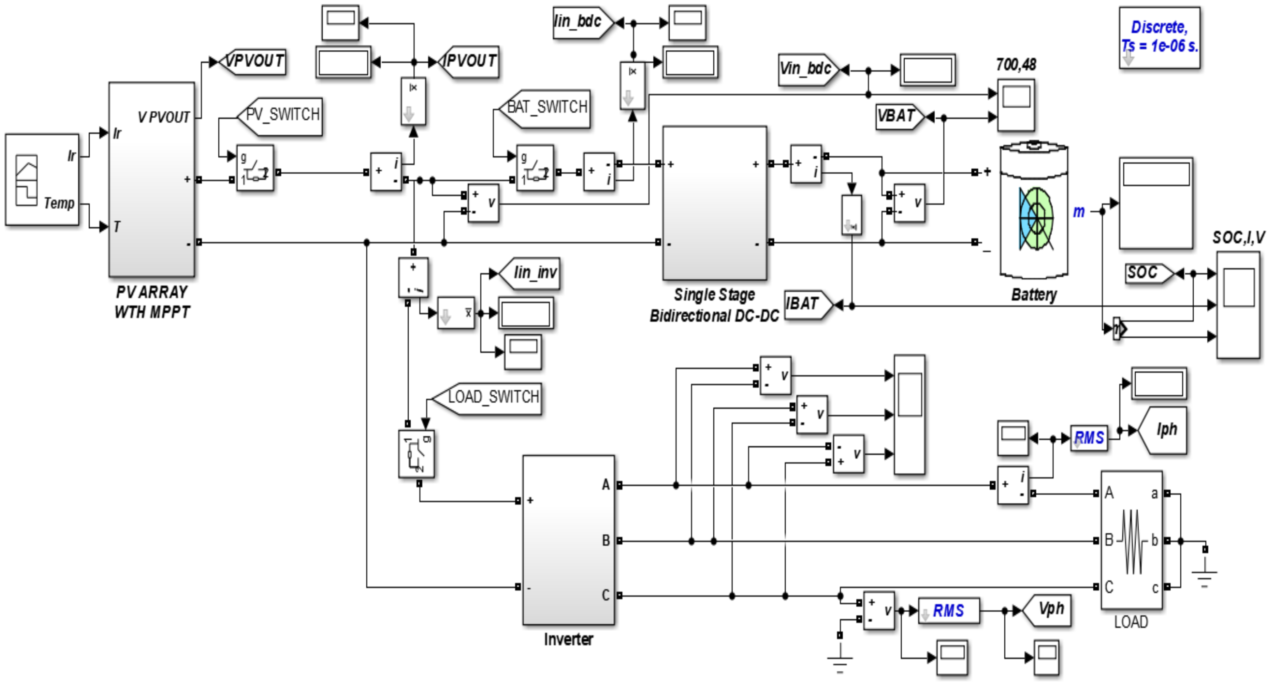

Figure 5. MATLAB Simulation Diagram of Solar Energy Storage System

V. DIFFERENT MODES OF OPERATION AND RESULTS

MODE 1: Solar Power supply to Load and Battery

During the mode 1 operation, solar power is more than the load demand. After supplying the load, excess power will charge the battery. The 32 Ω resistive load demand is 5 kW, catered by 10 kW PV module power. The remaining power will charge the ESS via a bidirectional DC-DC converter.

The output voltage from the solar PV module with MPPT gradually settled to 700 V as shown in figure 6. The power generated by the PV module is supplied to the battery after catering to the load via a bidirectional DC-DC converter. The input current to the bidirectional converter reaches 7.04 A as shown in figure 7. The state of charge of the battery is increasing as shown in figure 8 represents that the battery is charging. Current to the battery reaches 95.17 A and the voltage of the battery is 51.8 V. The remaining 7.26 A current from the PV module is supplied to the load via inverter indicated in figure 9. The three-phase inverter output is given to the three-phase resistive load of 32 Ω in each phase. The waveform and THD analysis of load line voltage is shown in figure 10 and 11 respectively. The RMS line voltage of the load is 403.2 V and THD is 1.38%. The power consumed by the load is shown in figure 12 which reaches 5 kW.

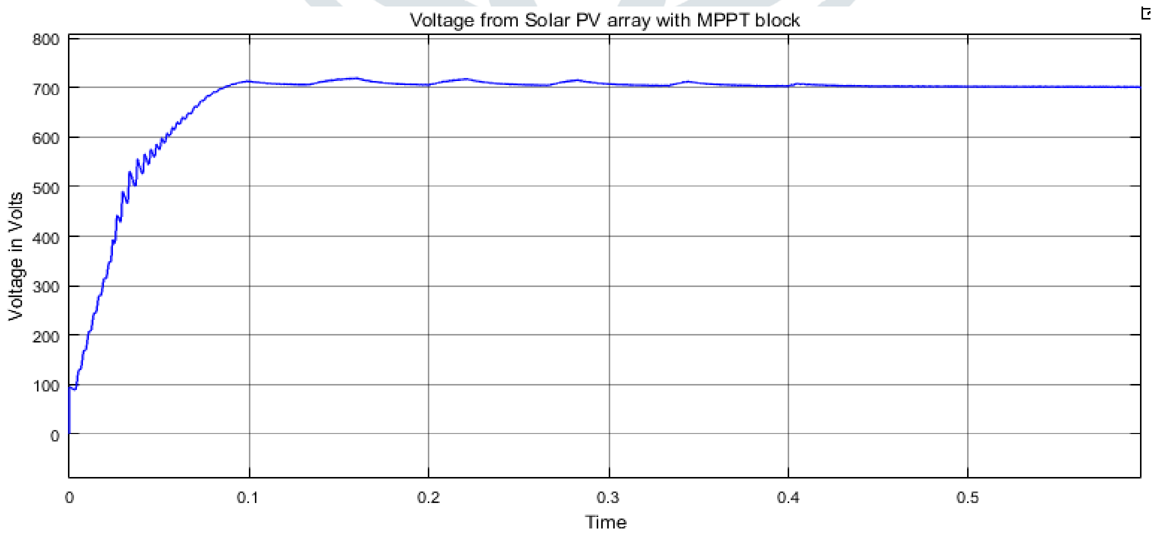

Figure 6. Output Voltage of solar PV module with MPPT Block for mode 1 operation

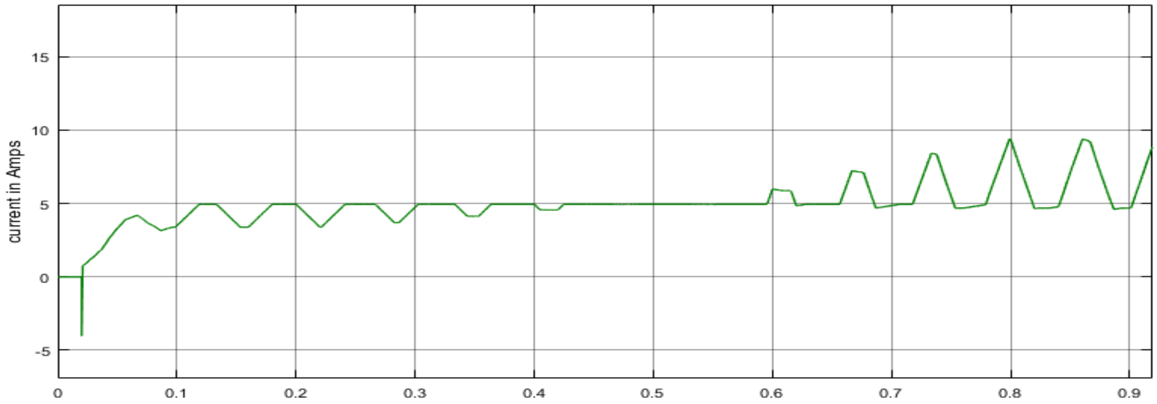

Figure 7. Input Current of Bidirectional Buck-Boost DC-DC Converter

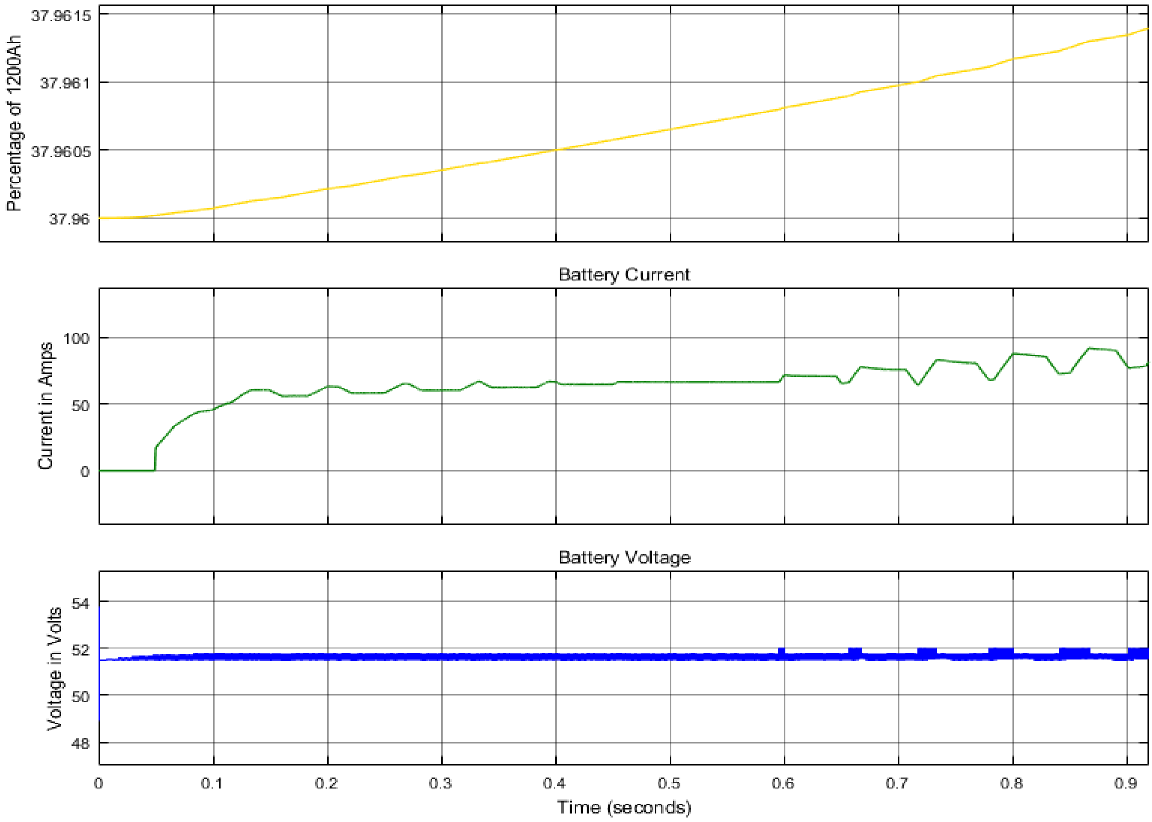

Figure 8. State of Charge, Current and Voltage of the Battery

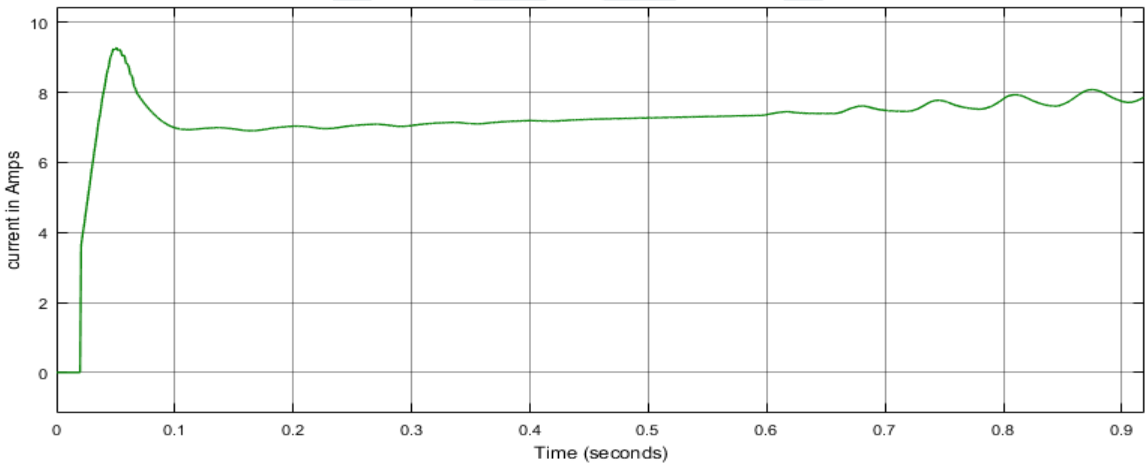

Figure 9. Input Current for inverter

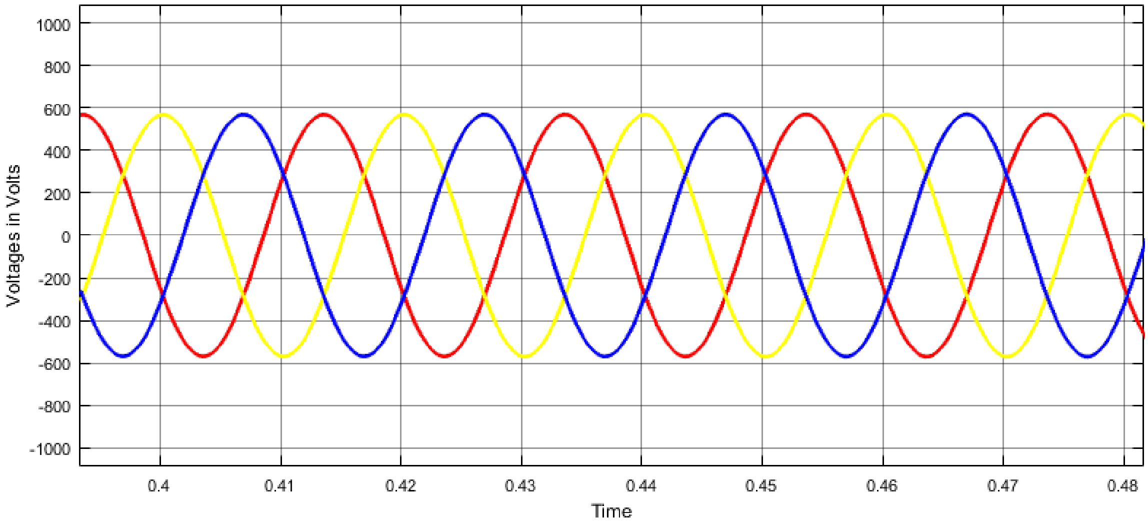

Figure 10. Three Phase Line Voltages of Load

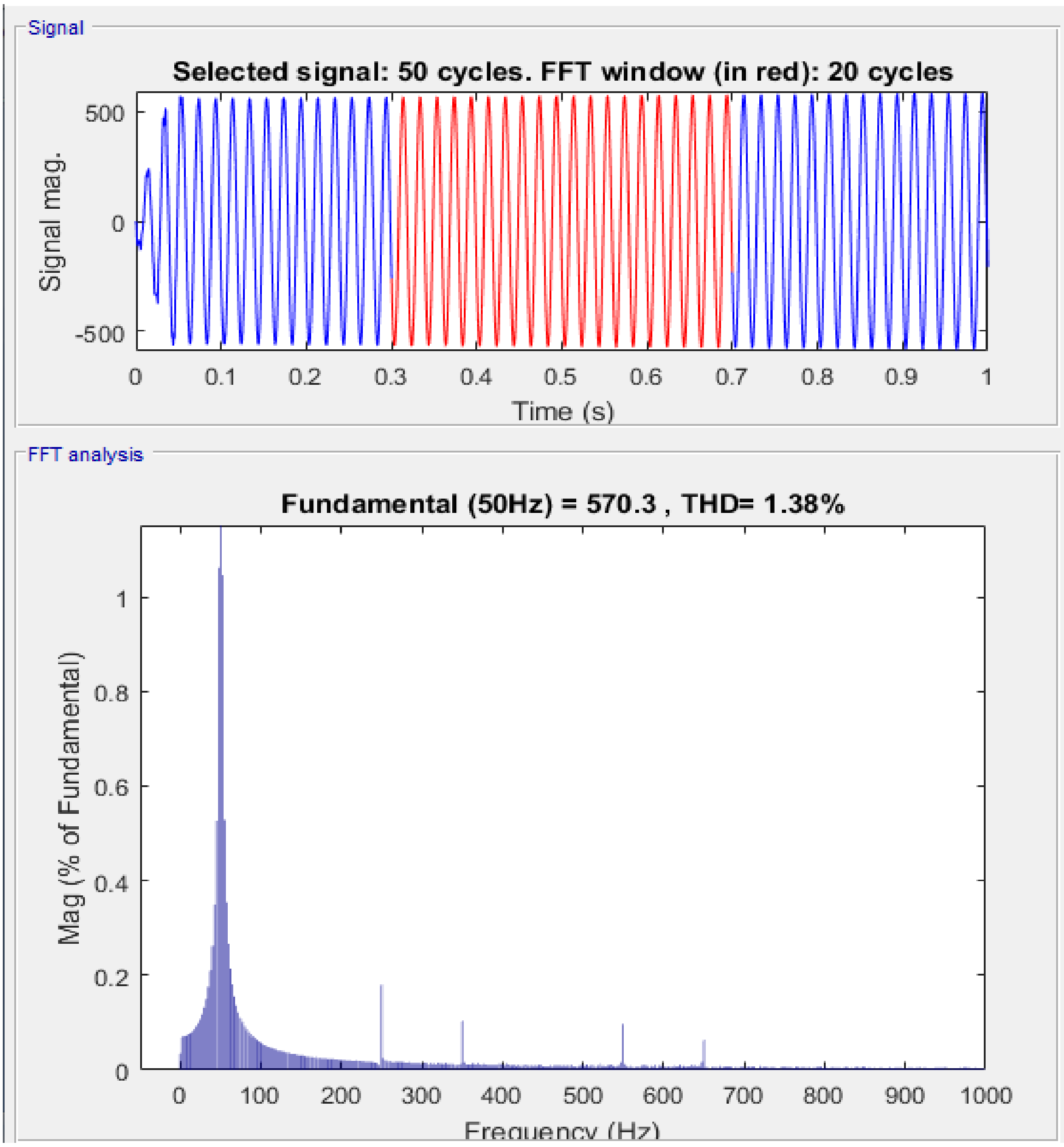

Figure 11. Line voltage THD of load with harmonic percentage for mode 1 operation

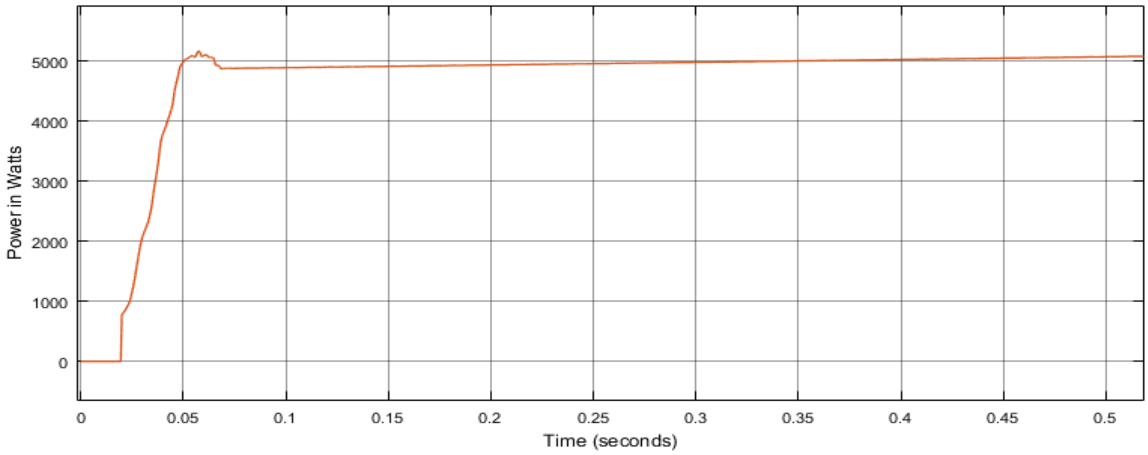

Figure 12. Load Power during mode 1 operation

MODE 2: Solar Power supply to Load

In the mode 2 operation, the generated solar power is sufficient to meet only the load demand. Hence bidirectional buck-boost DC-DC converter doesn't operate. The output voltage from the solar PV module with MPPT gradually settled to 690V as shown in figure 13. The current from the PV module reaches 15 A as shown in figure 14, is supplied to the load via an inverter. The output power of the PV module is 10 kW as shown in figure 15. The three-phase inverter output is supplied to the load. The power consumed by the load is shown in figure 16 which reaches 10 kW. The line voltage and THD analysis is shown in figure 17 and 18 respectively. The RMS line voltage of the load is 399.20 V and THD is1.38%.

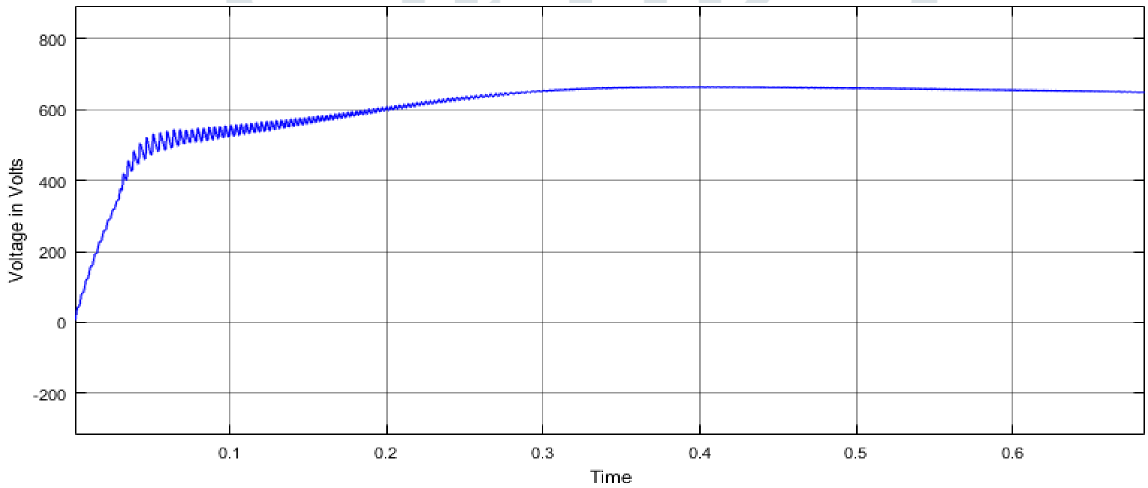

Figure 13. Output Voltage of solar PV module with MPPT Block for mode 2 operation

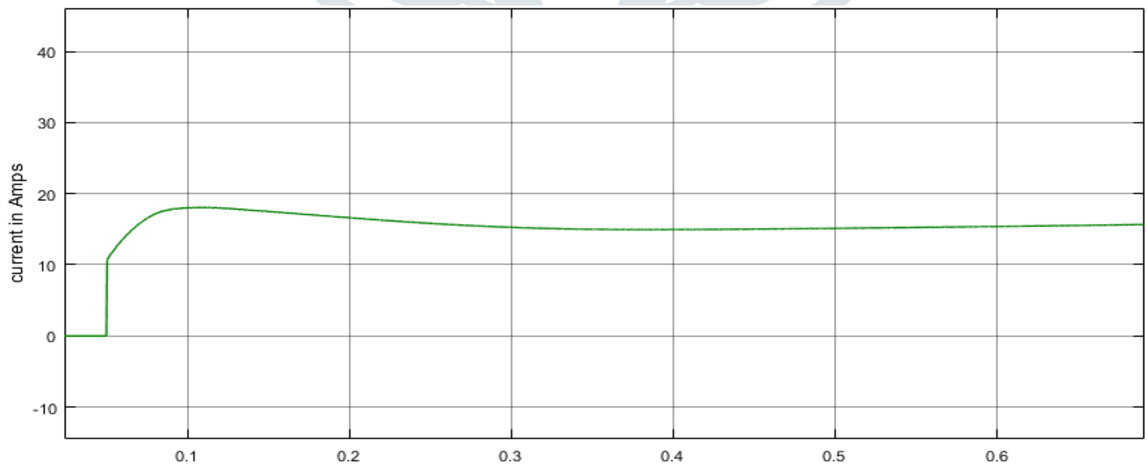

Figure 14. Output Current of the solar PV module with MPPT Block

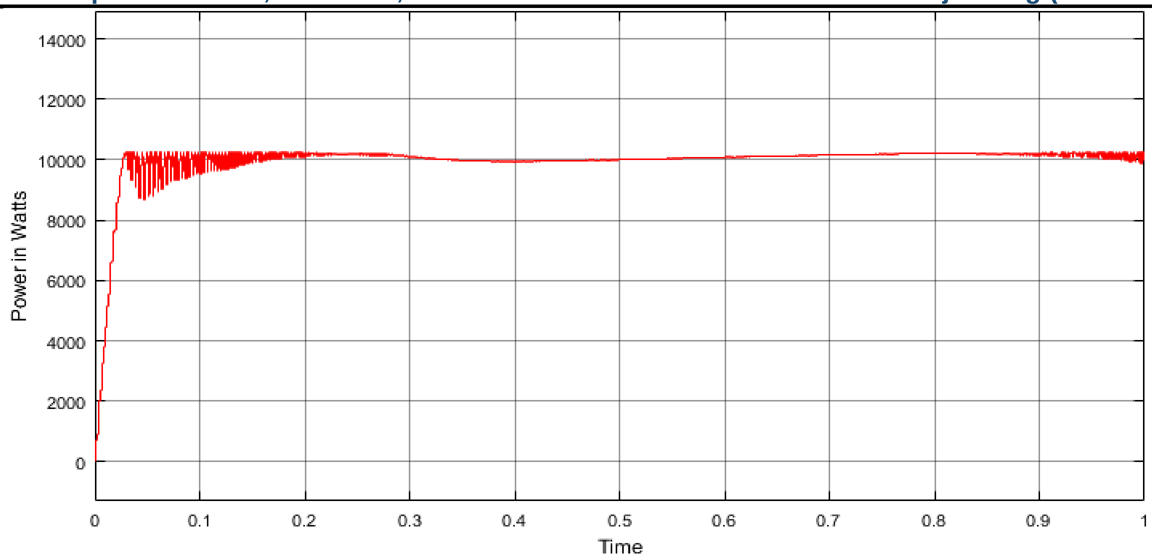

Figure 15. Output Power of solar PV module with MPPT Block

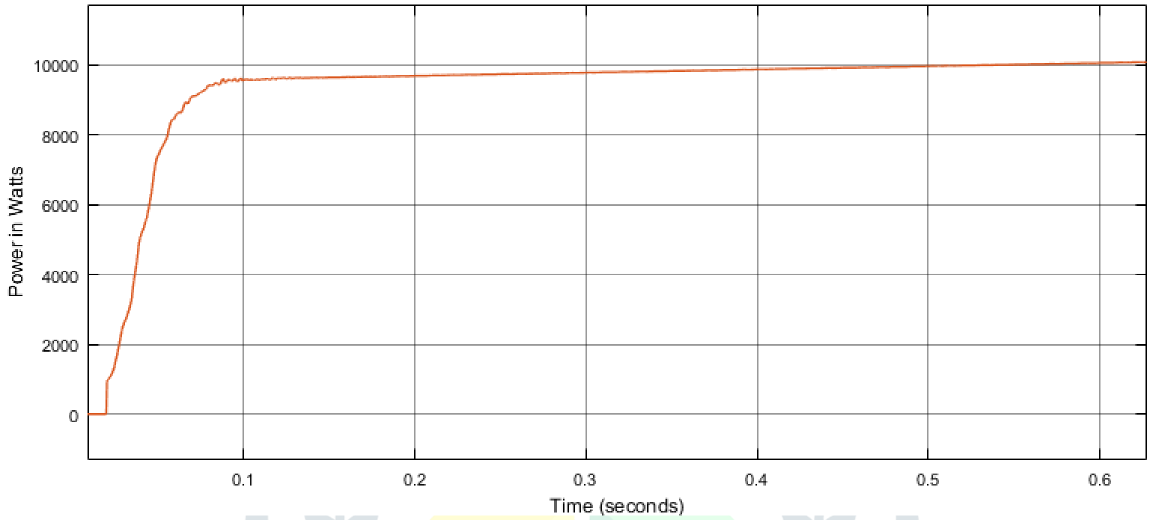

Figure 16. Output Load Power for mode 2 operation

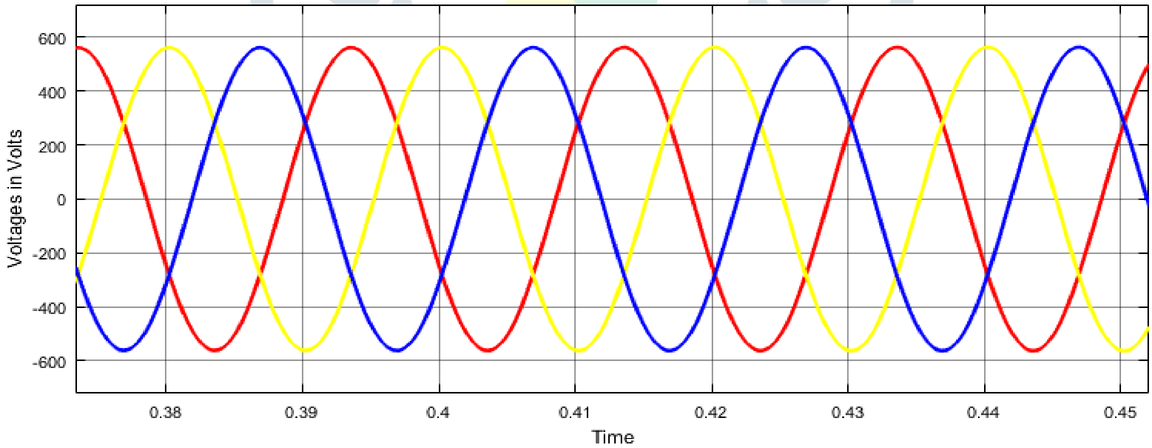

Figure 17. Three-phase line voltages of load during mode 2 operation.

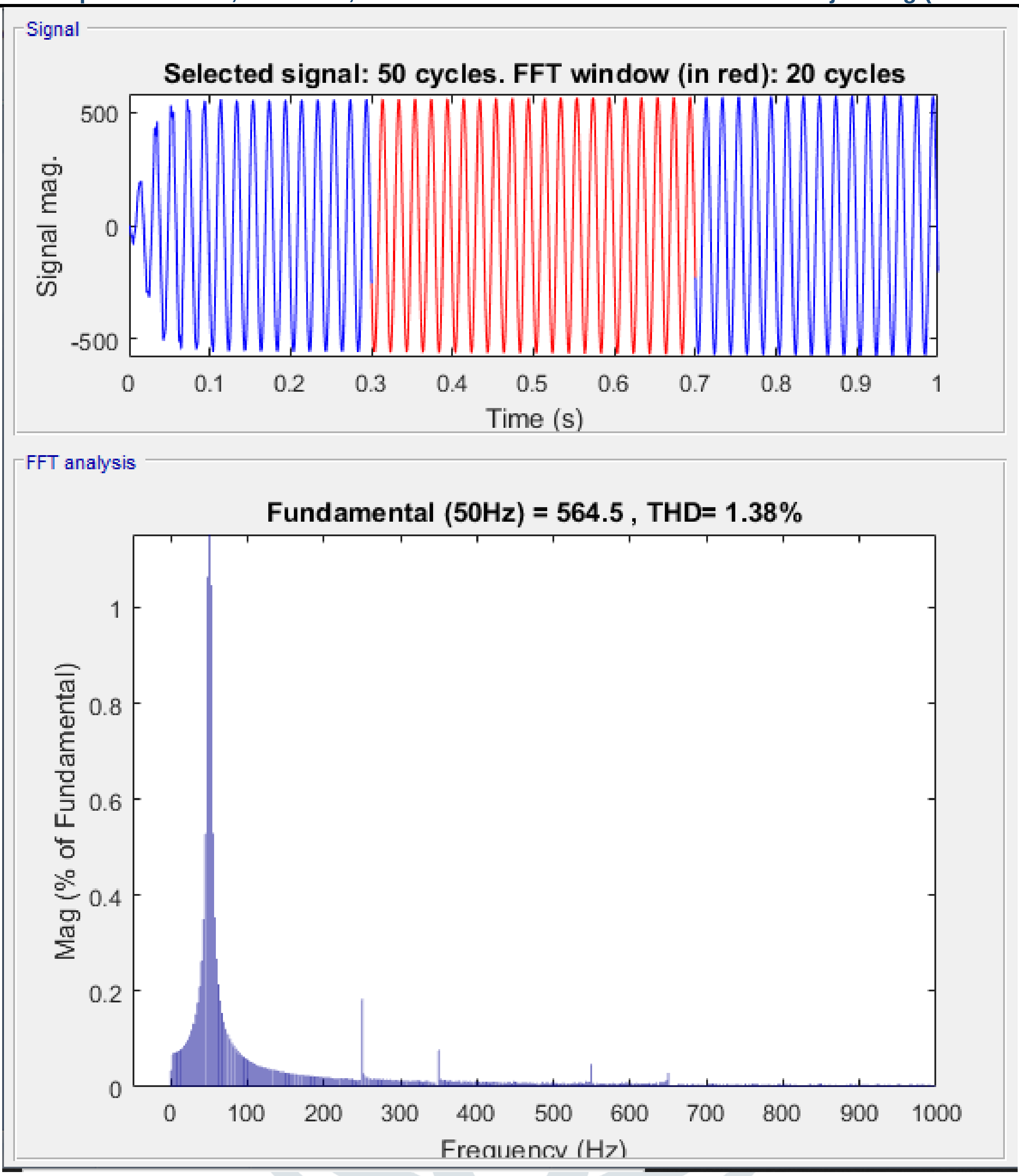

Figure 18. Line voltage THD of load with harmonic percentage for mode 2 operation

MODE 3: Solar Power and Battery Power supply to Load

MODE 3: When the load demand is greater than the solar power generated, then the load is supplied by both solar power and ESS power. During this mode of operation, the battery discharges by supplying the load.

The output power from the PV module reaches 9.70 kW as indicated in figure 19. The output voltage of the battery is constant at 51.44 V as shown in figure 20. The output current of the battery gradually increases and settles at 69.00 A as shown in figure 21. The output power of the battery is 35.50 kW as shown in figure 22. Figure 23 shows the state of charge of the battery decreases which represents that the battery is discharging. The output current of the PV panel with MPPT settles at 13.9A as shown in figure 24 and the output current of the bidirectional DC-DC converter is 5A as shown in figure 25. The input current to the inverter is the sum of current from the PV module and bidirectional DC-DC converter and is 18.9 A as shown in figure 26. The line voltage of the load and the THD analysis is shown in figure 27 and 28. The overall efficiency of the system is 99% as shown in figure 29.

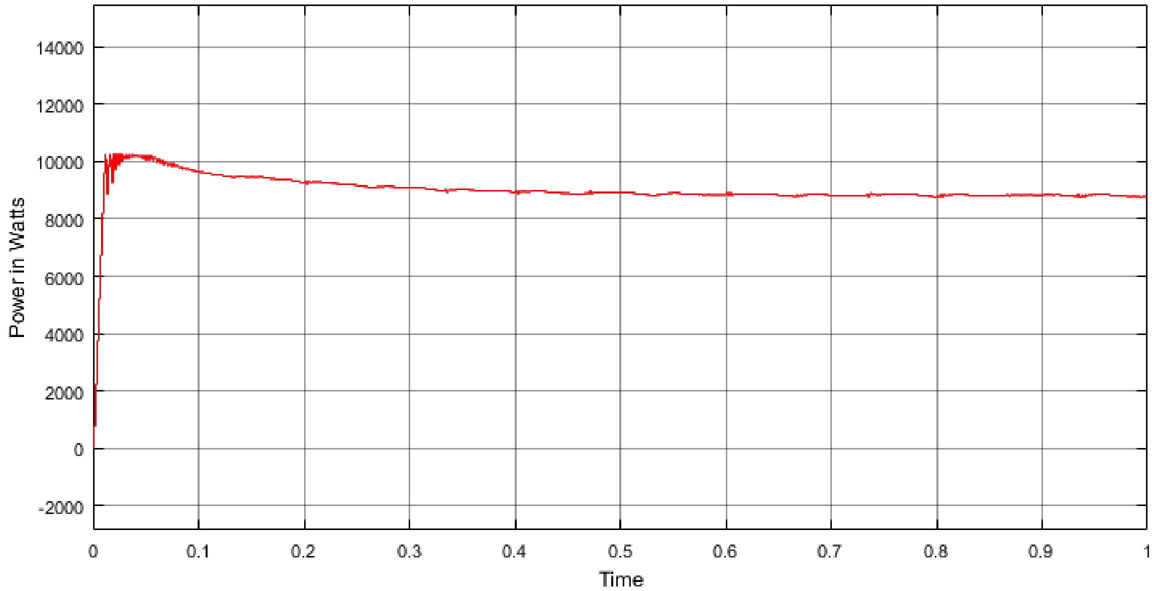

Figure 19. Output Power of solar PV module with MPPT Block for mode 3 operation

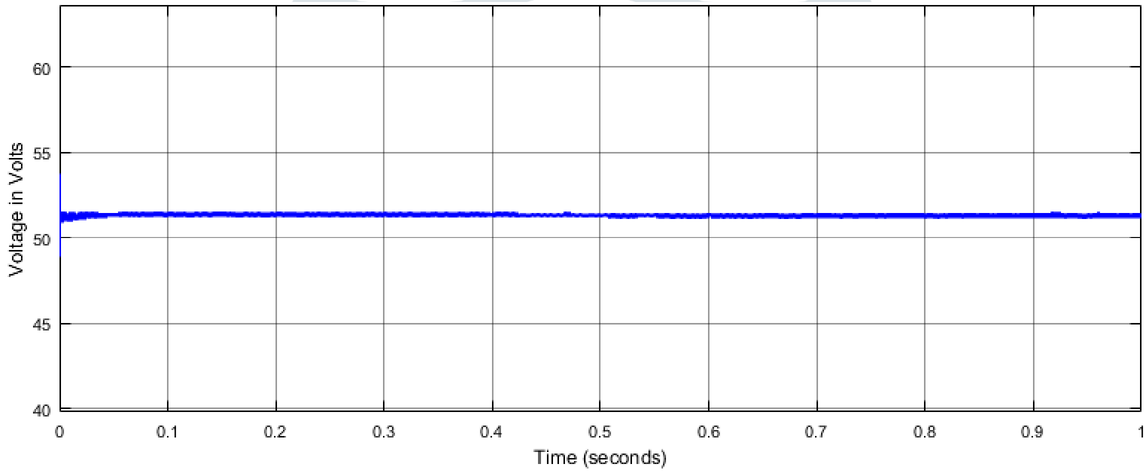

Figure 20. Output Voltage of the Battery for mode 3 operation

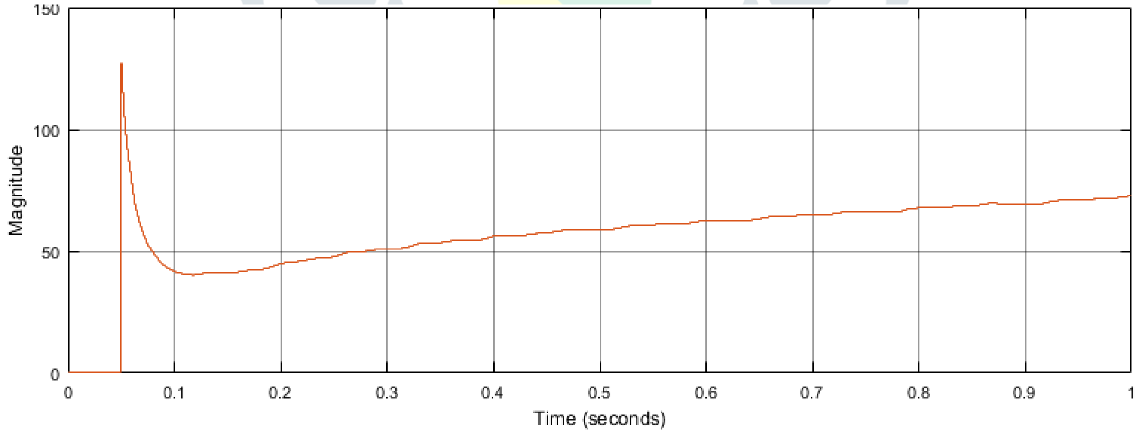

Figure 21. Output Current of the Battery for mode 3 operation

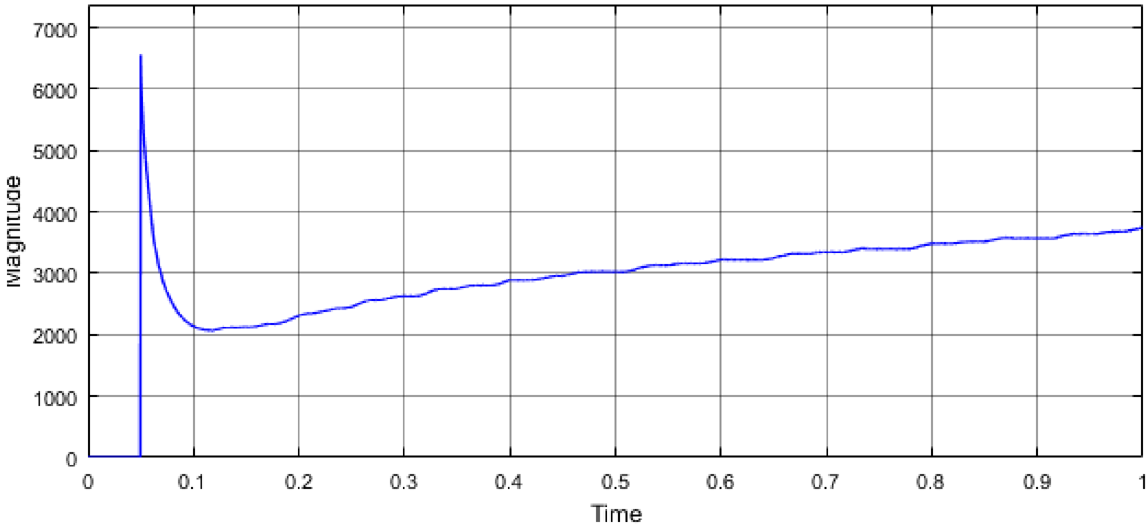

Figure 22. Output Power of the Battery for mode 3 operation

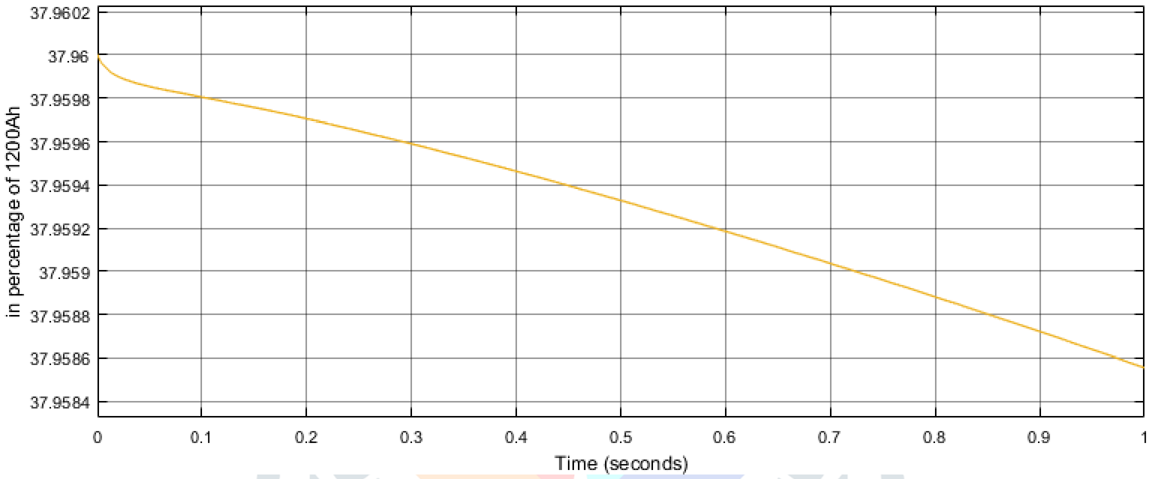

Figure 23. State of Charge of the Battery for mode 3 operation

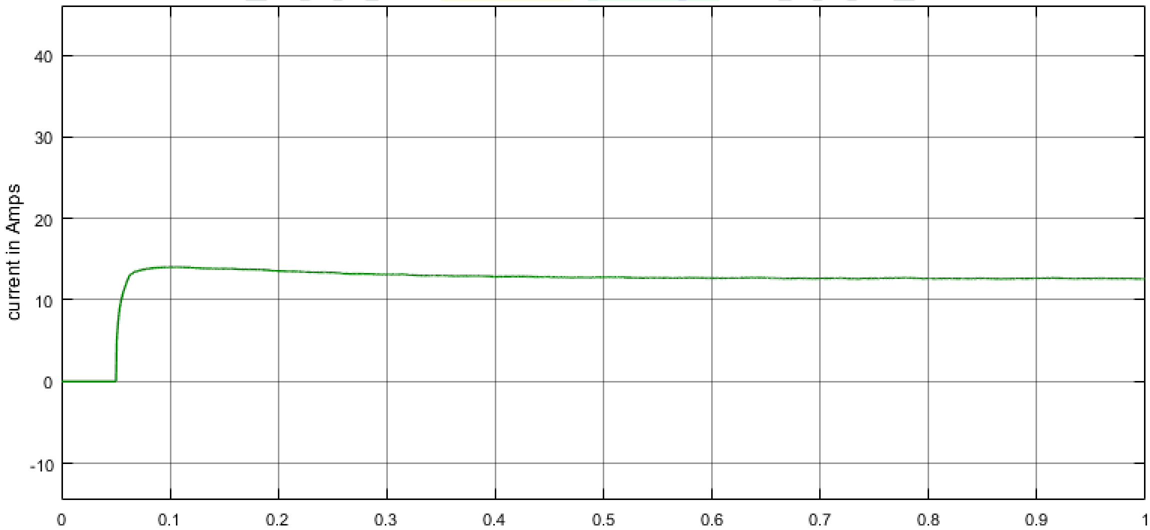

Figure 24. Output Current of solar PV array with MPPT Block for mode 3 operation

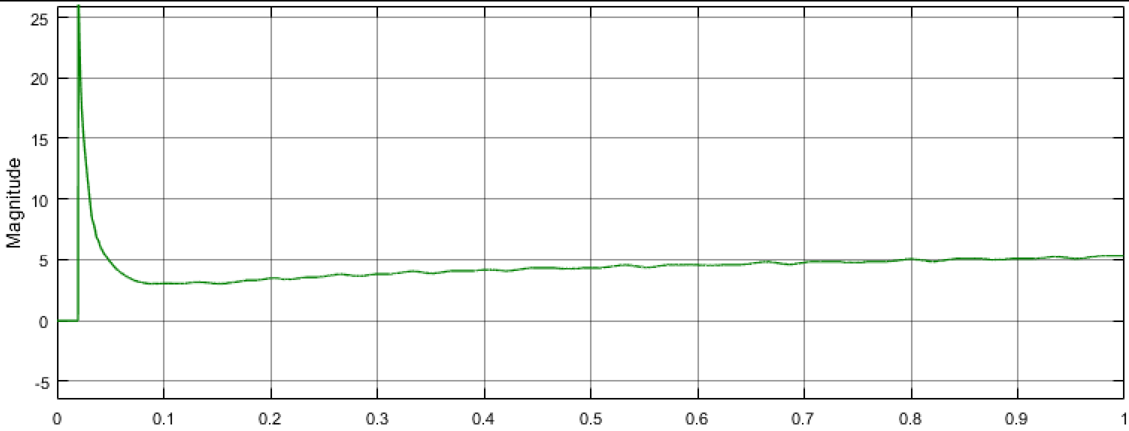

Figure 25. Output Current of the Bidirectional Converter for mode 3 operation

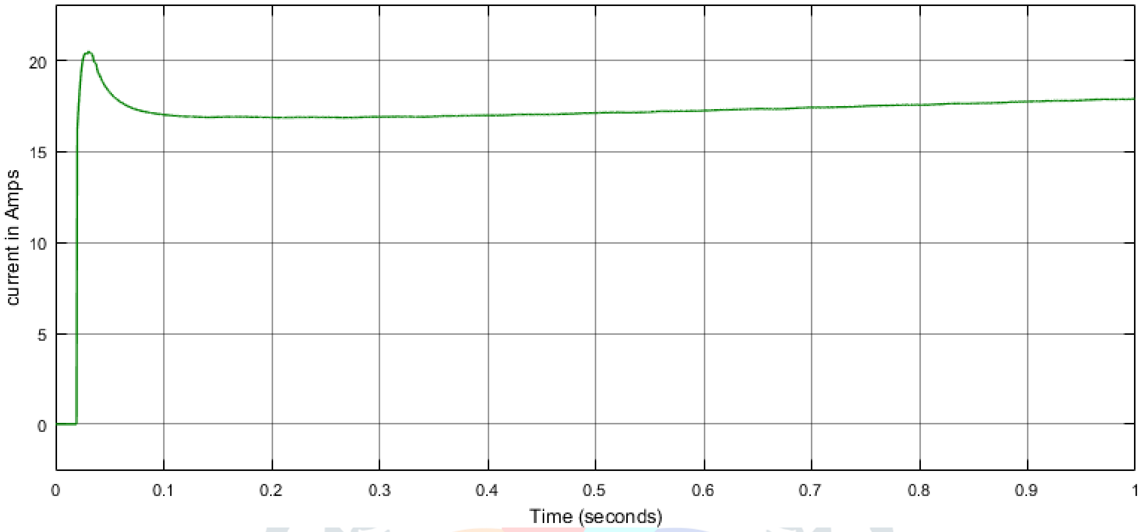

Figure 26. Input Current of the Inverter for mode 3 operation

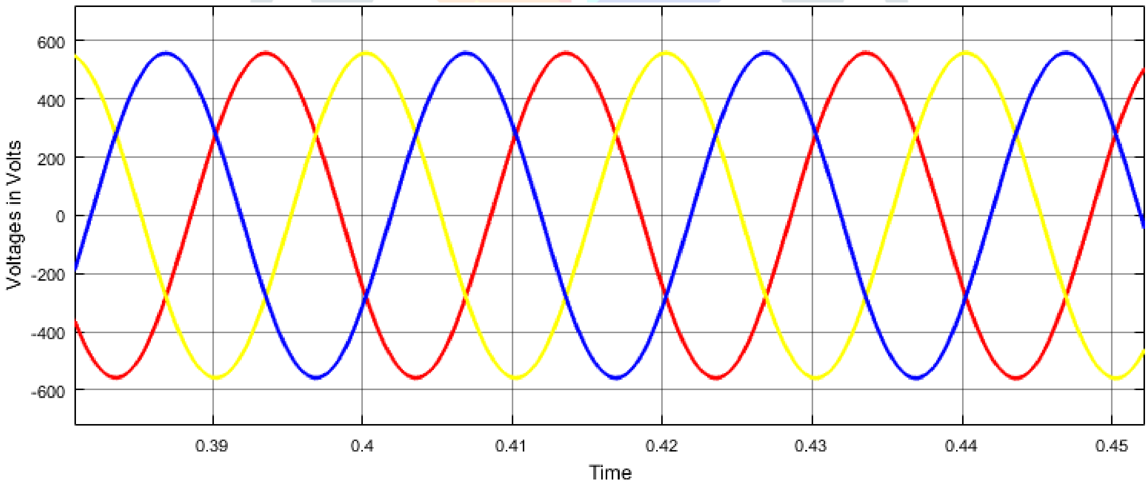

Figure 27. Three-phase line voltages of load for mode 3 operation

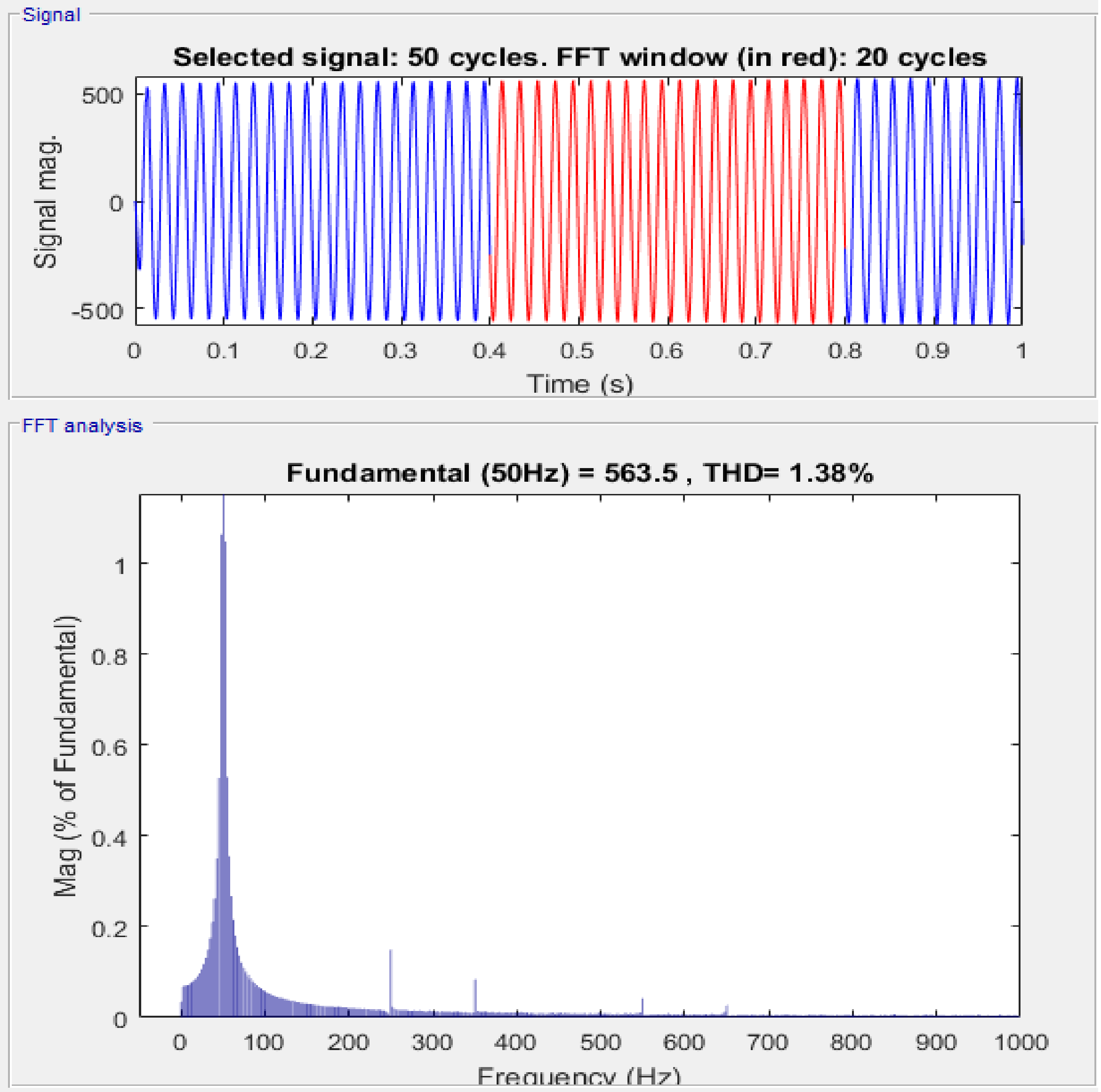

Figure 28. Line voltage THD of load with harmonic percentage for mode 3 operation

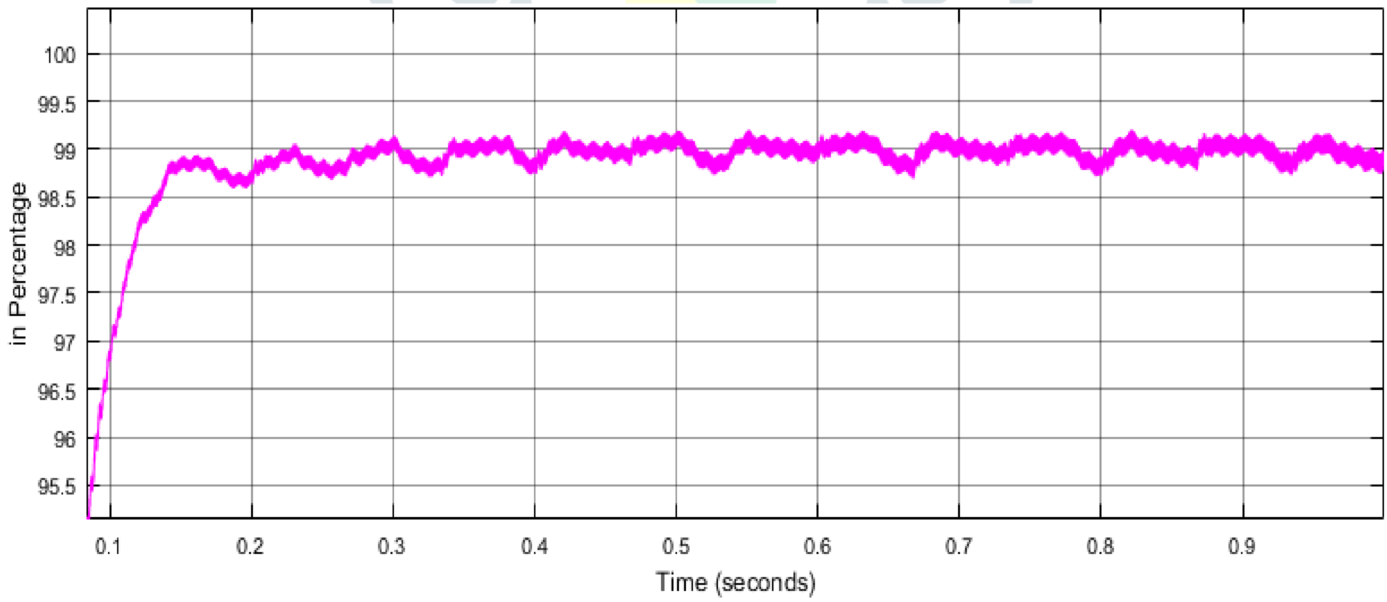

Figure 29. Overall efficiency of the System for mode 3 operation

MODE 4: Battery Power supply to Load

MODE 4: During night timings and seasons where solar irradiation is less solar power is not available. During such conditions, ESS will feed the load by discharging the battery. The voltage of the Battery, Output Power of the Battery, State of Charge of the Battery, Output Voltage of the Bidirectional DC-DC Converter, Power of the Load during this mode 4 the voltage of the battery is 51.41V as shown in figure 30. The output power of the battery is 5.14kW as shown in figure 31. The state of charge of the battery is decreasing as in figure 32 represents that the battery is discharging. The bidirectional converter boosts the battery voltage to 700V as shown in figure 33. The THD of the line voltage of the load are shown in Figures 34 and 35 respectively. The RMS load line voltage is 400.7V and THD is 1.38%. The overall system efficiency of the solar ESS is 98% as shown in figure 36.

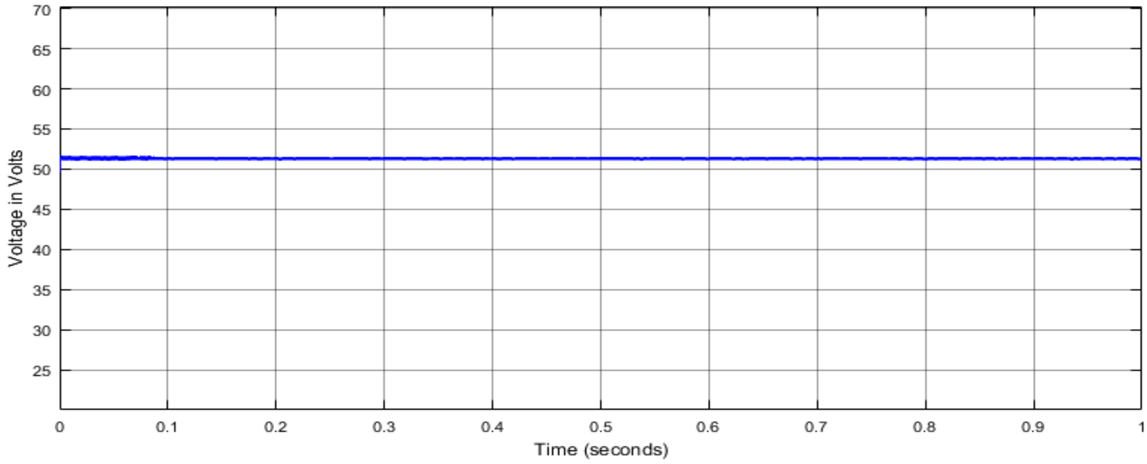

Figure 30. Battery Voltage during for mode 4 operation

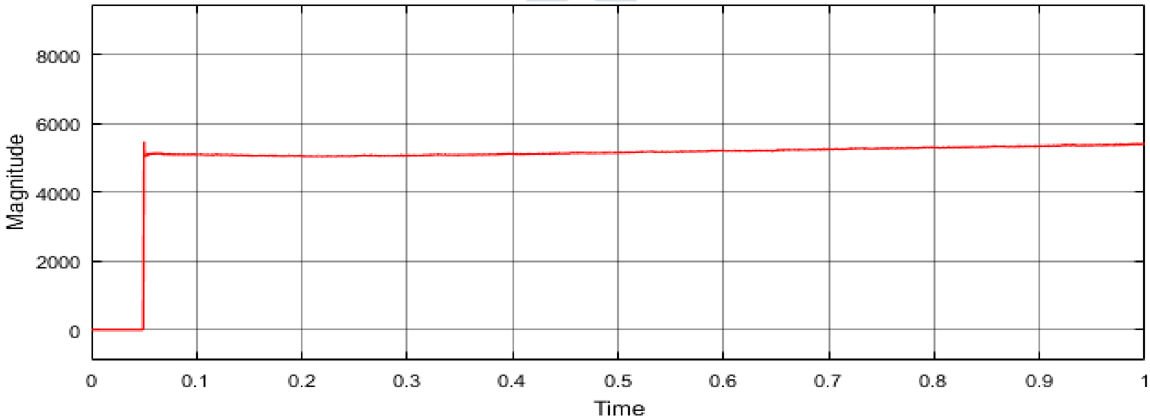

Figure 31. Output Power of the Battery

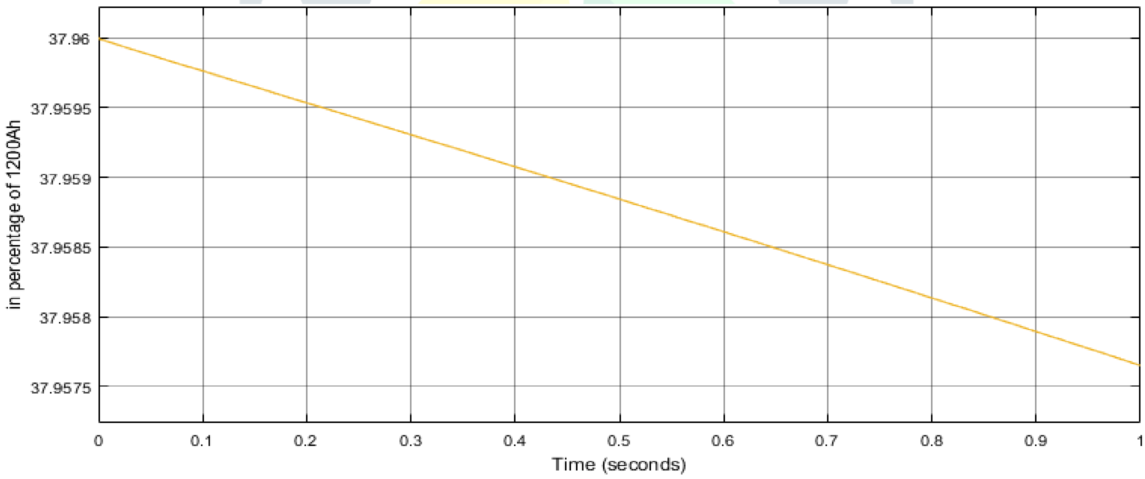

Figure 32. State of Charge of the Battery

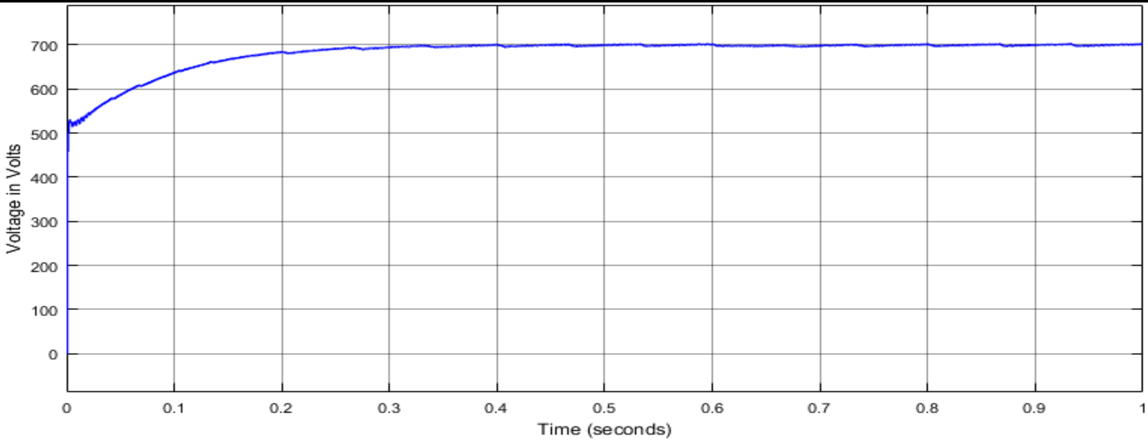

Figure 33. Output Voltage of the Bidirectional DC-DC Converter

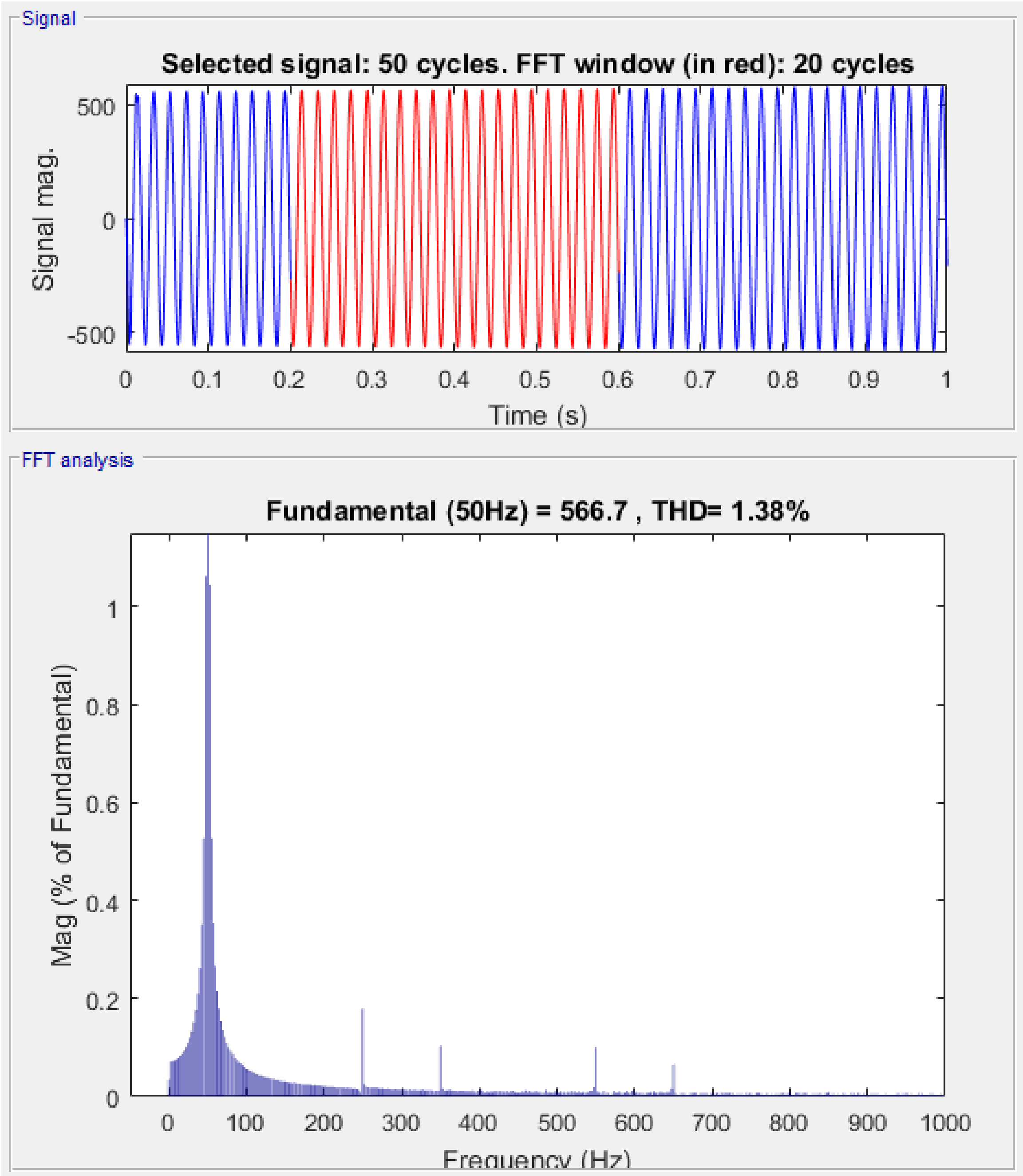

Figure 34 THD of line voltage of load with a bar graph showing harmonic percentages

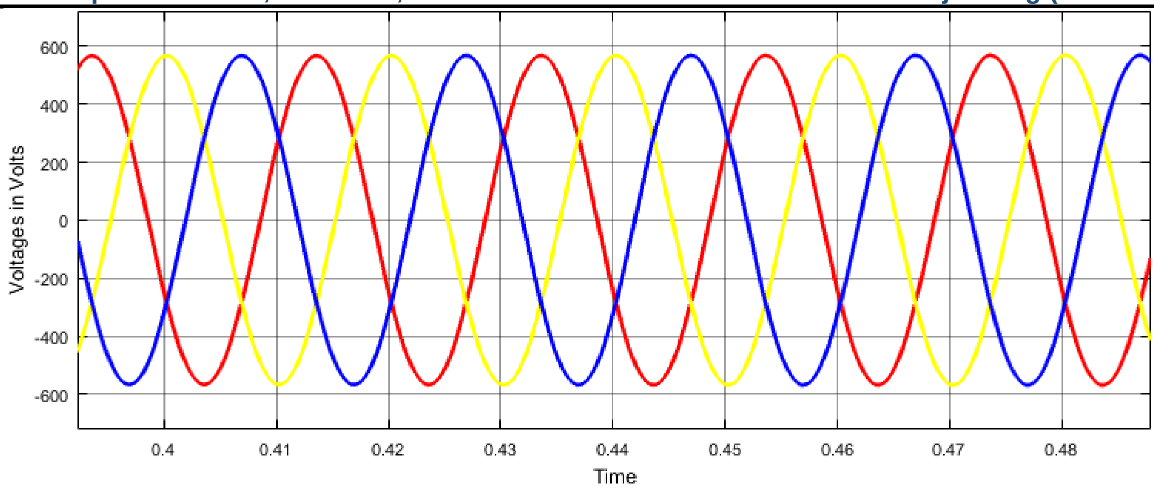

Figure 35. Three-phase line voltages of load

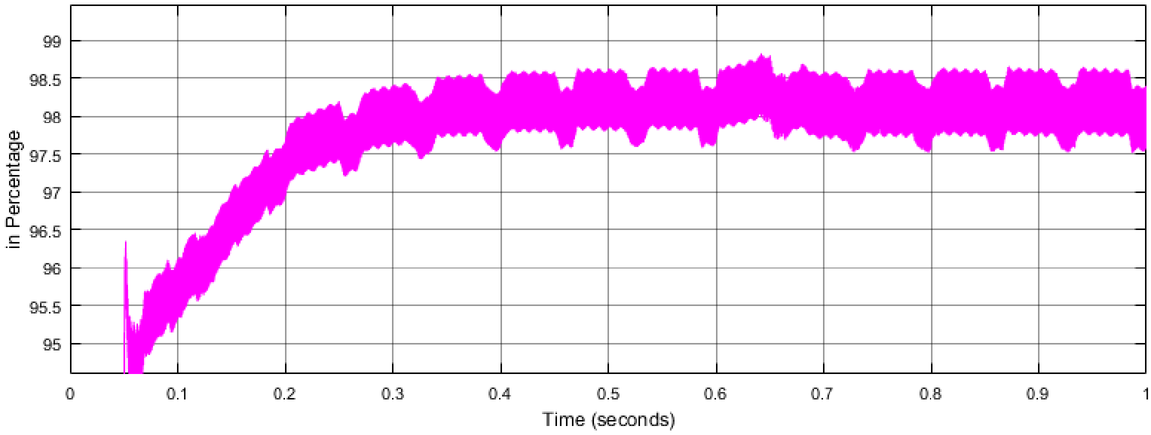

Figure 36. Overall system Efficiency

Power, voltage, current, THD, and overall efficiency of the system for different modes of operation at 1000 W/m^2 constant irradiation are tabulated in Table 3. Solar PV module output voltage is maintained at a constant maximum power of 10 kW by MPPT. The bidirectional DC-DC converter duty ratio is controlled to maintain the rated 700 V voltage during the charging and discharging modes of the battery. With the implementation of MPPT, ESS operation, and inverter control with PI control strategy, a constant load voltage of 230 V is maintained with a 1.36 % to 2.02 % THD value. 99% Overall system efficiency indicates the advantage of power electronic-based converters incorporation in Solar PV system at MPPT, ESS, and DC to AC conversion stages.

Table 3. Power levels of the system during different modes of operation

	Solar power (kW)	**Bidirectional DC-DC Converter**		**Battery**	**Inverter**		**Load**			**Overall system efficiency (%)**
		Voltage (V)	**Current (A)**		**Voltage (V)**	**Current (A)**	**Voltage (V)**	**Current (A)**	**Voltage THD**	
Mode 1	10	700	7.04	Charging	700	7.26	232.70	7.27	1.36%	99
Mode 2	10	-	-	-	690	15.00	231.40	14.51	2.02%	99
Mode 3	10	700	5.00	Discharging	700	18.90	230.00	17.40	2.02%	99
Mode 4	-	-	-	Discharging	700	7.50	231.30	7.23	1.36%	98

VI. CONCLUSION

The operation of the solar PV module with ESS is simulated in MATLAB. Implementation of MPPT is demonstrated in simulation. Simulation of the PI control circuit to maintain uninterrupted and rated load demand is detailed. Important modes of operation of the system are analyzed with line voltage, THD, ESS voltage and current, battery current parameters which play a significant role in the operation of the solar power system. The advantage of the solar system is indicated numerically with THD and overall system efficiency. This complete thorough analysis of different modes of solar system operation presented in this paper will help in a basic understanding of the system. Based on this basic analysis it is possible to develop and implement improved configurations and control strategies for higher efficient solar power system

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