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INTEGRATION OF PHOTOVOLTAIC SYSTEM TO THE GRID AND BATTERY STORAGE SYSTEM

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Abstract:
Photovoltaic system integration with grid and battery storage system using power electronic converters and control strategies. This paper mainly focuses on design and control of the power electronic converters like boost converter and bidirectional DC-DC converter working as the interface between the PV, grid and battery. (ii) MPPT tracking performance of boost DC-DC converter with less current ripple are presented in this paper. The PV side Boost Converter is controlled by Fuzzy Logic Controllers MPPT algorithm to extract the maximum power from the variable solar irradiation. It also focuses on the current control of the grid using proportional integral controller and proportional resonant controller. multi-functional features of a bidirectional AC-DC converter working as interface between the PV & battery pack and AC grid system, This paper uses an "voltage source full bridge" type inverter with proportional integral and proportional resonant controllers, adopted to ensure desired voltage and currents with less harmonics. The considered control scheme provides with the desired power flow between PV Panel, battery energy storage system (BESS) and utility grid based on the given reference settings. This model is obtained at maximum power and also the battery charging and discharging conditions are observed.

Key words- *Photovoltaic system, boost converter, fuzzy logic controller, maximum power point tracking, battery storage system, single phase voltage source full bridge Inverter, grid, Proportional resonant and proportional integral controller bidirectional DC-DC converter.*

1. Introduction

Among various renewable energy resources, photovoltaic system[1] and wind power are most rapidly growing ones. The PV source is a nonlinear energy source and direct connection with load will not give optimum utilization of it. In order to utilize the PV source optimally, it is necessary to provide an intermediate electronic controller in between source and load for various operating conditions. Using this electronic controller it is possible to operate the PV source at maximum power point (MPP), thus improving the energy efficiency of the PV system. Many control algorithms have been reported in the literature to track maximum power from the PV arrays, such as incremental conductance (INC), constant voltage (CV), perturbation and observation (P&O), fuzzy logic algorithm[3] and neural network algorithm.

Rather than using fossil fuel, energy storage using battery or ultra-capacitor systems can be used to provide fast frequency regulation, load following, and ramping services when the distribution or generation systems are integrated with the power grid.

The renewable-energy source based Distributed Generation systems are normally interfaced to the grid through power electronic converters and energy storage systems [2]. Which provides benefit of controlling the system.

Recent developments in Lithium-ion battery technology show many advantages compared to Lead-acid and Nickel-metal hydride batteries, such as high power and energy density, high working cell voltage, low self-discharge rate, and high charge and discharge efficiency. The system shown in Fig.1 consists of three subsystems, a battery pack and PV system [4], a bidirectional ac–dc converter, and the central control unit that controls the operation mode and grid interface of the energy storage system. The bidirectional ac–dc converter works as the interface between the PV/battery pack and the AC grid, which should meet the requirements of bidirectional power flow capability and to ensure low total harmonic distortion as well as regulate the DC-side power regulation.

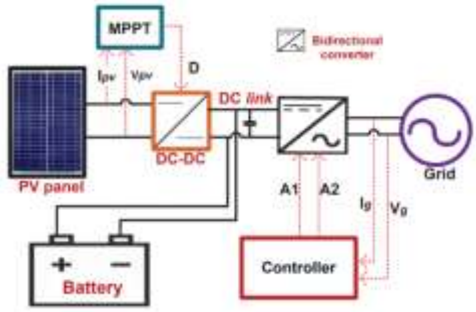


Figure 1. Grid integration with Photo Voltaic (PV) and Battery system.

PV system and battery storage system operate parallel at DC link. PV system operates with fuzzy logic MPPT [5] method using boost converter. The PV panel supplies power to DC grid. The bidirectional converter operates in two modes; in the presence of DC grid, the battery is being charged, and in the absence of the DC grid, the battery supplies power to the grid. A single phase voltage source inverter is used to convert DC – AC using proportional integral and proportional resonant controller. The details of the control architecture and converters implementation are discussed in Section II to IV. The simulation results are presented and explained considering the output waveforms as shown in Section V.

2. Design of a Boost Converter.

Based the flow chart of the P&O algorithm the fuzzy logic controller is designed. Five triangular membership functions are considered for voltage, current and output[6].

2.1 Calculation of Boost converter Parameters:

To calculate the parameters of boost converter consider the parameters of PV module.

Power at maximum point(P_{mp})	2097.54W
Open circuit voltage(V_{oc})	309V
Voltage at maximum point (V_{mp})	258V
Short circuit current(I_{sc})	9.4A
Current at maximum point(I_{mp})	8.13A
Irradiance	1000
Operating temperature	25^0C

Table 1: Parameters of PV module.

In conventional converter the input voltage is fixed or constant as the ripple voltage and ripple currents are normally given or known. So parameters of a conventional boost converter can be calculated using below equations.

In a normal condition, i.e. when the solar irradiance on the entire PV array is uniform, the power-voltage (P-V) and current-voltage (I-V) curves exhibits a single global MPP . To simulate the fast changing solar irradiance, two different levels of irradiance were selected, 1) highest (Point A, G=1000W/m2) and lowest (Point B, G= 300W/m2). It can be seen that, the maximum power point (MPP) has changed from point A to B when the irradiance (G) level decreases from 1000W/m2 to 300W/m2 . As a result, RMP increased from 31.7Ω to 86Ω which is calculated using;

$$R_{mp} = \frac{V_{mp}}{I_{mp}} = 31.7\Omega \qquad (1)$$

It is not practical to change the load resistance manually at any moment the solar irradiance changes [8]. Therefore, MPPT algorithm has been designed to continuously adjusts the duty cycle of the converter, in order to match the input resistance to the internal resistance of PV array at MPP (Rin=RMP), and hence extracts maximum available power. At MPP, the duty cycle of the converter is calculated as[6].

$$D_{mp} = 1- \sqrt{\frac{R_{mp}}{R_L}} =0.367 \qquad (2)$$

By assuming a lossless converter (PPV=Pout), the output voltage (Vout) of the converter at MPP is determined as;

$$V_{out} = \frac{V_{mp}}{1-D_{mp}} = 407V \qquad (3)$$

2.1.1 Selection of resistance:

The relationship between load resistance (RL) of boost converter and optimal internal resistance of PV array at MPP (RMP) can be expressed as [6];

$$R_L = \frac{R_{mp}}{(1-D_{mp})^2} = 79.25\Omega \qquad (4)$$

2.1.2 Selection of inductance:

Boost inductor value is selected based on the maximum allowable current ripple which occurs at the MPP under highest solar irradiance (1000W/m2). The higher the inductor value, the lower is the ripple output current and vice versa. To realize a low cost converter, the lower inductor value is preferred, because inductor is the most expensive component compared to the others. In this work, the switching frequency (fs) is set at 20 kHz and the permitted amount of ripple current (ΔI) is selected as 40% of the input current [6]. Hence, the minimum value of inductor is determined as.

$$L_{min} = \frac{V_{mp}*D_{mp}}{2*\Delta I_{out}*f_s} = 600\mu H \qquad (5)$$

2.1.3 Selection of capacitor:

In this study, the input and output filter capacitor (Cin & Cout) are chosen to meet the voltage ripple requirement of 0.2%. An approximate expression for the required capacitance is given as[6];

$$C_{min} = \frac{V_{mp} * D_{mp}}{2 * \Delta V_{out} * R * f_s} = 3000\mu F \quad (6)$$

3 Grid Connection

Generally the power converter interface from the dc source to the load and/or to the grid consists of a two stage converter: the dc-dc converter and the dc-ac converter.[8] An interesting alternative solution could be the use of a single-stage converter where the dc-dc converter is avoided and in order to ensure the necessary dc voltage level the PV array can be a string of PV panels or a multitude of parallel strings of PV panels. In the classical solution with two-stage converter, the dc-dc converter requires several additional devices producing a large amount of conduction losses, sluggish transient response and high cost while the advantages of the single-stage converters are: efficient, a lower price and easier implementation. The disadvantages of the single-stage converter are the fact that the PV panels are in series and if the shading occurs on one or several PV panels then the efficiency of the whole system is reduced.

As shown in Fig. 2, the PV inverter system consists of a solar panel string and a dc link capacitor Cd, on the dc side with an output ac filter (LCL), insulation transformer and grid connection on the ac side. The number of panels in the string has to ensure a dc voltage higher than the ac voltage peak at all time. The energy conversion from dc to ac side is made by a single-phase voltage source inverter.

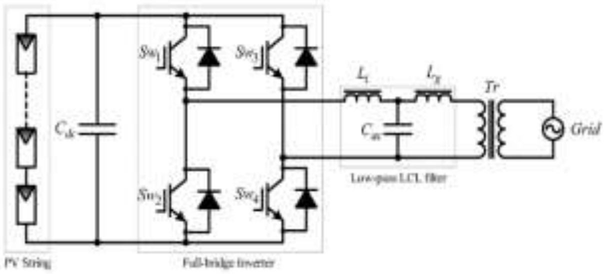


Figure 2. The voltage source PV inverter connected to the grid through an LCL filter.

3.1 Control Strategy:

For the grid-connected PV inverters in the power range of 1-5 kW, the most common control structure for the dc-ac grid converter is a current-controlled H-bridge PWM inverter having a low-pass output filter. Typically L filters are used but the new trend is to use LCL filters[14] that have a higher order (3rd) which leads to more compact design. The drawback is its resonance frequency which can produce stability problems and special control design is required [10]. The control structure of the PV energy conversion system is shown in Fig. 3.

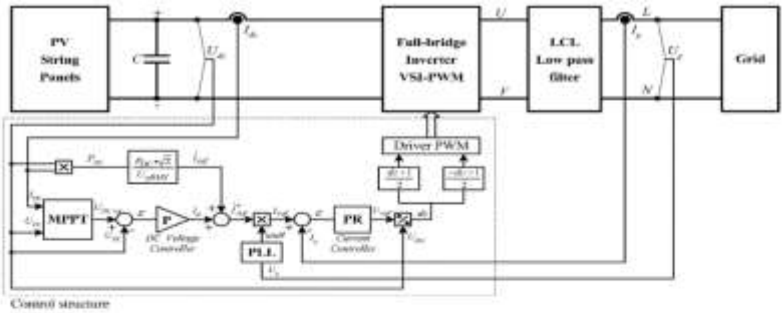


Fig 3: Control diagram of the PV energy conversion system

The main elements of the control structure are the synchronization algorithm based on PLL, the MPPT, the input power control and the grid current controller.

3.2 Phase Locked Loop(PLL) Structure[16]:

The PLL is used to provide a unity power factor operation which involves synchronization of the inverter output current with the grid voltage and to give a clean sinusoidal current reference. The PI controller parameters of the PLL structure are calculated in such a way that we can set directly the settling time and the damping factor of this PLL structure. The PLL structure is also used for grid voltage monitoring in order to get the amplitude and the frequency values of the grid voltage. The general form of the PLL structure is presented in Fig. 4.

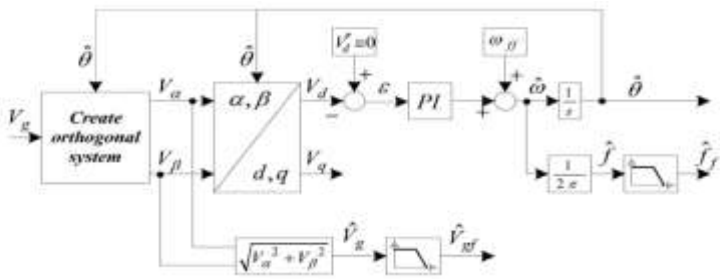
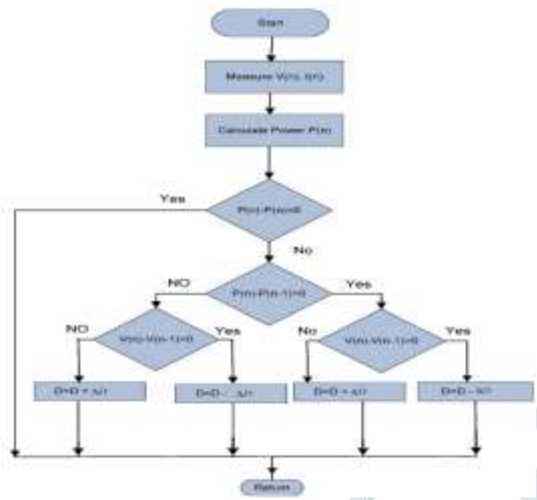


Fig. 4: General structure of a single phase PLL

3.3 MPPT algorithm :

The task of the MPPT in a PV energy conversion system is to tune continuously the system so that it draws maximum power from the solar array regardless of weather or load conditions. Since the solar array has non ideal voltage-current characteristics and the conditions such as irradiance, ambient temperature, and wind that affect the output of the solar array are unpredictable, the tracker should deal with a nonlinear and time-varying system. The conventional MPPT algorithms are using dP/dV = 0 to obtain the maximum power point output. Several algorithms can be used in order to implement the MPPT as follows [10]: perturb and observe, incremental conductance, parasitic capacitance and constant voltage, but only the first two are the most frequently used.



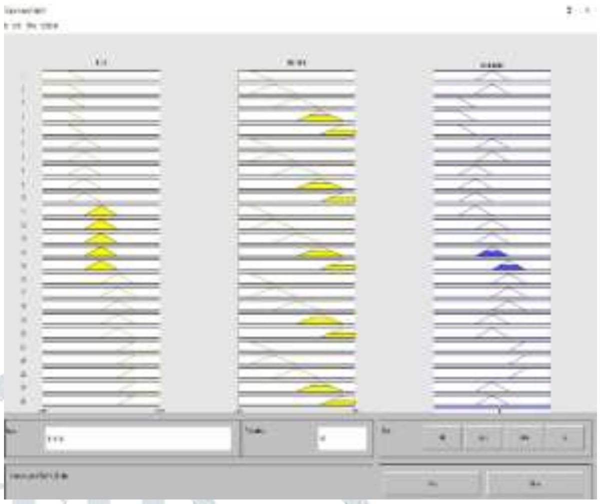


Fig 5: The flow chart of the P&O algorithm. **Fig 6: Rules of the fuzzy logic.**

3.4 Grid Current Controller :

Classical PI control[15] with grid voltage feed-forward (Ug) as depicted in Fig. 7a, is commonly used for current-controlled PV inverters.

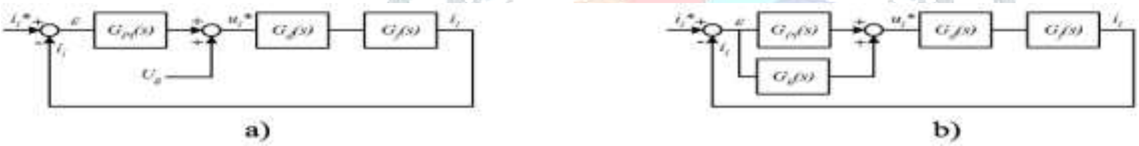


Fig. 7: The current loop of PV inverter: a) with PI controller; b) with PR controller.

The PI current controller GpI(s) is defined as[15]:

$$G_{PI}(s) = K_p + \frac{K_i}{s} \quad (7)$$

The filter transfer function G1(s) is expressed in (8).

$$G_f(s) = \frac{i_i(s)}{u_i(s)} = \frac{1}{L_i s}\frac{(s^2+Z_{LC}^2)}{(s^2+\omega_{res}^2)} \quad (8)$$

3.4.1 Calculation of Kp value:

a. Voltage Controller :

Controller time constants = 200μS

Filter Capacitance = 6.23µF

$$\text{Value of Kp} = \frac{capacitance}{time\ constant} = 0.03115 \quad (9)$$

b. Current controller :

Controller time constants = 150µS

Filter Inductance = 4.06mH

Inductor Series Resistance = 0.001

$$\text{Value of Kp} = \frac{Inductance}{time\ constants} = 27.066 \quad (10)$$

$$G_n = \frac{K_r \omega_n}{\omega_n^2 - \omega^2} \qquad \because \omega_n = \frac{1}{\sqrt{LC}} \quad \because \omega = 2*pi*50 \quad (11)$$

$G_n = 0.1$

3.4.2 Calculation of Kr value :

Kr value of voltage controller = 100

$$\frac{\omega^2}{K_r} = \frac{(2*pi*50)^2}{100} = 986.83 \quad (12)$$

Kr value of voltage controller = 400

$$\frac{\omega^2}{K_r} = \frac{(2*pi*50)^2}{400} = 246.7 \quad (13)$$

4 Connection of Battery Storage System:

the interconnection of battery storage system to the PV system consists of a bidirectional DC-DC converter which helps in charging and discharging of the batteries.

When the battery is charging the bidirectional converter operates in buck mode. in discharging condition it operates in boost mode. The design of bidirectional DC-DC converter plays a major in connection of PV system to battery storage system. The control of bidirectional converter switches is done by using a proportional integral controller.

4.1 Design of a bidirectional converter:

4.1.1 Buck mode:

Duty cycle: The duty cycle of the switch with estimated efficiency of 90% to 95% [12] is given by equation (14).

$$D = \frac{V_o}{V_{in}*\eta} \quad (14)$$

where = input voltage, = desired output voltage, η = efficiency of the converter, e.g. estimated 90% to 95%.

Selection of Inductor: The inductor ripple current is taken as 10% to 20% of the output current [12]. The ripple in inductor current is given by equation (15).

$$\Delta I_L = (0.1 \text{ to } 0.2) \text{ x } I_o \quad (15)$$

where I_o = output current necessary in the application. Higher the inductor value, higher is the maximum output current because of the reduced ripple in output current. The inductor value is calculated using equation (16).

$$L = \frac{DT_s \times (V_i - V_o)}{\Delta I_L} \quad (16)$$

Selection of Output Capacitor: Best practice is to use low ESR capacitors to minimize the ripple in the output voltage. Generally output ripple voltage is taken as 10% of output voltage [12]. Output capacitor values for a desired output voltage ripple is calculated as in equation (17).

$$C_o = \frac{(1-D)\times V_o \times T_s\text{^}2}{8L\times \Delta V_o} \quad (17)$$

where C_o = output capacitance, ΔV_o= desired output voltage ripple.

4.1.2 Boost Mode

Duty cycle: The duty cycle of the switch with estimated efficiency of 90% to 95% is given by equation (18).

$$D = 1 - \frac{V_i \times \eta}{V_o} \quad (18)$$

where V_i= input voltage, V_o= desired output voltage, η = efficiency of the converter.

Selection of Inductor: Inductor ripple current of 10% to 20% is assumed. Hence the ripple in inductor current is given by equation (19).

$$\Delta I_L = (0.1 \text{ to } 0.2) \times I_i \quad (19)$$

Where I_i= input current. The inductor value is calculated using equation (20).

$$L = \frac{DT_s \times V_i}{\Delta I_L} \quad (20)$$

Selection of Output Capacitor: Output capacitor is chosen with 10% ripple in output voltage. Output capacitor values for a desired output voltage ripple is calculated as in equation (21).

$$C_o = \frac{I_o \times D}{f \times \Delta V_o} \quad (21)$$

where C_o= output capacitance,

ΔV_o= desired output voltage ripple [11].

Sr.no	Parameters	Values
1.	Duty Cycle	0.0631
2.	Switching Frequency	25000
3.	Output Power	2kW
4.	Input DC Voltage	400
5.	Battery Voltage	24
6.	Inductor	1.247mH
7.	Ripple in Inductor current	10%
8.	Input and Output Capacitor	9.87μF and 47.15μF
9.	Ripple in Capacitor Voltage	5%

Table 2: shows the design values of the selected B.

Manual PID tuning is done by setting the reset (integral) time to its maximum value and the rate (Derivative) to zero, and increasing the gain until the loop oscillates at a constant amplitude. (When the response to an error correction occurs quickly a larger gain can be used. If response is slow a relatively small gain is desirable). Then set the gain of the PID controller to half of that value and adjust the reset time so it corrects for any offset within an acceptable period. Finally, increase the rate of the PID loop until overshoot is minimized

Zeigler and Nichols' two **heuristic methods** of tuning a PID controller were first published in 1942. These work by applying a step change to the system and observing the resulting response. The first method entails measuring the lag or delay in response and then the time taken to reach the new output value. The second depends on establishing the period of a steady-state oscillation. In both methods, these values are then entered into a table to derive the values for gain, reset time and rate for the PID controller.

5 Simulation Results

in this section the results from the Simulink model is discussed using the waveform results. The waveforms are taken for maximum power point tracking, boost converter output voltage(V_{DC}), grid voltage(V_{grid}) and grid current(I_{grid}).

From this results we can observe that the integration of PV system to the grid and battery storage system is done with less harmonics as the control strategies are designed to avoid the harmonics. The maximum power point tracking is done by using fuzzy logic controller. for grid connection a full bridge inverter model is designed to convert DC to desired AC output as the grid parameters are 230V and 50Hz. The connection battery storage system requires a bidirectional DC-DC converter model for charging and discharging of batteries. In this project lead acid battery is considered and parameters are nominal voltage is 24V,capacity 83.3Ah and state of charge at 50. Graph is observed at the battery. The /MATLAB Simulink model is shown as below.

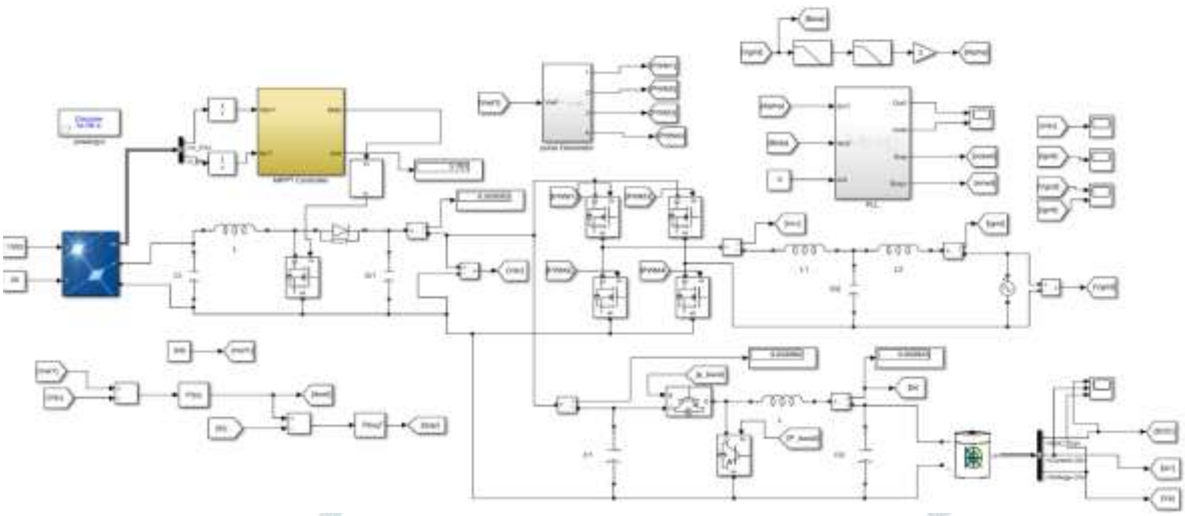


Fig 8: Simulink model of integrated PV system with single phase grid and battery storage system.

5.1 Analysis of Simulink Results:

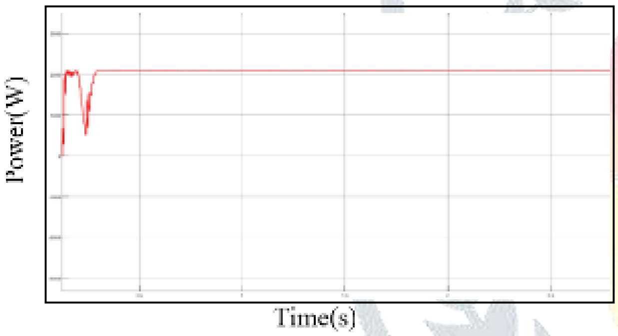


Fig 9: Maximum power point tracking(MPPT).

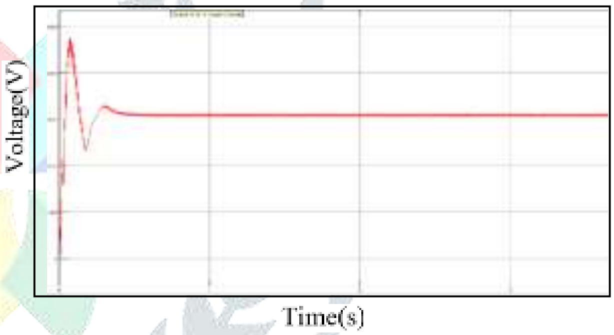


Fig 10: Boost converter voltage(Vdc).

To extract the maximum power output from the photovoltaic module, maximum point tracking is used in this paper Fuzzy logic control is considered and the maximum power obtained is 2096W.

The output voltage of the boost converter is observed from the graph, initially the voltage is fluctuating at time 0.75sec it started to settle down. The voltage is settles around 309V.

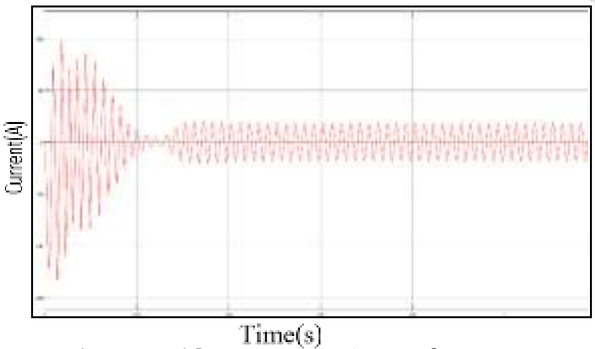


Fig 11: Grid Current(I_{grid}) waveform

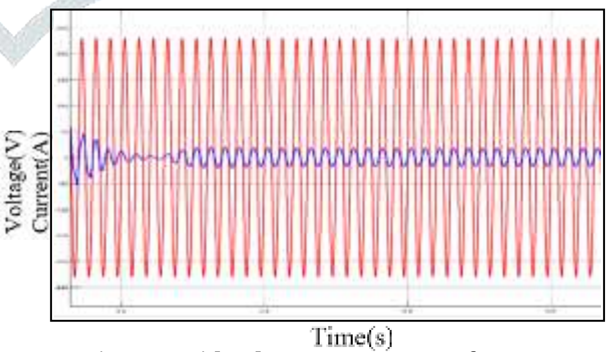


Fig 12: Grid voltage current waveforms.

From the above graphs, initially current was stable at 0.25sec it started becoming stable by the combination battery storage the power observed at the grid is higher than the power of PV system. Phase shift between voltage and current is set to zero using the phase locked loop. The grid current rises up to 18Amps and grid voltage(V_{grid}) is set to 230V. the voltage and current control of the grid is done using PI and PR controllers.

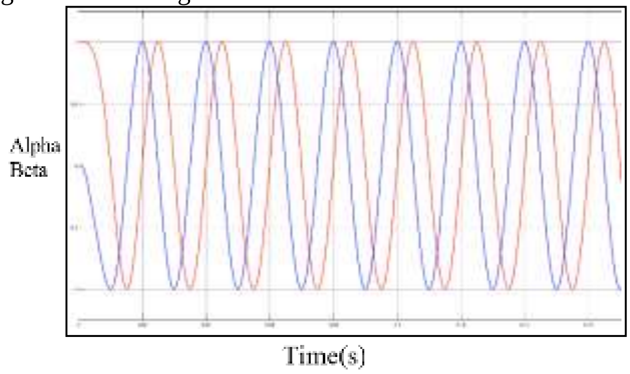


Fig 13: Alpha Beta waveforms.

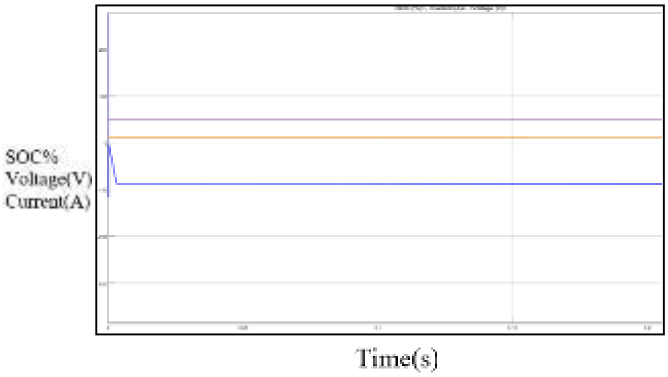


Fig 14: Battery SOC%, Voltage, Current.

The alpha beta are obtained from the grid voltage by using double first order filter which provides 45^0 phase shift each. Alpha is the phase shifted voltage where as Beta is the actual grid voltage. The alpha beta voltages are given to the phase locking loop to set the phase shift between the current and voltage. The phase between alpha and beta is 90^0.

Fig 14, shows the graph of the battery parameters state of charge which is observed at 50% voltage at 24V and current at 84. When ever the power from the photovoltaic system is less or below the maximum power the battery storage system discharges to supply the grid and when the photovoltaic system provides maximum power the battery storage system starts charging.

Conclusion:

This paper is combination of converters starting with boost converter, the design of boost converter and bidirectional DC-DC converters is discussed. Control strategies for controlling the current and voltage using proportional integral controller and proportional resonant controller while converting DC-AC using voltage source inverter with less harmonics using phase locking loop is discussed and also battery storage system charging and discharging conditions are discussed. Finally a model is designed to integrate PV system with single phase grid and battery storage system and output waveforms are analyzed.

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