Control & Design for Battery Energy Integrated Grid-Connected Photovoltaic System

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***Abstract*— In this paper, a concept of photovoltaic system integrated with battery storage is developed with coordinated, simple and robust control structure. In grid connected mode of operation current injection control or power injection is required to control whereas in islanded mode of operation, voltage and frequency control is required for stable operation of the power system. In proposed photovoltaic system, DC-DC boost converter is operating at MPPT for maximum power extraction, current injection control is implemented on inverter and battery control with SOC (State Of Charge) is taking care of battery's charge and discharge mode. The control philosophy shows an effective coordination between current injection control, MPPT control and battery storage charging and discharging control. The simulation studies are performed in MATLAB and SimPower Systems to verify the effectiveness of proposed control.**

Index Terms*— Renewable energy, Photovoltaic system, Maximum Power Point Tracking (MPPT), Coordinated Current injection control,, Battery storage, Battery Model, SOC control.

I. Introduction

With the ever increasing energy demands and cost of fossil fuels, many new sources of energy have been proposed in the last few years. Fossil fuels also have a huge negative impact on the environment. In this context, the new energy sources are essentially renewable in nature. In Indian context Photovoltaic (PV) energy is one of the types of renewable energy which is available in large amount and if efficient conversion of PV energy to electrical energy is done than country would be able to deal with the electricity deficiency problem and in a more environmental friendly manner. Broadly two types of PV system are possible i.e grid connected and offgrid PV systems. In both cases, essentially an electricity storage system is required so that in case when load is less than the power produced by PV system or vice-versa, maximum utilization of solar energy would be possible. For instance the Photovoltaic systems used in the solar projects require interfacing power converters between the PV arrays and the grid. These power converters are used for two major tasks. First, to ensure the PV arrays are operated at the Maximum Power Point (MPPT) [2-7]. Second objective is to ensure that inverter is injecting a sinusoidal current into the grid. Normally there are two power converters in a two stage PV system [8, 9]. The first one is a DC/DC power converter that is used to operate the PV arrays at the maximum power point. The other one is a DC/AC power converter to interconnect the photovoltaic system to the grid. On the other hand in case of single stage PV system one DC/AC power inverter takes care of both the objectives i.e PV operation at MPPT and sinusoidal current injection to the grid.

In literature integration of Battery storage with PV system in both cases i.e grid connected and offgrid mode is reported in large number. But few papers are reported in which battery State of Charge (SOC) is considered in control architecture. This is the novelty of presented work. Control architecture presented in this paper considers SOC of battery which will directly enhance the life of battery and thus will indirectly reduce the cost.

II. Description of Considered grid connected system

In the considered grid connected PV system, two PV arrays are connected in series to reduce the size and current rating of conductors. PV arrays connected in series are further connected to DC-DC converter as first stage of power conversion. As second stage DC-AC converter is connected to 3 phase grid as shown in Figure 1. MPPT control is implemented on DC-DC converter to extract maximum power from PV. Inverter control is taking care of power injection to grid. Battery storage is connected to DC bus as shown in Figure 1. Battery storage controller is taking care of optimal charging and discharging of battery. Depending upon the voltage of power generated by photovoltaic system, need of step up transformer is required to calculate. In considered case step up transformer is required as voltage level of utility grid is high as compared to power generated by PV source.

A. PV system mathematical model and implementation

The modules in a PV system are typically connected in arrays in series and parallel configurations. Electrical modeling of suggested PV array system is represented in the following equations [1]:

$$V_{pv} = \left(\frac{B \times K \times T \times N_s}{q}\right) \times \ln\left(\frac{N_p\,(I_L + I_{os} - I_{pv})}{N_p \times I_{os}}\right) \quad (1)$$

$$I_{os} = I_{or}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{q\,E_{Go}}{BK}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \quad (2)$$

$$T_c = T_{air} + 0.2 \times H\% \quad (3)$$

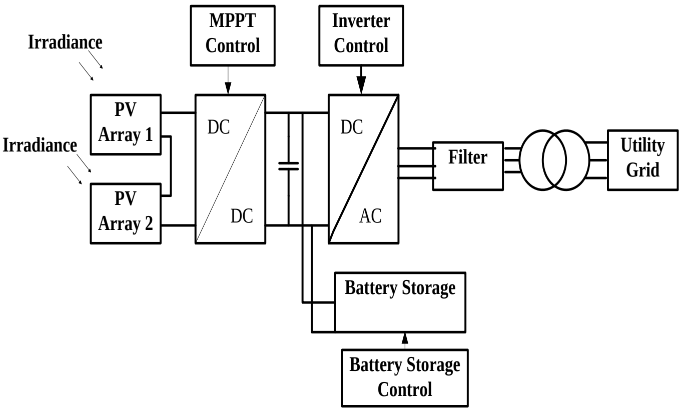

Figure 1 Block diagram of considered system

Where, V_{pv} is the PV array output voltage (V), I_{pv} is the PV array output current (A), I_{or} is the reverse saturation current, I_{os} is the cell reverse saturation current (A), N_s is the number of cells connected in series, N_p is the number of cells connected in parallel, I_L is the light generated current (A), B is the ideality factors , K is the Boltzmann's constant, is the electronic charge, T_r is the reference temperature, T_r is the cell temperature (ºC), T is the cell temperature (ºK), K_I is the short-circuit current temperature coefficient (0.0017 A / ºC), H is the cell irradiance (W/m^2), I_{sc} is the module short-circuit current, E_{Go} is the band gap for silicon. The output of a PV module changes depending on the amount of solar irradiance, the angle of the module with respect to the sun, the temperature of the module and the voltage at which the load is drawing power from the module [10].

B. Boost Converter

Boost converter is DC-DC converter which converts output voltage of PV array to higher voltage level. A typical boost converter is composed of an inductor, switching device, diode, capacitor, load and gate signal for switching device. The boost converter with MPPT algorithm is used in solar PV system to generated maximum power at different weather condition and constant voltage across the load so that it can be converted to AC power easily by using inverter. The inductor is used to store the energy. By switching IGBT on and off, the stored current from the inductor is transformed to load through the diode. The output voltage is kept continuous and constant by using large capacitor [11]. Reference voltage signal is generated by using any Maximum power tracking algorithm (MPPT). In this work Perturb and Observe algorithm is used. Reference voltage signal is compared with actual common bus DC voltage. Difference of V_{pvref} and V_{pv} is fed to the proportional and integral controller and output of controller is given to pulse generator which generates pulses for switching of DC booster IGBT as shown in Figure 2.

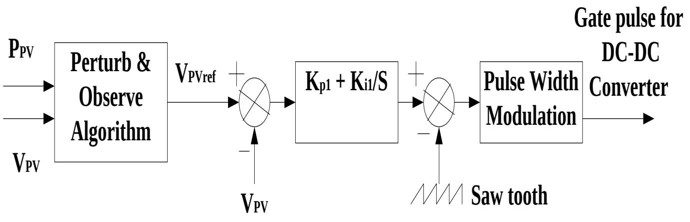

Figure 2 Control structure for MPPT control

C. Inverter Control

Point of common coupling (PCC) voltage and current is measured and Park's transformation is applied on it which will provide corresponding V_d, V_q , I_d, and I_q components. V_{dref} is compared with V_{dc} and error is fed to the Proportional and Integral (PI) controller; which will result in I_{dref}. I_{dref} is then compared with I_d and error signal is send to PI controller in order to ensure that reference is tracked efficiently. As shown in Figure 3 Pulse width modulation (PWM) will give pulses of gate firing of IGBT. In this control structure there are two control loops; inner control loop and outer control loop. Outer control loop provides a signal which contributes as reference current signal for inner loop control.

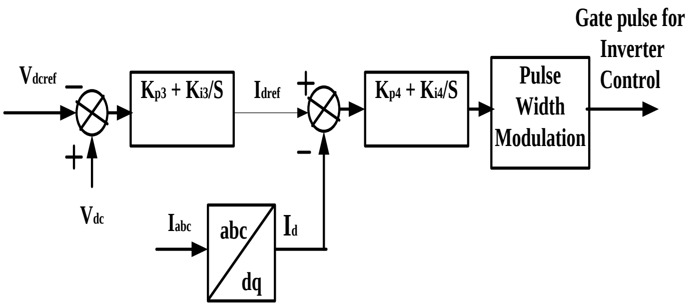

Figure 3 Control structure for inverter control

D. Battery model and implementation

Considering the advantages and usage of lead acid battery, model of lead acid battery is considered for simulation. General purpose lead acid batteries consist of two plates, positive and negative, immersed in a dilute sulfuric acid solution. Anode i.e. the positive plate is made up of lead dioxide (PbO_2) and the cathode i.e. the negative plate is made up of lead (Pb). SOC defines battery's charging condition; for healthy and long life SOC should be considered. Battery model has two modes of operation: charge and discharge. The battery is in charge mode when the battery input current is positive while the discharge mode is in case of the input current being negative. The terminal voltage (V_b) of the battery is given by (4). V_l and R_l are governed by a set of equations depending on which mode of operation the battery is in.

$$V_b = V_l + I_b \times R_l \qquad (4)$$

Where,

V_l : battery open circuit voltage (V),

I_b : battery current (A) and

R_l : internal resistance of the battery (I) respectively

Charge Mode

The battery voltage and state of charge (SOC) during charging mode can be described using the following equation [2]:

$V_1 = V_{ch} = [2 + 0.148 \times SOC(t)] \times ns$ (5)

$$R_1 = R_{ch} = \frac{0.758 + 0.1309/[1.06 - SOC(t)] \times ns}{Q_m} \quad (6)$$

Discharge Mode

During discharging, the battery voltage – SOC relationship is given by [7]:

$V_1 = V_{ch} = [1.926 + 0.124 \times SOC(t)] \times ns$ (7)

$$R_1 = R_{dch} = \frac{0.19 + 0.1037/[SOC(t) - 0.14] \times ns}{Q_m} \quad (8)$$

Where, SOC (t) is the current state of charge and Q_m is the maximum battery capacity (Wh). The SOC (t) is the ratio between the present capacity and the nominal capacity and can be estimated using the following equation [9]:

$$SOC(t) = SOC(t-1) + \int_{t-1}^{t} \left(\frac{K_b \times VI \times I_b}{Q_m} - SOC(t-1) \times D \right) \quad (9)$$

Where, K_b is the battery charge/discharge efficiency and D is the battery self discharge rate (h^{-1}). The SOC (t) can be found by knowing the previous condition. Since SOC (0) = SOC(1) = initial state of charge, SOC(1) can be found.

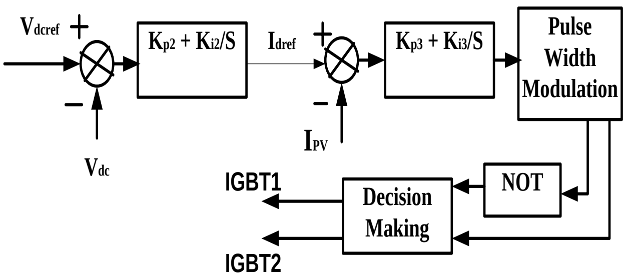

Figure 4 Control structure of Battery Storage Control

III. Simulation Results and Discussion

Grid connected solar photovoltaic system (Figure 1) integrated with battery storage simulated in MATLAB/Simulink and results of simulation are presented from Figure 5 to Figure 8. For testing and analyzing the designed system and to understand the battery storage functioning; irradiation as per Figure 5 is considered. Initially irradiation is 1000 W/m^2 and then suddenly reduced to 300 W/m^2 at t = 3 second. Reference common DC bus voltage is considered as 500 volt and is shown in Figure 6 (V_{dcref}). Implementing control structure as shown in Figure 2 for MPPT control, common DC bus voltage is obtained as shown in Figure 6 (V_{dc}). From Figure 6 it is evident that actual measured common DC bus voltage is almost equal to the reference common DC bus voltage; considered as 500V.

Here it is important to note that as irradiation reduced to 300 W/m^2 from 1000 W/m^2, there is great reduction in energy available from photovoltaic system. At that time when energy available from photovoltaic system is less than the required as per agreement with energy producer. In this case energy which is stored in battery during the period when energy generated by photovoltaic system is more than required as per agreement must be utilized to avoid any penalty. When available power from PV source is reduced suddenly at t = 3 second, there is dip in common DC bus voltage is noticed as shown in Figure 6. At t = 3 second battery mode changes from charging mode to discharging mode and thus supports to maintain desired common DC bus voltage of 500 volt.

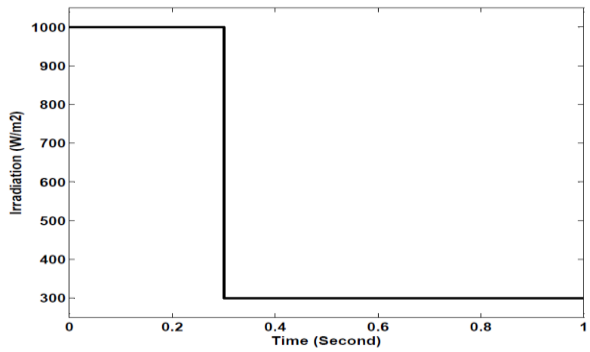

Figure 5 Considered signal for irradiation variation

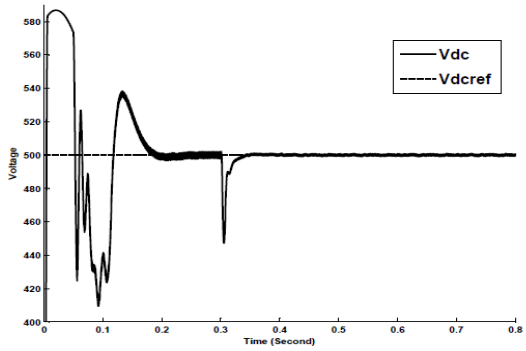

Figure 6 Common DC bus reference voltage and common DC bus voltage

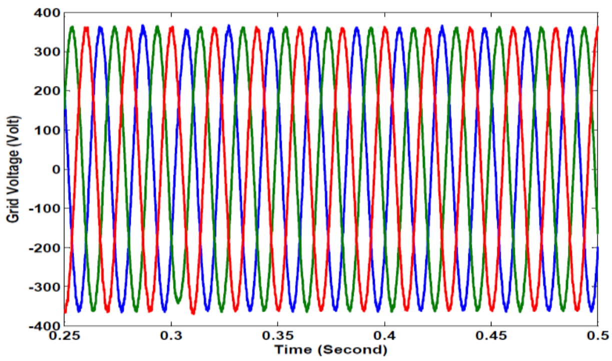

Figure 7 Grid Voltage (Volt)

Figure 7 represents the grid voltage for considered grid connected PV system. At t = 3 second when there is sudden reduction in irradiance (Figure 5), a dip in DC bus voltage is realized but due to effective battery control and inverter control action no such kind of dip or fluctuation is seen in 3 phase grid voltage. For long life and efficient usage of battery it is must to consider its SOC. SOC of battery is considered in control structure implemented for battery storage control. Battery storage control is also implemented in literature widely but a few papers considered SOC in control loop. But this type of control structure (without considering SOC) will finally lead to decrease in battery's life and performance. When SOC is less than or equal to 20% or greater than 80% then both charge and discharge mode are equal to zero i.e battery current is zero. When SOC is between 40% and 80% than charge mode is zero and discharge mode = 1 i.e. as battery is discharging .

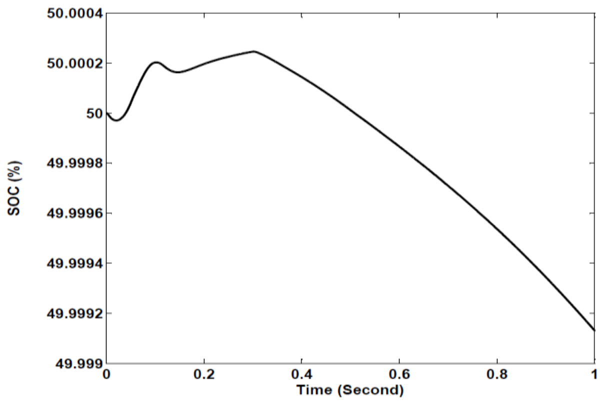

Figure 8 SOC of Battery

Figure 8 shows the battery SOC. Initial SOC is considered as 50%. Initially when irradiance is 1000 W/m^2, Battery SOC is 50%; battery operating in charging mode. Suddenly when irradiance falls to 300 W/m^2, battery control leads to operate battery in discharging mode (refer Figure 8).

CONCLUSION

This paper presented an integrated current injection control for grid connected PV system with PV generator and battery storage. PV generator is operated with the Maximum Power point tracking algorithm and the battery storage is added as back up to meet the deficit or surplus power need by using the charge or discharge mode of operation. SOC control is implemented for battery storage control to enhance the life of battery instead of simple capacitor charging/discharging base control. An efficient MPPT control, power control and Battery storage control is obtained as discussed in previous section. The implemented algorithm can be effectively used in supplying some critical loads of a microgrid with solar PV and battery. Proposed PV system in grid connected mode with battery storage will be useful in cases where grid load changes widely; as an additional power support can be provided even in night hours when PV system will not be able to produce electricity directly, but excess energy which was produced by PV system can be used using battery storage.

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