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Modeling of Grid-connected Solar Photovoltaic Energy Generation System

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This paper coversthe design and modelling of a grid-connected solar photovoltaic energy generation system. Solar-PV system with MPPT (maximum power point tracking) controller to track maximum power point is designed with a dc-dc converter. The output of PV array is fed to the VSI converter through a dc-dc converter. For regulating the output voltage and current under varying conditions,a VSI is designed with closed loop controllers. Simulation model for this designed system is developed in Simulink/Matlab platform and simulated results are presented to demonstrate its performance under steady and dynamic conditions.

Keywords: *Closed loop controller, DC-DC converter, Maximum power point tracking, Solar photovoltaic.*

1.0 INTRODUCTION

Solar energy is an emerging technology and it has experienced rapid growth over the last decade. Photovoltaic cells are the main component in the photovoltaic energy conversion systems and efforts are needed to improve their performance and to optimize the interactions between the cells and other components of the system. The purpose of this investigation is to improve the control of the power interface and to optimize the operation of the overall system [1]. Many types of photovoltaic (PV) energy conversion systems have been developed including the grid-connected system and the stand-alone system. Solar photovoltaic energy system in a grid-connected configuration is proven as a reliable source of electricity and used in many applications as the energy storage component in such systems is optional [2]. The PV cells produce electrical power when exposed to sunlight and connected to a suitable load, without any moving part in the module.It has very low amount of tear and wear, which makes it more suitable[3]. Solar energy conversion system usually consists of a PV array that converts the solar energy into the electrical energy, a DC-DC converter that converts low dc voltage produced by the PV array to a high dc voltage, aVSI to convert the high dc voltage to the single ac voltage and a controller that controls the system for maximum power tracking and grid characteristics. The characteristic of the PV module varies with the solar insolations as well as with the temperature, thus MPPT controllers are used. Several approaches have been proposed with different types of control strategies [4-5]. Here a solar energy conversion system with a full bridge dc-dc boost converter and a controller is designed and modeling of the system is done inMATLAB platform and simulated results of proposed PV system are presented for a variety of consumer loads.

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2.0 SYSTEM CONFIGURATION

Figure 1 shows the system configuration of a solar energy conversion system with a PV array, a full bridge dc-dc boost converter, a controller for maximum power tracking and a single phase full bridge VSI. This system is designed for a 2000 W maximum power rating. The output voltage of a PV array obtained for this system is in the range of 135-165 V for solar radiations varying as 200 W/m^{2}to 1000 W/m^2.

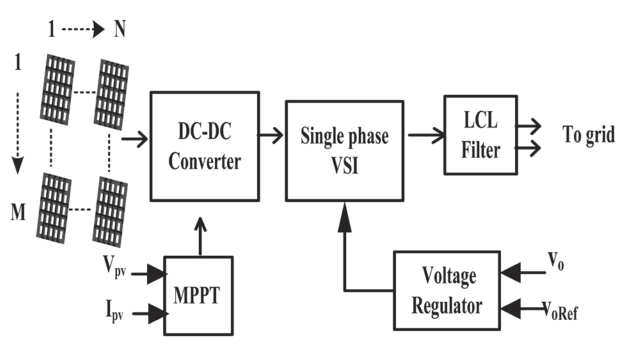

FIG. 1 BLOCK DIAGRAM OF SYSTEM CONFIGURATION

A full bridge converter converts this voltage to 380V for feeding the VSI. The VSI supplies this power to consumer loads. A low pass filter is connected for achieving a sinusoidal output voltage of 230 V (rms), 50 Hz. A full bridge boost dc-dc converter used here is operating in CCM (continuous conduction mode). In isolated mode,a high frequency transformer is used with this topology which reduces weight and provides an efficient way of the stepping up voltage and transferring large amount of power [6]. The controller for MPPT is designed based on Incremental Conductance (IC) technique. It is the most commonly used technique because of its easy implementation in the system. It works well for the varying conditions of the solar insolation and the temperature. A feedback PID controller is used for controlling the output voltage under varying conditions.

3.0 MODELLING OF SOLAR CELL

Equivalent circuit of a solar cell is realized as a current source in parallel with a diode with series and parallel resistances [7]. The output of the current source is directly proportional to the light falling on the cell (photocurrent I_{ph}). During darkness, the solar cell is not an active device, it works as a diode, i.e. a p-n junction. It does not produce a current or voltage. However, if it is connected to large supply voltage, it generates a current called diode current. The diode determines the I-V characteristics of the cell. The mathematical model of the pv array can be given as [8],

$$I_{pv} = n_1 I_{ph} - n_1 I_s \left\{ \exp\left(\frac{q}{AKT} \frac{V+IR_a}{n_2} \right) - 1 \right\} - \frac{(V+IR_a)}{R_b} \quad ....(1)$$

$$I_{ph} = [I_{sc} + k_1 \Delta T] \frac{G_1}{G_2} \quad .... (2)$$

$$I_s = \frac{I_{sc} + k_1 \Delta T}{\exp\left(\frac{V_{oc} + k_2 \Delta T}{AKT/q} \right) - 1} \quad .... (3)$$

where, $V_{pv}$is the output voltage of PV(*V*). I_{pv} is the output current of PV. I_{ph} is the short circuit current.$I_s$is the reverse saturation current of diode (*A*).*q* is the electron charge ($1.602\times10^{-19}C$).*K* is the Boltzmann's constant ($1.381\times10^{-23}J/K$).*T* is the junction temperature in *Kelvin (K)*. A is ideality factor of the diode.$R_a$is the series resistance of diode.$R_b$is the shunt resistance of diode, where, I_{pvt} is the light generated current at the nominal condition which are 25°C and 1000 W /m^2. $\Delta T = T_1 - T_2$, T_1 and T_2 is the actual and nominal temperature in Kelvin. G_1 (W/ m^2) is the value of solar irradiation by the PV surface and G_2 is the nominal value of solar irradiation. K_a is short-circuit current/temperature coefficient. K_b is open-circuit voltage/temperature coefficient. I_{SC} is the short-circuit current. V_{OC} is open-circuit voltage under the nominal condition [9]. Specifications for PV module are given in Table 1.

TABLE 1

CHARACTERISTICS OF PV MODULE

Peak power	250 W
Open circuit voltage	43.21 V
Short circuit current	7.63 A
Voltage at max. power	35.5 V
Current at max. power	7.04 A
Max system voltage	1000

For modeling of this system, a PV panel of 250 W nominal maximum power is selected andeightpanels are connected in series-parallel for an output power of 2000 W. The model of the PV module is implemented in a Matlab/Simulink. The influence of the variation in solar insolation and the cell temperature *T* on the cell characteristics are obtained from the model equations. Figure 2 shows the characteristics of PV model under rated condition i.e. solar insolation of 1000 W/m^2 and temperature 25°C. Characteristics of this module for varying conditions of solar insolation obtained through model are shown in Figure 3.

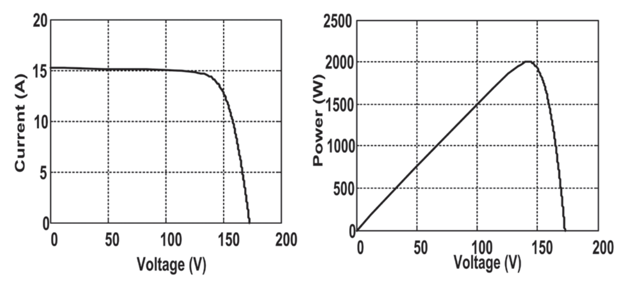

FIG. 2 CHARACTERISTIC OF PV ARRAY UNDER RATED CONDITION OF TEMPERATURE AND SOLAR INSOLATION

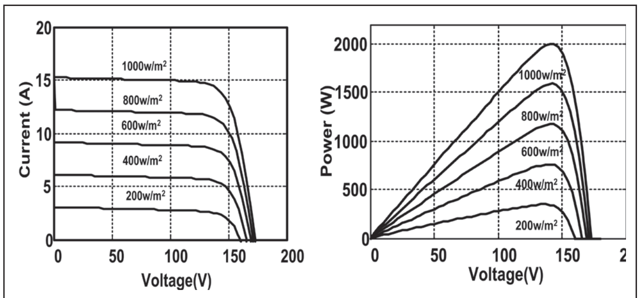

FIG. 3 CHARACTERISTIC OF PV MODULE UNDER CHANGING CONDITIONS OF SOLAR INSOLATION

4.0 DESIGN OF SYSTEM COMPONENTS

Figure 4 shows the circuit configuration of the proposed system. Here PV array is connected to an isolated full bridgeboost dc-dc converter through MPPT controller using an incremental conductance algorithm.

4.1 Modelling of MPPT Controller

Many techniques for MPPT (maximum power point tracking) are proposed to maximize the energy production in solar PV energy conversion systems. These techniques can be differentiatedwith different parameters i.e. simplicity, efficiency, digital or analogical implementation, sensors required, cost in implementation, range of effectiveness etc. These solar energy conversion systems are facing problems of low conversion efficiency and energy produced by these depends on amount of solar insolation and temperature. Characteristic curves i.e P-V and I-V are not linear but there is certain point on which system operates on its maximum efficiency and produces maximum energy. This point is known as maximum power point. It can be achieved by mathematical model or algorithms and system can be forced to operate at this point to produce maximum power. Here an IC (incremental conductance) method is used for MPPT. This algorithm can efficiently track the maximum power point under rapidly changing conditions of temperature and solar insolation. The output voltage and current from the PV panel are monitored and the MPPT algorithm is implemented through calculation of the conductance and incremental conductance and to make its decision to increase or decrease duty ratio of the dc-dc converter. This method is more efficient because panel terminal voltage is changed according to its value relative to the maximum power point voltage. Therefore, this method is independent on solar panel characteristics [10]. The incremental conductance method is derived from the fact that at maximum power point,

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \qquad ....(4)$$

With this eq.(4) one can get a relation i.e.

$$-\frac{I}{V} = \frac{dI}{dV} \qquad ....(5)$$

This eq.(5) shows that at maximum power point, the opposite of a PV source conductance should be equal to its incremental conductance.So this algorithm searches the voltage operating point at which the conductance is equal to the incremental conductance. So here maximum power point is tracked by comparing instantaneous value of conductance to the incremental conductance.

Once the maximum power point is reached, the system operates on that point unless a change in incremental conductance is noted and then algorithm again changes the value of duty ratio of dc-dc converter to track the new maximum power point.

4.2 Design of Full Bridge DC-DC Converter

Basic topology of a full bridge boost dc-dc converter (as shown in Figure 4) consists of four switches arranged in a bridge configuration with the primary winding of the transformer connected in between.

The secondary winding of transformer is center tapped and connected to a diode rectifier. This topology gives us advantage of lower current rating in secondary winding of the transformer and output inductor which makes it smaller in size.

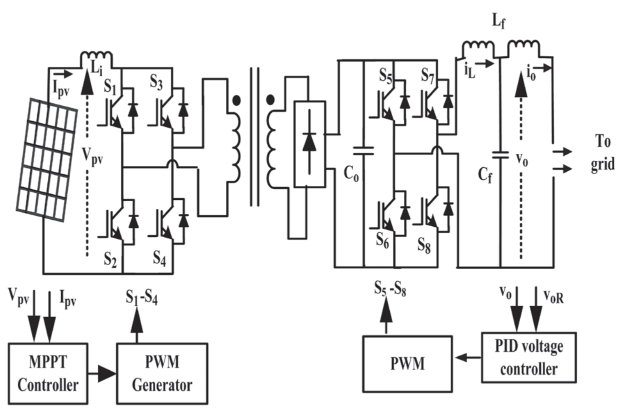

FIG. 4 CIRCUIT DIAGRAM OF PROPOSED SOLAR ENERGY CONVERSION SYSTEM

In this converter topology, the voltage appears across the primary winding is square wave of $\pm V_{dc}$ and the maximum voltage stress on switches is only the maximum dc input voltage. A PWM generator is used for generation of pulses for switches. Parameters considered for design of this full bridge converter are as, P_o (Output Power)= 2000 W, V_o (output voltage)= 380 V, V_{in} (Input voltage)= 135-165V, f_s (Switching Frequency) = 100 kHz, n (Turns ratio), ΔI_{Lo} (Ripple current through output inductance), D_{max} (duty cycle) = 0.4, η(efficiency)= 80%. Equations (6)-(8) are used for the calculation of design parameters as,

Turns ratio, $$n = \frac{V_o}{2\ Dmax.V_{in}} \quad \text{....(6)}$$

Turns ratio of the transformer windings is calculated as 1:5 as shown in eq.(6) considering maximum duty ratio of the dc-dc converter as 0.4.

Output inductance, $$L_0 = \frac{V_{in}D}{4\ \Delta I_{L0} f_s} \quad \text{....(7)}$$

The minimum value of output inductance, L_o required for operating the converter in CCM is calculated using eq.(7) as 100μH.

Output capacitance, $$C_0 = \frac{(1-2D)V_o}{32 L_o \Delta V_{co} f_s^2} \quad \text{....(8)}$$

The value of output capacitance, $C_o$iscalculated as 10μF, using eq. (8). Different parameters of the full bridge converter have been designed with its characteristics equations. The output of this converter is supplied to a full bridge VSI which generates 230Vac at 50Hz.

5.0 RESULTS AND DISCUSSION

A model of a stand-alone solar-PVsystem is developed with an isolated full bridge dc-dc converter with maximum power tracking controller for extracting maximum power from PV array and a PID controller is used in feedback of VSI for voltage regulation. Simulated results are obtained for different load conditions. Figure 5 shows the performance of the system under steady state solar radiations.

In these figures, V_{pv} is output voltage of PV array. I_{pv} is output current of PV array. $V_C$is output voltage of the full bridge converter. P_C is output power of full bridge converter. I_C output current of the full bridge converter. V_o and I_o are output voltage and current of VSI.

Figure 5 presents the system performance under steady state condition and the solar radiations under this case are considered as 1000W/m^2.

The output voltage and current are found sinusoidal and the same is connected to the grid.

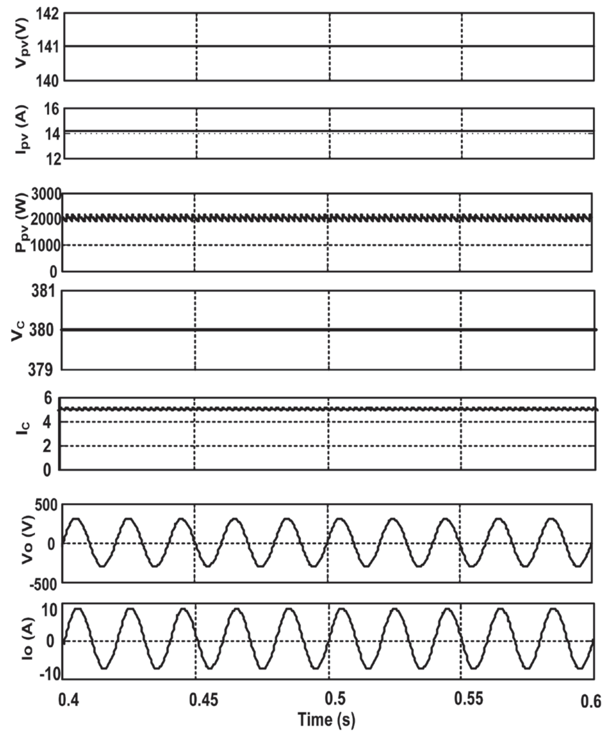

FIG. 5 PERFORMANCE OF THE SYSTEM WITH LINEAR LOAD CHANGES AT T=0.3S

Figure 6 and Figure 7 shows the harmonic analysis of the output voltage and current at linear load conditions which gives THD (Total Harmonic Distortion) of voltage 3.11% and current THD is 2.34%.

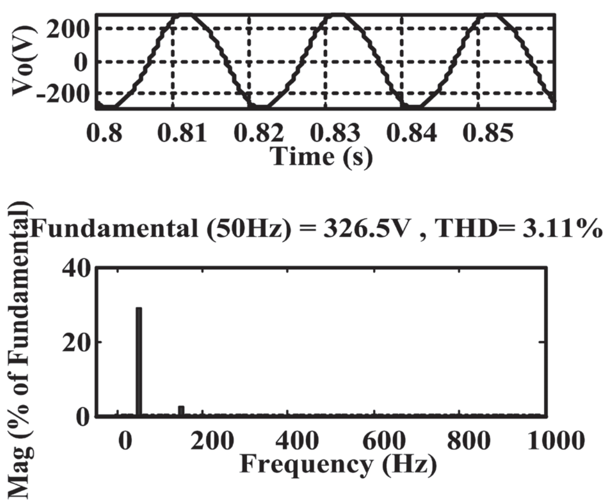

FIG. 6 HARMONIC ANALYSIS OF THE OUTPUT VOLTAGE IN LINEAR LOAD CONDITIONS

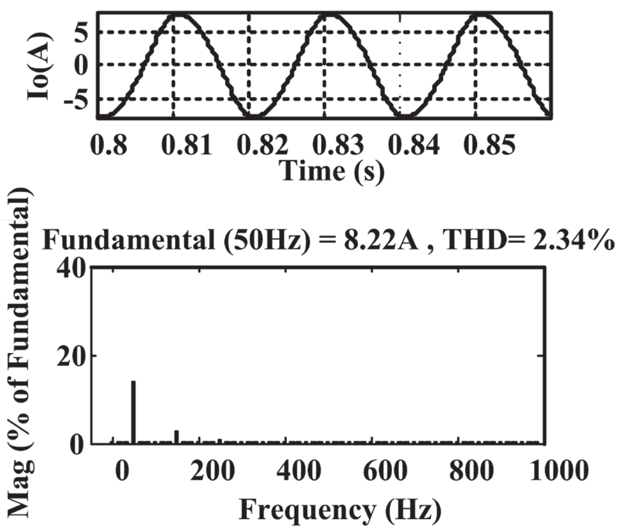

FIG. 7 HARMONIC ANALYSIS OF THE OUTPUT CURRENT IN LINEAR LOAD CONDITIONS

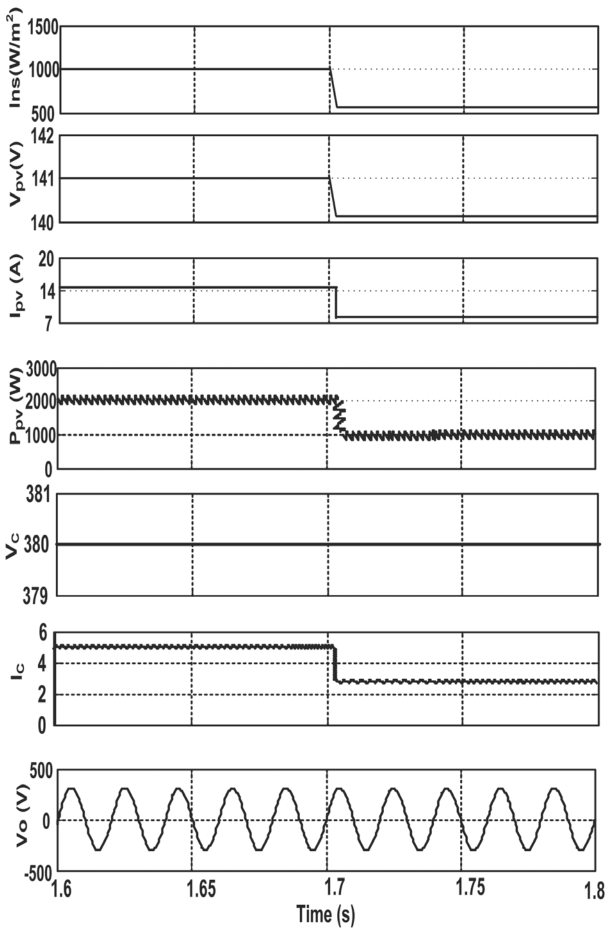

FIG. 8 PERFORMANCE OF THE SYSTEM WITH VARYING SOLAR RADIATIONS

Figure 8 shows the system results under varying solar radiations. The solar-PV voltage and current is varying due to variation in the solar radiations.

The output voltage of the dc- dc converter is remains constant in spite of the variations in solar radiations. The MPPT controller is found working satisfactorily in tracking of voltage and current. The change in output power is also observed due to variation in solar radiations. The output voltage is found as sinusoidal, thus the output voltage regulator is operating as per the designed reference.

6.0 CONCLUSION

The design, modeling and performance study of solar-PV isolated system has been carried out. Performance of the system has been found satisfactory in steady state and varying solar radiationsconditions. The system has been operated with MPPT controller of a PV array and a PID controller to control VSI, which has performed satisfactorily under varying conditions. Simulated results obtained for harmonic distortion of output voltage and current have been found in acceptable range.

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