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Design and Implementation of DC-DC Converter with Inc-Cond Algorithm

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***Abstract*—**The most important component affecting the efficiency of photovoltaic power systems are solar panels. In other words, efficiency of these systems are significantly affected due to the being low efficiency of solar panel. Thus, solar panels should be operated under maximum power point conditions through a power converter. In this study, design of boost converter has been carried out with maximum power point tracking (MPPT) algorithm which is incremental conductance (Inc-Cond). By using this algorithm, importance of power converter in MPPT hardware design, impacts of MPPT operation have been shown. It is worth noting that initial operation point is the main criteria for determining the MPPT performance. In addition, it is shown that if value of load resistance is lower than critical value, failure operation is realized. For these analyzes, direct duty control is used for simplifying the control.

***Keywords*—**Boost converter, Incremental Conductance (Inc-Cond), MPPT, Solar panel.

I. Introduction

INTEREST to renewable energy sources has increased in recent years. Reasons of this interest are depletion of fossil resources, legal regulations based on concerns of global warming, environmentalist movements of the World and taken measures for reduction air pollution [1]. Among renewable energy sources, solar energy is promising due to the its huge potential.

Solar energy is one of important renewable energy sources. Although geographical location of Turkey is convenient for use of solar energy where annual average solar irradiance and sunshine duration is quite high, electricity generation from solar energy is not common. Even if enactment of Renewable Energy Law (REL) in 2005 can be considered as a milestone for changing energy policy, significant progress has been made recently. REL updated in 2013 encourages to investors to install renewable energy sources based electricity generation plants. Each renewable source has different feed in tariff and locally manufactured equipments are also supported with bonus price. All these prices have been prepared by Turkish Ministry of Energy and Natural Resources (MENR). Furthermore, renewable energy sources based power plants capacity of 1 MW is exempted electricity generation license [2].

Equipments used in photovoltaic power plants are briefly summarized as solar panels, power converter, measurement system or data acquisition system, on-grid inverter and batteries. In these plants, solar panels must be operated under maximum power point tracking condition in order to extract available power from solar panel. For this purpose, MPPT algorithms have been developed and presented in [3]-[10]. In this study, Inc-Cond algorithm, which is very popular and most cited algorithm in literature, has been performed with a boost converter by using direct duty control method for simplicity. Remains of this paper are as follows. Mathematical model of solar panel and definition of MPPT and its dependency are presented in Section II. Inc-Cond algorithm is explained in Section III. Section IV shows the designing of boost converter with MPPT operation. Finally, results of three different experimental studies are analyzed and some important conclusions are drawn in the last section.

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II. Solar Panel

Solar cells consist of p-n junction. They can generate photo current when sunlight is absorbed and they behave as a basic diode without sunlight. Furthermore, a solar cell can generate 0.6V approximately. However, this voltage level is not enough almost for all applications. Therefore, solar cell connects with series or parallel in order to increase voltage and current, respectively. On the other hand, solar cells have nonlinear voltage-current (V-I) characteristics due to the p-n junction of diode. Fig. 1 shows a typical voltage current characteristic of solar panel.

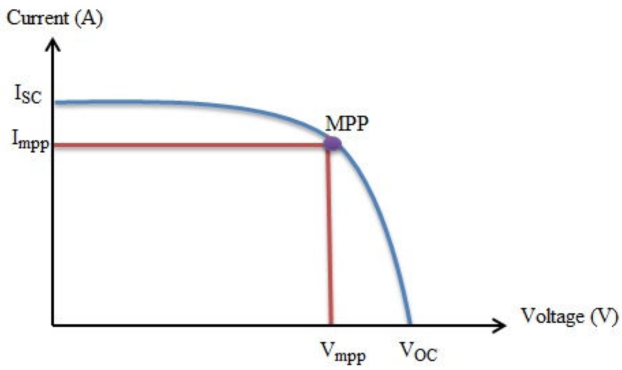

Fig. 1 V-I characteristic curve of solar panel

Since current of solar panel is approximately constant on the left side of maximum power point (MPP), this region can be defined as current source region. On the other hand, voltage range of solar panel is rather a limited on the right side of MPP and this side can be named as constant voltage source [11]. It is also noted that as shown in Fig. 2, since solar panel

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is modeled by using diode, V-I relationship is not linear due to the exponential characteristic of diode current.

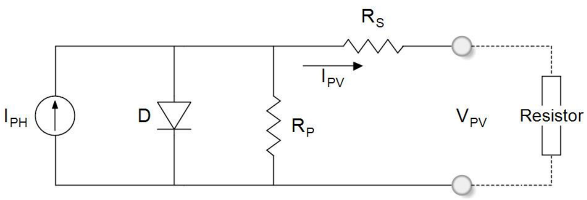

Fig. 2 Equivalent circuit of solar panel

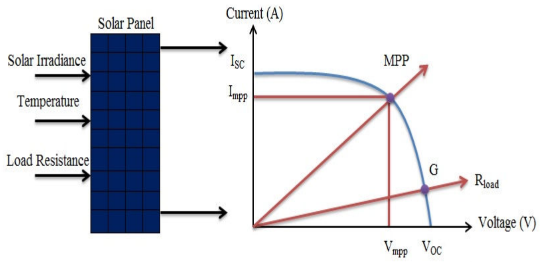

Fig. 3 Operation point of solar panel: MPP and G

In this equivalent circuit, I_{PH} is the photo current, D is the diode included p-n junction, R_P is the parallel resistance which corresponds to resistance of semi conducting component, R_S is resistance which corresponds to general transmission and joule losses. I_{PV} and V_{PV} are the solar panel current and voltage, respectively. As given in (1), photo current depends on reference and ambient solar irradiance, short circuit current, temperature and temperature coefficient:

$$I_{PH} = I_{SC}\frac{Q_A}{Q_R} - K_I(T_J - T_R) \tag{1}$$

where I_{SC} is the short circuit current, Q_A and Q_R are the ambient and reference solar irradiance, respectively, K_I is the temperature coefficient of solar panel current, T_J and T_A are the junction and ambient temperature, respectively. Solar panel current can be calculated as given in (2):

$$I_{PV} = I_{PH} - I_S\left(e^{\frac{[q(V_{PV} - I_{PV}R_S)]}{kT_JA}} - 1\right) - \frac{V_{PV} - I_{PV}R_S}{R_P} \tag{2}$$

where I_S is the saturation current, k is the Boltzmann constant (k=1.38 x 10^{-23} J/K), q is the electron charge (q=1.6 x 10^{-19}).. Output power of solar panel depends on ambient solar irradiance, temperature and load resistance as presented in Fig. 3. Since output performance of solar panel changes by the variations of these parameters, inefficient operation condition can be occurred. Therefore, solar panel and load should be connected by a power converter. With the help of this power converter, voltage and current of solar panel are automatically adjusted to MPP value and MPPT operation is provided. As given in Fig. 3, point G is not efficient point. If solar panel operated under this point, capacity of solar panel is not used. By using power converter which is a DC-DC boost converter in this study, optimum operation condition (MPP) is realized by sensing the voltage and current of solar panel. In MPPT operation, voltage and current are processed and required signal is generated by control unit.

III. Incremental Conductance Algorithm

Inc-Con is very popular algorithm running concurrently with solar panel which is based on measurement of voltage and current of solar panel for a certain frequency. According to the measurement results, incremental and instantaneous conductance are calculated and compared. Finally, required control command is generated by MPPT control unit. Fig. 4 shows flowchart of this algorithm.

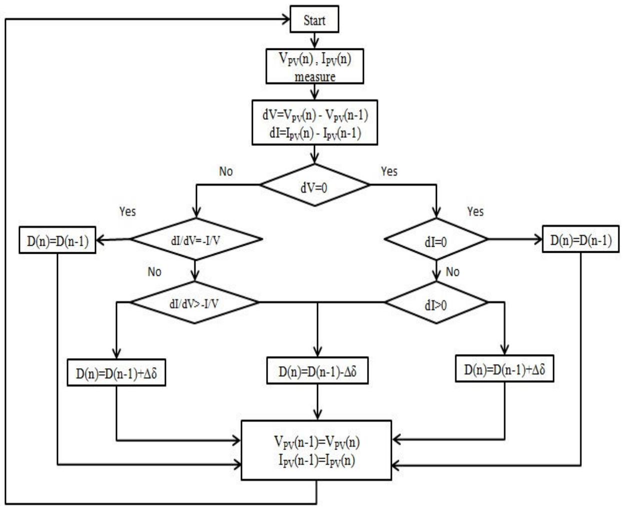

Fig. 4 Inc-Cond algorithm

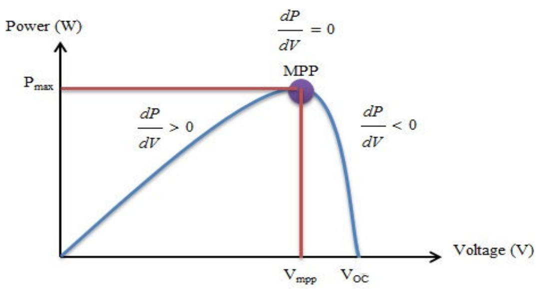

Fig. 5 Power voltage characteristic of solar panel

Power-voltage characteristic of solar panel is shown in Fig. 5. Equations (3)-(5) are the main equations that can be written for this algorithm as given below:

$$\frac{dP}{dV} = 0 \rightarrow \frac{\Delta I}{\Delta V} = -\frac{I}{V} \rightarrow MPP \tag{3}$$

$$\frac{dP}{dV} > 0 \rightarrow \frac{\Delta I}{\Delta V} > -\frac{I}{V} \tag{4}$$

$$\frac{dP}{dV} < 0 \rightarrow \frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad (5)$$

IV. DC-DC Boost Converter with MPPT Control

Solar panels are nonlinear energy source in DC form. For this source, amount of generated energy depends on solar irradiance, temperature and load resistance. However, some limitations can cause to fail MPPT operation. These limitations may be amount of solar irradiance, temperature and value of load resistance. In order to provide MPPT operation in high reliability, these limitations have to be determined.

In addition, MPPT is needed for almost all photovoltaic systems. This requirement can be accepted as a standard for a photovoltaic system. Therefore, solar panels should be connected to the load, battery or grid through a power converter. While photovoltaic array is connected to the AC load via an inverter with MPPT control, in DC applications, DC-DC converter is used for MPPT operation.

While analyzing MPPT performance of DC-DC converter theoretically, load resistance, solar irradiance and temperature are assumed as constant. A typical MPPT or DC-DC converter with MPPT control can be analyzed as follows: Input voltage of DC-DC converter is solar panel voltage and input equivalent resistance of solar panel is calculated as given in (6):

$$R_{PV} = \frac{V_{PV}}{I_{PV}} = \frac{V_i}{I_i} \quad (6)$$

where V_i is the input voltage of boost converter and I_i is the input current of boost converter. Output voltage of boost converter is calculated as given in (7).

$$V_o = V_i \frac{1}{1-D} = I_o R_{load} \quad (7)$$

where V_O is the output voltage of solar panel, D is the duty ratio of PWM signal, I_O is the output current of solar panel and R_{load} is the value of load resistance. Input voltage or voltage of solar panel can be defined as given in (8).

$$V_{PV} = I_{PV} R_{PV} \quad (8)$$

As can be seen in (9), equivalent resistance of solar panel depends on load resistance and duty ratio of PWM signal. That is, MPPT operation can be realized by changing duty cycle. On the other hand, this procedure can be applied to other DC-DC converter topology. Fig. 6 shows the relationship between solar irradiance and equivalent resistance of solar panel. It is clear that by increasing of solar irradiance, equivalent resistance of solar panel under MPP decreases.

$$R_{PV} = \frac{V_{PV}}{I_{PV}} = \frac{V_i}{I_i} = R_{load}(1-D)^2 = \frac{V_o}{I_o}(1-D)^2 \quad (9)$$

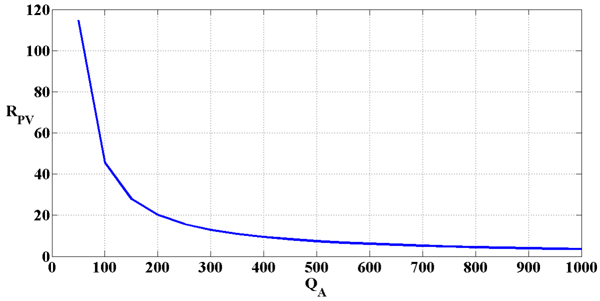

Fig. 6 Relationship between solar irradiance and equivalent resistance of PV module

Fig. 7 shows that relationship between duty ratio and different solar irradiance. Range of load resistance increases in case of increasing of solar irradiance and possibility of MPPT success improves. On the other hand, under low solar irradiance conditions, range of load resistance is limited and MPPT capability is reduced.

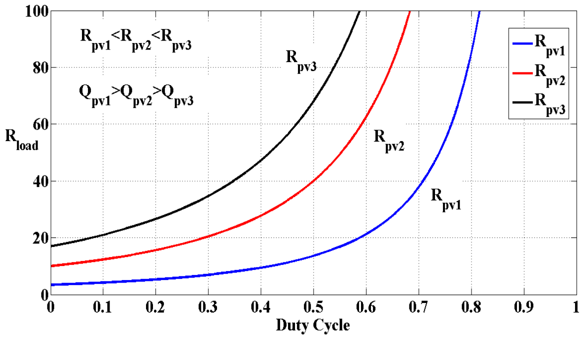

Fig. 7 Relation of R_{load} and D under constant solar irradiance

V. Experimental Results

In this study, MPPT operation has been carried out by a DC-DC boost converter controlled Inc-Cond algorithm. Minimum input voltage of boost converter which is solar panel voltage is assumed as 75% of open circuit voltage of solar panel. Inductance value is calculated by maximum power current value of solar panel under standard test condition (STC). Inductance value is 1mH; output capacitor is selected as 68 uF by assuming 1% voltage ripple. IRFP450 and MUR840 are selected as power switch and recovery diode, respectively. LTS25-NP and voltage divider circuit are also used for current and voltage sensing, respectively. Current and voltage data are converted to digital data by PIC18F452. Then, optimum duty cycle of PWM signal is generated [11].

In experimental studies Maximum power of solar panel is 90W under STC. Besides, maximum power voltage and current are 17.5V and 5.4A, respectively. Amount of solar irradiance is approximately 600W/m^2 under first experiment sensed by Sunny Sensor Box manufactured by SMA. Efficiency of boost converter is approximately 85% and maximum output power of boost converter is 40W for this condition.

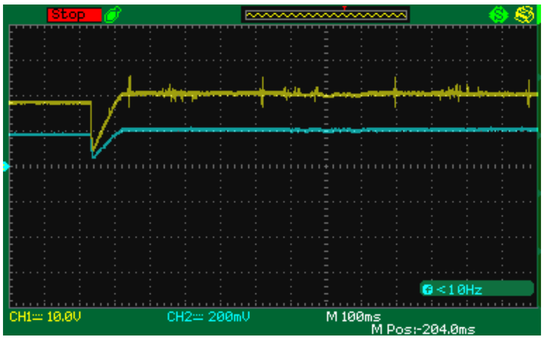

Fig. 8 First condition (R_{load} =10Ω)

As shown in Fig. 8, voltage and current of solar panel is 18V and 1.8A, respectively before MPPT operation starts. Value of load resistance is 10Ω and solar panel connects to the load directly. When MPPT operation starts, new output voltage and current become 20V and 2A respectively in 100 msec. Since value of load resistance is close to optimum value. Therefore, power increment is low. However, if load resistance doubles or increases, effect of MPPT operation is more significant than the first condition. Power increment is higher than the first case. Fig. 9 shows that voltage and current waveforms.

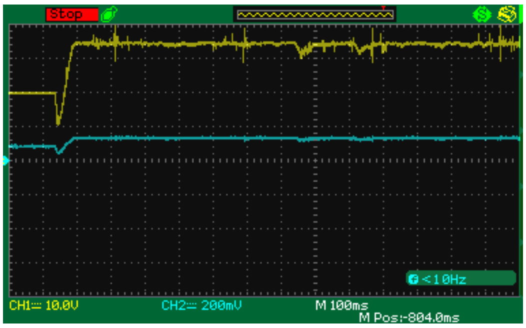

Fig. 9 Second Condition (R_{load} =20Ω)

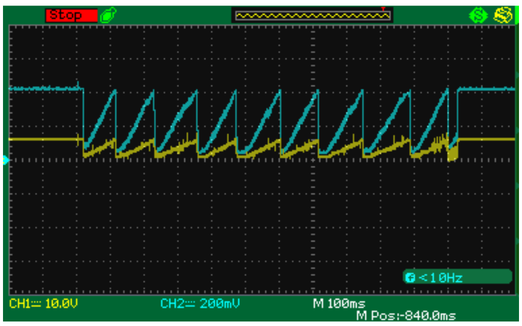

Fig. 10 Failure MPPT condition (R_{load} =2Ω)

If load resistance decreases significantly, MPPT operation can fail. Because boost converter has some limitations related to limitation in range of load resistance. In order to show failure condition of boost converter, duty ratio of PWM signal is not limited. Fig. 10 shows that when sharp decreases in Fig. 10 occur, duty ratio of PWM signal converges to 0% and MPPT operation is not active and MPPT has not been accomplished.

VI. Conclusion

In this study, design of DC-DC boost converter design and MPPT operation has been conducted under different loading conditions. Besides, a failure case for MPPT has been shown and analyzed. It is shown that power converter circuit is an important element of MPPT systems.

MPPT operation of DC-DC converter has been analyzed by making some assumptions. Load resistance, solar irradiance and temperature have been assumed as constant value during the experimental studies. Relationship between duty ratio of PWM signal and equivalent resistance of solar panel are determined by using basic equations of a DC-DC converter topology.

Boost converter has been performed with Inc-Cond algorithm by using direct duty control for the simplicity and low cost. It is shown that MPPT operation performs better under high load resistance condition than low load resistance one. But, if load resistance decreases more, MPPT operation may fail. Therefore, duty ratio should be limited and range of load resistance should be determined for the purpose of high MPPT success.

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