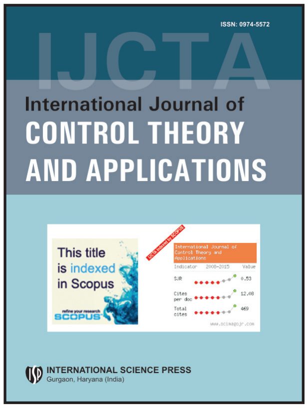

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Speed Control of Solar powered Separately Excited DC Motor

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Abstract: This paper presents speed control of solar powered Separately Excited Direct current Motor (SEDM) for both variations in solar irradiance and set point. The solar photovoltaic (PV) array takes solar irradiance as input and produces DC output voltage to the load. In this paper, the source side variations are controller by using Maximum Power Point Tracking (MPPT) strategy in boost converter and set point variations are controlled by a PID controller with buck-boost converter. The MPPT controller used in this paper maintains the operating point of the system at maximum power point by using Incremental Conductance (IC) algorithm. From the simulation study, it is proved that the source side variations and set point variations are controlled effectively by the proposed method.

Keywords: Photovoltaic (PV), Separately Excited Direct current Motor (SEDM), MPPT control, IC algorithm, Boost converter, Buck-boost converter, PID controller.

1. INTRODUCTION

As the conventional source of energy is reducing fast and the cost of the energy is rising, solar PV generators are considered as infinite and clean source of energy. Due to fast reduction in solar PV panel cost, the usage of solar power for different applications has increased in recent years.

To provide the maximum possible power under varying conditions, the control system aims to regulate the PV generators so that they are always at the maximum power point. The maximum power point changes with the input like solar irradiance, panel temperature and with the characteristics of the load. Therefore, MPPT techniques are employed in solar array powered systems to optimize the power from the array output.

In this paper, an off-grid application like powering an electric motor using solar PV generator is considered. A comparative study for steady state performance of different excitation types for the dc motors (separately, series and shunt) directly coupled to PV generators has been presented in [1] and it was concluded that the SEDM is the best candidate to be matched to the PV generator. The steady state performance of a dc motor supplied from a solar PV array with boost converter (step up) was studied in [2] and it was concluded that there is a unique duty ratio at which the maximum utilization efficiency can be achieved.

Similarly, the performance of a dc motor driving a centrifugal pump supplied from the PV generator via the step-up converter is studied in [3]. In this study, the converter duty ratio is controlled using a feedback current locked loop (Whenever the input irradiance changes, the output current of the PV generator is adjusted by the feedback loop). Generally, the MPPT controllers are designed to adjust the converter duty cycle to achieve maximum power. Different MPPT techniques have been proposed and implemented to various degrees of success. Some of the commonly implemented MPPT techniques are Constant current, Constant voltage, Perturb and Observe (P&O) and Incremental Conductance (IC) methods.

A comparative analysis on different types of MPPT techniques like conventional, artificial intelligence based and hybrid methods was done in [4]. From the simulation results, it has been concluded that the conventional method is simple and cheap than the artificial intelligence and hybrid methods. Among the conventional methods, it was found that the performance of IC MPPT is better as compared to other methods. In [5], a comparative study on MPPT techniques like First-Order Differential (FOD), P&O and IC methods was done. From the results, it was concluded that P&O and IC methods showed less MPPT errors and better efficiency than FOD method.

The Simulink model of P&O and IC algorithms are implemented and simulated in [6]. From its comparative analysis, it was concluded that P&O method is easy but IC method is suitable than P&O to track MPP under rapidly changing conditions. A comparative analysis between P&O and IC methods was done in [7]. From the results, it was concluded that the IC method requires less iterations than the P&O method. Due to this, the IC method has faster tracking speed than the P&O method.

The Solar power based DC-DC converter for armature voltage controlled separately excited motor is implemented in [8]. In this study, depending upon the firing angle speed of the buck-boost converter, torque and armature current of motor is varied to achieve speed control. Similarly, a comparative analysis of PID and fuzzy logic control for solar powered SEDM was implemented in [9]. In this study, the rise time, peak time, settling time and steady state errors for PID and fuzzy control are compared. From the results, it was seen that PID control had a high settling time than the fuzzy control.

The speed control of a separately excited DC motor powered by photovoltaic energy for both source and load variations was implemented in [10]. In this study, the variations in SEDM speed due to variations in solar irradiances was controlled by a MPPT controller (P&O) method and that due to load were controlled using a cascaded PID controller.

In the proposed system, a speed control of SEDM powered using solar PV array is achieved using an IC MPPT controller and a PID controller. In this paper, the MPPT controller calculates the duty cycle of a boost converter and adjusts it to achieve the maximum power under various conditions. Similarly, the load variations are controlled by a conventional PID controller through the duty cycle of a buck-boost converter. The speed control system consists of components like Solar PV array, Boost Converter, MPPT controller, Buck – Boost controller, PID controller and SEDM.

The paper is organized as follows: Section 2 deals with the modelling and working of solar PV array, Section 3 provides a brief explanation on the speed control system for the solar powered SEDM, Section 4 deals with the working of MPPT with IC algorithm, Section 5 deals with the design of the solar powered SEDM control system, Section 6 deals with the simulation study of the solar powered SEDM control system and Section 7 represents the conclusion of the paper.

2. SOLAR PHOTOVOLTAIC ARRAY

The solar PV array is a power system designed to supply usable solar power by means of photovoltaic effect. The solar PV cell is made of semiconductor material which converts the solar radiation into direct current electricity.

A solar PV cell model consists of a photocurrent, diode, parallel and series resistors. But a solar PV array consist of Ns cells connected in series to form a module and Np modules connected in parallel to form a PV array. Thus, the equivalent circuit of a solar PV array is as shown in Figure 1.

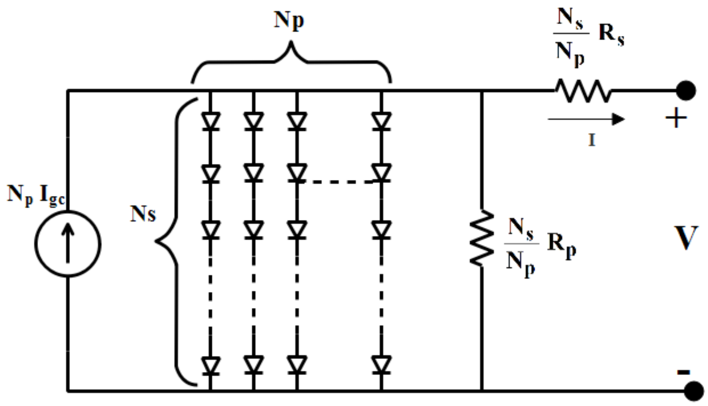

Figure 1: Equivalent circuit of a solar PV array

The specific characteristics of the PV array depend on the number of modules connected in series (*ns*) and parallel (*np*), that are selected according to the type of the solar modules used, and the expected solar radiation, and ambient temperature of the location where the PV array would be used. The photovoltaic current can be calculated by applying Kirchhoff's current law and its parameters are listed in Table 1.

$$I = N_P I_g - N_P I_S \left[\exp\left(\frac{q}{K_B\, FT} \left(\frac{V_{pv}}{N_S} + I_{pv} \frac{R_S}{N_P} \right) \right) - 1 \right] \frac{V_{pv}\left(\frac{N_P}{N_S}\right) + I_{pv} R_S}{R_P} \tag{1}$$

Table 1
Parameters of Solar PV array

Symbol	*Description*
I_g	Photocurrent
I_S	Cell saturation of dark current
q	Electron charge ($1.6 * 10^{-19}$ C)
K_B	Boltzmann's constant ($1.38 * 10^{-23}$ J/K)
T	Cell's working temperature
F	Ideal factor
R_P	Shunt resistance
R_S	Series resistance

3. SOLAR POWERED SEDM CONTROL SYSTEM DESCRIPTION

In this system, the speed of the SEDM powered by solar PV array is controlled by using MPPT and PID controllers. The solar PV array takes the solar irradiance (G) and temperature (T) as input and produces a DC output voltage (V_{pv}). The boost converter amplifies the PV array voltage to the required level (V_s). The duty cycle (α) of the boost converter is controlled by a MPPT controller. Thus, speed control of SEDM for variations in the input is achieved using MPPT controller.

The output voltage (V_s) from the boost converter is fed as input to the buck – boost converter The PID controller takes the difference in speed (error) as input and varies the converter duty cycle (D) to produce the required output voltage (V_a). This output from the buck-boost converter is fed as input to the armature of the SEDM. Due to this, the PID controller maintains the speed of SEDM even under load fluctuations.

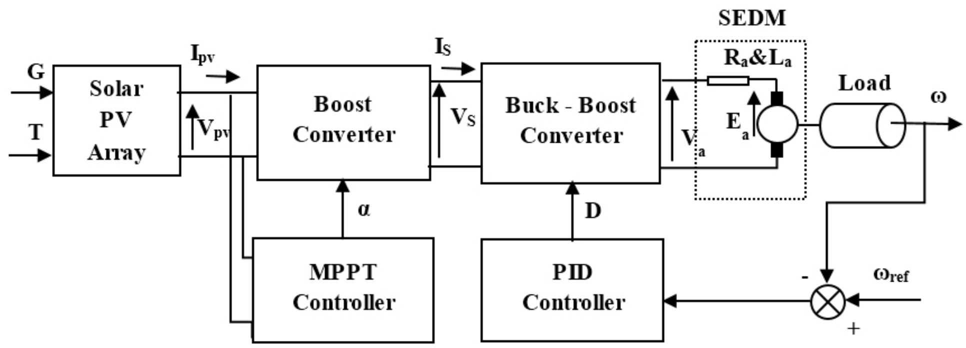

Figure 2: Block diagram of solar powered SEDM control system

Here the speed variations due to change in input irradiance and temperature will be controlled by an MPPT controller whereas the variations due to change in load will be controlled by a load controller. Hence variation in speed of SEDM due to both irradiance and load can be controlled simultaneously. The design and the control of the proposed system are elaborated in the following section 5.

4. MAXIMUM POWER POINT TRACKING

The speed control of solar powered SEDM under varying solar irradiance is achieved by using MPPT controllers. MPPT is a real-time process that is used to locate the combination of current and voltages at the output of the PV generator that gives the maximum possible power which can be extracted from the PV under given operating conditions.

Although there are many MPPT techniques, the most frequently implemented MPPT techniques are Constant current, Constant voltage, Perturb and Observe (P&O) and Incremental Conductance (IC) methods. In the comparative analysis studied in [4], [5], [6] and [7], it was concluded IC method was better than P&O method. Thus, IC method is implemented in this paper for speed control of solar powered SEDM.

4.1. Incremental Conductance Algorithm

The IC method is based on the fact that the slope of the solar P-V curve is zero at the maximum power point, negative at the right and positive at the left (i.e)

$$\frac{dP}{dV} > 0 \text{ at left of MPP}, \ \frac{dP}{dV} < 0 \text{ at right of MPP} \ \text{ and } \ \frac{dP}{dV} = 0 \text{ at MPP}$$

Since $\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} = I + V\frac{dI}{dV}$ the above equations can be rewritten as:

$$\frac{dI}{dV} > \frac{-I}{V} \text{ at left of MPP}, \frac{dI}{dV} < \frac{-I}{V} \text{ at right of MPP and } \frac{dI}{dV} = \frac{-I}{V} \text{ at MPP}$$

Due to this, the IC method tracks the maximum power point by using the incremental and instantaneous conductance. Thus, the IC algorithm takes the output current and voltage of the solar PV array as input and then computes and compares the instantaneous and incremental conductance to produce the converter duty cycle as output. Figure 3 shows the flowchart for the IC algorithm.

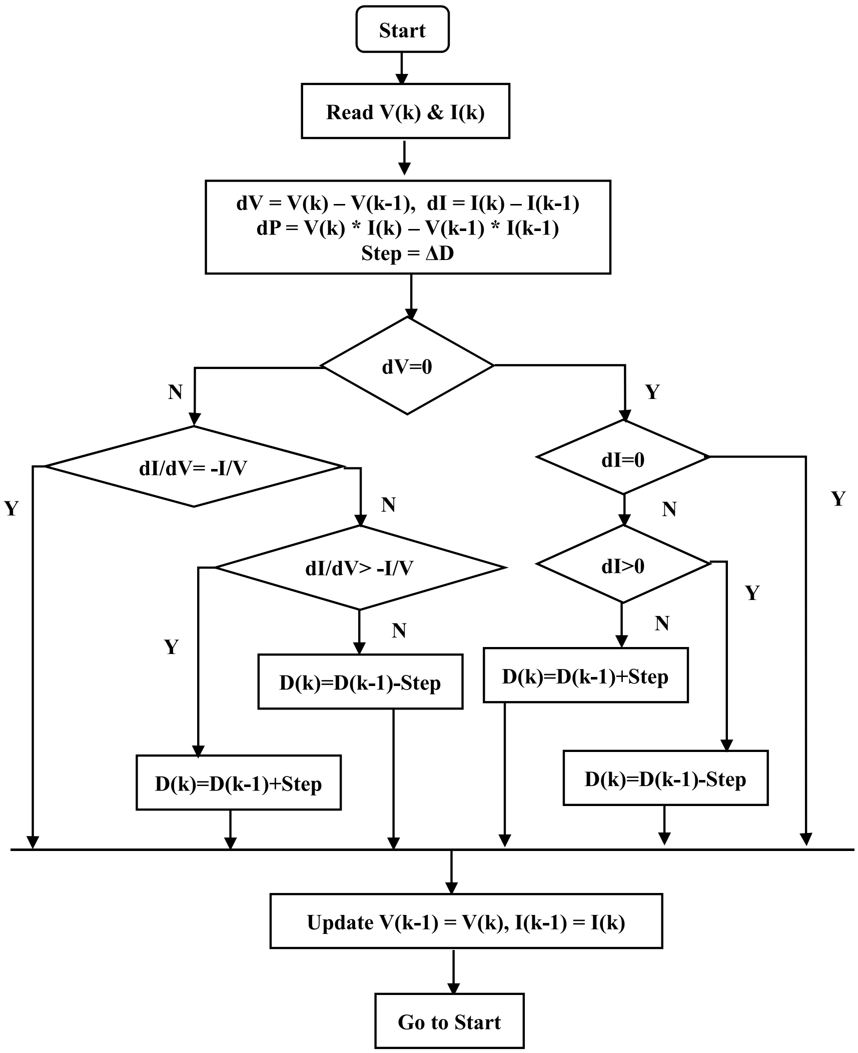

Figure 3: Flowchart of Incremental Conductance algorithm

Due to this, the IC algorithm uses the incremental conductance to find the sign of dP/dV without perturbation. Thus, under rapidly changing environmental conditions, the IC method will not perturb around the maximum power point.

5. DESIGN OF SOLAR POWERED SEDM CONTROL SYSTEM

The various operating stages of the solar powered SEDM control scheme such as solar PV array, boost converter, MPPT controller, buck-boost converter, PID controller and SEDM are designed to operate satisfactorily under any change in input irradiance and setpoint.

5.1. Solar PV Array

The solar PV array type used in the system is Soltech 1STH-215-P with 4 series modules and 10 parallel strings. The specifications of the solar PV module used in this system are listed in Table 2.

Table 2
Solar PV module Specifications

Parameters	*Values*
Cells per module (Ncell)	60
Maximum power (W)	213.15
Open circuit voltage Voc (V)	36.3
Short circuit current Isc (A)	7.84
Voltage at MPP Vmp (V)	29
Current at MPP Imp (A)	7.35
Temperature coefficient of Voc (%/deg C)	–0.36099
Temperature coefficient of Isc (%/deg C)	0.102

5.2. Boost converter Design

The solar PV array voltage appears as input to the boost converter and the output from this converter is given as input to the buck – boost converter. The boost converter consists of a switch, inductor on the input side and capacitor on the load side. Since it is a step-up converter, the output voltage will always be greater than the input voltage. Thus, it is also known as step-up converter. The circuit diagram of boost converter is as shown in Figure 4.

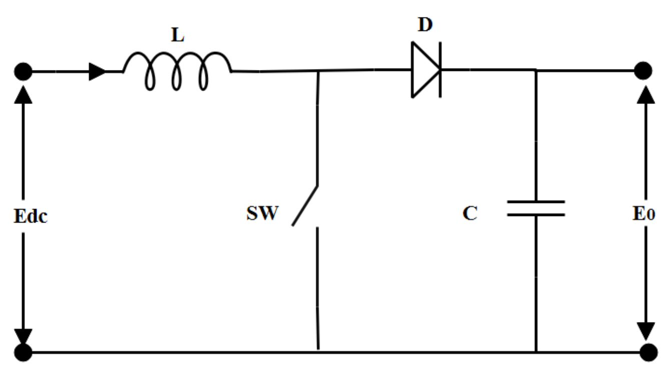

Figure 4: Circuit diagram of a Boost converter

Based upon the duty cycle of the switch, the boost converter amplifies the applied input PV array voltage. In order to obtain maximum power, the duty cycle of the switch is controlled by a MPPT controller in this paper. The inductor and capacitor values are designed by using the following formulae:

$$L = \frac{E_{dc}\,\alpha}{F_s\,\Delta I}$$

$$C \geq \frac{E_0\,\alpha}{F_s R\,\Delta V}$$

where, $\alpha = \frac{E_0 - E_{dc}}{E_0}$ (2)

By substituting the values listed in Table 3 in (2), the inductor and capacitor of the boost converter are calculated as L = 12 mH and C = 8 mF.

Table 3
Parameters of Boost converter

Parameters	*Value*
Input voltage (E_{dc})	120 V
Output voltage (E_0)	130 V
Switching frequency (F_S)	5000 Hz
Load resistance (R)	2.581 Ω
Ripple current (ΔI)	0.15 A
Ripple voltage (ΔV)	0.1 V

5.3. MPPT Controller Design

The speed control of solar powered SEDM under source side variations is achieved using MPPT controller. The MPPT controller implemented in this paper uses IC algorithm. Thus, the MPPT controller takes the solar PV array voltage and current as input and provides the duty cycle as output. This value of duty cycle is fed to the boost converter through a PWM generator. Thus, whenever there are variations in the input irradiance, the MPPT controller varies the converter duty cycle to maintain the maximum power.

5.4. Buck-Boost Converter Design

The output from the boost converter is fed as input to the buck – boost converter in the load side. The output voltage from this is given as input to the SEDM. Figure 5 shows the circuit diagram of a buck – boost converter.

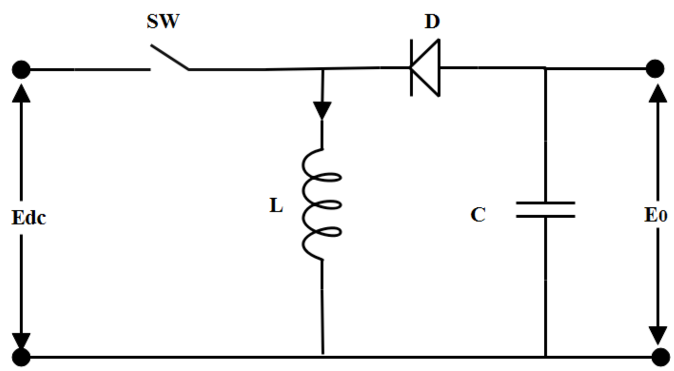

Figure 5: Circuit diagram of a Buck - Boost converter

The buck – boost converter is a cascade connection of boost (step-up) and buck (step-down) converters. Thus, based upon the duty cycle of the switch, the output voltage can be made either greater or lesser than the input voltage. In this control, the PID controller varies the duty cycle to minimize the error in the speed of the SEDM. The inductor and capacitor values are designed by using the following formulae:

$$L = \frac{E_{dc}\alpha}{F_s \, \Delta I}$$

$$C \geq \frac{E_0 \, \alpha}{F_s R \, \Delta V}$$

where, $\alpha = \dfrac{E_0}{E_0 - E_{dc}}$ (3)

Table 4
Parameters of Buck - Boost converter

Parameters	*Value*
Input voltage (E_{dc})	130 V
Output voltage (E_0)	240 V
Switching frequency (F_S)	40 KHz
Load resistance (R)	2.581 Ω
Ripple current (ΔI)	0.3 A
Ripple voltage (ΔV)	2 V

By substituting the values listed in Table IV in (3), the inductor and capacitor of the converter are calculated as L = 2.4 mH and C = 11.2 mF.

5.5. PID Controller Design

The speed control of solar powered SEDM for variations in set point is achieved by using a PID controller. The PID controller takes the error (Set point – Actual Speed) as input and produces the converter duty cycle value as output. The PID controller parameters are tuned optimally by using a Real coded Genetic Algorithm (RGA) and are listed in Table V.

Table 5
PID controller values

Parameters	*Value*
Proportional (P)	10
Integral (I)	0.1
Derivative (D)	0.5

The output from PID controller is fed as input to the buck-boost converter through a PWM generator. Thus, whenever there are variations in the set point, the PID controller maintains the speed at the required level.

5.6. Separately Excited Direct Current Motor (SEDM)

In a SEDM, the field and armature circuit has independent voltage sources. This means that the armature and the field voltages can be controlled separately, which give it the advantage of better electrical and mechanical performances than the other DC motor configuration.

The characteristic equations of SEDM are represented as:

$$\frac{di_a}{dt} = \frac{1}{L_a}\left(U_a - R_a i_a - E_a\right) \tag{4}$$

$$\frac{di_f}{dt} = \frac{1}{L_f}\left(U_f - R_f i_f\right) \tag{5}$$

$$\frac{dw}{dt} = \frac{1}{J}\left(T_e - T_L - B_w\right) \tag{6}$$

where, T_e is the developed electrical torque, E_a is the back EMF, B denotes the viscous friction coefficient and J is the moment of inertial. The torque developed by the SEDM is given by $T_e = K_t * i_f * i_a$, where K_t is torque constant in V/A-rad/ sec.

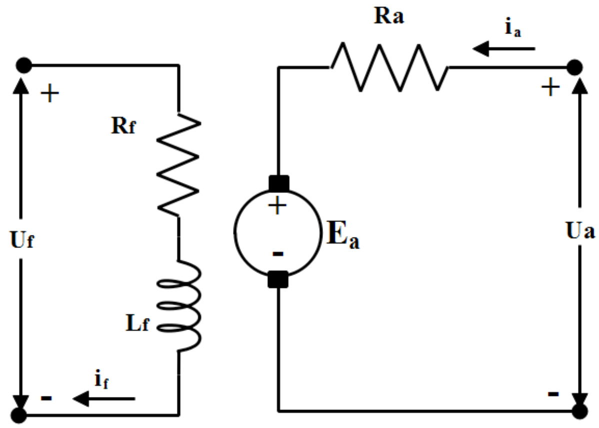

Figure 6: Equivalent circuit of a Separately Excited DC Motor

Thus, the equivalent circuit of SEDM is as shown in figure 6 and its specifications are listed in Table VI.

Table 6
SEDM Parameters

Parameters	*Value*
Rated motor voltage (U_a)	240 V
Field excitation voltage (U_f)	300 V
Rated motor speed (ω_m)	1750 RPM
Armature Resistance (R_a)	2.581 Ω
Armature Inductance (L_a)	0.028 H
Field Resistance (R_f)	281.3 Ω
Field Inductance (L_f)	156 H
Load torque (T_L)	1 Nm

For the SEDM used in this paper, the field is excited by using a constant voltage source and the armature is excited by using the output voltage from the buck-boost converter. Thus, both the MPPT and PID controllers are designed to maintain the speed of the SEDM.

6. SIMULATION STUDY OF SOLAR POWERED SEDM CONTROL SYSTEM

The performance of the proposed solar powered SEDM control system is simulated in the MATLAB/Simulink environment using its Sim power system toolbox. The performance of the proposed system is studied for set point variation and source side variation (Solar irradiance variation).

6.1. Performance under Setpoint Variation Condition

Based on the expected application in SEDM, the simulation is performed for step changes in setpoint (Reference speed). In this simulation study, solar irradiance is kept constant at 800 W/m^2, ambient temperature is assumed as constant at 25° C and load torque kept constant at 1 Nm. The simulation result for setpoint variation is shown in Figure 7.

From the Figure 7, it is understood that the speed of SEDM is able to track the variation in setpoint. In this simulation study, the PID controller parameters are tuned optimally using RGA to minimize overshoot, rise time, peak time and settling time.

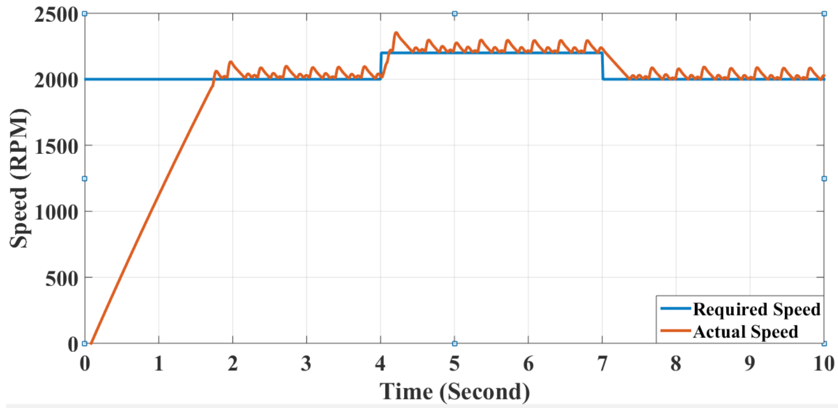

Figure 7: Profile of Speed and Reference Speed

6.2. Performance under Source Side Variation Condition

The performance of solar powered SEDM control system under source side variation is studied by varying the irradiance level as shown in Figure 8.

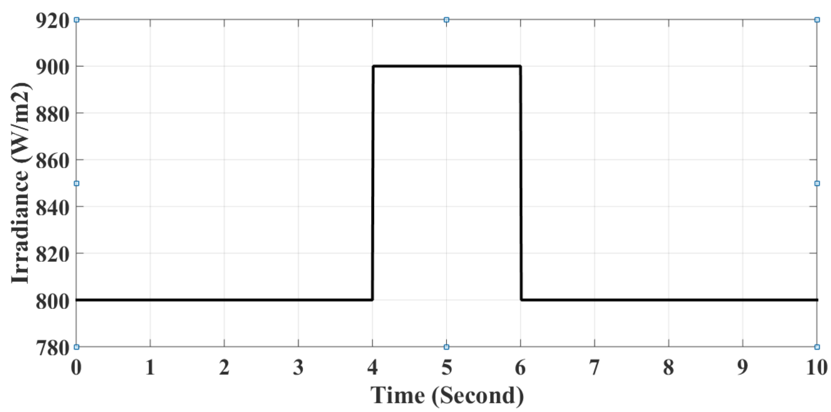

Figure 8: Profile of Irradiance

Even though there is a variation in input irradiance, the speed of SEDM is kept constant and is shown in Figure 9.

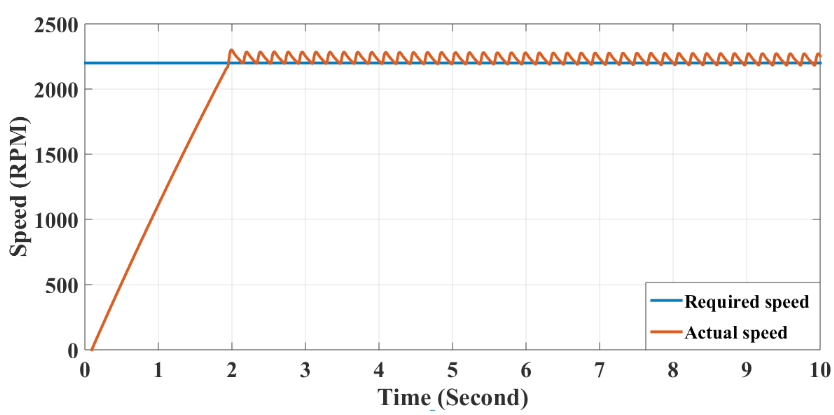

Figure 9: Profile of Speed of SEDM under source side variation

This performance implies that the proposed solar powered SEDM control system operates successfully even at a variation of 10% of solar irradiance.

7. CONCLUSION

The performance of the proposed solar powered SEDM is modelled, designed and simulated in MATLAB/ Simulink environment using its Sim power system toolbar. The MPPT algorithm calculates the maximum power point of the solar PV array and tracks it continuously for variations in input irradiance. The PID controller is used for independently regulating the speed of SEDM. The buck-boost

converter provides the flexibility to increase or decrease the input voltage to the SEDM. Due to this, the working of MPPT controller is not limited within a region. Using the simulated results, a MPPT controller, buck-boost converter and PID controller with SEDM is proved as a suitable combination for solar powered SEDM control system.

REFFERENCES

[1] Appelbaum J., "Starting and steady-state characteristics of dc motors powered by solar cell generators", *IEEE Transaction on Energy Conversions*, Vol. EC-1, No. 1, March 1986.

[2] Alghuwainem S M., "Steady-state performance of dc motors supplied from photovoltaic generators with step up converter", IEEE Transactions on Energy Conversion, Vol. 7, No. 2, pp. 267-272, June 1992.

[3] Alghuwainem S M., "Matching of a dc motor lo a photovoltaic generator using a step-up converter with a current-locked", IEEE Transactions on Energy Conversion, Vol. 9, No. 1, pp. 192-198, March 1994.

[4] Ankit Gupta, Yogesh K. Chauhan and Rupendra Kumar Pachauri, "A comparative investigation of maximum power point tracking methods for solar PV system", *Elsevier, Solar Energy*, Volume 136, October 2016, Pages 236–253

[5] Nafaa Jeddi., & Lilia El Amraoui Ouni., "Comparative Study of MPPT techniques for PV Control." *In Electrical Sciences and Technology (CISTEM), International Conference on Electrical Science and Technology in the Maghreb*, 2014.

[6] Soubhagya Kumar Dash, Deepak Verma, Savita nema and Nema R K., "Comparative Analysis of Maximum Power Point (MPP) Tracking Techniques for Solar PV Application using MATLAB Simulink", *IEEE International Conference on Recent Advances and Innovations in Engineering (ICRAIE),* May 2014.

[7] Pratik U. Mankar and Moharil R M., "Comparative analysis of the Perturb-and-observe and incremental Conductance mppt methods", *International Journal of Research in Engineering and Applied Sciences (IJREAS)*, Vol. 02, July 2014

[8] Jayaprakash S and Ramakrishnan V., "Simulation of solar based DC-DC converter for armature voltage controlled separately excited motor", *IEEE International Conference on Advances in Electrical Engineering (ICAEE)*, 2014.

[9] Jayaprakash S and Ramakrishnan V., "Analysis of Solar based Closed loop DC-DC Converter using PID and Fuzzy Logic Control for Separately Excited Motor Drive", *IEEE National Conference On Emerging Trends In New & Renewable Energy Sources And Energy Management (NCET NRES EM)*, 2014.

[10] Nafaa Jeddi, Nada Ouasli, Lilia El Amraoui Ouni, Fernando., "Speed Control of a Separately-Excited DC Motor Powered by Photovoltaic Energy", IEEE 6th International Renewable Energy Congress and Information Science, 2015.