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Peak Power Tracking Using Revised Variable Step Size Incremental Conductance Method

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Abstract: The solar panels require Maximum Power Point Tracking (MPPT) methods to operate at the unique operating point called as Maximum Power Point (MPP) in spite of changing environmental conditions. For a given solar irradiation and temperature the maximum power that a panel can deliver is extracted by the use of power converter whose duty cycle is adjusted based on the MPPT method. In this study, revised form of variable step size Incremental Conductance (INC) method that adjusts the step size considering the PV panel current is introduced. Also, the method has all the merits of conventional INC method. The simulation is carried out in MATLAB/SIMULINK environment and results of conventional, variable step size and revised variable step size Incremental Conductance methods are compared. The simulation works confirms that the proposed method is better in terms of its convergence speed and accuracy. Moreover, the suggested method is well suitable for practical operating conditions due its wide operation range.

Key words: DC-DC power converter, impedance, matching, maximum power point tracking, photovoltaic system

INTRODUCTION

Solar energy is considered as one of the best reliable renewable energy resources. It draws attention because of its advantages such as readily available nature and low maintenance requirements (Zacharias *et al*., 2010). The PV panel provides an opportunity to generate electricity but depends on the environmental factors such as irradiation and temperature thereby becoming an unstable energy source (Altin, 2013). To improve the efficiency of the PV system the PV module must be operated at maximum power point according to the prevailing environmental conditions for which MPP controller is employed (Durusu *et al*., 2014). Maximum power point is also called as Peak Power Point (PPP). Since, the VI curve of the PV panel is non linear and peak power point is not priorly known, methods that can locate PPP that uses either mathematical calculations based on valid model or search methods has to be used (Lin *et al*., 2011; Hussein *et al*., 1995; Villalva *et al*., 2009a; Mei *et al*., 2011; Solodornik *et al*., 2004).

The search methods vary with range of operation, sensor requirements and speed of convergence, complexity and cost. Methods such as Hill climbing, Perturb and observe, incremental conductance, fractional open circuit voltage and fractional short circuit current are commonly used (Villalva *et al*., 2009b; Berrera *et al*., 2009; Wilamowski and Li, 2002). Fractional open circuit voltage and short circuit methods incur more loss because of the periodical shorting or disconnection of PV terminals to obtain open circuit voltage and short circuit current. Hill climbing and Perturb and Observe methods are widely used because of its ease of implementation (Femia *et al*., 2004). The two methods are the same except that duty ratio is altered in the first case while voltage is perturbed in the later. The major disadvantages with these methods are oscillations around PPP and its inability to track PPP under rapidly changing atmospheric conditions (Hussein *et al*., 1995). However, oscillations can be suppressed to an extent by reducing the perturbation step. On the other hand, the reduction in the perturbation step slows down tracking (Coelho *et al*., 2010; Femia *et al*., 2004).

Fuzzy logic and neural network methods are suitable for tracking under changing environmental conditions. Fuzzy logic method requires knowledge or experience to choose right error computation and rule base table. Different PV modules have different characteristics and the neural network has to be trained for each module. Also, it demands periodical training to guarantee accurate tracking as the characteristics change with time. The improvement in dynamic performance and PPP tracking accuracy under varying conditions can be achieved by the use of conventional Incremental Conductance method which is based on the fact that the slope of power versus voltage curve at PPP is zero (Altin, 2013).

The conventional INC method is slightly complex when compared to hill climbing and perturb and observe

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methods but became easier to implement because of the advent of microcontrollers and digital signal processors (Femia *et al*., 2004, 2005). It uses a fixed iteration step size determined by the accuracy at steady state and response speed of MPPT. There must be an adjustment between dynamics and steady state oscillations that has to be addressed by corresponding design (Liu *et al*., 2008). Also when the solar irradiation level changes suddenly from low to high, the conventional method fails to observe the change and implements inaccurate first step change. To solve these issues, methods with variable step size are proposed in literatures (Mei *et al*., 2011) and (Salmi *et al*., 2012). The step size for variable step size INC method is determined based on the inherent characteristics of the PV module. If the operating point is far away from PPP, the step size is increased to improve the fast tracking ability and if the operating point is close to MPP, the step size is largely decreased such that the oscillations gets reduced contributing to higher efficiency.

In this study, the variable step size incremental conductance method is revisited and revised form of the method that adjusts the step size according to the solar irradiation levels using the output current of PV module is proposed. Simulation is carried out and observed that the proposed method improves the convergence speed making the wide operation of PV module without reduction in the steady state response possible.

Standalone photovoltaic system: The Standalone Photovoltaic (SPV) system consists of a PV panel, power converter, maximum power point tracker and load. The block diagram of the SPV system is shown in Fig. 1.

Photovoltaic panel: The basic component of the Photovoltaic panel is the solar cell. The solar cells consist of a p-n junction fabricated in a thin layer or a wafer of semiconductor. The cell takes the advantages of Photovoltaic effect thereby converting electromagnetic radiation directly into electric current. The panel is composed of number of solar cells connected either in series or in parallel. The solar cell equivalent is shown in Fig. 2. R_s and R_p are respectively the shunt and series resistances that accounts to the ohmic losses in the cell. In most practical cases the shunt resistance is high and often neglected during analysis (Nema *et al*., 2010; Ding *et al*., 2012; Villalva *et al*., 2009a; Hohm and Ropp, 2003). The Eq. 4 of a single cell using the single diode model (Patel and Agarwal, 2008; Kiranmayi *et al*., 2008) is given by:

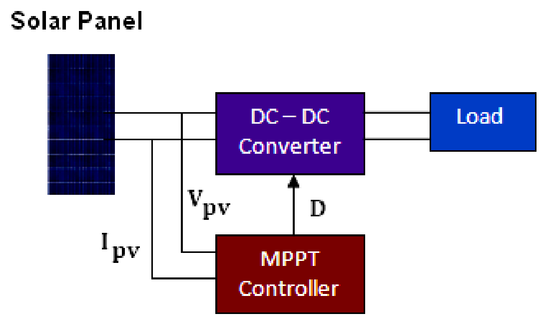

Fig. 1: Standalone photovoltaic system

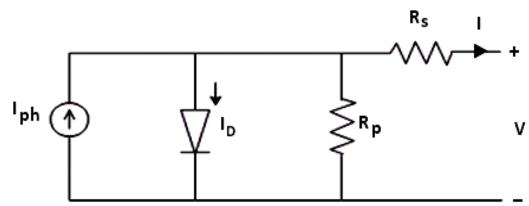

Fig. 2: Solar cell equivalent circuit

$$I = I_L - \left[I_o \exp\left(\frac{q(V+IR_s)}{nkT}\right) - 1\right] - \left[\frac{V+IR_s}{R_p}\right] \quad (1)$$

Where:

I_L = Light generated current
I_o = Reverse saturation current
n = Diode ideality factor
k = Indicated in Eq. 1 is Boltzmann's constant
T = Temperature

Equation 4 of PV module is similar to that of solar cells and is the combination of IV curves of all solar cells connected in the module.

The module output current represented as I_{pv} is given by:

$$I_{pv} = N_p \times I_{ph} - N_p \times I_o \left[\exp\left\{\frac{q\times(V_{pv}+I_{pv}R_s)}{N_s knT}\right\} - 1\right] - \left[\frac{V_{pv}+I_{pv}R_s}{R_p}\right] \quad (2)$$

where, N_p and N_s are the number of parallel and series cells, respectively. As mentioned, the parallel resistance of higher value is neglected for simplicity. The equation for I_{pv} there by becomes:

$$I_{pv} = N_p \times I_{ph} - N_p \times I_o \left[\exp\left\{\frac{q\times(V_{pv}+I_{pv}R_s)}{N_s knT}\right\} - 1\right] \quad (3)$$

The characteristic curves of the solar panel are shown in Fig. 3. The 37 W Solkar module is taken as the reference module in the current work and the key specifications for Standard Test Conditions (STC) of 1000 W m^{-2} and 25°C are given in Table 1.

Boost converter: The voltage steps up and the current steps down in a boost converter. The basic design of boost converter is shown in Fig. 2. The output voltage is greater than the input voltage in a boost converter. A high speed switching is done utilizing a power MOSFET. The PWM signal provided to the gate of MOSFET controls the output voltage. The task of stepping up the voltage is accomplished by controlling the time the inductor conducts electric current. The charging and discharging of inductor takes place very fast when the inductor is connected and disconnected rapidly. A pulsating current is produced during the switching process which then is smoothened by the use of capacitor in parallel. Capacitor provides the voltage to load. Rheostat is connected as load and power gets dissipated when the current flows through it.

There are two modes namely mode I and mode II in which a boost converter can operate. In mode I when the power MOSFET is switched on, the current flows through the inductor and MOSFET. The energy gets stored in the magnetic coil of inductor. No current will flow through other elements present in the circuit. In mode II when the MOSFET is turned off, the current flows through the inductor, capacitor, diode and load. The inductor current tends fall until the MOSFET is turned on again. The current change cannot take place instantaneously and so the inductor reverses the EMF. Source voltage gets added to the inductor voltage. The energy stored in the inductor is transferred to load (Jain and Agarwal, 2007).

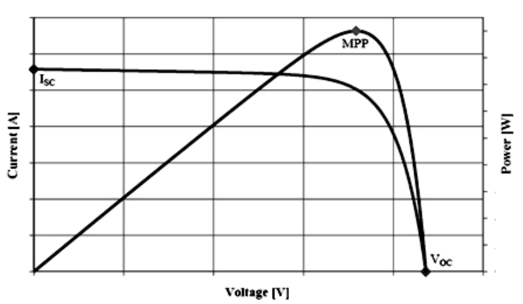

Fig. 3: Characteristic curves of solar panel

Table 1: Key specifications of 37 W Solkar PV panel

Description	Rating
Rated power	37.08 W_p
Voltage at maximum power (V_{mp})	16.56 V
Current at maximum power (I_{mp})	2.25 A
Open circuit voltage (V_{oc})	21.24 V
Short circuit current (I_{sc})	2.55 A
Total number of cells in series (N_s)	36
Total number of cells in parallel (N_p)	1

The relationship that exists for the boost converter is given in Eq. 4. Duty cycle is represented by ‘k’:

$$\frac{V_o}{V_{in}} = \frac{1}{1-k} \tag{4}$$

The average input current which is same as the inductor average current can be derived by equating input and output powers:

$$I_L = I_{in} = \frac{V_o \times I_o}{V_{in}} = \frac{I_o}{1-k} = \frac{V_{in}}{R_{in}} = \frac{V_{in}}{R(1-k)^2} \tag{5}$$

From Eq. 5 it is observed that the output voltage gets regulated in addition to variation of input impedance of the converter when the duty cycle of the converter is changed. Appropriate control of the converter is required so, as to present optimum impedance across the PV module that facilitates maximum power extraction.

V_{mp} and I_{mp} are the voltage and current at maximum power point condition respectively and therefore:

$$\frac{V_{mp}}{I_{mp}} = R_L(1-k_{op})^2 \tag{6}$$

Where:

k_{op} = The optimal duty cycle to be generated to achieve tracking of MPP:

$$k_{op} = \sqrt{\frac{V_{mp}}{R \times I_{mp}}} \tag{7}$$

The critical value of the inductor is:

$$L_{critical} = \frac{R \times k(1-k)^2}{2f} \tag{8}$$

To operate the converter in continuous conduction mode Inductor value must be $>L_{critical}$. The ratio of the desired constant output voltage $\Delta V_o/V_o$ is the allowed ripple which determines the value of the filter capacitor needed as given in Eq. 9:

$$C = \frac{k}{R \times (\Delta V_o / V_o) \times f} \tag{9}$$

The selected component values for the boost converter for simulation works are given in Table 2.

Table 2: Selected component values for boost converter

Description	Rating
Inductor	120 μH
Capacitor	330 μF
Resistor	50Ω, 1A
Switching frequency	10 kHz

MPPT technique: A typical solar panel converts only 35-45% of incident solar irradiation to electrical energy. The MPPT techniques are employed to improve the efficiency of solar panel. When the PV panel impedance matches with that of the load impedance, maximum power gets transferred from PV panel to load as per maximum power transfer theory. The impedance matching can be carried out by varying the duty cycle of power converter. The duty cycle of power converter is varied based on the tracking methods which in turn pave a way to achieve impedance matching. Several approaches have been proposed to track MPP (Subudhi and Pradhan, 2013; Esram and Chapman, 2007; Liu *et al*., 2008; Coelho *et al*., 2010). Among the methods conventional and VSS incremental conductance methods are considered in order to compare with the proposed method. Fixed iteration step size used in the former method is determined by accuracy and tracking speed requirement. In the latter method, the step size is varied such that it would be large when the operating point is far away from MPP and would be small when operating point is close to MPP. The dynamic performance of the variable step size INC method is comparatively better than conventional method. An attempt is made in the present work to improve the dynamic performance still better by incorporating additional changes to the existing one.

MATERIALS AND METHODS

Conventional INC method works based on the truths that slope of the PV curve is zero at the peak, positive and negative on the left and right sides of PPP respectively. The slope of the curve is calculated every time so as to locate the PPP. Voltage and current are measured and the instantaneous and incremental conductances are calculated. Equations 10-12 are the possible conditions that prevail at MPP, left of MPP and right of MPP respectively during the operation of PV module:

$$\frac{dP}{dV} = 0 \rightarrow \frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad (10)$$

$$\frac{dP}{dV} > 0 \rightarrow \frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad (11)$$

$$\frac{dP}{dV} < 0 \rightarrow \frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad (12)$$

Fixed iteration step size irrespective of the gap between operating point and PPP is utilized by the conventional INC method. The step size determines the speed of tracking and dynamic performance. Though, bigger increments increase the speed of tracking system, it is prone to oscillations around MPP accounting to decrease in efficiency. The situation gets inverted when the increments are smaller. Thus, there must be an adjustment between oscillations and dynamics for the conventional method. To address this problem, variable step size INC MPPT methods are developed (Salmi *et al*., 2012). Variable step size INC method that directly varies the duty cycle of the power converter is developed so as to reduce the complexity of the system. Duty cycle expression incorporating variable step size is shown in Eq. 13:

$$K(n) = K(n-1) \pm N\left|\frac{dP}{dV}\right| = K(n-1) \pm N\left|\frac{P(n)-P(n-1)}{V(n)-V(n-1)}\right| \quad (13)$$

where, V, P and K are PV module voltage, PV module power and power converter duty cycle respectively. The scaling factor denoted as N is fixed during the design stage and is an important parameter that determines the performance of variable step size INC method. Equation 14 is the condition that the variable step rule must meet in order to ensure convergence of tracking update rule:

$$\Delta K_m > \left|\frac{dP}{dV}\right| \quad (14)$$

where Δk_m is the maximum fixed step size set for the conventional INC method which is considered as the upper limit for the variable step size INC method. To obtain the scaling factor Eq. 14 is rewritten as follows:

$$N < \frac{\Delta K_m}{\left|\frac{dP}{dV}\right|} \quad (15)$$

There might also be situations in which Eq. 15 does not get satisfied. In such situations, the variable step size INC method will work with fixed step size set in the conventional INC method. The slopes of the PV curves change for different solar irradiation levels and the step sizes are calculated based on the scaling factor and variable slopes of PV curve. Equation 14 can also be written as follows:

$$\left|\frac{dP}{dV}\right| < \Delta K_m / N \quad (16)$$

where, $\Delta k_m/N$ is a constant, as the coefficients in the numerator as well as in the denominator are constants. The slope is compared with a constant all the time. Though this method increases the convergence speed and reduces oscillation, there arises a problem of operation over wide range. Figure 4 shows the PV curves for various solar irradiation levels at constant temperature.

Let P_1 and P_2 be the PPPs of the curves corresponding to 1000 and 400 W m^{-2}, respectively. Assume that the value of $\Delta k_m/N$ is smaller value. The power at P_1 is much larger than P_2. The scaling factor obtained as from Eq. 15 cannot make the system to realize variable step size method for the power P1 because $\Delta K_m/N$ is very small that Δk_m is too large such that the following step size lies within the variable step size range. For the power P_2, the same scaling factor lets the system work within the variable step size range but reduces the system response. There arises a dead band for the fixed scaling factor N. There is no possibility in variable step size INC method to find the suitable scaling factor for both the PV curves in the dead band at the same time.

To overcome the above mentioned problem, the revised INC method is developed to obtain variable step size according to the existing solar irradiation level. The plan in the revised work is to move the fixed line $\Delta k_m/N$ up and down based on the irradiation change. The irradiation level is directly related to the PV current and the change in irradiation affects the PV current. Therefore, PV module current is used to estimate the irradiation level. Additional sensor is not required for the implementation of the proposed method. Equation 14 is the expression for duty cycle when variable step size with PV module current is adapted:

$$K(n) = K(n-1) \pm \frac{N}{I} \times \left|\frac{dP}{dV}\right| \tag{17}$$

The revised method will work based on the condition as given in Eq. 18:

$$\left|\frac{dP}{dV}\right| < (\Delta K_m / N) \times I \tag{18}$$

It is observed that the slope of the curve is always compared with a value that changes based on the PV module current. A line when drawn for $\Delta K_m/N$ moves up and down when multiplied with the module current providing an optimal scaling factor. The flow chart pertaining to the revised variable step size INC method is shown in Fig. 5.

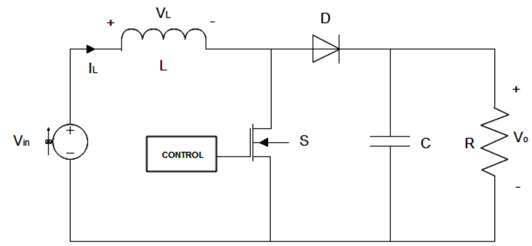

Fig. 4: Basic design of boost converter

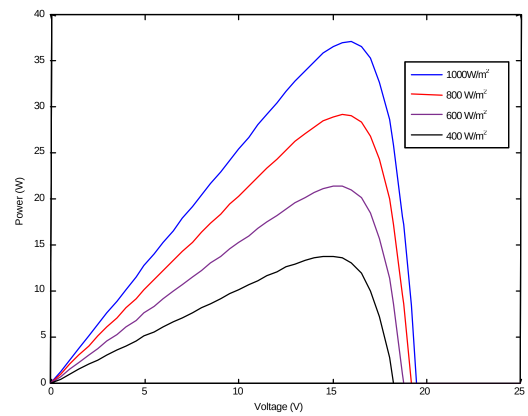

Fig. 5: PV curves of solar panel at various solar irradiation levels

RESULTS AND DISCUSSION

A standalone PV system utilizing boost converter and MPPT control is designed and simulated in MATLAB/SIMULINK environment in order to analyze the feasibility and the performance of the proposed variable step size INC method. Constant temperature of 25°C and varying irradiation levels between 500 and 1000 W m^{-2} is considered to test the system operation and compare the conventional, variable step size and revised variable step size methods. The temperature and solar irradiation levels are set as same for all the three methods. The irradiation profile is shown in Fig. 6. The irradiation level is set to 400 W m^{-2} from t = 0-0.5 sec and from t = 1.5-2 sec. Irradiation levels of 1000 and 700 W m^{-2} is set from t = 0.5-1 sec and from t = 1-1.5 sec, respectively. The MPPT block continuously updates the duty cycle of the boost converter every 0.5 μs.

To compare the performances of various INC methods, the simulation configurations are set to be the same. The conventional INC method is tested through simulation and PV module power waveform with fixed step sizes of 0.01 and 0.02 are shown respectively in Fig. 7 and 8. It is observed from the waveforms that whenever conventional method uses larger fixed step size

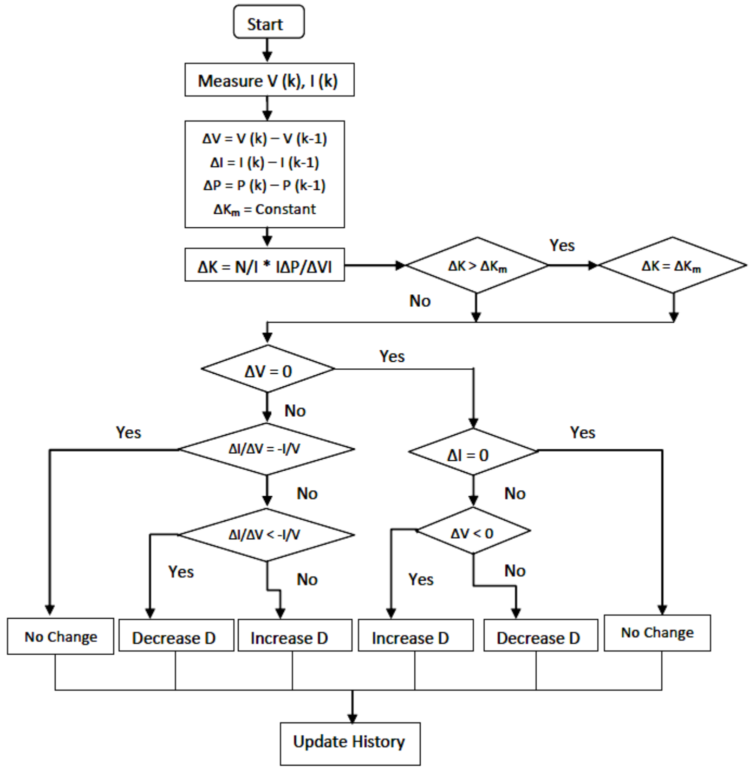

Fig. 6: Flowchart of revised variable step size INC method

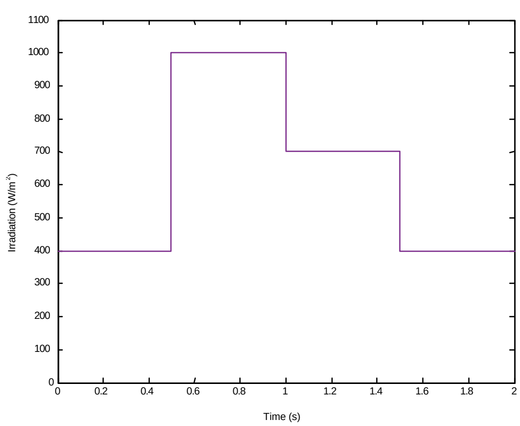

Fig. 7: Irradiation profile

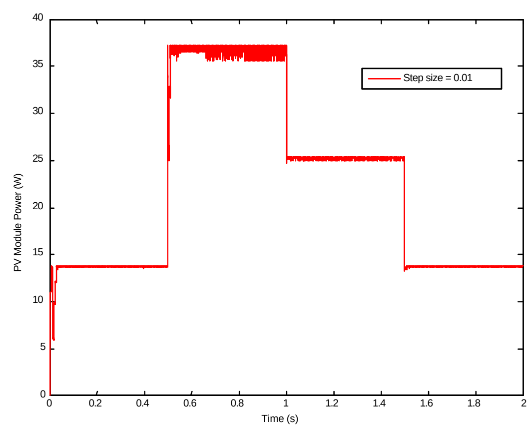

Fig. 8: PV module power waveform of the conventional INC method with fixed step size of 0.01

both the steady state oscillations around maximum power point and the speed of convergence increases causing reduction in the efficiency of the system.

Figure 9 shows the PV module power waveform while simulation is carried out for variable step size INC method with scaling factors 0.01 and 0.02. It is obvious from the results that the efficiency and speed of convergence has improved when compared with conventional INC method that uses fixed step size. When N = 0.02 is used, the system oscillates and does not converge at 1000 W m^{-2} because of the larger value of ΔK and if N = 0.01, the oscillations and the convergence speed reduce due to smaller value of ΔK. The revised variable step size INC method is compared with variable step size INC method in order to compare the effectiveness. Figure 10 and 11 shows PV module power waveforms of the variable step size INC method with N = 0.01 and revised variable step

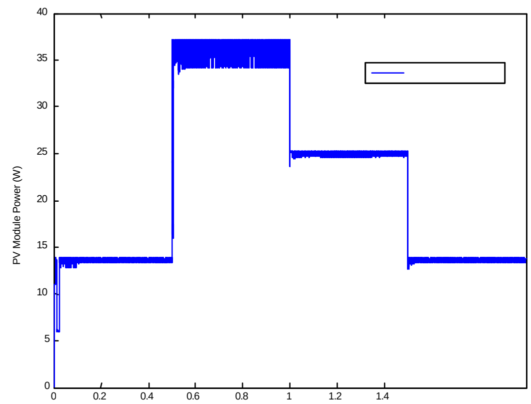

Fig. 9: PV module power waveform of the conventional INC method with fixed step size of 0.02

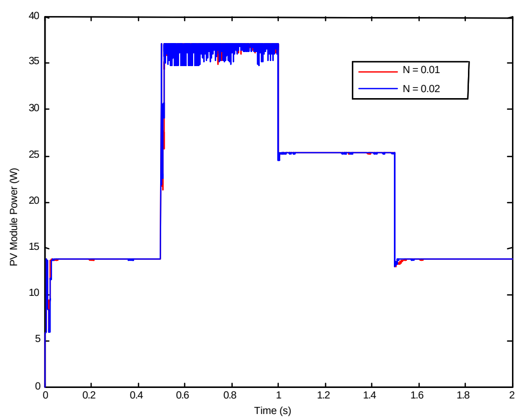

Fig. 10: PV module power waveform of the variable step size INC method with scaling factors 0.01 and 0.02

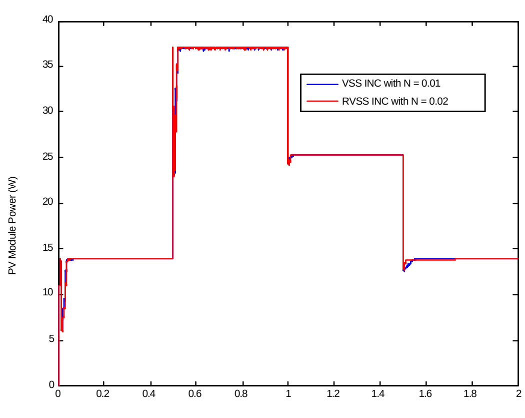

Fig. 11: PV module power waveforms of the variable step size and revised variable step size INC methods

Table 3: Efficiency comparison for various INC methods

Method	ΔK	N	Efficiency (%)
Conventional INC	0.01	-	97.8
	0.02	-	97.41
Variable step size INC	-	0.01	98.53
	-	0.02	97.94
Revised variable step size INC	-	0.02	98.56

size INC method with N = 0.02. Based on the results, it is observed that the steady state response of both the methods are almost same but found to have different speed of convergence. ΔK_m is set to be same for both the methods. Proposed method can adapt with varying solar irradiation level using larger values of N attaining same steady state response. The system converges at a faster rate and oscillations are very less in the case of small irradiation levels. This is because scaling factor divided by the module current has paved way for the MPPT system to select larger value of N that result in convergence speed. Efficiency of various INC methods obtained through simulation is shown in Table 3. The dynamic response of the revised INC MPPT method is certainly better than the other INC methods.

CONCLUSION

In this study, a revised variable step size INC method is proposed. Both steady state response and dynamic response are improved. By using the PV module current wide range of operation is made possible as a result of adjustment of step sizes according to solar irradiation level. The method is found to be suitable for all operating conditions. The standalone photovoltaic systems constitutes of a power converter and MPPT control block that allows direct control of converter from PV module output power measurements. The design of the standalone photovoltaic systems with MPPT control is discussed and a simple rule to track the PPP is presented. The simulation results evidently confirm that revised variable step size INC MPPT method increases the PV module power by as much as 80% compared to the case that does not employ MPPT control.

REFERENCES

Altin, N., 2013. Interval type-2 fuzzy logic controller based maximum power point tracking in photovoltaic systems. Adv. Electr. Comput. Eng., 13: 65-70.

Berrera, M., A. Dolara, R. Faranda and S. Leva, 2009. Experimental test of seven widely-adopted MPPT algorithms. Proceedings of the IEEE Conference on PowerTech 2009 Bucharest, June 28- July 2, 2009, IEEE, Bucharest, Romania, ISBN: 978-1-4244-2234-0, pp: 1-8.

Coelho, R.F., F.M. Concer and D.C. Martins, 2010. Analytical and experimental analysis of DC-DC converters in photovoltaic maximum power point tracking applications. Proceedings of the IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society, November 7-10, 2010, IEEE, Glendale, AZ., ISBN: 978-1-4244-5225-5, pp: 2778-2783.

Ding, K., X. Bian, H. Liu and T. Peng, 2012. A MATLAB-simulink-based PV module model and its application under conditions of nonuniform irradiance. Energy Convers. IEEE. Trans., 27: 864-872.

Durusu, A., I. Nakir, A. Ajder, R. Ayaz and H. Akca *et al*., 2014. Performance comparison of widely-used maximum power point tracker algorithms under real environmental conditions. Adv. Electr. Comput. Eng., 14: 89-94.

Esram, T. and P.L. Chapman, 2007. Comparison of photovoltaic array maximum power point tracking techniques. IEEE Trans. Energy Convers., 22: 439-449.

Femia, N., G. Petrone, G. Spagnuolo and M. Vitelli, 2004. Perturb and observe MPPT technique robustness improved. Proceedings of the 2004 IEEE International Symposium on Industrial Electronics, May 4-7, 2004, IEEE, New York, USA., ISBN: 0-7803-8304-4, pp: 845-850.

Femia, N., G. Petrone, G. Spagnuolo and M. Vitelli, 2005. Optimization of perturb and observe maximum power point tracking method. IEEE Trans. Power Electr., 20: 963-973.

Hohm, D.P. and M.E. Ropp, 2003. Comparative study of maximum power point tracking algorithms. Prog. Photovolt: Res. Appl., 11: 47-62.

Hussein, K.H., I. Muta, T. Hoshino and M. Osakada, 1995. Maximum photovoltaic power tracking: An algorithm for rapidly changing atmospheric conditions. Proceedings of the IEE Conference on Generation, Transmission and Distribution, January 29, 1995, IET, UK., pp: 59-64.

Jain, S. and V. Agarwal, 2007. Comparison of the performance of maximum power point tracking schemes applied to single-stage grid-connected photovoltaic systems. Electr. Power Appl. IET., 1: 753-762.

Kiranmayi, R., K.V.K. Reddy and M.V. Kumar, 2008. Modeling and a MPPT method for solar cells. J. Eng. Applied Sci., 3: 128-133.

Lin, C.H., C.H. Huang, Y.C. Du and J.L. Chen, 2011. Maximum photovoltaic power tracking for the PV array using the fractional-order incremental conductance method. Appl. Energy, 88: 4840-4847.

Liu, F., S. Duan, F. Liu, B. Liu and Y. Kang, 2008. A variable step size INC MPPT method for PV systems. Ind. Electr. IEEE. Trans., 55: 2622-2628.

Mei, Q., M. Shan, L. Liu and J.M. Guerrero, 2011. A novel improved variable step-size incremental-resistance MPPT method for PV systems. Ind. Electr. IEEE. Trans., 58: 2427-2434.

Nema, S., R.K. Nema and G. Agnihotri, 2010. MATLAB/Simulink based study of photovoltaic cells/modules/array and their experimental verification. Intl. J. Energy Environ., 1: 487-500.

Patel, H. and V. Agarwal, 2008. MATLAB-based modeling to study the effects of partial shading on PV array characteristics. Energy Convers. IEEE. Trans., 23: 302-310.

Salmi, T., M. Bouzguenda, A. Gastli and A. Masmoudi, 2012. Matlab/simulink based modeling of photovoltaic cell. Intl. J. Renew. Energy Res., 2: 213-218.

Solodovnik, E.V., S. Liu and R.A. Dougal, 2004. Power controller design for maximum power tracking in solar installations. Power Electr. IEEE. Trans., 19: 1295-1304.

Subudhi, B. and R. Pradhan, 2013. A comparative study on maximum power point tracking techniques for photovoltaic power systems. Sustain. Energy IEEE. Trans., 4: 89-98.

Villalva, M.G., J.R. Gazoli and E.R. Filho, 2009a. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron., 24: 1198-1208.

Villalva, M.G., J.R. Gazoli and E.R. Filho, 2009b. Modeling and circuit-based simulation of photovoltaic arrays. IEEE Transection of Power Electronic, Sept. 27-Oct. 1, Bonito-Mato Grosso do Sul, pp: 1244-1254.

Wilamowski, B.M. and X. Li 2002. Fuzzy system based maximum power point tracking for PV system. Proceedings of the IEEE 2002, 28th Annual Conference on the IECON, 02 Industrial Electronics Society, November, 5-8, 2002, IEEE, New York, USA., ISBN: 0-7803-7474-6, pp: 3280-3284.

Zacharias, P., R. Teodorescu, P.R. Cortes, M. Liserre and W. Knapp *et al*., 2010. Renewable energy operation and conversion schemes: A summary of discussions during the seminar on renewable energy systems. IEEE. Ind. Electr. Mag., 4: 38-51.