Real Time Implementation and Comparison of PI and Modified Inc Cond Control Algorithms for Solar Applications

Venkata Ratnam Kolluru
Ph.D. Scholar, NITR
Rourkela, Odisha, India
Email:venkataratnamk@gmail.com

Kamalakanta Mahapatra
Professor, ECE, NITR
Rourkela, Odisha, India

Bidyadhar Subudhi
Professor, EEE, NITR
Rourkela, Odisha, India

***Abstract*—This paper depicts the comparison of control algorithms for a Photovoltaic (PV) system in real time. Modified Incremental Conductance (Inc Cond) with fixed step size algorithm is used with a DC-DC boost converter to track maximum power from a PV system. PV output is connected to a Boost converter to regulate and increase the voltage upto a desired level. The modified inccond MPPT technique is compared with a conventional PI controller and was observed that, the modified Inc Cond MPPT is tracking 7.4% more power than the conventional PI controller. MPPT control algorithms are developed, compared and simulated in MATLAB/SIMULINK. Simulated and real time results are presented and discussed in this paper. The real time results are verified with digital simulator OPAL-RT experimental setup.**

Keywords: DC DC boost converter, Incremental conductance, Maximum power point tracking, OPAL-RT, PI controller.

I. Introduction

Renewable energy is the best solution for the global growing problem of energy scarcity. Solar energy is a virtually inexhaustible resource; obtained all around the world. In recent years, with its advantages of pollution-free, efficient, cost-effective and long-term using, solar energy have been greatly developed [1]. The PV power generation is based on the principle of the photovoltaic effect [2], and observed that, there is a unique point at which the PV cell produces maximum power. At this point, the rate of change of power with respect to the voltage is equal to zero [3]. PV array has to be operated at MPP in order to extract maximum power output. Various power management issues concerning improvement in the conversion efficiency of a PV array [4], thus maximizing PV power output. The maximum power of the PV array changes with shading and/or climatic conditions.

Thus, an important challenge in a PV system is to ensure that maximum energy is generated from the PV array with a dynamic variation of its output characteristic when connected to a variable load [4]. A solution for this problem is the insertion of a power converter between the PV array and load, whichcould dynamically change the impedance of the circuit by using a control algorithm [5]. DC DC Converters are required to regulate the output voltage [6] at a required level. In this paper, a step up converter is used, that has a capability of providing an output voltage which is higher than the input voltage [4].

Maximum Power Point Tracking (MPPT) is becoming more and more important as the amount of energy produced by PV systems is increasing [7]. A large number of control techniques have been proposed for tracking of Maximum Power Point (MPP) of PV. In those algorithms Incremental Conductance (inc cond) algorithm is one of the best suited algorithm to track MPPT [8]–[11]. Variation of voltage and current values plays key role to track the MPPT. The inc cond algorithm can be implemented either with fixed step size or with variable step size to track the MPPT [11]. In this paper inc cond with fixed step is used to track the maximum power point.

We need a platform to run our implemented models to run in real time. So, here in this paper we used a RTDS simulator to develop the real time hardware. The RTDS simulator is able to run the hardware model up to micro seconds interval [12]–[14]. In this paper OPAL-RT digital simulator is used to check the outputs in real time.

Second section of this article shows the modeling of a PV cell with simulation results. The third Section is devoted to the DC DC boost converter with state space analysis. Fourth Section is dedicated for control algorithms to track the MPPT. The fifth section analyzes about Real Time Digital Simulator (RTDS); the section VI presents comparison and discussion on simulation results and real time results. Finally section VII concludes the paper.

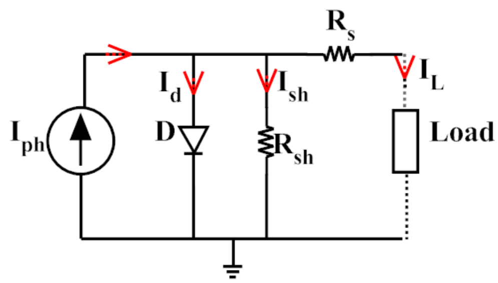


Fig. 1. fundamental circuit of a PV cell

II. Modelling of a Single Diode PV Cell

PV is one of the methods of renewable energy generations, which means generating electrical power by converting solar irradiation into direct current. In this paper, single exponential model is preferred to model the PV cell because of simplicity and fewer complications [15]. The equivalent circuit diagram of a single diode PV cell [4] is shown in Fig. 1. From the theory of semiconductors the basic I-V characteristic equation of a PV cell is derived mathematically [4] as follows:

$$I_{ph} - I_0[e^{qV_d/nkT} - 1] = I_L \tag{1}$$

Final expression of the PV cell drawn in Fig. 1 is computed and shown below:

$$V_L = \frac{nkT}{q}\left[\ln\left(\frac{I_{ph} - I_L}{I_0} + 1\right) - \frac{V_L + I_L R_S}{R_{sh}}\right] - I_L R_S \tag{2}$$

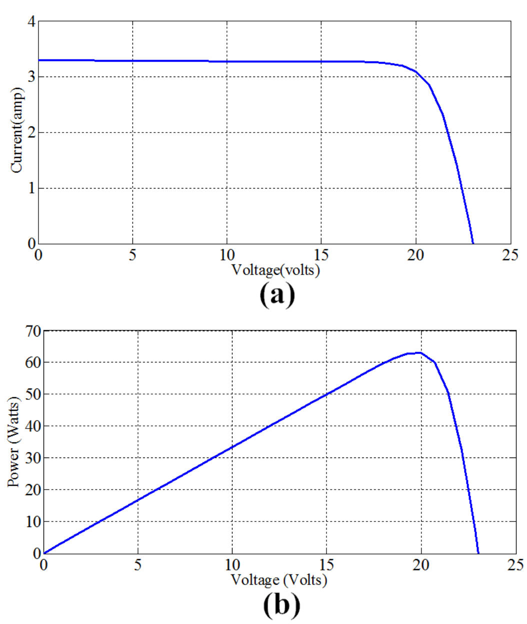


Fig. 2. characteristics curves of a PV system at STC a) I-V and b) P-V

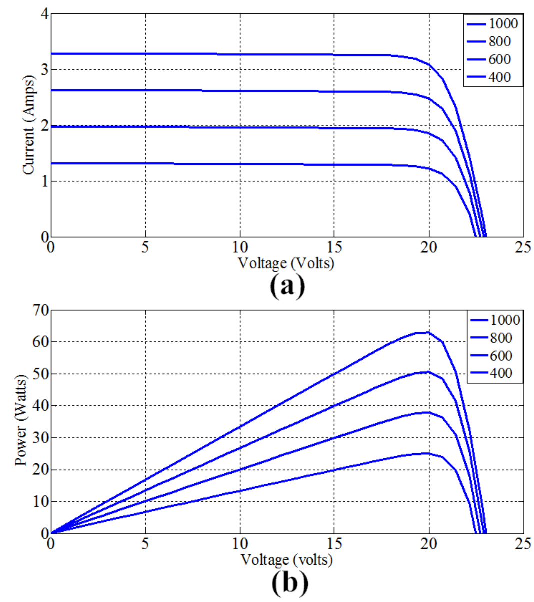


Fig. 3. Characteristic curves of PV system at different irradiations a) I-V and b) P-V

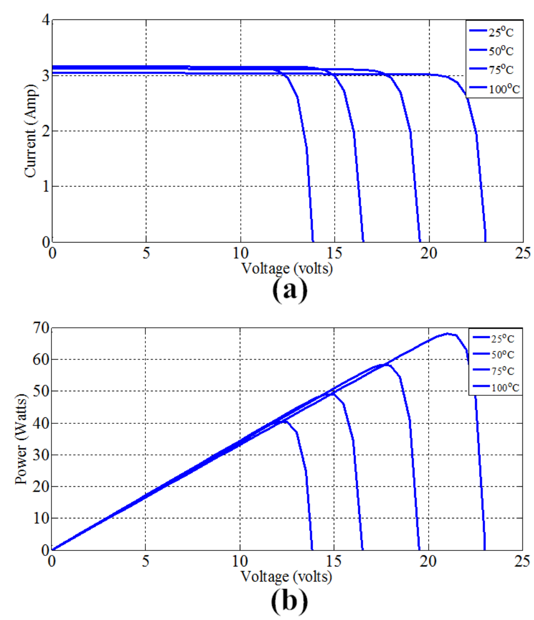


Fig. 4. Characteristic curves of PV system at different temperatures a) I-V and b) P-V

After mathematical modeling of a PV cell is done, we simulated it in MATLAB/SIMULINK and obtained the I-V and P-V characteristic curves at Standard Test Conditions (STC). The simulated waveforms are shown in Fig. 2. The PV array is tested at STC as well as different irradiation levels and at different temperatures, and the simulation results are plotted in Fig. 3 Fig. 4.

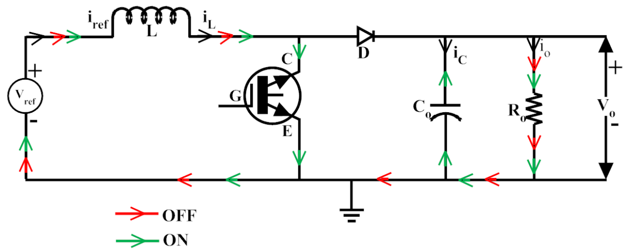


Fig. 5. Conventional Boost converter with directions for all switching actions

III. Controller Based DC DC Boost Converter

The DC DC boost converter is a power electronics device is also called as a step up converter [6]. The conventional circuit of a boost converter is shown in Fig. 4 (the directions mentioned for all possible swithcing actions). It has a capability of providing the output voltage higher than the input voltage [5]. The equivalent circuit diagram of the boost converter is shown in Fig. 5, and energy flow is mentioned with green arrows, when the transistor is ON.

When the transistor is turned ON, the current flows from the supply to the inductor L, and the diode D is reverse biased. Hence the inductor stores the current, then inductor current rises, and the capacitor C maintains the voltage V_o and supplies current i_o. The state space modelling expressions of a boost converter [4] is as follows:

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_o R_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{ref} \tag{3}$$

$$V_o = \begin{bmatrix} 0 & -\frac{1}{C_o R_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} \tag{4}$$

When the transistor is turned OFF, the inductor generates a large voltage to maintain the current i_L, and the diode D is starts conducting. The equivalent circuit diagram of boost converter when transistor turns OFF, is shown in Fig. 5.and energy flow is mentioned with red arrows, when the transistor is OFF. Hence the output voltage can be expressed as

$$V_o = V_{ref} + L\frac{di_L}{dt} \tag{5}$$

Thus the output voltage of the converter is higher than the supply voltage V_s, at this situation the capacitor C charges to the boosted voltage. The inductor and power supply provides energy to the load when the transistor is turned OFF. The current through the inductor decreases because its stored energy goes on

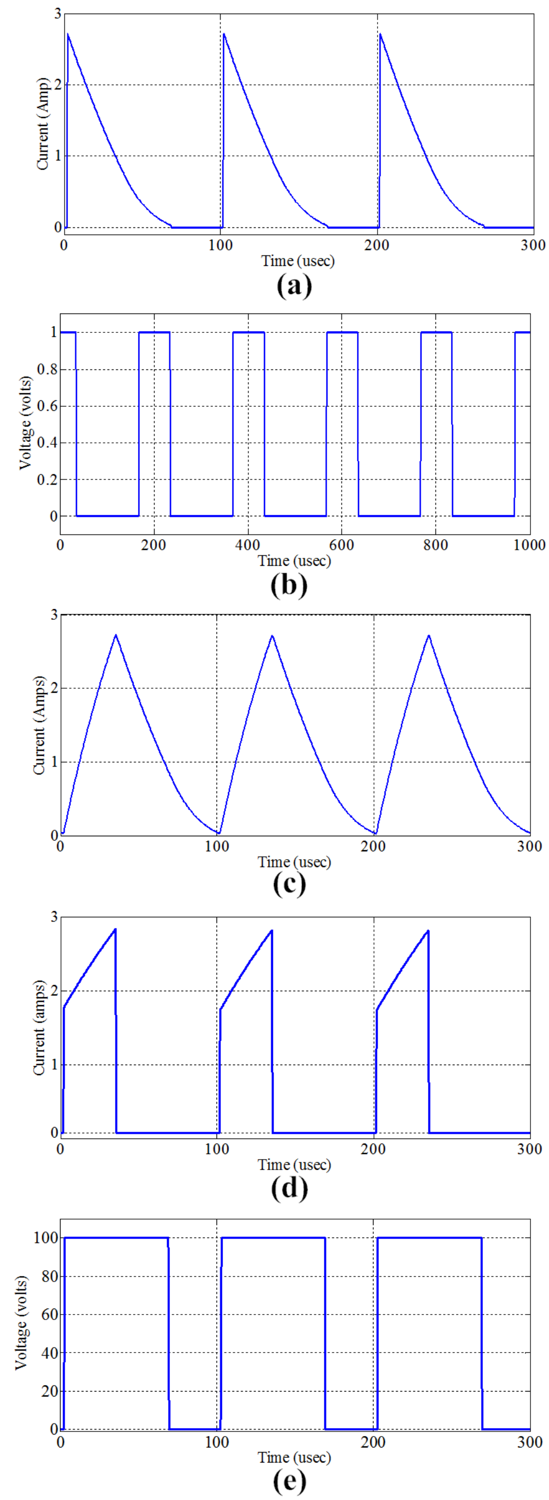


Fig. 6. Results of a boost converter a) Diode current, b) Gate voltage, c) Inductor Current, d) Switch current and e) Switch voltage

reducing. After some time the transistor is again turned ON and the cycle repeats. The mathematical model of a boost converter when the transistor is OFF can be simply expressed in state space as

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_o} & -\frac{1}{C_o R_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_0 \end{bmatrix} + \begin{bmatrix} I_L \\ 0 \end{bmatrix} [V_{ref}] \tag{6}$$

$$V_o = \begin{bmatrix} \frac{1}{C_o} & -\frac{1}{C_o R_o} \end{bmatrix} \begin{bmatrix} I_L \\ V_o \end{bmatrix} \tag{7}$$

The results of a converter is shown in Fig. 6. We can analyze all the possible switching actions with the help of these results.

IV. Control Techniques To Track MPPT

A. Modified Inc Cond MPPT Controller

Among all other MPPT techniques Inc Cond MPPT controller with fixed step size tracks MPP accurately and tracking speed is high [4], [8]. The controller measures the incremental changes in PV current and voltage to predict the effect of voltage change. This method utilizes incremental conductance (dI/dV) of a PV array to compute the sign of change in power with respect to voltage (dP/dV). Inc Cond MPPT controller algorithm is shown in Fig. 7. The controller compares incremental conductance (I/V) to array conductance (I/V). If the difference between both the conductances is zero then we can call that voltage as MPP voltage, and the corresponding current as MPP current [11]. Inc Cond controller maintains the MPP voltage until the irradiation changes and the process is repeated. [4], [11].

The slope of the PV curve at MPP is equal to zero.

$$\frac{dP}{dV} = 0 \tag{8}$$

Mathematical calculations based on Eq. (8), finally

$$I + V\frac{dI}{dV} = 0 \tag{9}$$

Based on Eq. (8) and Eq. (9) if any small error occurs then Eq. (10) becomes

$$I + V\frac{dI}{dV} = e \tag{10}$$

B. Conventional PI Controller

A conventional PI controller is a feedback mechanism, extensively used in industrial control applications. A PI controller calculates the "error", as the difference between a reference point and a measured process variable [4]. This error can be minimized in few attempts by adjusting the process control inputs. For MPP tracking

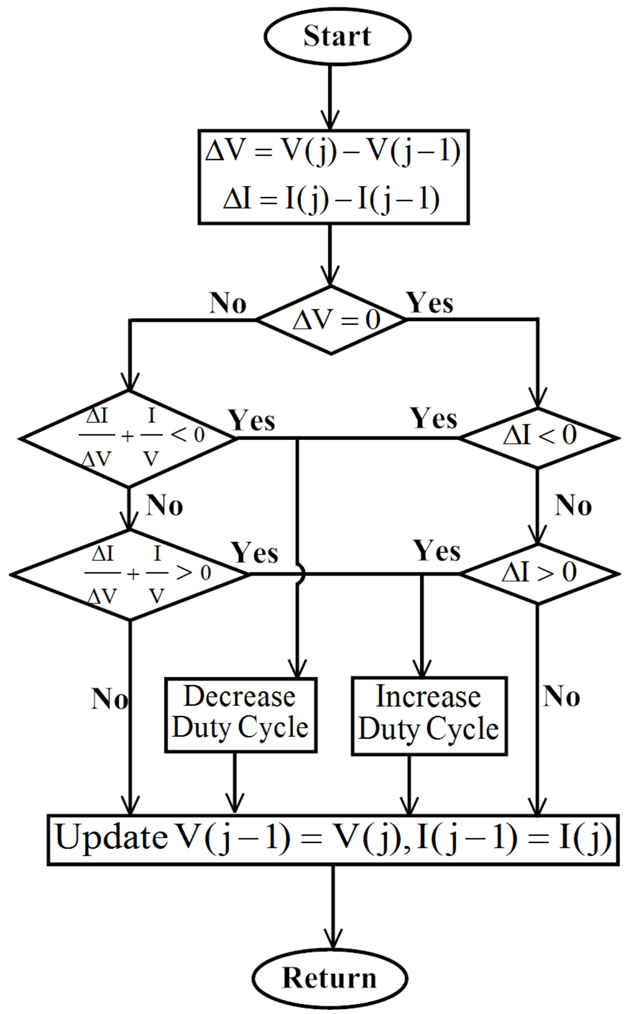


Fig. 7. Flowchart of Inc Cond MPPT controller

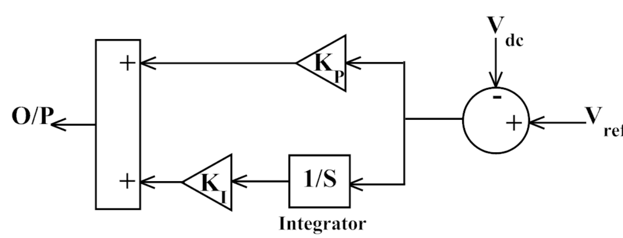


Fig. 8. PI controller

of a PV system, a PI controller is used because of its simple operation, past success record, ease of design and use, low cost and maintenance. MATLAB/SIMULINK PI controller model is shown in Fig. 8.

The algorithm calculation involves two constant parameters, the proportional, and the integral values denoted as K_P and K_I. P is present error; I is the accumulation of past errors based on current rate of change. The weighted sum of these two actions is used to adjust the process via a control element.

V. Real Time Digital Simulator (RTDS)

The RTDS allows the users to simulate the electrical power system models with precision and efficiently [16]. The RTDS simulator not only runs in real time but also tests the physical protection and control structure of the model. This gives the users to test and prove their archetypes and final products in a realistic and practical environment [17]. The RTDS is a digital power system simulator capable of continuous real time operation and it performs simulation with a classical time step of 50 microseconds [12]. The RTDS simulator meets the dead line within the specified time for all simulations. It is a perfect tool for the design, development and testing of power system protection and control schemes with a large capacity for both digital and analog signal exchange to interact with the simulated power system. The RTDS consists of two main tools, they are 1)real-time distributed simulation package (RT-LAB) for the execution of simulink block diagrams on a PC-cluster, and 2)algorithmic toolboxes designed for the fixed-time-step simulation of electric circuits and their controllers [12]. Real-time simulation and Hardware-In-the-Loop (HIL) In-the-Loop (HIL) applications are increasingly recognised as essential tools for engineering design and especially in power electronics and electrical systems. The mathematical computations for power system components and network equations are performed by using either a Wanda 3U module or Wanda 4U module based on Opal-RT simulation system. It communicateswith the target PC via a PCI-Express ultra-low-latency real-time bus interface.

VI. Comparison and Discussion On Simulation and RTDS Results

The output of a PI is given to a comparator to compare with the pulse width modulation (PWM) signal. The comparator output is fed to gate terminal of transistor in the converter. Heuristic values of K_P and K_I are 0.9 and 203 respectively to get undistorted output.The reference voltage given to the PI controller is 250V, and outputs are collected at the load. The output voltage exactly reached to 250V, current 2.1A and power to 521W.

In the modified inccond controller, the error chosen on the basis of hit and trial is 0.0024. According to the MPPT algorithm in the flowchart, duty cycle is calculated. Compared output waveforms of a) voltage, b) current and c) power of the two controllers are shown in Fig. 9 and RTDS results are shown in Fig. 10 and Fig. 11 respectively.

The electrical parameters are tabulated in Table I, readings are taken from the resultant curves shown in Fig. 2. The MPPT techniques are compared in Table II. The parametric values of PI and inc cond are collected from resultant curves shown in Fig. 9.

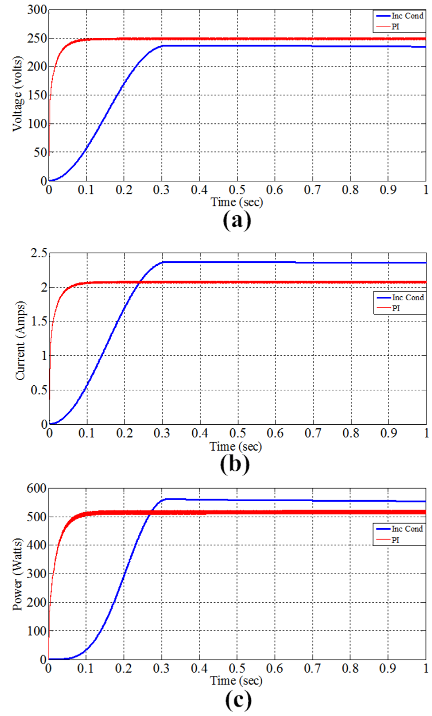


Fig. 9. Inc cond MPPT and PI controller Outputs comparison with a Boost converter (a) Voltage (b) Current and (c) Power

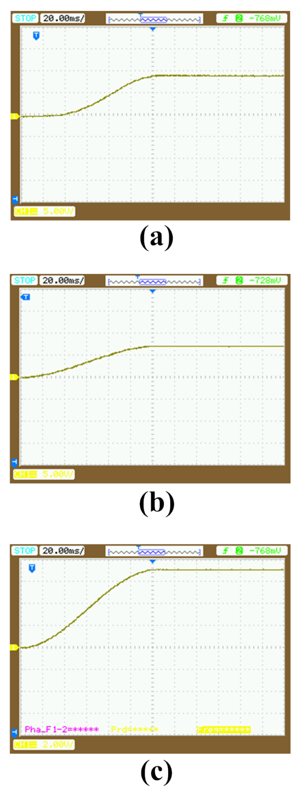


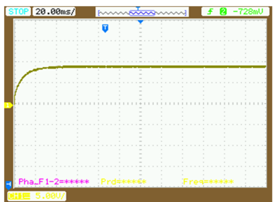
Fig. 10. RTDS results of a modified inc cond MPPT controller a) voltage, b) current and c)power

TABLE I. ELECTRICAL PARAMETERS OF PV ARRAY

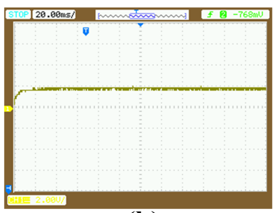
Maximum power (P_{max})	56W
Voltage at MPP (V_{MPP})	18V
Current at MPP (I_{MPP})	3.13A
Open circuit voltage (V_{oc})	21.9V
Short circuit current (I_{SC})	3.46A

TABLE II. COMPARISON OF MPPT TECHNIQUES

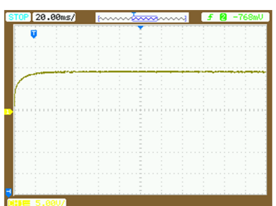
	PI MPPT	Inc Cond MPPT
Output voltage	250v	235v
Output current	2.1A	2.4A
Output power	521W	563W



(a)



(b)



(c)

Fig. 11. RTDS results of a PI controller a) voltage, b) current and c)power

VII. CONCLUSIONS

In this paper, a PV cell with series and shunt resistances is modeled. PV array is arranged by series and parallel combinations of PV cells to extract the parameters like V_{oc} and I_{sc} etc., and plotted the characteristic waveforms at STC, different irradiations and different temperatures. The PV output is connected to a DC DC boost converter for voltage regulation. Control algorithms like modified inc cond and PI are developed to track maximum power from PV system; and observed that the modified inc cond algorithm tracked 7.4% more power than the conventional PI controller. RTDS simulator is used to develop the real time hardware for the developed simulink models. Simulation and real time results were plotted and compared.

REFERENCES

[1] C. Wu, F. Jiang, Q. Wang, and H. Hu, "The maximum power point tracking algorithm for photovoltaic power system based on fuzzy logic double loop control," in *Electronics, Communications and Control (ICECC), 2011 International Conference on*, pp. 1130–1133, IEEE, 2011.

[2] M. G. Villalva and J. R. Gazoli, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electronics*, vol. 24, no. 5, pp. 1198–1208, 2009.

[3] R.-J. Wai, W.-H. Wang, and C.-Y. Lin, "High-performance stand-alone photovoltaic generation system," *IEEE Tran. Ind. Electron.*, vol. 55, no. 1, pp. 240–250, 2008.

[4] V. R. Kolluru, K. Mahapatra, and B. Subudhi, "Development and implementation of control algorithms for a photovoltaic system," in *Students Conference on Engineering and Systems (SCES'13)*, pp. 1–5, IEEE, 2013.

[5] A. Mousavi, P. Das, and G. Moschopoulos, "A comparative study of a new zcs dc–dc full-bridge boost converter with a zvs active-clamp converter," , *IEEE Trans. Power Electronics*, vol. 27, no. 3, pp. 1347–1358, 2012.

[6] J.-H. Su, J.-J. Chen, and D.-S. Wu, "Learning feedback controller design of switching converters via matlab/simulink," *IEEE Trans. Education*, vol. 45, no. 4, pp. 307–315, 2002.

[7] D. Sera, T. Kerekes, R. Teodorescu, and F. Blaabjerg, "Improved mppt algorithms for rapidly changing environmental conditions," in *Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International*, pp. 1614–1619, IEEE, 2006.

[8] B. Subudhi and R. Pradhan, "A comparative study on maximum power point tracking techniques for photovoltaic power systems," *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 89–98, 2013.

[9] Y. Levron and D. Shmilovitz, "Maximum power point tracking employing sliding mode control," *IEEE Trans. Circuits and Systems*, vol. 60, no. 3, pp. 724–732, 2013.

[10] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, p. 439, 2007.

[11] A. Safari and S. Mekhilef, "Simulation and hardware implementation of incremental conductance mppt with direct control method using cuk converter," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1154–1161, 2011.

[12] "Rt-lab professional. http://www.opal-rt.com/product/rt-lab-professional."

[13] W. Ren, M. Sloderbeck, M. Steurer, V. Dinavahi, T. Noda, S. Filizadeh, A. Chevrefils, M. Matar, R. Iravani, C. Dufour, *et al.*, "Interfacing issues in real-time digital simulators," *IEEE Trans. Power Delivery*, vol. 26, no. 2, pp. 1221–1230, 2011.

[14] L.-F. Pak, M. O. Faruque, X. Nie, and V. Dinavahi, "A versatile cluster-based real-time digital simulator for power engineering research," *IEEE Trans. Power Systems*, vol. 21, no. 2, pp. 455–465, 2006.

[15] A. N. Celik and N. Acikgoz, "Modelling and experimental verification of the operating current of mono-crystalline photovoltaic modules using four-and five-parameter models," *Applied energy*, vol. 84, no. 1, pp. 1–15, 2007.

[16] T. Logenthiran, D. Srinivasan, A. M. Khambadkone, and H. N. Aung, "Multiagent system for real-time operation of a microgrid in real-time digital simulator," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 925–933, 2012.

[17] R. Meka, M. Sloderbeck, M. O. Faruque, J. Langston, M. Steurer, and L. DeBrunner, "Fpga model of a high-frequency power electronic converter in an rtds power system co-simulation," in *Electric Ship Technologies Symposium (ESTS), 2013 IEEE*, pp. 71–75, IEEE, 2013.