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Residual Incremental Conductance Based Nonparametric MPPT Control for Solar Photovoltaic Energy Conversion System

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ABSTRACT Maximum power point tracking (MPPT) algorithms have become key elements in improving solar photovoltaic (PV) energy conversion systems. Numerous algorithms have been developed and implemented successfully in recent technology. This paper intended to introduce an improved incremental conductance (IC) algorithm based on the mathematical residue theorem. The major difference introduced in this paper is in considering the residual value of the IC to ensure MPPT achievement. Ensuring the minimal residue in IC improves the operation and eliminates the fluctuation around the operation points. Improved energy conversion efficiency has been achieved and the system has been proved mathematically and by simulations. One of the advantages that the system is free of parameters affect and atmospheric condition data are not required. The controller gain is based on sliding mode compensator to improve the uncertainty handling ability of the developed control approach.

INDEX TERMS Incremental conductance, MPPT, nonparametric control, photovoltaic energy, residue theorem.

I. INTRODUCTION

Due to the environmental concern and the lake of energy resources, developments of renewable energy technology have received many attentions in the last decades. Solar energy, which is the major energy resource of the globe, considered a highest area of interest for researchers and industries. There are several ways in extracting energy from the sun; one of them is PV energy conversion systems. PV energy conversion systems directly convert Sun energy to electrical energy with DC nature of power.

As the conversion efficiency is low, it becomes necessarily to implement a technique that maximizes the conversion efficiency. A MPPT algorithm is well known technique in improving the system efficiency by increasing the amount of extracted energy during the day. The key objective of MPPT is to regulate the DC voltage level of the PV system to the MPP level by regulating the output power [1]. The MPPT techniques could be parametric in which the technique depends on the array parameter or nonparametric technique. Nonparametric approach uses the PV voltage and current measurement regardless the parameter values and PV configuration [2]. Following such approach allows the control system to be independent of atmospheric conditions or solar irradiance data. Most parametric techniques require prior knowledge of PV panels P-V curves and a measurements or estimation for the solar irradiance [3].

The perturb and observation MPPT technique is considered as a highly implemented technique in searching for MPP in PV energy generation system. In perturb and observation MPPT technique the operating point is perturbed by a fixed step and the difference in output power is observed until reaching the MPP. As a result of fixed perturb, the operating point oscillates around the MPP [4]. Perturb and observation method has two major drawbacks, i.e. the oscillations around the MPP during steady state and a poor tracking performance. Also and under changing atmospheric condition, it should be taken into considerations the possibility of tracking in wrong direction under MPP recovery. Solutions in improving tracking efficiency and minimizing the oscillations such as variable step size has been proposed and resulted in slowing the down the system. [4]–[6].

An improvement in P& o technique is attained in another MPPT, namely Incremental Conductance MPPT. However in

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Incremental conductance MPPT technique the operating point is adjusted following the P-V curve slop of the P-V panel [7]. Incremental conductance MPPT technique equalizes the incremental conductance which is the rate of change of the PV current with respect to PV voltage and the negative value of the instantaneous conductance, which is the ratio of the PV current to the PV voltage. Reaching the equalized point stops the perturbing of operation point which indicates the achievement of MPP operation. It has been recorded that following such techniques increases the computational time. Also, the sampling frequency of the PV voltage and current is slowing down [2], [4], [8]. A fixed-step-size IC MPPT with direct control method and eliminated any other control loop has been developed in [9], It has been proved that a well-designing system and proper power electronics selections as well as efficient IC algorithm can lead to acceptable efficiency level of the PV system.

For the most common types of MPPT (perturb and observation and incremental conductance) any fast change in the environmental conditions will cause some problems for the MPPT. Moreover these two techniques increase the PV system losses and consequently decrease the system efficiency. Some of these problems are handled by different control schemes, like fuzzy control, genetic algorithm optimization for minimizing the losses [10], [11]. A new optimization technique, cuckoo search, is introduced to optimize the PI control parameters of the DC-DC chopper used to MPPT as in [12]. However all these techniques tried to improve the performance of MPPT but they did not update the reference voltage and power for the tracking purpose. The key solution for such problem using some adaptive technique for updating the power and voltage references for MPPT.

First implementation of mathematical residue theorem in control system has been proposed in [13]. The proposed control theory redefines the error equation by the residue equation. Hence, the controller considers a residual boundary which is dynamic between the controlled variable and the set point. The uncertainty handling ability as well as the soft dynamics was proved in wind energy generation system. The overall conversion efficiency has been improved too.

In this research, the residue based control strategy has been implemented to the classical incremental conductance MPPT technique. The improvement took place in the definition of the condition of MPPT. Hence, rather than equalizing the rate of change of current with respect to voltage and the negative ratio of actual PV current to PV voltage, the proposed technique equalize the residue value of incremental conductance of the change and the negative instantaneous conductance. The proposed MPPT algorithm generates a reference maximum voltage for a sliding mode controller. Therefore, a sliding mode compensator had been designed to be the adaptive gain for the controller. The uncertainty handling capability is a key element in evaluating the proposed research.

This research paper is structured as follows. The state of the art literature has been presented in Section I. Also, in this section the problem statement has been presented and the claimed contributions have been highlighted. Section II demonstrates an overview on PV generation system modeling. The classical IC MPPT design is demonstrated in Section III. Then, the proposed MPPT design is explained in the same section. In Section IV, the sliding mode controller is illustrated. The simulation results and analysis are discussed in Section V. The performance comparison is highlighted in Section VI. The paper is concluded in Section VII.

II. PV ENERGY CONVERSION SYSTEM

The investigated PV energy generation system is a small scale batteryless system. It consists of a PV module and DC-DC boost converter supplying DC load. The characteristics of the system is explained below.

A. PV CHARACTERISTICS

It is well known that the solar cell is the basic element of photovoltaic modules. When a solar cell received effective solar radiations the free electrons move and cause a flow of charge or current. The effective solar radiations can be a combination of direct radiation and diffused radiations. The solar cell is connected in series-parallel combination to form a PV module. For adjusting the current and voltage capability the PV modules are connected in series and parallel combination respectively to form the PV array. The energy extracted from the sun depends on the hourly solar irradiance. In order to estimate the amount of energy a window of peak sun hour is determined. Therefore, the average energy is the area under the curve caused by the peak sun hour. Not only the solar irradiance will affect the energy conversion ratio but there are several atmospheric conditions affect such as temperature have dominant effects.

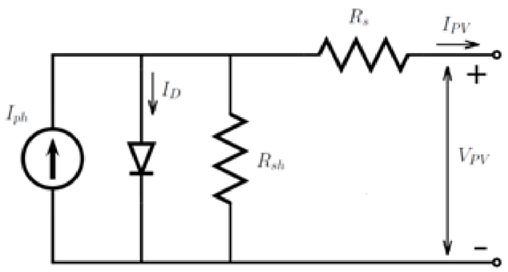

FIGURE 1. The equivalent circuit of the solar cell.

The solar cell can be represented in equivalent circuit shown in Fig. 1, where I_{ph} is the photocurrent of the solar cell, the generated photovoltaic current is I_{pv} and the equivalent photovoltaic voltage is V_{pv}. For simplified model the shunt resistance R_{sh} is neglected because of its large value. Also, the small series resistance R_s is neglected [14]. Therefore, the following equation can represents the PV characteristic [15].

$$I_{pv} = I_{ph} - I_{sat}[\frac{q(V_{pv} + I_{pv}R_s}{AKT - 1}],$$
$$I_{ph} = \frac{\lambda}{1000}[I_{sc} + K_I(t - 25)] \quad (1)$$

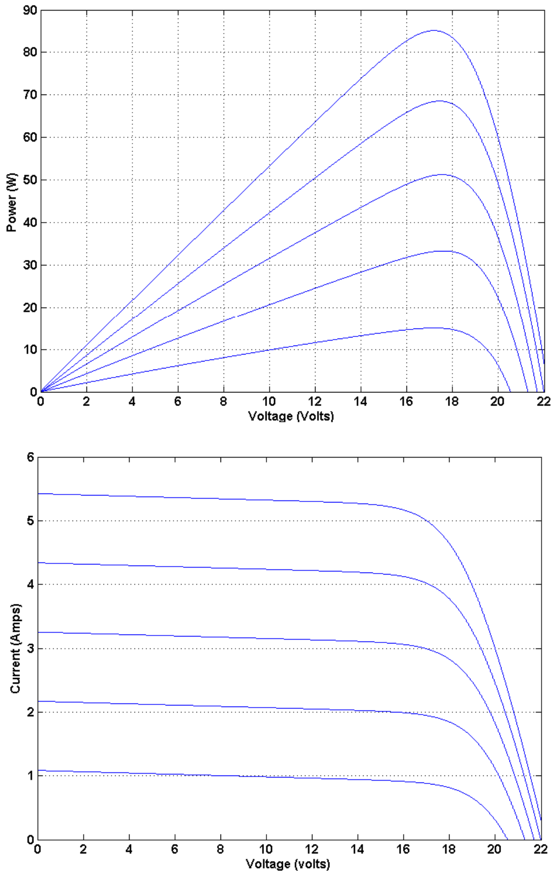

FIGURE 2. The PV panel P-V and I-V characteristics.

where, q is the charge of an electron ($1.602 \times 10^{-19}C$), λ is Solar irradiance, A is the idealist factor of a p-n junction (1 or 2), k is the Boltzman's factor ($1.381 \times 10^{-23}J/K$), T is the temperature of the cell array and I_{sc} and K_I are the short-circuit current and the short-circuit current temperature respectively. The output power characteristics of the PV panel as functions of solar irradiance are shown in Fig.2.

B. DC-DC BOOST CONVERTER

DC-DC boost converter is a power electronics circuit employed in applications that require a grater output voltage value than the input. Moreover, it can perfectly regulate the output voltage level even when the input is unregulated. The employed converter in this work is designed to work in continuous conduction mode where the inductor current is always above zero. Typical boost converter configured is based on using IGBT, inductor and capacitor. The state equations of the boost converter can be shown as the followings:

ON STATE

$$\begin{aligned} L\frac{di_L}{dt} &= V_{in}, \\ C\frac{dV_o}{dt} + \frac{V_o}{R} &= 0. \end{aligned} \tag{2}$$

OFF STATE

$$\begin{aligned} L\frac{di_L}{dt} + V_o &= V_{in}, \\ i_L - C\frac{dV_o}{dt} - \frac{V_o}{R} &= 0. \end{aligned} \tag{3}$$

The ON and OFF states can be modulated using several techniques. In this research PWM modulation has been followed. By considering the ratio of the ON state to the OFF state the above equation can be averaged over one cycle and the duty ratio D is introduced as follows:

$$\begin{aligned} \frac{di_L}{dt} &= \frac{V_{in} - (1-D)V_o}{L}, \\ \frac{dv_o}{dt} &= \frac{(1-D)I_L}{C} - \frac{V_C}{RC}. \end{aligned} \tag{4}$$

Unlike the buck converter, the control of DC-DC boost converter is quite difficult since the controlled variable is present in both equations of voltage and current [16].

III. MAXIMUM POWER POINT TRACKING DESIGN

A. CLASSICAL INCREMENTAL CONDUCTANCE

As mention earlier, classical incremental conductance works on the principle that the summation of the incremental conductance and the instantaneous conductance is zero [2]. The condition can be shown in equation 5. This equation is used to generate reference voltage for the controller. It has been used to design the classical MPPT for the comparison analysis.

$$\frac{di}{dv} + \frac{I}{V} = 0. \tag{5}$$

B. PROPOSED RESIDUAL INCREMENTAL CONDUCTANCE

The proposed MPPT technique works on the principle of redefining the condition to be the residue of the summation of the incremental conductance and the instantaneous conductance is zero. The redefinition of equation 5 is shown below:

$$Res\left[\frac{di}{dv} + \frac{I}{V}\right] = 0. \tag{6}$$

By setting the residual value to zero, it can be claimed that the condition is further forced to zero and error of the classical condition is eliminated. The new maximum voltage definition is shown in the following equations:

$$\begin{aligned} Res\left[\frac{di}{dv}\right] &= \frac{1}{2\pi}\int \frac{di}{dv} \quad didv, \\ Res\left[\frac{di}{dv}\right] &= \frac{I}{2\pi} + C_{c1}, \end{aligned} \tag{7}$$

where, (C_{c1}) is constant, and,

$$\begin{aligned} Res\left[\frac{I}{V}\right] &= \frac{1}{2\pi}\int \frac{I}{V} \quad didv, \\ Res\left[\frac{I}{V}\right] &= \frac{1}{2\pi}\left[\int Idi + \int \frac{1}{V}dv\right], \\ Res\left[\frac{I}{V}\right] &= \frac{1}{2\pi}\left[\frac{I^2}{2} + C_{c2} + \ln(V)\right]. \end{aligned} \tag{8}$$

where (C_{c2}) is constant. Therefore,

$$\frac{I^2}{2} - I + \ln(V) + C_{c3} = 0, \tag{9}$$

where (C_{c3}) is a constant which replace the constants (C_{c1}) and (C_{c2}),

$$\begin{aligned} \ln(V) &= \frac{-I^2}{2} + I - C_{c3}, \\ \ln(V) &= \frac{-1}{2}(I-1)^2 + C_c, \end{aligned} \tag{10}$$

where (C_c) is a constant which replace the constant $(2C_c)$. Hence, a new definition of the output voltage is obtained. This reference voltage ensures a MPPT operation at constant voltage without the need of atmospheric conditions measurements. The improved maximum reference voltage equation can be defined:

$$V_{o-max} = e^{(-0.5(I-1)^2+C_c)}. \tag{11}$$

IV. PV ENERGY CONVERSION SYSTEM CONTROL

The controller of the PV energy conversion system has been designed based on improved sliding mode control strategy. The improvement has been made on the convergence equation. The forward Euler equation has been proved for high capability in converging the operating point to its reference [13]. The error definition based on forward Euler equation is as follows, where (k) is constant:

$$\begin{aligned} \dot{e} &= e + k, \\ e &= V_{o-max} - V_o, \\ \dot{V}_{o-max} - \dot{V}_o &= V_{o-max} - V_o + k, \\ \dot{V}_{o-max} &= (1-I)e^{(-0.5(I-1)^2+C_c)}. \end{aligned} \tag{12}$$

By employing the control equation to the duty ratio of the boost converter the control equation can be presented as the followings:

$$\begin{aligned} &(1-I)e^{(-0.5(I-1)^2+C_c)} - \frac{(1-D)I_L}{C} + \frac{V_C}{RC} \\ &\quad = e^{(-0.5(I-1)^2+C_c)} - \left[\frac{1}{1-D}\right]\left[V_{in} - L\frac{di}{dt}\right] + k, \end{aligned} \tag{13}$$

$$\begin{aligned} &-Ie^{(-0.5(I-1)^2+C_c)} \\ &\quad = \frac{(1-D)I_L}{C} - \frac{V_o}{RC} - \left[\frac{1}{1-D}\right]\left[V_{in} - L\frac{di}{dt}\right] + k, \end{aligned} \tag{14}$$

The controller equation can be rearranged in the form of quadratic equation as below,

$$\begin{aligned} &(1-D)^2\,[I_L R] + (1-D)\left[IRCe^{(-0.5(I-1)^2+C_c)} - V_o\right] \\ &\qquad + RC\left[L\frac{di}{dt} - V_{in}\right] + k_k = 0, \end{aligned} \tag{15}$$

$$\begin{aligned} q &= (1-D), \qquad a = I_L R, \\ b &= IRCe^{(-0.5(I-1)^2+C_c)} - V_o, \\ c &= RC\left[L\frac{di}{dt} - V_{in}\right] + k_k. \\ q &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}. \end{aligned} \tag{16}$$

A sliding mode compensator $[A_1\, sgn(q) - A_2]$ can be used to compensate the value of D, where $(A_{1,2})$ are constants.

V. SIMULATION RESULTS AND DISCUSSION

The proposed residue MPPT controller has been tested on a stand-alone bases. The solar irradiance has been designed to be variable between maximum (1000 w/m^2) and minimum (200 w/m^2) to cover the possible operation level during a day. The system has been simulated using MATLAB/SIMULINK.

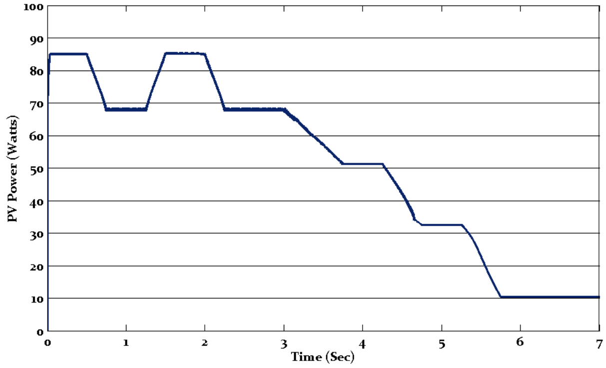

FIGURE 3. The output power of the PV under variable solar irradiance.

The performance of the PV energy conversion system under variable solar irriadance is illustrated in Fig.3. The system performance shows successful achievements of MPPT operations. The dynamics of the system are satisfactory and the transitions between different solar irradiance occurred smoothly. The name plate data and the achieved results are presented in the comparison section.

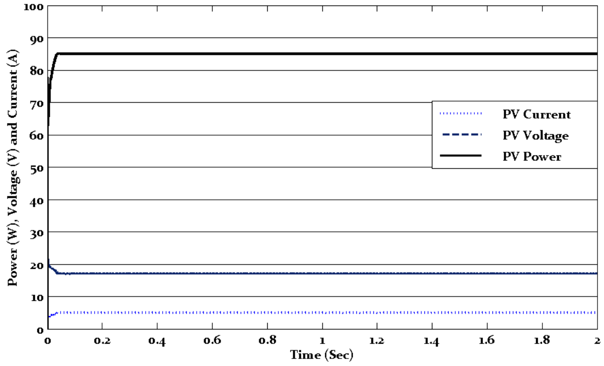

FIGURE 4. The output voltage, current and power of the PV at 1000 w/m^2.

The system shows improved uncertainty handling capability. Also it is clear from Fig.3, that the output power is stable and perfectly tracks the maximum. Further investigations of the system performance have been done based on maximum solar irradiance (1000 w/m^2). The photovoltaic voltage and current ensures the achievement of MPPT operation. The photovoltaic MPP voltage, current and power is demonstrated in Fig.4. AS shown in figure the voltage and current show constant and stable operation at maximum solar irradiance.

VI. COMPARISON ANALYSIS

Conventional IC algorithm has been designed and tested in [17]. The results show a very high deviation from the actual tracking that the tracking time has been increased and the efficiency has been decreased. It has been claimed that the reason is due to insolation shifting from a level to another. A complex solutions has been proposed and tested at different scenarios in [18]. The result shows improvement in efficiency and duration but the complicity of the algorithm is high.

The proposed residue IC MPPT has been compared to classical IC MPPT. The comparison in terms of achieving power at maximum solar irradiance as can be shown in Fig.5. It can be indicated clearly from the figure that the proposed residual IC shows improved stability on the operating point. Hence, it can be claimed that the residual IC overcome the drawback of the oscillation around the reference point which occur in most nonparametric techniques.

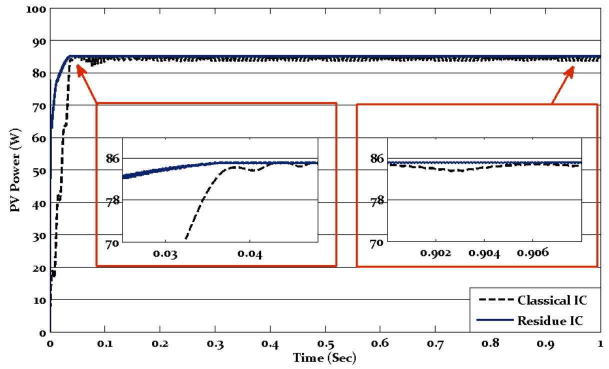

FIGURE 5. Comparison of the output power of the PV at 1000 w/m^2.

Considering the residual is equal to zero influences the achievement of MPPT and the stability on the operating point as well. Also, it can be seen clearly that the response based on residue IC MPPT technique is smoother and faster compared to the classical MPPT technique. The energy conversion efficiency is improved and that could be accumulated in higher PV array ratings.

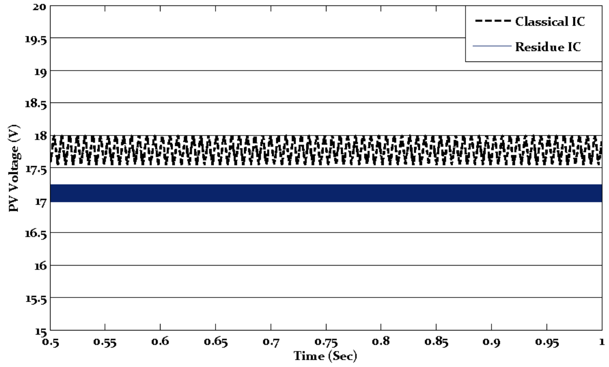

FIGURE 6. Comparison of the output voltage of the PV at 1000 w/m^2.

Also, the performance has compared based on the voltage at maximum power. Fig.6 shows the output voltage of the PV using the two techniques. It is clear from the figure that the voltage is constant and contain less ripple. It can be claimed that when implementing the residual IC, the PV voltage has better regulations.

TABLE 1. Comparison between Residue IC and Classical IC techniques.

	Name plate value	Classical IC	Resicue IC
$1000w/m^2$ Solar irradiance			
Power (W)	85.14	84.8	85.1
Voltage (V)	17.2	17.8	17.2
$800w/m^2$ Solar irradiance			
Power (W)		68.4	68.4
Voltage (V)		17	17.1
$600w/m^2$ Solar irradiance			
Power (W)		51.1	51.25
Voltage (V)		17.6	17.6
$400w/m^2$ Solar irradiance			
Power (W)		32.1	32.44
Voltage (V)		16.15	18.42
$200w/m^2$ Solar irradiance			
Power (W)		9.75	10.35
Voltage (V)		9.85	10.95

In the proposed MPPT technique the maximum overshoot is almost zero at 1000 w/m^2 compared to 0.4% when using IC MPPT method. Moreover the steady states error is 0.1% at 1000 w/m^2 compared to 1.5% in IC. The improvement in steady states error indicates an enhanced performance and less oscillations around the reference point.

Detailed performance can be presented in 1. It is clearly shown in the table that the output power of the PV is enhanced while using the residual IC MPPT technique.

VII. CONCLUSION

In this paper the photovoltaic energy conversion system has been investigated. Several MPPT algorithms have been reviewed. A novel MPPT based on residue theorem has been proposed. The proposed MPPT is an improved version of Incremental conductance algorithm. The improved residue based IC has been developed in such a way that the residue of the addition of the incremental conductance and the instantaneous conductance is zero. The convergence has been improved and designed based on forward Euler method of convergence. Moreover, the controller gain has been improved and designed following sliding mode compensator. The aim of sliding mode compensator is to improve the uncertainty handling capability of the controller since the uncertainty appears due to the fact that the algorithm is nonparametric.

The proposed controller has been tested and analyzed based on simulations. The performance of the PV energy conversion system shows satisfactory dynamics and MPPT operation has been successfully achieved. The proposed residue IC MPPT has been compared to classical IC MPPT algorithm. The comparison demonstrate the improvement in the energy conversion performance and better achievement. The stability on the operating points gives a solid evidence on the claim, that the proposed residue IC MPPT overcomes the disadvantage regarding the oscillation around the reference point.

The comparison has been demonstrated based on different solar irradiance. Overall implementing residue IC MPPT can improve the efficiency and tracking performance of the PV energy conversion system.

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