An isolated photovoltaic power generation system with a novel fractional order PID controller based control strategy

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Abstract: The renewable energy resources such as photovoltaic systems have major role in the development of sustainable energy systems. An efficient controller for standalone photovoltaic system based on fractional calculus is proposed in this work. The power extracted from the PV systems are continuously varies with respect to the dynamic changes of solar irradiance value and climate temperature. Here we introduce a Maximum Power Point Tracking (MPPT) algorithm is which realized with the support of Fractional Order PID (FOPID) controllers to extract the maximum possible power from the Photo Voltaic(PV)modules. The PID controller and FOPID controllers are also ensures the constant dc bus voltage and hence the ac output voltage at become stable. The effectiveness of the controller are compared using various performance time domain specifications like overshoot percentage, rise-time, settling-time, etc. The various analysis were done under the variation of irradiance and temperature in MATLAB Simulink platform. The FOPID controller give improved performance compare with conventional PID controllers.

1. INTRODUCTION

The solar photovoltaic (PV) energy offers free, abundant, pollution-free and distributed in the entire life of earth. The PV generation systems are popularly used as energy resources in standalone, grid connected and hybrid systems. The PV system provides clean energy [1-2]. The various technological enhancement in PV cell based power generation is contributing a major role in fulfillment of increased requirement for standalone configurations in low level voltages and also in high power applications, even those applications are normally grid connected. The main benefit of the solar system is that it directly converts energy from light into electrical energy through semiconductor materials. However, the renewable energy based power production is not continuous

The major components of the PV based power system is the Maximum Power Point Tracking (MPPT) from PV array. The MPPT is a technique used to regularly to amplify the power extraction under all conditions. The MPPT control is utilized to vary the duty ratio of converter connected between PV input and load to extract the maximum available power from the renewable energy sources and to deliver sustainable power to the loads connected. The popular MPPT control algorithms are Perturb and Observe based (P&O) Incremental Conductance (IC) based methods.

A novel control strategy is suggest in this paper for a standalone PV structure using FOPID controller. The PV generation rely upon on climate conditions and the power electronic based interfaces utilized to improve the coherence and stable power production. But the efficient extraction of peak available power from the PV system is still a challenge. A standalone PV system consist of PV arrays that
transforms energy from sun into the electric current, DC-DC power converter, MPPT controller and a load. Generally, the MPPT control is challenging and it is considered as non-linear complex problem. But while we using MPPT techniques, the continuous modulation of the converter associated is required with respect to variation of irradiance value and temperature. Hence the output voltage also varies. Thus, a constant alternating voltage cannot be obtained at the load side. In order to achieve a constant voltage output under varying weather conditions and to reduce oscillations, controllers are used along with the MPPT. Isolated PV systems are usually designed to work independently and supplies DC and/or AC electrical loads.

2. MODELLING OF SOLAR PV SYSTEM

An analogous circuit of a PV cell can be drawn as shown in the figure 1. The attributes a solar cell can be obtained using mathematical equation. The mathematical model of a PV module can be derived as given in [3]. The series connected PV is gives an open circuited voltage ($V_{oc}$) and a short circuited current ($I_{sc}$). The current source $I_{ph}$ denotes the photocurrent of cell. $R_s$ and $R_{sh}$ are the series connected and parallel connected resistances of the cell respectively. In practical case, the PV cells are merged into extensive units which are termed as PV modules. These solar modules are connected in series and parallel to create PV arrays that are used to large electricity production.

![Solar cell equivalent circuit](Image)

**Figure 1.** Solar cell equivalent circuit

Photocurrent, $I_{ph} = \frac{G}{1000} (I_{sc} + K_i(T - 298))$

(1)

Here, $I_{ph}$ - photo current (Amp), $I_{sc}$ – short-circuit current (Amp), $K_i$ – temperature coefficient of short circuited current, $T$ – operating temperature in Kelvin, $G$ – solar irradiation (W/m²).

Reverse saturation current, $I_{rs} = \frac{I_{sc}}{\exp(\frac{qV_{oc}}{nKT}) - 1}$

(2)

Here, q is charge of electron =1.6 × 10⁻¹⁹C, Ns is the number of series connected cells, n is diode ideality factor, k – Boltzmann’s constant whose value is 1.3805 × 10⁻²³ J/K.

Saturation value of PV current,$I_o = I_{rs} \left(\frac{T}{T_r}\right)^3 \exp \left[\frac{qE_g}{nKT} \left(\frac{1}{T} - \frac{1}{T_r}\right)\right]$

(3)

Here, $T_r$ – nominal temperature = 298K, $E_g$ – band gap energy = 1.1eV

The current expression at output of PV module is given by,

Output current, $I = N_p I_{ph} - N_p I_0 \left[\exp \left(\frac{V + N_s I \frac{R_s}{N_p}}{nV_T}\right) - 1\right] - I_{sh}$

(4)

where,
\[ V_t = \frac{k \times T}{q} \] 

(5)

Current through shunt resistor, \( I_{sh} = \frac{(N_p + R_s)}{R_{sh}} \) 

(6)

Here, \( N_p \) is the number of PV units which are parallel connected, \( R_s \) is the resistance connected in series(\( \Omega \)), \( R_{sh} \) is the resistance in shunt(\( \Omega \)), \( V_t \) is the thermal equivalent voltage of diode(\( V \))

3. PERTURB & OBSERVE (P&O) BASED MPPT ALGORITHM

The PV power generation characteristics are non-linear as it is vary with temperature, solar irradiation and load. The operating voltage and current on the I-V curve is obtained by the amount of power generated by PV array [4]. The knee point of the curve occurs only at one point of maximum power. The MPPT in PV system is tuning the system continuously to draw peak available power from the solar array. The MPP of PV array changes continuously and thus operating point must change depending upon the weather or load conditions. The operation of MPPT [5] can be achieved using a matching network to interface the load of PV array. The flow-chart of Perturb & Observe (P and O) based MPPT algorithm is given in the figure 2.

![Figure 2. P&O based MPPT Algorithm](image)

The P and O based control is the most popular MPPT control algorithm due to its ease and low-cost implementation. In this method, PV voltage is first perturbed a little and the corresponding output power is estimated using PV current and PV voltage. If the power increases on increment of voltage,
then voltage is increased. If the power reduces on increment in voltage, then voltage is lowered so that high power is achieved. The variations in operating voltage is obtained by proper variation of duty cycle of the DC-DC power converter in the system. But, under variable irradiation or weather or load change, the output power oscillates and this weakens the algorithm without the presence of any other controller. Here we introduce a FOPID controller to effectively track the maximum power with adequate voltage stability.

4. PROPOSED CONTROL OF SOLAR PV SYSTEM

In this paper, a novel controller for isolated solar photovoltaic system is proposed as shown in the figure 3. The topology mainly including the PV array, Boost converter, MPPT algorithm and PID/FOPID controller. The MPPT receives the input as PV panel current $I_{pv}$ and panel voltage $V_{pv}$. Instead of connecting the reference voltage generated corresponding to the maximum power point directly to the PWM block, we introduce a fractional order PID controller to trace the actual panel voltage more exactly to the reference voltage. Hence the entire system efficiency can be improved. The non-integer order based PID controllers or $P^\lambda I^\mu D$ controllers have the components such as non-integer integrator and non-integer derivative to enhance the performance of the closed loop systems[6]. The use of FOPID controllers results large improvements in steady state and transient performance of the dc-dc converter output compared with conventional PID controllers.

![Figure 3. Proposed control scheme of isolated PV system](image)

4.1 PID (Proportional-Integral-Derivative) Controller

A PID controller estimates the error signal obtained from the difference between desired state and feedback output signal. The controller helps to minimize the error by tuning the various gain constants used in controller. The PID controller involves three constant parameters, they are termed as the proportional (P) gain, the integral (I) gain and the derivative (D) gain components. The PID controller tuner uses the formula

$$G_c(s) = (K_P + \frac{K_I}{s} + K_D s)$$

(7)

Where, $K_P$ is the proportional gain constant, $K_I$ is the integral gain constant and $K_D$ is the derivative gain constant.

The Ziegler Nichols rules are popular tuning method for the PID controllers [4]. The drawbacks of PID controller in PV system are (a) the drastic changes in solar irradiance available will correspondingly reduce the performance of the PID controller and (b) oscillations are present around desired operating point at maximum power.
4.2 FOPID (Fractional order PID) Controller

A. Notes on fractional-calculus

Non integer calculus is a classical topic in computational research that is acquiring more acceptance nowadays. The paper published by Miller and Ross, provides good introduction to fractional calculus. There are numerous scientific definitions for non-integer integral and derivatives[4-5]. The currently used definitions are presented below.

**Definition by Riemann-Liouville (R-L)**

It gives one of fundamental definitions of the non-integer order integrals and derivative. The R-L definition of integral of non-integer order \( \lambda > 0 \) is given as

\[
I_{RL}^\lambda g(t) = D_{RL}^{-\lambda} g(t)
\]

\[
= \frac{1}{\Gamma(\lambda)} \int_0^t (t-\zeta)^{\lambda-1} g(\zeta) d\zeta
\]

Also, the R-L definition of derivative of non-integer order \( \mu \) is

\[
D_{RL}^\mu g(t) = \frac{1}{\Gamma(n-\mu)} \frac{d^n}{dt^n} \int_0^t (t-\zeta)^{n-\mu-1} g(\zeta) d\zeta
\]

Where the integer limit, \((n-1) < \mu < n\). The non-integer order derivative alternatively communicated from eq. (8) as

\[
D_{RL}^\mu g(t) = \frac{d^n}{dt^n} \left[ I_{RL}^{(n-\mu)} g(t) \right]
\]

**Definition by Grunwold – Leitnikov (G-L)**

The G-L definition based non-integer order integral with order \( \lambda > 0 \) is

\[
I_{GL}^\lambda g(t) = D_{GL}^{-\lambda} g(t)
\]

\[
= \lim_{h \to 0} h^\lambda \sum_{j=0}^k (-1)^j \binom{\lambda}{j} g(kh - jh)
\]

where, \(h\) denotes the period of sampling with the coefficients \(\omega_j^{(-\lambda)}\) satisfying

\[
\omega_0^{(-\lambda)} = \left( \lambda \right)_0 = 1
\]

Which includes to the given polynomial equation:

\[
(1 - z)^{-\lambda} = \sum_{j=0}^\infty (-1)^j \binom{\lambda}{j} g(kh - jh)
\]

The G-L based definition for non-integer order derivative with order \( \mu > 0 \) is

\[
D_{GL}^\mu g(t) = \frac{d^\mu}{dt^\mu} g(t)
\]

\[
= \lim_{h \to 0} h^{-\mu} \sum_{j=0}^k (-1)^j \binom{\mu}{j} g(kh - jh)
\]

Where the coefficients

\[
\omega_j^{(\mu)} = \binom{\mu}{j} = \frac{\Gamma(\mu+1)}{\Gamma(j+1)\Gamma(\mu-j+1)}
\]

with \(\omega_0^{(\mu)} = \binom{\mu}{0} = 1\), are those of the polynomial:
\[(1 - z)^\mu = \sum_{j=0}^{\infty} (-1)^j \binom{\mu}{j} z^j = \sum_{j=0}^{\infty} a_j(\mu) z^j \]  

\[\text{(19)}\]

**Stability definitions of fractional-order system**

The definition of stability is based on Mitag-Lefler functions

First Definition: The Mitag-Lefler functions is given as 

\[E_\alpha(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(k\alpha+1)} \]  

\[\text{(20)}\]

Where \(\alpha > 0\). The Mitag-Lefler function takes mathematical formulation as 

\[E_{\alpha,\beta}(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(k\alpha+\beta)} \]  

\[\text{(21)}\]

Where \(\alpha > 0\) and \(\beta > 0\). For \(\beta = 1\), we have \(E_{\alpha}(z) = E_{\alpha,1}(z)\).

Second definition: The R-L based non-autonomous fractional system given as 

\[D_{RL}^\alpha x(t) = f(x,t) \]  

\[\text{(22)}\]

Where \(f(x,t)\) is Lipschitz and having Lipschitz constant \(l > 0\) and \(\alpha \in (0,1)\).

The result can be consider as Mitag-Lefler stable if 

\[\|x(t)\| \leq m(x(t_0)) E_\alpha(-\lambda(t-t_0)) \eta \]  

\[\text{(23)}\]

Where \(t_0\) is the initial value of time, \(\alpha \in (0,1), \lambda > 0\) and \(b > 0, m(0) = 0, m(x) \geq 0\) and \(m(x)\) is locally Lipschitz on \(x \in B \subset R^n\) with a Lipschitz constant \(m_0\).

The stability statement is

**Lemma 1.** Let \(x=0\) be an equilibrium point for the non-integer system. Suppose there exist a Lyapunov function as \(V(t, x(t))\) defined as 

\[\epsilon_1 \|x\|^q \leq V(t, x) \leq \epsilon_2 \|x\|, \]  

\[\dot{V}(t, x) \leq -\epsilon_3 \|x\|, \]  

Where \(\epsilon_1, \epsilon_2, \epsilon_3\) and \(\eta\) are non-negative constants. Then the equilibrium point is Mitag-Lefler stable asymptotically.

**B. Structure and tuning of FOPID Controller**

FOPID controller is the fractional order modification of conventional PID control system and it offers a great variety of tuning parameters [7-8]. The fractional controllers are touchy to changes of parameters. With the two extra additional degrees of freedom, it is better to vary the behaviors of the system. The higher adaptability can be acquired in FOPID controller due to the presence of five parameters to tune the controller than using convention PID controllers. Thus, better closed loop performance can be obtained using FOPID. The structure of FOPID controller is shown as in the figure 4.

The controller transfer function in Laplace transform of the FOPID is given as 

\[T(s) = K_p + K_i s^{-\lambda} + K_D s^\mu \]  

\[\text{(24)}\]

where, \((\lambda, \mu) > 0\). The modeling and simulations of fractional order based control can be done using toolboxes in MATLAB. The common FOPID toolboxes are FOMCON toolbox, NINTEGER tool
box, etc.

Figure 4. Structure of FOPID Controller

5. SIMULINK BASED EXPERIMENTAL AND RESULTS

The analysis of the isolated solar power system under various condition of irradiance and temperature were carried out. The effectiveness of the conventional PID and FOPID controllers are analyzed by comparing the performances under different conditions. These results are depicted in proceeding sections. The PV current, PV output power, DC bus voltage and inverter output voltage are plotted under different conditions. The PV module used in this paper is SUNPOWER SPR-305E-WHT-D. The boost type converter is designed to produce a voltage of 300V at output with minimum ripples. The DC link capacitor = 100 µF, Inductance=5mH, Capacitance, C=12000µF and switching frequency $f_s = 5$KHz. are the other designed elements of boost converter. The tuning parameter of PID and FOPID controllers are shown in the Table 1 and Table. 2

Table 1. Gain Parameters of PID controller

| Controller | $K_p$ | $K_i$ | $K_d$ |
|------------|------|------|------|
| PID        | 0.01 | 45   | 0.15 |

Table 2. Tuning Parameters of FOPID controller

| Controller | $K_p$   | $K_i$    | $\lambda$ | $K_d$  | $\mu$ |
|------------|---------|---------|----------|--------|-------|
| FOPID      | 0.2065  | 11.7906 | 0.8887   | 0.016  | 0.0019|

5.1 System response under various conditions of temperature & irradiance using PID Controller

Figure 5. System response under constant temperature and irradiance using PID Control
Figure 5 gives the PV current, output power, dc bus voltage and inverter output voltage at constant temperature of 25°C and irradiance of 1000W/m² using PID controller. As there is no change in irradiance and temperature, almost smooth results are obtained. Still the overshoot and the settling time are larger with PID controllers as seen in the waveforms. The transient period can be viewed during the period 0 to 0.3 sec.

![Waveforms for constant temperature and irradiance](image)

**Figure 6.** System response under constant temperature and variable irradiance using PID Controller

Figure 6 shows the response of the system under constant temperature of 25°C and variable irradiance. The variation of the irradiance are shown in figure. PV current and power shows transient period during 0-2.5sec. These waveforms shows some spikes at the point where the irradiance is abruptly changes. But, the controller succeeded to ensure the solar dc bus voltage constant under these changes in irradiance too.

![Waveforms for variable temperature and constant irradiance](image)

**Figure 7.** System response under variable temperature and constant irradiance using PID Controller

Figure 7 gives the various waveforms under variable temperature and constant irradiance (1000W/m²) with PID controller. The current and power waveforms exhibits spikes when the temperature increases from 25°C to 50°C at the t=1sec. The dc bus voltage maintained at constant voltage. The
inverter output voltage also maintained balanced even with the variation of temperature.

Figure 8 gives the system response under the simultaneous variation of irradiance and temperature using PID controller. Here we introduce a multi changing irradiance. The system responds well with the fast variation of the irradiance. As in the previous cases, here also the spikes are present in point of transition of irradiance from one level to another level. The dc bus voltage maintained constant and inverter output voltages are well balanced.

5.2 System response under various conditions of temperature & irradiance using FOPID Controller

The system is analysed using FOPID controller. Figure 9 shows the response under the condition of constant temperature value of 25°C and irradiance value of 1000W/m². The improvements in the transient performance can be viewed from the PV current, power and voltage waveforms compared with conventional PID controller.
Figure 10. System response under constant temperature and variable irradiance using FOPID Controller

Figure 10 shows the system response under constant temperature 25°C and variable irradiance. The transient performance is improved as shown in the PV current, power and dc bus voltage waveforms. Figure 11 describes the nature of the output of the system with variable temperature and constant irradiance of 1000W/m².

Figure 11. System response with variation in temperature and constant irradiance using FOPID Controller
Figure 12 gives the system response under the simultaneous variation of irradiance and temperature using FOPID controller. Here we introduced a multi changing irradiance. The system responds well with the fast variation of the irradiance than with ordinary PID controller. The spikes present in the waveforms are very less in amplitude in comparison with conventional PID controller. The value of dc bus voltage maintained constant and inverter output voltages are well balanced.

6. COMPARATIVE ANALYSIS OF PERFORMANCES OF PID AND FOPID CONTROLLERS

6.1 DC Bus Voltage at Constant temperature & irradiance
The performance comparison of the solar PV system with conventional PID and FOPID controllers can be one by comparing the dc bus voltage waveforms under various dynamic changes of temperature values and irradiances. Figure 13 shows the dc bus voltage waveforms at temperature value, 25°C and irradiance 1000W/m² using conditional PID and FOPID based controllers. The comparison of the performances of the system response with integer order PID and FOPID are listed in Table 3. The various time domain performance measurements such as rise time, settling time, overshoot etc. are compare and tabulated. The dc bus voltage reaches the final steady state value with smaller settling time and rise time using fractional controllers. The voltage ripple is very less with the use of FOPID based controller comparing with ordinary PID controller. The peak overshoot also reduced. The under-shoot and slew rates are also decreased using FOPID based controllers.

| Controller | Rise-time (ms) | Slew-rate (/ms) | Pre-shoot (%) | Overshoot (%) | Undershoot (%) | Settling-time (ms) | Ripple Voltage (V) |
|------------|----------------|-----------------|---------------|--------------|---------------|-------------------|-------------------|
| PID        | 8.725          | 28.292          | 0.862         | 71.552       | 2.000         | 8.567             | 6                 |
| FOPID      | 9.262          | 24.720          | 95.098        | 0.980        | 0.998         | 6.976             | 2                 |
Figure 13. Performance comparison of PID & FOPID controllers at constant temperature & irradiance

6.2 DC Bus voltage at constant temperature & variable irradiance

Table 4. Performance comparison of controllers at constant temperature and variable irradiance

| Controller | Rise-time (ms) | Slew-rate (/ms) | Pre-shoot (%) | Overshoot (%) | Undershoot (%) | Settling-time (ms) | Ripple Voltage (V) |
|------------|----------------|----------------|--------------|--------------|---------------|--------------------|-------------------|
| PID        | 13.938         | 17.374         | 0.814        | 42.143       | 2.000         | 13.65              | 6.5               |
| FOPID      | 23.087         | 14.873         | 0.505        | 21.150       | 1.890         | 11.432             | 1.3               |

Figure 14 shows the waveforms obtained at invariant temperature value of 25°C and variable irradiance values of 600W/m², 800W/m² and 1000W/m². The effectiveness of the controller is compared using system response with ordinary PID and FOPID are given in Table 4. The dc bus voltage reaches the desired value with improved settling-time and rise-time using FOPID type controller. The voltage ripple is also reduced. The overshoot, under-shoot and slew-rates are minimized using FOPID controller as given in the table.
6.3 DC Bus voltage at variable temperature & constant irradiance

Table 5. Performance comparison of controllers at variable temperature and constant irradiance

| Controller | Rise-time (ms) | Slew-rate (/ms) | Pre-shoot (%) | Overshoot (%) | Undershoot (%) | Settling-time (ms) | Ripple Voltage (V) |
|------------|----------------|-----------------|---------------|---------------|----------------|-------------------|-------------------|
| PID        | 14.505         | 29.049          | 0.847         | 61.52         | 24.999         | 10.715            | 8                 |
| FOPID      | 8.893          | 24.420          | 0.704         | 0.980         | 21.899         | 8.893             | 2                 |

Figure 15. Performance comparison of PID & FOPID at variable temperature & constant irradiance

Figure 15 shows the dc bus voltage obtained at variable temperature 25°C to and 50°C and constant irradiance of 1000W/m². The performance comparison of system response with ordinary PID and FOPID are shown in the Table 5. The performance at transient period of the FOPID controller is much better than that of ordinary PID controllers. The over-shoot and settling-time are minimized with the introduction of FOPID based controllers.

6.4 DC Bus voltage at variable temperature & irradiance

Table 6. Performance comparison of controllers at variable temperature and irradiance

| Controller | Rise-time (ms) | Slew-rate (/ms) | Pre-shoot (%) | Overshoot (%) | Undershoot (%) | Settling-time (ms) | Ripple Voltage (V) |
|------------|----------------|-----------------|---------------|---------------|----------------|-------------------|-------------------|
| PID        | 10.007         | 23.749          | 0.806         | 60.485        | 1.993          | 11.657            | 4.2               |
| FOPID      | 13.422         | 17.769          | 0.704         | 32.484        | 1.8            | 6.060             | 1.5               |
Figure 16 shows the dc bus voltage obtained at variable temperature and multi changing irradiance. Table 6 shows the time domain specification obtained for the above condition. In this case, the system under goes the simultaneous variation of temperature an irradiance. Still the controller can effectively stabilize the voltage level constant. The FOPID controller gives the better results in terms of performance specifications listed in the table. The settling time and rise time are reduced using fractional controllers. The voltage ripple is negligible with FOPID controller.

7. CONCLUSION

A novel control strategy of isolated PV system using P&O based MPPT with fractional controllers were implemented. The system performances were analyzed under different dynamic conditions of temperature and multi changing solar irradiances. The transient and steady state performances are compared with conventional PID controllers. The FOPID controller with MPPT results more accurate tracking of maximum power under dynamic conditions. The dc bus voltage can be maintained at constant level with improved transient performances using FOPID controllers. Hence the ac output voltage also become constant in amplitude even with fast change in the irradiances. The fractional controllers optimise the performances of the system by minimizing the settling time and rise time. The voltage ripple is very less with fractional controllers and hence the steady state error is negligible. This helps to maintain inverter output voltage balanced under dynamic conditions. The controller performance can be still improved by optimizing tuning parameters of FOPID controllers.

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