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Fractional Order PID Controller Design for Maximum Power Point Tracking of Dynamic Loaded PV System

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ABSTRACT

PV installations and systems running under variable irradiation and temperature, produce a variance in its output voltage, resulting in control challenges. The constant output voltage from such systems despite the variations in the produced voltage and load is maintained by employing a DC converter. This paper presents the design of a maximum power point tracking (MPPT) on DC converter controller for a system. Fractional Order Proportional-Integral-Derivative (FOPID) and Proportional-Integral-Derivative (PID) controllers have been implemented to the system converter as a proposed control approach. Particle Swarm Optimization (PSO) is used as optimization technique for determining the optimal parameters of (FOPID & PID) controllers for tracking the output voltage from trained Adaptive Neuro Fuzzy Inference System (ANFIS) that is corresponding to maximum power generated from (PV) module. The PV system with the dynamic load is modeled and simulated by using the MATLAB/Simulink environment. The system performance is displayed in the form of a family of curves under different operating conditions.

Keywords: PV Systems, PV Stand-alone system, DC-DC converters, boost converter, PID controller, FOPID controller, DC motor, PSO optimization, ANFIS, and MATLAB/Simulink program.

1 INTRODUCTION

Renewable energy sources-based systems are now being employed to address rising electricity demands while also reducing global warming. Solar energy is the most viable option among the numerous renewable energy sources. However, when compared to other energy sources, the solar panel system only converts 30–40% of solar irradiation into electricity. For a long time, substantial study has been conducted to examine the performance of PV systems and investigate the different difficulties associated to the effective use of solar PV systems in order to extract the most output from them [1].

However, because of the high initial cost of a PV system, it is not widely used. Again, there is no guarantee that the energy delivered by PV will be consistent because it is entirely dependent on the sun's irradiance and the temperature of the PV modules, cell region, and load. An adequate technique for achieving maximum power from the PV cell under current climatic circumstances is required for efficient functioning, which is referred to as maximum power point tracking (MPPT) in the literature. The MPPT improves the PV module's efficiency and lifespan. Researchers all over the world are developing new approaches to extract as much energy as possible from renewable energy sources, particularly solar panels. Until now, the literature has a significant variety of MPPT algorithms for both off-grid and grid-connected PV systems. Selecting a specific MPPT system from among the many extant MPPT techniques is a difficult task, as each method has its own set of pros and downsides. The hill climbing (HC) and perturb and observe (P&O) approaches, for example, are widely used as MPPT algorithms due to their ease of implementation and lack of sensor requirements. The incremental conductance (INC) algorithm can follow the maximum power point (MPP) of a PV system and interchange high PV power to the load by looking at incremental and momentary conductance of PV systems [2].

A maximum power point tracker, or MPPT, is an electronic DC to DC converter that optimizes the match between the solar array and the load. It is an electrical system that controls the operation of photovoltaic (PV) modules so that they can produce all of the electricity they are capable of. The MPPT system adjusts the electrical operating point of the modules so that they can supply the greatest amount of available power. Increased battery charge current is made accessible as a result of the additional power gathered from the modules [3].

This study presents the design of a maximum power point tracking MPPT controller on the DC converter for a dynamic loaded PV system. As a control technique, the optimal PID (PID) and a fractional order PID (FO-PID) controllers are proposed. The introduced MPPT method employs an Adaptive Neuro Fuzzy Inference System (ANFIS). The system converter will be controlled by the proposed controllers. The parameters of both PID & FO-PID controllers have been optimized using the Particle Swarm Optimization PSO method to track the output voltage from the ANFIS unit which will be equivalent to the maximum power generated by the PV module. The PV system with the dynamic load is modeled and simulated using the MATLAB/Simulink environment. A family of curves are used to illustrate the system performance under various operating conditions

2 SYSTEM MODELLING

A stand-alone PV system is investigated in this paper, which includes a PV array, a boost converter that supplies a DC motor load, and an MPPT controller (PSO for Tuning PID or FOPID + ANFIS). The following is the model for each of the system elements:

2.1 PV Array

The stand-alone PV system to be evaluated in this study is shown in Figure (1). The suggested system should be operated using the following strategies: maximum power point operation, boosting the PV array voltage to the required level of the load voltage applied to DC motor.

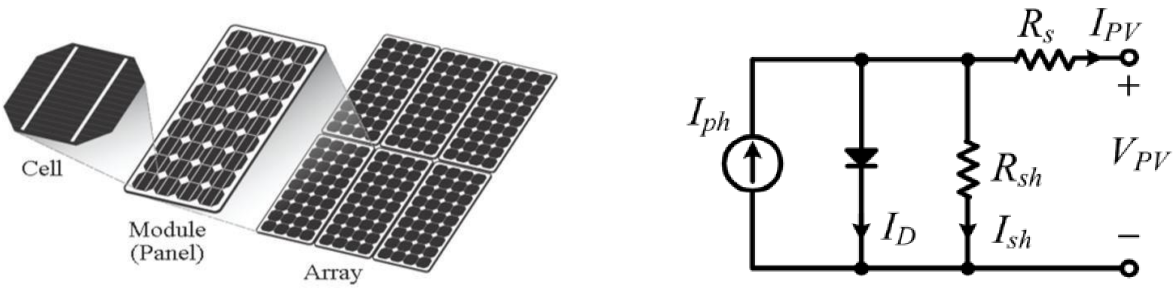

Fig (1) - Single-diode equivalent circuit for PV cell

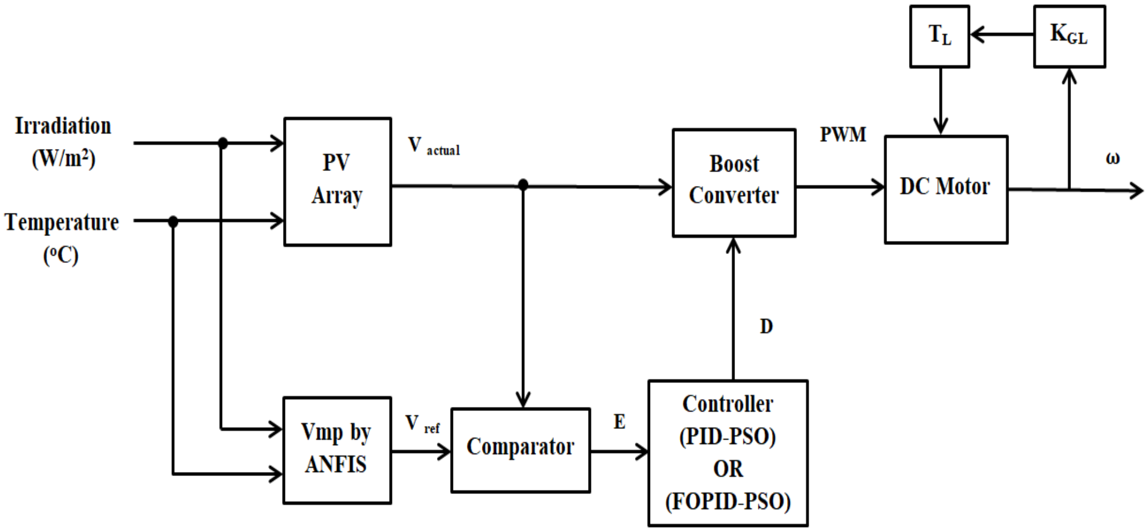

Fig (2) - Proposed PV stand-alone system with dynamic load.

Figure 2 show the whole electrical equivalent circuit for a PV cell, which may be represented by the following equations [9]:

$$\boldsymbol{I_{pv} = I_{ph} - I_0 \left[e^{\frac{V_{pv}+I_{pv}R_s}{n_s v_t}} - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}}} \tag{1}$$

$$V_{pv} = \frac{A\,k\,T_c}{e}\ln\left(\frac{I_{ph}+I_o-I_{pv}}{I_o}\right) - R_s\ I_{pv} \tag{2}$$

The MATLAB Simulink block for the PV array was used in the system modeling based on equation (1) by configuring the array parameters in line with the selected data in appendix A. Figure (3) shows (MPP) maximum power point on the I-V and P-V characteristics of the PV array at different values of irradiations:

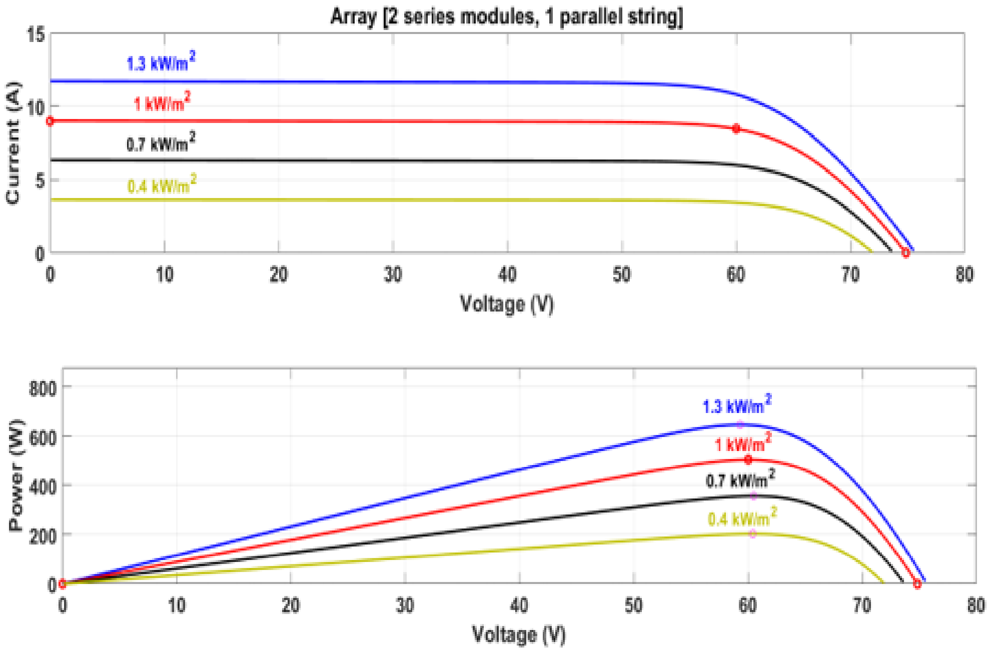

Fig (3) - PV array characteristics

2.2 Boost converter

The proposed stand-alone PV system includes the boost converter in figure (4), which has a switching time of T and a duty cycle of D.

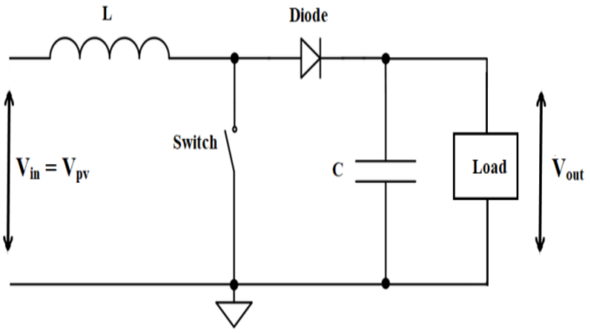

Fig (4) - Boost converter

Figure (5) illustrates waveforms of boost converter circuit; especially switching signal is applied to the gate of the switching element in order to get the desired switching operation of the converter, operation of boost converter is described by equations (3) to (7) [10].

$$V_{pv} \times T_{on} = (V_{out} - V_{pv}) \times T_{off} \tag{3}$$

$$V_{out} = \frac{T_{on} + T_{off}}{T_{off}} \times V_{pv} \tag{4}$$

where:

$$T = T_{on} + T_{off} \tag{5}$$

$$D = \frac{T_{on}}{T} \tag{6}$$

From equation (3), the output voltage can be derived as:

$$V_{out} = \frac{1}{1 - D} \times V_{pv} \tag{7}$$

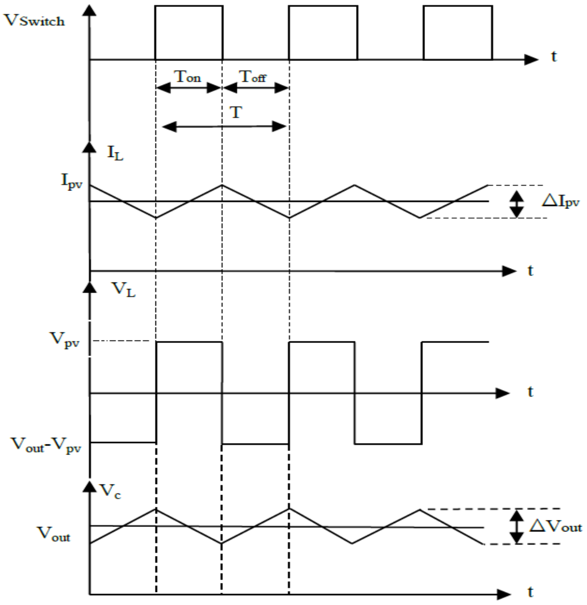

Figure (5): Typical waveforms of boost converter

2.3 Maximum Power Point Tracking Techniques

The fundamental goal of MPPT is to maximize the power generated by PV arrays while controlling the maximum useful voltage. This suggests that MPPT regulates the output of the PV array. When compared to non-MPPT systems, MPPT improves the extracted power output's efficiency by about 30% or more. The literature suggests several MPPT methods, including [4]:

- **Perturb and Observe (P&O) Method:** Due to the fluctuation in PV module power; this method tracks the MPP of a PV system in a mirror scale. The output power may be compared to the prior output power while measuring it, and it is periodically monitored. The same procedure is sometimes repeated when power levels rise in order to prevent the P&O from going backwards. The power of a PV module depends on the voltage and current; as they rise or fall, so does the power. To obtain the highest power outcome and to increase and decrease the PV outcome, the P&O algorithm is compelled to use the MPP [5].

- **Incremental Conductance (INC) Method:** The slope of the PV module characteristic curve is used by the tracking algorithm in the INC approach to track MPP. The operational point is at MPP when the slope is 0; if it is positive, this means that it is at the left of MPP, on the other hand, a negative sign indicates that it is to the right of the MPP [6].
- **Fuzzy Logic Controller (FLC) Method:** To get the most power out of PV modules, nonlinearity situations are simply handled by FLC. It can operate in every type of weather, regardless of temperature changes or levels of irradiance [7].
- **Artificial Neural Network (ANN) Method:** To forecast the output voltage (V) or power (P) at any time, ANN is utilized as an MPPT controller. To determine the load cycle, the computed value is contrasted with the instantaneous data acquired. The first layer of the network's input variables will be independent variables like temperature (T) and radiation (G). Additionally, other variables like the panel's (V) and (I) can be used as input. They will be processed by the concealed layers. The number of neurons in the hidden layers, the activation function selected, and the preferred training technique will all affect the performance in the end. It is important to collect and process a sizable amount of data in order to further improve the ANN's accuracy [8].

- **Adaptive Neuro Fuzzy Inference System (ANFIS)**

ANFIS is a hybrid intelligence approach that combines an artificial neural network and a fuzzy inference system. Additionally, ANFIS may integrate the benefits of both models into one unified approach to solving engineering challenges. Figure (8) shows a schematic representation of the ANFIS architecture.

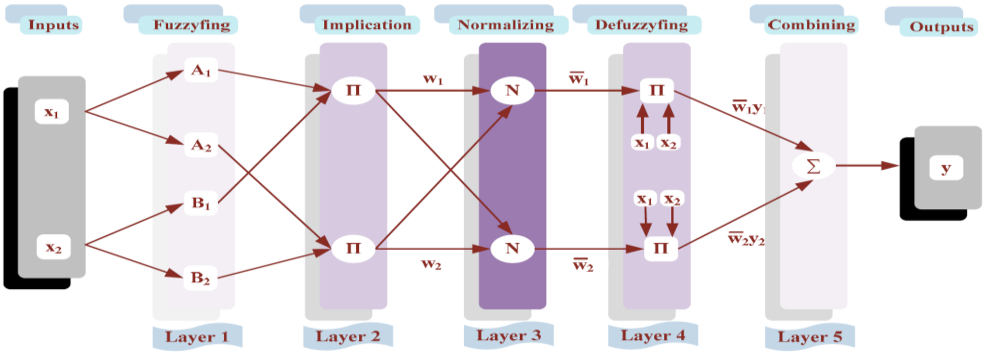

Figure (8): ANFIS architecture

ANFIS is a nonlinear model that uses the benefits of a neural network's learning capacity within the framework of a fuzzy system to represent the input-output connection of a real system. The suggested ANFIS model is based on learning the ANFIS model from the PV module's inputs temperature and irradiance data.

2.4 DC Motor (Dynamic load)

The following equations (8) and (9) can be used to describe a DC motor. MATLAB/Simulink may be used to simulate these nonlinear model equations. DC motor parameters are provided in appendix B [11].

$$\frac{di_a(t)}{dt} = A - B - C \tag{8}$$

where: $A = \frac{V_t(t)}{L_a+L_f}$ $B = \frac{R_a+R_f}{L_a+L_f} i_a(t)$ $C = \frac{M_{af}}{L_a+L_f} i_a(t)\omega_r(t)$

$$\frac{d\omega_r(t)}{dt} = \frac{M_{af}}{J_m} i^2{}_a(t) - \frac{f}{J_m}\omega_r(t) - \frac{T_L}{J_m} \tag{9}$$

2.5 Optimal PID Controller Design for MPPT

The proportional-integral-derivative (PID) controller is the most widely used control algorithm in industry and has gained widespread acceptance. PID controllers' success may be due in part to their resiliency under a broad range of operating situations, as well as its functional simplicity, which allows engineers to operate them in a simple and easy manner [13]. Figure (9) shows the PID controller's block diagram and MATLAB Simulink model.

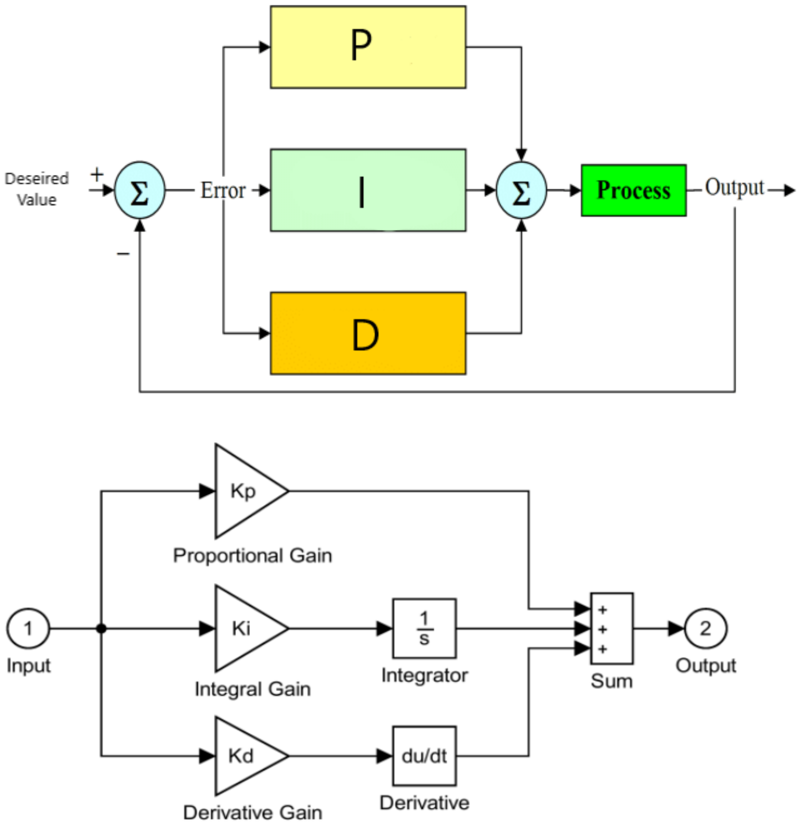

Figure (9): Block diagram of PID controller and MATLAB Simulink model.

The PID controller can be modelled as illustrated in equation (10) [17]:

$$\boldsymbol{u(t) = K_t\, e(t) + K_i \int_0^t e(t)\, dt + K_d \frac{d}{dt}\, \mathbf{e}(t)}$$

Or (10)

$$\boldsymbol{u(s) = K_t\, E(S) + K_i \frac{\mathrm{E(S)}}{D} + K_d . s\, E(s)}$$

where the controller provides a proportional term, an integration term, and a derivative term.

To achieve optimal control performance at nominal operating circumstances, the Stochastic Algorithm may be used to tune PID controller gains. Using the PV system model, PSO is used to optimize PID gains/parameters (Kp, Ki, Kd). PSO creates an initial swarm of particles in the search space, which is represented by a matrix. Each particle represents a potential solution for PID parameters, with values ranging from 0 to 100. Position and velocity are represented in this three-dimensional issue by matrices of 3xSwarm size. The swarm size is defined as the number of particles, with 50 being deemed sufficient. A good selection of PID controller settings can result in a responsive system [14].

The parameters of OPID and MPPT-based PID controllers have been designed and optimized using the PSO technique with the objective function is chosen to be the Integral Time Square Error (ITSE) which can be defined as in equation (11):

$$\textbf{ITSE} = \int \boldsymbol{t\, .\, e^2\, dt} \qquad (11)$$

In addition, among the evolutionary computation, the updated velocity and position for each particle in the swarm can be calculated using the current velocity and the distance from the particle best solution **p_{besti}** and the global best solution **g_{besti}** by employing equations (12) and (13) [12]:

$$\boldsymbol{v_i^{k+1} = w \times v_i^k + r_1 \times c_1 \times \left(P_{besti} - x_i^k\right) + r_2 \times c_2 \times \left(G_{beat} - x_i^k\right)} \qquad (12)$$

$$\boldsymbol{x_i^{k+1} = x_i^k + v_i^{k+1}} \qquad (13)$$

Initialization parameters used for PSO are population size = 30, maximum number of iterations =2000, minimum and maximum velocities are 0 and 2, cognitive and social acceleration coefficient C1 = 2, C2 = 1.4, minimum and maximum inertia weights are 0.6 and 0.9.

2.6 Optimal FOPID Controller Design for MPPT

Fractional calculus [15] has been used in the modeling and control of numerous types of physical systems in recent years, as is extensively documented in several control theories and application literatures. The order of fractional integration λ and the order of fractional derivative δ are two additional parameters in the FOPID controller, in addition to the proportional, integral, and derivative parameters (Kp, Ki, and Kd). As a result, there are five factors that make the FOPID more versatile. To obtain an optimum controller, an ideal collection of values for Kp, Ki, Kd, and must be discovered.

In truth, there is growing of clever search strategies available to locate any best answer. PSO, an evolutionary computing methodology, is one of these strategies. This method blends evolutionary calculations with social psychology concepts in social-cognition human agents. It is determined by creature activities such as fish schooling and bird flocking. It has a basic idea, is simple to implement, has a computationally efficient method, a flexible and well-balanced mechanism to improve global and local exploration skills, and it is more efficient than genetic algorithm (GA). It is same as conventional PID controller when λ=1 and δ=1, it is PI controller when δ=0, and it is PD controller when λ=0. The block diagram of a single input - single output closed loop control system with fractional (P I_λ D_δ) controller (FOPID) is illustrated in figure (10).

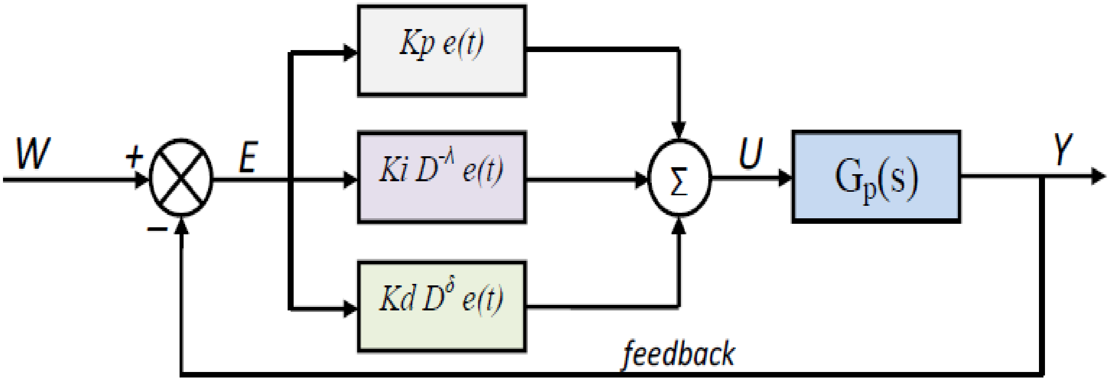

Figure (10): Block diagram of FOPID controller

The integral-differential equation defining the control action of a fractional order PID controller is given by:

$$\boldsymbol{u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t)} \quad (14)$$

The transfer function of FOPID in S domain is given by:

$$\boldsymbol{u(s) = \left(K_p + \frac{K_i}{s^{\lambda}} + K_d . s^{\mu}\right) e(s)} \quad (15)$$

The five parameters Kp, Ki, Kd, λ, and μ of the FO-PID controller have been designed and optimized using the PSO technique with the previously used objective function as the integral time square error ITSE.

3 RESULTS AND DISCUSSION

PID & FOPID Controllers for DC converter of stand-alone PV system is employed to maintain a constant output voltage despite variations in input voltage due to the variable of irradiation and temperature. The proposed system simulation has been carried out using MATLAB R2020b. The parameters of the PV array model are given in appendix A. Simulink model for the overall system under study is illustrated in appendix C.

To validate the effectiveness of the proposed controller, the system has been tested under two case studies:

Running the system under constant temperature and irradiation.

Running the system under variable temperature and irradiation.

For case (1), the PV stand-alone system has been considered to be running under constant converter input voltage [constant temperature and irradiance] as shown in table (1) for the PV array.

Table (1): Data for case (1)

Temp. (°C)	Irr. (W/m^2)	$V_{ref} = V_{mpp}$ (Volt)
25	1000	60.02

The PV output voltage, current and power responses associated with this case are displayed in figures (11) to (13) respectively. From these responses it is clear that FOPID controller succeeded in reducing overshoot and minimizing the settling time.

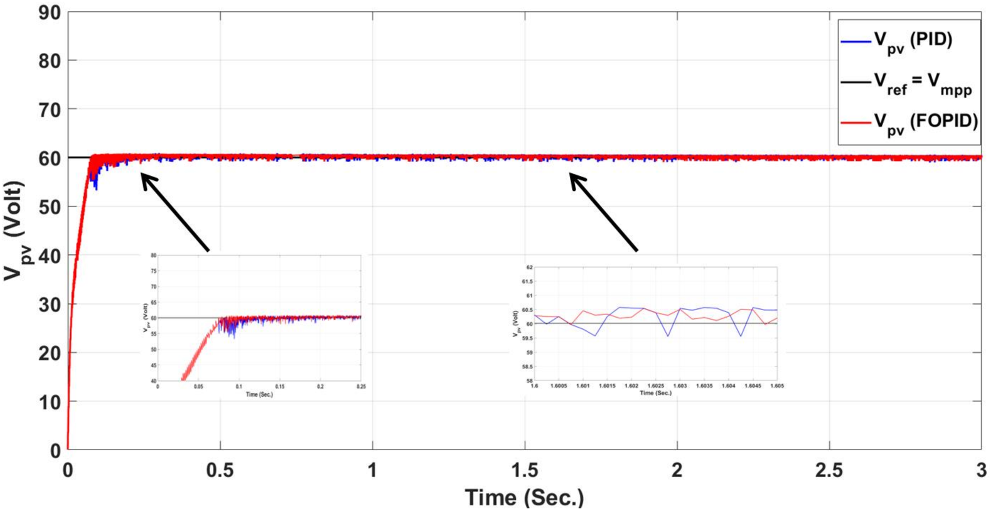

Figure (11): PV Output voltage

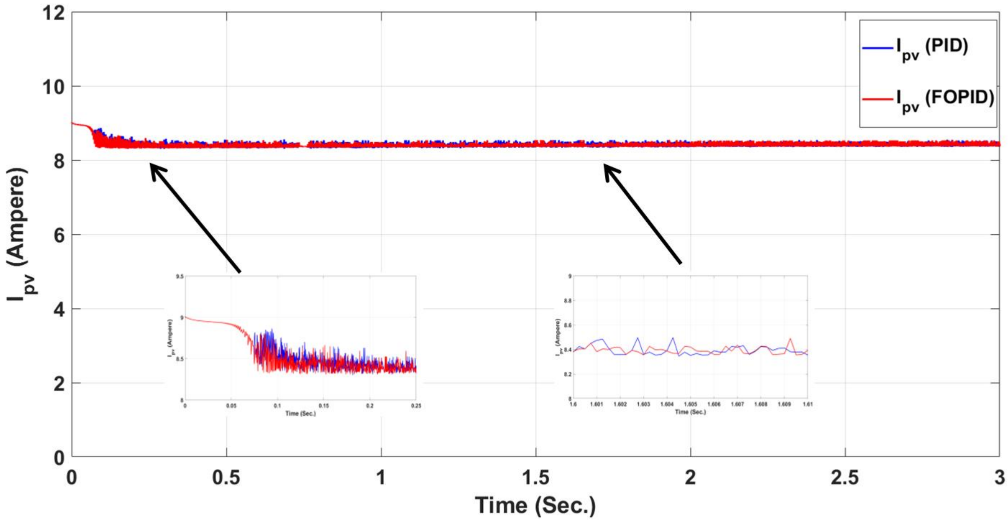

Figure (12): PV Current

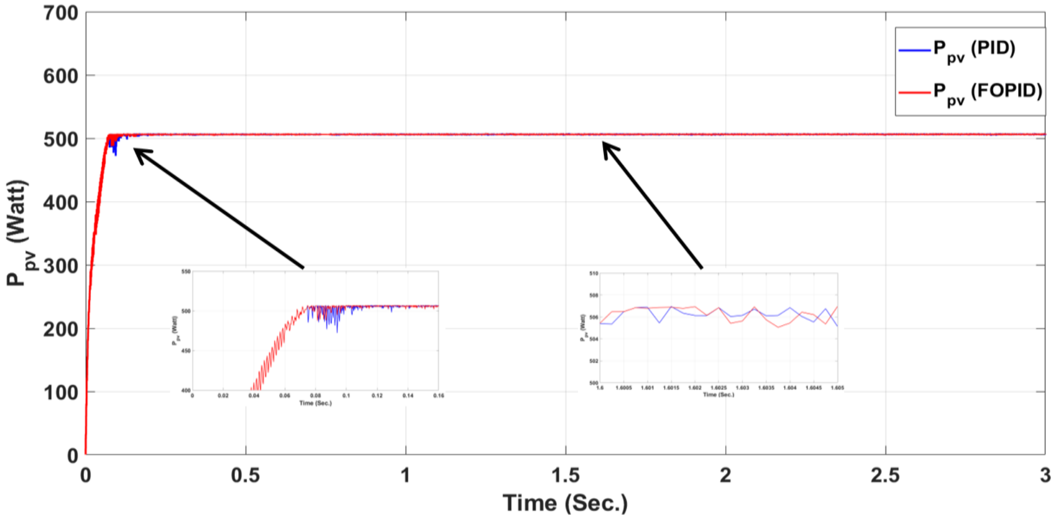

Figure (13): PV Output power

For case (2), the PV stand-alone system has been considered to be running under variable converter input voltage [variable temperature and irradiance] as shown in table (2) for the PV array.

Table (2): Data for case (2)

Time (Sec.)	Temp. (°C)	Irr. (W/m^2)	$V_{ref} = V_{mpp}$ (Volt)
0 to 1	25	1000	60.02
1 to 2	55	500	49.1
2 to 3	25	1000	60.02

The PV output voltage, current and power responses associated with this case are displayed in figures (14) to (16) respectively. From these responses it is clear that FOPID controller succeeded in reducing overshoot and minimizing the settling time.

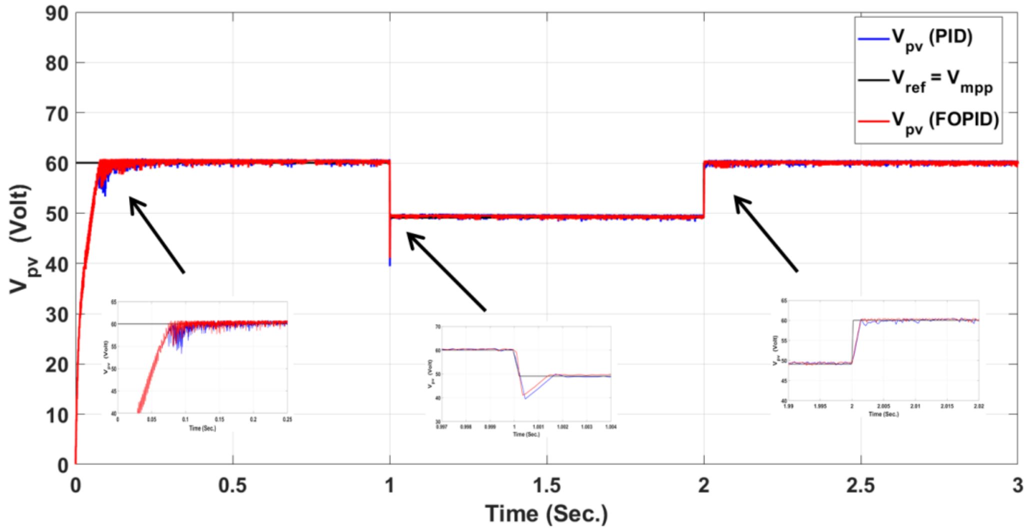

Figure (14): PV Output voltage

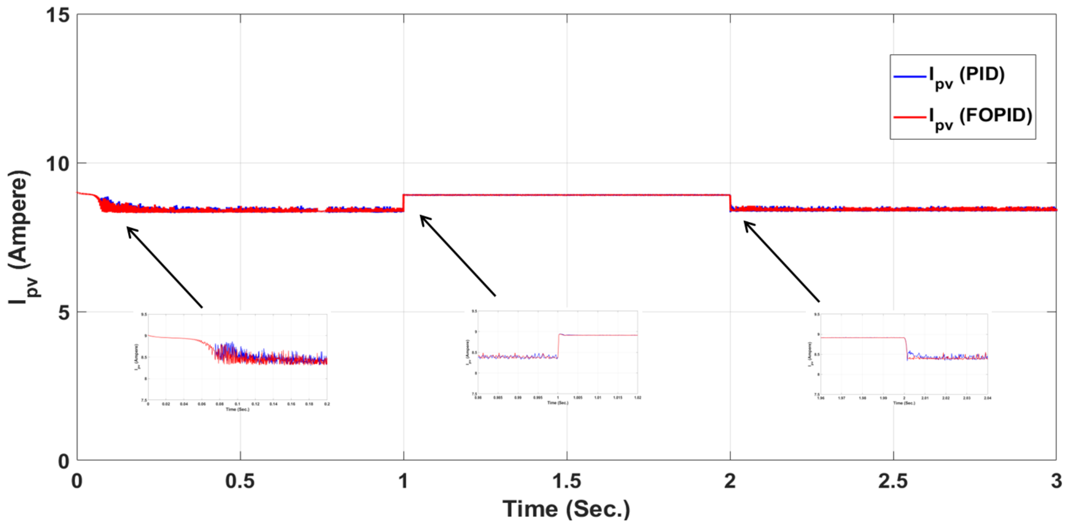

Figure (15): PV Current

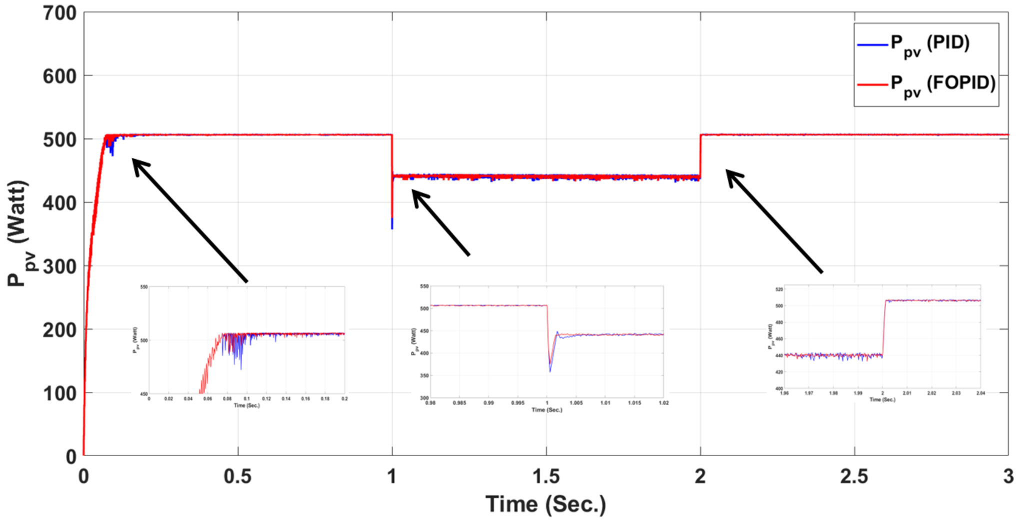

Figure (16): PV Output power

4 CONCLUSION

This work presents a model of photovoltaic PV array supplying a dynamic load as a DC motor via DC– DC converter. PID & FOPID controllers are used for tracking the voltage Vmpp corresponding to the maximum power point Pmpp of the PV array. The desired value for Vmpp of the PV has been generated from a trained Adaptive Fuzzy Inference System ANFIS. Particle swarm optimization PSO is used as the optimization technique for determining the optimal parameters of both the PID and the FOPID controllers for maximum power point tracking MPPT of the PV system. The overall system is modeled and simulated by Simulink in MATLAB program. FOPID controller was more efficient in improving the response characteristics as well as reducing the steady state-error, rise time, settling time and maximum overshoot.

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Appendix A: Parameters of PV module

Parameter	Value
Number of cells	60
Maximum power rating (±3%)	254 W
Open circuit voltage (V_{oc})	37.42V
Short circuit current (I_{sc})	8.97 A
Maximum power point voltage (V_{mp} = 80.2% of V_{oc})	30.01 V
Maximum power point current (I_{mp} = 94.2% of I_{sc})	8.45 A

Appendix B: Parameters of DC motor

$V_t(t)$ (Armature voltage)	100 V
$i_a(t)$ (Armature Current)	2 A
n (Angular Displacement)	1500 RPM
L_a (Armature Inductance)	0.003 H
R_a (Armature Resistance)	5 Ω
J_m (Inertia of rotor)	0.005 Kg.m^2
f (Viscous friction coefficient)	0.001 N.m.sec.
K_t (Torque Constant)	0.6366197 N.m/A
K_b (Back E.M.F Constant)	0.5729577 V/RPM
K_{GL} (Generator load Constant)	0.00810568 N.m.sec./Rad.

Appendix C: ***Simulink model for the stand-alone PV system with controller***