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# Parallel Distributed Compensation-PID Controller Design for Maximum Power Point Tracking of Dynamic Loaded Photovoltaic System

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A B S T R A C T

Control issues come from the output voltage of PV installations and systems operating in a range of irradiance and temperature. By using a DC converter, such systems are able to keep the output voltage stable despite fluctuations in the voltage produced and load. The design of a maximum power point tracking (MPPT) on DC converter controller is presented in this article for a system. Fractional Order-Proportional Integral Derivative (FO-PID) and Parallel Distributed Compensation-Proportional Integral Derivative (PDC-PID) controllers have been implemented to the system converter as a recommended strategy for control. Particle Swarm Optimization (PSO) is used as optimization technique for determining the optimal parameters of (FO-PID) and (PDC-PID) controllers for tracking the output voltage from trained Adaptive Neuro Fuzzy Inference System (ANFIS) that is corresponding to maximum energy generated from (PV) module. The PV system with the dynamic load is modeled and simulated. The effectiveness of the system is shown in the form of a family of curves under various operating states.



**Nomenclature**

| | |
|---|---|
| PV | Photovoltaic |
| MPPT | Maximum Power Point Tracking |
| T | Temperature |
| Irr | Irradiation |
| PD | Proportional derivative |
| PID | Proportional-integral-derivative |
| FO-PID | Fractional Order PID |
| PDC-PID | Parallel Distributed Compensated PID |
| PSO | Particle Swarm Optimization |
| GA | Genetic Algorithm |
| P&O | Perturb and Observe |
| HC | Hill Climbing |
| INC | Incremental Conductance |
| FLC | Fuzzy-Logi Control |
| ANN | Artificial Neural Networks |
| ANFIS | Adaptive Neuro Fuzzy Inference System |
| V | Output Voltage |
| P | Output Power |
| G | First Layer of ANN input Variables |
| D | Converter Duty Cycle |
| Pbest | Particle Best Solution Space |
| Gbest | The Best Value Acquired by the Particle in its Vicinity |
| Kp | Proportional Control Gain |
| Ki | Integral Control Gain |
| Kd | Derivative Control Gain |
| TS | Takagi-Sugeno Fuzzy Metho |

## Introduction

Systems based on renewable energy sources are currently being used to address the increase in electricity demand while simultaneously lowering global warming. The most practical alternative among the several renewable energy sources is solar energy. However, Only 30 to 40 percent of solar radiation is converted into power by the solar panel system. when compared to other energy sources. Long-term, extensive research has been done to assess PV system performance and look into the various challenges that come with using solar PV systems effectively to get the highest output possible. [1-10].

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However, a PV system is not extensively employed due of its expensive initial cost. Once more, there is no guarantee that PV energy will be consistently delivered because it is fully reliant on the sun's irradiance as well as the PV module's temperature, cell region, and load. Greatest power point tracking, or MPPT as it is known in the literature, is an appropriate method for obtaining the peak power from the PV cell under the present climatic conditions. The PV module's efficiency and lifespan are increased by the MPPT. Researchers from all over the world are creating innovative methods to get the most energy possible from solar panels and other renewable energy sources. Up to this point, the literature has covered a wide range of MPPT algorithms for both grid-connected and off-grid PV systems. It is challenging to choose a specific MPPT system from the numerous existing MPPT approaches because each technique has a unique mix of benefits and drawbacks. Perturb and observe (P&O) and hill climbing (HC) techniques, for instance, are frequently employed as MPPT algorithms because to their simplicity and lack of sensor requirements. By examining the incremental and momentary conductance of PV systems, the incremental conductance (INC) algorithm may track the maximum power point (MPP) of a PV system and transfer high PV power to the load. [10-20]. An electronic DC to DC converter called a maximum power point tracker, or MPPT, improves the match between the solar array and the load. It is an electrical system that regulates the functioning of photovoltaic (PV) modules to enable them to produce as much electricity as is feasible. The MPPT system modifies the modules' electrical operating point so that they can supply the maximum amount of power that is available. The extra power received from the modules makes it possible to use a higher battery charge current. [20-25].

This study presents the design of a maximum power point tracking (MPPT) on control for a DC converter for a dynamic loaded PV network. As a control technique, the FO-PID and PDC-PID controllers are suggested. The prosed MPPT method employs the Adaptive Neuro Fuzzy Inference System (ANFIS). The system converter will be controlled by the suggested controllers. The parameters of both FO-PID & PDC-PID controllers have been optimized using the Particle Swarm Optimization PSO method to track the output voltage from the ANFIS unit that 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 (R2020b)/Simulink platform. A series of curves are used to describe the system performance under various operating situations.

## 1. System Modelling

In this work, a standalone PV system that consists of a PV array, a boost converter that supplies a DC motor load, and an MPPT controller (PSO for Tuning PDC-PID or FO-PID + ANFIS) is explored. The model for each component of the system is as follows:

### *1.1. PV Array*

Figure (1) depicts the standalone PV system that will be assessed in this study. The following tactics should be used to run the suggested system: maximum power point operating, raising the voltage of the PV array to the necessary voltage level of the load applied to the DC motor.

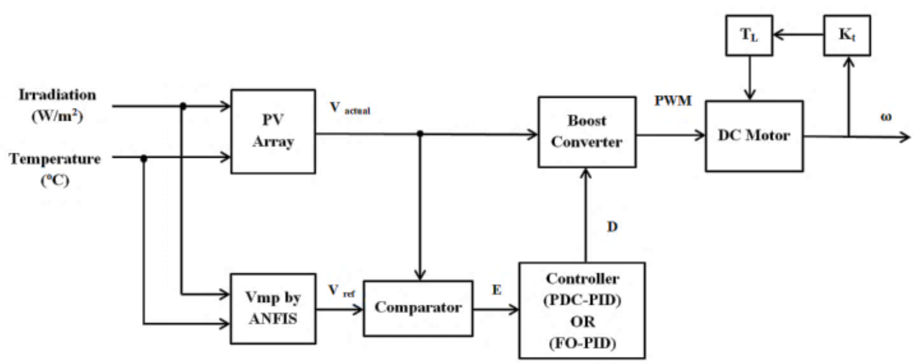



**Fig. 1 - suggested PV stand-alone system with dynamic load.**

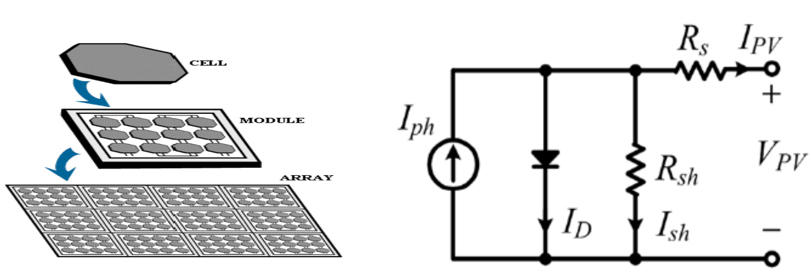


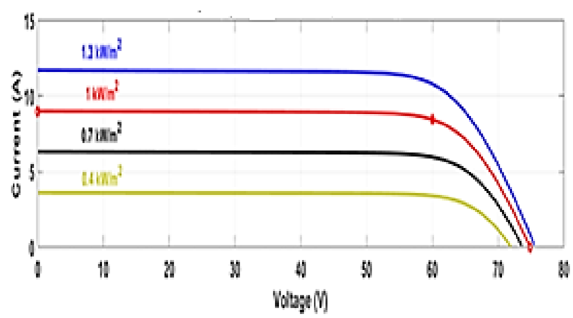

**Fig. 2 - Single-diode analogous circuit for PV cell**

The whole electrical equivalent circuit for a PV cell is shown in Figure (2), and it may be modelled using the equations below [9]. As shown equations (1) and (2).

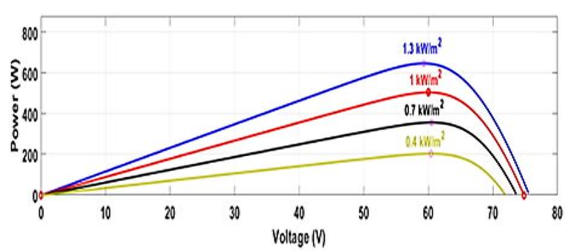
$$I_{pv} = I_{ph} - I_0\left[e^{\frac{V_{pv}+I_{pv}R_s}{n_s v_t}} - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \tag{1}$$

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

By establishing the array parameters in accordance with the chosen data in appendix A, the MATLAB Simulink block for the PV array was dedicated in the system modelling based on equation (1). Figure (3) depicts the maximum power point (MPP) for the PV array's I-V and P-V characteristics at various irradiation levels:




(a)




(b)

**Fig. 3 – PV array characteristics.**

### *1.2. Boost Converter*

The boost converter in figure (4) of the suggested standalone PV system has a switching time of T and a duty cycle of D.

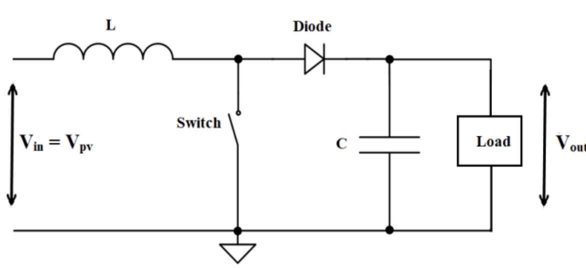



**Fig. 4 - Boost converter.**

Waveforms of the boost converter circuit are shown in Figure 5, a switching signal is applied, in particular, to the gate of the switching element to achieve the converter's desired switching operation, Theory of operation for boost converter is described by equations (3) to (7) [10].

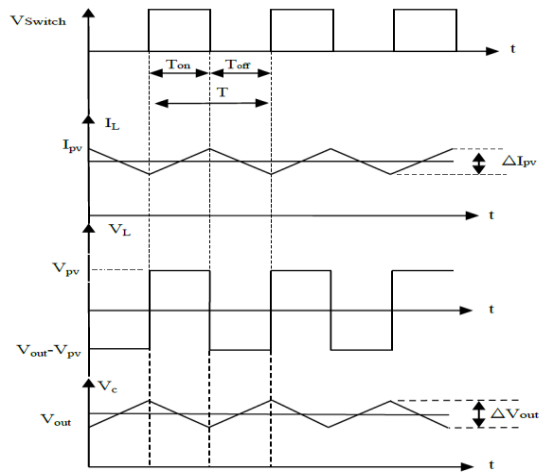



**Fig. 5 - Typical waveforms of boost converter.**

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

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

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:

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

***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 voltage and current of a PV module determine its power; as they rise or fall, so does the power [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 inputs. 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 at 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 (6) displays a schematic representation of the ANFIS architecture.

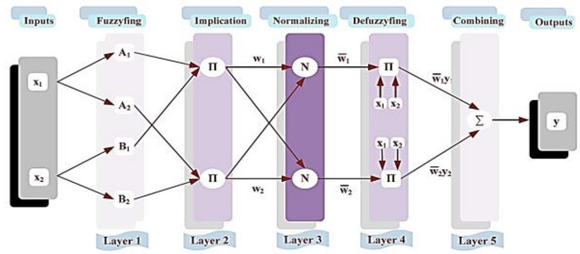



**Fig. (6) - ANFIS architecture**

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.

### *1.3. DC Motor (Dynamic Load)*

The model of a DC motor can be found in equations (7) & (8). These nonlinear model equations can be simulated using MATLAB (R2020b)/Simulink. DC motor specifications are given in appendix B. [11].

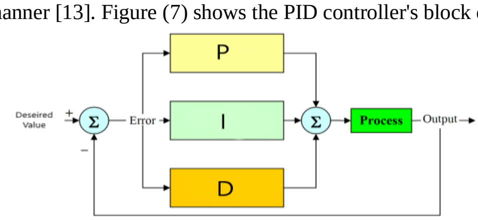
$$\frac{di_a(t)}{dt} = A - B - C \quad (8)$$

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

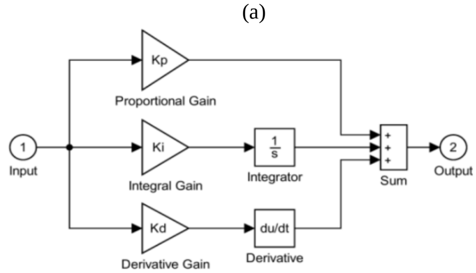
$$\frac{d\omega_r(t)}{dt} = \frac{M_{af}}{J_m} i^2{}_a(t) - \frac{f}{J_m}\omega_r(t) - \frac{T_L}{J_m} \quad (9)$$

## 2. Parallel Distributed Compensated PID Controller Design

The proportional-integral-derivative PID controller is most frequently employed controller 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 (7) shows the PID controller's block diagram and MATLAB Simulink model.




(a)




(b)

**Fig. 7 - PID controller's block diagram and MATLAB Simulink model.**

The PID controller can be modelled as demonstrated in equation (10) [15]:

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

**Or** (10)

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

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

The Integral Time Square Error (ITSE), which can be written as in equation (11), was chosen as the objective function for the PSO technique used to develop and optimise the parameters of optimum PID and MPPT-based PID controllers:

$$\text{ITSE} = \int t\,.\,e^2\,dt \quad (11)$$

The evolutionary computation also includes, the swarm's updated position and velocity for each particle can be calculated by utilising the distance and the current speed from the particle best solution $\mathbf{p}_{besti}$ and the global best idea $\mathbf{g}_{besti}$ by utilising equations (12) and (13) [12]:

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

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{13}$$

Population size = 30 were utilised as the initialization settings for PSO, most iterations possible =2000, 0 and 2 are the minimum and maximum velocities, Coefficients of cognitive and social acceleration C1 = 2 and C2 = 1.4, the inertia weights range between 0.6 and 0.9.

In the majority of applications, it is necessary to regulate the converter's output voltage regardless of changes in the load or its input voltage. This study project suggests a parallel distributed compensated PID controller PDC-PID design using TS-Fuzzy to be utilized with the converter as illustrated in figure (8).

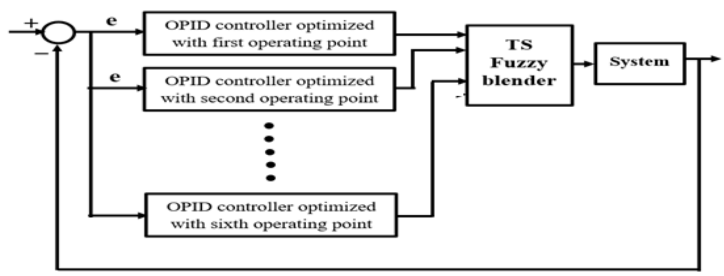



**Fig. 8 - Block diagram of the blending technique of TS-Fuzzy for the PID controllers**

The steps of designing the PDC-PID depend on designing six separate PID controllers, each has its own parameters that have been optimized using PSO to fit in a specified system operating condition. Such operating conditions and their optimal PID's gains are mentioned in table (1). The Simulink model for the proposed PDC-PID controller is illustrated in figure (9)

**Table (1) – Separate system operating conditions and corresponding OPID's parameters**

| Temp (C°) | Irr.(W/m$^2$) | $K_p$ | $K_i$ | $K_d$ |
|---|---|---|---|---|
| 25 | 800 | 600.7908 | 400 | 0.317 |
| 30 | 900 | 706.8122 | 600 | 0.837 |
| 35 | 1000 | 459.4290 | 250 | 0.536 |
| 40 | 1100 | 424.0885 | 200 | 0.175 |
| 45 | 1200 | 353.4076 | 150 | 0.643 |
| 50 | 1300 | 282.7266 | 70 | 0.462 |

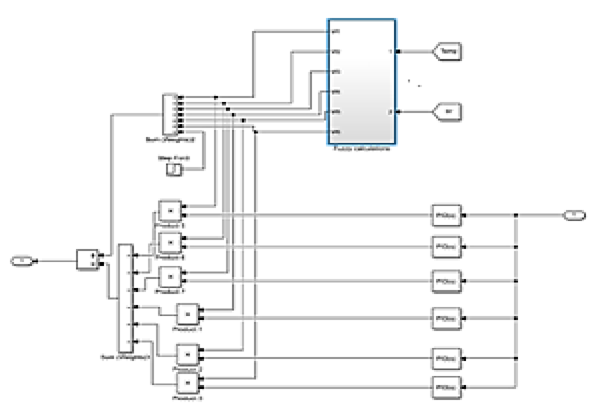
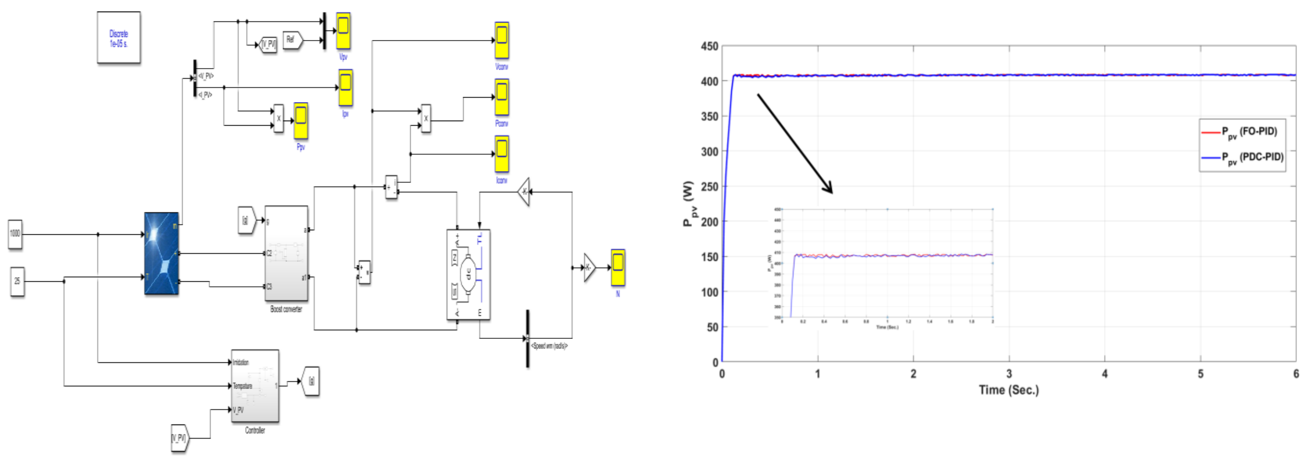


**Fig. 9 - Simulink model for the TS parallel distributed PDC-PID controller**

## 3. Simulation Results and Analysis

The parallel distributed compensated PDC-PID & FO-PID controllers for DC converter of a stand-alone PV system is dedicated to have a tracking for MPP despite the fluctuations in input voltage caused by the temperature and irradiation variables. The suggested system simulation has been carried out using MATLAB R2020b. The PV array model's parameters are given in appendix A. Figure (10) offers the Simulink model for the systems in researching.




(a) (b)

**Fig. 10 - Simulink model for the stand-alone PV system with PDC-PID controller**

To verify the suggested controller's efficiency, two case studies have been used to test the system:

1) Launching the system under constant temperature and irradiation.
2) Launching the system under variable temperature and irradiation.

For case (1), the PV stand-alone system has been launching under constant reference input voltage [constant temperature and irradiation] as shown in table (2) for the PV array.

**Table (2) - Data for case (1)**

| Temp. (ºC) | Irr. (W/m$^2$) | $V_{ref} = V_{mpp}$ (Volt) |
|---|---|---|
| 25 | 800 | 60.62 |

The output voltage from PV, output current from PV and output power from PV responses related with this case are presented in Fig. (11), Fig. (12), and Fig. (13) respectively. From these responses, it has been noticed that FO-PID controller succeeded in eliminating overshoot and decreasing the settling time.

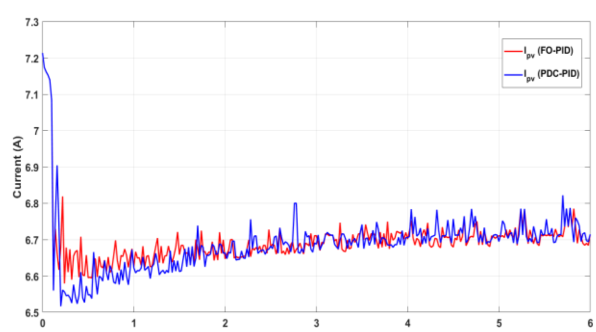



**Fig. (12) - PV Output current**

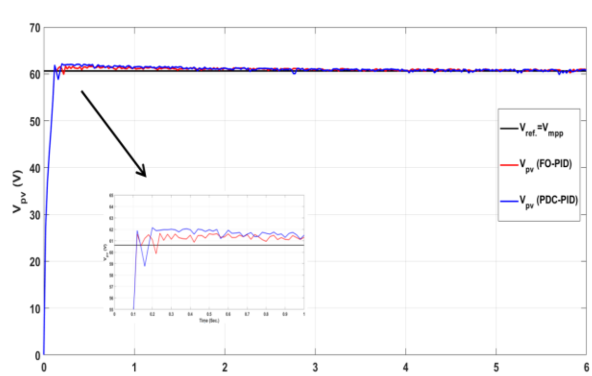



**Fig. (13) - PV Output power**

For case (2), the PV stand-alone system has been thought of to be launching under variable reference input voltage [variable temperature and irradiation] as mentioned in table (3) for the PV array.

**Table (3) - Data for case (2)**

| Time (Sec.) | Temp. (ºC) | Irr. (W/m$^2$) | $V_{ref} = V_{mpp}$ (Volt) |
|---|---|---|---|
| 0 to 2 | 25 | 800 | 60.02 |
| 2 to 4 | 30 | 900 | 58.74 |
| 4 to 6 | 25 | 800 | 60.02 |

The output voltage from PV, output current from PV and output power from PV responses related with this case are presented in Fig. (14), Fig. (15), and Fig. (16) respectively. From these responses it has been noticed that FO-PID controller succeeded in eliminating overshoot and decreasing the settling time.

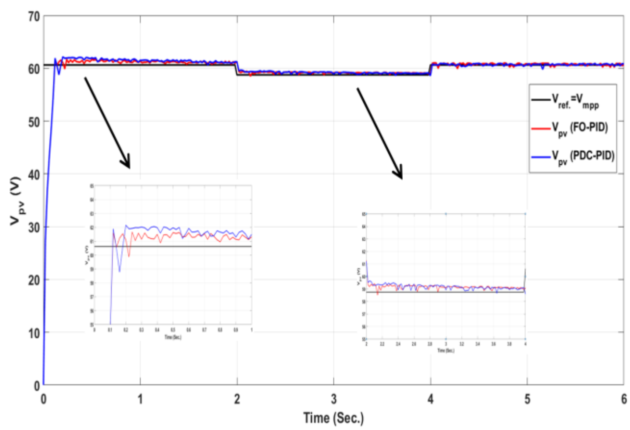



**Fig. (14) - PV Output voltage.**

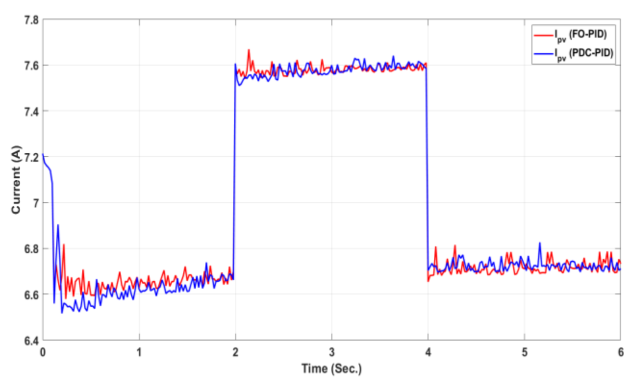



**Fig. (15) - PV Output current**

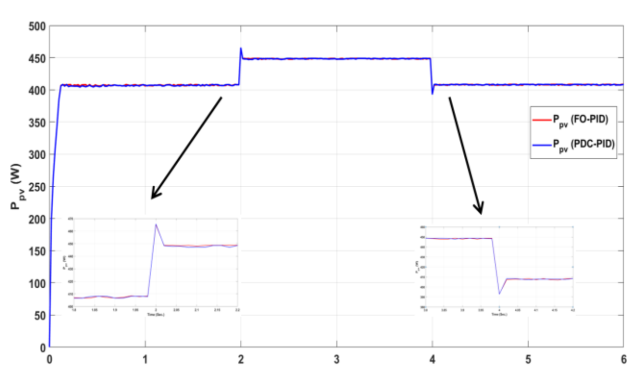



**Fig. (16) - PV Output power**

## Conclusion

This work presents a model of Photovoltaic PV array powering a dynamic load as a DC motor via DC – DC converter. PDC-PID & FO-PID 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 PV has been generated from a trained Adaptive Fuzzy Inference System ANFIS. Particle Swarm Optimization PSO is used as the optimization strategy for determining the optimal parameters of PDC-PID and FO-PID controllers for maximum power point tracking MPPT of the PV network. The overall system is modeled and simulated by Simulink in MATLAB (R2020b) program. FO-PID controller was more efficient for dynamic load in enhancing the criteria of time response in additional decreasing the steady state-error, rise time, settling time and maximum overshoot.

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## APPENDIXES

***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. |