A PSO Optimized Fractional-Order PID Controller for a PV System with DC-DC Boost Converter

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Abstract— **In this study, a fractional-order PID (FOPID) controller is designed to control a DC-DC boost converter in a PV-system. Because of the nonlinear V-I characteristic of a PV-panel, a power electronic interface is required to obtain a desired and fixed voltage level. In order to obtain the best system performance, parameters of the proposed controller are tuned by using Particle Swarm Optimization (PSO) algorithm. Both of the system responses with the FOPID and classical PID are tested under various power conditions by changing the load resistor and solar irradiation values. The simulation results are compared in terms of integral of time weighted squared error (ITSE) criterion, percentage overshoot (M_p) and rising time (T_r). The results show that the FOPID controller performs better performance than the classical PID controller.**

Keywords-component; FOPID controller, PID controller, PV panel, Boost converter, PSO algorithm.

I. Introduction

Energy is one of the important necessities in human life. It is being used in many stages of life all the time. Although it surrounds us in different forms, such as light, heat, wind and electricity, it is easily converted from one form to another. As it is well known, the sun has poured out huge amounts of energy in several forms, including light, heat, radio waves, and even x-rays. In order to avoid damaging the ecosystem and environment while using fossil fuel, people develop alternative green energy resources [1]. This green energy comes from natural resources such as wind, sun and geothermal heat.

The energy obtained by PV solar cells (PVSCs) is the most essential energy. Although the PVSCs system is getting cheaper it is still expensive besides the existing grid. Albeit the fact that it is useful for places far away from the electrical grid, it can be connected to the AC grid and by using power electronic equipments which are developing day by day, the energy derived by electrical grid can be reduced [2].

Since the power obtained from the sun depends on some factors such as solar temperature, solar irradiation, number of the PV panel connected in series and parallel, load resistance and the solar incidence angle, a power electronic equipment, which is selected as a Boost Converter in this study, is needed to get a stable power level.

Classical PID controllers are used in industry and literature more over the years because of the easy implementation and robustness. On the other hand, FOPID controller has received the attention of the researchers recently and it is suggested for control of the dynamic systems. FOPID controller provides more accurate system response than the classical PID controller [3].

Also, there are lots of studies based on tuning of the parameters of the FOPID controller which includes Genetic Algorithms (GA) [4], Differential Evolution (DE) algorithm [5] and PSO algorithm [6].

This paper represents FOPID controller design for PV powered resistive load with a boost converter. Parameters of the controller are tuned by PSO algorithm to obtain the best system response.

II. System implementation

A boost converter is selected as a power electronic interface between the load and PV panel. System implementation is given in Fig. 1. The proposed controller is designed to fix the output voltage at desired level against the changes in solar irradiation and resistive load values.

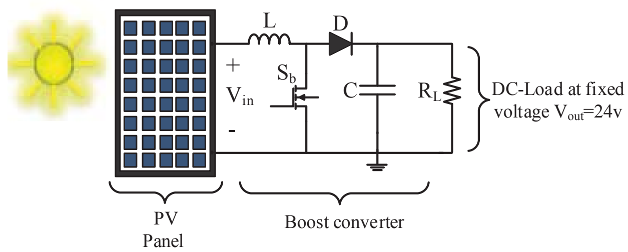

Fig. 1. The whole system.

A. Boost Converter Model

The Boost DC-DC switching mode converter is a power electronic device used to produce a higher regulated output voltage from a lower unregulated input voltage [7]. The circuit of the boost converter is given in Fig. 2. The converter consist of an inductor *L*, a power switch *S*, a diode, *D*, a filter capacitor *C* and a load resistor *R*.

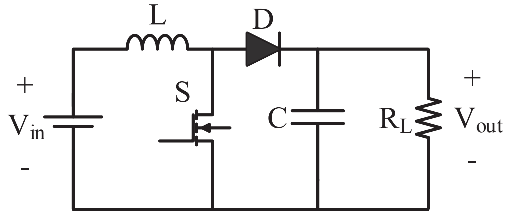

Fig.2. Boost converter circuit.

The working principle of the converter is explained with a few sentences as follows: When the switch is ON mode, the diode is reverse biased (OFF). In this mode, inductor directly connected to the input voltage source and stores energy. Meanwhile, the load is powered by the capacitor. When the switch is OFF mode, the diode is forward biased (ON). In this mode, both stored energy of the inductor and input voltage source supply power to the load. At the end, a higher voltage level than the input voltage is produced [8]. The capacitor and the inductor values of the converter are calculated respectively by using the formulas given below [9].

$$C_{\min} = \frac{I_{out(\max)} D}{f_S \Delta V_{out}} \qquad L_{\min} = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L f_S V_{out}} \tag{1}$$

Where C_{min} and L_{min} are the minimum capacitor and inductor values, V_{in} and V_{out} are the input and output voltage of the converter, f_s is the switching frequency, ΔV_{out} is the output voltage ripple, ΔI_L is the inductor current ripple, *D* is the duty cycle which is the ratio between the pulse duration and period of a rectangular waveform.

B. The Mathematical Model of PV Array

A Photovoltaic panel converts the irradiation coming from the sun into DC electricity by using semiconductors. There are various models in order to describe a PV panel characteristics in simulation environment. Some of these models are one diode model and two diode model [10]. In this study a standard one diode model is used. The equivalent circuit of the PV cell model is given in Fig. 3. Where I_{ph}, I_d and I_{sh} are the irradiation generated current, diode current and current loss because of the R_{sh} shunt resistance, respectively. R_s is the series resistance of the PV panel that is used to implement the voltage drop in the output of the PV cell voltage [11].

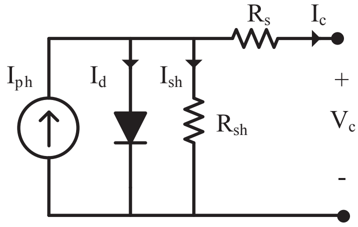

Fig. 3. One diode model of a PV cell.

The PV cell current (I_c) and voltage (V_c) equations used for modeling are respectively given below.[12-12]

$$V_c = -\beta(T_c - T_{cr}) - R_s \Delta I + V_r \tag{2}$$

$$\Delta I = \left[\alpha\left(\frac{G}{G_r}\right)(T_c - T_{cr}) + \left(\frac{G}{G_r} - 1\right)I_{sc}\right] \tag{3}$$

$$I_c = I_r + \Delta I \tag{4}$$

In the above equations and Fig. 1, I_r and V_r are the reference current and voltage of the PV panel, *G* and G_r are the irradiation and the reference irradiation, T_c and T_{cr} are the temperature and the reference temperature of the PV panel, α is the temperature constant of the I_{sc} short circuit current. β is the temperature constant of the open circuit voltage of the PV panel. The values of these parameters used for modeling PV panel are given in appendix part [12-13].

The PV module (Number of series and parallel connected PV cells) outputs which are current (I_{pv}) and voltage (V_{pv}) are calculated by using equation (5) and equation (6), respectively. Where Ns is the series connected PV cell number that effects module voltage and Np is the parallel connected PV cell number that effects the module current [12-13].

$$I_{pv} = N_s I_c \tag{5}$$

$$V_{pv} = N_p V_c \tag{6}$$

III. FRACTIONAL-ORDER PID CONTROLLER

Fractional order calculus (FOC), a subject of the mathematics, is based on the definition of noninteger orders of derivative and integral. Recently, FOC is widely used in many number of fields with the called names fractional order control and fractional order identification of dynamical systems [14].

FOPID controller is more preferred than classical PID controller in a wide range area for controlling the linear and nonlinear systems. With respect to classical PID controller, FOPID controller provides more flexibility in controller design and this advantage increases the quality and robustness of the controller. It is proved that fractional algorithms used to design a fractional order controller are more stable and robust than integer order designed controller [15]. On the other hand, it has five parameters to be selected whereas classical PID has three parameters. It implies that tuning of the parameters of the FOPID controller is more complex [16]. Block diagram representation of the FOPID controller are given in Fig. 4.

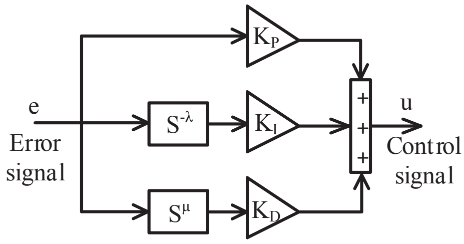

Fig. 4. Block diagram of the FOPID controller.

The transfer function of the proposed controller whose common form is $PI^{\lambda} D^{\mu}$ is defined as [17]:

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{7}$$

Where, λ and μ are the order of integrator and differentiator, respectively. Time domain representation of equation (7) is given below where *D* is the differentiation operator.

$$G_c(t) = K_p + K_i D_t^{-\lambda} + K_d D_t^{\mu} \tag{8}$$

IV. PSO ALGORITHM

Particle swarm optimization method suggested by Kennedy and Eberhart is a computational search algorithm used to optimize a problem iteratively [18]. The algorithm is based on imitating the behaviors of a bird flock (particles) with the help of the mathematical velocity and position formulas of the particles. Each particle in the population has a memory to keep its previous best position called P_{best} (candidate solutions, local minima) and fitness value. Also, the particle with minimum fitness value is called G_{best} (global minima). The flowchart of the algorithm is given in Fig 5.

Mathematical representations of the velocity and position of the particles are given below respectively [19]. Where *i* is the number of the particle, *d* is the dimension, c_1 and c_2 are the acceleration constant of the velocity, w is the inertia weight, r_1 and r_2 are the uniformly random numbers. Selected parameter values of the algorithm are given in appendix part.

$$V_{id} = w \times V_{id} + c_1 \times r_1 \times (P_{id} - X_{id}) + c_2 \times r_2 \times (G_{id} - X_{id}) \tag{9}$$

$$X_{id} = X_{id} + V_{id} \tag{10}$$

The algorithm is ended when the stopping criteria is met. In this study, integral of time weighted squared error (ITSE) criterion, one of commonly used performance indices, is used as a fitness function. The aim of the PSO algorithm is to find the controller parameters that minimizes the ITSE criteria. Mathematical description of the criteria is given below where *r* is the reference signal, *y* is the output signal and *e* is the error signal.

$$ITSE = \int_0^t t\big(r(t) - y(t)\big)^2 dt = \int_0^t t e(t)^2 dt \tag{11}$$

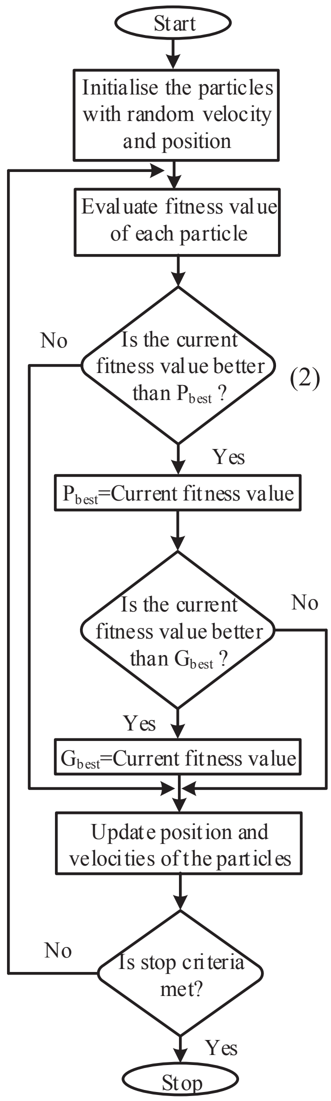

Fig. 5. Flowchart of the PSO algorithm.

V. SIMULATION RESULTS

The whole system is modeled in Matlab/Simulink environment and tested for different operating conditions by changing the solar irradiation and load resistance values in order to evaluate system performance. Designed system model is shown in Fig.6.

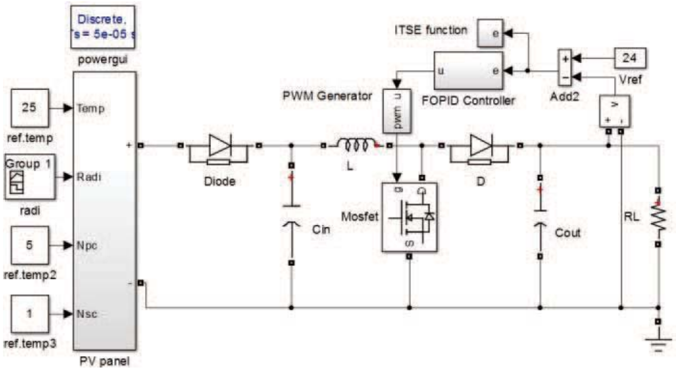

Fig. 6. Simulink representation of the whole system.

PSO algorithm results of the FOPID controller are given in Table I and the best parameters which minimizes ITSE criterion are selected.

TABLE I. PSO RESULTS

	K_P	K_I	K_D	λ	μ	ITSE	$\%M_p$	T_r
PID	19.22	8.32	0.056	-	-	1.272	2.5	0.72
FOPID	19.22	8.32	0.056	0.84	0.65	1.118	0.8	0.72

Variable solar irradiation values applied to the PV panel as input is given in Fig. 7.

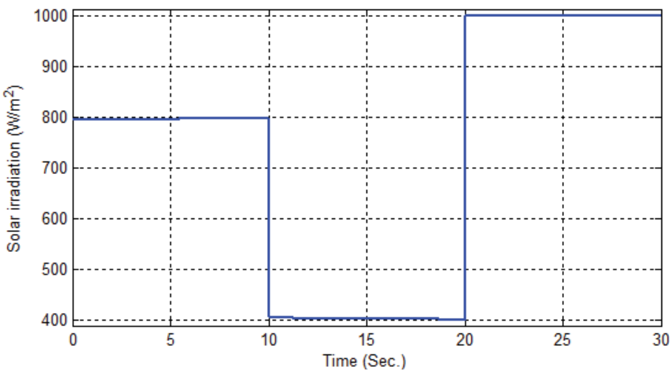

Fig. 7. Solar irradiation data.

Boost converter input voltage and output voltage with PID and FOPID controllers against variable solar irradiation and load resistance values are seen in Fig.8. Also, a zoomed view of the system responses of the controllers are given in Fig. 9.

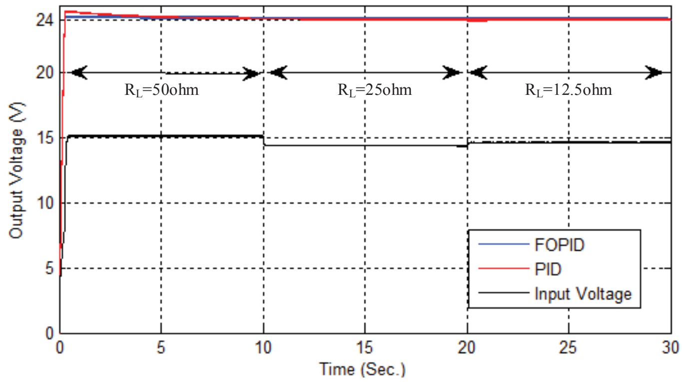

Fig. 8. Output voltage response with PID and FOPID.

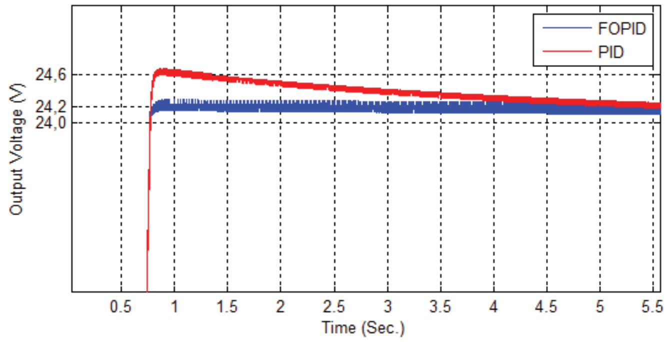

Fig. 9. Zoomed view of the output voltage.

VI. CONCLUSION

Performance data of the controllers are given in Table I. As it is seen, a lower ITSE criterion and percentage overshoot values are obtained by using the fractional-order PID controller. Whereas, both of the controllers have the same rising time and a very small steady-state error. The results shows that FOPID controller has a better system response than the classical PID controller.

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APPENDIX

TABLE II. SYSTEM PARAMETERS

Parameters of Boost Converter	
Sampling frequency (T_S)	20kHz
Switching frequency (f_S)	5kHz
Output voltage (V_O)	24V
Max. output voltage ripple (ΔV_C)	%5
Max. input current ripple (ΔI)	%5
Input Capacitor (C_{in})	6.8mF
Output Capacitor (C_{out})	11.5mF
Inductor (L)	1.25mH
Load (R)	12.5-25-50ohm
PV panel Parameters	
N_{sc}	1
N_{pc}	5
V_r	17V
I_r	3A
α	3.10^{-3}mA/^{o}C
β	-73.10^{-3}mW/^{o}C
I_{sc}	3.5
G_r	1000w/m_2
T_{cr}	25^{o}C
PSO Parameters	
Population size	5
Number of dimensions	3
Number of iterations	5
Acceleration coefficient (C_1)	1
Acceleration coefficient (C_2)	3
Weight index (w)	(10-iter No.)/10
Random numbers (r_1, r_2)	(0,1)
Limit ranges of the optimized parameters	
$0<K_e<20$ $0<K_{de}<10$ $0<K_{du}<1$	