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Academic Performance Indices: Error Calculation in Distributed MPP Tracking using PID and FLC

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Abstract

The extensive use of PV panels in Distributed and Renewable Electricity Generation is significantly driving Green energy revolution globally. The core of Distributed generation i.e. maximization of power output from panels is being propelled by Maximum Power Point Trackers. However, fully tracked systems with outputs 40-45% can be made to accomplish reduced loss with determination of errors. This includes convergence of iterative output sequences for distributed temperature and irradiance functions. Different sets of tuning parameters based on academic performance indices for PID and FLC are investigated in this paper. These are optimized through MATLAB/SIMULINK to obtain converter output close to the desired with minimum error. The analysis of Integral of Squared Error (ISE), Integral of Absolute Error (IAE), Integral of time multiplied by Squared Error (ITSE) and Integral of time multiplied by Absolute Error (ITAE) is carried out on validated model (PID as well as FLC). A comparative study for both models is presented in the paper. The simulation results shown in the present paper confirms that the errors (ISE, IAE, ITSE and ITAE) are minimized even for changing temperature and irradiance and the best results are obtained using an FLC system. The model designed is intended to be beneficial source for PV engineers and researchers to provide high efficiency with the use of MPPT.

Keywords -PID, FLC, MATLAB/SIMULINK, ISE, IAE, ITSE, ITAE

1. Introduction

Energy is the main prerequisite of the life on the Earth. Solar radiation is a direct source for generating heat, electricity and power to meet global demands of energy efficient systems. Abundance of solar energy appears as an ultimate choice for power consumption and distribution applications. It directly converts sunlight into electricity either through direct capture or distributed reception. Distributed reception refers to change in power output from panel due to deviations in temperature and irradiance by partial or complete shaded environmental conditions. Distributed and Renewable Electricity Generation multiplexes production of power through use of solar MPPT (Maximum power point Tracking). These systems monitor and control panel or converter power output for fluctuating environmental conditions.

Maximum power point describes operating point that delivers maximum efficiency and power output from panel. Using MPPT, the distributed energy is efficiently captured and utilized. MPPT maintains MPP on panel by regulating Standard Test Conditions (STC) even under in

distributed conditions. STC corresponds to panel ooperated for 25°C temperature and 1000 W/m^2 irradiance to generate maximum power output from panel (Chu and Majumdar, 2012).
A number of research techniques are available on MPPT. Until 2007, only offline MPPT techniques (Phang et al., 1984; Masoum et al., 2002; Chen et al., 2004; Jiang et al., 2005; Rodriguez et al., 2007; Khatib et al., 2010; Subudhi and Pradhan, 2011) were available including Curve fitting, Fractional Short Circuit Current, Fractional Open Circuit Voltage, Look Up Table and Analytic based MPPT. Advanced techniques came into existence for online direct systems divided into sampling techniques (Lim and Hamill, 2000; Liu et al., 2004; Xiao and Dunford, 2004; Salas et al., 2005; De Cesare et al., 2006; Femia et al., 2006; Salas et al., 2006; Femia et al., 2007; Garrigos et al., 2007; Liu et al., 2008; Calavia et al., 2010; Piegari and Rizzo, 2010; Yu et al., 2010; Kumari and Saibabu, 2013) comprising One Cycle Control, Perturb and Observe, Estimated Perturb and Observe, Improved Perturb and Observe, Incremental Conductance, Feedback techniques, Differentiation technique, Parasitic capacitance, Linearization, Sliding Mode, Gauss Newton, Steepest Descent technique and Hybrid techniques.

Later on modulation techniques (Hua and Shen, 1998; Jain and Agarwal, 2004; Salas et al., 2005; Enrique et al., 2010; Lopez-Laperia et al., 2010) were introduced such as Forced Oscillation, RCC (Ripple Correction Control) technique, Current sweep technique and DC link capacitor Droop Control Technique followed by intelligent methods (Hohm and Ropp, 2003; Pongratananukul, 2005; Tan et al., 2005; Xiao et al., 2006; Amrouche et al., 2007; Esram and Chapman, 2007; Xiao et al., 2007, Li-Qun and Zhi-Xin, 2008; Chu and Shen, 2009; Ramaprabha and Mathur, 2011; Hua et al., 2011; Kumari and Saibabu, 2013) Fuzzy logic, Artificial Neural Network and Particle Swarm Optimization and Global MPP for mismatched conditions. The selection of particular MPPT method is done on the basis of control strategy used (direct or indirect), control variable (single or double: voltage or current), implementation (simple or complex), circuit design (analog or digital), converters (DC or AC) and applications (standalone or grid).

PV (Photovoltaic) arrays act as real time simulators to generate electric output in proportion to sunlight received on surface. The power output across load is product of electric current generated from panel and panel driven voltage (Subudhi and Pradhan, 2013). The change in MPP relative to different temperatures and irradiance is observed by changes in Current Voltage (IV) and Power Voltage (PV) curves (Tasar and Guler, 2015). The challenge to maintain constant MPP is evaluated by identifying specific application of system and operating load at that voltage. This voltage is obtained using a converter. To maintain constant voltage output controller is connected that regulates output voltage from converter.

In the present work, firstly PV subsystem is modeled for generating 60W. Buck converters are used for voltage stabilization by reduction in voltage at the output of panel (Sharma and Jain, 2014; Sharma and Jain, 2015). To maintain constant output voltage from buck converter

(Sharma and Jain, 2014), controller is required. Two controllers PID and FLC are developed and implemented (Sharma and Jain, 2015).

2. Maximum Power Point Tracker

Different techniques have been surveyed and implemented for tracking MPP. The Block diagram of MPPT is shown in Figure 1.

This section describes the various blocks shown in Figure 1.

2.1 PV System

PV system comprises solar panel formed using solar cell equations. These include equations of Thermal Voltage, Diode Current, Load Current, Photocurrent, Shunt Current, Reverse Saturation Current, Reverse Current and Output Power. When modeled in SIMULINK-MATLAB, the subsystem obtained appears as shown in Figure 2 (Sharma and Jain, 2014).

2.2 Buck-Converter

Buck converter is used to reduce output across load by stepping down the voltage. Two models are studied for Buck converter using State space equations and direct components available in SIMULINK/MATLAB (Sharma and Jain, 2015). The Direct components model using Diode, MOSFET, Inductor, Capacitor and Load Resistor gave superior results over state space model using ON-OFF switching functions when compared for controllers.

The Block diagram of Buck converter using direct components is shown in Figure 3.

2.3 Controller

The effectiveness of converter operation is dependent on controller. A Controller generates control function for monitoring converter to get desired output. For Buck converter, switching pulse for MOSFET is obtained using Controller that initiates current pulses in inductor to deliver output voltage at capacitor and finally across load by turning MOSFET ON and OFF.

Two different controllers are modeled in MATLAB. These include (a) Proportional-Integral-Derivative Controller and (b) Fuzzy Logic Controller.

2.3.1 Proportional-Integral-Derivative Controller (PID)

The conventional PID controller is used to evaluate past error using proportional tuning factor, present error using integral factor and future error using derivative. The control function for controller is given by equation (1).

$$U_C(t) = K_P e(t) + K_I \int e(t) + K_D \frac{de}{dt} \tag{1}$$

Where,

U_C (t): Control signal
e (t): tracking error

K_P: Proportional gain
K_I: Integral gain
K_D:Derivative gain

The controller is simulated for different gains and tuned to get most appropriate value.

2.3.2 Fuzzy Logic Controller (FLC)

The intelligent controller use Artificial Intelligence (AI) to evaluate error. There are various AI techniques; these include fuzzy logic, neural networks, genetic algorithm, evolutionary computation, Bayesian probability, machine learning etc. In present work, Fuzzy Logic Controller is designed and simulated.

A two-input single-output fuzzy logic controller is designed with the input variables error (E) and change in error (ΔE) equation (2) and (3) tuned for output voltage ratio by Duty cycle (D) with changing temperature and irradiance in equation (4).

$$E(n) = \frac{P(n) - P(n-1)}{I(n) - I(n-1)} \tag{2}$$

$$\Delta E\ (n) = E\ (n) - E\ (n\text{-}1) \tag{3}$$

$$DC = \frac{V_{OUT}}{V_{IN}} \tag{4}$$

Where,

E (n): Error
ΔE (n): change in error
D: Duty cycle
V_{OUT}: Output voltage from converter
V_{IN}: Input voltage to converter

Duty cycle obtained for FLC is 0.978. This is less than unity as desired for buck converter. The rules formulated for developing FLC are given below:

For different rules, Defuzzification method gives a quantitative summary. The Defuzzification method used is the centroid method given by equation (5).

$$D = \frac{\sum_{j=1}^{n} \mu(Dj) - Dj}{\sum_{j=1}^{n} \mu(Dj)} \tag{5}$$

Where,

µ (Dj): Degree of the membership function

D: Defuzzified value and
The Union of the membership functions is found by the MAX aggregation method.

2.4 Load

It relates to specific value of resistance or any other specific application device to be driven using MPPT circuitry (Salas et al., 2005).

3. Measures of Controlled System Performance

Most practical systems are based on quantitative measurement using Statistical Quality Control Techniques (SQCT) in industries. The elementary issue in designing process control systems to be employed for applications in these techniques is to maintain suitable Controller gain. Generally a system with low gain gives slow response and high gain gives oscillatory fast response. The best system will correspond to be steady with no transients and being adaptive to speed of response, settling time and overshoot providing optimum gain irrespective of variations (Xiao and Dunford, 2004).

MPPT efficiency can be improved by estimating errors. Best response is calculated by detecting and reducing error between measured and required set point. The closed loop system implemented by controller reduces error and optimizes quickly for appropriate gain from PV system. The analytical method to check system performance is by calculating Performance indices.

Performance indices are of two types, academic and practical. Academic measures give direct comparison between control systems using different sets of tuning parameters. They are directly and quickly obtained. However they are not preferred for real plant systems (Gopal, 2013). To optimize a digital simulated system to its most precise value, academic indices must be computed to get minimum error (Sharma and Jain, 2014).

The analogy to achieve best response from controller using Academic performance indices is by selecting minimum value for Integral of Squared Error (ISE), Integral of Absolute Error (IAE), Integral of time multiplied by Squared Error (ITSE) and Integral of time multiplied by Absolute Error (ITAE) as direct integral computation will result zero. The system parameters are adjusted such that these indices reach minimum values. These are explained below:

3.1 ISE (Integral of Squared Error)

It is analytical manipulation method using linear quadratic weights for tracking set point by calculating cumulative sum of error. It gives low amplitude oscillation after minimizing large errors quickly. It is a statistical parameter used in linearization and optimal control estimation. It is calculated using Parseval’s theorem that states the integral or sum of the squares of function equals to square of its transform. The expression for ISE is (6).

$$ISE = \int_{0}^{\infty} \{e(t)\}^2 dt \tag{6}$$

3.2 IAE (Integral of Absolute Error)

It is not analytical form of error. It uses integral for sum of areas below and above set point without adding weights and penalizing errors equally. Its response is limited to slow response with larger deviation than ISE. It gives less sustained oscillations and minimum overshoots. It is mostly preferred in computer simulation studies and calculated using expression (7).

$$IAE = \int_{0}^{\infty} |e(t)| dt \tag{7}$$

3.3 ITSE (Integral of time multiplied by Squared Error)

This criterion is used to check long duration errors, where additional factor of time is multiplied with fast settling time. It eliminates steady state offset rapidly and removes long time deviations when compared with ISE. It is less sensitive for computations and is calculated using expression (8).

$$ITSE = \int_{0}^{\infty} t.\{e(t)\}^2 dt \tag{8}$$

3.4 ITAE (Integral of time multiplied by Absolute Error)

This measure tunes system rapidly when compared to all other indices. The slow response at initial start removes sustained oscillations. It possesses various other features like easy applicability, optima selectivity and reliability. It provides best selectivity of performance is calculated using expression (9).

$$ITAE = \int_{0}^{\infty} \mathrm{t}.|e(t)| dt \tag{9}$$

The system with smallest ITAE is considered the best one.

On the basis of these Results, the tuning gains of the PID [K_P (Proportional gain), K_I (Integral gain) and K_D (Derivative gain)] and scale factors for FLC [GE (Gain for process error (e) and GCE (Gain for change in error (che)] are selected.

4. Simulations for Errors

Simulations are carried out for obtaining performance indices for variable temperature and irradiance. Different temperatures are taken in range of Gaussian function with varying irradiance unevenly.

PV and converter subsystem are designed and simulated using PID and FLC controller.

The block diagrams of implemented systems are given in Figures 4 (PID system) and 5 (FLC system).

The controller monitors appropriate action. The range of the input variables can be changed according to the changing demand for the varying input. Different values of input variables are tested and appropriate response is detected. The optimum value of tuning parameters for PID is taken K_P (Proportional gain), K_I (Integral gain) and K_D (Derivative gain) as unity each (Sharma and Jain, 2015).

The universe of discourse in FLC is taken as [-0.24, +0.06] for error input and [-0.5, +0.5] for change in error voltage. The output variable duty cycle is chosen to be as [21, 21.4]. The optimum value of the tuning parameters for FLC is taken GE and GCE as unity each.

The comparison of different errors with and without Controllers is tested and tabulated for different temperatures with error curves.

This is shown in Tables 2 to 5 and Figures 6 to 9.

It can be seen from the readings that the direct uncontrolled system gives very large errors in comparison to controlled system. When a controller system is implied using FLC, the system is best controlled and shows minimum error whereas with PID the error is still larger. Also, for non linear conditions of change in temperature and irradiance; FLC gives satisfactory response for fast changing parameters. MPP is monitored and errors appear to be constant in FLC and thus FLC Controller accelerates response and increases stability of system (Subudhi and Pradhan, 2013; Tasar and Guler, 2015).

5. Results

The PV and converter subsystem designed was simulated for using three different models with and without controllers. Two controllers PID and FLC were tested using tuning gains at different environmental conditions. The tuning parameters for PID controller were tuned to achieve least disturbance at the output whereas for FLC various iterations on subsets of error and change in error with changeable crossover points were computed. The values which gave the best results in terms of the minimum values of errors, overshoot and settling time were then finally chosen for the controller. The converter outputs corresponding to two controllers are observed and shown in Table 6.

The scope outputs are detailed in Figure 10.

Outputs of PID and FLC depict similarity at the starting, however with temperature and irradiance change, PID converter output drops to 0.01093V whereas the FLC gives more linear and consistent output (21.2V).

Thus it can be seen that the system output is very close to the desired output while using a Fuzzy Logic Controller.

6. Conclusions and Future Work

The developed MPPT system was simulated for variable temperature and irradiance and academic performance indicators (ISE, IAE, ITSE and ITAE) were calculated. The error calculations show that the estimated errors are reduced greatly after simulation using FLC. The FLC system presents better performance over PID and can be incorporated for number of PV driven applications and thus, the efficiency of Photovoltaic cell can be increased using Fuzzy Logic Control system.

Acknowledgements

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ΔE E	NB	NS	Z	PS	PB
NB	Z	Z	NB	NB	NB
NS	Z	Z	NS	NS	NS
Z	NS	Z	Z	Z	PS
PS	PS	PS	PS	Z	Z
PB	PB	PB	PB	Z	Z

Table 1. Fuzzy rules

T °C	DIRECT	PID	FLC
5	0.7211	0.6302	0.5781
10	2.781	1.818	1.766
15	5.603	2.915	2.863
20	10.01	3.964	3.912
25	20.72	4.878	4.826
30	35.79	4.958	4.906
35	46.17	11.5	4.907
40	59.17	25.5	4.911
35	64.98	31.31	4.913
30	79.22	45.54	4.918
25	117.5	83.85	4.933
20	179.1	145.4	4.958
15	1933.9	160.2	4.963
10	206.8	173.2	4.965
5	213.4	179.7	4.965

Table 2. ITSE (Integral of time multiplied by squared error)

T °C	DIRECT	PID	FLC
5	0.03423	0.03191	0.3062
10	0.132	0.106	0.1047
15	0.266	0.01894	0.1881
20	0.4754	0.2912	0.2899
25	0.9836	0.4351	0.4338
30	1.699	0.4714	0.4701
35	2.145	0.7834	0.4738
40	2.809	1.448	0.4842
35	3.085	1.724	0.4894
30	3.761	2.4	0.5024
25	5.58	4.219	0.5389
20	8.503	7.141	0.5976
15	9.207	7.846	0.6097
10	9.822	8.461	0.6174
5	10.13	8.77	0.6201

Table 3. ITAE (Integral of time multiplied by absolute error)

T °C	DIRECT	PID	FLC
5	1.201	1.154	1.106
10	2.359	2.041	1.993
15	3.348	2.66	2.613
20	4.476	3.212	3.164
25	6.438	3.782	3.735
30	8.462	3.893	3.846
35	9.506	4.612	3.854
40	10.88	5.985	3.876
35	11.4	6.507	3.885
30	12.59	7.694	3.908
25	15.33	10.44	3.963
20	18.93	14.03	4.035
15	19.69	14.8	4.049
10	20.34	15.45	4.057
5	20.66	15.76	4.06

Table 4. IAE (Integral of absolute error)

T °C	DIRECT	PID	FLC
5	25.3	23.45	21.51
10	49.69	37.82	35.88
15	70.43	46.02	44.08
20	94.29	51.75	49.81
25	135.6	55.46	53.52
30	178.2	55.71	53.77
35	200.2	70.78	53.77
40	229.1	99.7	53.78
35	240.1	110.7	53.78
30	265.1	135.7	53.79
25	322.9	193.5	53.82
20	398.6	269.2	53.85
15	414.8	285.3	53.85
10	428.4	299	53.85
5	435.1	305.7	53.85

Table 5. ISE (Integral of squared error)

Direct	PID	FLC
.01093	.01093	21.2

Table 6. Converter outputs comparison

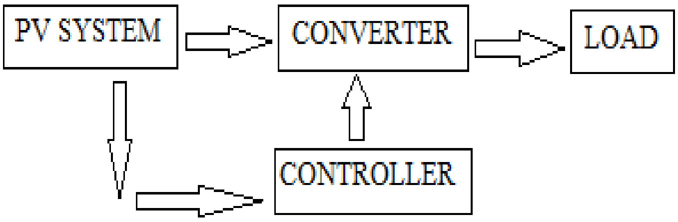

Figure 1. Block diagram of MPP tracker circuit

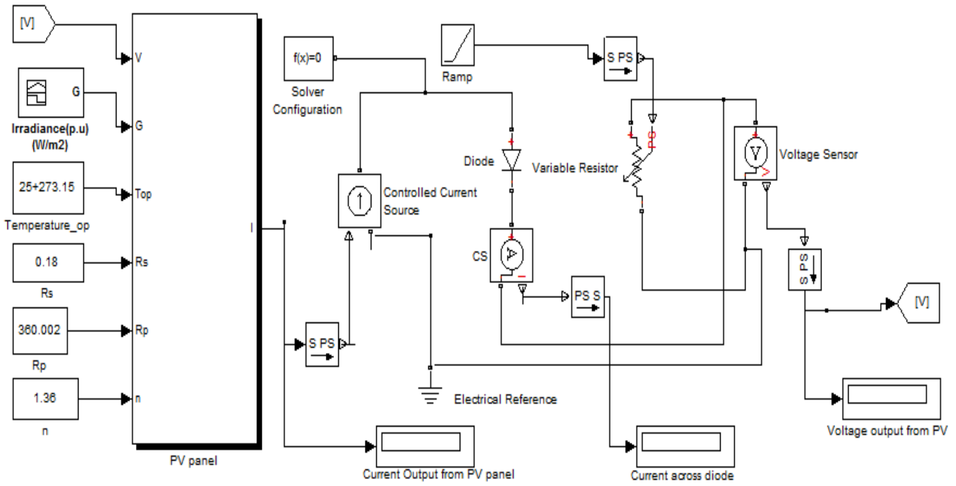

Figure 2. Solar panel subsystem

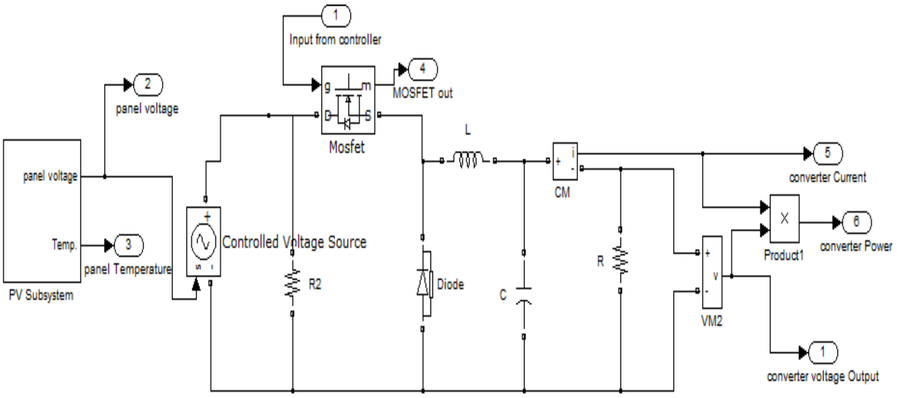

Figure 3. Buck converter using direct components

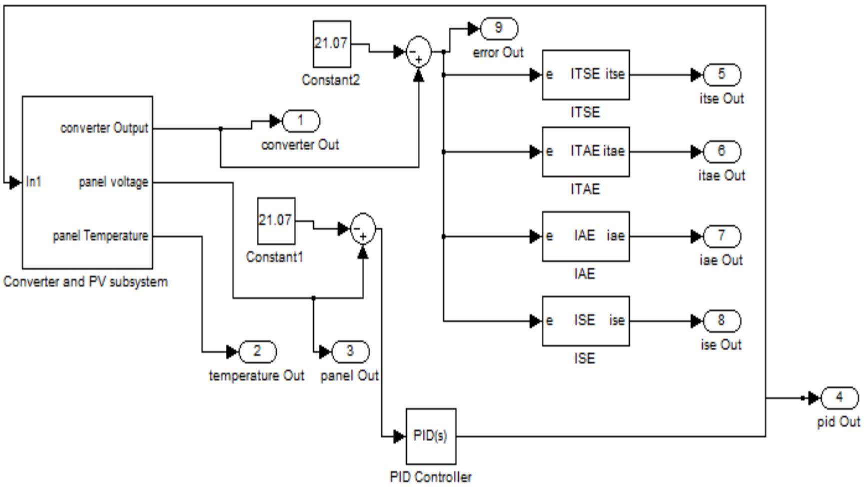

Figure 4. Block diagram of implemented PID for error check

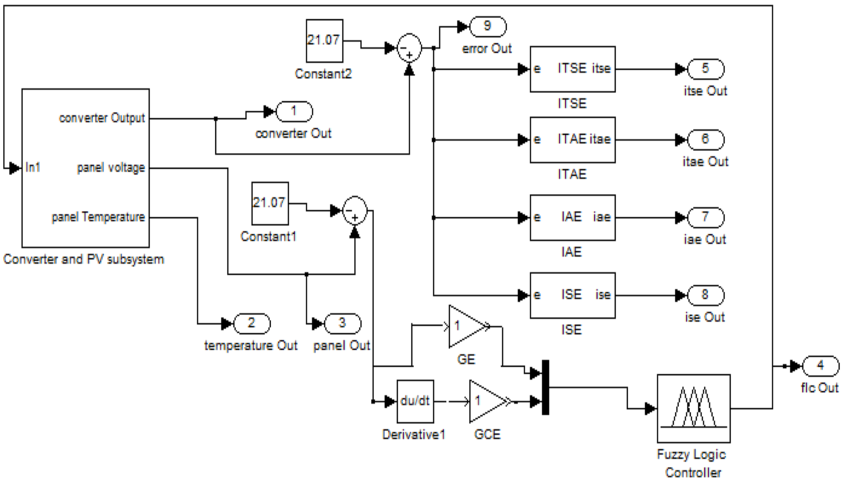

Figure 5. Block diagram of implemented FLC for error check

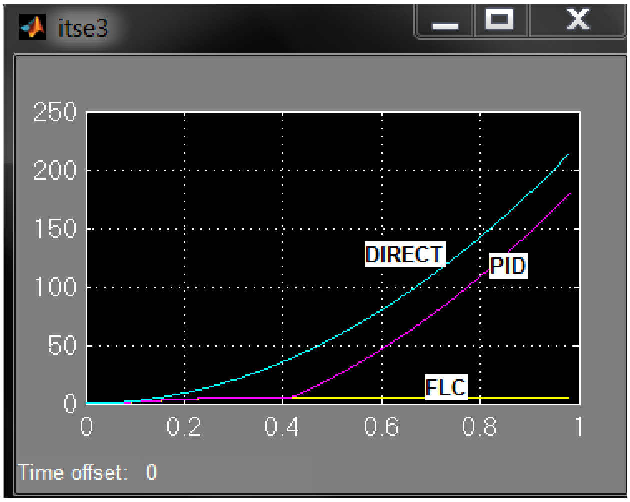

Figure 6. Integral of time multiplied by squared error

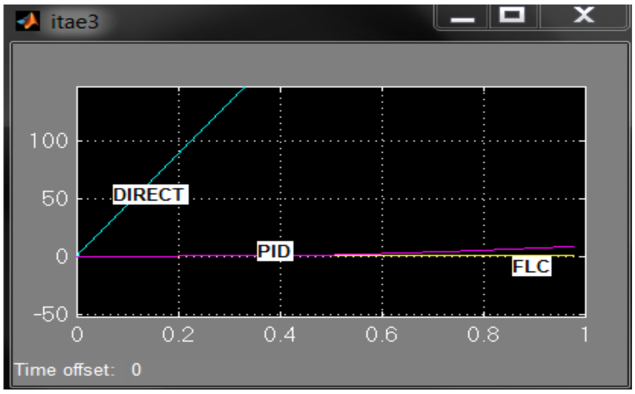

Figure 7. Integral of time multiplied by absolute error

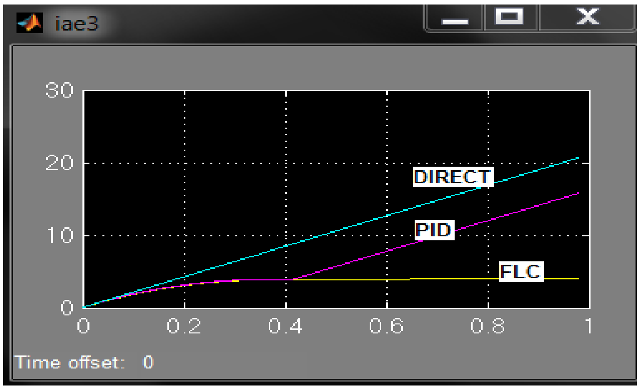

Figure 8. Integral of absolute error

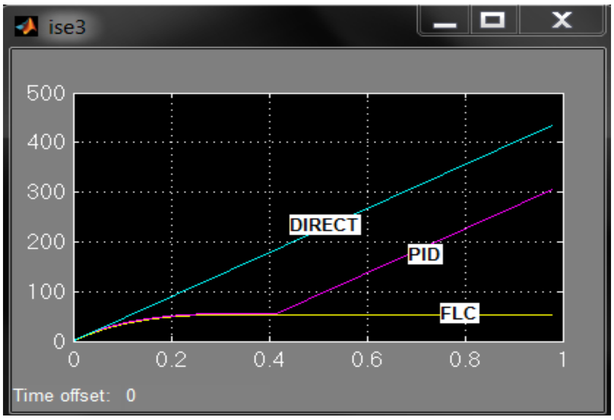

Figure 9. Integral of squared error

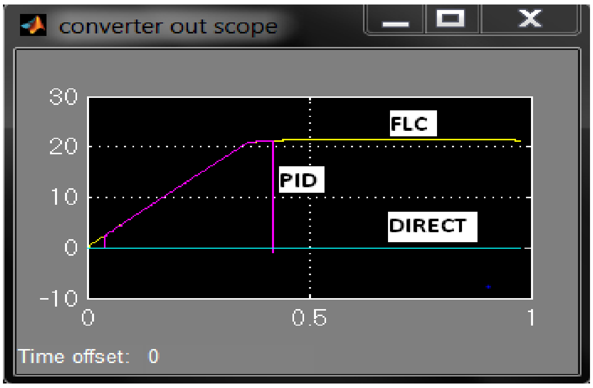

Figure 10. FLC, PID and direct converter output

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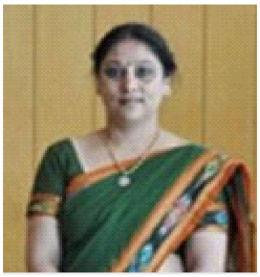

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