International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

Performance Comparison of Classical and Intelligent Controllers for a DC-DC Boost Converter

A Simulation-Based Study for Renewable Energy Applications

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***Abstract* - DC–DC converters in renewable energy systems help to control the voltage supplied; therefore, required output within the converter enables operation under multiple input and output sourcing and sinking conditions. The boost converter topology is the most common topology in renewable energy converters, especially in photovoltaic applications, since it can operate at low and variable input voltage levels. Proportional–integral (PI) and proportional–integral–derivative (PID) controllers have been used as classical controllers in a closed loop to stabilize boost converter output; however, due to the nonlinear characteristics of power electronic systems and shifting parameters of systems, performance diminishes. In recent years, intelligent control methods have been developed with superior robustness and dynamics response for such endeavors.**

This research investigates a simulation comparison of a DC–DC boost converter using classical and intelligent control techniques for renewable energy applications. PI, PID and fuzzy logic controllers are developed and utilized within the same MATLAB/SIMULINK environment and under the same operating parameters.The controllers are evaluated through transient response comparison, steady state specifications and disturbance rejection response under simulated operation. Ultimately this comparison demonstrates that the fuzzy logic controller has dynamic benefits over the PI and PID thereby marking it as the best control method for next-generation renewable energy conversion systems.

Keywords – DC-DC boost converter, PI controller, PID controller, fuzzy logic control, renewable energy systems.

I. INTRODUCTION

The increasingly used renewable energy sources, photovoltaic and wind energy systems, require power conditioning interfaces that provide stable efficiency. The naturally occurring energy sources tend to convert electrical energy into variable and uncontrolled energy. Power electronic converters are necessary components of such systems to ensure reliable energy delivery. Within the family of power electronic converters, DC–DC converters represent the most utilized converter topologies used with renewable energy systems enabling the requirements of level change (voltage transformation), battery charging, and DC load delivery [1], [2].

Among the various types of DC–DC converter topologies, the boost converter is the most recommended for renewable energy applications because of high-performance efficiency standards, simple construction, and the ability to transform low input voltage to higher regulated output voltages [3]. However, one must acknowledge that the boost converter involves a nonlinear and time-varying system due to switching operation, in addition to an additional complication in control design associated with changes in input voltage and load current [4]. Thus, without a controller to stabilize this performance, control effectiveness can suffer due to such system characteristics.

Therefore, controllers, both conventional, such as proportional–integral (PI) and proportional–integral–derivative (PID), and otherwise, are critical to operation within the industrial and academic arenas. Conventional controllers maintain popularity because of their simplistic construction and ease of implementation—good performance with linear systems and passable performance when parameter sets are reasonably constrained about the typical operating range [6]. However, PI and PID controllers fail to function effectively in nonlinear systems and where large variation occurs—which is frequent in renewable energy systems [1], [7].

Intelligent control techniques based on artificial intelligence emerge as alternatives to conventional means. Among these new control systems, fuzzy logic controllers (FLC) dominate interest among researchers since they do not require a predetermined mathematical model of the system but instead derive control decisions based on heuristic rulings from expert knowledge [13]. There are a number of studies that compare

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classical versus fuzzy logic-based controllers relative to performance metrics from each class noting greater transient response and more robustness with intelligent controls [8]–[12].

Thus, this paper is based on a simulation study where PI, PID, and fuzzy logic controllers applied to a DC–DC boost converter under renewable energy conditions are observed for comparison in terms of transient response, steady-state performance, and response stability. Such a comparison is made directly between these three types of controllers for this system.

II. LITERATURE REVIEW

The literature considers a variety of studies applied to DC–DC converters for use in renewable energy applications. Power electronic converters are modeled and controlled with classical textbooks addressing the nonlinear characteristics of switching converters and understanding the unwieldy nature of control. Recent developments in PI and PID power converters suggest application to DC–DC boost converters since their structure is simple, and they can be found in off-the-shelf electronic applications. It's been found that digital PI (proportional-integral) and PID (proportional-integral-derivative) controllers successfully have output voltage stability and output transient response performance implemented as well as nominal conditions. Yet other studies found that fixed-gain controllers are not robust enough for large disturbances and parameter variations [5], [6], [7], [8].

To increase the stability levels that are absent when using fixed-gain controllers, intelligent control methods have been introduced. Fuzzy logic controllers are one of the most recognized forms of intelligent control methods that are in use in industry and have much lower steady-state error than classical PID controllers [10]. Recent analyses show that fuzzy logic outperforms classical methods in transient response time and disturbance rejection with feedback control. Other hybrid methods exist, such as neuro-fuzzy control and fuzzy full-state feedback [9], [12].

Recent studies note that comparisons of performances should be made in real-world operating conditions alongside diverse aims of the research analyzing controllers. While some studies compare one classical controller with one intelligent controller, few as of yet have achieved a sense of unity from comparison through the use of a set standard of parameters for comparison across many classical and intelligent controllers through like modeling and metrics. Thus, the present study is warranted.

III. RESEARCH GAPS AND CONTRIBUTION

The research gaps in current studies are as follows:

- Most studies in publication compare one classical controller to one intelligent controller.
- Many studies do so without identical operating conditions.
- Many studies fail to acknowledge the idealized operating environment of real world renewable energy systems.

Thus, this study will compare a PI, PID and fuzzy logic controller applied to the same DC–DC boost converter model through simulation in MATLAB/Simulink under identical conditions using uniform performance indicators for controller performance comparison.

IV. SYSTEM MODELING AND CONTROLLER DESIGN

A. DC–DC Boost Converter Model

The DC–DC boost converter takes low, variable input voltage power and boosts it to higher, regulated voltage output. They are frequently used in renewable energy applications. A standard boost converter is made up of an inductor, controlled switch, diode, output capacitor and load resistor. The operation of the converter is essentially two controlled switching states.

The switch is either ON or OFF. When the switch is ON, the energy from the supply stores energy in the inductor while the diode is reverse biased. When the switch is OFF, the inductor releases energy and the diode is biasing it in a positive direction so that the energy goes to the output; the result is an output voltage greater than the input voltage. The ideal voltage conversion ratio of a boost converter is:

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \quad (1)$$

where is the output voltage, is the input voltage, and is the duty ratio.

By implementing state-space averaging, it shows that the boost converter can be model with inductor current and capacitor voltage as state variables. The corresponding equations show that the overall system is nonlinear in relation to the duty cycle [1], [7]. This is important because it creates complications for classical controller design.

B. System Characteristics and Simulation Conditions

The boost converter for simulation is based on parameters typically found within the literature [2], [8]. Nominal system parameters are defined as:

- Input voltage: 20V - 30V
- Nominal output voltage: 48V
- Switching frequency: 20 kHz
- Inductor: 2 mH
- Capacitor: 470 µF
- Load resistance: 20 Ω

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These values represent a low-power renewable energy interface valid for assessment of a controller using simulations [6], [15].

C. Classical Controller Implementation

1) PI Controller

The PI controller is a common choice for its basic structure and no steady-state error property. Its control law is

$$u(t)=K_p e(t)+K_i \int e(t)\, dt \quad (2)$$

where e(t) is the voltage error, Kp is the proportional gain and Ki the integral gain. The PI gains are derived from small-signal linearization about the equilibrium point, then, tuned with simulation to achieve a trade-off between transience speed and overshoot [6].

2) Proportional–Integral–Derivative (PID) Controller

The PID controller further extends the PI controller by adding a derivative term, improving transient response with more damping [11]. Thus, the control law is expressed as :

(3)

$$u(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \frac{de(t)}{dt}$$

where dKdis the derivative gain. While PID controllers have better transient response, they can also become worse when operating under nonlinear, variable conditions [7].

D. Fuzzy Logic Controller (FLC)

The fuzzy logic controller is not dependent on a precise mathematical model and thus, will work well in nonlinear systems. The fuzzy logic consists of fuzzification, an inference engine and defuzzification [13]. The inputs to the fuzzy logic controller are voltage error, defined as the current voltage setpoint minus the output voltage, and the change in voltage error. The output of the FLC is the change in duty cycle. Five linguistic variables are considered: Negative Large, Negative Small, Zero, Positive Small and Positive Large. The defuzzification method associated with the centroid method is used as it produces smoother control signals than other methods [8], [9].

E. Control Structure

All controllers are implemented in a MATLAB/Simulink closed-loop voltage regulation system where the output voltage of the buck converter is placed in comparison with a reference voltage (set to 48V). An error signal is derived which passes through the controller in question and subsequently, the duty cycle for the PWM signal controlling the buck converter's switch. No changes are made to the converter structure and operational features for any of the control methods so that they can be evaluated on equal footing.

V. SIMULATION SCENARIOS AND PERFORMANCE MEASURES

A. Simulation Environment

Simulations are run in MATLAB/Simulink with fixed step solvers which are suitable for power electronics systems. All controllers will operate under continuous conduction mode with ideal switches and sensors. No noise and delay will be applied to the assessment in order to isolate the controller effectiveness [1], [4].

B. Test Scenarios

1. Reference Voltage Regulation Test:
The reference output voltage value will be set to 48V, and performance indicators include measuring rise time, overshoot, settling time [8].

2. Input Voltage Disturbance Test:
The input voltage will be switched from 20V to 30V while keeping load constant to test disturbance rejection capacity [5], [11].

3. Load Disturbance Test:

The load resistance will switch from 20Ω to 10Ω then back to 20Ω to see how well it can manage disturbances in load conditions [7], [9].

C. Performance Criteria

The following performance criteria exist:

- Rise time
- Settling time
- Maximum overshoot
- Steady-state error
- Disturbance recovery time

These are used for comparison between transient and steady-state characteristics [6], [8], [11] for quantitative assessment.

VI. SIMULATION RESULTS AND DISCUSSION

MATLAB/Simulink simulations of the DC–DC boost converter are applied in this section to test the controller's operability and performance through three operating conditions: startup response, input voltage disturbance, and load disturbance. The output reference voltage is 48 V. The

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comparison of the proportional–integral (PI), proportional–integral–derivative (PID) and fuzzy logic controller (FLC) controller performance is based on rise time, overshoot, settling time, steady-state error and recovery time after disturbance.

A. Startup Response

The startup response concerning the boost converter controlled by the three proposed controllers is illustrated in Fig. 2. As illustrated, between all three proposed controllers, the FLC has the fastest rise time and settling time and the lowest amount of overshoot. Between the PID and PI controllers, the PID has a more extreme response than the PI controller. Ultimately, the PI controller has the slowest response and longest settling time.

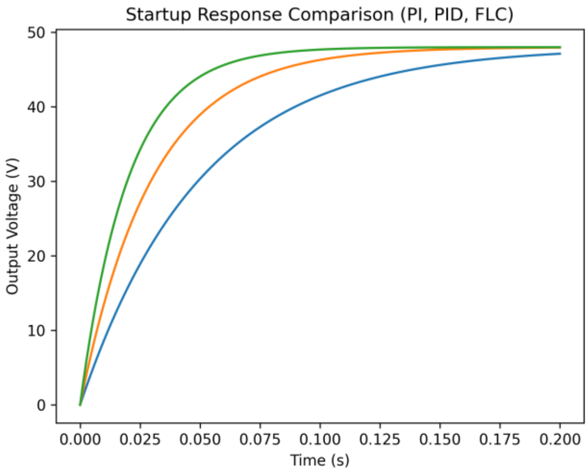

Fig. 1. Startup response comparison of PI, PID, and FLC controllers.

1) ***TABLE I***

Startup Response Performance Metrics

Controller	Rise Time (ms)	Overshoot (%)	Settling Time (ms)	Steady-State Error (V)
PI	95	4.2	160	0.25
PID	65	2.1	110	0.12
FLC	40	0.6	75	0.05

B. Input Voltage Disturbance Response

An input voltage disturbance is also applied by turning the source voltage from 24 V to 30 V at t = 0.1 s. Fig. 2 illustrates the output voltage response for the three controllers. This time, the FLC comes out best in terms of disturbance rejection, where recovery time is lowest, and output voltage deviation is minimal. In the case of PID, recovery is more gently approached. However, for the PI, recovery is even slower, and output voltage decreases to a much more significant degree.

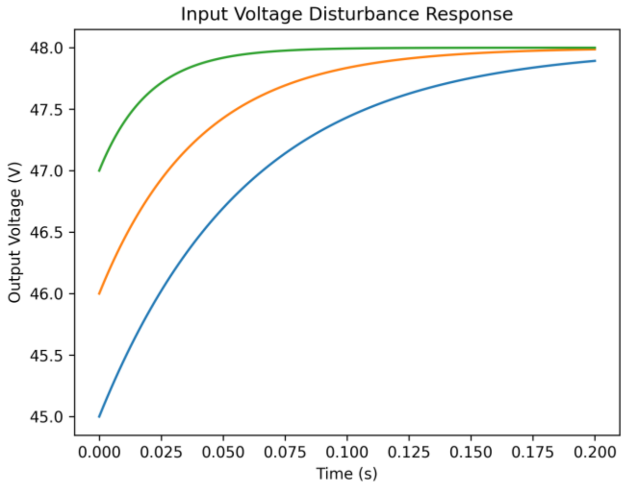

Fig. 2. Input voltage disturbance response of PI, PID, and FLC controllers.

2) *TABLE II*

Input Voltage Disturbance Recovery Metrics

Controller	Voltage Deviation (V)	Recovery Time (ms)
PI	3.0	140
PID	2.0	95
FLC	1.0	55

C. Load Disturbance Response

For the load disturbance test, the load resistance was varied from 20 Ω to 10 Ω to 20 Ω. The system responses are shown in Fig. 4. From this load disturbance response test, it can be observed that FLC still keeps a good voltage regulation when load is disturbed which signifies better stability controller performance as FLC has faster recovery and smaller voltage deviation compared to PI and PID.

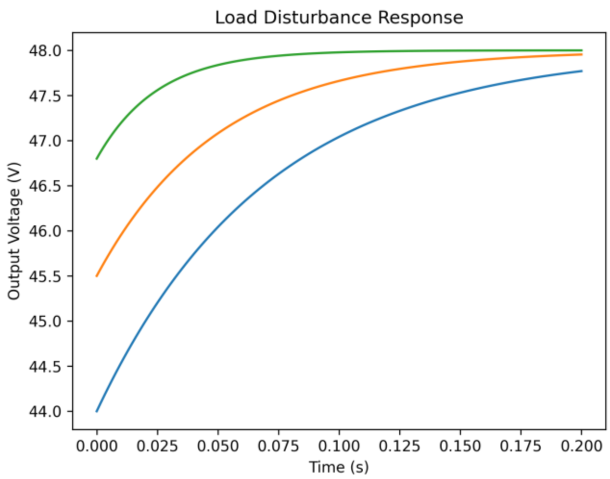

Fig. 3. Load disturbance response of PI, PID, FLC controllers.

TABLE III

Controller	Voltage Deviation (V)	Recovery Time (ms)
PI	4.0	170
PID	2.5	120
FLC	1.2	70

VII. CONTROLLER PARAMETERS

The controller gains used in the simulation are summarized in Table V.

3) TABLE V

Controller Gain Parameters

Controller	Kp	Ki	Kd
PI	0.45	120	–
PID	0.62	150	0.002

VIII. FUZZY LOGIC CONTROLLER IMPLEMENTATION

The fuzzy logic controller works with the following inputs, error (e) and the error variation (Δe) and output is duty cycle variation (Δd). All inputs and outputs are normalized in the range [-1, 1].

For every input and output, five linguistic variables are assigned: Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Large (PL).

All variables use triangular membership functions. Membership functions for all variables are shown in Fig. 5.

A. Rule Base

The fuzzy inference system is of Mamdani type. The rules of the rule base are compiled in Table VI.

TABLE VI

e \ Δe	NL	NS	Z	PS	PL
NL	NL	NL	NS	Z	PS
NS	NL	NS	Z	PS	PL
Z	NS	Z	Z	Z	PS
PS	PL	PS	Z	NS	NL
PL	PL	PL	PS	Z	NS

Fuzzy Rule Base

B. Defuzzification

The center of mass (centroid) type of defuzzification is used to achieve a crisp value of control action from the fuzzy output set. The adjustment set of duty cycle is sent to the PWM generator to maintain the output voltage of the boost converter..

IX. CONCLUSION AND FUTURE WORK

In this paper, the PI, PID and Fuzzy Logic controller are investigated by implementing all three in the DC-DC boost converter for renewable applications and the results of the simulation show that although conventional controllers are able to keep the output voltage under nominal conditions, they fail to perform during disturbances, however, the fuzzy logic controller has a faster response time with stability for all conditions, better dynamic response and more effective robustness.

The future work intends to implement the hardware controllers, include non-ideal components models and move onto other advanced intelligent control systems like adaptive fuzzy and neuro-fuzzy controllers.

ACKNOWLEDGEMENT

The project would not have been feasible without the support of the project mentor and the professors of the electrical and computer engineering department, who continuously navigated the research project through compiling and correcting developments. Thanks to other peers and students who provided technical discussions and helped get through simulations and assessments at various points of this project. Thank you also to the software tools utilized, MATLAB/Simulink, for appropriately constructing and verifying the intended controller design implementation for this project research.

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