



Genetic Algorithm Fitness Function Comparison for PID Controller Optimization in DC–DC Boost Converters

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Abstract

DC-DC boost converters are extensively employed in power supply and renewable energy applications. Maintaining a stable output voltage under changing input and load conditions is a major difficulty in such systems. Among different control approaches, the Proportional–Integral–Derivative (PID) controller remains the most widely applied due to its simple structure and reliable performance. However, selecting the optimal set of PID gains that balance steady-state accuracy and transient response is often complex. In this study, a Genetic Algorithm (GA) is employed to optimize the PID parameters of a boost converter using four different fitness functions: Integral of Time-weighted Absolute Error (ITAE), Integral of Absolute Error (IAE), Integral of Time-weighted Squared Error (ITSE), and Integral of Squared Error (ISE). MATLAB/Simulink has been utilized to model the proposed converter to evaluate the dynamic performance achieved by each optimization criterion. Simulation results illustrate that the choice of fitness function has a significant effect on the converter's transient and steady-state behavior. Among the tested criteria, the ITAE-based tuning yields the best performance, providing minimal overshoot, faster rise time, and reduced steady-state error.

Keywords: PID controller, Boost converter, Genetic Algorithm, Fitness functions, IAE, ISE, ITAE, Optimization

INTRODUCTION

Renewable energy, electric vehicles, and portable devices which are requiring voltage step-up systems and many other applications commonly employ DC–DC boost converters due to their ability to step up voltage efficiently. These converters receive variable input voltages typically supplied by Rectifiers and Fuel Cells, or photovoltaic (PV) cells and regulate the output voltage that supplies the connected load by adjusting the duty cycle (D) of the switching component. (Agrawal et al., 2018; Nouh et al., 2024).

The duty cycle is dynamically controlled according to the input voltage and load conditions to ensure a stable and constant output voltage. However, DC–DC converters exhibit nonlinear behavior during operation, often resulting in significant output voltage ripples and overshoots under transient conditions (Almalih et al., 2023; Zambrano-Gutierrez et al., 2024). Therefore, a controller with a fast and adaptive dynamic response is essential to improve performance and minimize these effects. PID controllers are commonly utilized for this purpose because of their simplicity and effectiveness. Nonetheless, their performance largely depends on accurate parameter tuning, and finding the optimal values remains a major challenge in nonlinear systems (Faraj et al., 2021; Saharia et al., 2025).



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Numerous optimization algorithms have been reported in previous studies to refine the tuning process and strengthen system stability and robustness. In (Bandong et al., 2021), two type of optimization techniques were utilized to achieve optimal PID tuning, and compared based on the minimization of the ITAE performance index. In recent years, Genetic Algorithms (GAs) have received considerable attention for their effectiveness in the automatic tuning of PID controller gains. For example, in (Rajamani et al., 2022), a GA-based approach was applied to tune a PI controller for voltage-mode regulation in a buck–boost converter, yielding superior performance compared to conventional tuning techniques. Likewise, the study in (Alfergani et al., 2021) employed GA optimization to determine the PID parameters of DC–DC buck converters, aiming to minimize integral error indices and enhance transient performance. Moreover, the work in (Aguila-Leon et al., 2021) investigated the use of GA, Particle Swarm Optimization (PSO), and the Grey Wolf Optimizer (GWO) for PID tuning, where the results demonstrated that both GWO and GA outperformed the PSO method in terms of overall system response and stability.

This study focuses on analyzing the influence of various fitness functions within a Genetic Algorithm (GA) framework for optimizing the PID controller gains in the voltage regulation loop of a DC–DC boost converter. The primary goal is to determine which fitness function achieves the most suitable compromise among key performance indicators, including maximum overshoot (OS%), rise time (T_r), settling time (T_s), and steady state error (SSE) during transient operation. Building upon previous studies, the PID tuning process is carried out to obtain the optimal controller parameters (K_p , K_i , and K_d) based on the converter's output voltage response under different GA-based fitness criteria. Given that the selection of the fitness function has a significant effect on the optimization outcome, this work performs a comparative evaluation to identify the function that delivers the best overall system performance.

This work arrangement is as follows: The first section presents the fundamentals of the proposed converter and the main structure of the PID controller. The principle operation of GA has been introduced in the second section, while the third shows GA-based PID controller optimization. The last section presents the simulation results, where the overall comparison between the different indexes has been discussed.

SYSTEM MODELING AND CONTROLLER DESIGN

Basic Principle of a Boost Converter

A DC-DC boost converter primarily increases the input voltage to a specified higher level, as defined by the relationship in Equation (1). In this equation, V_{out} denotes the output voltage, V_{in} represents the input voltage, and D is the duty cycle, defined as the ratio between the switch ON duration and the total switching period (Aguila-Leon et al., 2021; Rai et al., 2016).

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

Figure 1 presents the circuit configuration of the boost converter, includes of an inductor, an IGBT switch, a fast recovery diode, and an output capacitor. The converter operates in two modes depending on the switching condition of the IGBT. When the switch is turned ON ($0 \leq t < t_{on}$), the inductor is connected directly to the input voltage source, causing the current through it to rise and magnetic energy to be stored. During this interval, the diode remains reverse-biased, isolating the output stage from the input. The pre-charged capacitor maintains an

approximately constant voltage across the load. When the IGBT is turned OFF ($t_{on} \leq t < T$), the inductor current continues to flow, releasing the stored energy. The diode becomes forward-biased, providing a current path to both the load and the capacitor. Consequently, the combined energy from the inductor and the input source raises the output voltage above the input level. This switching behavior allows the converter to step up the input voltage while supplying a continuous current to the load (Hasaneen et al., 2008; Rai et al., 2016).

In the proposed design, the boost converter functions in Continuous Conduction Mode (CCM), where the inductor current remains continuously above zero throughout the switching cycle. The corresponding duty cycle is calculated using Equation (2). To maintain the converter within the CCM region, the inductance value is selected to exceed the minimum limit specified by Equation (3), thereby ensuring continuous energy transfer and stable output behavior.

$$D = 1 - \frac{V_o}{V_{in}} \tag{2}$$

$$L_{min} = \frac{D(1-D)^2 R}{2f_s} \tag{3}$$

In this study, L_{min} represents the minimum inductance required to maintain continuous conduction under steady-state operation. The duty cycle D , load resistance R , and switching frequency f_s of the IGBT are fundamental parameters that influence the converter’s performance. The output capacitor is appropriately selected to restrict the output voltage ripple within acceptable limits. The minimum capacitance necessary to achieve a specific ripple level is determined using Equation (4). When the switch is in the ON state, the diode is reverse-biased, and the capacitor discharges through the load. During the OFF state, the diode conducts, allowing the inductor current to transfer energy to both the capacitor and the load. (Hasaneen & Mohammed, 2008; Rai et al., 2016). A summary of the principal design parameters of the employed DC–DC boost converter is presented in Table 1,

$$C_{min} = \frac{D}{V_r * R * f_s} \tag{4}$$

Table:(1). Specification of Electrical Parameters for the Boost Converter

Descriptions	Value	Descriptions	Value
Input voltage	12V	Switching Frequency	25KHz
Output Voltage	20V	Voltage Ripple	1%
Load (R)	4	Current Ripple	30%
Capacitor (C)	400 μf	Inductance (Lmin)	11.52 μH
Duty Cycle	0.4		

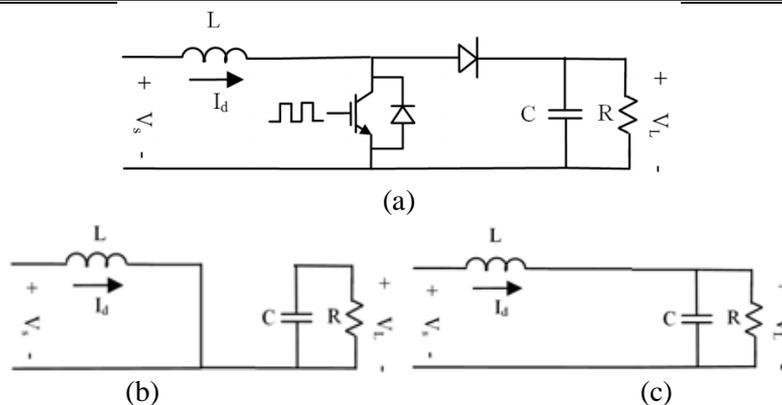


Figure: (1). Circuit diagram of converter (a). Boost Converter circuit (b) ON state of the switch. (c). OFF state of the switch (Hasaneen & Mohammed, 2008).

PID Control Structure

The PID controller is applied to manage the fluctuating input voltage of the DC–DC boost converter and maintain a consistent DC output, as illustrated in Figure 2. It functions through a closed-loop feedback system that continuously reduces the difference between the reference setpoint and the measured output. This is accomplished by modifying the control signal to guide the system toward the desired operating conditions. A standard PID controller comprises three key components: K_p responds to the present error, K_i eliminates steady-state deviation by accumulating past errors, and K_d anticipates future errors by evaluating the rate at which the error changes. Correct adjustment of these parameters P, I, and D ensures both stable operation and the desired transient response (Faraj et al., 2021).

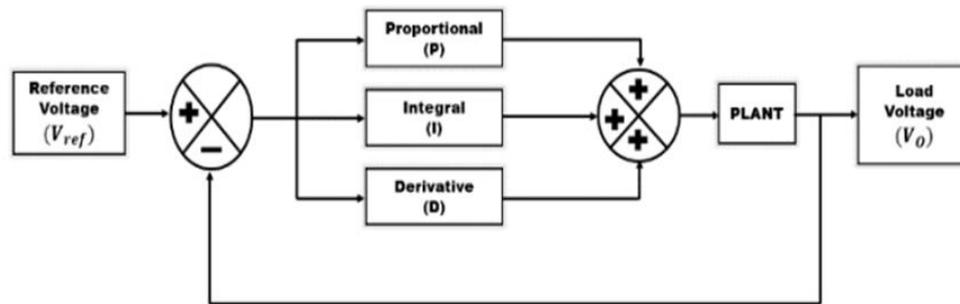


Figure: (2). Circuit diagram of converter (a). Boost Converter circuit (b) ON state of the switch. (c). OFF state of the switch

The PID design also considers performance indicators such as OS%, T_d , T_p , T_r , T_s , and SSE to ensure SS operation of the converter. To achieve optimal PID coefficients for the boost converter model, a genetic algorithm (GA) is employed. The GA-based tuning method enhances optimization, ensuring the PID parameters are well-suited for the system's dynamic behavior.

GENETIC ALGORITHM OVERVIEW

GA is a robust optimization approach that draws its concept from the processes of natural selection and biological evolution. It is frequently used to address both constrained and unconstrained optimization problems by continuously improving a population of potential solutions. During each iteration, known as a generation, a subset of individuals is selected from the current population to serve as parents, and their characteristics are combined to produce offspring for the next generation. This evolutionary process is repeated until convergence is achieved, resulting in an optimal or near-optimal solution. In GA terminology, each candidate solution is represented as a chromosome (or genotype), which encodes a specific set of parameters defining a possible solution to the given problem. The entire set of chromosomes forms the population. The quality of each chromosome is evaluated using a fitness function, which quantifies how closely a solution meets the desired objective. Higher fitness values indicate better performance relative to the optimization goal (Almalih et al., 2022; Ganesan et al., 2021).

Genetic Operators

The evolutionary process in GA is driven by three key genetic operators: The selection operator determines which individuals are chosen to reproduce based on their fitness levels, thereby favoring the propagation of superior traits to the next generation. The crossover operator, analogous to biological reproduction, combines portions of two parent chromosomes to produce new offspring that inherit characteristics from both parents. This operator enhances diversity and

enables exploration of new regions in the search space(Lambora et al., 2019). Meanwhile, the mutation operator introduces random alterations to one or more genes within a chromosome, ensuring that genetic diversity is preserved throughout the evolution process. Mutation helps prevent premature convergence and enables the algorithm to escape from local optima. The overall sequence of operations in the GA is illustrated in Figure 3(Lambora et al., 2019).

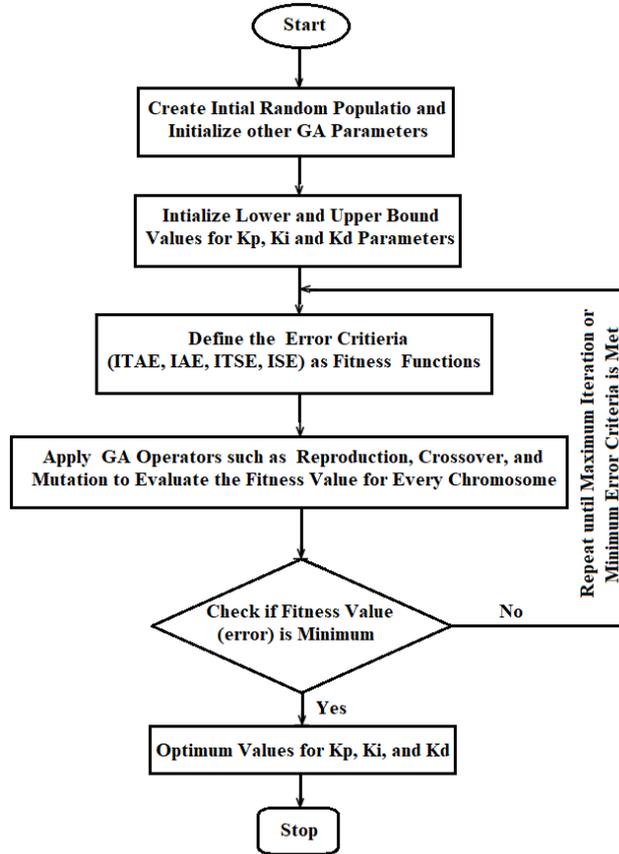


Figure: (3). The sequence of operations in the GA

GA-BASED PID CONTROLLER OPTIMIZATION

This paper investigates the application of GA in tuning PID parameters for Boost converters using different fitness functions and compares their effect on the system's dynamic performance.

The basic configuration of the system analyzed in this study is illustrated in Figure 4. The Genetic Algorithm (GA) is utilized to optimize k_p , k_i , and k_d gains of the PID controller. In the GA framework, each chromosome encodes a unique combination of these three control parameters, as defined by the three-row ‘bounds’ matrix during population initialization. During the evaluation phase, each chromosome is decomposed into its respective P, I, and D components, which are subsequently used to construct the PID controller in accordance with the governing control law expressed by the following equation.

$$PID(s) = k_p + \frac{k_i}{s} + k_d s \tag{5}$$

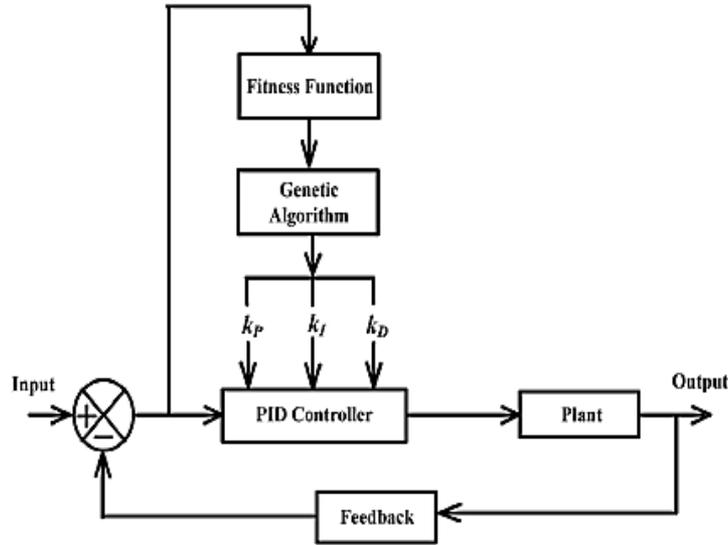


Figure: (4). Fundamental block diagram of a Genetic Algorithm-based PID controller

The main objective is to minimize the error between the reference input and the plant output, thereby improving system stability and dynamic performance. The effectiveness of the GA heavily depends on the definition of the objective function, which is used to assess the fitness of each chromosome (Lambora et al., 2019). In this study, four standard performance indices are selected to minimize system error and enhance control system accuracy:

$$ITAE = \int_0^{\tau} t |e(t)| dt \tag{6}$$

$$IAE = \int_0^{\tau} |e(t)| dt \tag{7}$$

$$ITSE = \int_0^{\tau} t e(t)^2 dt \tag{8}$$

$$ISE = \int_0^{\tau} e(t)^2 dt \tag{9}$$

where $e(t)$ denotes the instantaneous error between the reference input and the system output. These indices quantitatively describe the system’s transient and steady-state behavior. Minimizing these integrals ensures less T_s , T_r , reduced %OS, and improved SSE.

SIMULATION RESULTS

The MATLAB/Simulink model employed for designing and evaluating the performance of the boost converter under varying operating scenarios is presented in Figure 5. The converter parameters used in the simulation are summarized in Table 1. Initially, a conventional PID controller was incorporated to establish baseline system performance and assess stability. The resulting system response is shown in Figure 6. The PID gains (k_P , k_I , and k_D) were determined using the MATLAB PID Tuner tool through a trial-and-error procedure.

The output response was analyzed to evaluate the dynamic behavior of the converter. As illustrated in Figure 6, the PID controller improved T_r , T_p , %OS, and SSE. Nevertheless, the settling time and output voltage ripple remained suboptimal, indicating the need for further enhancement. These limitations motivated the adoption of a Genetic Algorithm (GA) to optimize the PID parameters and achieve improved overall system performance.

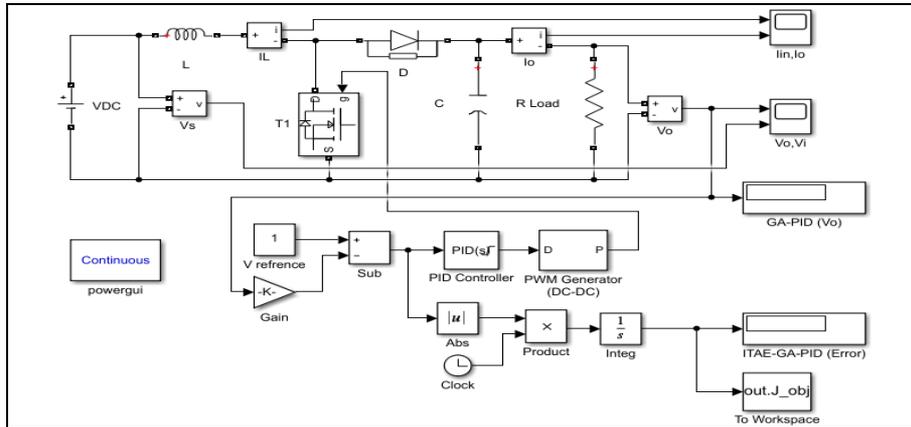


Figure: (5). MATLAB/ Simulink of boost converter

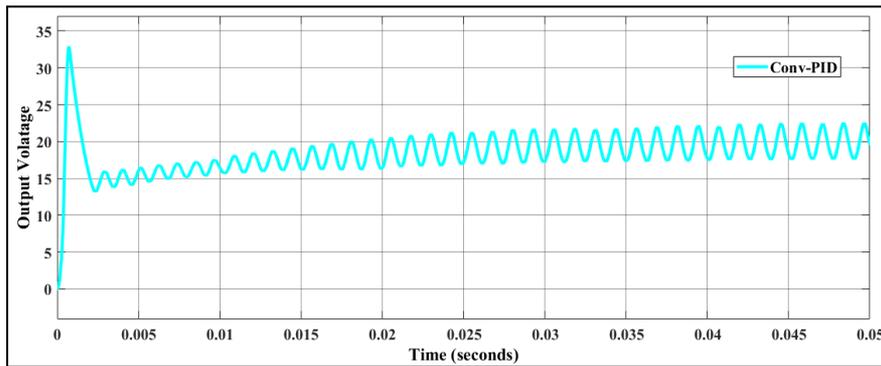
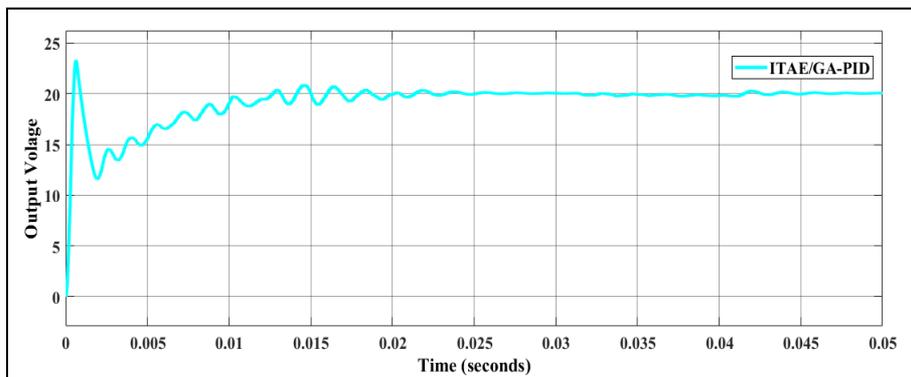
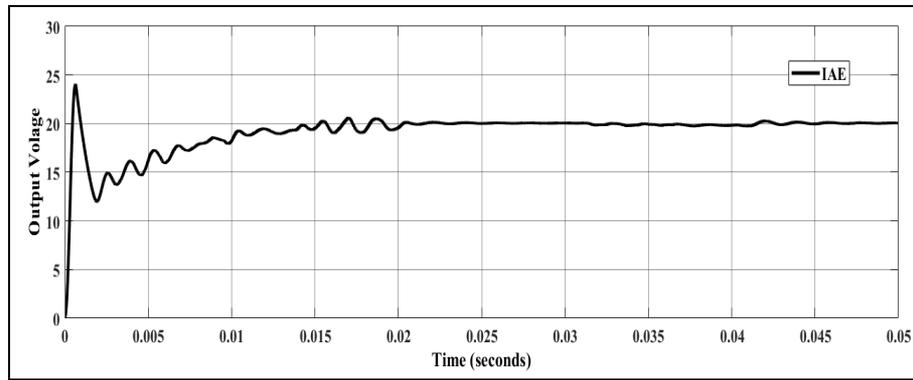


Figure: (6). The response of conventional PID

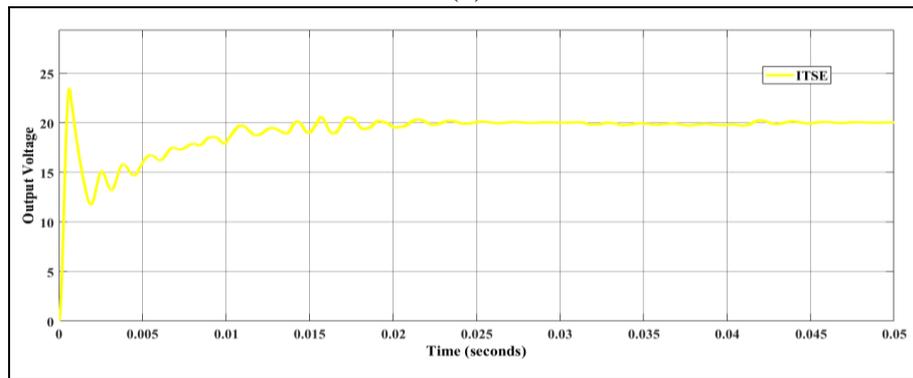
After the initial configuration, a Genetic Algorithm (GA)-based PID controller was implemented to determine the optimal controller parameters, as shown in Figure 7. The GA was executed for ten generations with a population size of 40. Stochastic uniform selection was employed, and the mutation and crossover probabilities were set to 0.1 and 0.8, respectively. To assess the controller’s performance and the effect of different objective functions, the step responses corresponding to ITAE, IAE, ITSE, and ISE were analyzed. For each objective function, the fitness values determined the optimal proportional (kP), integral (kI), and derivative (kD) gains. The resulting gain values are summarized in Table 2. The error signal, defined as the difference between the reference voltage and the measured output voltage, was extracted from the nonlinear DC–DC boost converter model implemented in MATLAB/Simulink. The step responses and associated performance indices for each objective function are presented in Figures 7.



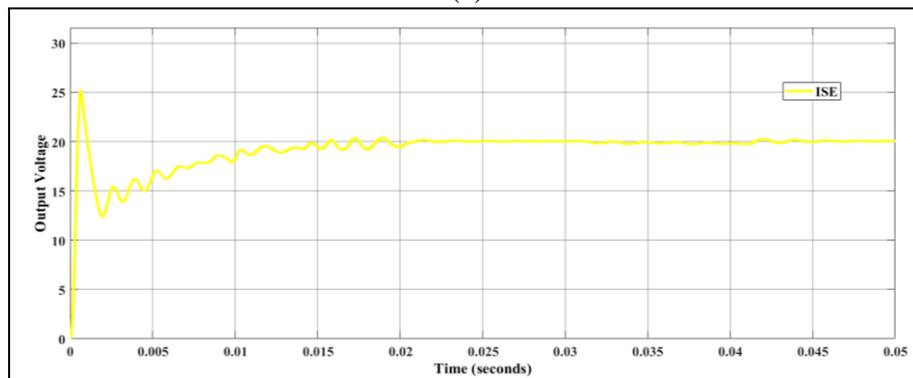
(a)



(b)



(c)



(d)

Figure: (7). The response of GA-PID (a) ITAE, (b) IAE, (c) ITSE, (d) ISE

Table:(2). The PID control parameter for both the conventional and GA methods

Gain	Conventional PID	GA=PID			
		ITAE	IAE	ITSE	ISE
Kp	0.7	0.051	0.192	0.141	0.282
Ki	100	196.676	191.247	186.962	198.663
Kd	0	0	0	0	0

In this study, the controller structure was not fixed in advance. The GA was given full freedom to search the complete parameter space of the PID controller (K_p , K_i , K_d). The repeated convergence to $K_d=0$ therefore reflects the behavior of the system itself rather than a constraint

imposed by the optimization settings. This outcome suggests that the derivative term does not provide a meaningful performance benefit under the operating conditions and objective function considered. In effect, the GA identified a PI controller as the most suitable configuration within the full PID search domain.

The key performance parameters, including OS%, Tr, Ts, final output voltage, and SSE, were evaluated for both the conventional PID controller and the GA-optimized PID controller. The corresponding quantitative results are summarized in Table 3. Furthermore, a comprehensive comparative analysis of the step responses for both controllers is presented in Figure 8, highlighting the performance improvements achieved through Genetic Algorithm-based tuning.

Table:(3). Comparative Analysis of Performance Parameters

Performance parameters	Conventional PID	GA=PID			
		ITAE	IAE	ITSE	ISE
OS%	68.87%	15.64%	19.33%	16.62%	25.25%
Tr	0.275ms	0.312ms	0.306ms	0.310ms	0.456ms
Ts	0.0413s	0.0413s	0.0413s	0.0413s	0.0413s
peak amplitude	32.91V	23.32V	24.06V	23.51V	25.25V
Vo	19.45V	20.13V	20.13V	20.13V	20.13V

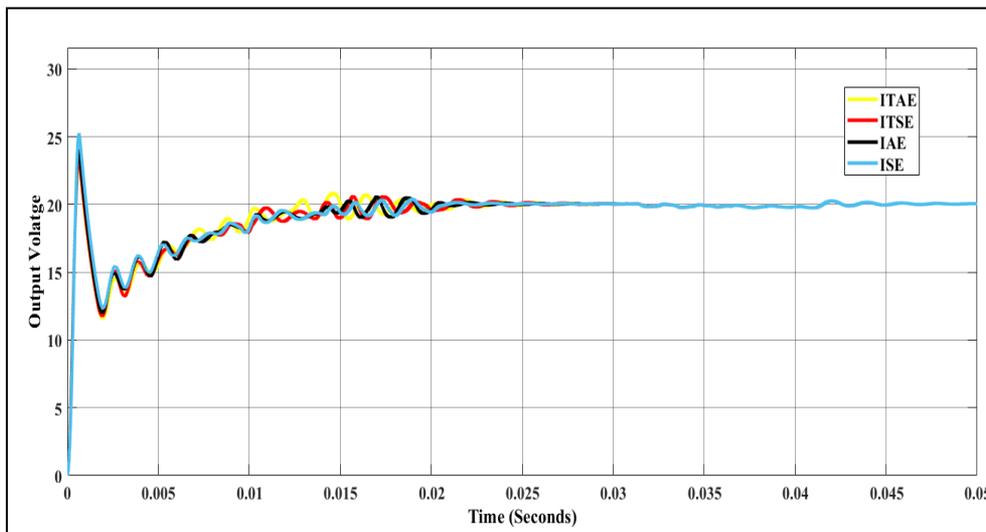


Figure: (8). Comparative analyses of step responses

From the results summarized in the table, it is evident that the GA-optimized PID controller exhibits a marked improvement in performance compared to the conventionally tuned PID controller. Among the evaluated objective functions, the ITAE-based optimization produced the most desirable response, characterized by reduced overshoot, shorter settling time, and improved steady-state accuracy. This enhanced performance is primarily due to the inherent property of the ITAE criterion, which places greater emphasis on errors that persist over time, thereby effectively minimizing long-duration deviations and enhancing overall system stability.

CONCLUSION

The analysis, design, and simulation of the boost converter were successfully carried out using MATLAB/Simulink. This study presented a detailed investigation of the closed-loop stability performance of the boost converter using both a conventional PID controller and a Genetic Algorithm (GA)-optimized PID controller. The system was tested at V_{in} of 12 V, and the corresponding output voltage responses were obtained for various operating conditions. Through extensive simulation, the optimal controller gains were determined for each of the four GA-based performance indices. Among these, the ITAE-based optimization demonstrated the most favorable results, achieving a %OS of 15.64%, a T_r of 0.312 ms, and a T_s of 0.0413 s, outperforming the other performance criteria. The comparative analysis of the step responses confirmed that the GA-based PID controller provides superior dynamic performance and improved stability compared to conventional tuning approaches. Hence, it concluded that the Genetic Algorithm offers a more effective and reliable method for tuning PID controllers in DC–DC boost converters, resulting in enhanced system efficiency and robustness. Future work may focus on extending this approach to real-time (online) implementation, which would further improve adaptability and control precision. Additionally, performance comparisons with other advanced optimization techniques, such as PSO, CS, and GWO, could provide deeper insights into the relative effectiveness of different evolutionary algorithms for converter control applications.

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