Performance evaluation of a GA-tuned PID controller for a buck–boost converter based on integral error metrics

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ABSTRACT

DC–DC buck–boost converters are widely used in photovoltaic (PV) systems to maintain a regulated output voltage under varying source and load conditions. Although genetic algorithms (GA) based proportional–integral–derivative (PID) controllers are commonly used, the influence of different integral error performance indices on controller behavior has not been systematically examined. This paper presents a detailed study of GA-based PID tuning for a buck–boost converter operating in both buck and boost modes. Four integral error metrics—integral absolute error (IAE), integral time absolute error (ITAE), integral square error (ISE), and integral time square error (ITSE)—are employed as fitness functions to obtain optimal controller gains. A detailed MATLAB/Simulink model of the converter working in continuous conduction mode (CCM) is developed to evaluate controller performance under step input, source transients, and load transients. The results demonstrate that the selected error metric significantly affects transient characteristics, including rise time, settling time, overshoot, and steady-state error. Controllers tuned using ITAE and ITSE provide better transient performance compared to IAE and ISE based tuning. The results highlight the critical role of objective function selection in GA based PID optimization and provide practical guidelines for buck–boost converters in PV applications.

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1. INTRODUCTION

With the increasing complexity of modern power electronic systems, there is a notable transition from classical proportional–integral–derivative (PID) tuning methods to intelligent, optimization-based strategies that offer improved adaptability and performance under real-world operating conditions [1]. DC–DC converters play a central role in these systems, enabling the reliable transformation of voltage levels needed to support safe and efficient power delivery across diverse and dynamic conditions [2]. Among various topologies, the buck–boost converter supports both step-up and step-down operation, making it suitable for systems that must regulate output voltage across a wide range of input conditions [3]. This capability is particularly important in renewable energy systems, such as PV arrays, where output voltage is highly sensitive to changes in irradiance, shading, and temperature. In such systems, maximum power point tracking (MPPT) algorithms are typically integrated with DC–DC converters to optimize energy extraction.

The buck–boost converter is frequently employed in MPPT implementations due to its ability to maintain regulated output despite wide variations in the PV panel's operating point [3], [4].

Recent studies have emphasized the need for accurate and responsive control in nonlinear and dynamic systems, where classical tuning methods often fail to meet performance requirements [5]. In power electronic applications, the PID controller remains a commonly used solution due to its structural simplicity, ease of implementation, and suitability for real-time operation [1], [6]. However, conventional tuning techniques such as Ziegler–Nichols and Cohen–Coon often result in high overshoot, longer settling times, and poor disturbance rejection under changing operating conditions [7]–[9]. These challenges become particularly evident in time varying systems like PV-connected DC-DC converters, where input and load variations are frequent and often unpredictable [3].

To address these challenges of conventional PID tuning, many recent studies have turned to metaheuristic optimization techniques, with genetic algorithms (GA) standing out as a flexible and effective alternative. Unlike classical methods, GA can efficiently explore a wide range of possible solutions to identify optimal PID gain values by minimizing time-domain error metrics such as the integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time square error (ITSE) [10]–[12]. GA-based tuning applied to a buck converter achieved a reduction in overshoot to 4.17%, with a settling time of 538 μs [13]. Similarly, an improvement of approximately 32.6% in overshoot, along with a faster rise time, was achieved using GA optimized PID gains [14]. Furthermore, enhanced dynamic response in electrohydraulic systems was obtained by employing GA-based tuning with IAE and ITAE as objective functions [15].

However, the performance of GA optimized PID tuning is affected not only by the optimization process itself, but also by the choice of error criterion. These are typically selected from four integral metrics: IAE, ISE, ITAE, and ITSE. Each of these indices prioritizes a different aspect of dynamic response, with ITAE and ITSE often associated with smoother transients and better damping characteristics. The ITAE criterion has been employed to design a wide-area damping controller, where time-weighted error minimization was shown to effectively enhance damping performance and suppress low-frequency oscillations in power systems [15]. It has been shown that ITSE-based tuning leads to improved damping performance in microgrid frequency regulation [16]. In a related study, a grey wolf optimizer (GWO) tuned using root mean square error (RMSE) achieved superior voltage regulation in a DC–DC boost converter compared to GA and particle swarm optimization (PSO), with fewer transient oscillations during load variations [11]. A GA and PSO-based ITAE optimization were proposed for tuning a FOPID controller in DC motor position control, where GA tuning demonstrated superior transient response compared to PSO [17]. Broader surveys further confirm that metaheuristic tuning strategies enhance both transient response and overall system robustness [9], [18]. Additionally, a detailed comparative analysis of IAE, ISE, ITAE, and ITSE discovered that ITSE delivered the most favorable control response for an active magnetic bearing system, highlighting the critical role of objective function selection in achieving optimum system performance [19].

A systematic and comparative analysis of multiple integral error metrics for a buck–boost converter working in both buck and boost modes under identical conditions has not been thoroughly investigated in the literature. As a result, this limitation reduces the applicability of existing studies to systems that regularly undergo mode transitions. Previous studies [20], [21] have estimated multiple error metrics for buck–boost converters for varying input voltages and load, providing insights into how each metric affects controller performance under dynamic conditions. Even though [22] demonstrates the impact of integral error metrics on PID performance in a GA based converter, the analysis is limited to a buck converter. Despite the demonstrated effectiveness of PID controllers tuned using metaheuristic approaches [23], a comprehensive assessment of their performance across multiple integral error metrics for converters operating in both buck and boost modes remain lacking.

To address this research gap, this paper presents a GA-based PID controller for a buck–boost converter, with a performance evaluation based on four integral error metrics: IAE, ITAE, ISE, and ITSE. The originality of this work lies in the systematic multi-metric comparison under step input, source transient, and varying load conditions for both buck and boost modes. This comparison provides practical insights into error-metric selection for robust controller tuning.

The major contributions of this proposed work are as follows: i) A systematic analysis of the effect of four integral error metrics (IAE, ISE, ITAE, and ITSE) on GA–based PID tuning for a buck–boost converter operating in both buck and boost modes. ii) A comparative evaluation of the resultant controller performance under step input, source voltage transients, and varying load conditions using MATLAB/Simulink simulations.

Section 2 introduces the buck–boost converter design, including the system parameters and component selection. Section 3 describes the tuning process of PID controller using GA, with integral error metrics IAE, ISE, ITAE, and ITSE individually applied as a fitness function. Section 4 evaluates the simulation results under test conditions like step input, source transients, and varying load conditions. Section 5 concludes the work by summarizing the key findings and providing recommendations for selecting suitable error metrics based on control objectives.

2. METHOD

The buck–boost converter used in this study is modelled in continuous conduction mode (CCM), based on ripple-limited design techniques proposed in [2]. The system used in this study works with a switching frequency f_s = 20 kHz. The inductor and capacitor values are chosen to limit the load current ripple (Δi_L) and load voltage ripple (ΔV_O) to under 3% and 1% of their average values, respectively. The converter supplies an output voltage (V_O) of 12 V to three DC loads: an LED tube light (7 W), a DC fan (17 W), and a modem (6 W), totaling 30 W. These loads result in a combined resistive load of R_{eq} = 4.8 Ω. Based on the given power and voltage specifications, the individual load currents are calculated to be approximately 0.583 A for the LED tube light, 1.417 A for the DC fan, and 0.5 A for the modem. Since the loads are connected in parallel, the total current drawn from the converter is around 2.5 A. The equivalent resistance of the combined load is determined to be 4.8 Ω.

In this work, the input voltage is allowed to vary within the range of 7 V to 25 V. The minimum inductance required to maintain a current ripple below 3% across the entire input voltage range is calculated using (1).

$$L = \frac{V_{in}.D}{f.\Delta i_L} \tag{1}$$

Here, D is the duty cycle. For V_{in} = 7 V, the calculated duty cycle is D = 0.632, the inductance is L_1 = 1.0853 mH, while for Vin = 25 V, it is 3.65 mH. Based on these values, an inductance of L_1=3.7 mH is selected for the simulation. Next, the minimum high-frequency output capacitor required to limit the voltage ripple to 1% is calculated using (2).

$$C = \frac{V_O.D}{R.f.\Delta V_O} \tag{2}$$

For V_{in} = 7 V and a maximum allowable voltage ripple of 0.12V, the required capacitance is C_1 = 658.3 µF. Similarly, for V_{in} = 25 V, C_1 is calculated to be 337.5 µF. For simulation, C_1 = 660 µF is selected. The calculated component values are listed in Table 1.

Table 1. The calculated component values of load and converter components

Component/parameter	Value
R_1	20.57 Ω
R_2	8.47 Ω
R_3	24 Ω
Equivalent load R_{eq}	4.8 Ω
Capacitance(C_1)	660 µF
Inductance (L_1)	3.7 mH
Output voltage (V_O)	-12 V (regulated)

2.1. State-space modelling and stability analysis

In the state-space modelling, the capacitor equivalent series resistance (ESR) and inductor DC resistance (DCR) are neglected since their effect at the low crossover frequency is insignificant. DCR would only introduce a small damping term, while ESR produces an LHP zero in the kHz range. Let the state vector be x = $[\,I_L \quad V_C]^T$. The averaged CCM state-space equations are given in (3) and (4).

$$\frac{dx}{dt} = Ax + BV_{in} \tag{3}$$

$$V_o = -V_c \tag{4}$$

Where the system parameter matrix A is (5).

$$A = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ \frac{1-D}{C} & -\frac{1}{R_{eq}C} \end{bmatrix} \tag{5}$$

The input matrix B describes how the input effects the state derivatives.

$$B = \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix} \quad (6)$$

The characteristic polynomial is described by (7).

$$LCs^2 + \frac{L}{R_{eq}}s + (1 - D)^2 = 0 \quad (7)$$

Thus, the natural frequency and damping ratio are (8).

$$w_n = \frac{1-D}{\sqrt{LC}} \quad (8)$$

$$\zeta = \frac{\sqrt{L}}{2R_{eq}(1-D)\sqrt{C}} \quad (9)$$

The poles are located at (10).

$$s = -\zeta w_n \pm j w_n \sqrt{1 - \zeta^2} \quad (10)$$

The duty cycle-to-output small-signal transfer function is defined by (11).

$$G_{vd}(s) = -\frac{V_{in}}{R_{eq}} \frac{1 - \frac{s}{w_Z}}{LCs^2 + \frac{L}{R_{eq}}s + (1-D)^2} \quad (11)$$

This expression incorporates the RHP zero angular frequency, defined as (12).

$$w_{z,RHP} = \frac{(1-D)^2 R_{eq}}{L} \quad (12)$$

The RHP zero produces an inverse initial response and enforces a conservative crossover frequency. Its location shifts outward with increasing V_{in}, but the most restrictive case occurs at V_{in} = 7 V, where $f_{z,RHP} \approx 28$ Hz, setting the global bandwidth limit. In the proposed GA-based tuning framework, as candidates attempting excessive crossover frequencies generate large error integrals in simulation, they are consequently discarded during the evolutionary search. For all input conditions in the 7 to 25 V range, the linearized poles remain in the left half-plane, confirming that the averaged CCM model is internally stable.

The controller used is a classical PID structure whose parameters are optimized using GA. The optimization is implemented in MATLAB/Simulink using the Simulink model, optimization toolbox, and MATLAB programming. This structure follows the tuning framework presented in [13], [19], where each of the four integral error metrics—IAE, ITAE, ISE, and ITSE—is used as an independent fitness function. The GA searches the parameter space to minimize the selected cost function and return optimal PID gains for each case.

The converter's response is evaluated under three conditions: i) step response operation, ii) source voltage transients, and iii) dynamic load changes. Input voltage steps and resistive load switching are introduced to test dynamic performance. This evaluation methodology is consistent with those used in [11], [22]. Performance metrics such as rise time, settling time, overshoot, and steady-state error are recorded for each error metric and operation mode (buck and boost).

The PID controller regulates the converter by changing the duty cycle to minimize the error between the output and reference voltage [23]. The control law is expressed in (13).

$$u(t) = K_p e(t) + K_i \int e(t) + K_d \frac{de(t)}{dt} \quad (13)$$

The PID controller comprises of three parameters: proportional gain (K_P), integral gain (K_I), and derivative gain (K_D). These parameters are tuned to minimize the error signal e(t), which is defined as the difference between the output voltage V_{out} and the reference voltage V_{ref} of the system.

3. GA-BASED PID OPTIMIZATION METHOD

The PID controller parameters KP, Ki, and KD are optimized using a GA, where the fitness function is defined by an integral error-based performance metric. Optimization techniques typically employ data-driven modelling and cost function minimization strategies to effectively tune the controller parameters [24], [25]. These methods rely on performance indices, referred to as cost or objective functions, which are minimized to achieve the desired dynamic response of the system.

In this study, four objective functions are utilized to guide the GA-based PID tuning. The mathematical expressions of these performance indices are provided in (14)–(17). IAE represents the accumulated magnitude of the output error over the observation period [26]. It provides a balanced measure of total deviation without differentiating whether the error is positive or negative.

$$IAE = \int_0^T |e(t)|\, dt \tag{14}$$

ISE sums the squared error, thereby assigning greater weight to large deviations.

$$ISE = \int_0^T e^2(t)\, dt \tag{15}$$

ITAE incorporates a time weighting into the absolute error. This formulation penalizes errors that persist for longer durations, thereby encouraging quicker error elimination and shorter settling times.

$$ITAE = \int_0^T t \cdot |e(t)|\, dt \tag{16}$$

ITSE combines time weighting with squared error emphasis, making it particularly effective at suppressing prolonged, large-magnitude deviations and improving damping performance.

$$ITSE = \int_0^T t \cdot e^2(t)\, dt \tag{17}$$

Each of these error metrics serves as an independent fitness function for the GA, with the tuning process executed separately for each. The resulting controller parameters are then evaluated based on system performance under various transient conditions. In summary, IAE offers an overall measure of accuracy, ISE focuses on minimizing peak deviations, ITAE promotes rapid convergence, and ITSE enhances stability by reducing overshoot and oscillations.

The PID controller gains were optimized using a GA implemented in MATLAB R2018b with Simulink on a system with an Intel® Core™ i3-10110U, 8 GB RAM, 256 GB SSD. The GA targeted the minimization of one of four performance indices—IAE, ISE, ITAE, or ITSE—employing a population size of 50, PID gains constrained between [0,0,0] and [5,10,5], roulette-wheel selection, arithmetic crossover, and adaptive feasible mutation. Each candidate solution was simulated in the model for T_{stop} = 2 s using the variable-step stiff solver ode23tb with a relative tolerance of 1×10^{-4}, suitable for stiff converter dynamics. The fitness function was computed using the trapezoidal rule, with a penalty of 10^6 for invalid or excessively large values (10^3). The GA stopped after 40 generations or when the improvement in best fitness between successive generations fell below 10^{-6}. Total optimization runtimes ranged from 82 min to 94 min, depending on the objective function. The parameters used for the GA are listed in Table 2.

Figure 1 describes the process of generating PID controller gains using a genetic algorithm. The GA algorithm evaluates each set of gains through simulation and updates them based on the selected performance metric. The pseudocode for PID tuning using IAE minimization is presented in Algorithm 1. Identical procedures were implemented for the remaining three performance metrics, with each fitness function modified accordingly. These four independent GA-based tuning runs produced distinct PID gain sets tailored to their respective error criteria, enabling a comprehensive comparative analysis of control performance across all metrics.

Table 2. GA parameters used for PID tuning process

Parameter	Value/description
Search bounds	Lower: [0, 0, 0], Upper: [5, 10, 5]
Population size	50
Number of generations	40
Crossover probability	0.8
Mutation probability	0.2
Selection method	Roulette wheel
Crossover method	Arithmetic
Mutation strategy	Adaptive feasible
Fitness functions	IAE, ISE, ITAE, ITSE (evaluated separately)

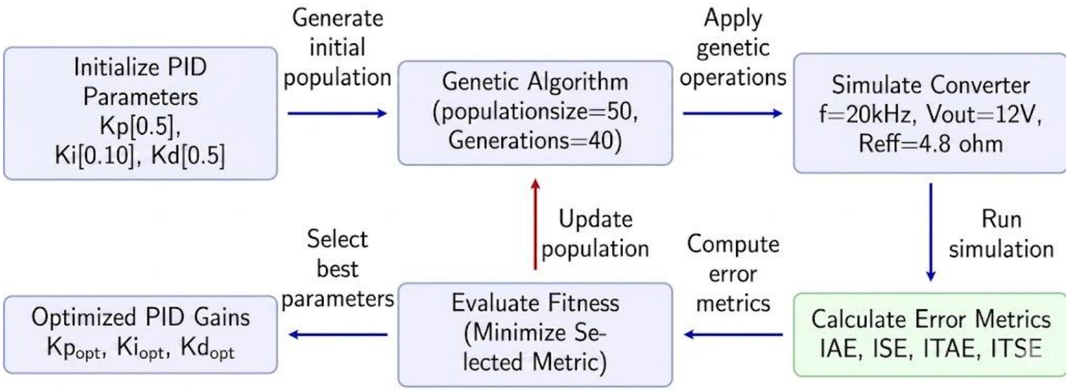


Figure 1. The process for generating optimized PID gains

Algorithm 1: GA-based PID tuning with IAE metric
Input:
  Simulink model: model _pid_iae
  Simulation stop time: T_stop = 2 s
Output:
  Optimized PID gains: [Kp_opt, Ki_opt, Kd_opt]
1: Initialize:
    lb ← [0, 0, 0]
    ub ← [5, 10, 5]
    GA_opts←{PopulationSize=50,Generations=40,Selection=roulette,Crossover=arithmetic(0.8),Mutation = adaptive}
2: Define iae_fitness(x):
    Kp, Ki, Kd ← x[1:3]
    assign gains to workspace
    try: simulate model for T_stop
      err(t) ← error signal
      iae ← ∫|err(t)| dt via trapz
      if iae is invalid or >1e^3: iae ← 1e^6
    catch: iae ← 1e^6
    return iae
3: [x_opt, fval] ← ga(@iae_fitness, 3, lb, ub, GA_opts)
4: Kp_opt, Ki_opt, Kd_opt ← x_opt[1:3]
   Min_IAE ← fval
5: Display Kp_opt, Ki_opt, Kd_opt, and Min_IAE

The PID controller parameters obtained from the tuning process are presented in Table 3. The PID gains vary depending on the selected error metric. This variation highlights how each criterion influences controller behavior in distinct ways.

Table 3. The optimized PID gains for various integral error performance metrics

Controller parameters	IAE	ISE	ITAE	ITSE
K_P	0.00912	0.00917	0.00805	0.00988
K_I	9.9808	9.9210	9.5073	9.9965
K_D	2.615×10^{-5}	5.892×10^{-5}	1.960×10^{-6}	5.455×10^{-5}
Optimized metric value	0.0512	0.09244	0.001338	0.0005043

The ITAE-tuned controller produced the smallest derivative gain, indicating a preference for gradual corrections and less sensitivity to fast transients. This reflects the findings of [11], [13], where ITAE-based tuning improved system stability, reduced voltage ripple, and enabled faster settling in converter setups. The proportional and integral gains remain relatively close across all four metrics. This may be a result of the converter's dynamic characteristics or the GA's search constraints, which could have confined the optimization to a narrow but effective region of the parameter space. The ISE-based controller showed the highest cost value, supporting the observation in [22] that squaring the error tends to amplify early deviations, often leading to increased overshoot and slower response. In contrast, the ITSE-based tuning provided a more balanced response, with moderate gain values and strong damping characteristics, consistent with the results presented in [16]. Therefore, the selection of an error metric has to be made depending on the specific dynamic goals of the system.

4. RESULTS AND DISCUSSION

The proposed system is modelled in MATLAB/Simulink as a closed-loop buck–boost converter controlled by a PID controller, whose gains are adjusted using a genetic algorithm. GA-based optimization was carried out separately for each performance index—IAE, ISE, ITAE, and ITSE—yielding four distinct sets of PID gains. The converter's dynamic response was evaluated under abrupt changes in input voltage and load, allowing assessment of key transient parameters such as rise time, overshoot, settling time, and steady-state error. This approach enables a clear comparison of how each error metric affects controller performance, highlighting the adaptability of GA-tuned PID control for varying design objectives. Figure 2 shows the model of the proposed system.

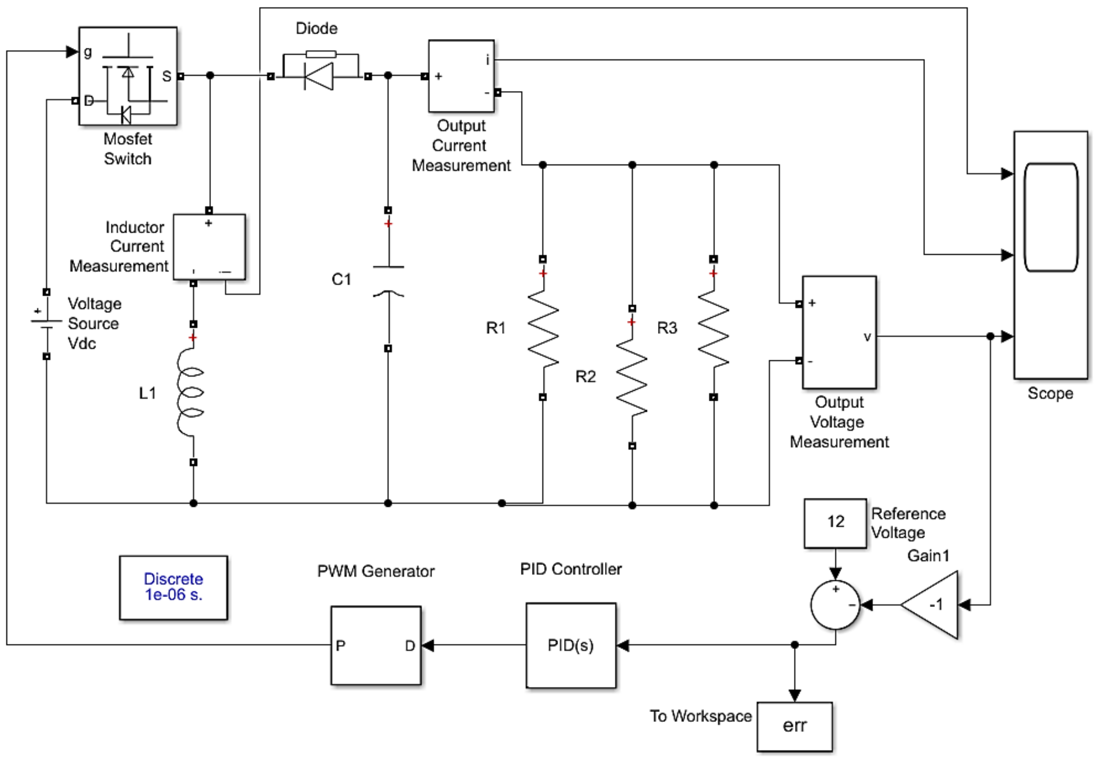


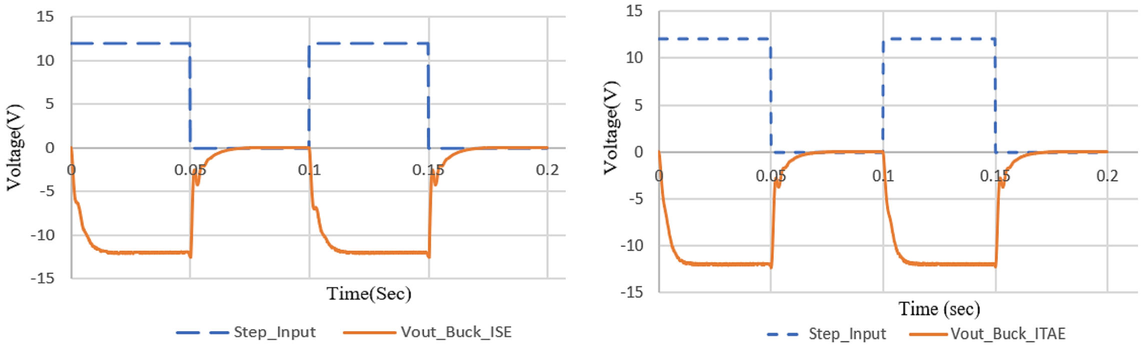
Figure 2. Simulink model of the proposed GA tuned PID controlled buck–boost converter

4.1. Step response

The step response evaluation is done by applying a square waveform reference that alternated between 0 V and 12 V at 0.05-second intervals. The error signal is estimated by subtracting the converter's output voltage from this reference and applied to the PID controller. For each performance metric, the optimized PID gains are applied in closed-loop simulations under both buck and boost modes.

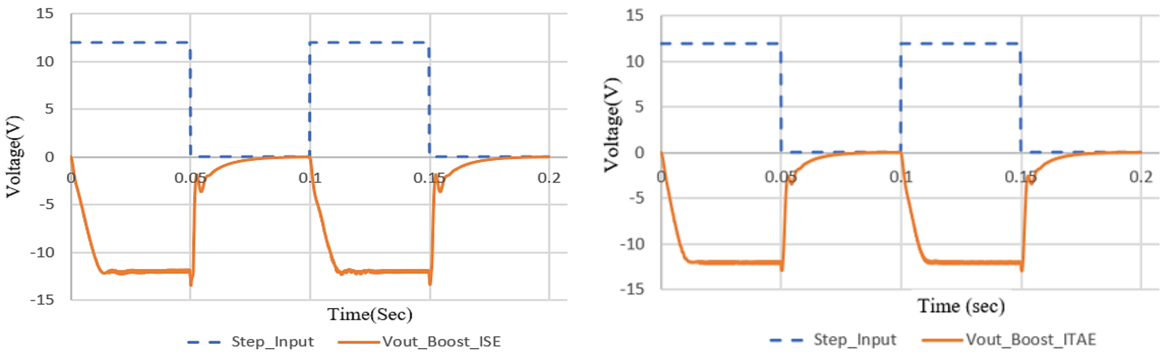
The ITAE-based controller delivered the fastest rise time, minimal steady state error (SSE), and shortest settling duration, while the ITSE-based controller achieved the lowest overshoot with well-damped and stable output behavior. These findings are supported by [27]-[29], which confirm that ITAE and ITSE optimization consistently yields superior transient and steady-state performance in PID controller designs for buck converters. The IAE-tuned controller produced moderate performance, whereas the ISE-based controller showed delayed response and higher overshoot. ITAE's advantage in dynamic response is supported by [11], [30], while ITSE's effectiveness in reducing overshoot and enhancing damping aligns with observations in [16]. The relatively weaker performance of ISE reflects result in [22], highlighting its sensitivity to initial transients. The observed behavior under buck mode operation is depicted in Figure 3, comparing the ISE-tuned controller (worst case) with the ITAE-tuned controller (best case).

Figure 4 presents the boost mode response by comparing the ISE-tuned controller, which represents the worst case, with the ITAE-tuned controller, which represents the best case. Similar to the buck mode, the ITAE-based controller provided the shortest settling time, lowest SSE, and fastest response. Meanwhile, the ITSE-based controller produced the smallest overshoot and a well-damped output.



(a) (b)

Figure 3. The step response for (a) ISE and (b) ITAE under buck mode



(a) (b)

Figure 4. The step response for (a) ISE and (b) ITAE under boost mode

4.2. Source transient analysis

In buck mode, the converter is subjected to a sequence of four input voltage transients to assess its dynamic behavior. The input starts at 20 V, increases to 24 V at t = 0.05 s, then drops to 19 V at t = 0.10 s, and finally decreases further to 15 V at t = 0.15 s. The total simulation time is set to 0.20 s, allowing for a detailed evaluation of the system's transient response under rapid source variations. The transient performance metrics for each case are given in Table 4 for direct comparison.

In buck mode, the ITAE-based PID controller provided the most effective transient performance among the four-performance metrics. It achieved the fastest rise time (0.00741 s), shortest settling time (0.00694 s), and lowest steady-state error (0.577%), while maintaining a moderate overshoot of 16.6%. These results align with earlier findings by [11], [13], where ITAE-based tuning was shown to reduce overshoot and settling time in buck and boost converters. Although the ITSE-tuned controller achieved the lowest overshoot (15.53%), it resulted in slightly higher SSE (0.602%) and longer settling time (0.00928 s), reflecting the damping-prioritizing behavior discussed in [16]. The IAE-based controller offered moderate performance but did not outperform ITAE in any key parameter. In contrast, the ISE-tuned controller recorded the highest overshoot (17.46%), greatest SSE (0.605%), and longest settling time (0.00966 s), confirming observations from [22], which showed that ISE tends to amplify early transients and prolong convergence.

In boost mode, the system was subjected to a sequence of input voltage changes over a 0.2-second duration, with variations from 10 V to 8 V, 10.5 V, and finally to 7.5 V. Under these conditions, the ITAE-based controller again demonstrated superior dynamic behavior, showing the smallest rise time (0.00920 s), lowest SSE (0.845%), and shortest settling time (0.01694 s). The ITSE-based controller exhibited the lowest overshoot (18.80%) and smoother damping, but its settling time (0.02136 s) was longer than ITAE's, mirroring its behavior in buck mode. The ISE-tuned controller performed the worst across all parameters with highest overshoot (19.44%), largest SSE (0.882%), and slowest rise time (0.01004 s) confirming the limitations discussed in [22]. The IAE-based controller again fell between ISE and ITAE in performance. These results confirm that time-weighted integral metrics, especially ITAE and ITSE, offer more balanced and responsive control behavior for buck–boost converters operating under dynamic input conditions, consistent with insights from [11], [13], [16], [27]-[29].

Table 4. The performance under source transients

Controller mode	Performance metric	Rise time (sec)	Overshoot %	SSE %	Settling time (s)
Buck	IAE	0.00766	16.20	0.590	0.00741
	ISE	0.00812	17.46	0.605	0.00966
	ITAE	0.00741	16.6	0.577	0.00694
	ITSE	0.00804	15.53	0.602	0.00928
Boost	IAE	0.00936	19.09	0.861	0.01918
	ISE	0.01004	19.44	0.882	0.02197
	ITAE	0.00920	18.81	0.845	0.01694
	ITSE	0.00995	18.80	0.855	0.02136

4.3. Load transient analysis

The transient performance of the GA-tuned PID controller is evaluated under dynamic load conditions for both buck and boost operating modes. In the buck mode, the input DC voltage is set to 20 V. A time-varying resistive load is applied to the system, where resistors of 4.5 Ω, 4 Ω, 5 Ω, and 6 Ω are connected at time instants 0 s, 0.05 s, 0.1 s, and 0.15 s, respectively, as described in Table 5, to evaluate the controller's performance under varying load conditions.

Table 5. The performance under load transients

Controller mode	Performance metric	Rise time (sec)	Overshoot %	SSE %	Settling time (s)
Buck	IAE	0.00768	5.11	0.583	0.00614
	ISE	0.00815	5.24	0.593	0.00752
	ITAE	0.00742	5.19	0.577	0.00464
	ITSE	0.00790	5.01	0.585	0.00562
Boost	IAE	0.00992	17.89	0.793	0.02764
	ISE	0.01054	20.11	0.865	0.03092
	ITAE	0.00964	17.96	0.756	0.02580
	ITSE	0.01019	17.32	0.817	0.02399

In the buck mode, the PID controller tuned using the ITAE criterion consistently outperformed others across all key time-domain metrics. It achieved the fastest rise time (0.00742 s), shortest settling time (0.00464 s), and lowest steady-state error (0.577%), with a moderate overshoot of 5.19%. These results are in strong agreement with previous findings [11], [13], which demonstrated the effectiveness of ITAE-based tuning in enhancing transient recovery and minimizing residual error in converter systems.

The ITSE-tuned controller delivered the lowest overshoot (5.01%) in buck mode, with marginally higher settling time, indicating improved damping characteristics. This outcome is consistent with the damping-oriented behavior noted in [16]. The IAE-based controller offered a well-balanced transient response but did not surpass ITAE or ITSE in any specific performance metric. In contrast, the ISE-based controller recorded the highest overshoot (5.24%) and longest settling time (0.00752 s), supporting prior observations [22] that ISE's quadratic error formulation disproportionately emphasizes initial deviations, often at the expense of transient stability in fast-switching applications.

In boost mode, with resistive load variation between 4.5 Ω and 6 Ω over a 0.2-second simulation window, a similar trend was observed. The ITAE-based controller again yielded the shortest settling time (0.02580 s) and lowest SSE (0.756%), confirming its robustness under dynamic loading. The ITSE controller exhibited the lowest overshoot (17.32%), though with a slightly increased settling time (0.02399 s), reinforcing its ability to suppress oscillations as discussed in [15], [16]. The IAE-based controller delivered moderate, stable performance, whereas the ISE-based controller consistently exhibited the least favorable dynamic behavior, including the highest overshoot (20.11%), largest SSE (0.865%), and the slowest rise time (0.01054 s), aligning with performance degradation trends reported in [11], [22].

These findings are consistent with literature on intelligent control of power converters [1], [2], [13], affirming that time-weighted integral error metrics—particularly ITAE and ITSE—are more effective in managing the nonlinear and time-varying dynamics typical of buck–boost converters. The ITAE metric, defined by the time-multiplied absolute error integral ($\int t \cdot |e(t)| dt$), inherently penalizes sustained deviations, leading to faster convergence and reduced steady-state errors. In contrast, ITSE ($\int t \cdot e^2(t) dt$) minimizes overshoot and enhances damping, making it suitable for applications with oscillation-sensitive load profiles.

Although ISE ($\int e^2(t) dt$) remains widely adopted in traditional control system design, its application in fast-switching DC–DC converters appear limited. The emphasis on squared error amplifies initial transient deviations, resulting in degraded time-domain performance, as also highlighted in [11], [22]. The IAE metric ($\int |e(t)| dt$) provides a compromise between transient responsiveness and stability, delivering smoother control action without excelling in rise time or overshoot minimization. This is consistent with findings in [9], [11], which support IAE's suitability for systems requiring conservative, non-aggressive control behavior.

These findings are consistent with literature on intelligent control of power converters [1], [2], [13], reaffirming the effectiveness of time-weighted error metrics—particularly ITAE and ITSE—in enhancing dynamic behavior under non-linear and time-varying conditions. ITAE's emphasis on penalizing prolonged deviations accelerates convergence and improves steady-state accuracy, while ITSE enhances damping by minimizing overshoot and oscillatory effects. On the other hand, ISE's sensitivity to large initial errors limits its suitability for high-speed converter systems, despite its historical prevalence in conventional control. The IAE criterion remains a practical middle ground, offering smoother transitions without aggressive tuning. Overall, the results underscore the need for context-aware objective function selection, particularly in fast-switching applications where dynamic disturbance rejection is critical to ensuring stable converter performance.

5. CONCLUSION

This work carried out a systematic comparison of GA tuned PID controllers for a DC-DC buck-boost converter, using four commonly used integral error criteria - IAE, ITAE, ISE, and ITSE. The analysis was performed on the same converter while operating in both buck and boost modes, and its behavior was studied under step input, input voltage variations, and load changes. The results show that closed-loop performance is strongly dependent on the selected error metric. The PID controller tuned using the ITAE criterion achieved the fastest dynamic response, with source-transient settling times of 0.00694 s in buck mode and 0.01694 s in boost mode, while maintaining lower steady-state error compared to the other three metrics. By comparison, ITSE-based tuning resulted in the smallest overshoot of 15.53% in buck mode and 18.8% in boost mode, indicating better damping behavior during transient conditions. The controller optimized using the ISE criterion showed the weakest performance, with overshoot reaching 20.11% during boost-mode load transients and comparatively longer settling times. The IAE-based controller provided a more conservative response, offering stable operation but without notable advantages in either response speed or damping. Similar performance characteristics were also observed under load transient conditions.

While the general advantages of ITAE and ITSE have been described in broader control-system studies, this work adds practical insight by clearly distinguishing their influence within a single buck–boost converter under both buck and boost modes. The findings show that ITAE is more suitable when fast voltage recovery and minimal steady-state deviation are required, whereas ITSE is preferable when overshoot suppression and damping are the primary objectives. These differences are noticeable during boost-mode operation and under load variations, providing useful guidance for objective-function selection in GA-based PID tuning of non-minimum-phase converters.

It is important to note that this study is limited to simulation-based analysis using an averaged CCM model. Practical non-idealities, including switching losses, parasitic elements, and digital implementation constraints are not considered in the present work. Therefore, experimental validation, along with further study into hybrid or multi-objective optimization approaches that combine complementary error metrics, represents an important direction for future research to enhance buck–boost converter performance.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mahabaleshwara Bhat P.		✓	✓	✓	✓	✓	✓	✓	✓	✓				
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, [SB], on request.

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