IMPLEMENTATION OF BIO-INSPIRED ALGORITHMS IN DESIGNING OPTIMIZED PID CONTROLLER FOR DC-DC CONVERTERS FOR ENHANCED PERFORMANCE

by

Md. Rafid Kaysar Shagor (160021029)
Sayka Afreen Mim (160021039)
Hafsa Akter (160021043)

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CERTIFICATE OF APPROVAL

The thesis titled "Implementation of Bio-inspired Algorithms in Designing Optimized PID controller for DC-DC Converters for Enhanced Performance" submitted by Md. Rafid Kaysar Shagor (160021029), Sayka Afreen Mim (160021039), and Hafsa Akter (160021043) has been found as satisfactory and accepted as partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical and Electronic Engineering on 10th March, 2021.

Approved by:

(Signature of the Supervisor)
Dr. Md. Ashraful Hoque
Professor
Department of Electrical and Electronic Engineering
Islamic University of Technology

(Signature of the Co-Supervisor)
Fahim Faisal
Assistant Professor
Department of Electrical and Electronic Engineering
Islamic University of Technology

(Signature of the Co-Supervisor)
Mirza Muntasir Nishat
Lecturer
Department of Electrical and Electronic Engineering
Islamic University of Technology

DECLARATION OF CANDIDATES

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for award of any degree or diploma.

(Signature of Candidate)
Md. Rafid Kaysar Shagor
Student ID: 160021029

(Signature of Candidate)
Sayka Afreen Mim
Student ID: 160021039

(Signature of Candidate)
Hafsa Akter
Student ID: 160021043

DEDICATION

We would like to dedicate this thesis to our family members for being the support system of our life in every situation. They always have been our source of inspiration. They encouraged us to move forward and taught us how to choose the right path. Without their motivation, we could never overcome the hurdles of our life. They have given us the protection, guidance, and strength to fight against tough situations. Their affection towards us is the main power of our success.

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ABSTRACT

This thesis represents an investigative analysis on the closed-loop stability of the Cuk converter and Zeta converter by implementing Bio-Inspired Algorithms (BIA) for designing an optimized PID controller. The applicability and compatibility of four bio-inspired algorithms such as Firefly Algorithm (FA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Genetic Algorithm (GA) are analyzed in optimizing the control mechanism of the power converters. The improvement of performance parameters is observed and the outcomes are compared with the help of various fitness functions. The thesis emphasizes two higher-order power converters (fourth-order) and the advantages of higher-order converters lie in terms of further lowering ripple currents, simplifying Electromagnetic Compatibility (EMC) filtering, and avoiding current spikes due to resistive losses. The converters are designed through the State Space Averaging (SSA) technique for providing a promising feedback control fashion and evaluating the transfer functions. Bio-Inspired Algorithm (BIA) is an artificial intelligence-based optimization tool catering to non-linear problems. The mentioned BIAs are based on swarm intelligence, functioning according to the custom followed by swarm creatures. Swarm intelligence guarantees better exploitation of data which concentrates the search method within the vicinities of optimal solutions and simultaneously assists the procedure to escape from the confinement of the local minima materializing successful exploration of the search space. Hence, the algorithms are evaluated for better performances in the system through different fitness functions (IAE, ITAE, ISE, and ITSE) and performance parameters like percentage of overshoot, rise time, settling time, and peak amplitude. MATLAB is used to carry out the simulations for both converters. After analyzing the performances for the case of the Cuk converter, it is observed that the percentage of overshoot FA-PID (IAE) provides a lower value than PSO-PID, GA-PID, and ABC-PID for each of the error functions. For rise time and settling time, the values of ABC-PID (IAE) are better but overshoot is high. Then comparing among the BIA-based PID controller for Zeta converter, we obtained that FA-PID (ISE) is the most optimized controller where the value of overshoot is minimum. Moreover, the rise time and settling time for the Zeta converter also have the lowest value for FA-PID (ISE) than other optimized controllers. Hence, better optimization was provided for both converters in this investigative study by the FA-based PID controller.

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LIST OF ACRONYMS

Abbreviated Form	Description
DC	Direct Current
FET	Field-Effect Transistor
BJT	Bipolar Junction Transistor
SCR	Silicon Controlled Rectifier
PWM	Pulse Width Modulation
SSA	State Space Averaging
PID	Proportional Integral Derivative
BIA	Bio-Inspired Algorithm
PSO	Particle Swarm Optimization
FA	Firefly Algorithm
GA	Genetic Algorithm
ABC	Artificial Bee Colony
SI	Swarm Intelligence
ACO	Ant Colony Optimization
THD	Total Harmonic Distortion
MPPT	Maximum Power Point Tracking
GMPP	Global Maximum Power Point
LMPP	Local Maximum Power Point
MPP	Maximum Power Point
PI	Proportional Integral
ITSE	Integral Time Square Error
ITAE	Integral Time Absolute Error
IAE	Integral Absolute error
ISE	Integral Sum Error
MCN	Maximum Number of Cycles
DCM	Discontinuous Conduction Mode
CCM	Continuous Conduction Mode
SMPS	Switch Mode Power Supplies
EMI	Electromagnet Interference

CHAPTER 1

INTRODUCTION

DC-DC power converters have been applied in power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, as well as dc motor drives. They are being utilized in battery-operated portable electronic systems as they have the attribute of manipulating output voltage at a low charge point [1]. However, these devices show nonlinear characteristics because of the operations of the switches; manifesting peak overshoot, larger ripples in output voltage, and instability [2]. This thesis work attempts to diminish the mentioned issues and provide better control over the converter system to make their applications the utmost effective. Thus, Bio-Inspired Algorithms were infused with the PID controller in an investigative approach to enhance the controller performance and deliver optimized system output with stable performance parameters.

1.1 Historical Background

Power electronics is a unification of control systems, power systems, and electronics. The domain of power electronics deals with processing and regulating electrical energy to enhance its suitability for providing the load. It was introduced in the year of 1902 by the usage of mercury arc rectifier invented by Peter Cooper Hewitt [3]. With the advancements in technology, the concepts of Field-Effect Transistor (FET) and Bipolar Junction Transistor (BJT) were proposed. Moreover, powerful semiconductor diodes and silicon-controlled rectifiers (SCR) were introduced which greatly increased the range of power electronics applications. By the 1960s, the enhanced speed of switching of bipolar junction transistors permitted high-frequency DC-DC converters [4].

The revolutionary improvement of the control over electrical energy was acquitted by introducing DC-DC power converters being capable of delivering a regulated and steady DC power supply. The switching power converters and the progress achieved on them made it possible to enhance the performance and to improve the thermal temperaments, while simultaneously minimizing the dimension, weight, and price of power supplies. Switching converters also portray an added advantage of reduced power loss. Such converters exercise the conventional Pulse Width Modulation (PWM) control method to manipulate the quantity of energy transitioned from input to output by a changeable pulse width with a fixed time duration [5]. Among the DC-DC converters, traditional Buck, Boost, Buck-Boost belong to lower-order converters, and Ćuk, SEPIC, Zeta are the higher-order converters.

Our thesis work employs the Cuk converter and the Zeta converter to produce a stable output with promising performance parameters which meet the demands. The Cuk converter was invented by Slobodan Ćuk and was also named after him. It is a fourth-order non-linear system that is essentially a boost converter cascaded to an inverted buck converter. It can convert an input voltage into a regulated, inverted output voltage higher or lower than the former relying on the duty cycle tuned by the PWM technique. The Zeta converter, on the other hand is known as the inverse SEPIC converter with an added advantage of positive input and output polarities over the original SEPIC converter. The Zeta converter is also a non-linear system which is essentially a Buck converter cascaded with a Boost converter. This converter also applies the PWM control method and relatively has more stability than the other converter topologies [5]. The Cuk converter and the Zeta converter deployed in this thesis work are designed and analyzed by the State Space Averaging (SSA) method which was developed by R. D. Middlebrook [3].

To revise the steady-state and transient responses of the power converter, a control mechanism called Proportional Integral Derivative (PID) was utilized. The PID controller uses a control loop to maintain the stability of the system by adapting the proportional, integral, and derivative gains. The concept of this controller was introduced in the 1900s and the first PID-like device was developed by Elmer Sperry in 1911 [6]. The theoretical investigation of the PID controller was reported by Nicolas Minorsky in 1922. The tuning method used in this research work is the Ziegler Nichols tuning method. But such a tuning method has limitations and often fails to provide the optimum regulation. This control method is also heavily based on the trial and error method which consumes an enormous amount of time to provide the controller gains making the system less effective [7].

To refine the regulation over the PID controller for optimizing the output of the Cuk converter, Bio-Inspired Algorithms (BIA) namely Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Genetic Algorithm (GA), and Artificial Bee Colony (ABC) are implemented. BIA is associated with artificial intelligence and machine learning. These intelligent computational techniques are metaheuristic, stochastic, and inspired by biology. One of the sectors of biology that models the search techniques is the social etiquettes of swarm animals, also known as swarm intelligence (SI). The origin of bio-inspired computation and SI stretches half a century back with the introduction of evolutionary search methods in 1960 and genetic algorithm (GA) in 1970. In the 1990s, the bio-inspired computing technique became quite popular among researchers for its adaptive nature and abilities to provide optimized outcomes, and advancements were made on it [8]. Among such techniques, the bio-inspired algorithm named Ant Colony Optimization (ACO) was first explained by Marco Dorigo in his Ph.D. thesis in the year 1992. Later, in 1995, Particle Swarm Optimization (PSO) was introduced by J. Kennedy and R. Eberhart which enabled the swarm intelligence driven bio-inspired algorithms to be explored, investigated, improved, and applied for optimization purposes. In 2005, artificial bee colony (ABC) was formulated by D. Karaboga and in 2008, Xin-She Yang came forward with the Firefly Algorithm (FA).

1.2 Literature Review

There are an innumerable amount of implementations of the BIAs to optimize different types of systems and a substantial amount of literature exists on such work. In the paper by

Arora et al. (2020), a hybrid renewable energy system was optimized by using the PSO algorithm on a PID controller where voltage THD was reduced from 5.13% (with traditional PID) to 1.95 % (with PSO-PID), and the current THD was reduced from 9.80% (with traditional PID) to 0.12 % (with PSO-PID) [9]. Efendi et al. (2017) displayed the optimization of an MPPT Sepic converter by using Modified PSO (MPSO) to locate the GMPP without getting trapped in the LMPP for partially shaded conditions with an accuracy larger than 95% and a rapid time convergence from about 0.5 to 1 second to obtain an MPP [10].

In the work of Yaqoob et al. (2014), a PID controller-regulated Buck converter was optimized by applying the PSO algorithm which provided improved transient responses through the performance criterion PSO-ITSE [11]. Likewise, Ragavendra et al. (2014) optimized the Cuk converter feeding DC motor by employing the Artificial Bee Colony (ABC) algorithm with the PI controller and delivered increasing efficiencies from 93% to 97.5% for corresponding rising input voltages [12]. Furthermore, the enhanced performance of the Buck converter, regulated by the Genetic Algorithm (GA) operated PID controller, was presented in the paper of Nishat et al. (2020) with stable and improved percentage overshoot, settling time, and rise time [13]. All this research work helped researchers and non-experts to comprehend the sector of intelligent search algorithms and exercise them accordingly.

1.3 Problem Statement

The Cuk converter is a widely used power converter in power systems. But regulation of such converters becomes challenging due to its non-linear characteristics, ripple currents, variable input voltages, variable loads, etc. Furthermore, the elevated ripple currents create high temperature making the converter less operative. Moreover, the emergence of resonances has to be checked which might be generated due to the reactive elements used in the circuit and hence the PWM control system needs to be modeled very cautiously. Using a PID controller in such cases delivers better regulation and stability but at the cost of time and lower efficiency. Thus procuring the suitable controller gains is accomplished by applying intelligent search algorithms which induces learning abilities to assess the problem and adapt the controller accordingly. The BIAs implemented in this thesis work exercises SI which uses population, memory, competition, and cooperative interaction to find better results. Engaging PSO, FA, GA, and ABC with the PID controller to optimize the converter system makes the overall system more secure, stable, and competent.

1.4 Thesis Objectives

The objectives of this thesis work are pointed out as follows:

- Investigation of stability through regulating the output voltage of the Cuk power converter to the desired level.
- Observing the performance of Proportional Integral Derivative (PID) in controlling the steady-state and transient responses of the closed-loop feedback system.

- Analyzing the applicability and compatibility of Bio-Inspired Algorithms (BIA) such as Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Genetic Algorithm (GA), and Artificial Bee Colony (ABC) in optimizing the control mechanism of the power converter.

1.5 Limitation of the Study

This thesis work was simulated for an ideal case of the Cuk converter with unchanging load and constant input voltage. All the simulations were done in MATLAB software. But real-life applications will have more complex and demanding environments which will influence the output of the system. Therefore, the control system programmed for this case might not hold for more challenging situations. Additionally, the hardware implementations introduce some unavoidable errors and might reduce efficiencies. To maintain the optimization level, the algorithms need to be modified accordingly to suit the imposed issues.

CHAPTER 2

DC-DC CONVERTERS

The requirement of constant voltage in various appliances exhibits the need of dc power supply. The sources of dc supply such as – solar cells, batteries, and thermocouples are the main input element in dc conversion. DC-DC converters are the electromechanical devices operating in a process of conversion which takes a dc input voltage and converts the supply voltage to a lower or higher value. So, they are known as switching-regulators [14]. Being a high-frequency power electronics circuit, a dc-dc power converter is structured with high-frequency switching and inductors, transformers, and capacitors to minimize the switching noise into constant voltages. A closed feedback system ensures regulated voltage on the output side regardless of whether the input voltages and output currents are changing [1].

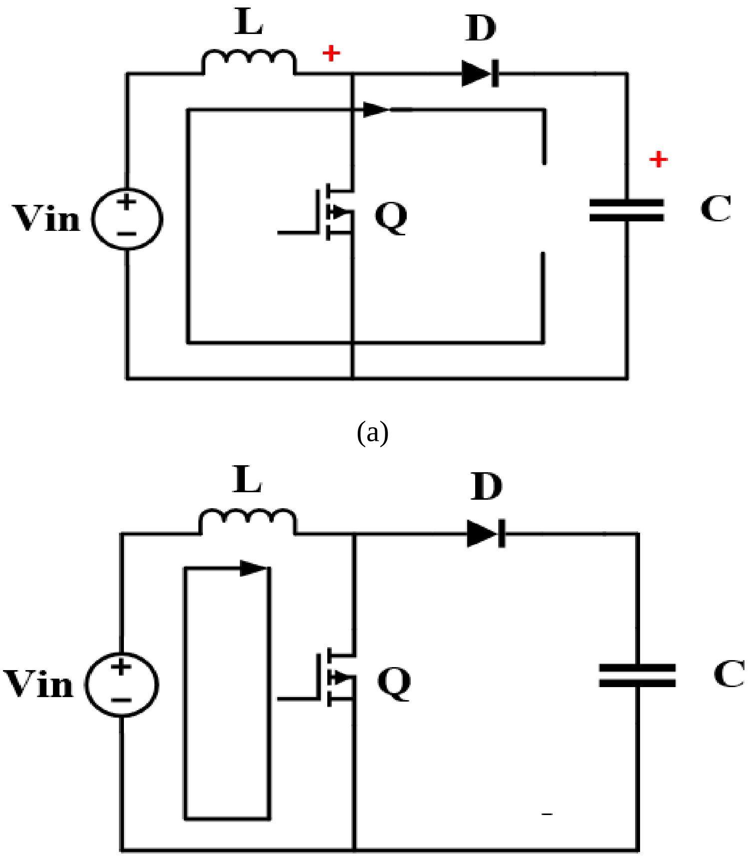
In practical appliances, switched-mode dc-dc converters have gained much popularity. The relevant property of these converters is conserving the input energy and then discharging that energy to the output at a certain voltage. The energy storage elements can be of two types – inductors and transformers as magnetic field storage components and capacitors as electric field storage components. The higher efficiency of these power converters accelerates the cooling procedure and increases battery durability. The improvement in efficiency has been done with the use of power FETs which can switch very efficiently with fewer losses than the bipolar junction transistors. The regulation rating of dc-dc converters signifies the deviation of the output from the input voltage and load current and the voltage rating is the limitation of step-up or step-down voltage transformation [15].

2.1 Operating Principle and Utilizations

A basic circuit configuration of dc-dc converters can be a boost converter that operates in the step-up principle. So, the conversion of low input dc voltage to high output dc voltage is demonstrated through this electronic circuit [16]. Semiconductor switching devices, electrical and electronic components are the main elements in the dc-dc converter. These converters have two operating modes which are named as – 1. Continuous Conduction Mode (CCM) and 2. Discontinuous Conduction Mode (DCM).

A dc-dc boost converter operating in CCM mode is presented in Fig. 2.1(a) which is structured with an inductor, capacitor, switching device, diode, and input voltage source. A pulse width modulator (PWM) is connected to the circuit for controlling the switch. In the ON switching condition, energy will be stored in the inductor which eventually delivers more energy to the output. In the OFF switching state, the current in the inductor is decreased and the magnetic field primarily generated will be low in energy to retain the current to the load [17].

The DCM mode operation of the same dc-dc boost circuit is constructed in Fig 2.1(b). In the ON state condition, energy will be distributed to the inductor for storage purposes while in the OFF state portion, the inductor current will go to zero if this condition stays for some time. The charging and discharging of the capacitor is done in the procedure according to the input voltage [18]. The output voltage in DCM mode is lower than the output voltage in CCM mode.



(a)

(b)

Fig 2.1 Basic DC-DC boost converter in (a) CCM and (b) DCM operating modes.

The utilizations of dc-dc power converters are exhibited in various perspectives. The main reasons for the popularity of dc-dc converters in power electronics applications are - simplification of power supply systems, isolation of primary circuit and secondary circuit, equalization of the loads to the power supply, and the protection system to get rid of the electromagnetic interference (EMI). The use of these converters has spread out to new sectors. Primarily, the usage was confined to power supplies, voltage regulators, and electronic devices. But the development in the dc-dc converters directed the way of applications in renewable energy, automobile, telecommunication, and spacecraft power systems [19, 20].

2.2 Topologies of converter circuit

The linear regulators are replaced by the different types of dc-dc converters because of their low cost, higher efficiency, and compact size. The designing of the dc-dc cascaded converters has gained popularity. But the basic converters are the main power electronics circuit for understanding the switching modes. Depending on the electrical separation between the input and output of a dc-dc converter, two major classifications are found as – Isolated converters and Non-isolated converters. The non- isolated converters are briefly described in this part [21].

2.2.1 Non-isolated converters

A non-isolated power converter can be narrated as a single circuit in which common ground is present between the input and output. The main advantages of these type of converters are written below [22, 23]:

- Non-isolated converters are cost-effective because they do not need transformers for isolation purpose.
- These converters are smaller in size. They have the tendency to operate at higher switching frequencies which diminishes the size of other components.
- The absence of an isolation barrier is beneficial for better transient response and regulation. This increases the efficiency.

The non-isolated converters can be defined differently depending on the conversion procedure and design of the circuit. The basic commonly used non-isolated converters are –

i Buck Converter

ii Boost Converter

iii Buck-Boost Converter

iv SEPIC converter

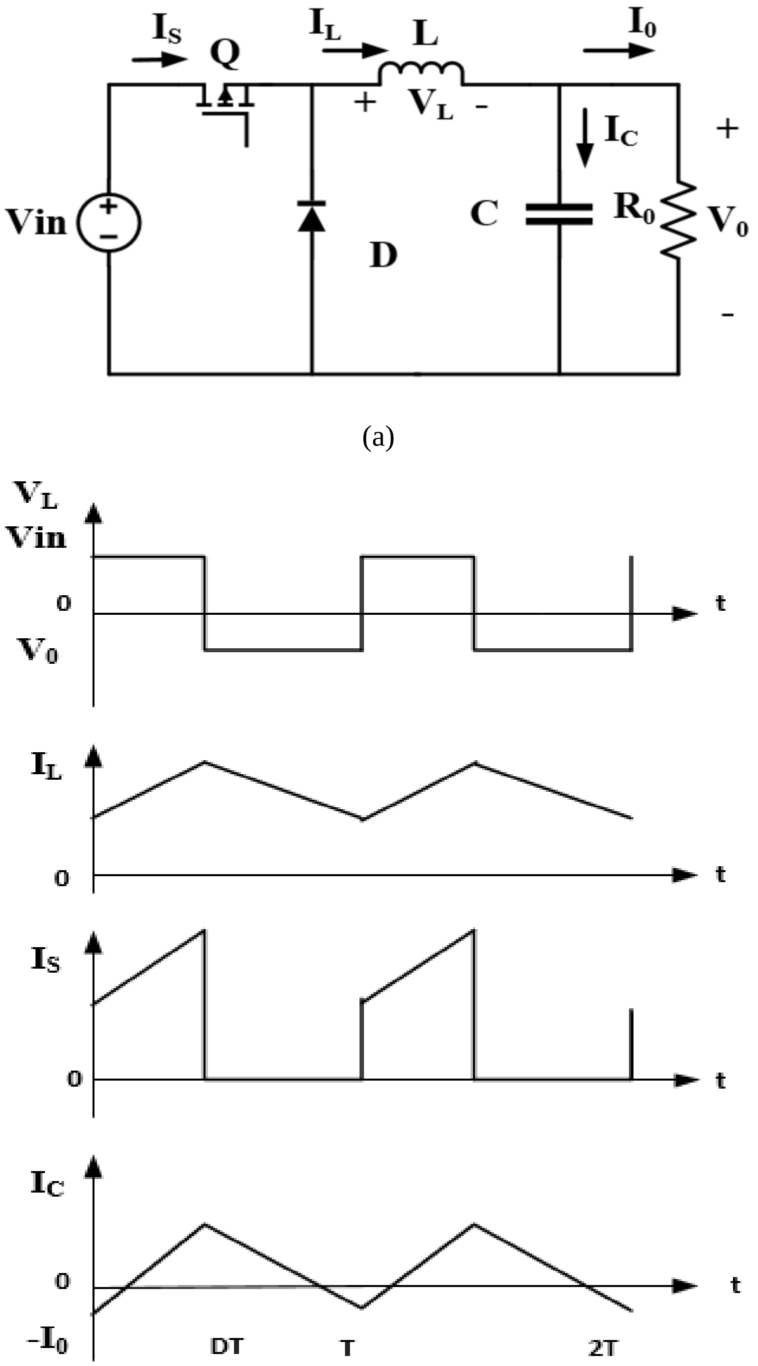
v Cuk Converter

vi Zeta Converter

The three primary converters are described in the following sections. Cuk converter and Zeta converter will be broadly composed later.

2.2.1.1 Buck Converter

The buck converter is the most common step-down converter between the Switch Mode Power Supplies (SMPS) topologies. It is used to deliver power in complex circuits where the conversion of higher input voltage to lower output dc voltage is desired. The basic configuration of the converter is portrayed in Fig. 2.2(a) which consists of one switching element, a rectifier, and filter elements. The inductor on the output portion provides continuous current to the load. The important waveforms are shown in Fig. 2.2(b) considering the assumption that the induction current is never negative. The converter is considered to be operated in the continuous conduction mode in which the inductor current never reaches to zero. When the switch is on, the diode is reverse biased and the inductor is charged by the input voltage. When the switch is off, the diode is forward biased and the inductor discharges to load [24, 25]. It has a voltage gain of $G = D$.



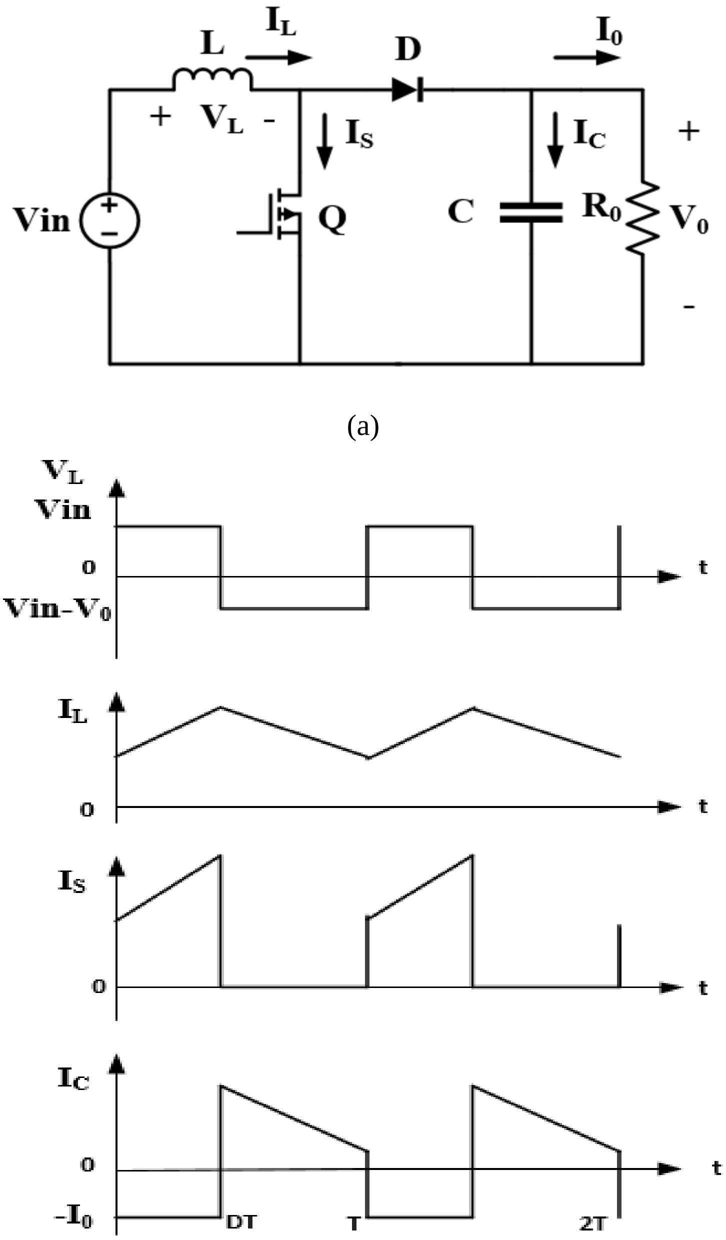
(a)

(b)

Fig. 2.2 (a) Basic configuration and (b) typical waveforms of Buck Converter.

2.2.1.2 Boost Converter

A boost converter is a step-up converter that increases the input dc voltage to a higher dc output voltage. The basic configuration of the converter is constructed in Fig. 2.3(a). The circuit has a voltage source, an inductor, a capacitor, a switching device, a diode, and a resistance as loading element. The waveforms in CCM mode are given in Fig 2.3(b) [16]. In the ON condition, the switch is on and the diode is reverse biased. The current will flow from the voltage source to the switching device and energy is stored in the inductor. In the OFF state, the diode is forward biased and the switch is off. The inductor releases the stored energy to the output load while ensuring the continuous flow of current and increases the output voltage. The gain of the converter is $G = 1/(1 - D)$.



(a)

(b)

Fig. 2.3 (a) Basic configuration and (b) typical waveforms of Boost Converter.

2.2.1.3 Buck-Boost Converter

A buck-boost converter is an inverting converter that can operate as a step-up or step-down converter. Thus, the output voltage is either higher or lower than the input voltage depending on the duty cycle. The buck-boost converter topology is demonstrated in Fig 2.4(a). The components of the converter are – dc input voltage source, controlled switch, inductor, capacitor, diode, and load resistance. The waveforms of this converter in CCM mode are presented in Fig 2.4(b) [26, 27]. When the switch is on, the diode is off and the inductor is in charging condition. The current will increase and flow through the voltage, the switch, and the inductor. When the switch is off, the diode is forward biased and the inductor delivers the stored energy to the capacitor and the load resistance. Hence, the voltage gain of buck-boost circuit is $G = -D/(1 - D)$.

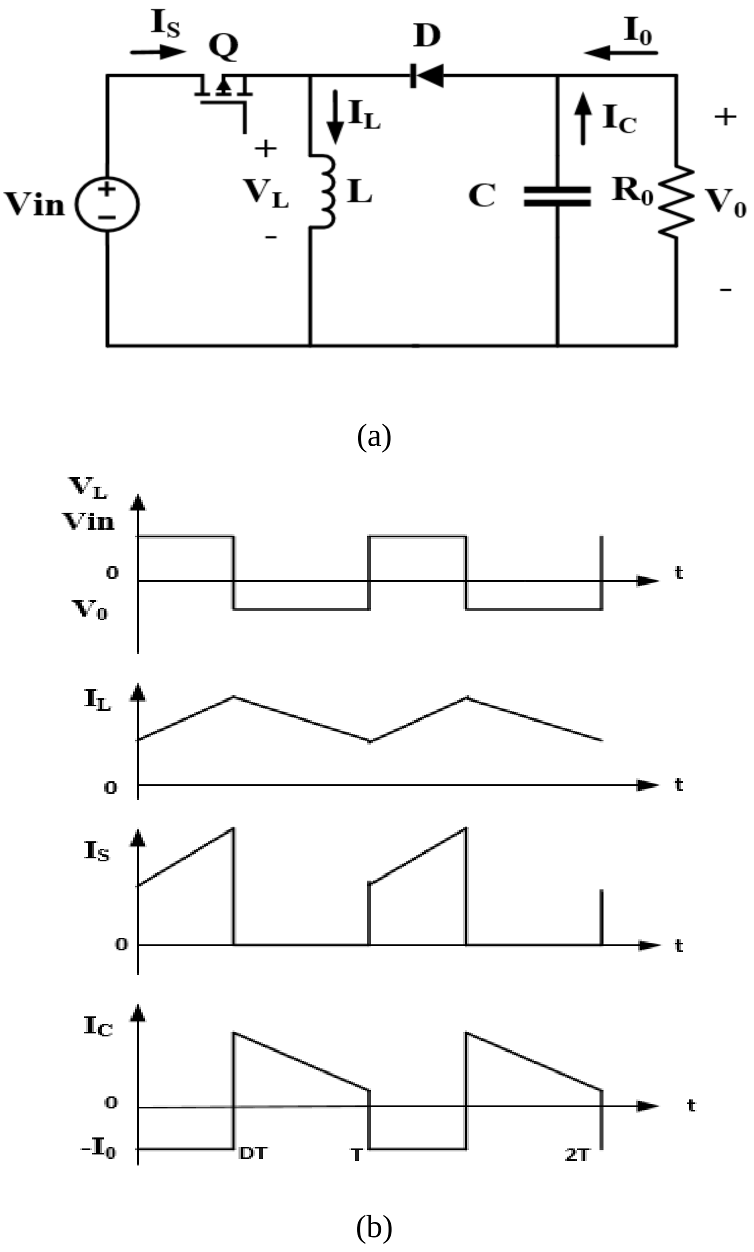


Fig. 2.4 (a) Basic configuration and (b) typical waveforms of Boost Converter.

2.3 Cuk Converter

The Cuk converter was introduced by Slobodan Cuk in 1979. This converter was stated as a switching regulator with a minimum number of components. The main motive behind the invention was to reduce the effect of pulsating current. The behavior of the ideal transformer is implemented in the cuk converter by providing dc input and output currents with no ripple. The concept of coupling inductances in dc-dc converters gained much popularity after examining the cuk converter. The converter even accelerated the research for the integrated magnetic circuits. Though the drawback of switching devices created some disadvantages of using the cuk converter, further engagement in finding the way to compensate for the problem led to many effective solutions. So, the cuk converter offers two individual sectors - the practical utilizations of managing the implication of multipurpose converter configuration and the theoretical cases which deal with new ideas of switching composition [28].

2.3.1 Outline of Cuk converter

Cuk converter is a series combination of buck and boost converter that operates in both step-up and step-down modes. It is a fourth-order non-linear dc-dc converter that has zero-ripple current. The output voltage of the cuk converter is inverted just like the buck-boost converter. Being an optimum topology converter, it is a boost converter followed by a buck converter that has the same switching device and one mutual capacitor. It can be a top-rated converter for applications of a wide range of voltage. The structure of the converter is designed in a manner that the current flowing through the input is always continuous in both the switching states [29]. The basic configuration is represented in Fig. 2.5. The main energy storage element is the capacitor. Moreover, the capacitor of the boost converter side acts as the energy source for the buck converter part. For smooth current facility, the filter elements are added at the input and output circuit. In addition, the useful features of cuk converters depending on the structure are – better steady-state performance, capacitive energy transfer, higher efficiency etc.

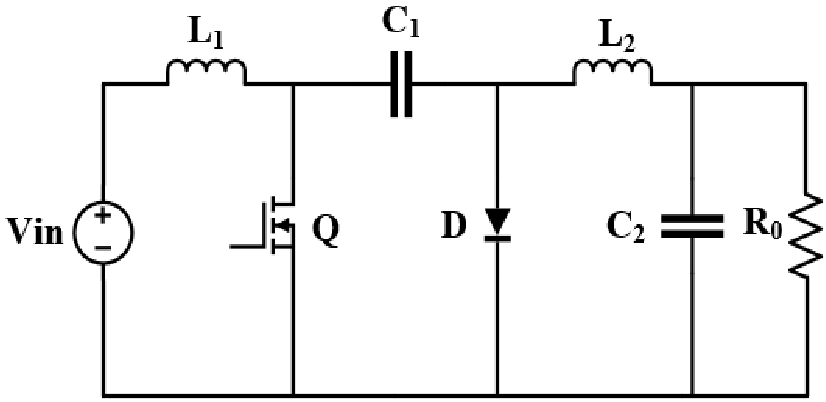
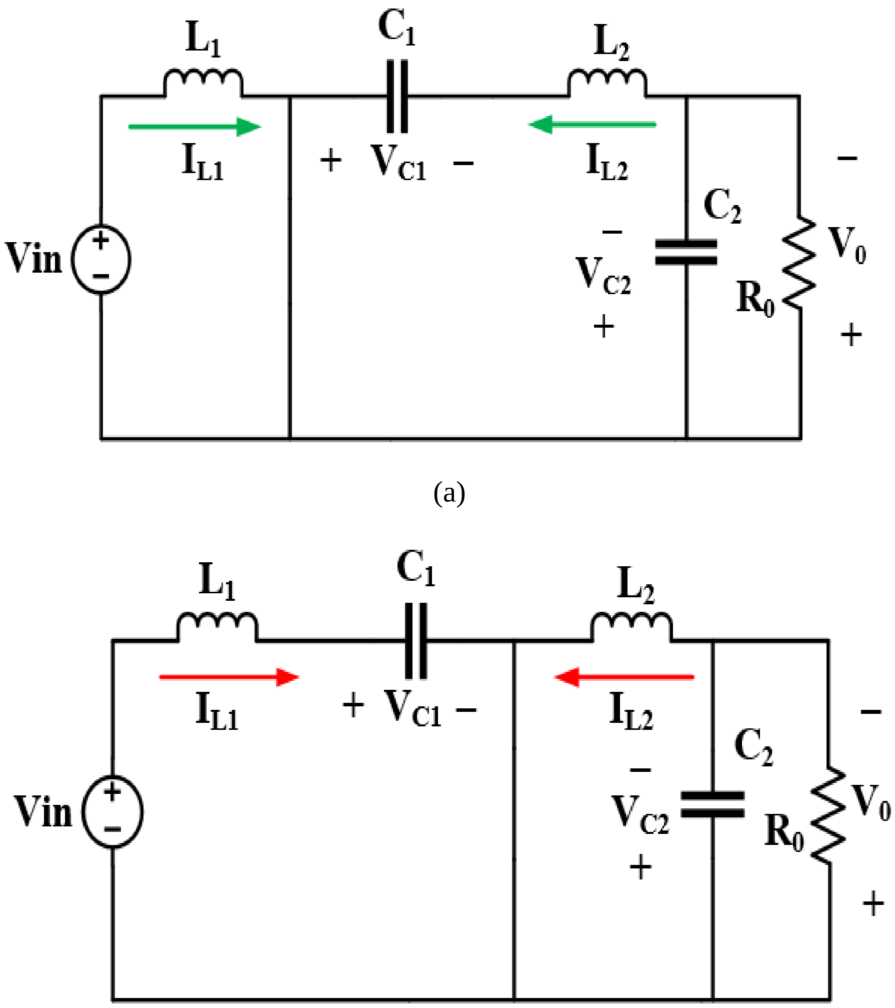


Fig. 2.5 The basic circuit diagram of Cuk converter

2.3.2 Circuit Analysis of Cuk converter

Cuk converter is a switched-mode dc-dc converter that provides the desired output voltage of either higher or lower in magnitude than the input voltage. The polarity of the voltage is also reversed in the full procedure of operation. The converter is assumed to operate in the CCM mode for the purpose of getting a proper result. The components used in the cuk converter are – a voltage source, MOSFET as a switching element, two capacitors, two inductors, one diode, and a load resistor. Though the inductors here are uncoupled, various researches are done followed by the usage of coupled inductors for better response. In the CCM mode, there are two switching operations for the converter. In the ON state operation, the MOSFET is operating in on condition, the diode is off, the current is flowing from the input voltage source to the first inductor, and capacitor C_1 is delivering the energy to the load. In the OFF state operation, the MOSFET is not conducting, the diode is forward biased, and inductor L_1 intends to maintain the flow of current in the output side by reversing the polarity, and C_1 is charged from the input energy. The circuit configurations for the OFF and ON state is shown in Fig. 2.6 [30, 31].



(a)

(b)

Fig 2.6 Cuk converter in (a) ON and (b) OFF state operation.

2.3.3 State-Space Average Method for Cuk converter

To extend the analytical knowledge about the power converters, the design modeling is developed with the help of the state-space average approach. The state-space average method can simplify a complex circuit configuration and offers an easy procedure for finding the solutions to difficult calculations. The validity of the application of this method was studied in various aspects and then applied for new modeling of the converters. It was primarily developed to exhibit the transfer characteristics of switched-mode power converters. It provides a set of equations for determining the transfer functions of the power converters. In the CCM mode, the basic state-space averaging approach is given below [32, 33]:

For the ON operation:

$$X' = A_1X + B_1V_{in} \quad ; \quad 0<t<dT \tag{2.1}$$

For the OFF operation:

$$X' = A_2X + B_2V_{in} \quad ; \quad 0<t<(1-d)T \tag{2.2}$$

$$V_0 = C_1X \quad ; \quad \text{during interval } dT \tag{2.3}$$

$$V_0 = C_2X \quad ; \quad \text{during interval } (1-d)T \tag{2.4}$$

The individual equations by merging the formulas of the two operations are –

$$X' = [A_1d + A_2(1-d)]X + [B_1d + B_2(1-d)]V_{in} \tag{2.5}$$

$$V_0 = [C_1d + C_2(1-d)]X \tag{2.6}$$

From these basic state-space averaging technique, the differential equations for the cuk converter of two operating modes are stated below [34]:

Mode 1:

When the switch is conducting and diode is off –

$$\frac{dI_{L1}}{dt} = \frac{V_{in}}{L_1} \tag{2.7}$$

$$\frac{dI_{L2}}{dt} = \frac{1}{L_2}\left[V_{C1} - V_{C2}\right] \tag{2.8}$$

$$\frac{dV_{C1}}{dt} = -\frac{I_{L2}}{C_1} \tag{2.9}$$

$$\frac{dV_{C2}}{dt} = \frac{1}{C_2}\left[I_{L2} - \frac{V_{C2}}{R_0}\right] \tag{2.10}$$

Mode 2:

When the switch is not conducting and diode is on –

$$\frac{dI_{L1}}{dt} = \frac{1}{L_1}\left[V_{in} - V_{C1}\right] \tag{2.11}$$

$$\frac{dI_{L2}}{dt} = -\frac{V_{C2}}{L_2} \tag{2.12}$$

$$\frac{dV_{C1}}{dt} = \frac{I_{L1}}{C_1} \tag{2.13}$$

$$\frac{dV_{C2}}{dt} = \frac{1}{C_2}\left[I_{L2} - \frac{V_{C2}}{R_0}\right] \tag{2.14}$$

Now the matrices can be written in the following format:

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & -\frac{1}{L_2} \\ 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{R_0 C_2} \end{bmatrix} \tag{2.15}$$

$$A_2 = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{R_0 C_2} \end{bmatrix} \tag{2.16}$$

$$A=\begin{bmatrix} 0 & 0 & \frac{d-1}{L_1} & 0 \\ 0 & 0 & \frac{d}{L_2} & -\frac{1}{L_2} \\ \frac{1-d}{C_1} & -\frac{d}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{R_0 C_2} \end{bmatrix} \tag{2.17}$$

$$B_1=B_2=B=\begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{2.18}$$

$$C_1=C_2=C=\begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.19}$$

$$E_1=E_2=E=\begin{bmatrix} 0 \end{bmatrix} \tag{2.20}$$

Where the main matrix equations are –

$$A=A_1 d+A_2(1-d)$$

$$B=B_1 d+B_2(1-d)$$

$$C=C_1 d+C_2(1-d)$$

$$E=E_1 d+E_2(1-d)$$

2.4 Zeta Converter

Zeta is a dc-dc converter topology that can provide higher or lower output voltage than the given input voltage. It is a non-inverting regulator because it balances the same polarity at the input and output sides. Zeta converter has given the least attention earlier for the complex designing and calculations of the higher-order converter. But the researchers paid attention to the converter after determining easy techniques in the applications. As the zeta converter is a cascaded power converter of the buck and boost converters, it provides the opportunity to get a better transient response. The former researchers named this converter a dual SEPIC converter. The improved switching techniques grab the attention for their tremendous property of permitting a way to minimize the resonant dc-dc converters with lighter components. This concept built the thought of designing a dual SEPIC converter. At that time, the utilization of the zeta converter was limited but the idea further developed with various attempts and the application spread out in many sectors [35].

2.4.1 Outline of Zeta converter

Zeta converter can be considered as either a Buck-Boost-Buck converter depending on the input energy or a Boost-Buck-Boost converter by analyzing the output characteristics. It was introduced with the knowledge of the duality property of a SEPIC converter. Zeta converter can also be derived from a forward converter but it does not need a reset circuit. This converter has many benefits such as - a stable feedback loop for wider input voltage range, input to output DC insulation, buck-boost cascaded properties, and continuous output current. It also gained attention over SEPIC converter for some striking features as – lower output-voltage ripple, easier compensation for wider loop bandwidth, and better load transient outcomes. Unlike SEPIC converter, the energy is transferred directly from input to output in a zeta converter. So, the zeta converter rends better dynamic performance than the SEPIC converter [36, 37]. The main configuration of zeta converter is shown in Fig. 2.7. The LC filter is located at the output and has a pulse current at the input. A single FET for switching purpose and a single rectifier is also constructed in the circuit.

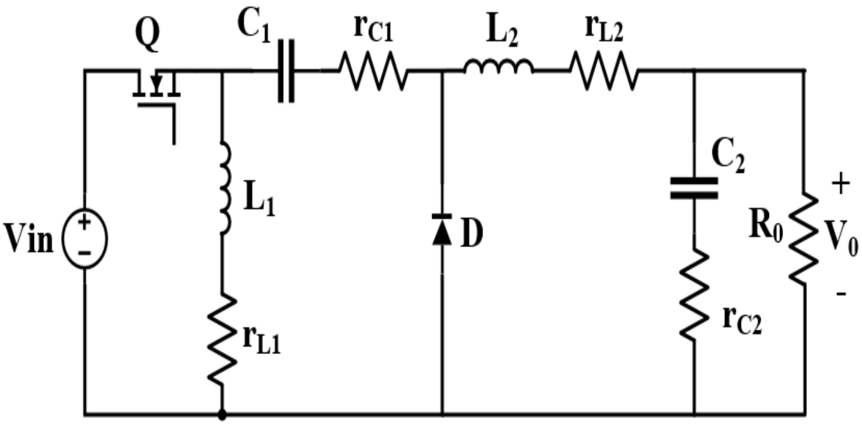


Fig. 2.7 The basic circuit diagram of Zeta converter.

2.4.2 Circuit Analysis of Zeta converter

Zeta converter is considered as inverting SEPIC converter. The converter consists of a switching device, two inductors, an output capacitor, a series capacitor, a diode, a load and parasitic resistances. PWM pulses are given to the MOSFET for the switching purpose. Depending on the duty cycle of the PWM, the converter gives either higher or lower output voltage. When the MOSFET is turned on, the diode is reverse biased, the impedance gradually decreases, the current flowing through the circuit increase, and the inductor is charged. When the MOSFET is turned off, the inductor changes the polarity for maintaining the same direction of current, the diode is forward biased and the series capacitor C_1 starts charging through inductor L_1. By the continuous conduction of these two modes, energy is transferred to the output. The two operating modes are portrayed in the Fig. 2.8 [38, 39].

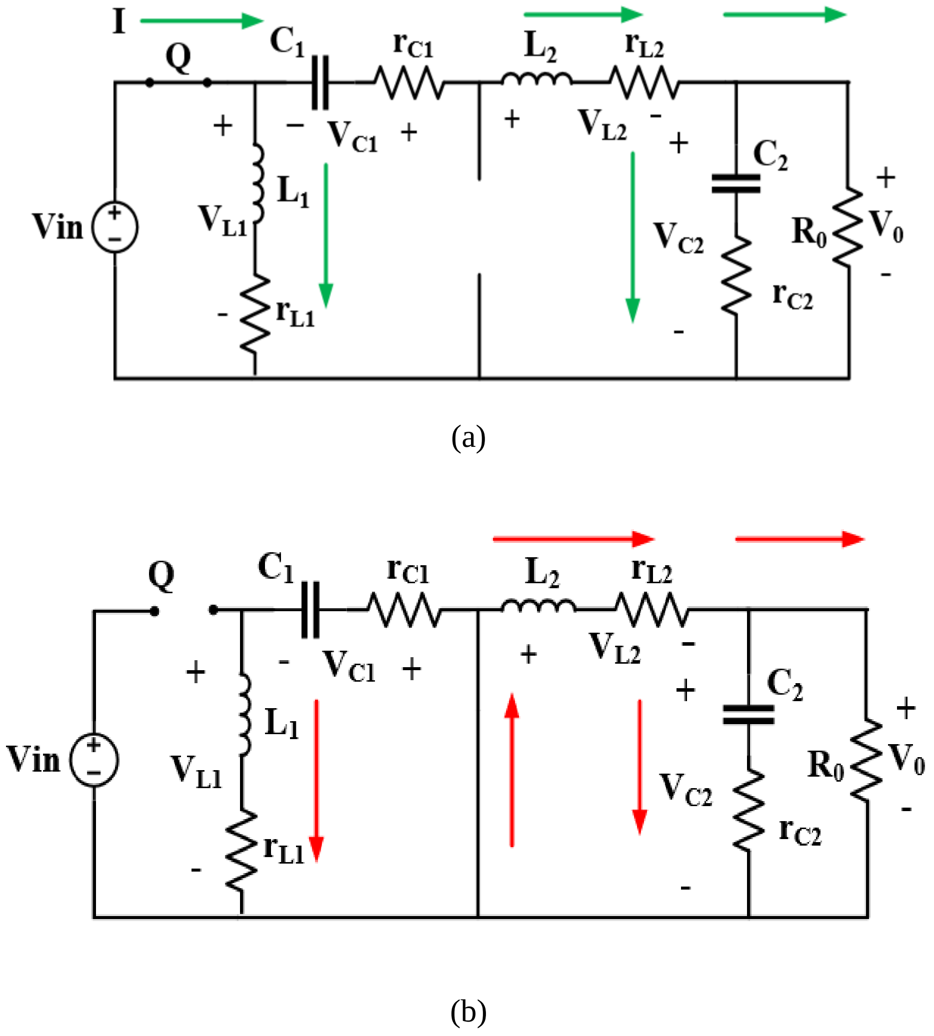


Fig 2.8 Zeta converter in (a) ON and (b) OFF state operation.

2.4.3 State-Space Average Method for Zeta converter

For the non-ideal case, the differential equations of the zeta converter are demonstrated with the help of state-space averaging technique. The equations for the operating modes are the following [40, 41]:

Mode 1:

When the switch is conducting and diode is off –

$$\frac{dI_{L1}}{dt} = \frac{1}{L_1}[-r_{L1}I_{L1} + V_{in}] \tag{2.21}$$

$$\frac{dI_{L2}}{dt} = \frac{1}{L_2}\left[-(r_{L2} + r_{C1} + \frac{r_{C2}R_0}{r_{C2}+R_0})I_{L2} + V_{C1} - \frac{R_0}{r_{C2}+R_0}V_{C2} + V_{in}\right] \tag{2.22}$$

$$\frac{dV_{C1}}{dt} = -\frac{I_{L2}}{C_1} \tag{2.23}$$

$$\frac{dV_{C2}}{dt} = \frac{1}{C_2}\left[\frac{R_0}{r_{C2}+R_0} I_{L2} - \frac{1}{r_{C2}+R_0} V_{C2}\right] \tag{2.24}$$

$$V_0 = \frac{r_{C2}R_0}{r_{C2}+R_0} I_{L2} + \frac{R_0}{r_{C2}+R_0} V_{C2} \tag{2.25}$$

Mode 2:

When the switch is not conducting and diode is on –

$$\frac{dI_{L1}}{dt} = \frac{1}{L_1}\left[-(r_{C1}+r_{L1})I_{L1} - V_{C1}\right] \tag{2.26}$$

$$\frac{dI_{L2}}{dt} = \frac{1}{L_2}\left[-(r_{L2}+\frac{r_{C2}R_0}{r_{C2}+R_0})I_{L2} - \frac{R_0}{r_{C2}+R_0} V_{C2}\right] \tag{2.27}$$

$$\frac{dV_{C1}}{dt} = \frac{1}{C_1} I_{L1} \tag{2.28}$$

$$\frac{dV_{C2}}{dt} = \frac{1}{C_2}\left[\frac{R_0}{r_{C2}+R_0} I_{L2} - \frac{1}{r_{C2}+R_0} V_{C2}\right] \tag{2.29}$$

$$V_0 = \frac{r_{C2}R_0}{r_{C2}+R_0} I_{L2} + \frac{R_0}{r_{C2}+R_0} V_{C2} \tag{2.30}$$

The average matrices for the state space equations are determined as below –

$$A = \begin{bmatrix} -\frac{r_{C1}(1-d)+r_{L1}}{L1} & 0 & -\frac{1-d}{L_1} & 0 \\ 0 & -\frac{(r_{C2}+R_0)(dr_{C1}+r_{L2})+r_{C2}R_0}{L_2(r_{C2}+R_0)} & \frac{d}{L_2} & \frac{-R_0}{L_2(r_{C2}+R_0)} \\ \frac{1-d}{C_1} & \frac{-d}{C_1} & 0 & 0 \\ 0 & \frac{R_0}{C_2(r_{C2}+R_0)} & 0 & \frac{-1}{C_2(r_{C2}+R_0)} \end{bmatrix} \tag{2.31}$$

$$B = \begin{bmatrix} \dfrac{d}{L_1} \\ \dfrac{d}{L_2} \\ 0 \\ 0 \end{bmatrix} \tag{2.32}$$

$$C = \begin{bmatrix} 0 & \dfrac{r_{C2}R_0}{r_{C2}+R_0} & 0 & \dfrac{R_0}{r_{C2}+R_0} \end{bmatrix} \tag{2.33}$$

$$D = [0] \tag{2.34}$$

CHAPTER 3
STUDY OF BIO INSPIRED ALGORITHM (BIA)

Bio-inspired algorithms (BIA) are algorithms that are based on biological systems, physical systems, chemical systems, and swarm intelligence. These algorithms are intelligent computation techniques to optimize data-driven problems. These are motivated by the custom and mannerisms witnessed in biological beings or organisms while being in their natural habitat to achieve efficacy in meeting the natural requirements such as acquiring food, preying, surviving from danger, mating, etc. Since nature is unpredictable and changing, the inhabitants living in nature show versatility, dynamic attitude, flexibility, and witty responses. These are incorporated in the BIA to provide robustness and resilience in the algorithms to search for optimum solutions to complex problems.

3.1 Survey of Particle Swarm Optimization (PSO)

PSO was first conceived by Eberhart and Kennedy in 1995 [42].The initial thoughts of Kennedy and Eberhart on swarms of particles aimed primarily at the development of intelligent calculation by taking advantage of basic social interaction analogs, rather than pure individual analytic capabilities [43]. PSO falls under the definition of Bio-Inspired Algorithms because it adheres to the rules followed by social creatures in nature. PSO is more specifically inspired by swarm intelligence which deploys a multi-agent population to search and find solutions for the optimization problem.

3.1.1 Identification of PSO

PSO is a stochastic, metaheuristic, and artificial intelligence based tool to find solutions for multifarious optimization problems. Being a stochastic method, PSO takes the approach of the random probability distribution to produce random locations of possible solutions which can be evaluated but cannot be predicted. Moreover, PSO being metaheuristic implies that even with incomplete data-set and insufficient computational capacities, PSO can find search techniques that provide promising solutions to relevant problems. As established by the authors, particle swarm optimization includes a very simple notion, and a concise code can perform the function. It needs only primitive numerical operators and is efficient in terms of both memory and speed requirements [42].

3.1.2 Objectives of PSO

The PSO algorithm has some objectives which essentially enable non-expert personnel to utilize the optimization tool to the utmost for reaching their goal. The objectives are cited as follows [44]:

- To develop a comprehensive review of the most common PSO variables so that long-term usage can be obtained from that.
- To develop a summary of the theoretical aspects of the algorithm and the influence of the PSO variables on them.
- To develop alternate methods to improve the execution of the algorithm.
- To provide an assessment of numerous applications and results of the algorithm to determine its workings and present guidelines.

3.1.3 Features of PSO

Particle Swarm Optimization is one of the frequently used search techniques among researchers for resolving continuous, non-convex, integer variable type, discrete, non-linear problems [45-47]. It is inspired by swarm intelligence which is heavily influenced by the competition and cooperation among colony or swarms. Some special features are noticed when swarm creatures function in unity to reach common goals of the community which were incorporated in the PSO algorithm to reach optimized solutions. Interaction, communication, sharing of information, taking decisions collectively are some of the helping attributes that are utilized in this optimization mechanism. The optimization problem is assessed in the form of an objective function which is designed in our work to be minimized. The solutions obtained through the algorithm are evaluated in terms of the objective functions to determine their suitability and efficacy.

3.1.4 Methodology of PSO

The algorithm is initiated with a population of particles, each set to find competent results in the search space. The useful aspect of having a population of particles is to lessen the time of computation as all individuals search for the same goal simultaneously. And also, the particles can travel to each point and corner to come across different information provided by the search space which is beneficial to reach conclusions.

The requirement also referred to as the optimization issue, is reproduced as the cost function in the algorithm which is programmed to be minimized in our thesis. After setting the objective function, the particles are ready to survey the solution space specified by the programmer.

Among the particles, each acquires an individual best location meaning the best solution. After the completion of each particle's motion, the information is shared among the population to agree on a global best location. These acts are repeated in each iteration and the values are updated accordingly. Three parameters are crucial in the algorithm to control and determine the movement of the particles and they are the velocity of the particle in the present iteration, the personal best location found by the particle, and the global best solution of the entire population. The cited three vectors are exercised in the mathematical model to obtain the displacement and velocity of the particle in the next iteration. Hence both the personal and overall experiences were valued in the calculation.

With an increasing number of iterations, the updated variants of the PSO algorithm become more optimized. More parameters are utilized in the equations for calculating particle locomotion to enhance the efficacy of the algorithm. Random functions are employed in the equations so that the variables are not trapped in the same region. Acceleration coefficients are also incorporated in the equation so that the agents can accelerate towards their personal and global best values. But a balance needs to be maintained while choosing the values of the constants since a higher quantity enforces the particles to reach towards or beyond the desired locations quickly and on the other hand, lower quantity results in particles passing the target locations while traveling in the search space without being called back [48]. A parameter called inertia weight is also applied with the velocity of the particles which ranges between 0.9 and 0.4 to bring equilibrium between the personal and global best outcomes [44]. A bigger value of inertia weight presents an inclination to global survey whereas a smaller value pushes the algorithm towards a local survey. And finally, when the specified number of iterations is completed, the algorithm is terminated.

3.1.5 Exploitation and exploration in PSO

Exploitation defines the intensification of the algorithm and exploration refers to the diversification of the algorithm. Both the features are witnessed in this algorithm.

Generally, the relevant data available from the optimization problem are used for exploitation. This process focuses on local searches to find optimum values. And on the contrary, the random functions contribute to the exploration of the search space.

In the PSO algorithm, the contributions of the personal best solutions are not very clear although the global best solution is exercised for selection in the accelerated particle swarm optimization [42]. Enhanced mobility is witnessed in the PSO algorithm exerting strong exploration due to the absence of crossover [49]. But a balance between exploitation and exploration is attempted so that the convergence rate is improved and premature convergence with non-profitable solutions is avoided.

3.1.6 Mathematical model of PSO

The mathematical model of PSO involves tracking the movements of the particles. The motion of the particles defers to the displacement and velocity of the particles in the search space.

The equation to find the velocity of the particles in the standard Particle Swarm Optimization algorithm is presented below [50]:

$$v_n^{t+1} = w * v_n^t + c_1 * R_1 * (p_{nb} - d_n^t) + c_2 * R_2 * (g_b - d_n^t) \tag{3.1}$$

The displacement of the particles is computed using the following equation [50],

$$d_n^{t+1} = d_n^t + v_n^{t+1} \tag{3.2}$$

And the terms denote the following meanings,

w= Inertia weight.

c_1, c_2 = Acceleration Constants

R_1, R_2 = Random functions

d_n^t = Displacement of the nth particle in the tth iteration

d_n^{t+1} = Displacement of the nth particle in the (t+1)th iteration

v_n^t = Velocity of the nth particle in the tth iteration

v_n^{t+1} = Velocity of the nth particle in the (t+1)th iteration

p_{nb} = Personal best value of the nth particle

g_b = Global best value among the entire population

3.1.7 Flowchart of PSO

The sequential path of the functions and computation of the algorithm is explained through the following steps below,

Step 1. Initialize the algorithm by generating a population of particles.

Step 2. Declare the objective function associating with the optimization problem.

Step 3. Find the updated velocity of each particle using the previous position data.

Step 4. Compute the updated displacement.

Step 5. Assess the personal best solution obtained by each particle.

Step 6. Compare the personal best solutions of all particles to get the global best value.

Step 7. Run the algorithm for a specified number of iterations.

Step 8. If the total number of iterations is not completed, repeat the algorithm from step 3.

Step 9. When the iterations are completed, terminate the program

The flowchart of the Particle Swarm Optimization is illustrated below [51]:

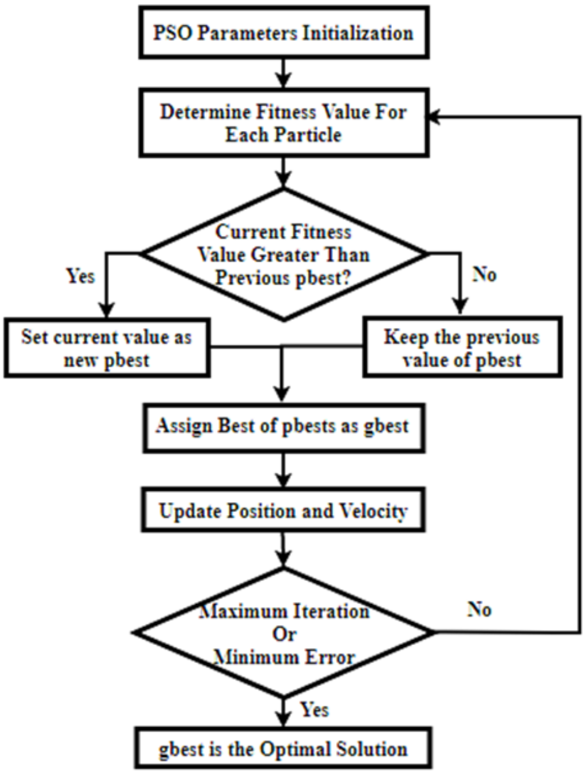


Fig. 3.1. Flow Chart of Particle Swarm Optimization [51].

3.2 Survey of Firefly Algorithm (FA):

Firefly Algorithm was introduced as a swarm intelligence (SI) based algorithm in 2008 by [52]. FA falls under the categories of Bio-Inspired Algorithms (BIA) and is frequently used as a search technique. This algorithm has taken the interactive colonial behavior of fireflies as an inspiration to perform optimization. Fireflies are insects with luminescent abdomens which result from a biochemical procedure called bioluminescence. Their light-emitting feature is a crucial part of their social custom. Fireflies display highly coordinated behavior in terms of searching for food, securing shelter, and protecting the community against predators using their glowing anatomy as signals. Such manners portray the proper use of group information to fulfill a common goal. The aforesaid phenomenon plays a key role in the algorithm to hunt for optimum solutions in a search space.

3.2.1 Identification of FA

Firefly Algorithm is a metaheuristic, stochastic and artificial intelligence based optimization tool. Metaheuristics by nature guide the acquisition of optimized or nearly-optimized solutions through an iterative creation procedure [53]. Moreover, it provides an approximation approach to search for solutions and is non-deterministic [54]. Since FA is also a stochastic process, it can address poorly defined problems with imperfect data-set. Furthermore, the swarm intelligence (SI) fueled firefly algorithm utilizes a multi-agent body with a decentralized strategy to sweep the search space which signifies the independent movement of individuals without the control of any external coordinator [55]. The SI approach also demonstrates robust, flexible, and self-orchestrated traits implementing FA in a straight-forward manner [56]. All these characteristics in unison make the FA a powerful candidate to perform optimization and produce promising results.

3.2.2 Features of FA

Firefly Algorithm is a metaheuristic, stochastic and artificial intelligence based optimization tool. Metaheuristics by nature guide the acquisition of optimized or nearly-optimized solutions through an iterative creation procedure [53]. Moreover, it provides an approximation approach to search for solutions and is non-deterministic [54]. Since FA is also a stochastic process, it can address poorly defined problems with imperfect data-set.

Firefly Algorithm, inspired by the flashing mannerisms of colonial fireflies, sustains some fundamental rules to carry out the optimization procedure. A brief presentation of the rules are stated as such [57]:

i. FA treats the fireflies as genderless creatures which means that the fireflies will be attracted to each other regardless of their sex.

ii. FA demonstrates the proportionality of attractiveness of the fireflies to their brightness. Therefore, a less bright firefly will be attracted to a brighter firefly but the attraction will decrease with increased distance between them.

iii. The random movement will be ensured for fireflies of the same level of brightness.

In the algorithm, brighter or more attractive fireflies signify better solutions. Therefore, the protocol enforces the less bright fireflies to always move towards brighter ones to ensure obtaining better results. This process also promises the migration of agents from places with no optimum solutions to areas with optimized solutions. FA uses multiple parameters namely, the randomization factor, the co-efficient of attraction, and the co-efficient of light absorption to manipulate the movement of the individuals towards optimal results [58].

3.2.3 Methodology of FA

The problem to be optimized is translated into an objective function in the algorithm. The objective function is associated with the brightness of the fireflies which is programmed to be minimized for our desired objective. This affirms the acquisition of better solutions as brighter fireflies denote optimal solutions. The generation of possible solutions occurs due to the free movement of the fireflies which is influenced by the attractive factor of relevant fireflies, distance between them, random functions, and their ability to absorb light [57].

The algorithm is initiated with a population of fireflies, ready to survey the search space pre-specified by the programmer. Each agent reaches a position in the search area following the attractiveness of the other fireflies to generate a solution. To pursue the attractive fireflies, both brightness and distance are taken into account. Likewise, the co-efficient of light absorption and randomization factor contribute to the acquisition of the position.

Afterward, the present position obtained by the attractive firefly is assessed in terms of attractiveness. If the attractiveness is more than that of the prior, the corresponding position is used to update the new position. And if the attractiveness is not higher, the firefly stays at the same position.

The algorithm is terminated after the defined number of iteration is performed while updating the positions of the fireflies and simultaneously finding better solutions.

3.2.4 Exploitation and exploration in FA

Swarm intelligence inspired Firefly Algorithm (FA) demonstrates two significant behavior which heavily dominates the performance of the algorithm- exploitation, and exploration.

Exploitation associates with the aspects of a local survey by utilizing the data availed from the optimization problem to produce more solutions. Attractiveness in FA is related to the problem to be solved and therefore, co-efficient of attraction plays an important role in exploitation.

On the other hand, exploration associates with the idea of exploring the entire search area to find diverse solutions. The randomization factor and random vectors contribute to the exploration.

A balance between exploitation and exploration is to be maintained to ensure the efficient performance of the algorithm [59]. The parameters used for both the processes are tuned according to necessity so that none of them are minimized or maximized.

3.2.5 Mathematical model of FA

The movement of each firefly in the search space can be evaluated with the help of the following equations [59]:

$$X_n^{(t+1)} = X_n^t + \rho(X_b^t - X_n^t) + ar \tag{3.3}$$

The co-efficient of attraction is deduced by the equation stated below [59]:

$$\rho = \rho_0 * exp\left(-\eta * {h_{bn}}^2\right) \tag{3.4}$$

The brightness of the firefly n on the brighter firefly b is calculated utilizing the physics of light intensity in the shape of the following equation [59]:

$$i(h_{bn}) = \frac{i_s}{{h_{bn}}^2} \tag{3.5}$$

The totems used in the equations above are described as such:

X_n^{t+1} = Position of Firefly n in the present state.

X_n^t = Position of Firefly n in the previous state.

X_b^t= Position of Firefly b, which is brighter than Firefly n, in the previous state.

h_{bn}= Relative distance between Firefly b and Firefly n.

ρ_0= Co-efficient of attraction of the Firefly when h_{bn}=0.

a= Randomization Factor

η= Co-efficient of absorption of light.

r= Boundaries of search space signified by a vector of random values following uniform distribution at time t.

i_s = The initial brightness of the firefly.

3.2.6 Flowchart of FA

The methodology of the algorithm is presented chronologically in a simple form using a flowchart. The steps involved in the FA are represented below:

Step 1. Generate a random population of fireflies to initialize the algorithm.

Step 2. Set the objective function to be minimized.

Step 3. Calculate the coefficient of attraction.

Step 4. Compute the position of each firefly.

Step 5. Compare the attractiveness of the firefly with respect to its previous position.

Step 6. If attractiveness enhances, use the corresponding position to update the new position.

Step 7. If attractiveness doesn’t increase, the position is not updated.

Step 8. If total iterations haven’t been performed, start from step 3.

Step 9. Terminate the algorithm after the completion of the total number of iterations.

The flowchart is illustrated as such [60]:

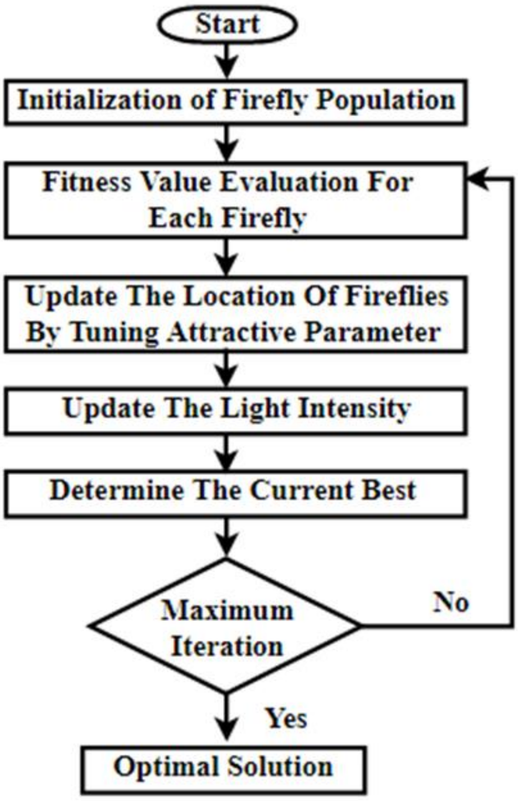


Fig. 3.2. Flowchart of Firefly Algorithm

3.3 Survey of Genetic Algorithm (GA)

Genetic Algorithm (GA) was introduced by John Holland in the 1970s as a search technique based on Darwin's theory of evolution [61]. Darwin's theory states that the population adapts itself to become the fittest for surviving and reproducing in unwelcoming situations. Genetic Algorithm (GA) utilizes this process of adaptation and mutation to generate more capable solutions for solving complicated issues. The algorithm employs chromosomes as agents to scan the search area for grasping optimized solutions where the chromosomes go through multiple stages of development and modification. Thus more competent agents are founded which shows significant improvement of the algorithm performance.

3.3.1 Identification of GA

Genetic Algorithm is a metaheuristic, stochastic and agent-based optimization technique following the laws of natural selection. The algorithm delivers the population of chromosomes with fitness and suitability through the steps of the evolutionary process to search for the optimal solution where each chromosome generates a possible solution to the imposed problem

[62]. The quality of a solution is generally measured in terms of the present population. The stages of reproduction, selection, crossover, and mutation are used to support the development process of generating enhanced solutions. The chromosomes are programmed to optimize a fitness function by which the system performance is improved. The chromosomes that correspond to better fitness functions are selected to recombine and mutate for obtaining a generation with better individuals in the algorithm and hence increasing the chances of optimization of various systems.

3.3.2 Steps of GA

Genetic Algorithm (GA) is inspired by the natural process of evolving for the sake of avoiding extinction. The process of evolution enables animals to survive in the most adverse of conditions making it an adept method to follow for acclimating the population while finding optimum solutions in the search space. The sequence of important steps followed in the algorithm as an imitation of the evolution process can be classified in the following ways [63],

- ***Reproduction:***

Similar to the natural laws of the animal kingdom, reproduction of the chromosome takes place in the shape of finding possible solutions to the cited problem. The objective function is evaluated for assessing the quality of the solution.

- ***Selection:***

Darwin's theory of evolution states that the fittest of the pack survives and hence the best solution producing chromosomes are selected for generating the next set of population. There are several processes for operating the selection criteria among which the roulette wheel selection procedure is selected.

- ***Crossover:***

After the completion of the selection step, the crossover is exercised which is witnessed in the production of new chromosomes from the combination of parent chromosomes. Similarly, the fit chromosomes go through the process of cross-over by exchanging their parts and thus producing better chromosomes. Single point and multi-point cross-overs are two of the popular method of cross-over.

- ***Mutation:***

Mutation in nature means the process of change in the gene. This modification or changes are also exercised in the newly generated chromosomes by introducing randomness in the algorithm.

3.3.3 Methodology of GA

The search algorithm GA is initiated by the process of creating a population. This thesis work employed 100 chromosomes to find optimized solutions. This population is randomized by using a Gaussian distribution process. Then the agents are set to survey the search space for coming up with possible solutions. Once each chromosome finds a solution, it goes through an assessment to find the quality of the fitness functions. After the assessment, the chromosomes with the enhanced fitness functions are selected through the selection operator to ensure optimization continuously. The selected chromosomes become the parent chromosomes whose parts are interchanged to produce children chromosomes. The newly produced chromosomes have a better qualification to find optimized solutions. Moreover, to avoid getting trapped in local areas, the diversity of the solutions are introduced by adding randomness. This process of creating modifications in the chromosomes is accomplished by the mutation process. Hence, the problem area is inspected thoroughly to produce optimized solutions for the stated problem using the technique of natural evolution. Multiple iterations are conducted to meet the completion requirement.

3.3.4 Exploitation and exploration in GA

Exploitation and exploration suggest taking advantage of the local search space and exploring the overall search space for finding optimized values respectively. Both the phenomena are exercised within this algorithm in the quest of finding the best solutions maintaining an appropriate balance. The random population initialized creates randomness promoting exploration of the search space. But after the evaluation of the fitness functions, chromosomes are selected following optimization which utilizes the phenomena of exploitation of data [64].

Tuning the parameters of the algorithm, the desired amount of exploitation and exploration can be achieved which helps the acquisition of improved solutions comparatively faster.

3.3.5 Mathematical model of GA

The fitness function of GA is determined by the following equation [65],

$$f_x = \vartheta + \varpi - \beta - \sum_{i=0}^{N} \lambda \tag{3.6}$$

The probability of selection is calculated by the equation below [65],

$$\gamma_s(i) = \frac{f_x(p)}{\sum_{i=0}^{N} f_x(i)} \tag{3.7}$$

Where, N is the total number of chromosome.

The expected measure of selection is computed in the cited way [65],

$$\mu = \frac{f_x(p)}{[\sum_{i=1}^{N} f_x(i)/N]} \tag{3.8}$$

3.3.6 Flowchart of GA

The methodology of the algorithm is presented chronologically in a simple form using a flowchart. The steps involved in the GA are represented below:

Step 1. Introduce a random population of chromosomes of a specific number.

Step 2. Assess the fitness function of solutions found by chromosomes.

Step 3. Select the chromosome with the best function by the Roulette Wheel method.

Step 4. Apply the crossover on the parent chromosomes.

Step 5. Implement mutation of the produced chromosomes.

Step 6. Repeat from step 2 till the completion criterion is met.

The flowchart is illustrated as such [66]:

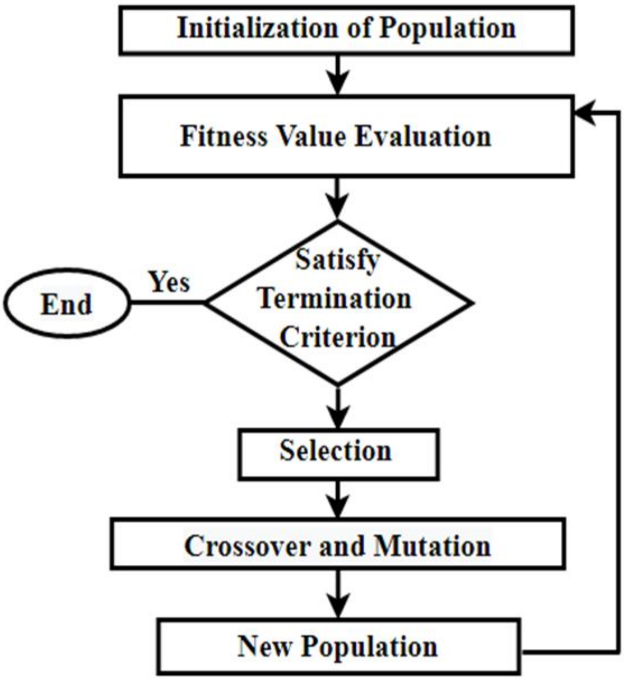


Fig. 3.3. Flowchart of Genetic Algorithm.

3.4 Survey of Artificial Bee Colony (ABC)

Artificial bee colony algorithm was initially reported by Karaboga in 2005 which complies with the protocol of swarm intelligence [67]. The ABC algorithm takes inspiration from the cooperative and social nature of honey bees portrayed while finding food in their daily lives. Honey bees are intelligent and active creatures working unitedly and relentlessly for acquiring an ample amount of food for the community. The algorithm enforces the selection of food sources by artificial bees depending on the quality of the food. The purposes and activities of the bees are categorized and each category performs its function and relates the information to the other categories for reaching ultimate efficiency in meeting their common goal. This exact procedure is mimicked in the ABC algorithm to find optimized solutions for a related problem. The algorithm has few control parameters making it easy to regulate the outcome by tuning the parameters according to necessity [68].

3.4.1 Identification of ABC

Artificial Bee Colony, similar to the previously mentioned algorithms, is a metaheuristic, stochastic and artificial intelligence based algorithm [68]. And therefore, this algorithm sustains the capability of continuously finding optimized solutions through an iterative process for a problem with limited information. Optimized solutions produced by the algorithm are signified by food sources with a high quantity of nectar found by the bee colony. One of the useful traits of the algorithm is computing the probability of the produced food locations in terms of fitness which enables faster convergence [69]. Moreover, the greedy selection method is utilized to evaluate both the past and present solutions and store the better solution between them [70]. The multiple assessments performed in the algorithm enhance the chances of getting optimal results. The activities of the bee colony incorporated in the ABC algorithm comprise of searching for the solutions, comparing the obtained solutions, selecting the best quality solutions in terms of fitness, discarding the low-quality food locations, and finally producing better solutions instead [69]. The entire communication process of the bees is executed in a form of ritual dance which takes place in the search area making the data transparent for other bees to see. Various parameters are attuned to amplify the suitability of the algorithm with the associated problem.

3.4.2 Classification of bees according to purposes in ABC

The honey bee swarm is classified into three groups based on their role in the algorithm [71]. The classification is displayed as such,

i. ***Employed Bees:***

The employed bees actively participate in the search process to find possible food locations. Each employed bee finds an appropriate food location and stores relevant information about that source such as position, direction, and quality of the food sources. Afterward, the fitness of the food sources is assessed to deliver a probability of the solution while sharing the information with the colony.

ii. ***Onlooker Bees:***

The onlooker bees evaluate the obtained solutions in terms of fitness and select the candidate solutions while wiggle dance takes place in the search space. These candidate solutions are later utilized to update the food sources in the next movement. The food locations that don't provide promising solutions are omitted and the corresponding employed bees become scout bees.

iii. ***Scout Bees:***

Scout bees are generated to compensate for the unsuitable solutions produced earlier by employed bees. The scout bees explore the search space and look for food locations missed by employed bees. But scout bees rarely find highly optimized food sources. The food sources produced by the scout bees are assessed again to see if they will transition into profitable solutions.

Both local and global searches are conducted in the ABC algorithm by engaging the employed bees and onlooker bees for the local aspect and the scout bees for the global aspect. This ensures a thorough survey of the search space and a favorable convergence rate [71].

3.4.3 Methodology of ABC

The entire process of the ABC algorithm is carried out in three phases by three categories of honey bees. The optimization problem is declared as an objective function that relates to the nectar amount in the food sources signifying better fitness of the solutions. The objective function in our work is programmed to be minimized.

The algorithm is initiated by generating a population of employed honey bees where each employed bee produces a possible food location. They store the information of position, direction, and food quality of the food locations. Afterward, the fitness of the solution is assessed in terms of nectar in the food sources to compute the probability of the solutions. The better solutions are stored by comparison between the previously found solutions and recently found solutions by utilizing the 'greedy selection procedure'. Later the probability data and the solutions are shared with the onlooker bees in the search space in the form of a ritual dance.

The number of onlooker bees is equivalent to the number of employed bees. The onlooker bees select the candidate food sources after analyzing the probability of solutions concerning the fitness. And the selected optimized solutions are used to update the new food sources.

Some food sources do not provide promising solutions and such sources are eliminated from the search space. The corresponding employed bees transform into scout bees to explore the search space to compensate for the omitted solutions. They concern themselves with searching for any quality food source. Therefore, the scouts deliver inexpensive search costs and poor quality food sources. Rarely, scouts can discover profitable food sources. The transition of employed bees to scout bees is determined by a limiting parameter [69]. The limiting parameter denotes that if the solutions don't improve within a certain amount of trails, they are discarded.

The algorithm is conducted according to the pre-defined number of iterations which is also termed as the maximum number of cycles (MCN) [69]. The methodology followed in the algorithm ascertains a robust, straight-forward, and fast converging search tool.

3.4.4 Exploitation and exploration in ABC

Exploitation and exploration are employed simultaneously in the algorithm to maintain a balance between swifter convergence and finding optimized solutions in the search space. Exploitation is exercised by employed bees and onlooker bees because they utilize the data provided for the objective functions and assures a better quality of the solutions. On the other hand, the exploration is achieved by scout bees as they survey the overall search space to find new solutions. Generally, the exploration by scout bees is quite effective, but convergence might be slow as the crossover is absent in this process, and hence the exploitation capability is quite limited [49]. For better balance, the parameters regulating the employed bees and scout bees can be further manipulated.

3.4.5 Mathematical model of ABC

The equation to compute the new candidate solutions by employed bees is [72],

$$X_{np} = x_{np} + \varphi_{np}\left(x_{np} - x_{kp}\right) \tag{3.9}$$

Where, $p \in 1,2,\ldots\ldots,N$

And, $k \in 1,2,\ldots\ldots,D$

The probability of each obtained solution with regards to fitness is computed by the following equation [72],

$$Probability_n = \frac{fit_n}{\sum_{n=1}^{N} \quad fit_n} \tag{3.10}$$

The new solutions produced by the scout bees are calculated by the equation below [72],

$$x_n^{p(new)} = x_{min}{}^p + rand()(x_{max}{}^p - x_{min}{}^p) \tag{3.11}$$

Where, $p \in 1,2,\ldots\ldots,D$

The descriptions of the symbols used in the equations above are provided as such,

N= Number of Employed bees= Number of onlooker bees.

X_{np}= New candidate solutions.

x_{np}= Initially developed solutions.

Φ_{np}= Random amount between -1 to 1.

$Probability_n$= Probability of each solution concerning fitness.

fit_n= Fitness of each solution n.

$x_n^{p(new)}$= New solutions produced by scout bees.

x_{max}^{p}= Upper bound of parameter j ∈1, 2,…., D.

x_{min}^{p}= Lower bound of parameter j ∈1, 2,…., D.

rand()= Arrays of random numbers whose elements are uniformly distributed in the interval (0 , 1)

D= Number of optimum parameters in each solution.

3.4.6 Flowchart of ABC

The process of the ABC algorithm is demonstrated through the chronological steps of its flowchart. The steps are elaborated below:

Step 1. Initiate a population of honey bees.

Step 2. Declare the objective function which associates with the nectar amount in food locations.

Step 3. Find the food source for each employed bee.

Step 4. Assess the fitness of the solutions.

Step 5. Compute the probability of the solutions in terms of fitness.

Step 6. Utilize the greedy selection procedure to store better solutions in employed bees.

Step 7. Select the candidate solutions with the help of onlooker bees.

Step 8. Update the new food sources using the candidate solutions.

Step 9. Monitor the limiting parameter to observe the quality of the food sources.

Step 10. If the quality doesn’t improve, discard those food sources.

Step 11. Find new food sources by scout bees.

Step 12. Monitor the number of iterations.

Step 13. Terminate the algorithm when the total number of iterations are completed or otherwise repeat the algorithm from step 3.

The steps of the ABC algorithm are displayed clearly through a flowchart for better understanding. The flowchart of the ABC algorithm is included below [73],

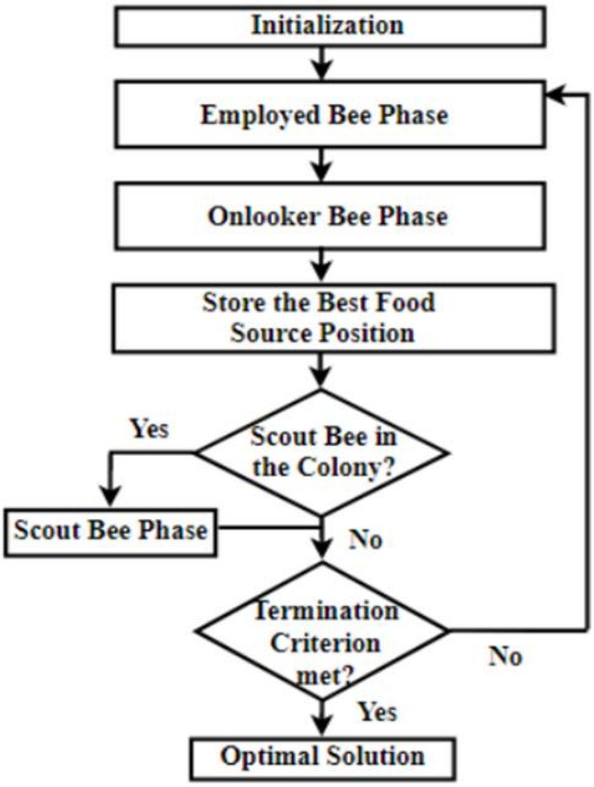


Fig. 3.4. Flowchart of Artificial Bee Colony.

CHAPTER 4

IMPLEMENTATION OF BIO-INSPIRED ALGORITHM BASED PID CONTROLLER FOR DC-DC CONVERTER

Power Electronics has brought a new kind of industrial revolution in the conversion and control of electric power by ushering DC-DC converters through the continual evolution of power regulators from linear to the switching stage [74-77]. DC-DC converters perform remarkably in comprehensive applications in LED drivers, laptops and computers, electric vehicles, hydropower plants, photovoltaic systems, and many more [78-81]. Yet, these converters show nonlinear temperaments due to the operations of the switches; manifesting larger ripples in output voltage and peak overshoot [82-84]. Therefore, assorted control techniques are employed in DC-DC converter based on regulating the output voltage for attaining better performance [85]. Among various control methods, PID control is the most familiar and broadly used method for power converters. However, the accurate value of the PID parameters is quite difficult and time-consuming to determine by following the conventional method. Hence, BIA is linked with the PID controller to gain optimum values of the PID parameters that it is applied for the closed-loop investigation of the stability of the DC-DC converter.

4.1 PID Controller

Feedback control is a control mechanism that keeps the value of output in check by feeding back the error to a controller and guiding the input towards achieving a system with more accuracy. Feedback control systems are mainly of two types- positive feedback and negative feedback. In positive feedback, the size of the input is increased by adding the output with input. Whereas, the size of the input is decreased in case of negative feedback by subtracting the output from the input. Therefore, positive feedback increases the gain of the amplifier and negative feed-back reduces it [86]. Based on this feedback mechanism many process controls are designed such as PI, PD, and PID controller for safe and productive plants.

In feedback control of the industrial process, the concept of PID is widely used in recent years. The first theoretical analysis and practical application were in the field of automatic steering systems [87]. It was then used for automatic process control in the manufacturing industry, where it was widely implemented in pneumatic, and then electronic controllers [88]. Nowadays, the PID concept is universally used in applications requiring accurate and optimized automatic control [89-91].

4.1.1 Outline of PID Controller

PID controller, a control loop feedback mechanism, is comprised of three parts known as Proportional, Integral, and Derivative. Therefore, it is also called a three-term controller where the terms are tuned by explorative methods like analytical methods and different optimization techniques such as PSO, FA, and ABC. Figure 4.1 displays the structure of a PID controller done by using MATLAB.

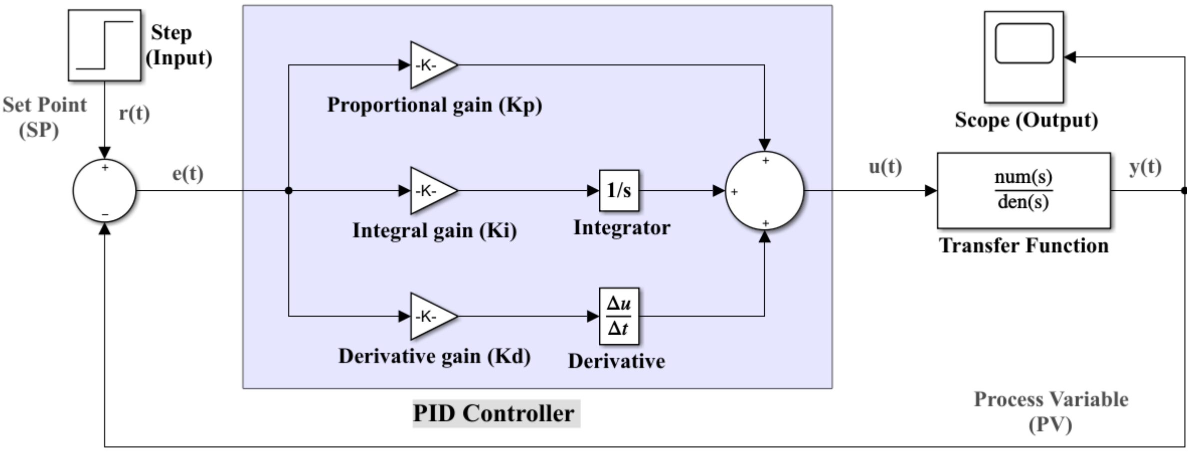


Fig. 4.1 Simulink Model of PID Controller

From Fig. 4.1 it is evident that e(t)=SP-PV expresses error value as the difference between a preferred set point (SP) and a computed process variable (PV). Based on this error value, a PID controller provides a correction by using proportional, integral, and derivative parts.

The equation of controller output according to the PID algorithm can be stated as [92],

$$u(t) = k_p e(t) + k_i \int e\,(t)dt + k_d \frac{d}{dt} e(t) \tag{4.1}$$

Thus, the transfer function of the PID controller is denoted as,

$$\frac{U(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s \tag{4.2}$$

Here, u(t) represents controller output. Error, e(t)=r(t)-y(t) where r(t) indicates reference variable and y(t) indicates computed process variable. The tuning parameter of controllers are k_p (proportional gain), k_i (integral gain), and k_d (derivative gain).

4.1.2 Tuning of PID Controller

Tuning of PID controller involves controlling gain values of proportional, integral, and derivative terms to obtain a better response of the system by eliminating the steady-state error as well as reducing overshoot and obtaining quick rise and settling time. Hence, the effect of the tuning parameters are described as follows:

i. Proportional term (P):

P relies on the present error while the value of k_p affects both the rise time and the steady-state error. Though complete elimination is not possible, it can reduce both the rise time and the steady-state error. The mathematical expression of P is given by,

$$P = k_p e(t) \tag{4.3}$$

ii. Integral term (I):

I depends on the aggregation of past errors. The tuning of k_i can eliminate the steady-state error in exchange for making the transient response slower. The mathematical expression of I is given by,

$$I = k_i \int e\,(t) dt \tag{4.4}$$

iii. Derivative term (D):

D counts on the projection of future errors. The tuning of k_d can increase the stability of the system by improving the transient response along with reducing the overshoot. The mathematical expression of D is given by,

$$D = k_d \frac{d}{dt} e(t) \tag{4.5}$$

Hence, the weighted sum of the above three terms, by using equation 4.1, is applied to regulate process variables and control specified system response. In Table 4.1, the effects of the tuning parameters of a PID controller on a DC-DC converter are tabulated [93].

Table 4.1 Effects of Tuning Parameters of PID Controller on a DC-DC Converter

Type of controller	Rise Time	Overshoot	Settling Time	Steady State Error
Proportional	Decrease	Increase	Small Change	Decrease
Integral	Decrease	Increase	Increase	Eliminate
Derivative	Minor Change	Decrease	Decrease	No effect

4.2 Objective Function

The objective function is defined as the real-valued function that is to be maximized or minimized for improving a system's response. Hence, different integral performance functions such as IAE, ITAE, ISE, and ITSE are used in this case to improve the stability of the system while minimizing the steady-state error [13].

i. ***Integral Absolute Error (IAE):***

IAE is based on the integration of the absolute error over time in which no weight is added to errors in a system's response. The mathematical expression of IAE is given by,

$$IAE = \int_0^\tau |e(t)|dt \tag{4.6}$$

ii. ***Integral Time-weighted Absolute Error (ITAE):***

ITAE is based on the integration of the absolute error that is multiplied by the time over time where errors are weighted. The mathematical expression of ITAE is given by,

$$ITAE = \int_0^\tau t.|e(t)dt \tag{4.7}$$

iii. ***Integral Squared Error (ISE):***

ISE is based on the integration of the square of the error over time where large errors are prioritized for elimination. The mathematical expression of ISE is given by,

$$ISE = \int_0^\tau e(t)^2dt \tag{4.8}$$

iv. ***Integral Time Squared Error (ITSE):***

ITSE is based on the integration of the square of the error that is multiplied by the time over time. The mathematical expression of ITSE is given by,

$$ITSE = \int_0^\tau t.e(t)^2dt \tag{4.9}$$

4.3 Layout of BIA based PID Controller:

In this investigating approach, a PID controller is tuned by optimizing values of K_P, K_I, and K_D using the BIA (FA, PSO, GA, and, ABC) mechanism to conduct closed-loop stability analysis on DC-DC converters [95-96]. A basic layout of this procedure is illustrated in Fig. 4.2 [13]. A compatible output is maintained through the continuous regulation of the error. For this purpose, the objective function performances are assessed through numerous iterations using four error formulas (IAE, ITAE, ISE, and ITSE) conducted by BIA. Hence, the optimized solution that is obtained through this process exhibits satisfactory results.

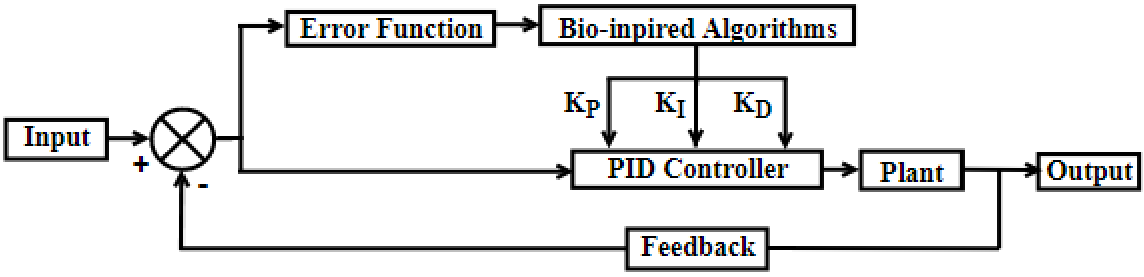


Fig. 4.2 Layout of Optimized PID controller

CHAPTER 5

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In this thesis work, all the simulation for stability analysis of DC-DC converter is carried out by using MATLAB based on the aforementioned mathematical modeling and layout of the optimized PID controller. Performance of the optimized PID controller is analyzed based on the value of the step response's characteristics such as percentage of overshoot, rise time, settling time, and peak amplitude. At first, the performance of the conventional PID controller is observed through the response of the system. Later, the gain parameters of the PID controller are optimized by using BIA to attain enhanced performance. Hence, a comparative analysis is done to find the optimum PID controller for ensuring better stability of the DC-DC converter.

5.1 Transfer Function

A transfer function is defined as the mathematical representation of interrelation between output and input of a system in terms of frequency. In addition, the output and input variable is shaped using Laplace transform while taking the initial conditions as zero [94]. Hence, a transfer function can be categorized into two types like open-loop and closed-loop transfer function based on the classification of the control system.

5.1.1 Open-Loop Transfer Function

An open-loop system refers to systems in which output has no impact on the control action of the input. In this thesis work, the circuit of the Cuk converter and Zeta converter is initially constructed as an open-loop system and transfer functions of such systems are known as an open-loop transfer function. Hence, the transfer function of the open-loop Cuk converter is expressed in equation 5.1 and Zeta converter in equation 5.2.

$$T(S)_{Cuk} = \frac{-3.364\times10^{-3}s^3-2.362\times10^{-4}s^2-2.488\times10^{-7}s-5.355\times10^{-11}}{s^4+1.795\times10^{-2}s^3+1.439\times10^{-4}s^2+1.564\times10^{-7}s+5.648\times10^{-11}} \tag{5.1}$$

$$T(S)_{Zeta} = \frac{1.64\times10^{3}s^3+8.744\times10^{8}s^2+1.758\times10^{12}s+6.505\times10^{16}}{s^4+8.452\times10^{3}s^3+1.647\times10^{8}s^2+5.878\times10^{11}s+4.696\times10^{15}} \tag{5.2}$$

5.1.2 Closed-Loop Transfer Function

A closed loop system refers to systems in which control actions are dependent on output as it controls the applied input. After open-loop analysis, the circuit of the Cuk converter and Zeta converter is converted into a closed-loop system by adding PID controller with the existing system and transfer functions of such systems are known as a closed-loop transfer function. Hence, the transfer function of the closed-loop Cuk converter is expressed in equation 5.3 and Zeta converter in equation 5.4.

$$T(S)_{Cuk} = \frac{0.07276s^5+0.7158s^4+0.07819s^3+2.039\times10^{-3}s^2+2.104\times10^{-6}s+4.504\times10^{-10}}{s^5+0.01795s^4+1.439\times10^{-4}s^3+1.564\times10^{-7}s^2+5.648\times10^{-11}s} \tag{5.3}$$

$$T(S)_{Cuk} = \frac{0.07276s^5+3.24\times10^5s^4+1.722\times10^{10}s^3+3.537\times10^{13}s^2+1.277\times10^{18}s+6.247\times10^{19}}{s^5+8452s^4+1.647\times10^8s^3+5.878\times10^{11}s^2+4.969\times10^{15}s} \tag{5.4}$$

5.2 Performance Parameters

A Performance parameters represent the characteristics of a method in which values are evaluated to analyze the system's response. In this case, the characteristics of the step responses such as percentage of overshoot, rise time, settling time, steady-state error, and peak amplitude are observed to analyze the stability of the DC-DC converter [13, 94].

i. Percentage of Overshoot (%OS):

Overshoot represents the concept of exceeding a signal's desired output. Hence, %OS represents overshooting the value of steady-state at the peak time in percentage. The mathematical expression of %OS is given by,

$$\%OS = e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}} \times 100 \tag{5.5}$$

Here, ζ represents damping ratio that prevents oscillation.

ii. Peak Time (T_p):

Peak time represents the time that is needed to gain the first or maximum peak. The mathematical expression of T_p is given by,

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \tag{5.6}$$

iii. Settling Time (T_s):

Settling time represents the time that is needed to hold out within $\pm 2\%$ of the steady-state value. The mathematical expression of T_s is given by,

$$T_s = \frac{4}{\zeta\omega_n} \tag{5.7}$$

iv. Rise Time (T_r):

Rise time represents the time that is needed to reach from 0.1 to 0.9 of the waveform's final value.

v. ***Steady-state Error:***

Steady-state error represents the deviation of the actual value from the desired value when the steady-state is obtained for a system.

5.3 MATLAB Simulation for Cuk converter

Under the aegis of the equations developed before, a higher-order transfer function of the Cuk converter is obtained from the state-space model as a means to simulate the stability of the system. Later, MATLAB is used to reduce the order of the model. Hence, the open-loop and closed-loop transfer function, stated in equations 5.1 and 5.3, are obtained. In Table 5.1 parameters of the Cuk converter are enlisted. Fig 5.1 and 5.2 represent the MATLAB Simulink model of open-loop and closed-loop Cuk converter.

Table 5.1 Parameters of Cuk converter

Parameter	**Symbol**	**Value**
Voltage (input)	V_{in}	15 V
Switching Frequency	fs	100 kHz
Duty Cycle	d	0.50
Inductor	L_1	117 µH
	L_2	50.4 µH
Capacitor	C_1	1 mF
	C_2	3 mF
Load Resistance	R_o	5 Ω
Voltage (output)	V_o	14.26 V

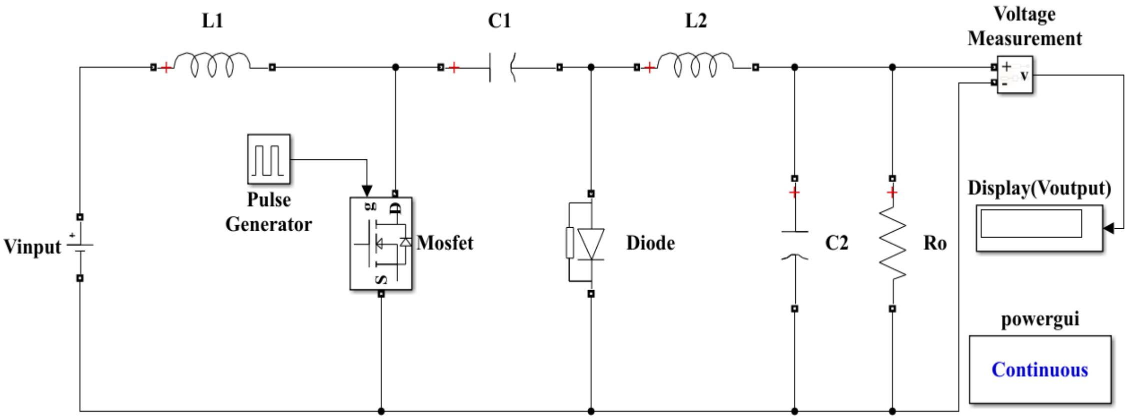


Fig. 5.1 MATLAB Simulink model of Open-loop Cuk Converter

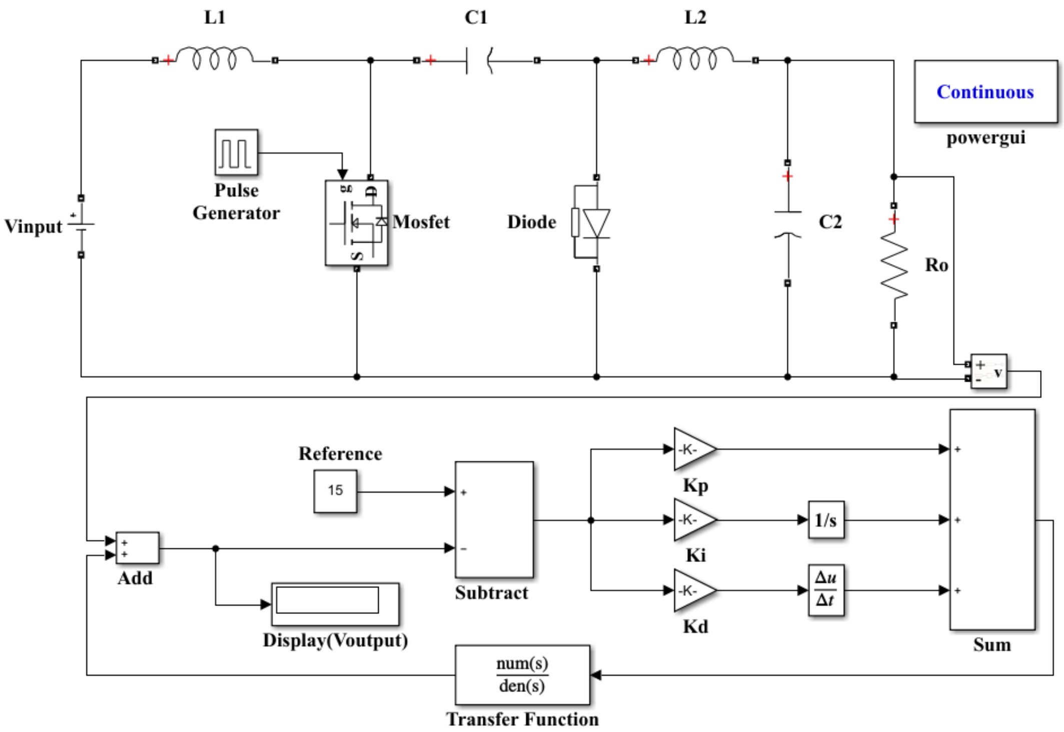


Fig. 5.2 MATLAB Simulink model of Closed-loop Cuk Converter

5.3.1 Conventional PID controller

At first, step response for conventional PID controller is observed that is displayed in Fig. 5.3. In Table 5.2 gain values and performance parameters of conventional PID controller are enlisted.

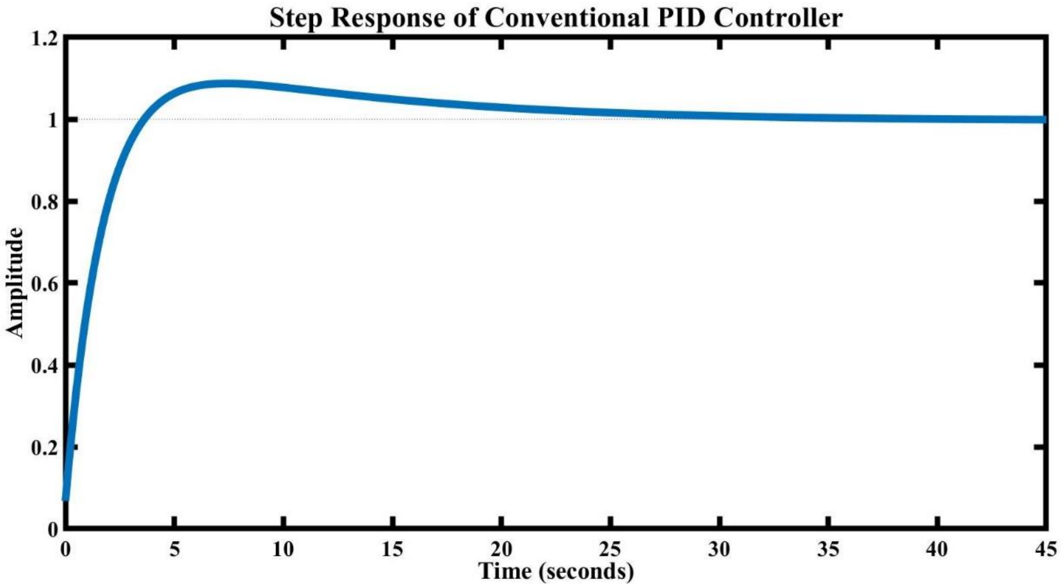


Fig. 5.3 Step Response of Conventional PID Controller (Cuk Converter)

Table 5.2 Gain and Performance Parameters of Conventional PID controller (Cuk Converter)

Attributes	**Symbols**	**Values**
Gain Values	**K_P**	-211.25
	K_I	-8.41
	K_D	-21.63
Performance Parameters	%OS	8.72
	Tr (seconds)	2.50
	Ts (seconds)	23.7
	Peak Amplitude	1.09

5.3.2 BIA-PID controller

After observing the performance of Conventional PID controller, BIA is implemented to optimize the gain parameters of PID controller. Hence, step responses are observed and gain values along with performance indices are tabulated for different BIA-PID controller such as PSO-PID, FA-PID, GA-PID, and ABC-PID.

5.3.2.1 PSO-PID controller

Initially, PSO is implemented for tuning of PID controller and parameters of PSO are given in Table 5.3. Next, step responses are simulated for different error functions illustrated in Fig. 5.4, 5.5, 5.6, and 5.7. Later, a comparative analysis of all these step responses are showed in Fig. 5.8. Gain and performance parameters of PSO-PID controller for Cuk converter are tabulated in Table 5.4 and a comparative illustration of performance parameters are displayed in Fig. 5.9.

Table 5.3 Parameters of Particle Swarm Optimization

Parameters		**Values**
Acceleration Constants	C_1	2
	C_2	2
Inertia	W_{max}	0.9
	W_{min}	0.2
Swarm size		100

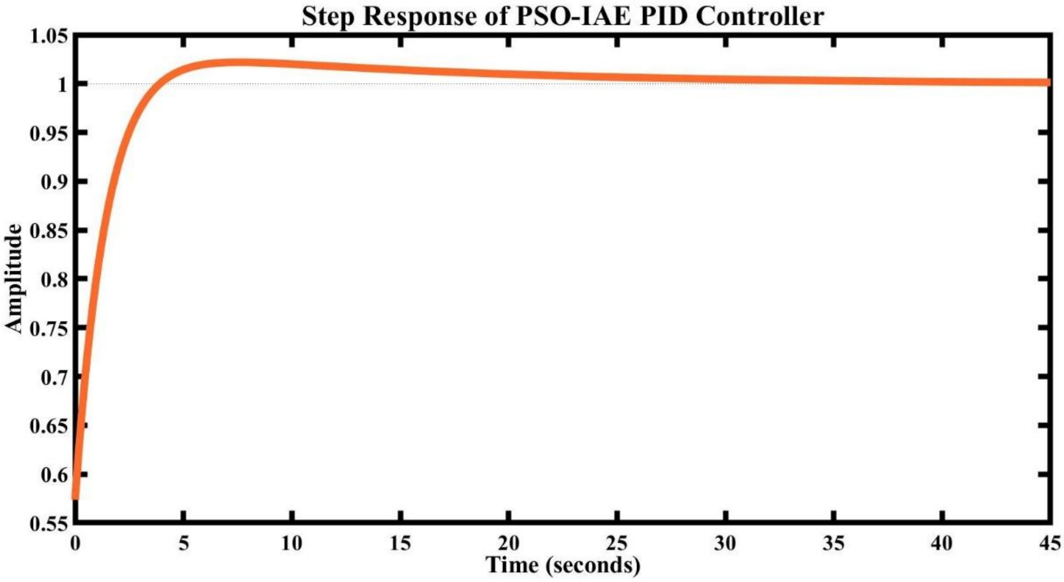


Fig. 5.4 Step Response of PSO (IAE) based PID Controller (Cuk Converter)

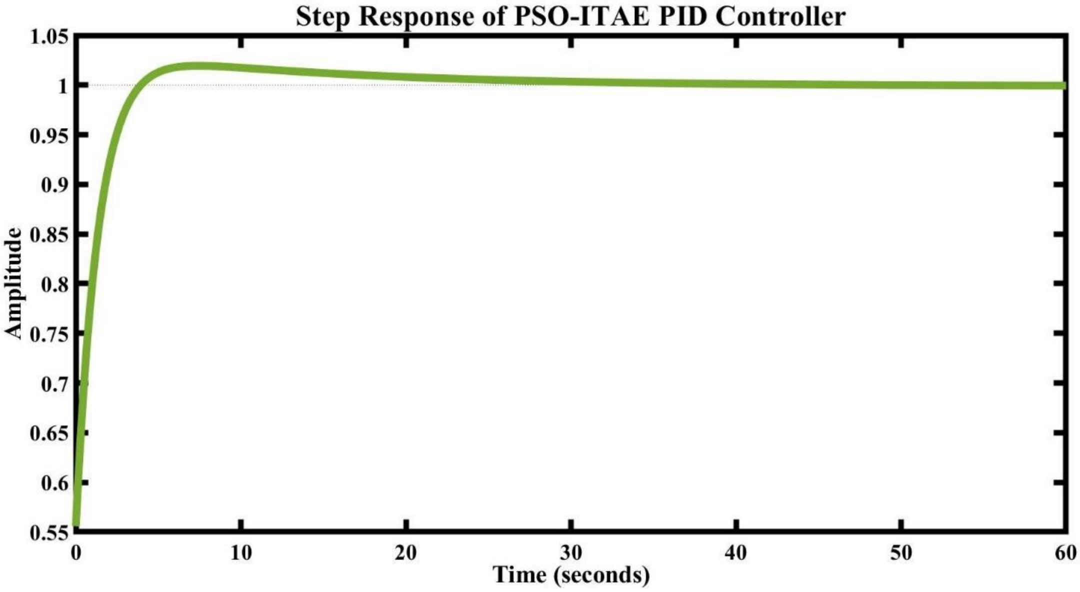


Fig. 5.5 Step Response of PSO (ITAE) based PID Controller (Cuk Converter)

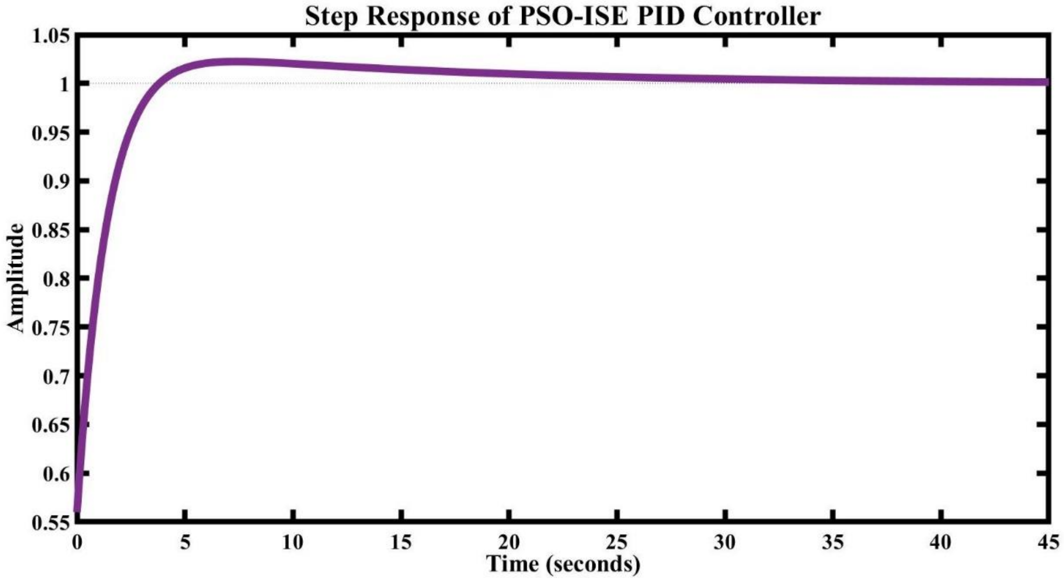


Fig. 5.6 Step Response of PSO (ISE) based PID Controller (Cuk Converter)

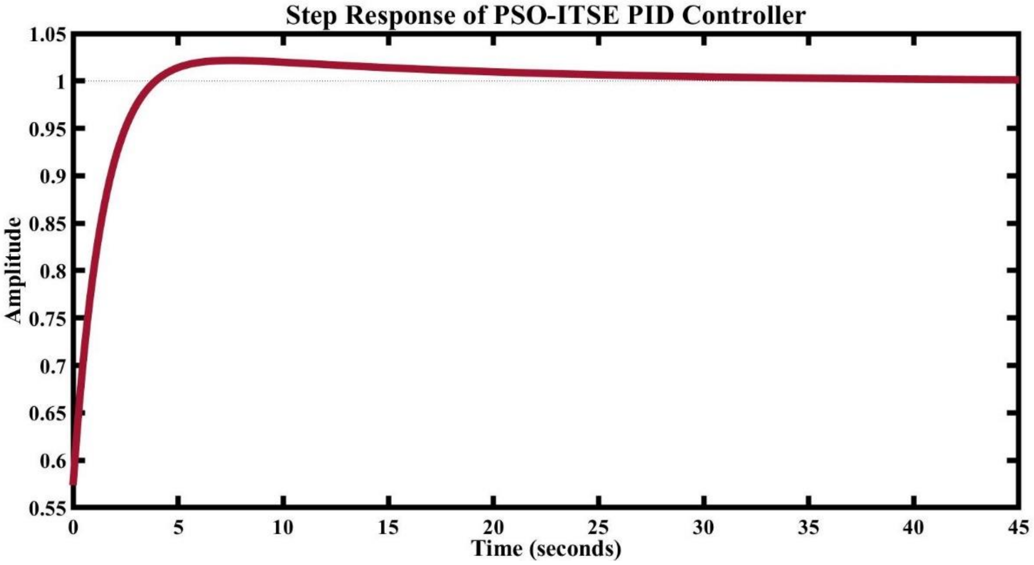


Fig. 5.7 Step Response of PSO (ITSE) based PID Controller (Cuk Converter)

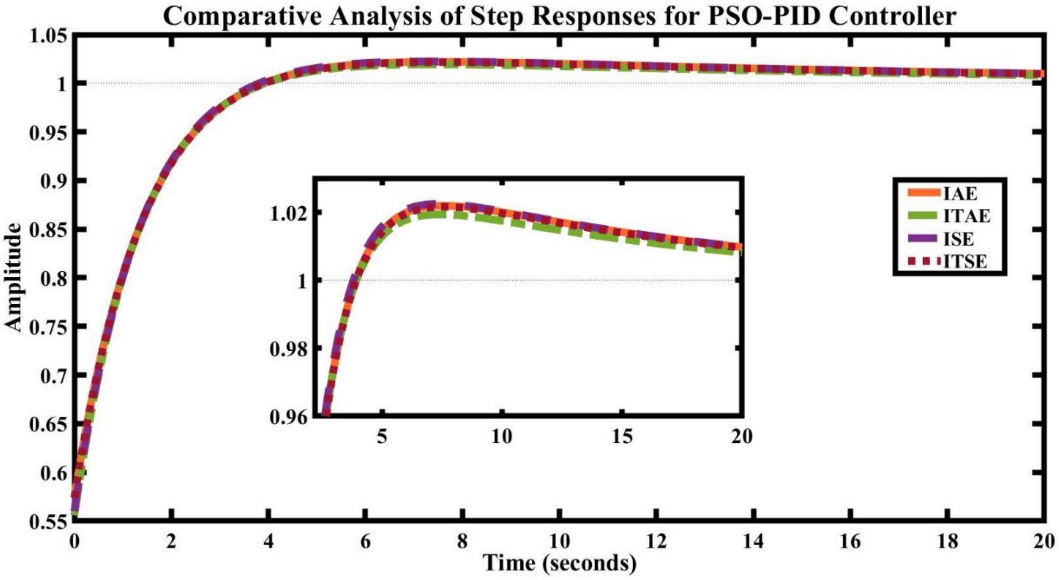


Fig. 5.8 Comparative Analysis of Step Responses for PSO-PID-CUK

Table 5.4 Gain and Performance Parameters of PSO-PID controller (Cuk Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	K_P	-500	-500	-500	-500
	K_I	-3.10	-0.01	-3.42	-2.74
	K_D	-400	-371.82	-378.15	-400
Performance Parameters	***%OS***	2.19	1.94	2.25	2.16
	Tr (seconds)	2.48	2.43	2.41	2.48
	Ts (seconds)	21.8	18.9	21.5	21.5
	Peak Amplitude	1.02	1.02	1.02	1.02

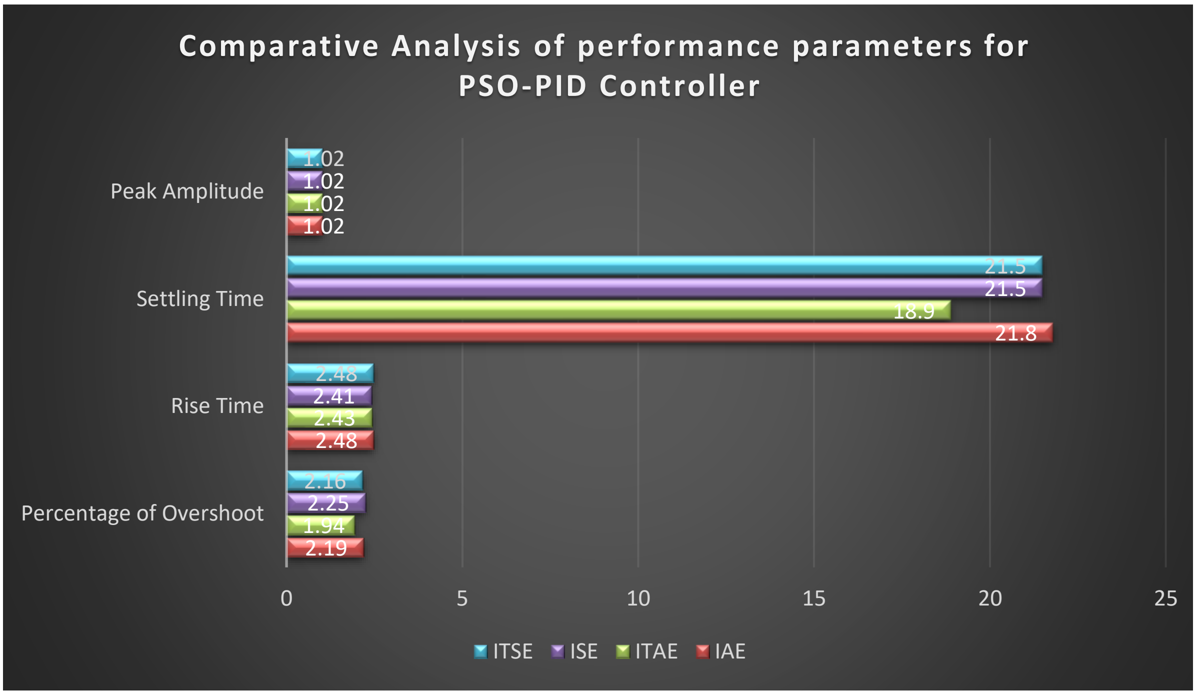


Fig. 5.9 Comparative Illustration of Performance Parameters for PSO-PID-CUK

5.3.2.2 FA-PID controller

Next, FA is introduced for optimization of PID controller and parameters of FA are given in Table 5.5. Afterward, step responses are simulated for different error functions illustrated in Fig. 5.10, 5.11, 5.12, and 5.13. Moreover, a comparative analysis of all these step responses are showed in Fig. 5.14. Gain and performance parameters of FA-PID controller for Cuk converter are given in Table 5.6 and a comparative illustration of performance parameters are showed in Fig. 5.15.

Table 5.5 Parameters of Firefly Algorithm

Parameters	**Values**
Mutation Coefficient(α)	0.2
Attraction Coefficient(β)	2
Light Absorption Coefficient(γ)	1
Number of fireflies	100

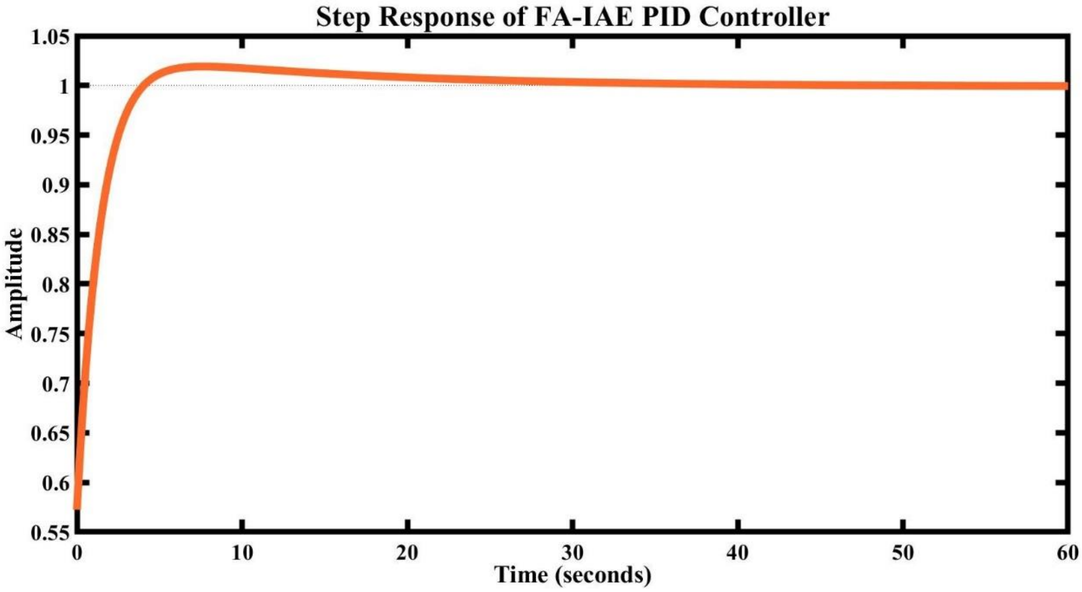


Fig. 5.10 Step Response of FA (IAE) based PID Controller (Cuk Converter)

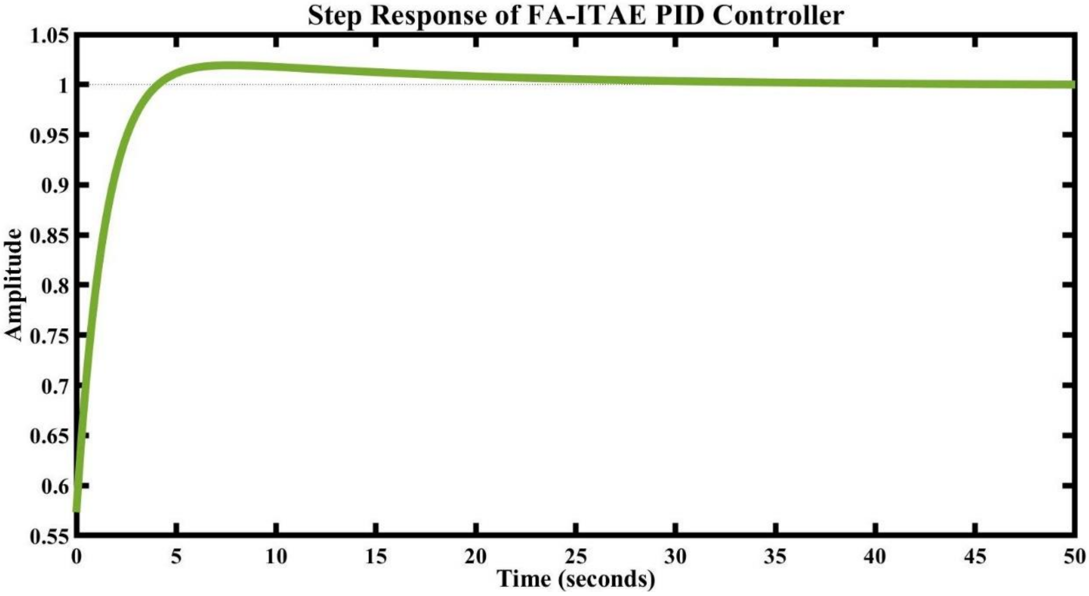


Fig. 5.11 Step Response of FA (ITAE) based PID Controller (Cuk Converter)

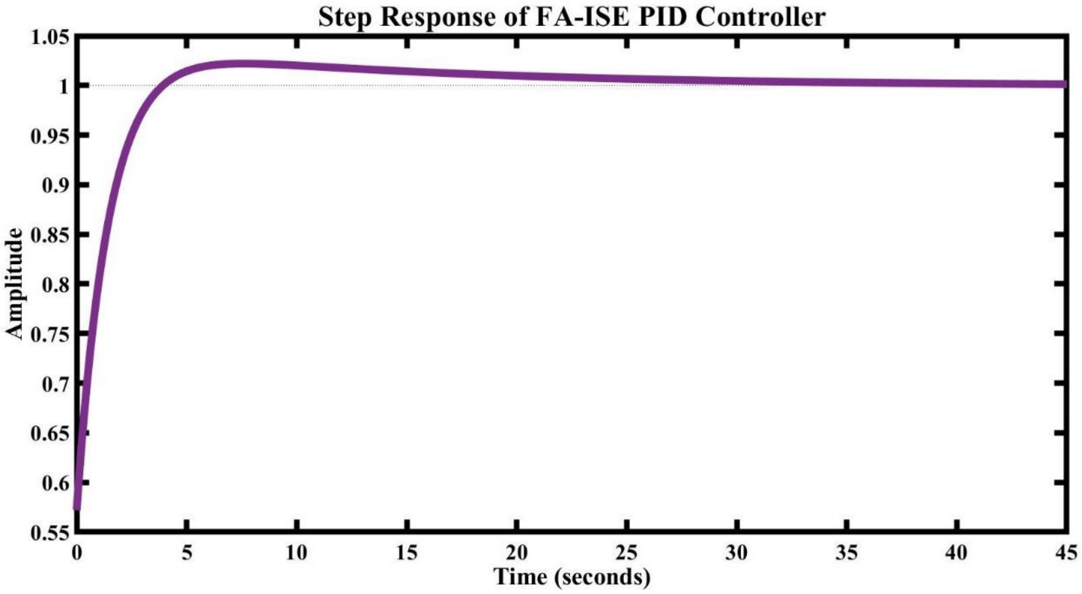


Fig. 5.12 Step Response of FA (ISE) based PID Controller (Cuk Converter)

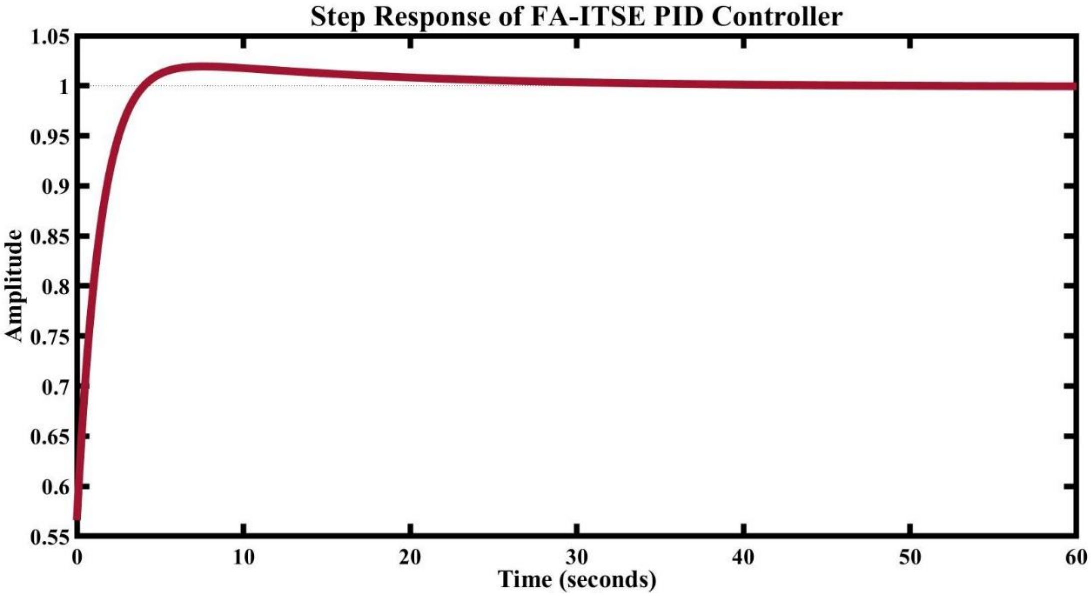


Fig. 5.13 Step Response of FA (ITSE) based PID Controller (Cuk Converter)

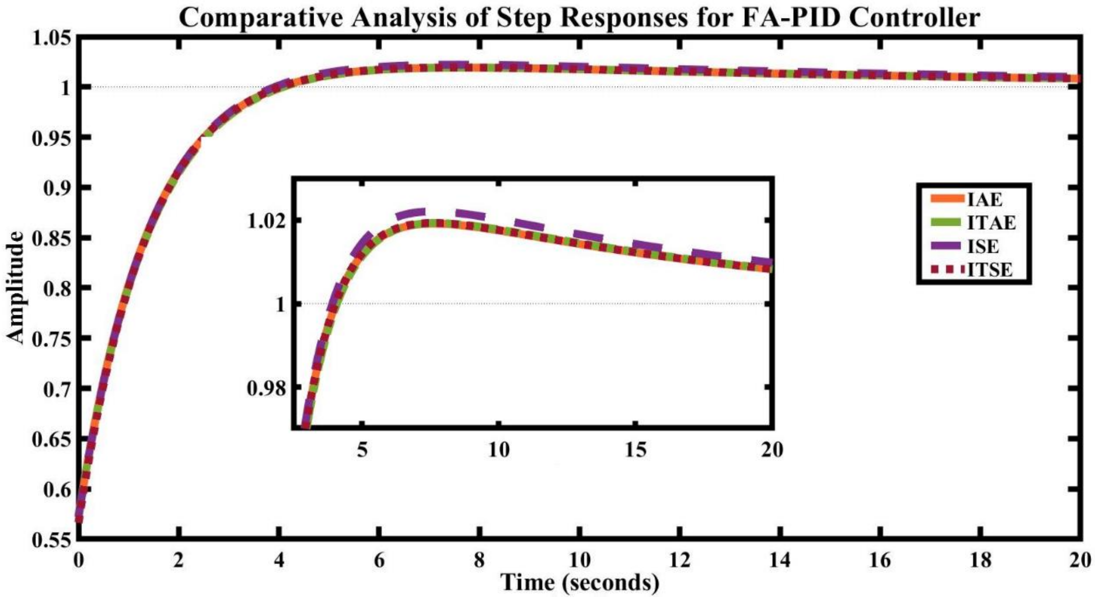


Fig. 5.14 Comparative Analysis of Step Responses for FA-PID-CUK

Table 5.6 Gain and Performance Parameters of FA-PID controller (Cuk Converter)

Attributes	Symbols	Values			
		IAE	*ITAE*	*ISE*	*ITSE*
Gain Values	K_P	-500	-493.61	-496.48	-496.06
	K_I	-0.071	-0.054	-3.06	-1×10^{-05}
	K_D	-398.07	-399.48	-397.26	-387.88
Performance Parameters	***%OS***	1.91	1.93	2.20	1.93
	Tr (seconds)	2.51	2.54	2.48	2.50
	Ts (seconds)	19.5	19.7	21.8	19.4
	Peak Amplitude	1.02	1.02	1.02	1.02

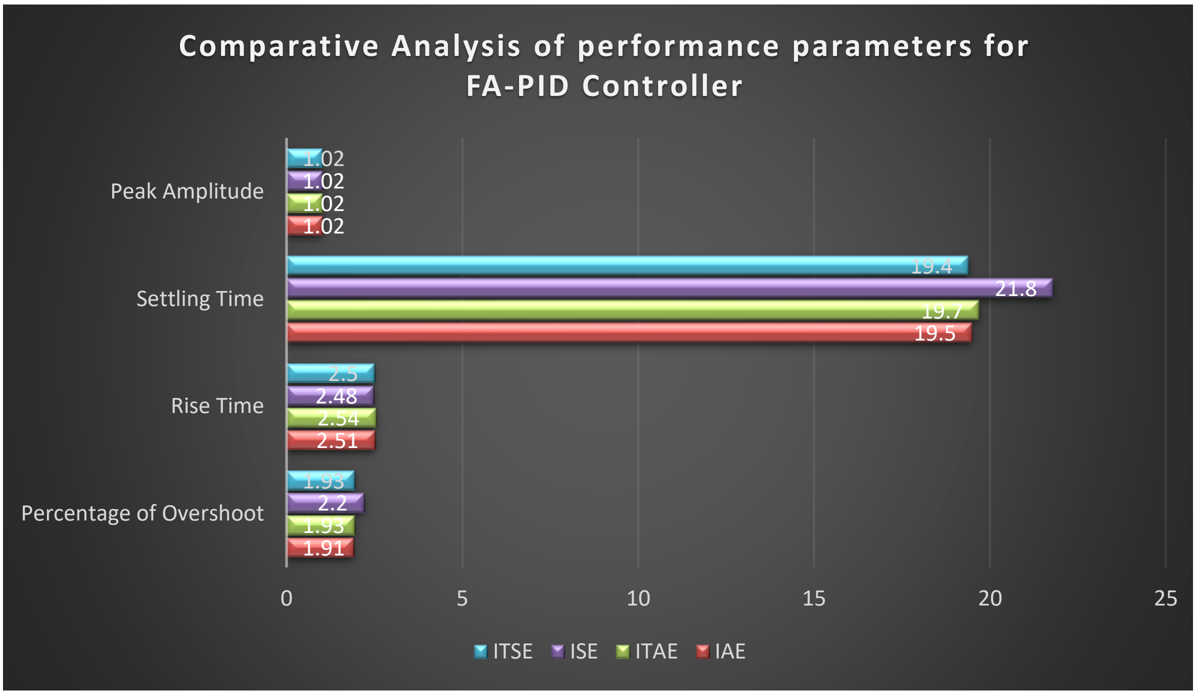


Fig. 5.15 Comparative Illustration of Performance Parameters for FA-PID-CUK

5.3.2.3 GA-PID controller

Similarly, GA is implemented to tune the gain parameters of PID controller and parameters of GA are given in Table 5.7 [13]. Afterward, step responses are simulated for different error functions illustrated in Fig. 5.16, 5.17, 5.18, and 5.19. Following that a comparative analysis of all these step responses are showed in Fig. 5.20. Gain and performance parameters of GA-PID controller for Cuk converter are given in Table 5.8 and a comparative illustration of performance parameters are illustrated in Fig. 5.21.

Table 5.7 Parameters of Genetic Algorithm

Parameters	**Values**
Fitness Scaling	Rank
Selection	Stochastic Uniform
Mutation	0.1
Crossover	0.8
Population	100

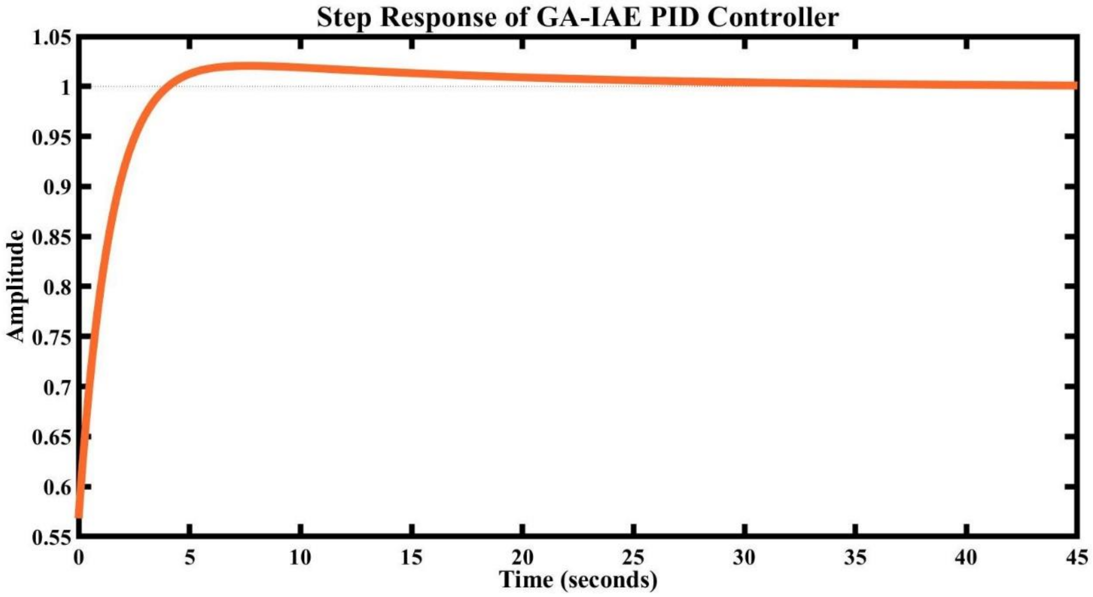


Fig. 5.16 Step Response of GA (IAE) based PID Controller (Cuk Converter)

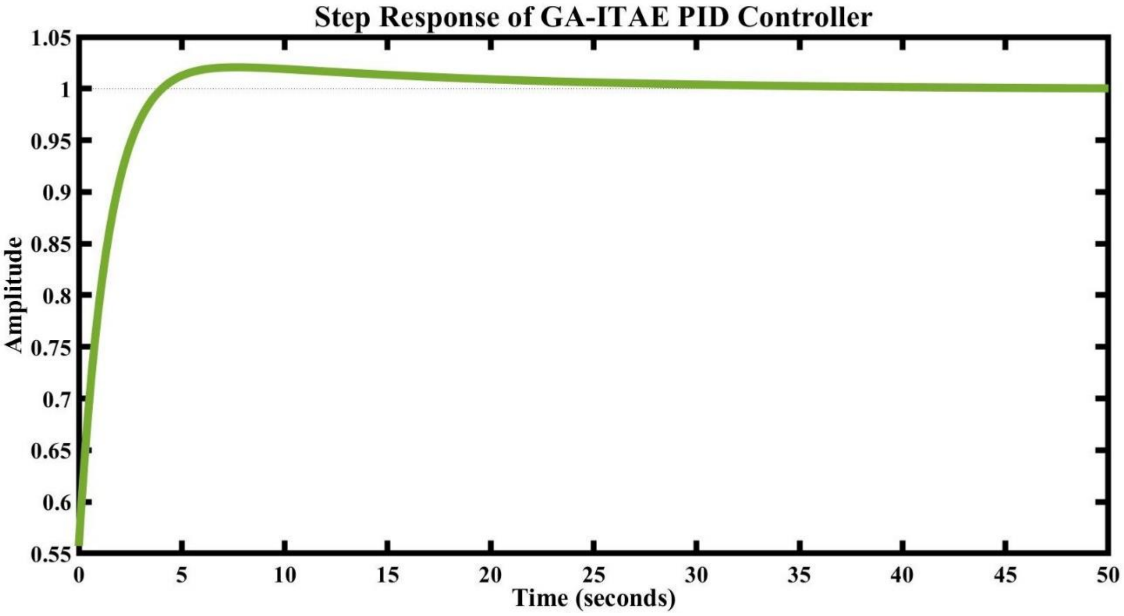


Fig. 5.17 Step Response of GA (ITAE) based PID Controller (Cuk Converter)

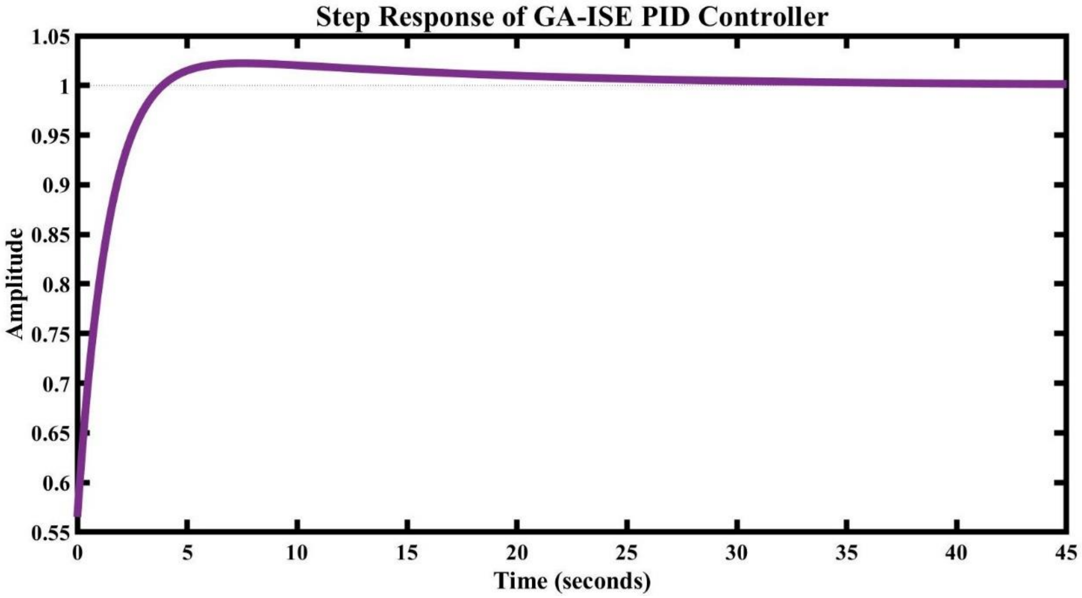


Fig. 5.18 Step Response of GA (ISE) based PID Controller (Cuk Converter)

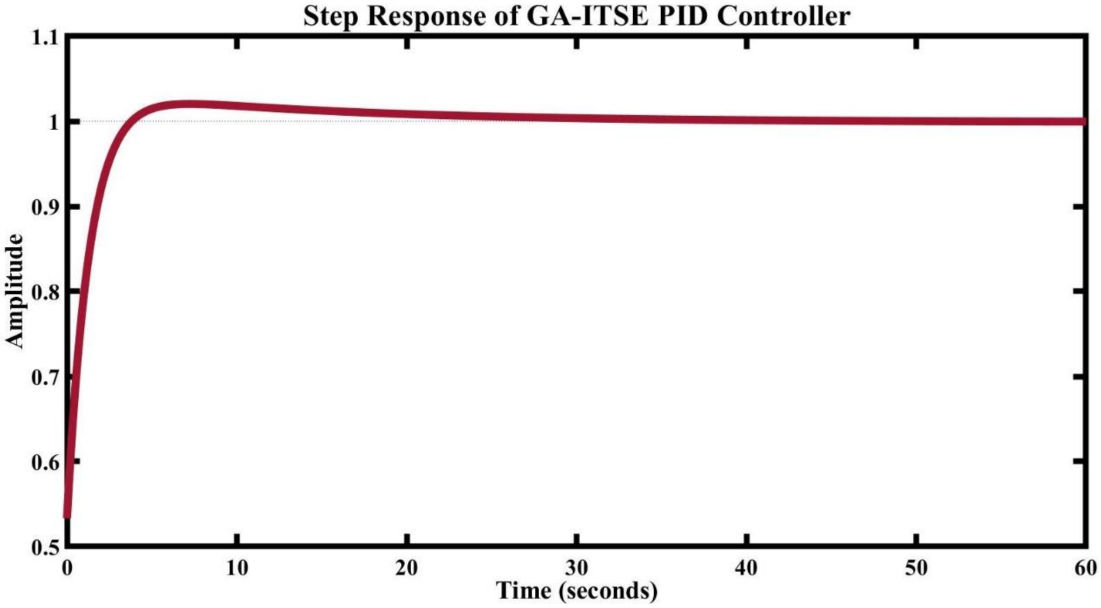


Fig. 5.19 Step Response of GA (ITSE) based PID Controller (Cuk Converter)

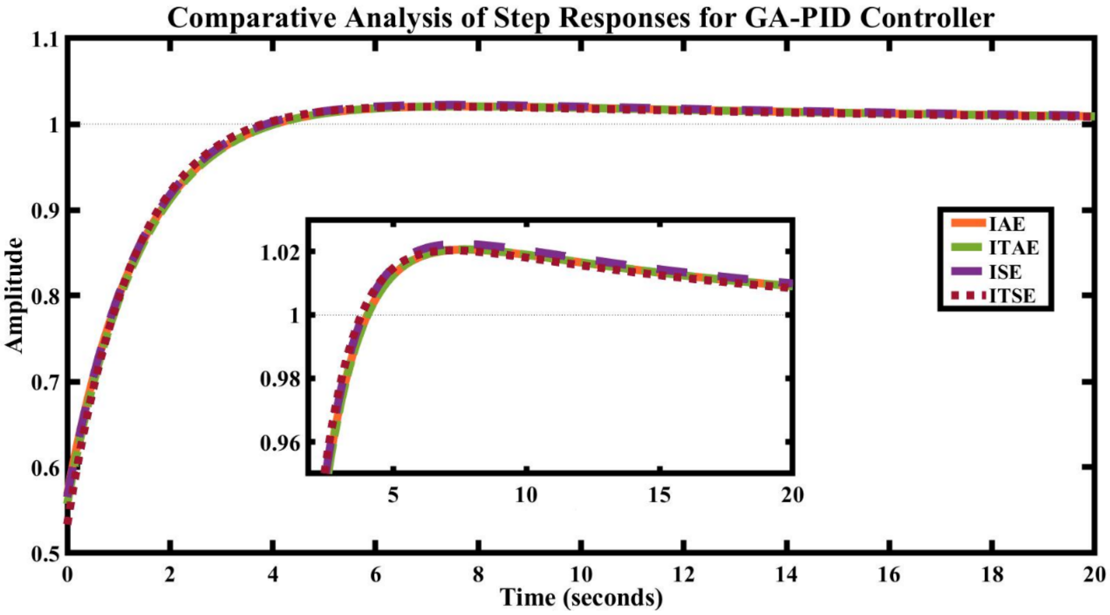


Fig. 5.20 Comparative Analysis of Step Responses for GA-PID-CUK

Table 5.8 Gain and Performance Parameters of GA-PID controller (Cuk Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	K_P	-488.14	-477.85	-495.21	-494.98
	K_I	-1.119	-0.707	-3.21	-0.463
	K_D	-391.24	-374.14	-386.48	-339.62
Performance Parameters	***%OS***	2.06	2.07	2.24	2.03
	Tr (seconds)	2.53	2.53	2.46	2.35
	Ts (seconds)	20.6	20.2	21.7	18.7
	Peak Amplitude	1.02	1.02	1.02	1.02

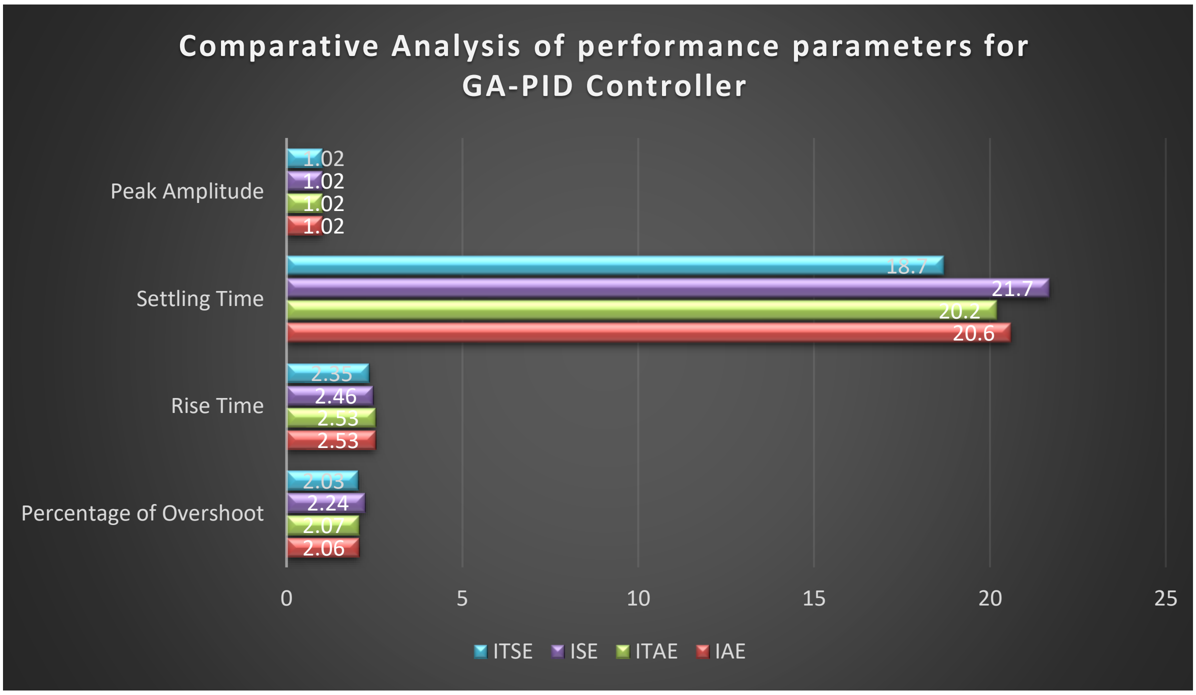


Fig. 5.21 Comparative Illustration of Performance Parameters for GA-PID-CUK

5.3.2.4 ABC-PID controller

Later, ABC is introduced for optimizing the gain parameters of PID controller and parameters of ABC are given in Table 5.9. Then step responses are simulated for different error functions illustrated in Fig. 5.22, 5.23, 5.24, and 5.25. Thereafter, a comparative analysis of all these step responses are showed in Fig. 5.26. Gain and performance parameters of ABC-PID controller for Cuk converter are given in Table 5.10 and a comparative illustration of performance parameters are displayed in Fig. 5.27.

Table 5.9 Parameters of Artificial Bee Colony

Parameters	**Values**
Colony size	100
Number of Onlooker Bees	50%% of the swarm size
Number of Employed Bees	50%% of the swarm size
Number of Scout Bees	1 per cycle

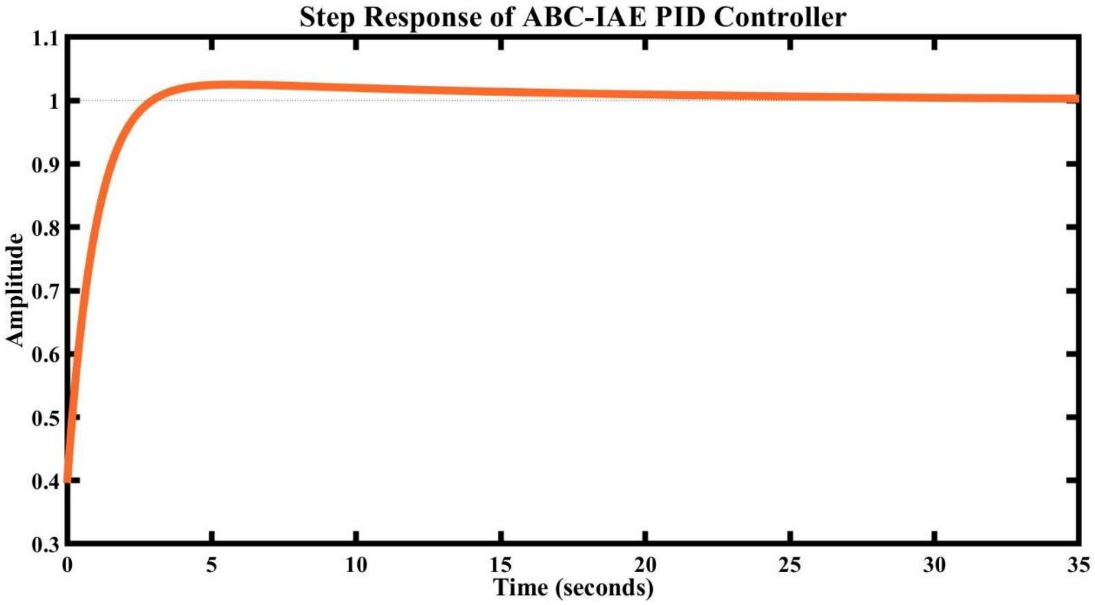


Fig. 5.22 Step Response of ABC (IAE) based PID Controller (Cuk Converter)

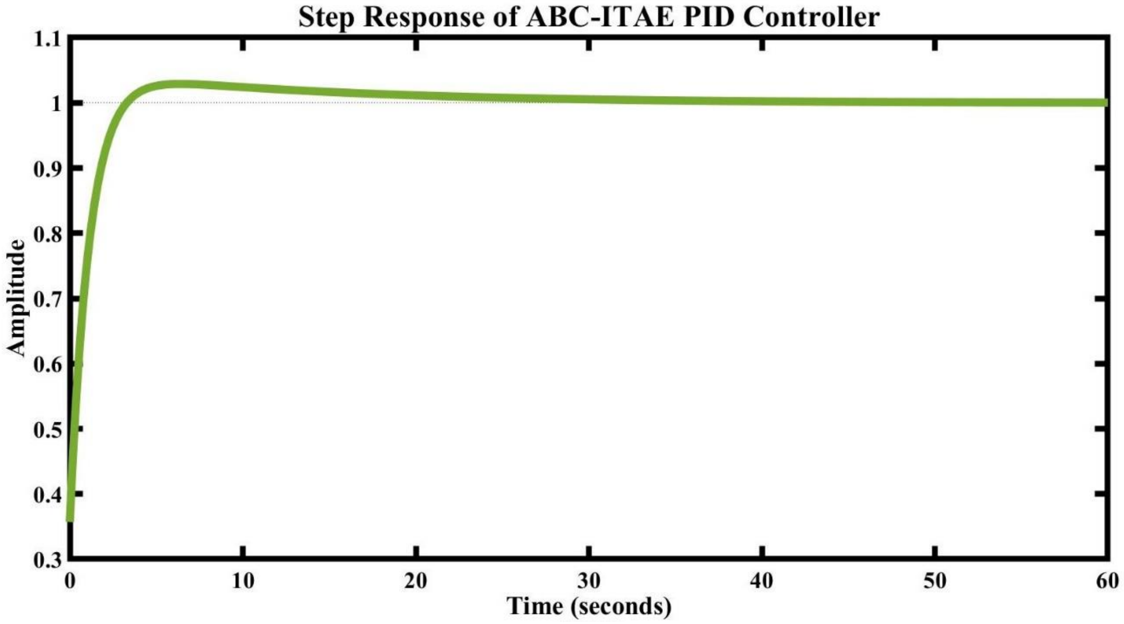


Fig. 5.23 Step Response of ABC (ITAE) based PID Controller (Cuk Converter)

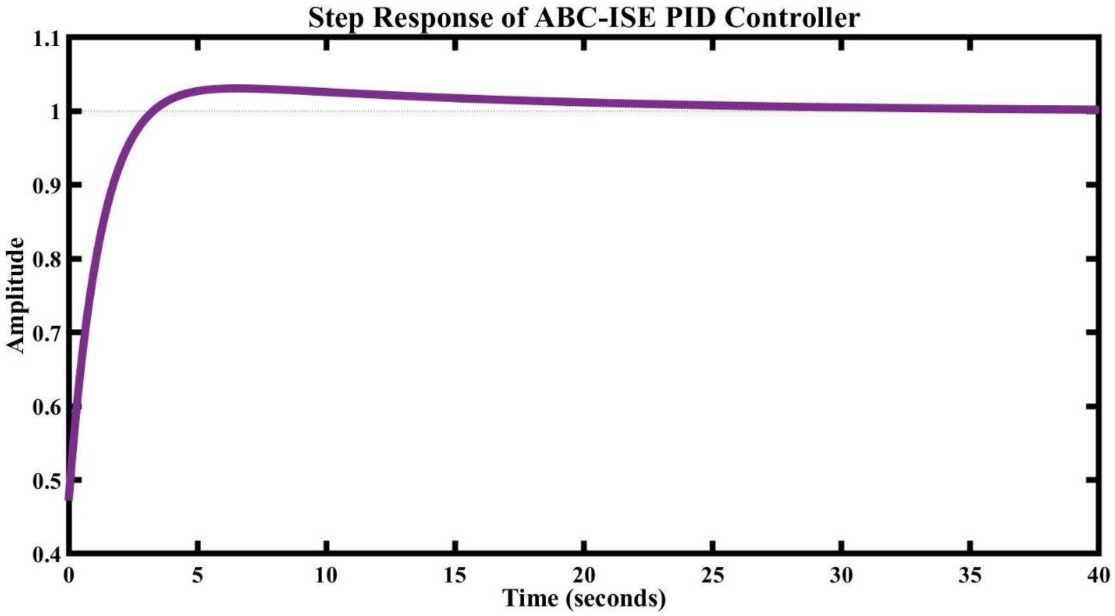


Fig. 5.24 Step Response of ABC (ISE) based PID Controller (Cuk Converter)

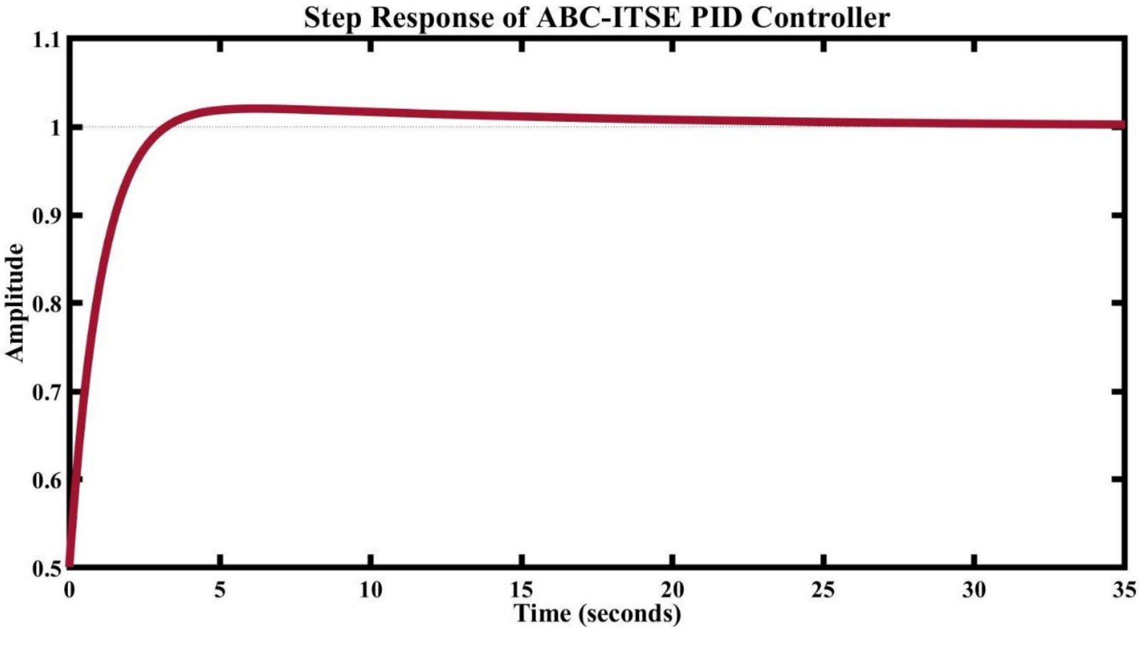


Fig. 5.25 Step Response of ABC (ITSE) based PID Controller (Cuk Converter)

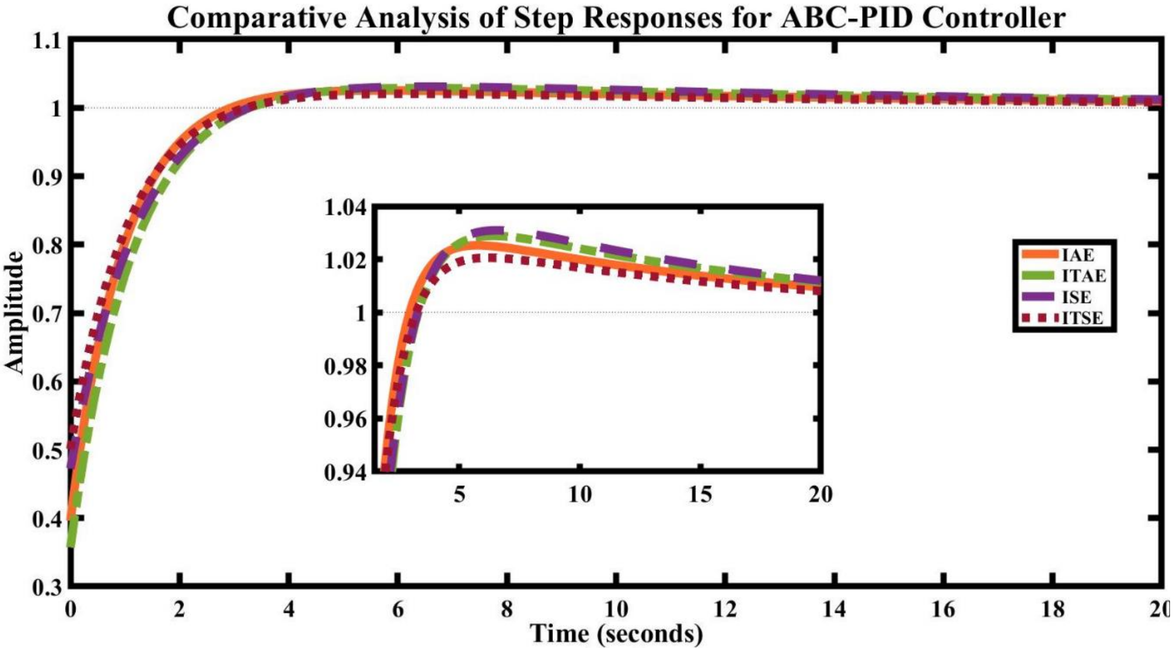


Fig. 5.26 Comparative Analysis of Step Responses for ABC-PID-CUK

Table 5.10 Gain and Performance Parameters of ABC-PID controller (Cuk Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	**K_P**	-516.76	-421.86	-474.54	-567.91
	K_I	-4.63	-2.86	-9.43	-2.82
	K_D	-194.93	-164.95	-265.92	-298.19
Performance Parameters	***%OS***	2.53	2.88	3.09	2.06
	Tr (seconds)	1.79	2.03	2.11	1.95
	Ts (seconds)	16.8	18.4	21.6	17.1
	Peak Amplitude	1.03	1.03	1.03	1.02

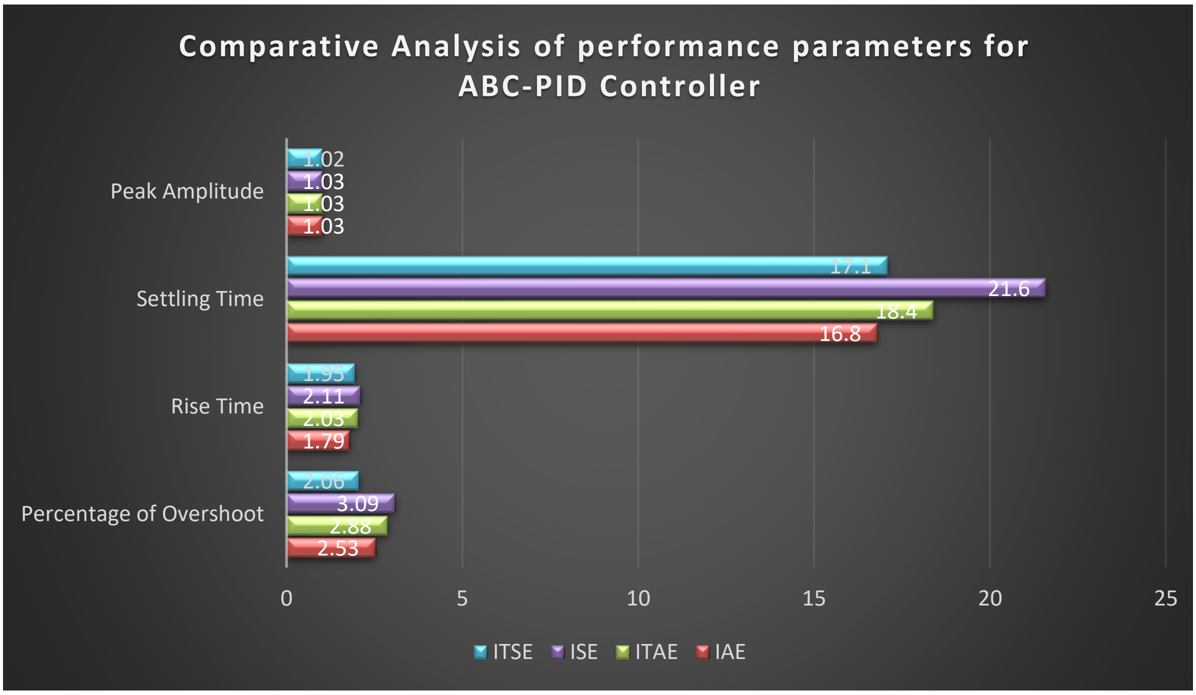


Fig. 5.27 Comparative Illustration of Performance Parameters for ABC-PID-CUK

5.3.3 Comparative Analysis

Lastly, a comparison of performance parameters for optimum BIA-PID controller is showed in Table 5.11 based on the data of Table 5.2, 5.4, 5.6, 5.8, and 5.10. Moreover, an overall comparative analysis of step responses, showed in Fig. 5.28, is done based on the values of performance parameters to find out the optimum PID controller for enhancing stability of Cuk converter. Hence, an overall comparative illustration of performance indices is displayed in Fig. 5.29 from which it is evident that FA-IAE performs better form the overshoot point of view.

Table 5.11 Comparative Performance Parameters of PID Controllers (Cuk Converter)

Performance Parameters	**PID Controllers**				
	Conventional	***FA_IAE***	***PSO_ITAE***	***GA_ITSE***	***ABC_ITSE***
Percentage of Overshoot (%OS)	8.72	1.91	1.94	2.03	2.06
Rise Time, Tr (seconds)	2.50	2.51	2.43	2.35	1.95
Settling Time, Ts (seconds)	23.7	19.5	18.9	18.7	17.1
Peak Amplitude	1.09	1.02	1.02	1.02	1.02

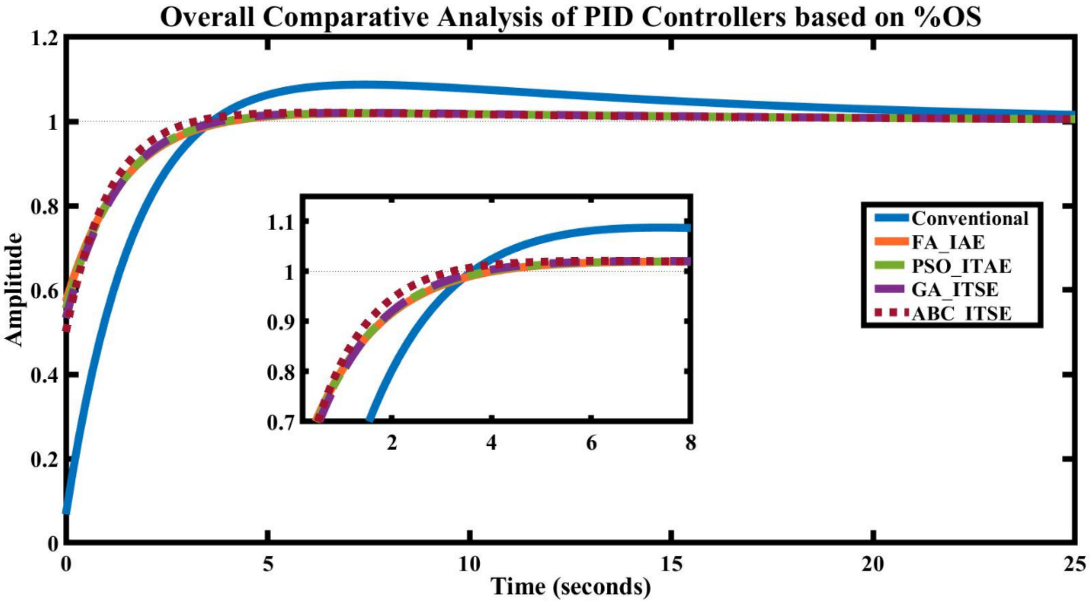


Fig. 5.28 Overall Comparative step response analysis of PID controllers (Cuk Converter)

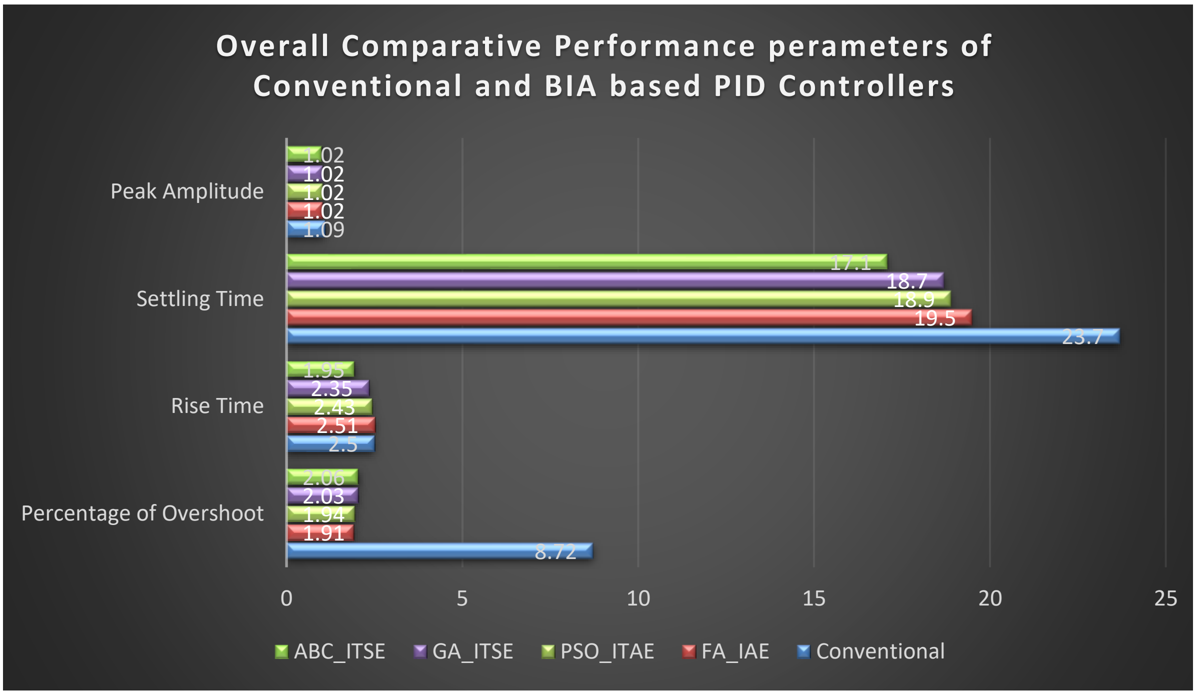


Fig. 5.29 Overall Comparative Illustration of Optimum PID Controllers (Cuk Converter)

5.4 MATLAB Simulation for Zeta converter

Similar as Cuk converter, a higher-order transfer function is also obtained for the Zeta converter from the state-space model as a means to simulate the stability of the system. Later, MATLAB is used to reduce the order of the model. Hence, the open-loop and closed-loop transfer function are obtained that are stated in equations 5.2 and 5.4. In Table 5.12 parameters of the Zeta converter are enlisted. The MATLAB Simulink model of open-loop and closed-loop Zeta converter are displayed in Fig. 5.30 and 5.31.

Table 5.12 Parameters of Zeta converter

Parameter	**Symbol**	**Value**
Voltage (input)	V_{in}	15 V
Switching Frequency	fs	100 kHz
Duty Cycle	d	0.50
Inductor	L_1	100 µH
	L_2	55 µH
Capacitor	C_1	100 µF
	C_2	200 µF
Load Resistance	R_o	5 Ω
Voltage (output)	V_o	14.25 V

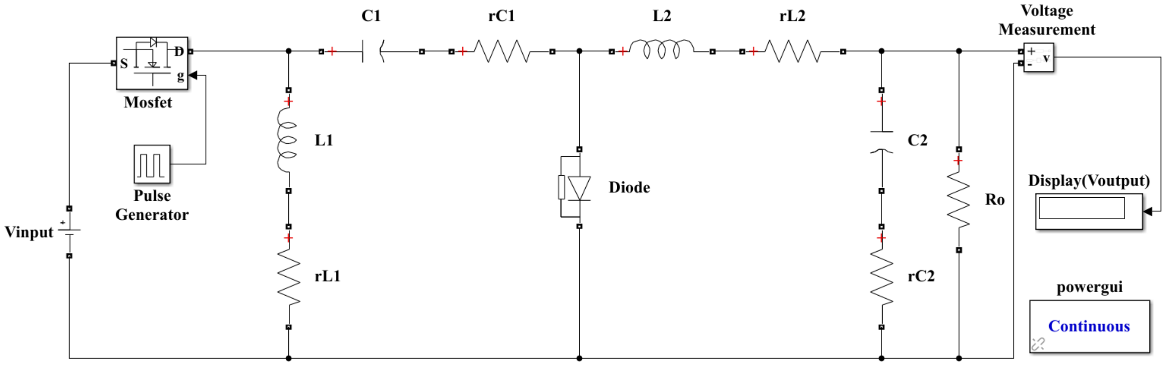


Fig. 5.30 MATLAB Simulink model of Open-loop Zeta Converter

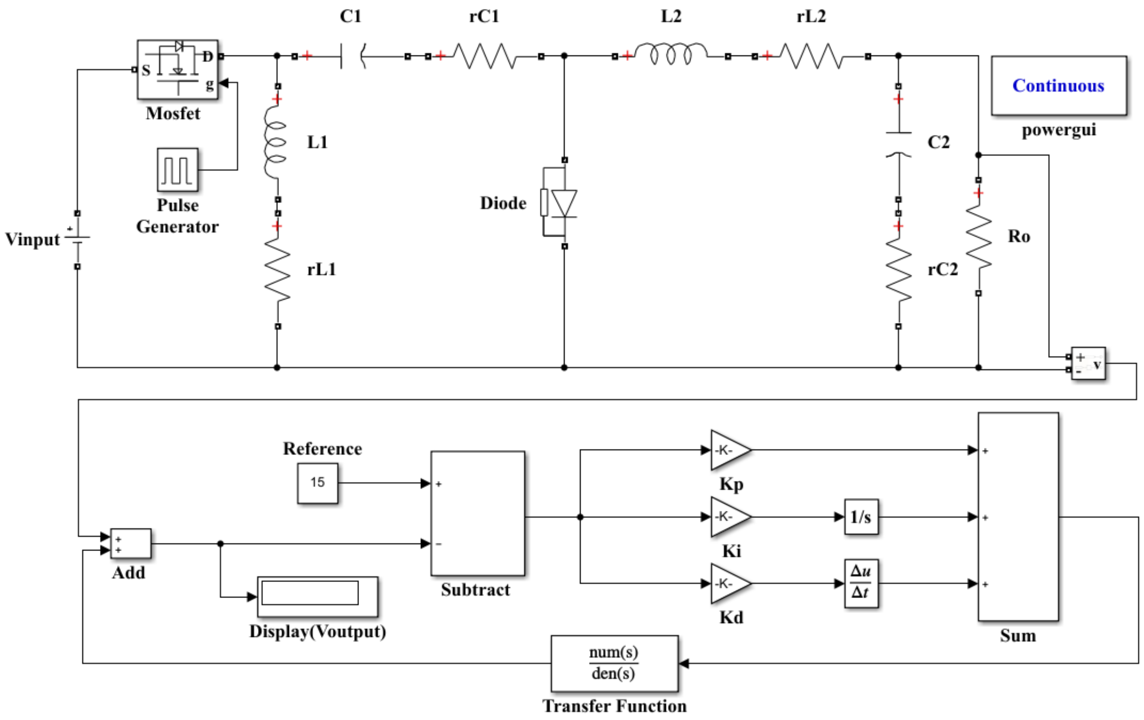


Fig. 5.31 MATLAB Simulink model of Closed-loop Zeta Converter

5.4.1 Conventional PID controller

Initially, step response for conventional PID controller is observed that is given in Fig. 5.32. The gain values and performance parameters of conventional PID controller are enlisted in Table 5.13

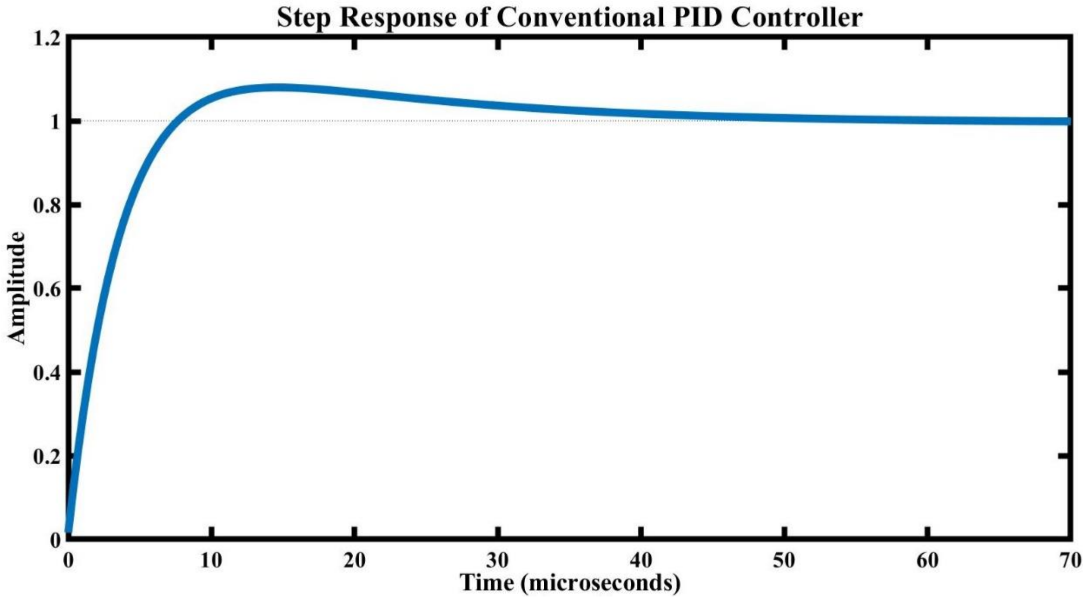


Fig. 5.32 Step Response of Conventional PID Controller (Zeta Converter)

Table 5.13 Gain and Performance Parameters of Conventional PID controller (Zeta Converter)

Attributes	Symbols	Values
Gain Values	**K_P**	19.605
	K_I	960.39
	K_D	1×10^{-06}
Performance Parameters	%OS	7.98
	Tr (seconds)	5.24×10^{-06}
	Ts (seconds)	3.83×10^{-05}
	Peak Amplitude	1.08

5.4.2 BIA-PID controller

Latterly, BIA is introduced for tuning the gain parameters of PID controller. Hence, step responses are observed and gain values along with performance indices are enlisted for different BIA-PID controller such as PSO-PID, FA-PID, GA-PID, and ABC-PID.

5.4.2.1 PSO-PID controller

At first, PSO is introduced for optimization of PID controller and step responses are simulated for different error functions illustrated in Fig. 5.33, 5.34, 5.35, and 5.36. Moreover, a comparative analysis of all these step responses are showed in Fig. 5.37. Gain and performance parameters of PSO-PID controller for Zeta converter are given in Table 5.14 and a comparative illustration of performance parameters are showed in Fig. 5.38.

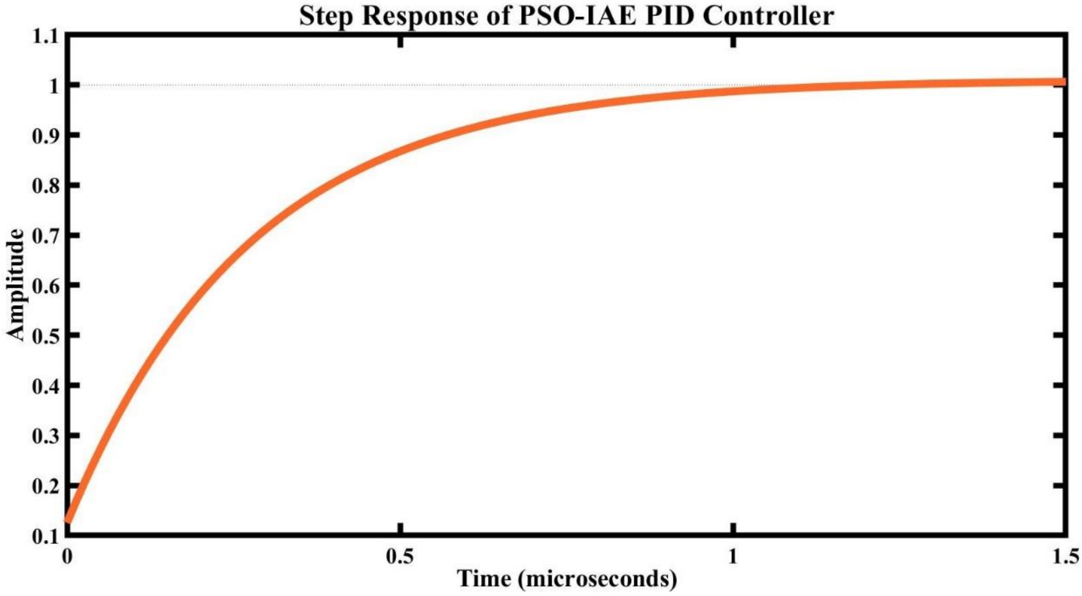


Fig. 5.33 Step Response of PSO (IAE) based PID Controller (Zeta Converter)

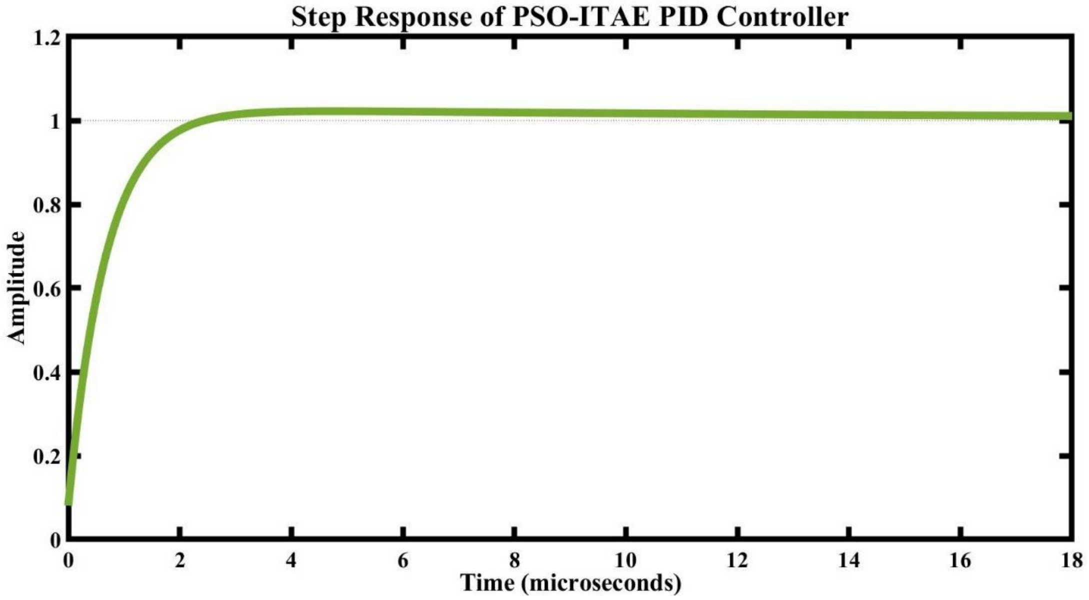


Fig. 5.34 Step Response of PSO (ITAE) based PID Controller (Zeta Converter)

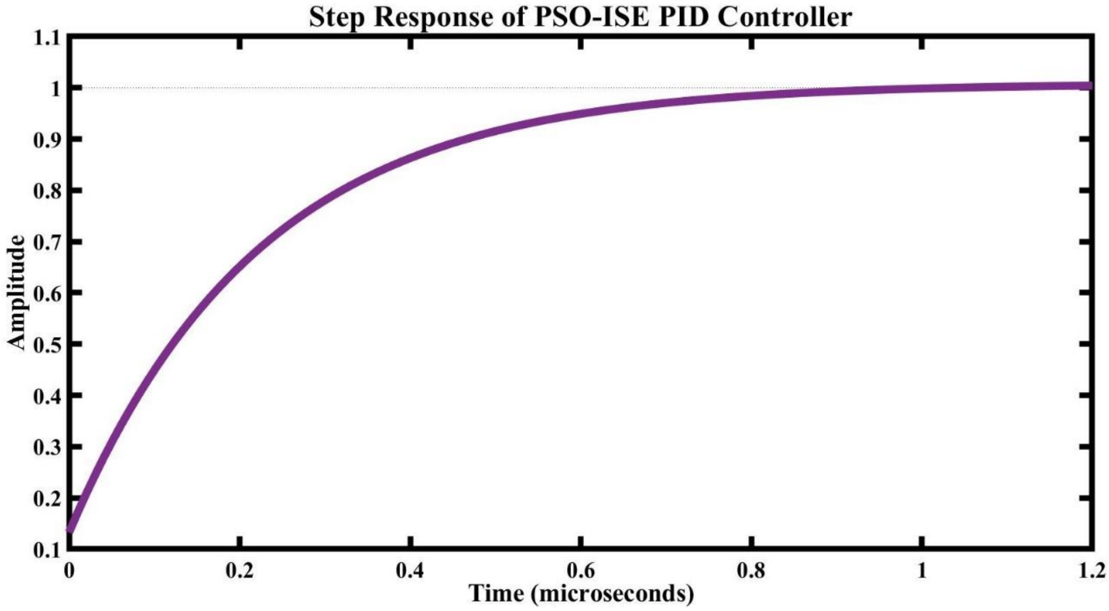


Fig. 5.35 Step Response of PSO (ISE) based PID Controller (Zeta Converter)

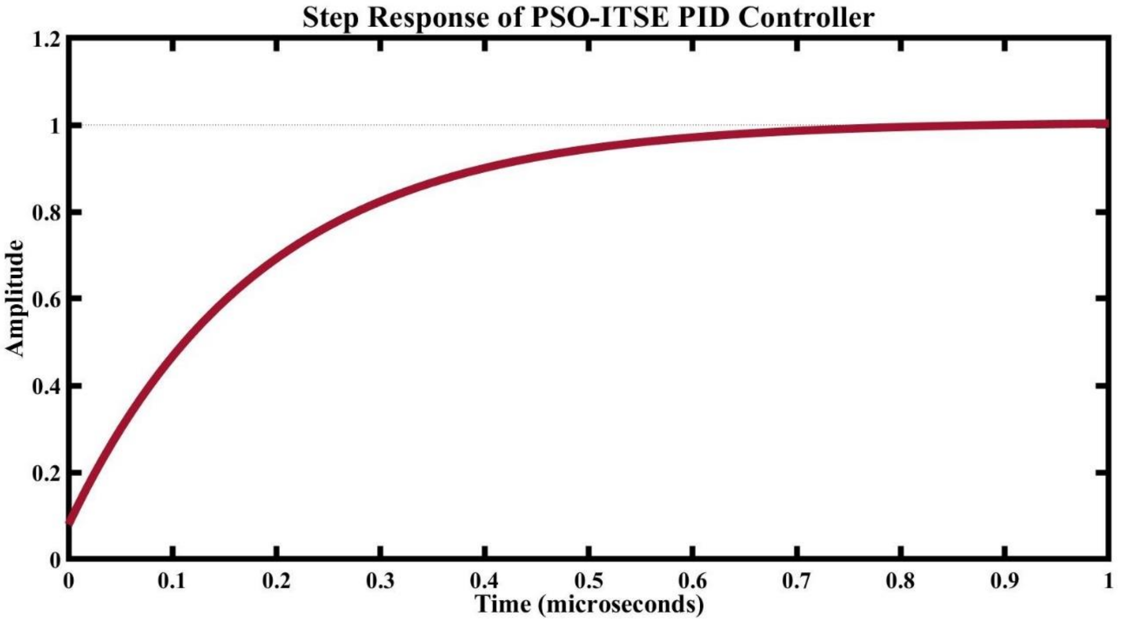


Fig. 5.36 Step Response of PSO (ITSE) based PID Controller (Zeta Converter)

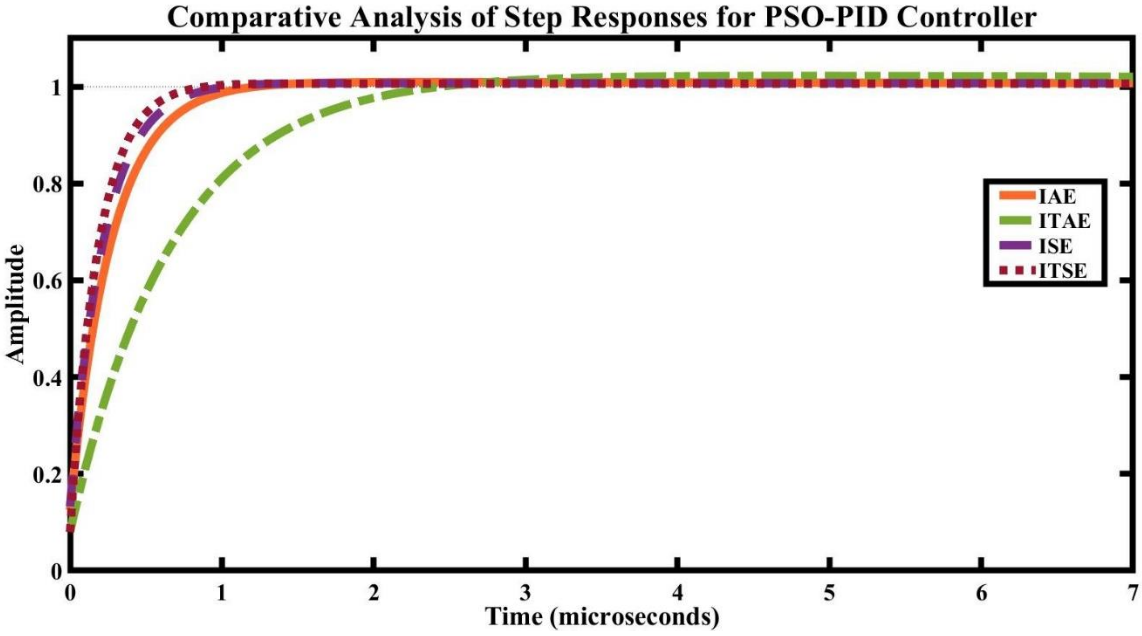


Fig. 5.37 Comparative Analysis of Step Responses for PSO-PID-ZETA

Table 5.14 Gain and Performance Parameters of PSO-PID controller (Zeta Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	K_P	255.39	100	316.22	358.93
	K_I	851.92	924.08	866.56	811.24
	K_D	8.70×10^{-06}	5.34×10^{-06}	9.27×10^{-06}	5.25×10^{-06}
Performance Parameters	***%OS***	0.955	2.22	0.724	0.628
	Tr (seconds)	5.76×10^{-07}	1.34×10^{-06}	4.72×10^{-07}	3.94×10^{-07}
	Ts (seconds)	9.49×10^{-07}	8.73×10^{-06}	7.86×10^{-07}	6.62×10^{-07}
	Peak Amplitude	1.01	1.02	1.00	1.00

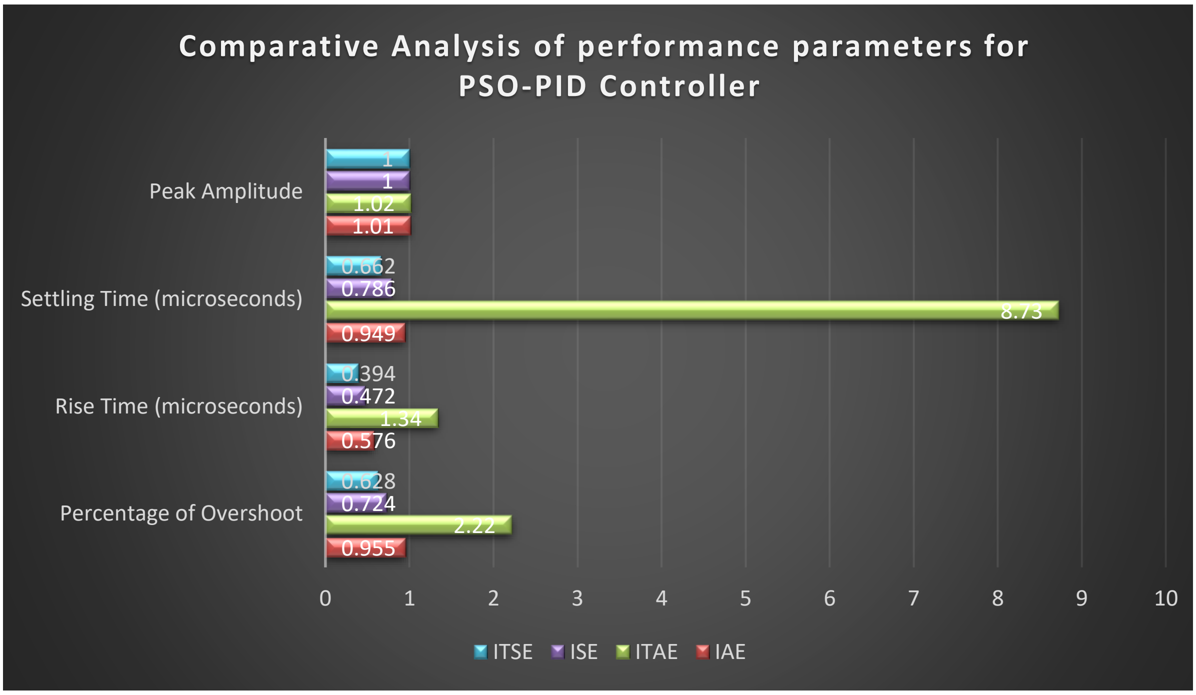


Fig. 5.38 Comparative Illustration of Performance Parameters for PSO-PID-ZETA

5.4.2.2 FA-PID controller

Afterward, FA is implemented for tuning of PID controller and step responses are simulated for different error functions illustrated in Fig. 5.39, 5.40, 5.41, and 5.42. Later, a comparative analysis of all these step responses are showed in Fig. 5.43. Gain and performance parameters of FA-PID for Zeta converter are tabulated in Table 5.15 and a comparative illustration of performance parameters are displayed in Fig. 5.44.

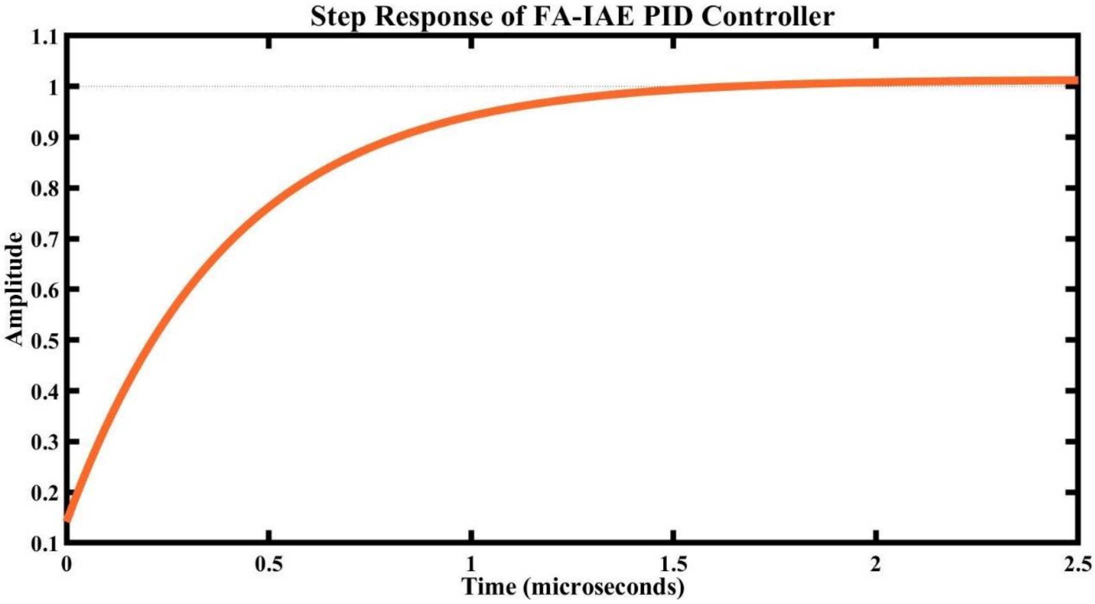


Fig. 5.39 Step Response of FA (IAE) based PID Controller (Zeta Converter)

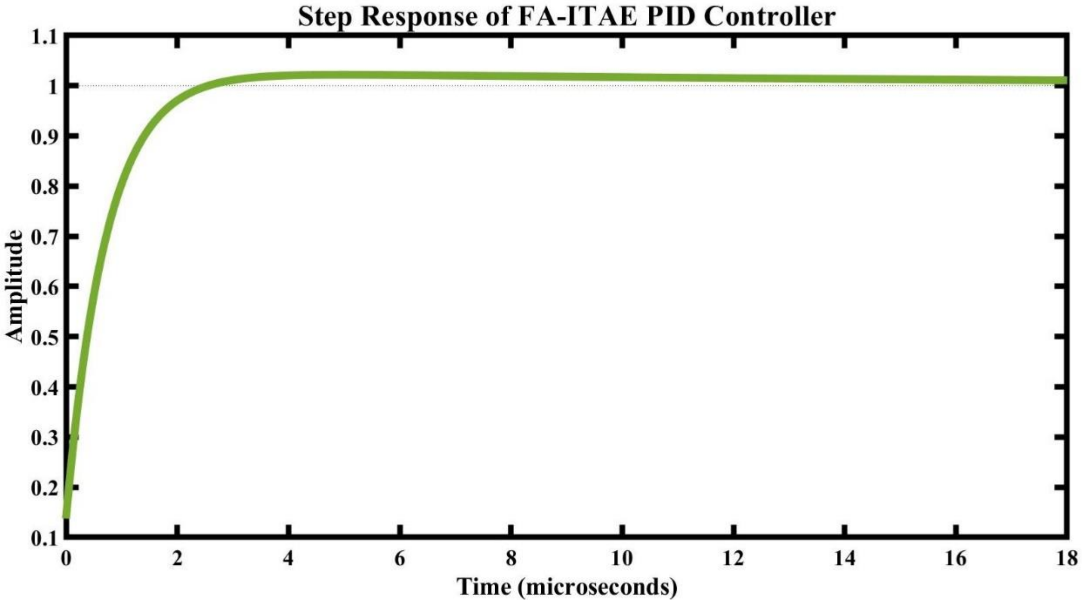


Fig. 5.40 Step Response of FA (ITAE) based PID Controller (Zeta Converter)

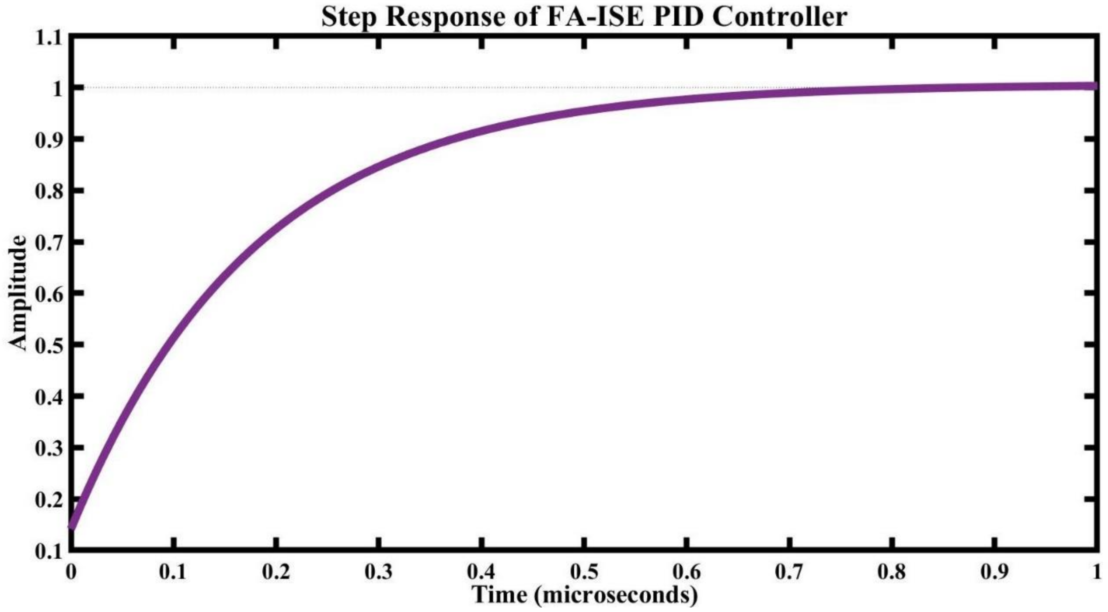


Fig. 5.41 Step Response of FA (ISE) based PID Controller (Zeta Converter)

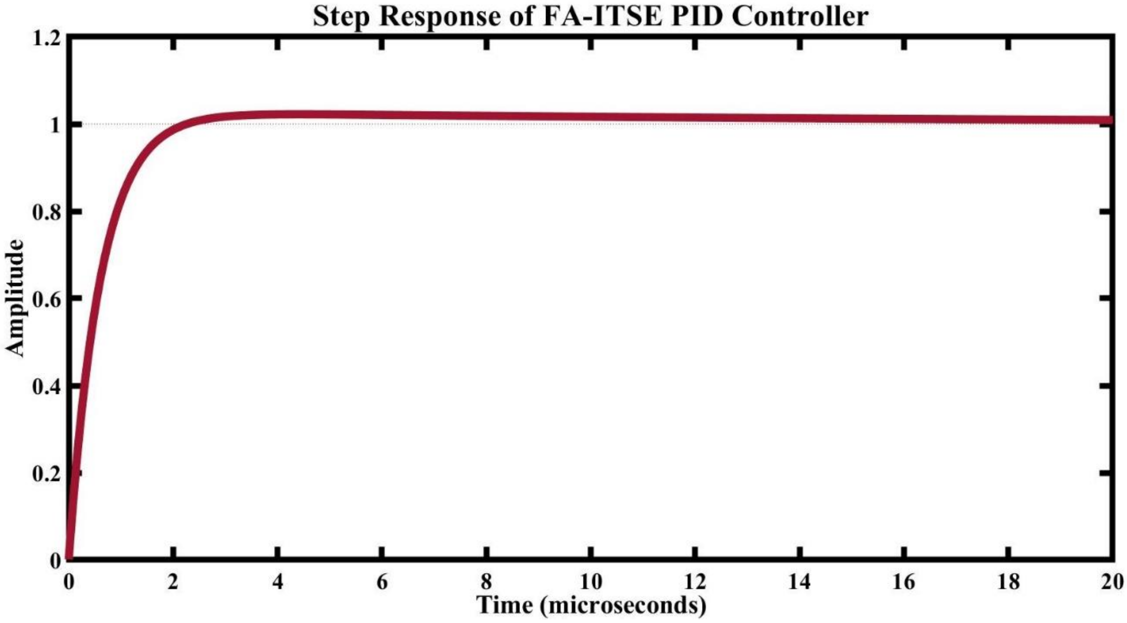


Fig. 5.42 Step Response of FA (ITSE) based PID Controller (Zeta Converter)

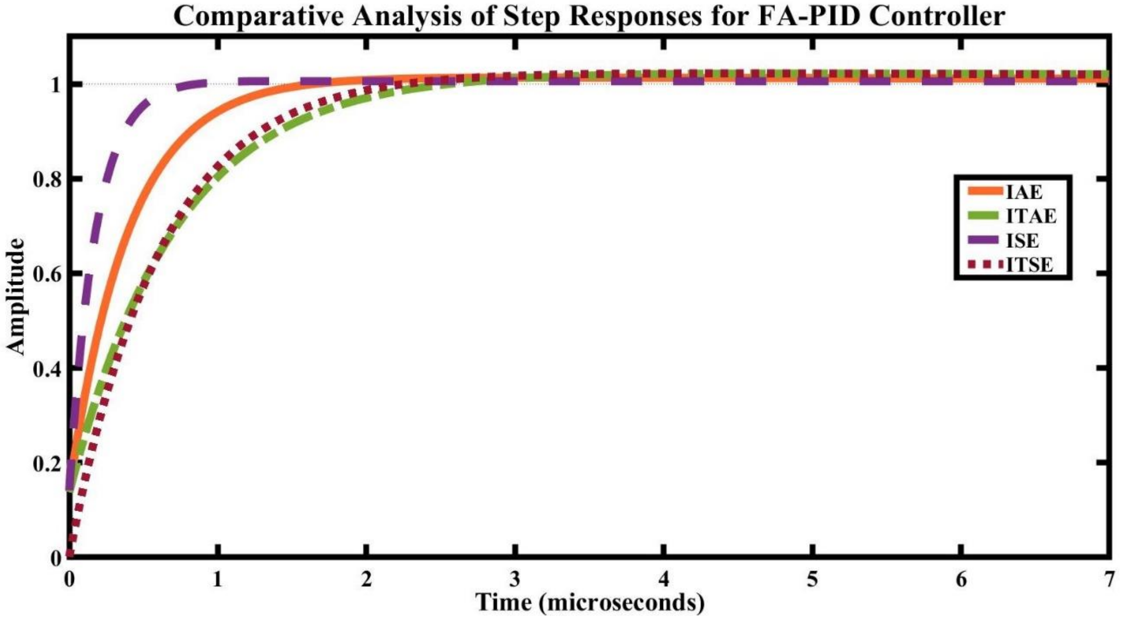


Fig. 5.43 Comparative Analysis of Step Responses for FA-PID-ZETA

Table 5.15 Gain and Performance Parameters of FA-PID controller (Zeta Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	K_P	177.86	100	400	101.74
	K_I	997.56	999.65	1000	1000
	K_D	1×10^{-05}	9.67×10^{-06}	1×10^{-05}	6.85×10^{-08}
Performance Parameters	***%OS***	1.32	2.19	0.561	2.22
	Tr (seconds)	8.29×10^{-07}	1.42×10^{-06}	3.79×10^{-07}	1.22×10^{-06}
	Ts (seconds)	1.33×10^{-06}	9.89×10^{-06}	6.39×10^{-07}	6.87×10^{-06}
	Peak Amplitude	1.01	1.02	1.00	1.02

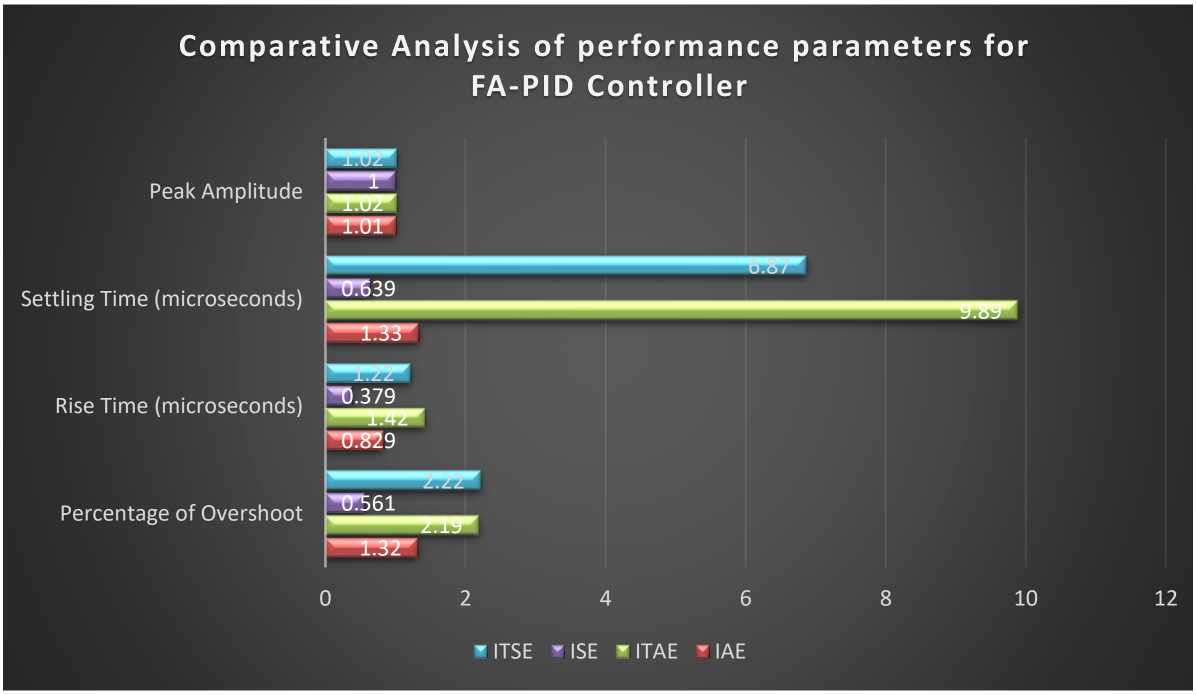


Fig. 5.44 Comparative Illustration of Performance Parameters for FA-PID-ZETA

5.4.2.3 GA-PID controller

Next, GA is introduced for optimizing the gain parameters of PID controller and step responses are simulated for different error functions illustrated in Fig. 5.45, 5.46, 5.47, and 5.48. Thereafter, a comparative analysis of all these step responses are showed in Fig. 5.49. Gain and performance parameters of GA-PID controller for Zeta converter are given in Table 5.16 and a comparative illustration of performance parameters are displayed in Fig. 5.50.

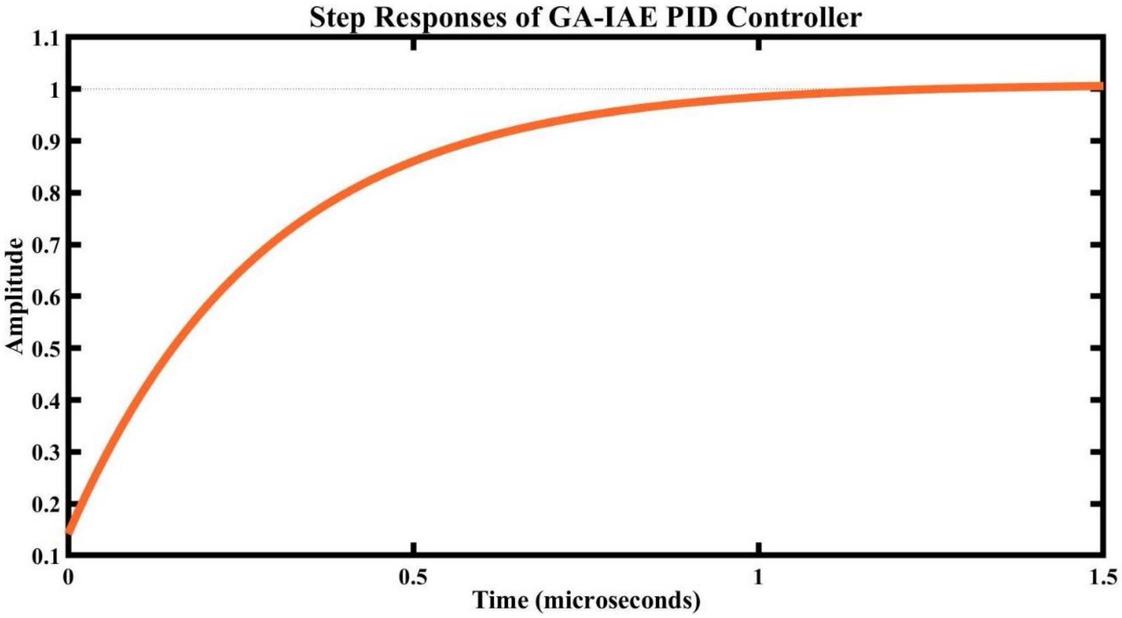


Fig. 5.45 Step Response of GA (IAE) based PID Controller (Zeta Converter)

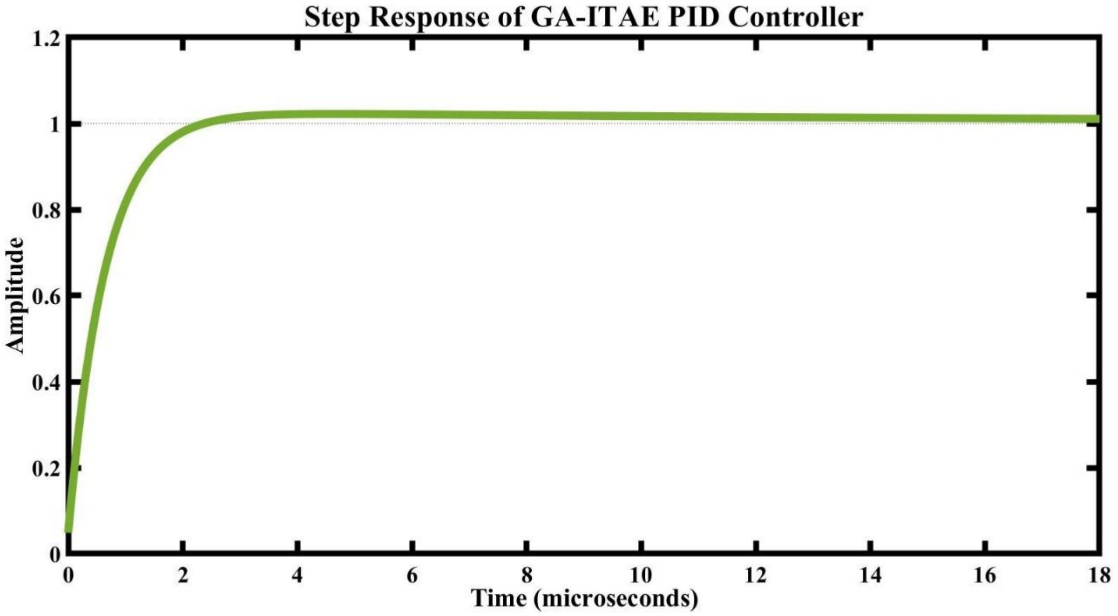


Fig. 5.46 Step Response of GA (ITAE) based PID Controller (Zeta Converter)

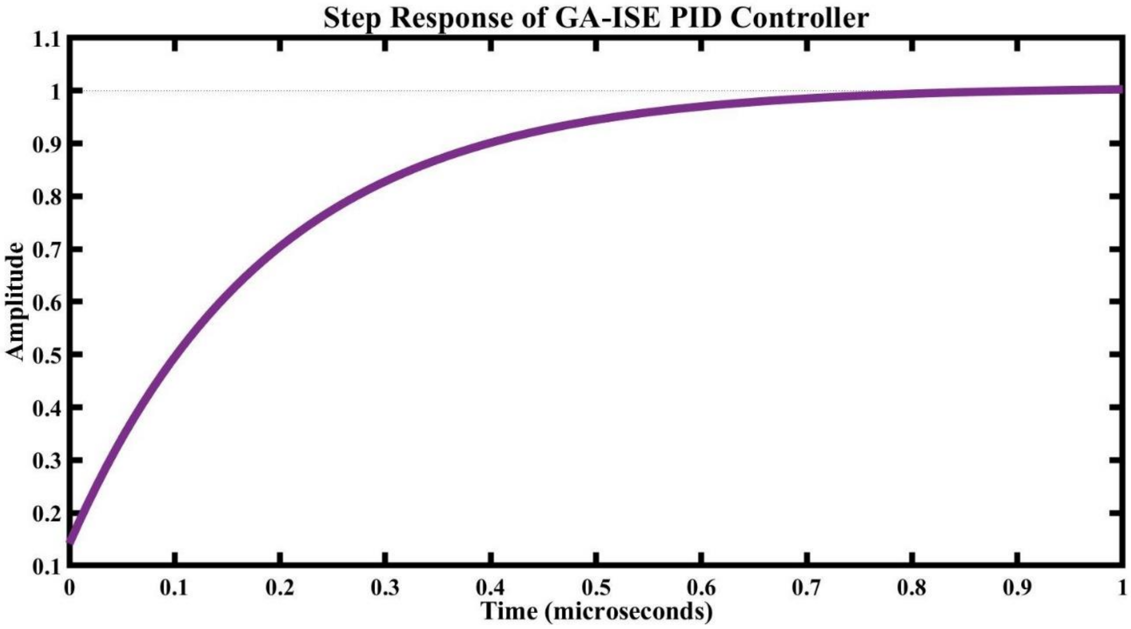


Fig. 5.47 Step Response of GA (ISE) based PID Controller (Zeta Converter)

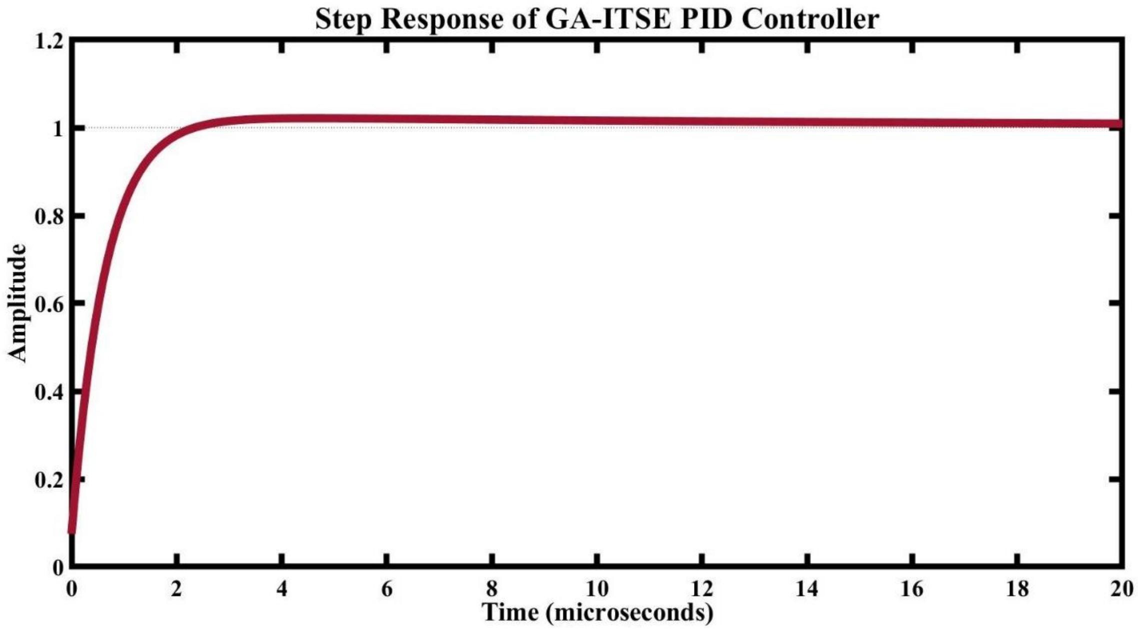


Fig. 5.48 Step Response of GA (ITSE) based PID Controller (Zeta Converter)

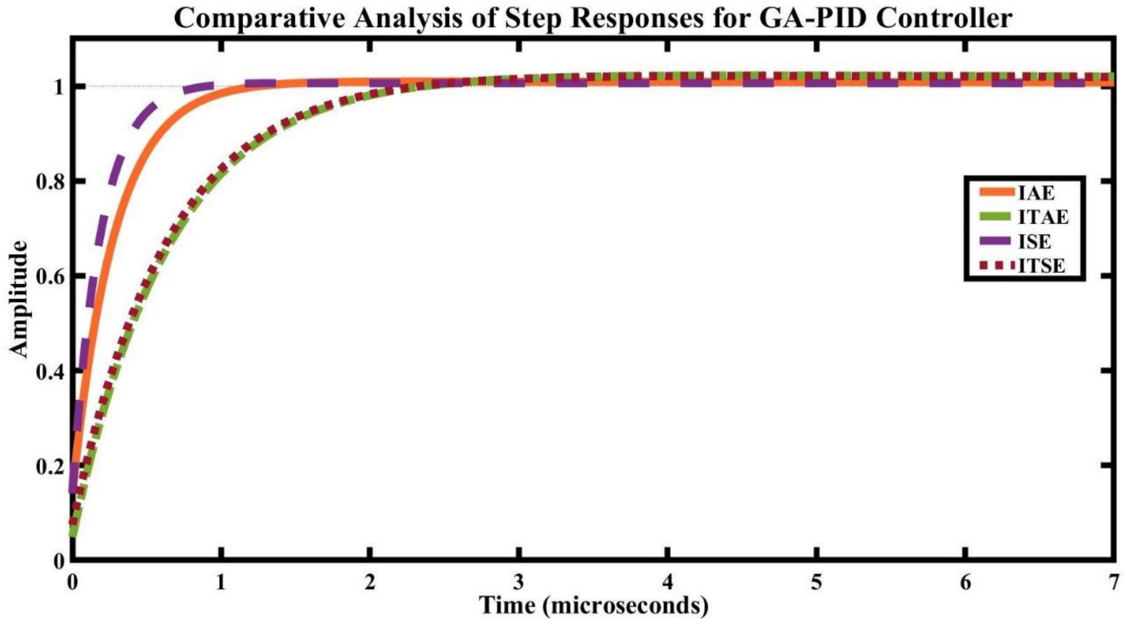


Fig. 5.49 Comparative Analysis of Step Responses for GA-PID-ZETA

Table 5.16 Gain and Performance Parameters of GA-PID controller (Zeta Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	K_P	250.73	100.22	374.08	104.63
	K_I	995.60	942.09	963.84	999.66
	K_D	9.99×10^{-06}	3.12×10^{-06}	1×10^{-05}	4.91×10^{-06}
Performance Parameters	***%OS***	0.97	2.23	0.604	2.14
	Tr (seconds)	5.96×10^{-07}	1.29×10^{-06}	4.05×10^{-07}	1.27×10^{-06}
	Ts (seconds)	9.81×10^{-07}	8.06×10^{-06}	6.80×10^{-07}	7.74×10^{-06}
	Peak Amplitude	1.01	1.02	1.00	1.02

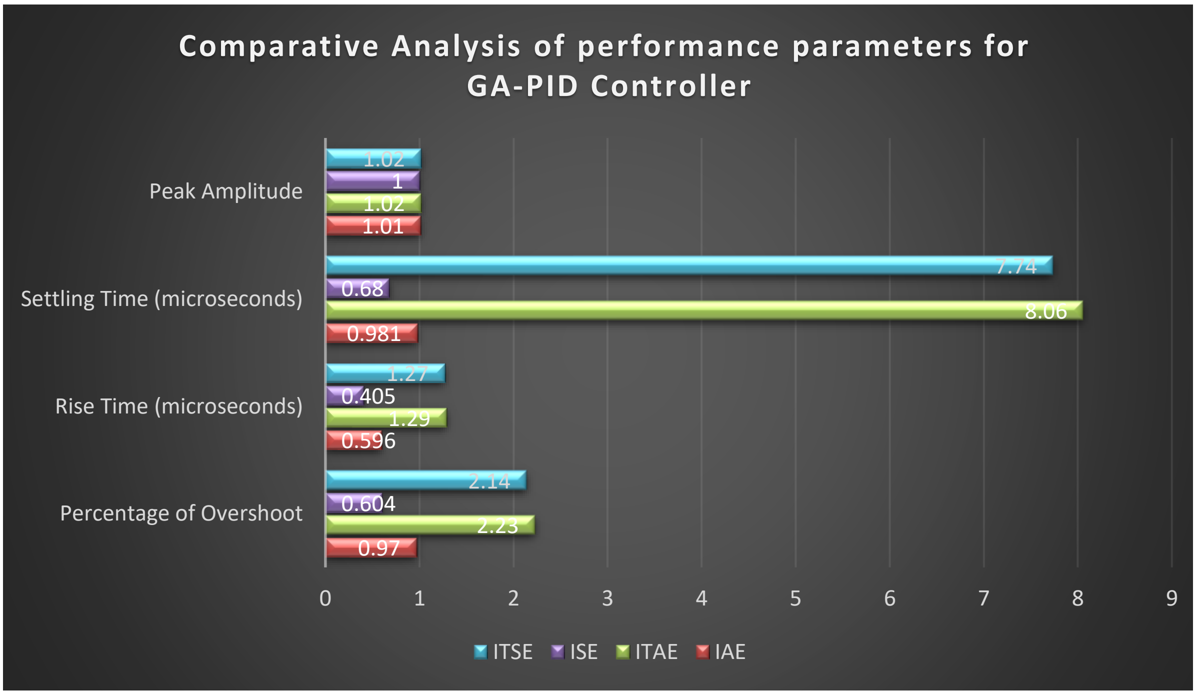


Fig. 5.50 Comparative Illustration of Performance Parameters for GA-PID-ZETA

5.4.2.4 ABC-PID controller

Later, ABC is implemented to tune the gain parameters of PID controller and step responses are simulated for different error functions illustrated in Fig. 5.51, 5.52, 5.53, and 5.54. Following that a comparative analysis of all these step responses are showed in Fig. 5.55. Gain and performance parameters of ABC-PID controller are given in Table 5.17 and a comparative illustration of performance parameters are illustrated in Fig. 5.56.

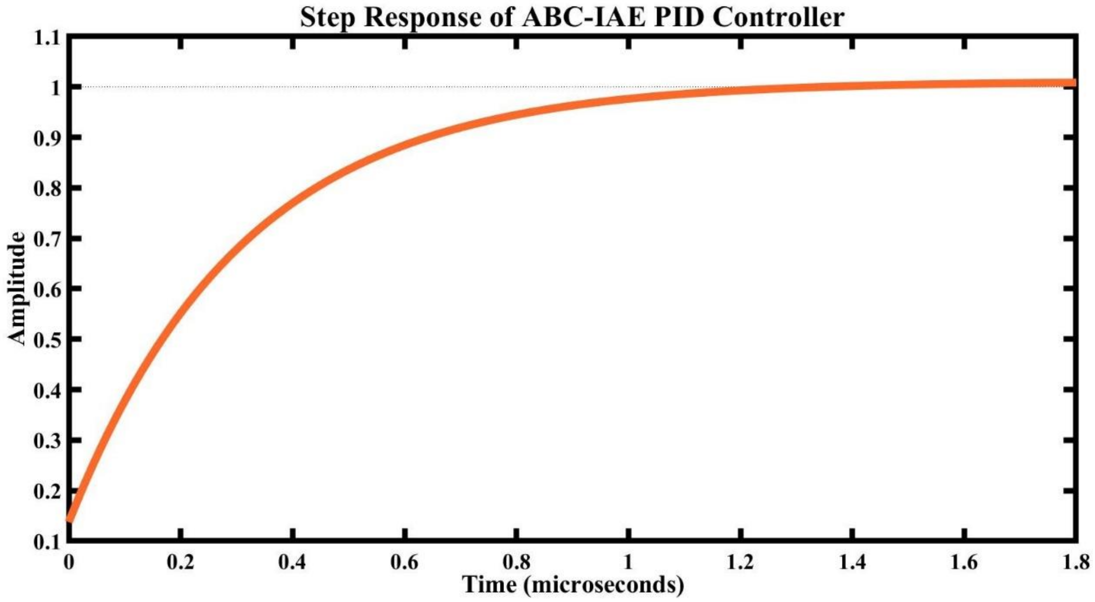


Fig. 5.51 Step Response of ABC (IAE) based PID Controller (Zeta Converter)

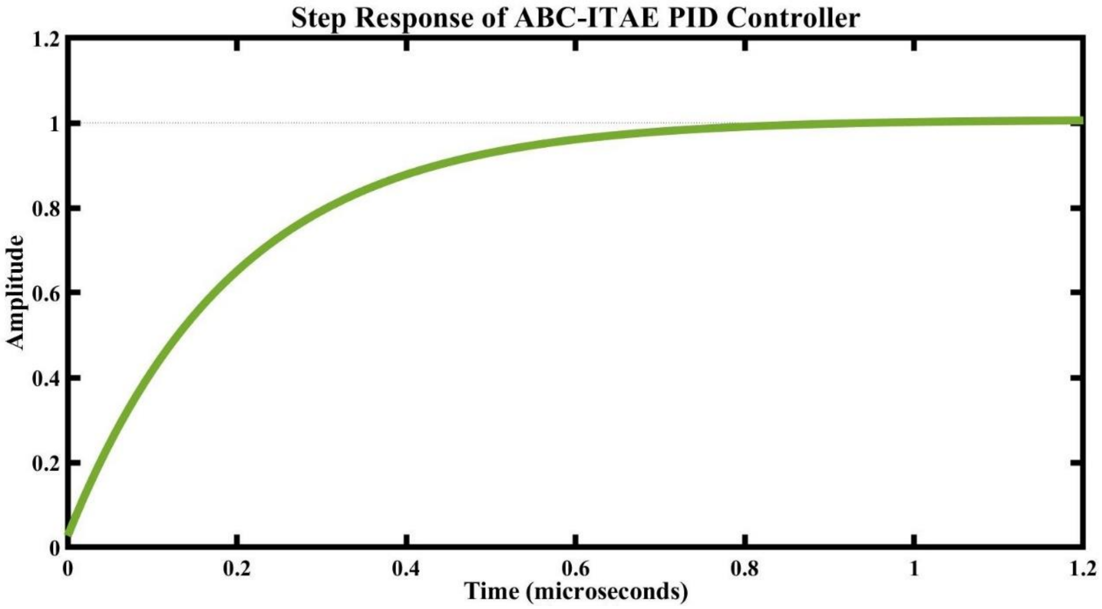


Fig. 5.52 Step Response of ABC (ITAE) based PID Controller (Zeta Converter)

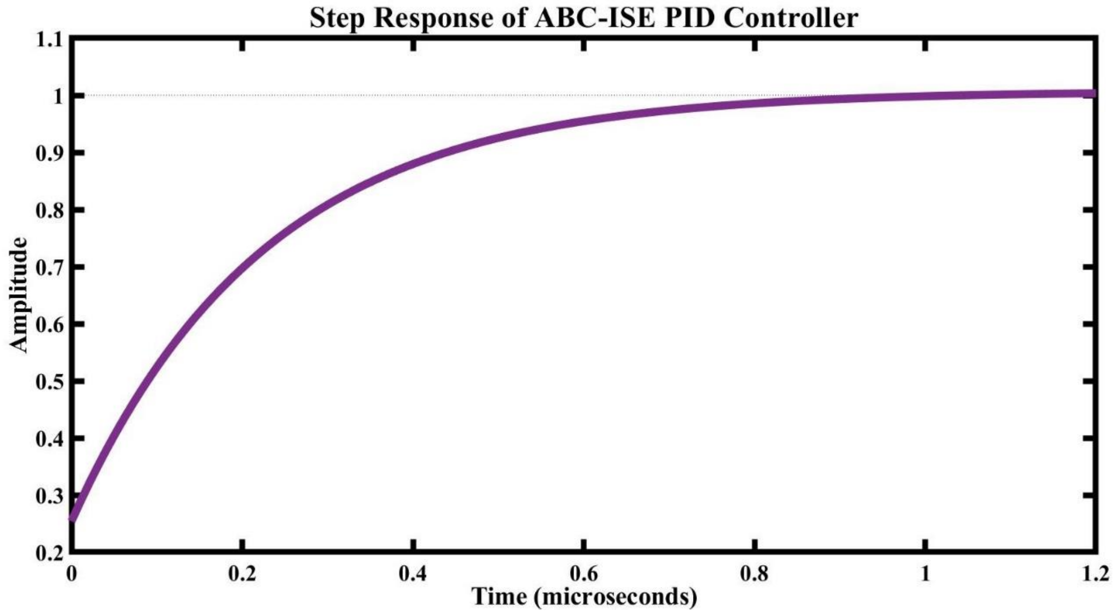


Fig. 5.53 Step Response of ABC (ISE) based PID Controller (Zeta Converter)

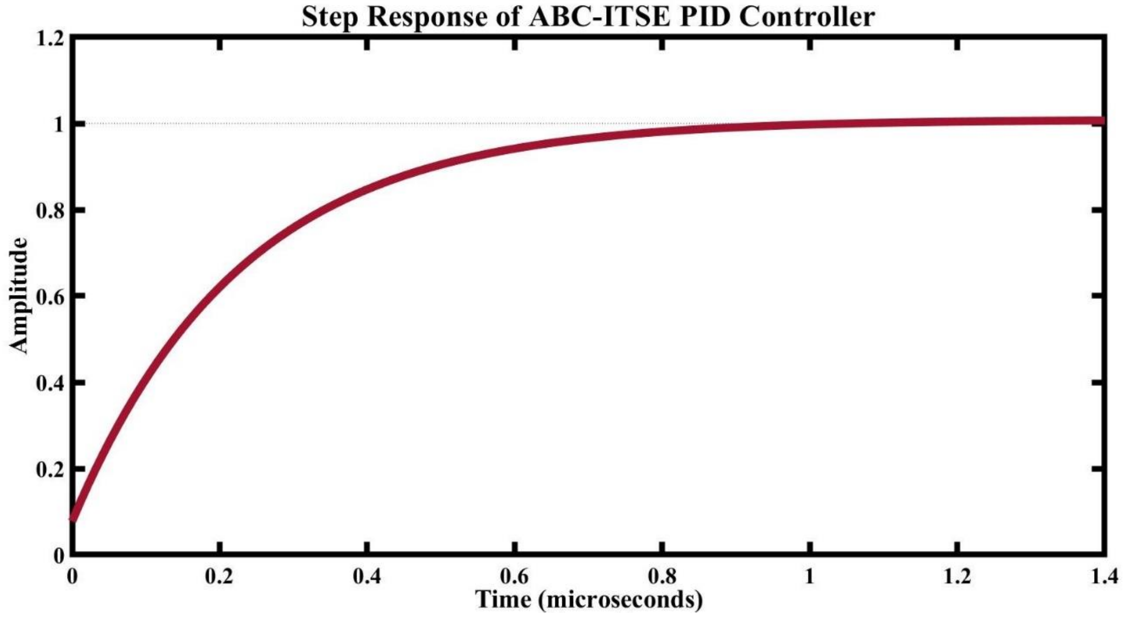


Fig. 5.54 Step Response of ABC (ITSE) based PID Controller (Zeta Converter)

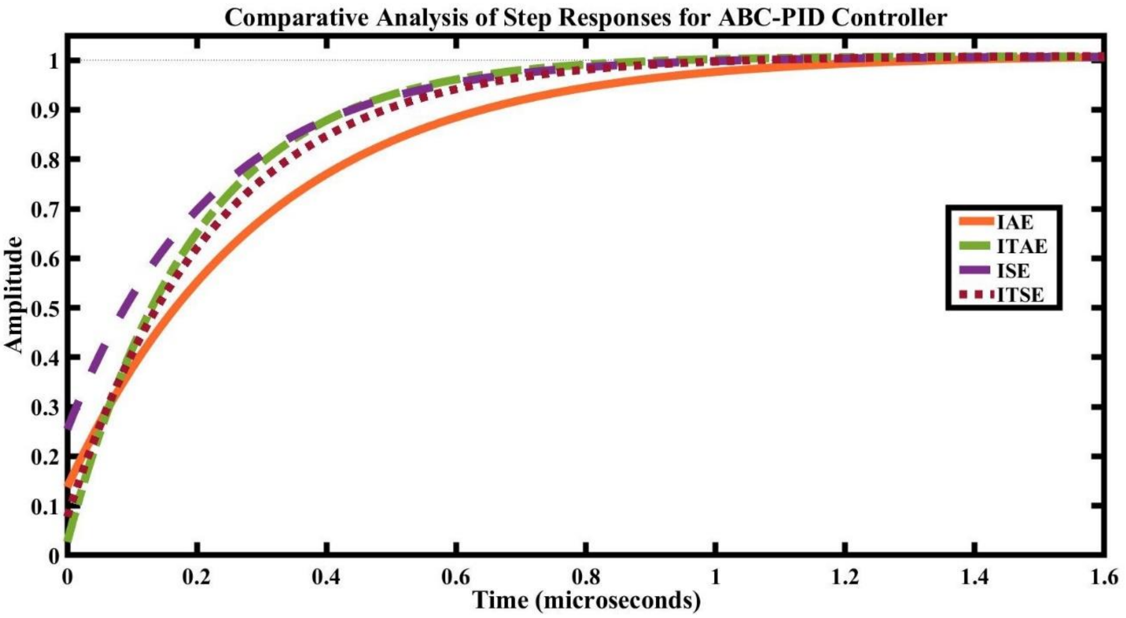


Fig. 5.55 Comparative Analysis of Step Responses for ABC-PID-ZETA

Table 5.17 Gain and Performance Parameters of ABC-PID controller (Zeta Converter)

Attributes	**Symbols**	**Values**			
		IAE	***ITAE***	***ISE***	***ITSE***
Gain Values	K_P	228.59	317.58	363.47	290.12
	K_I	459.53	944.40	338.44	709.72
	K_D	9.69×10^{-06}	1.68×10^{-06}	2.06×10^{-05}	5.11×10^{-06}
Performance Parameters	***%OS***	1.06	0.716	0.628	0.791
	Tr (seconds)	6.49×10^{-07}	4.20×10^{-07}	4.77×10^{-07}	4.83×10^{-07}
	Ts (seconds)	1.06×10^{-06}	7.05×10^{-07}	7.94×10^{-07}	8.05×10^{-07}
	Peak Amplitude	1.01	1.01	1.00	1.01

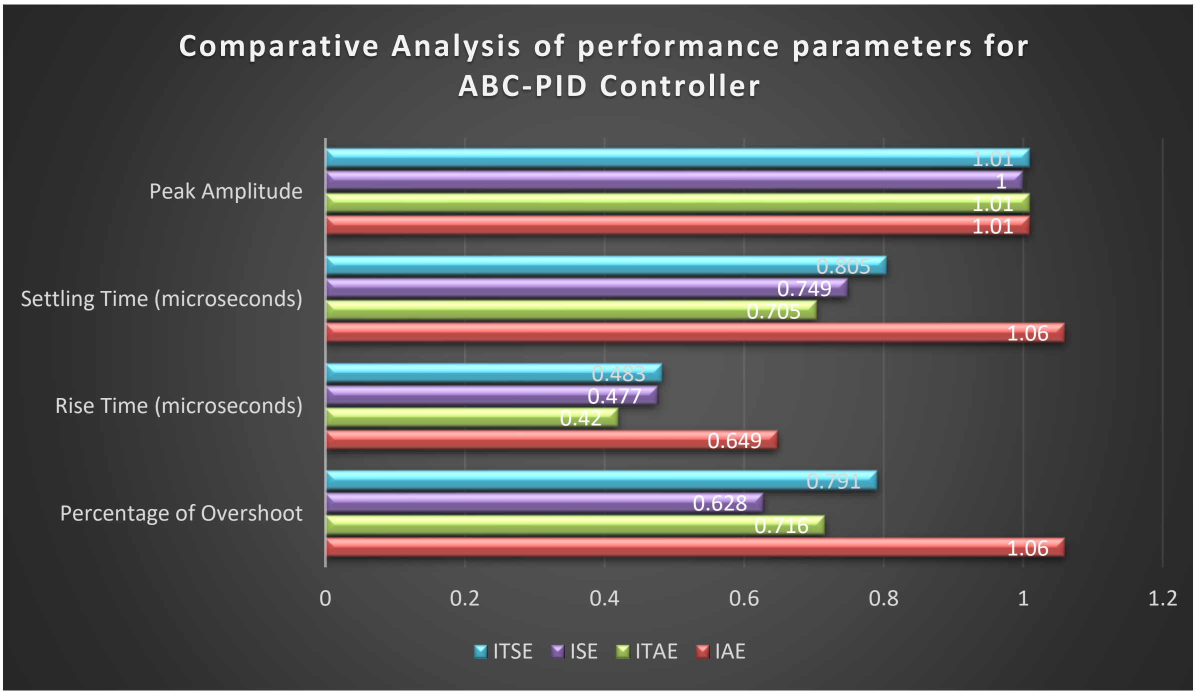


Fig. 5.56 Comparative Illustration of Performance Parameters for ABC-PID-ZETA

5.4.3 Comparative Analysis

Finally, a comparison of performance parameters for optimum BIA-PID controller is displayed in Table 5.18 based on the data of Table 5.13, 5.14, 5.15, 5.16, and 5.17. In addition, an overall comparative analysis of step responses, showed in Fig. 5.57, is done based on the values of performance parameters to find out the optimum PID controller for enhancing stability of Cuk converter. Hence, an overall comparative illustration of performance indices is displayed in Fig. 5.58 from which it is evident that FA-ISE performs better form the overshoot point of view.

Table 5.18 Comparative Performance Parameters of PID Controllers (Zeta Converter)

Performance Parameters	**PID Controllers**				
	Conventional	***FA_ISE***	***PSO_ITSE***	***GA_ISE***	***ABC_ISE***
Percentage of Overshoot (%OS)	7.98	0.561	0.628	0.604	0.628
Rise Time, Tr (seconds)	5.24×10^{-06}	3.79×10^{-07}	3.94×10^{-07}	4.05×10^{-07}	4.77×10^{-07}
Settling Time, Ts (seconds)	3.83×10^{-05}	6.39×10^{-07}	6.62×10^{-07}	6.80×10^{-07}	7.94×10^{-07}
Peak Amplitude	1.08	1.00	1.00	1.00	1.00

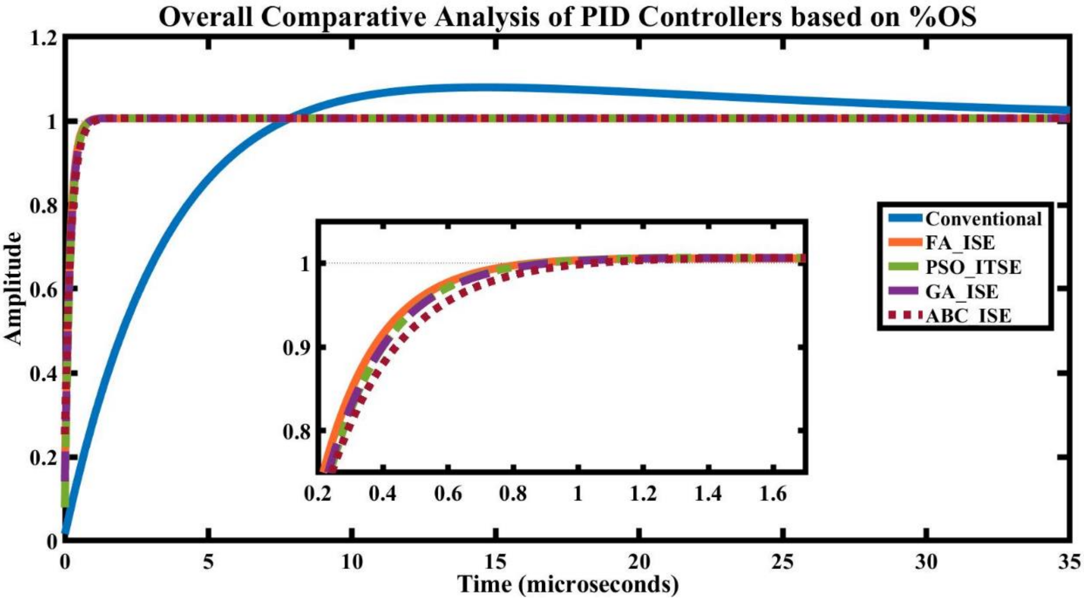


Fig. 5.57 Overall Comparative step response analysis of PID controllers (Zeta Converter)

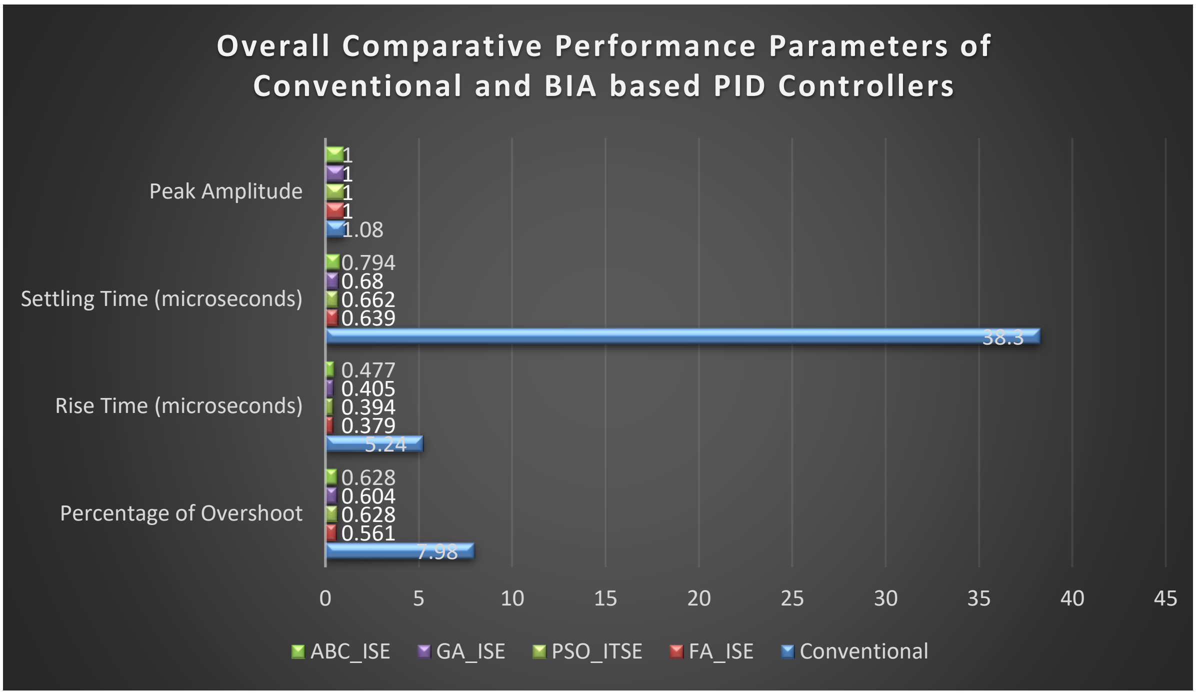


Fig. 5.58 Overall Comparative Illustration of Optimum PID Controllers (Zeta Converter)

CHAPTER 6

CONCLUSION AND PERSPECTIVE PLANS

6.1 Synopsis

This thesis enlightens the topic of optimizing the PID controller by implementing four types of bio-inspired algorithms for achieving better responses and developing the fitness functions for the Zeta and Cuk converter. Performance parameters named IAE, ITAE, ISE, and ITSE are used as objective functions to investigate the stability of the converters. **In Chapter 2**, the operating principle of dc-dc converters is discussed briefly and then a summary about the three basic topologies and their waveforms is presented. Moreover, the conventional approach of the two converters of our interest is portrayed and the modeling is also illustrated through State Space Averaging Technique. **Chapter 3** has demonstrated the overview of different Bio-Inspired Algorithms (BIA) and an elaborate discussion has been reported about Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Genetic Algorithm (GA), and Artificial Bee Colony (ABC). **Chapter 4** has referred to the implementation of the algorithms for designing an optimized PID controller. The tuning of the performance parameters has been discussed and the required objective functions are stated in a short discussion. **Chapter 5** has been dealt with the simulation results of the BIA-based tuned PID controller for Zeta and Cuk converter separately. Graphical representation of the outcomes has been displayed ad comparative analysis has been tabulated with the help of different types of optimized controllers.

After observing the graphical representation of all the step responses, the comparative analysis table is formed for a better understanding of the compatibility of bio-inspired algorithms in developing the PID controller. The parameters of the Cuk and Zeta converter have been defined and the gain values and performance parameters of the conventional PID controller have been observed. After the conventional PID controller, tuning of the PID controller is done by using different optimization techniques to achieve a better result. In the case of the Cuk converter, it is observed that FA-PID (IAE) is the most optimized controller among all the BIA-based PID controllers in terms of performance parameters because overshoot is the lowest (1.91%) for FA-PID (IAE). Moreover, rise time (2.51s) and settling time (19.5) are also within an acceptable limit. But, it is also observed that ABC-PID (ITSE) shows a quick rise (1.95s) and settling time (17.1s) but the overshoot of ITSE is 2.06% which is greater than the IAE of FA-PID. Therefore, FA-PID (IAE) is chosen as the most optimized and suitable controller for the Cuk converter. In the case of the Zeta converter, it is observed that FA-PID (ISE) is the most optimized controller among all the BIA-based PID controllers in terms of performance parameters because overshoot is the lowest (0.561%) for FA-PID (ISE). Moreover, rise time (0.379 microseconds) and settling time (0.639 microseconds) are also the lowest among different optimized controllers. So, it is evident that BIA-based optimization techniques for improving the PID controller are providing better responses.

6.2 Perspective Plans

This study will stimulate the attention of further research in designing and obtaining better performances of the Cuk and Zeta converter. As future work, different algorithms will be implemented in designing an optimized PID controller to investigate and enhance the stability of the converters. Even the four algorithms utilized here can be performed for improving the stability of other converters. There is also a scope of a hardware implementation for further experiments to validate this approach. So, the overall comparative analysis can be very effective to observe the stable condition for different applications in power electronics.

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