STABILITY ANALYSIS OF DC-DC BOOST CONVERTER BY EMPLOYING SIMULATED ANNEALING ALGORITHM BASED OPTIMIZED PI CONTROLLER

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Abstract - This paper proposes an analysis on stability of DC-DC Boost converter where a PI controller is used to investigate the performance. However, the parameters of the controller are achieved by employing Simulated Annealing (SA) algorithm. The algorithm is a probabilistic search algorithm which is brought into service in optimizing parameters of PI controller so that more satisfactory performance can be obtained from power converters. In order to model the boost converter, State Space Average method is utilized so that the transfer function of the system can be derived. Hence, SA-PI controller is implemented and different performance parameters like rise time, settling time and peak amplitude are reported and compared with conventional PI controller. The step responses are acquired through rigorous simulation in MATLAB and overall comparative analysis is carried out.

Keywords - Simulated Annealing Algorithm; Optimization; PI Controller; State Space Average Method

I. INTRODUCTION

Substantial researches have been carried out in designing and analyzing of power converter topologies and its controllers with a view to improving performance for different applications like renewable energy [1], electric vehicle [2], LED drivers [3] and many more. Consequently, the main aim of designing and modeling power converters is to meet the supply and demand. Hence, these power converters are needed to be modernized so that they exhibit satisfactory performance with load variation and other changes. Particularly, controllers of the power converters should be designed in a compact and robust way so that it can impose stability in overall system [4]. Amongst different power converters Boost converter is the simplest and widely employed converter. Stepping up voltage, low operating duty cycle and lower voltage on switch are some of the significant features of this converter. However, different topologies of this converter are proposed by many researchers where improved performance is displayed [5]. In this paper, the conventional DC-DC Boost converter is modelled by state space average technique. The closed loop system is analyzed by employing a PID controller [6]. PID controller consists of three terms named as Proportional, Integral and Derivative component which are tuned by Ziegler-Nicholas method [7], analytical methods and different optimization techniques [8-9]. Determining the exact values of these parameters is quite difficult as most of the classical methods demand explicit mathematical modeling of the processing plant and may not provide satisfactory results because of input-output disturbances or nonlinear behavior of the plant. Simulated Annealing (SA) algorithm is a probabilistic search algorithm which is widely applied in power electronics [10], robotics [11], bioinformatics [12] and optimization problems [13]. In order to make really strong metallic objects, slow and controlled cooling is followed which is known as annealing. Hence, the concept is applied in this paper with an intention of achieving the values of the PID controller (k_P, k_I and k_D) without the requirement of manual tuning. Thus, the closed loop response of DC-DC boost converter has been investigated and overall stability analysis is carried out.

In this paper, Section II deals with State Space Modeling of conventional Boost converter. The implementation of Simulated Annealing (SA) algorithm is deployed in Section III where overview of the algorithm, objective function and design of the SA-PI Controller are depicted. After that, simulation results and stability analysis of the system are shown in Section IV. Lastly, the overall comparative analysis is presented where the performance of different indices are illustrated. All the simulations are carried out in MATLAB environment.

II. STATE SPACE MODELING OF BOOST CONVERTER

The conventional DC-DC Boost Converter comprises of inductor (L), capacitor (C), diode D, switch (S) and load resistance (R). When the switch S is ON, the diode becomes open and capacitor (C) discharges through load resistance (R). When the switch (S) is OFF, the diode is closed and current i_L passes through the capacitor (C) and load resistance (R). For mathematical modeling of DC-DC Boost Converter,

State Space Modeling [15] is employed so that the system can be illustrated by first order differential equations followed by matrix representation.

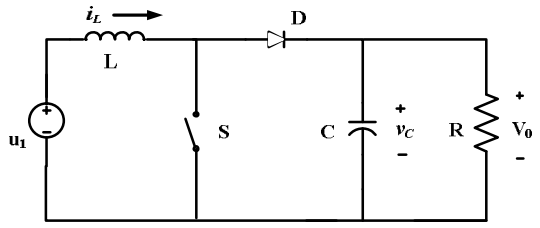


Fig. 1. Circuit Diagram of Conventional Boost Converter [14].

The system matrix is denoted as A, B, C and D; u and y are referred as input and output respectively. The state variable is indicated as x and x' is the derivative of state variables. Here, current i_L and voltage v_C are system variables which are mapped as $i_L = x_1$ and $v_c = x_2$.

$$x' = Ax + Bu \quad (1)$$

$$y = Cx + Du \quad (2)$$

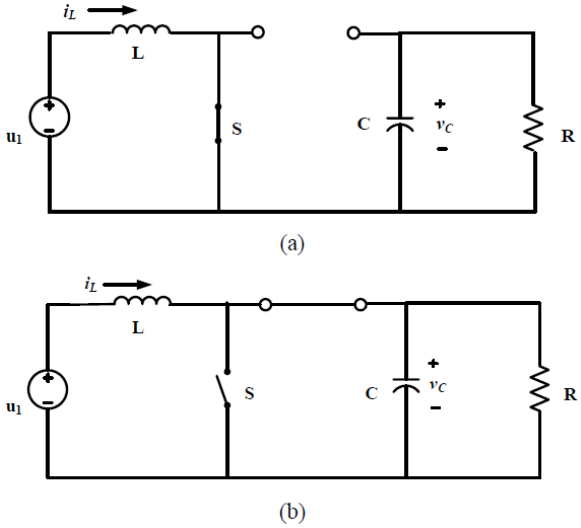


Fig. 2. Circuits of Boost converter at switch, S (a) ON and (b) OFF.

The circuit diagrams for ON and OFF condition of the switch (S) are shown in Fig. 2(a) and 2(b) respectively. The equations derived for these two conditions are presented below:

i) When S is ON:

$$u_1 = L\frac{di_L}{dt} \quad (3)$$

$$0 = C\frac{dv_C}{dt} + \frac{v_C}{R} \quad (4)$$

$$x'_1 = \frac{1}{L}u_1 \quad (5)$$

$$x'_2 = -\frac{1}{RC}x_2 \quad (6)$$

$$\begin{pmatrix} x'_1 \\ x'_2 \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix}u_1 \quad (7)$$

ii) When S is OFF:

$$v_C = u_1 - L\frac{di_L}{dt} \quad (8)$$

$$i_L = C\frac{dv_C}{dt} + \frac{v_C}{R} \quad (9)$$

$$x'_1 = -\frac{1}{L}x_2 + \frac{1}{L}u_1 \quad (10)$$

$$x'_2 = -\frac{1}{C}x_1 - \frac{1}{RC}x_2 \quad (11)$$

$$\begin{pmatrix} x'_1 \\ x'_2 \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix}u_1 \quad (12)$$

The average of the state space model is illustrated below where switching duty cycle (d) is taken into consideration.

$$A' = A_{ON}d + A_{OFF}(1-d) \quad (13)$$

$$A' = \begin{pmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{pmatrix}d + \begin{pmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{pmatrix}(1-d) = \begin{pmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{pmatrix} \quad (14)$$

$$B' = B_{ON}d + B_{OFF}(1-d) \quad (15)$$

$$B' = \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix}d + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix}(1-d) = \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} \quad (16)$$

Hence, the completed boost converter state space model is shown below:

$$\begin{pmatrix} x'_1 \\ x'_2 \end{pmatrix} = \begin{pmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix}u_1 \quad (17)$$

III. IMPLEMENTATION OF SIMULATED ANNEALING ALGORITHM

A. Overview of SA:

SA refers to an optimization technique, based on the principles of thermodynamics where the analogy of cooling of metal and freezing into a minimum energy level is utilized [16-17]. The objective of this algorithm is to find the global optimum value of the system. Moreover, the simulated annealing algorithm is capable of dealing complex nonlinear systems and appears to be more versatile, robust and handy than

other search algorithms. However, the algorithm is metaheuristic and computing time is high. The algorithm starts by initializing a very high temperature and perturbing the placement through a defined move. After that the score is calculated and depending on the change in score the decision is taken whether it is to be accepted or rejected. Hence the value is updated and process is repeated until freezing point is reached. The flowchart of the algorithm is illustrated in Fig. 3.

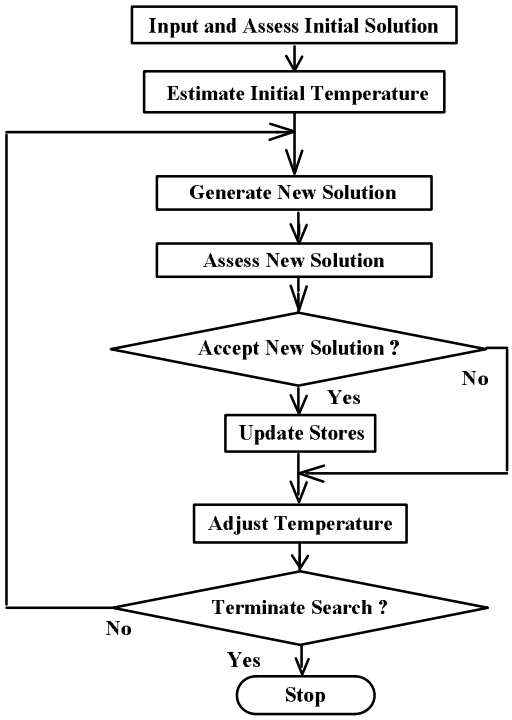


Fig. 3. Flow Chart of Simulated Annealing (SA) algorithm [18].

B. Objective Function:

In this paper, four performance indices are taken into account to minimize the error which imply quantitative measure in order to portray the performance of the PID controller. The indices are defined as Integral of Absolute Magnitude of Error (IAE), Integral of Time multiplied by Absolute Error (ITAE), Integral of Squared Error (ISE) and Integral of Time multiplied by Squared Error (ITSE) [18].

$$IAE = \int_0^\tau |e(t)|dt$$

$$ITAE = \int_0^\tau t|e(t)|dt$$

$$ISE = \int_0^\tau e(t)^2 dt$$

$$ITSE = \int_0^\tau te(t)^2 dt$$

C. Design of SAA-PI Controller:

Proportional-Integral (PI) controller is extensively used in improving the closed loop performance of different power converters. Here, PI controller parameters are attained with the help of Simulated Annealing (SA) algorithm. The fitness function will be evaluated and thus the optimized values of the controller will be obtained to inspect the stability of the system. The basic block diagram of SA-PI controller is displayed in Fig. 4.

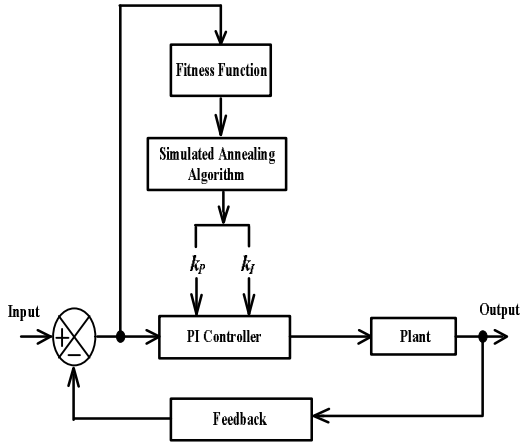


Fig. 4. Basic Block Diagram of SA-PI Controller.

IV. SIMULATION RESULTS AND STABILITY ANALYSIS

From state space modeling, the transfer function of the system is obtained which is utilized to inspect the stability of output. MATLAB is used for model order reduction so that the system can be transformed into a simpler form. Table I shows the parameters that are used to model the boost converter in order to investigate the performance [14]. At first, the conventional PI controller is implemented in the boost converter and the step response of the closed loop system is portrayed in Fig. 5. It is observed that the percentage of overshoot is 4.33%. However, rise time and settling time are 0.044s and 0.122s respectively.

TABLE I. **Parameters of Boost Converter**

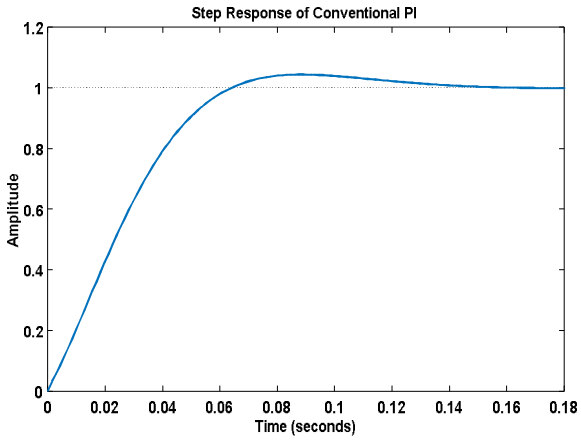


Fig. 5. Step Response of Conventional PI.

After that, SA-PI controller is employed in the boost converter and step response for the four performance

indices are collected. The objective of the fitness functions is to minimize the error and thus the value of the best fitness is obtained. The parameters of Simulated Annealing Algorithm are tabulated in Table II. In Table III, the gain values of PI controller for both conventional PI and SA-PI are presented.

TABLE II. **Parameters of Simulated Annealing Algorithm**

Initial Temperature:	100
Temperature Update Function:	Exponential Temperature Update
Reannealing Interval:	100
Annealing Function:	Fast Annealing

TABLE III. **Gain Values For Both Conventional and SA-PI Controller**

Gains	Conventional PI	SA-PI			
		IAE	ITAE	ISE	ITSE
k_P	111.7133	29.368	16.008	114.996	99.900
k_I	14692.065	3390.13	4796.0	1868.1	3536.0

Firstly, the step response for IAE is shown in Fig. 6 where rise time, settling time and peak amplitude are 0.2s, 0.355s and 0.996 respectively. The value for best fitness is 0.106007 which is presented in Fig. 7

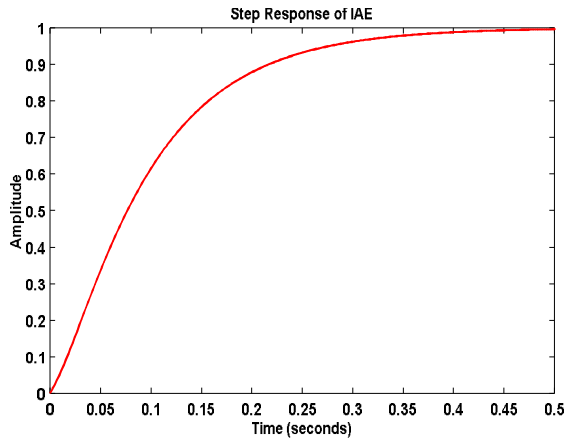


Fig. 6. Step Response of IAE.

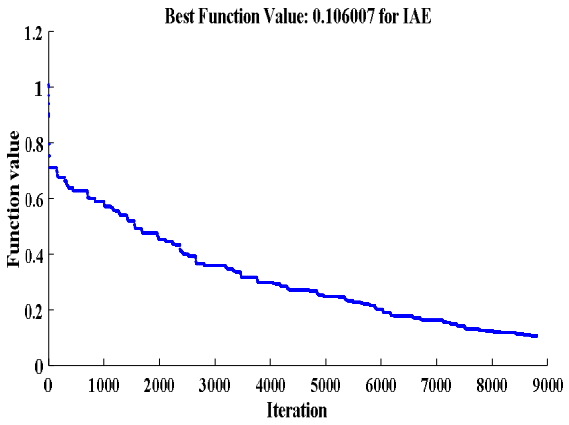


Fig. 7. Best fitness for IAE.

Secondly, the step response for ITAE is exhibited in Fig. 8 where rise time, settling time and peak amplitude are 0.125s, 0.212s and 0.998 respectively. The value for best fitness is 0.00354099 which is depicted in Fig. 9.

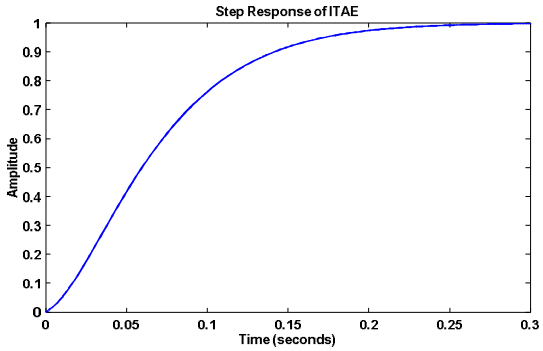


Fig. 8. Step Response of ITAE.

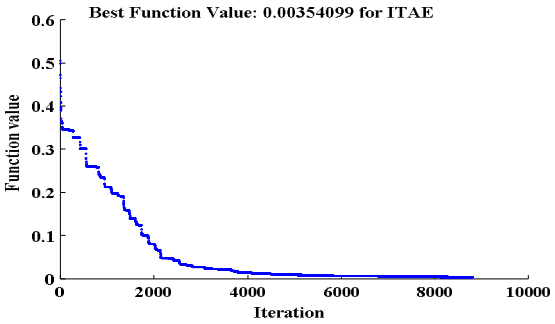


Fig. 9. Best fitness for ITAE.

Thirdly, the step response for ISE is displayed in Fig. 10 where rise time, settling time and peak amplitude are 0.465s, 0.84s and 0.998 respectively. The value for best fitness is 0.080074 which is shown in Fig. 11.

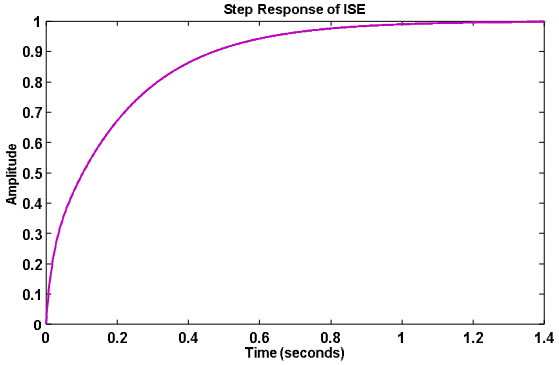


Fig. 10. Step Response of ISE.

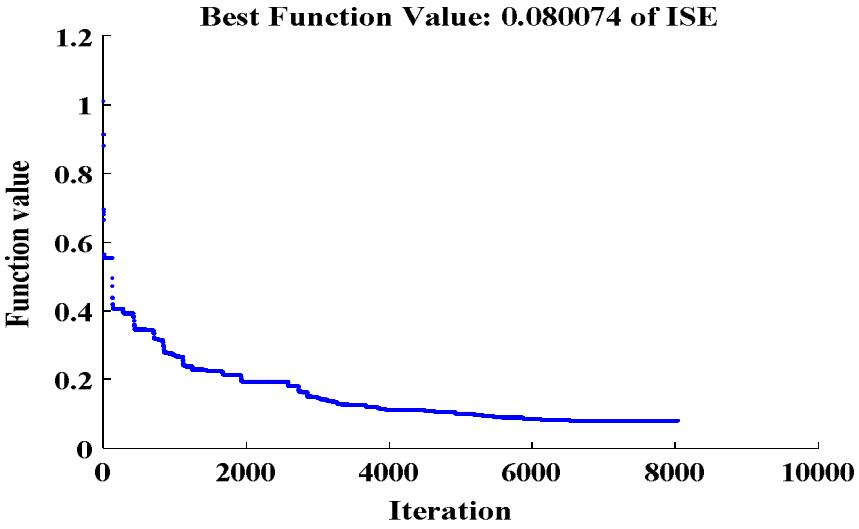


Fig. 11. Best fitness for ISE.

Fourthly, the step response for ITSE is displayed in Fig. 12 where rise time, settling time and peak amplitude are 0.226s, 0.405s and 0.997 respectively. The value for best fitness is 0.00224663 which is shown in Fig. 11. Lastly, the overall comparative analysis is illustrated in terms of step response in Fig. 14 and the performance parameters are tabulated in Table IV.

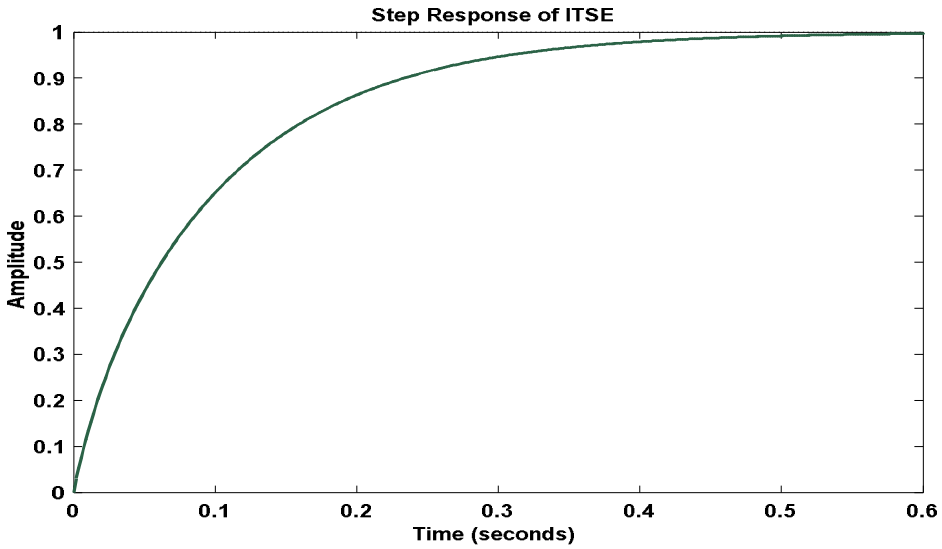


Fig. 12. Step Response of ITSE.

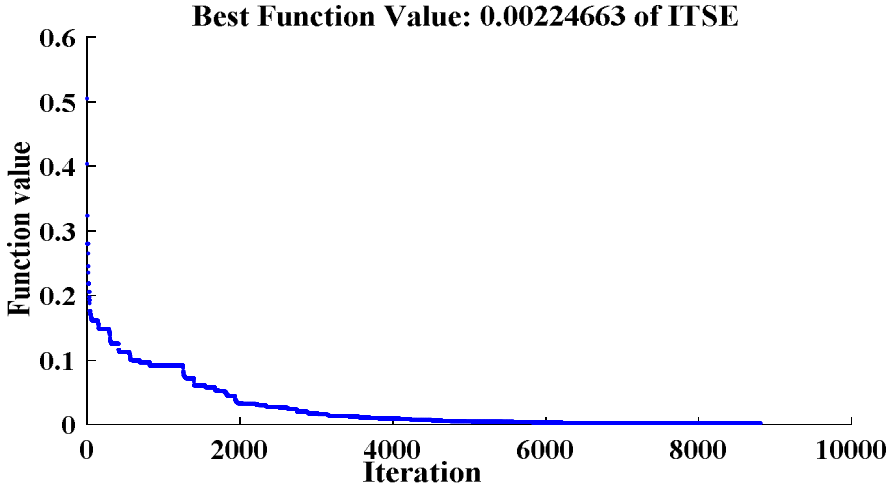


Fig. 13. Best fitness for ITSE.

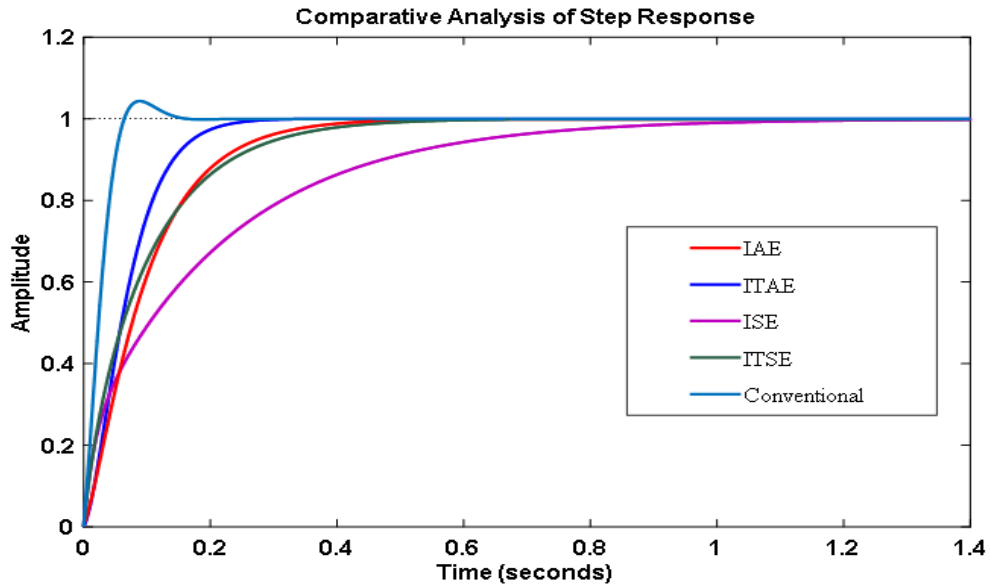


Fig. 14 Comparative Analysis of Step Responses.

TABLE IV. **Performance Parameters for both Conventional and SA-PI Controller**

Performance Parameters	Conventional PI	SA-PI			
		IAE	ITAE	ISE	ITSE
Tr	0.0444	0.2	0.125	0.465	0.465
Ts	0.122	0.355	0.212	0.84	0.84
Peak Amplitude	1.04	0.996	0.998	0.998	0.998

CONCLUSION

In this paper, an analysis is carried out in order to obtain optimized values of SA-PI controller to investigate stability of closed loop DC-DC boost converter. Conventional PI controller shows overshoot of 4.33% which is alleviated by SA-PI controller. The use of different performance indices has made the investigation more meticulous. Moreover, manual tuning of PI converter is not needed as the values are obtained by implementing such intelligent algorithm. The overall comparative analysis will help to understand the improvement made by employing such controller. This approach will be useful to design and analyze more robust nonlinear systems in the field of power electronics.

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