

PERFORMANCE ENHANCEMENT OF UNITY POWER FACTOR AC-DC BOOST CONVERTER USING BIO INSPIRED OPTIMIZATION ALGORITHMS

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Abstract: A comprehensive evaluation of using Bio Inspired Optimization Algorithms to enhance the dynamic performance of unity power factor AC-DC Boost Converter is presented in this paper. To achieve constant output voltage and unity power factor at supply mains, Sliding Mode controller in cascade with the PID voltage loop controller is normally used to control these converters and it is highly evident that the performance of these converters is highly influenced by PID controller gains. This paper reviews the feasibility of using Bio inspired Optimization Algorithms to find an optimal PID gain that enhances the dynamic and static performance of the converter. The objective function formed for the optimization problem is framed from time domain performance parameters. From simulation results, it is deduced that the Bio Inspired optimization based PID gain results in an enhanced converter performance compared to its traditional counterpart.

Key words: AC-DC converters, Bio Inspired Algorithms, PID Controller, Sliding Mode Controller, Variable Structure Controller (VMC)

1. Introduction

AC-DC converters finds a wide range of application in our day-to-day life in homes in the form of chargers, LED based lighting, etc. Conventional AC-DC converters use a diode rectifier followed by a DC link capacitor which draws a non-sinusoidal line current, thereby injecting higher order harmonics into supply mains and ultimately results in a lower power factor. With the emerging use of AC-DC converters at the consumer end, strict regulations such as IEC 61000-2-2 have been imposed to regulate the Power factor of these devices [1].

To mitigate the above problems, PWM based control [2 - 3] was proposed to regulate the output of these AC-DC converters while improving the quality of input line current. PWM converters compared to the traditional diode converters, have low line current distortion and high power factor. Several linear and nonlinear control methods have been proposed in the literature for the control of these PWM AC-DC converters.

Model based linear Average Current mode control proposed in [4] seems to work fine under predefined operating points, but its performance gets deteriorated with variable load conditions. Feed forward current mode control [5], mitigates the problems with averaged mode control by generating a duty cycle in proportion to the desired output, but suffers from duty ratio saturation at converter start up and slow response to load variations. Digital controllers proposed in [6] have faster response to load variations, but are complex to implement in real time.

Sliding mode controller (SMC) initially used for the control of Variable structure systems, is gaining importance in the field of power electronics because of its robustness to disturbances [7] & [8]. Even though the SMC is robust, the performance of these controller depends on the selection of sliding mode constants and the dynamic response is highly dependent on these sliding mode constants as proposed in [9]. To overcome the above difficulty a Rotating sliding mode control employing a time variable slope based sliding surface has been proposed in [9] and [10]. Even though the dynamic response of the converter is improved, it takes time for the tracking error to become zero as proposed in [11]. In general the control methods proposed in literature concentrates much on regulating the output voltage, maintaining near unity power factor at supply mains and robustness to disturbances with very little emphasise given over the dynamic and steady state performance parameters of the converter.

To improve the dynamic response and to reduce the settling time, PID based SMC - replacing sliding mode constants with PID parameters has been proposed in [11-14]. Even though the later method provides a better response, the performance of the controller is still dependent on the tedious tuning of the PID parameters.

In recent years, Bio-inspired metaheuristic PID tuning algorithms is gaining importance in the control of power electronic converters. A multi

objective optimal PID Controller tuning using Particle Swarm optimization [PSO] technique for minimizing peak overshoot, rise time, settling time, and steady-state error has been proposed in [15 - 17]. Harmonic reduction in AC-AC Converter using Bee Colony Optimization [BCO] has been proposed in [18]. It has been shown in [19 - 20] that the Ant Colony optimization [ACO] provides an improved set point tracking, compared to the other tuning methods. [21-22] have proposed a methodology to determine the optimum PID gains using the Krill Herd Optimization algorithm [KHO], to achieve the desired system response using a cost function based on the weighted sum of step response characteristics.

The main objective of this paper is to review the feasibility of using Bio-inspired tuning algorithms like BCO, ACO, PSO and KHO to find an optimal PID gain that enhances the dynamic and steady state performance of AC-DC Boost converter. Section II presents an overview of PID based Sliding Mode Control of these converters, along with the control objective and problem formulation. A general overview of Nature inspired algorithms is presented in section III. Section IV provides the comparative simulation results describing the enhancement in the dynamic and steady performance of these converters with the various Bio-inspired tuning algorithms followed by the conclusion.

2. System model and Problem formulation

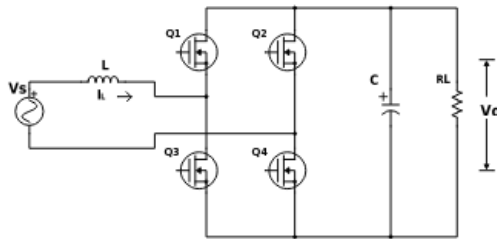


Fig.1. AC-DC Boost Converter Model

Fig.1 gives the model of AC-DC Boost converter. \$Q_1\$ to \$Q_4\$ are MOSFET switches. \$R_L\$ is the load connected to the converter. \$L, C\$ being the inductance and capacitance of the converter. \$v_s = V_m \sin \omega t\$ is the supply voltage and \$v_o\$ is the output voltage. The averaged model of the converter is given by

$$\begin{aligned} L \frac{di_L}{dt} &= v_s - uv_o \\ C \frac{dv_o}{dt} &= i_L - \frac{v_o}{R_L} \end{aligned} \quad (1)$$

Where, \$i_L\$ - Current through the inductor,
\$u\$ - Control signal injected into the system, with values in the finite set \$\{-1, +1\}\$ and is given by (2)

$$\begin{aligned} u &= +1 & \text{Switches } Q_1, Q_4 - ON \\ u &= -1 & \text{Switches } Q_2, Q_3 - ON \end{aligned} \quad (2)$$

Using small signal analysis, transfer function relating the control signal to the output voltage is given by Eq. (3)

$$\frac{v_o(s)}{d(s)} = \frac{2V_o(R - Ls)}{LCRs^2 + L(D - D')s + R(D - D')} \quad (3)$$

With \$D\$ being the averaged ON time of the Switches

The main control objectives are 1) Faster dynamic response under disturbances 2) The converter should draw a sinusoidal line current in phase with the line voltage guaranteeing a unity power factor at AC mains with low THD 3) Output DC voltage \$V_o\$ should be maintained constant irrespective of disturbances

2.1 Control Structure

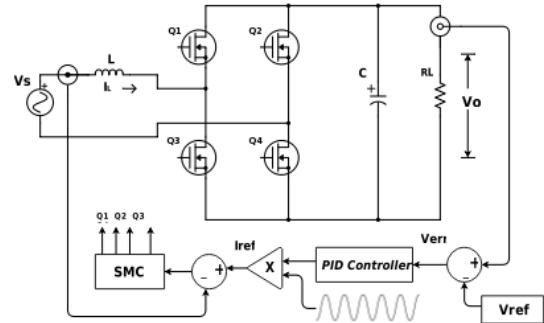


Fig.2. PID based Sliding Mode Control

Fig.2 gives the structure of PID based Sliding mode control (SMC). AC-DC boost converters are in general non minimum phase systems, and hence the output voltage of these converters is regulated indirectly by forcing the input line current to follow a reference current profile. As shown in Fig.2, the PID based SMC consists of an outer PID based voltage regulator, which generates the reference current amplitude for the inner current loop controller. The reference current profile for the inner SMC based current loop controller is obtained by modulating the reference current amplitude from the outer voltage loop controller with a sinusoidal signal. The inner SMC controller indirectly regulates the converter output voltage by controlling the input line current.

2.2 Voltage Loop Controller:

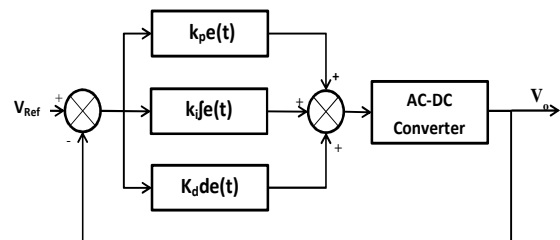


Fig 3 Outer Voltage loop controller

Fig.3 gives the structure of PID controller forming the outer voltage loop controller. The reference current amplitude for the inner current loop sliding mode controller is given by

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

$$e(t) = v_o - V_{Ref}$$
(4)

Where K_p , K_i , K_d are proportional, integral and derivative gain constants.

2.3 Current Loop Controller:

Sliding mode controller forms the inner current loop controller whose switching manifold is given by

$$s = i_L - i_{Ref}$$
(5)

And the control signal u is given by

$$u = \text{sign}(S)$$

$$S < 0, u = -1$$

$$S > 0, u = 1$$
(6)

2.4 Problem Formulation:

It is evident from Fig. 2 that the performance of the converter could be improved to a greater extend by selecting an optimum PID gain which guarantees a better dynamic and steady state response. Table 1 gives the effect of PID Coefficients on systems closed loop response.

Table 1 Effect of PID Coefficients on System Response

	Rise Time	Overshoot	Settling Time	Steady State Error
K_p	Reduces	Increases	Small Change	Reduces
K_i	Reduces	Increases	Increases	Eliminates
K_d	Small Change	Reduces	Reduces	No Change

With the aim of optimizing the systems dynamic and steady state behaviour under disturbances, the following cost function is selected for minimization and the PID gains are tuned so as to minimize the proposed Cost function, thus guaranteeing the desired dynamic performance. The Cost Function $F(t)$ is given by

$$F(t) = IAE^2 + 1.2 * MP + T_r$$
(7)

IAE is the Integral of Absolute Error, T_r and MP being the Rise Time and Percentage Peak Overshoot of the system subjected to unit step input. Inclusion of IAE in the cost function results in reducing the Steady state error and T_r . MP improves the dynamic response of the converter

3 Bio Inspired Algorithms

3.1 Bee Colony optimization

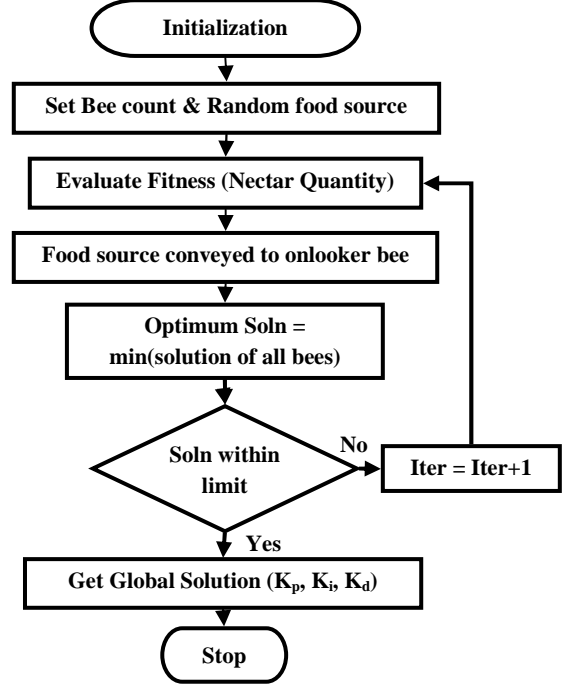


Fig.4. Flowchart of Bee Colony Optimization

The foraging behavior of honey bee colonies in search for nectar is used to find the solution for the optimization problem. In BCO algorithm, the possible solution for the given optimization problem is symbolized by the food source and the amount of nectar in that particular source (fitness value of the particular solution). Employed, onlooker and scout bees are used to find the optimum food source. BCO starts by relating every employed bee with a randomly created food source (solution). After every iteration, the employed bee discovers a neighbourhood food source and evaluates the nectar quantity (fitness) using Equation

$$v_{ij} = x_{ij} + \phi_{ij} (x_{ij} - x_{kj})$$
(8)

After the completion of a search process, the entire employed bee's shares the food source information with the onlooker bees – which in turn evaluates the employed bee's nectar information and selects a food source with a probability P_i proportional to the food source fitness using the Equation.

$$p_i = \frac{fit_i}{\sum_{i=1}^m fit_i}$$
(9)

Where fit_i - the fitness quantity for i th employed bee and m being the number of available food sources and is equivalent to employed bees number. When the food source gets exhausted, employed bee becomes a scout bee generating a

new random solution given by Equation

$$x_i^j = x_{\min}^j + rand(0,1)(x_{\max}^j - x_{\min}^j) \quad (10)$$

Where x_i is the abandoned food source. Fig. 4 gives the flowchart representation of BCO algorithm

3.2 Ant Colony Optimization:

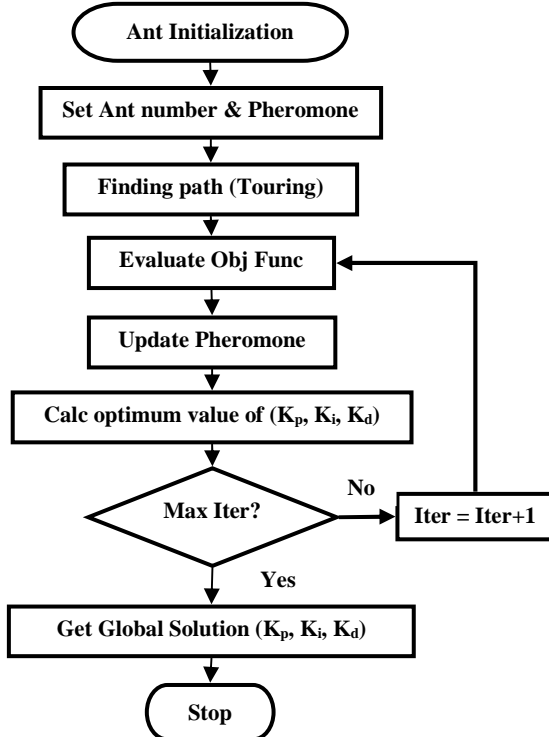


Fig.5. Flowchart of Ant Colony Optimization

ACO algorithm aims at finding the solution for the optimization problem based on the ant's behaviour in finding their food. Ant's while searching for food, selects a path with a higher trace of pheromone left over by ants that had already found the food location and mark the path again with their own pheromones. The pheromone level evaporates gradually thus reducing its trace along a particular path. Ants in general marches the shortest optimal path more frequently and thus makes the pheromone density for the particular path higher compared to the other paths. Pheromone evaporation plays a critical role in converging to the optimal path. In ACO algorithm, continuous time systems are divided into multiple regions forming the local nodes for artificial ants and the fitness for every region is calculated using the formula

$$p_{ij} = \frac{T_{ij}^{\alpha} \eta_{ij}^{\beta}}{\sum_{j \in \text{nodes}} T_{ij}^{\alpha} \eta_{ij}^{\beta}} \quad (11)$$

Where η_{ij} - value of Pheromone against heuristic value is given by

$$\eta_{ij} = \frac{1}{d_{ij}} \quad (12)$$

All ants finds a path and deposits the Pheromone and updates the nodes based on

$$T_{ij}(k+1) = (1-\rho)T_{ij}(k) + \sum_{\substack{k=\text{node} \\ u \text{ sing } egde(i,j)}} \frac{Q}{L_k} \quad (13)$$

P_{ij} - Probability between the node i and j

τ_{ij} - Pheromone associated with the edge joining nodes i and j

d_{ij} - Distance between nodes i and j

Q - Constant

L_k - Length of the path travelled by Kth ant

α, β - Constant ρ - Evaporation rate

Fig. 5 gives the flowchart representation of ACO

3.3 Particle Swarm Optimization Algorithm

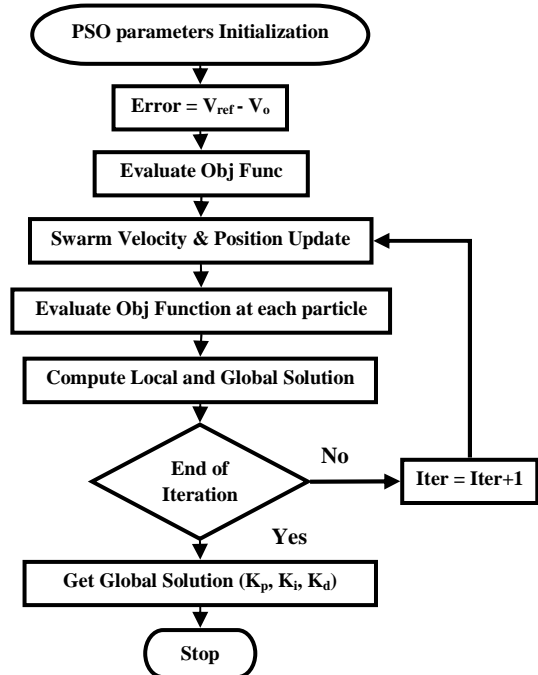


Fig.6. Flowchart of Particle Swarm Optimization

PSO aims at finding the solution for the optimization problem based on the collective behaviour of birds while searching for food. The effective way for a group of birds to search for food is to follow the bird which is nearer to the food. Normally, PSO optimization starts with some arbitrary solutions and the hunt for optimum solution is carried out through generation updates. Every particle in the swarm is characterized by its own position and velocity directing the flight of the particles flight. The fitness value of each particle is calculated based on their positions and velocities and thus represents the solution for the given optimization problem. At the end of each iteration, local best L and called global best G solution for each particle is updated. With the best values found, the velocity and position updates for each

particle is given by

$$\begin{aligned} v_i(k+1) &= w_i v_i(k) + c_1 r_1 [L_i(k) - x_i(k)] + c_2 r_2 [G(k) - x_i(k)] \\ x_i(k+1) &= x_i(k) + v_i(k+1) \end{aligned} \quad (14)$$

w – Inertia factor
 $v_i(k)$ – Particle velocity at iteration k
 $x_i(k)$ – Particle position in the search space at iteration k
 c_1, c_2 – Acceleration constants
 r_1, r_2 – Random numbers between (0,1)
 Fig. 6 gives the flowchart representation of PSO

3.4 Krill Herd Algorithm

KHA aims at finding the solution for an optimization problem based on the behaviour of Krill individuals while searching for food, and their herding behaviour to protect themselves from their predators. In general herding process of krill individuals is a multi-objective process with two main objectives: (1) increasing the density of krill herd (2) reaching the area with high food concentration in shortest optimal path and these objectives ultimately leads the individual krill to a herd around the global minima – higher Krill density and higher concentration of food. The position of a krill individual is induced by the following three actions 1) Movement due to other krill individual 2) Foraging activity 3) Random diffusions. Fig. 7 gives the flowchart representation of KHO

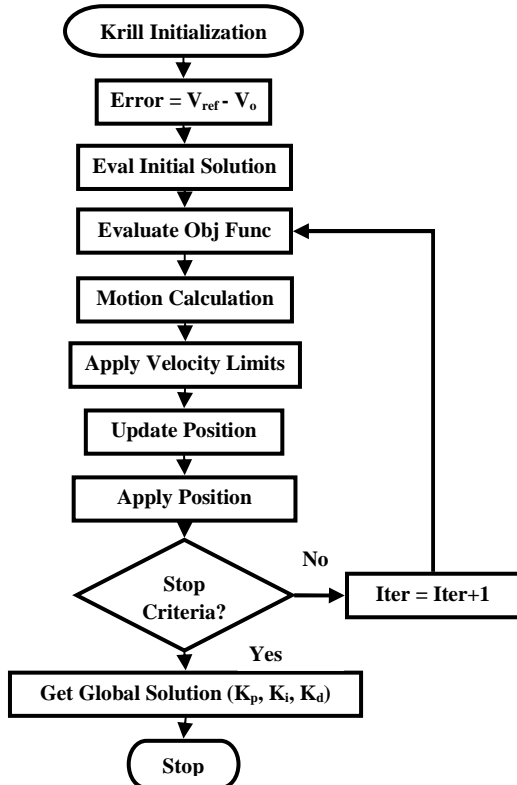


Fig 7 Flowchart of Krill Herd Optimization

The movement due to other Krill individual is

given by

$$\begin{aligned} N_i^{new} &= N^{\max} \alpha_i + \omega_n N_i^{old} \\ \alpha_i &= \alpha_i^{local} + \alpha_i^{tar} \end{aligned} \quad (15)$$

N_{\max} – Maximum speed induced
 ω_n – Inertia weight and lies between [0,1]
 N_i^{old} – Previously induced motion
 α_i^{local} – Local neighbor's effect
 α_i^{tar} – Target direction effect from the best krill individual

Foraging activity of the i th krill is given by

$$\begin{aligned} F_i &= v_f \beta_i + \omega_f F_i^{old} \\ \beta_i &= \beta_i^{food} + \beta_i^{best} \end{aligned} \quad (16)$$

Where,

v_f – Foraging speed
 ω_f – Foraging motion's inertia weight Ξ [0,1],
 F_i^{old} – Previous foraging motion.

Random diffusion of i th krill is given by

$$D_i = D^{\max} \delta \quad [17]$$

Where D^{\max} is the maximum diffusion speed of Krill and δ is the random directional vector in the range [-1,1]

4 Simulation Results

Evaluation of dynamic and steady state performance of the converter has been carried out in this section. The effectiveness of Bio Inspired tuned PID gains in enhancing the converter's performance is proved by analyzing the dynamic and steady state performance of the converter with traditionally tuned PID gains and Bio inspired tuned PID gains through Matlab/Simulink simulations. Table 2 gives the values of parameters used for the simulation purpose.

Table 2 Simulation parameters

Supply Voltage V_s	6 V
Desired Output Voltage V_o	12 V
Nominal Power Output	20 Watts
Inductor	2mH
Capacitor	2200 μ F
Switching Frequency	20 KHz

$$\frac{v_o(s)}{d(s)} = \frac{-0.048s + 1200}{0.00022s^2 + 0.004s + 10} \quad (18)$$

For the parameters selected, the transfer function relating the control signal to the output

voltage is given by Eq. (18)

Simulation results obtained is divided into following groups:

Group-1 represents the open loop and closed loop Step response characteristics of the outer voltage loop, demonstrating the Boost nature of the open loop system and its unstable behaviour under closed loop operation.

Group 2 represents the closed loop step response characteristics of the converters output voltage loop with the proposed Bio Inspired tuned PID gains and traditionally tuned PID gains. It demonstrates the enhancement achieved in the static and dynamic characteristics of the converter using Bio inspired PID gains.

Group 3 represents the output response of the converter under nominal operating conditions, giving an insight on the various performance characteristics of the converter controlled by Bio Inspired tuned PID gains and traditional tuned PID gains.

Group 4 represents the output response of the converter under various disturbances, giving an insight on the ability of Bio Inspired tuned PID gains in maintaining the system robust to disturbances.

4.1 Uncontrolled Step Response

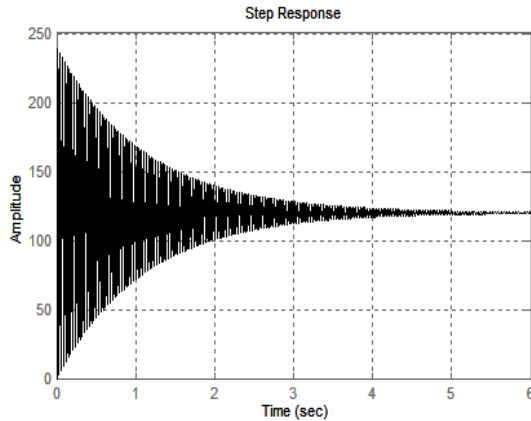


Fig. 8 Open loop Step Response of Converter

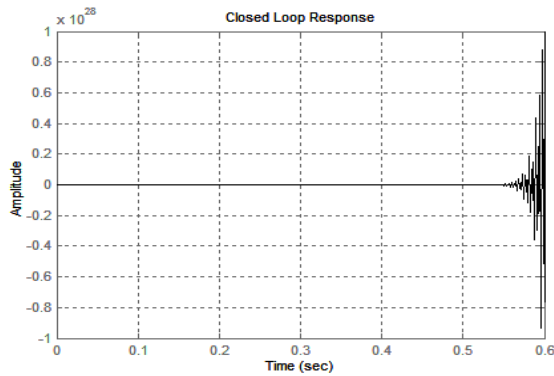


Fig. 9 Closed loop Step Response of Converter

Fig.8 and Fig. 9 gives the open-loop and closed loop step response characteristics of the converters voltage loop without any controller action. Fig. 8 depicts the inherent boost nature of the converter.

Fig. 9 depicts the unstable nature of the converter as proposed earlier, thus making it necessary to use controllers to control these converters.

4.2 Step Response with Optimal Tuned PID Controller

Table 3 Optimal PID Gains

	Kp	Ki	Kd	Cost Func
ISE	25	5	0.0027	68.4
BCO	0.94	0.009	0.0029	2.32
ACO	0.27	0.001	0.0031	0.83
PSO	0.81	0.005	0.0031	0.71
KH	0.09	0.430	0.0034	0.52

Table 3 gives the optimum value of PID gains for the converter obtained through traditional Integral Squared Error Tuning method (ISE) and Bio Inspired tuning methods along with their cost function.

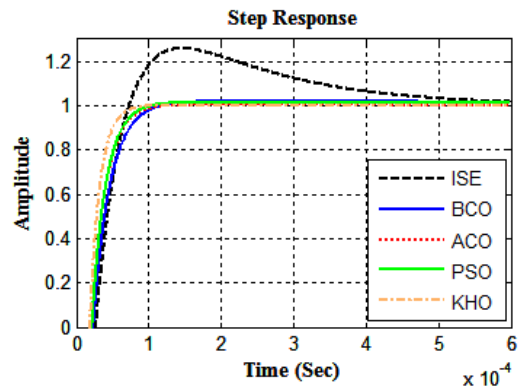


Fig. 10 Closed loop Step Response of Converter with PID Controller

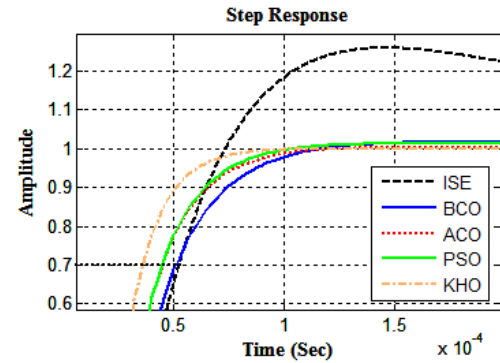


Fig. 11 Closed loop Step Response depicting Rise Time T_R

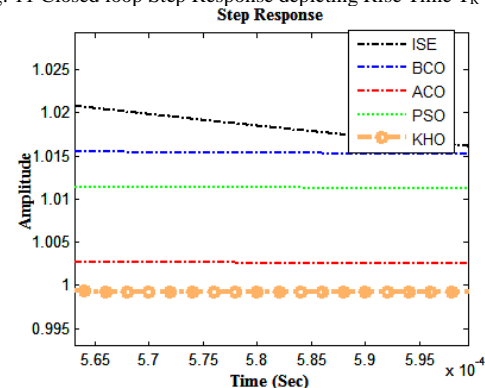


Fig. 12 Closed loop Step Response depicting Steady State Error

Fig.10 gives the closed loop step response characteristics of the converters voltage loop under various PID controller gains as presented in Table.3. More insight on the dynamic performance and the steady state performance of the converter under various PID gains is given in Fig.11 and Fig. 12 respectively and the same has been numerically represented in Table 4.

Table 4 Step Response Characteristics of Converter

	$M_p\%$	$T_R \text{ msec}$	$T_S \text{ msec}$
ITSE	57	0.058	0.6
BCO	1.6	0.049	0.2
ACO	0	0.045	0.2
PSO	0	0.043	0.1
KH	0	0.03	0.1

From Fig.10, it is evident that the traditional ISE tuned PID gains results in an overshoot (M_p) in system response, thus increasing the stress on the load connected at the output of the converter. Bio inspired tuned PID gains on the other hand, not only eliminates the system overshoots, but also enhances the system performance by reducing the rise time T_R and T_S settling time of the converter as depicted in Fig 11 and Fig 12.

From Table 4 and Fig 10 – 12 it could be deduced that, KHO based PID gain results in an enhanced converter performance compared to its counter parts.

4.3 Converter Performance under nominal condition

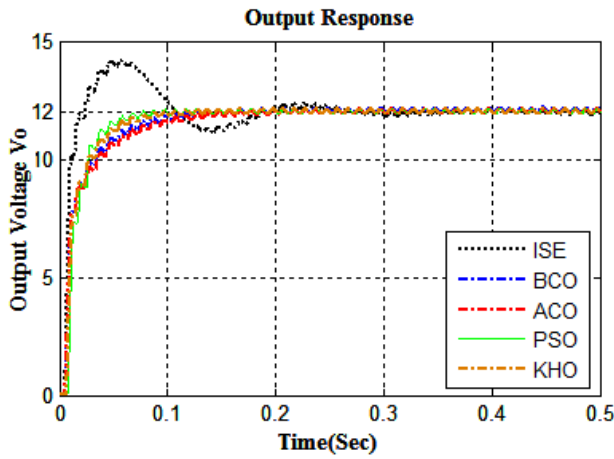


Fig. 13 Output Voltage under nominal condition

Fig.13 gives the output voltage waveform of the converter under nominal operating condition with traditional ISE tuned PID gains and with PID gains tuned using various Bio inspired optimization algorithms. The performance parameters of the converter under nominal operating condition are given in table 5.

Table 5 Performance Characteristics of Converter under Nominal Conditions

	$M_n\%$	$T_R \text{ sec}$	$T_S \text{ Sec}$	THD
ITSE	18.3	0.01	0.29	7.53
BCO	0	0.018	0.2	7.13
ACO	0	0.015	0.2	5.72

PSO	0	0.015	0.15	3.38
KH	0	0.01	0.1	2.81

From Fig.13 and Table 5, it is evident that dynamic and steady state performance of the converter has been improved to a greater extent using Bio inspired tuned PID gains compared to the traditional counterpart. With Bio inspired tuned PID gains, rise time and settling time of converter output voltage is reduced with almost zero overshoot and reduced Total Harmonic Distortion (THD). It is observed that KHO tuned PID gains provide a better performance characteristics compared to the other optimization algorithm.

4.4 Converter Performance under Disturbances

Since KHO tuned PID gains provide better performance characteristics, the converter performance under disturbances is carried out using KHO tuned gains alone and the same is compared with traditional ISE tuned PID gains.

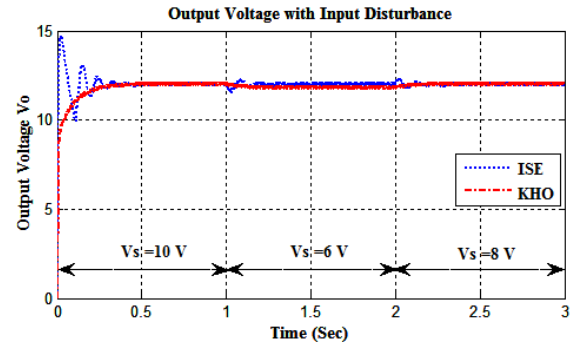


Fig. 14 Output Voltage under Supply Voltage Variations

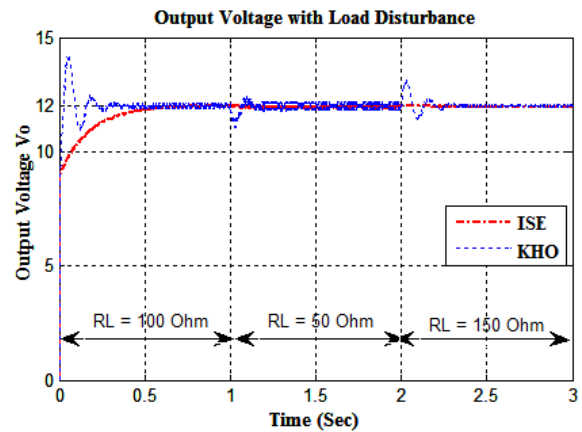


Fig. 15 Output Voltage under Load Variations

Fig 14, Fig 15 and Fig 16, gives the output voltage waveform of the converter controlled by Traditional ISE PID gains and by KHO tuned PID gains, with disturbances in supply voltage, load, and with changes in desired voltage. From the simulation results, it is observed that the voltage output of the converter under KHO tuned PID gains is free from Overshoot and undershoot which is evident in Traditional ISE PID gains. This reduces the stress experienced by the load connected at the output of the converter.

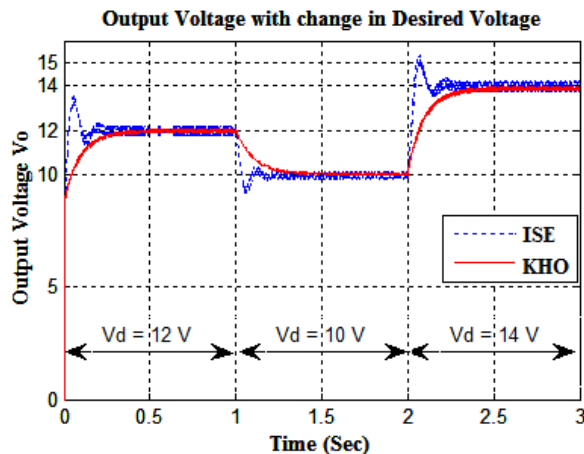


Fig. 16 Output Voltage under change in Desired Voltage

Apart from being robust to disturbances, the dynamic and steady state performance of the converter under KHO tuned PID gains is improved and is better compared to its counterpart.

5 Conclusion

In this paper, a comprehensive evaluation of using Bio Inspired Optimization Algorithms to enhance the dynamic performance and steady state performance of unity power factor AC-DC Boost Converter is carried out.

The simulation results of the converter controlled by Bio Inspired tuned PID gains seems to enhance the performance of AC-DC converter to a great extent compared to the traditional PID tuning methods. Among the various Bio Inspired Tuning Algorithms, KHO tuning methodology provides the converter with a faster dynamic response and a superior Steady state response, with reduced THD. Also the KHO tuned PID gains makes the converter robust to disturbances, making it an ideal choice to enhance the performance of AC-DC Boost Converters.

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