Optimization of PI Based Buck-Boost Converter by Particle Swarm Optimization Algorithm

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***Abstract*— In case of load change at the output of the converters, the inductor and capacitor sizes in the converters should also change. Otherwise, there will be distortions in the dynamic response of the converter in terms of performance criteria such as settling time, rise time, and maximum overshoot amount. This paper presents to improve the control's performance optimization using particle swarm optimization of the system consisting of a buck-boost converter. Thus, a stable control structure has been created by calculating the optimal values of the coefficients in the proportional-integral (PI) control structure with the partial swarm optimization (PSO) method. The input source is taken as DC source voltage. The simulation study is done in MATLAB/Simulink software.**

Keywords— Buck-Boost Converter, Optimization, Particle Swarm Optimization, PI Control.

Introduction

Today, the use of converters has increased due to the widespread use of renewable energy sources and the cheapening of semiconductor materials. Converters alter low-level DC (Direct Current) voltage to DC voltage at the desired level, providing sufficient current. In other words, converters provide control of DC electrical energy. IGBT and MOSFET semiconductor materials are generally used in the control process. These converters, which are referred to as DC-DC converters, are available in the literature: buck converter, boost converter, buck-boost converter, CUK, and Fly-Back converters. Output voltage control of these converters is more difficult, especially in boost and buck-boost type converters. The difficulty in controlling this type of converter is because the control input is included in both the voltage and current equations. By controlling the current, the output voltage is also controlled [1-4].

Due to the non-linearity and time-dependent variable structure of DC-DC converters, linear and conventional control techniques are not suitable for the control of these converters. Change of system parameters and wide signal transients produced against changes in the initial phase or load cannot be handled with these techniques. The suitable control technique for DC-DC converters provides fast transition responses and must be capable of coping with load variations with the wide input voltage, ensuring stability under any operating condition. Linear and unconventional robust control structures must be used to improve the performance of DC-DC converters. In addition to the preference of these control structures, the control parameters should also be determined optimally. The determination process is done by metaheuristic optimization methods apart from the trial and error method [5-8]. There are many computational techniques inspired by biological systems for this. Many of these have been developed inspired by natural events. For example, artificial neural networks are a simplified model of the human brain [9, 10]. Genetic algorithms are inspired by the evolutionary process in biology. Here, the subject discussed is social systems, which are different types of biological systems. In particular, the cooperative behaviors of simple individuals interacting with each other and their environment are examined. The most popular among these algorithms is the genetic algorithm inspired by Darwin's theory of evolution. This algorithm follows the steps in the natural evolution process [11]. However, it is not widely used in stable systems because the initial conditions are chosen randomly. The PSO algorithm has been inspired by the social behavior of bird flocks looking for their food [12, 13]. The Artificial Bee Colony (ABC) mimics the hunting behavior of the bee swarm. Ant Colony is another optimization algorithm inspired by the foraging behavior of ant colonies, like the ABC algorithm [14].

Each optimization algorithm has its characteristics in terms of performance and durability in different problem spaces, uncertain parameter situations, and noisy environments. PSO is an algorithm in this group that draws attention with its strong competitive feature. The PSO operates on the logic of finding the best solution for finding food in a given area, assuming that there is food in only one area, a group of birds is looking for food in that area and does not initially know where the food is. The advantages of PSO are that, unlike the traditional technique, it has a non-differentiable algorithm, has the flexibility to work with other optimization techniques, has few parameters to be adjusted, can be programmed easily, does not require a good initial solution to reach the result, and reaches the solution quickly. Another advantage of PSO is that it is easy to implement and has very few parameters to set. Particle swarm algorithm offers an optimal solution quickly because it is in the class of high-performance metaheuristic algorithms, and it has been preferred in this article because of its superior features [16-20].

This paper provides as the main contribution a procedure, based on PSO, to obtain fixed gains of PI controllers applied for voltage regulation of buck-boost converter with parameters not precisely known, but being on uncertain intervals. Fig. 1 shows the block diagram of the proposed methodology to design PI controller for buck-boost converter based on PSO algorithm. The proposed PSO algorithm is based on automatic tuning of the PI gains, guided by the minimization of an objective function.

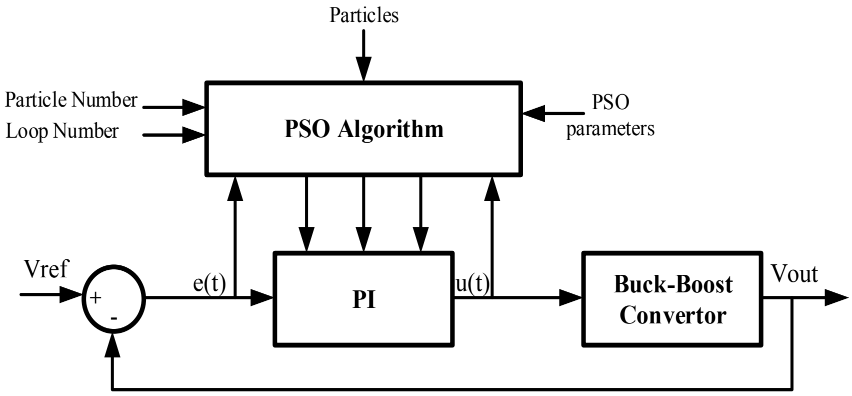


Fig. 1 Block diagram of the proposed system

I. BUCK-BOOST CONVERTER

Buck-boost converter is a type of dc-dc converter that combines the basic principle of the buck converter and boost converter in a single circuit. The converter gives the output voltage lower or higher than the input voltage [21]. The circuit diagram of the buck-boost converter is shown in Fig. 2.

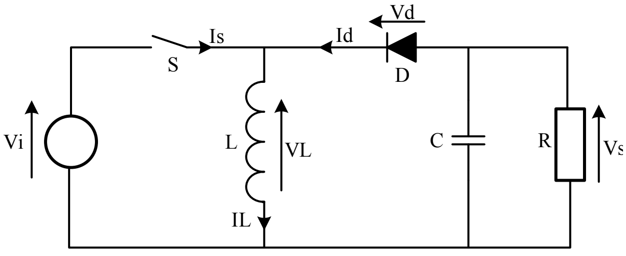
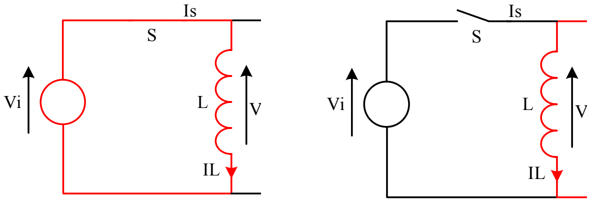


Fig. 2 Buck-boost converter circuit

In the circuit in Fig. 3.a, when the switch is ON, the input source is connected directly to the inductance. Thus, the energy is stored in the inductance *L*. At this stage, the capacitor supplies energy to the load. In the circuit in Fig. 3.b, when the switch is turned OFF, the inductance *L* is connected to the output load and the capacitor. Energy is transferred from inductance *L* to *R* and *C*. When the circuit is t_{on} state, the voltage on the inductance (V_L) is equal to the product of current and voltage. In the t_{off} state, V_L is equal to zero and has a negative sign in magnitude.

The output voltage may be greater or less than the input voltage depending on the duty period *D* in the operation of the circuit. The circuit works as a buck converter for $D<0.5$ and as a boost converter for $D>0.5$. There is no isolation between the input and output of the circuit. If the I_L inductance current never drops to zero during the cycle, the converter will operate in continuous mode [22, 23]. The current and voltage waveforms of an ideal converter are shown in Fig. 4.



a. Buck-boost converter circuit (Switch=On)

b. Buck-boost converter circuit (Switch=Off)

Fig. 3 Switch states of the buck-boost converter circuit

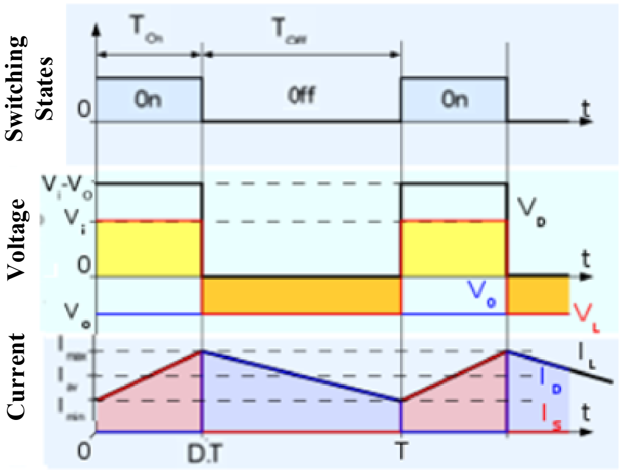


Fig. 4 Continuous mode graph of the buck-boost converter circuit

From t=0 to t=D. T, the converter is ON. The variation of I_L inductance current is given in Eq. 1.

$$\frac{dI_L}{dt} = \frac{V_i}{L} \tag{1}$$

The increase in I_L current at the end of the ON state is given in Eq. 2.

$$\Delta I_{Lon} = \int_0^{D.T} dI_L = \int_0^{D.T} \frac{V_i}{L} d_t = \frac{V_i.D.T}{L} \tag{2}$$

In the OFF state, I_L current flows towards the load.

$$\Delta L_{off} = \int_0^{(1-D).T} dI_L = \int_0^{(1-D).T} \frac{V_0.dt}{L} = \frac{V_0.(1-D).T}{L} \tag{3}$$

The expression of the energy accumulated in the inductance is given in Eq. 4.

$$E = \frac{1}{2}.L.{I_L}^2 \tag{4}$$

The sum of I_L is required to be zero during ON and OFF states.

$$\Delta I_{Lon} + \Delta I_{off} = 0 \tag{5}$$

$$\Delta I_{on} + \Delta I_{off} = \frac{V_i.D.T}{L} + \frac{V_0.(1-D).T}{L} = 0 \tag{6}$$

$$\frac{V_0}{V_i} = (\frac{-D}{1-D}) \tag{7}$$

D expression in Eq. 7 is obtained as in Eq. 8.

$$D = \frac{V_0}{V_0+V_i} \tag{8}$$

It can be seen from the above expressions that the output voltage sign is always negative. It is also observed that the expression increases with *D*. Capacitor and inductor values in the buck-boost converter topology are determined according to the expressions in Eqs. 9 and 10 [24].

$$L_{min} \geq \frac{R.(1-D)^2}{2f_s} \tag{9}$$

$$C_{min} \geq \frac{D}{r.f_s.R} \tag{10}$$

II. PI CONTROL

The control process has great importance in closed-loop and automatic control systems. The PI controller is at the forefront of the control systems. This method is widely used in industrial control systems. PI control is a linear control method and its mathematical model is given in Eq. 11. Here, K_p and K_i represent the proportional gain and integral gain, respectively, *F(t)* represents the control signal and *e* represents the error. The aim is to obtain the optimal values of these three gains [25].

$$F(t) = K_p.e(t) + K_i.\int e(t).d(t) \tag{11}$$

The PI control compares the input signal with the feedback from the output and creates an error from the difference between these two signals. According to this error, the PI controller makes an effect by trying to minimize the error and sends it to the output. In this way, errors are detected by continuous feedback from the output to the input until the error is minimized, and the error is reduced by sending the controller effect to the output. This control method is highly preferred because the mathematical model is simple and the number of adjustment parameters to be adjusted is low [26].

III. PARTIAL SWARM OPTIMIZATION (PSO)

The PSO algorithm developed by Eberhart and Kennedy simulates the social behavior of swarms of birds and fish. Here the individuals named as particles represent a potential solution to a problem, are evolved by cooperation and competition among themselves through generations, instead of using genetic operators [27].

The PSO algorithm is inspired by the social behavior of bird flocks looking for their food. The basic equations of velocity and particle position which govern the movement of the particle in standard PSO are given in Eqs.12-14.

$$Vij^{k+1} = w * Vij^k + c_1 rand()\left[{pbest_{ij}}^k - {X_{ij}}^k\right] + c_2 rand()\left[{gbest_j}^k - {X_{ij}}^k\right] \tag{12}$$

$${V_{ij}}^{k+1} = {X_{ij}}^k + {V_{ij}}^{k+1} \tag{13}$$

$${V_{ij}}^{k+1} = \begin{cases} V_{max} \ \ if \ \ {V_{ij}}^{k+1} \geq V_{max} \\ V_{min} \ \ if \ {V_{ij}}^{k+1} \leq \ V_{min} \end{cases} \tag{14}$$

Here, the closed-loop step response of the buck-boost converter is improved by employing PWM through the PI controller. The gains of the PI controller are determined using the PSO algorithm by minimizing the objective function as shown in Fig. 3. The integral square error (ISE) between output and the reference voltage, $V_{ref}(t)$ and $V_o(t)$, respectively, is used as a fitness function in this paper, which is given in Eq. 15.

$$Z = \int_0^\infty (V_{ref}(t) - V_0(t))^2 \, dt \tag{15}$$

The steps of the PSO algorithm are given in Table 1. The steps are used to obtain optimal values of controller parameters.

TABLE I. The steps of the PSO algorithm

1. Initialization
1.1. For each particle i in a swarm population size P:
1.1.1. Initialize X_i randomly
1.1.2. Initialize V_i randomly
1.1.3. Evaluate the fitness $f(X_i)$
1.1.4. Initialize $pbest_i$ with a copy of X_i
1.2. Initialize gbest with a copy of X_i with the best fitness
2. Repeat until a stopping criterion is satisfied:
2.1. For each particle i:
2.1.1. Update $\boldsymbol{V_i}^{\boldsymbol{t}}$ and $\boldsymbol{X_i}^{\boldsymbol{t}}$ according to Eqs. 13 and 14
2.1.2. Evaluate the fitness $\boldsymbol{f}(\boldsymbol{X_i}^{\boldsymbol{t}})$
2.1.3. $\boldsymbol{X_i}^{\boldsymbol{t}}$ =$pbest_i$ if $f(pbest_i) < \boldsymbol{f}(\boldsymbol{X_i}^{\boldsymbol{t}})$
2.1.4. $\boldsymbol{X_i}^{\boldsymbol{t}}$ =gbest if $f(pbest_i) > \boldsymbol{f}(\boldsymbol{X_i}^{\boldsymbol{t}})$

IV. SIMULATION RESULTS

After The Buck-boost converter circuit is simulated in MATLAB / Simulink environment in this section. The control of the output voltage of the buck-boost converter circuit is carried out with PI control methods using the simulation model. A PSO-based approach has been created to determine the PI control parameters. The model of the simulation performed in the MATLAB/Simulink environment is given in Fig. 5.

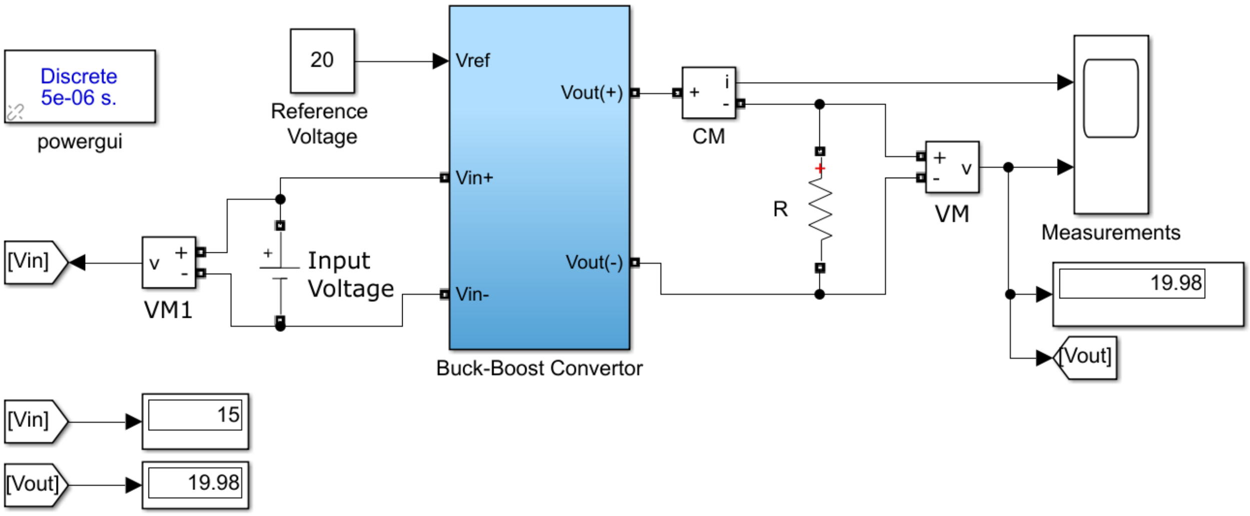


Fig. 5 MATLAB/Simulink simulation model of the buck-boost converter circuit

The switching frequency is taken as 10 kHz, the inductance value is 1.5e-3 H, the capacitance value is 250e-6 F, the load resistance value is 9Ω, and the input voltage is 15 V in the buck-boost converter model. The values have been calculated using the expressions in Eqs. 10 and 11.

In this study firstly, the PI algorithm is applied to the buck-boost converter. Then, the PSO-PI algorithm is applied to the buck-boost converter. The performance of the optimized controller concerning fitness functions is evaluated regarding output voltage response under constant load.

The comparison parameters of buck-boost converter parameters are visualized over a step response graph in Fig. 6. The comparison process is done in terms of settling time, rise time, peak time, peak value, overshoot.

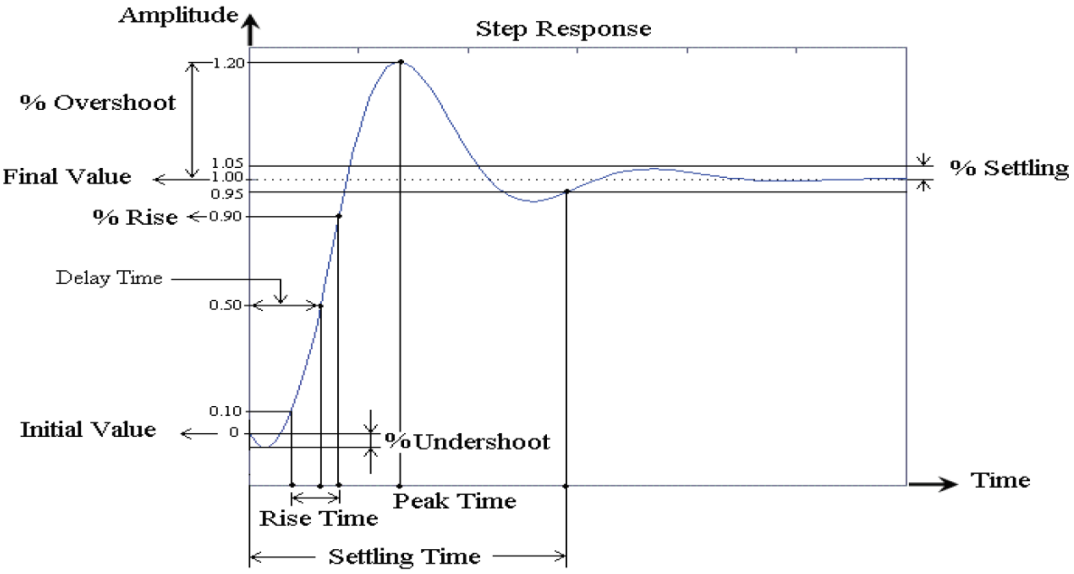


Fig. 6 Step response graph

A. *Control of PI-based Buck-Boost Converter Circuit*

Headings, The output voltage control of the buck-boost converter circuit was carried out using the PI control method in the simulation study. Control studies are carried out for 15 V input voltage and 5V, 10V, 20V reference output voltage to reveal the control success of the PI control on the buck-boost circuit. The block diagram of the simulation study carried out in MATLAB/Simulink environment using the model of the PI-controlled buck-boost circuit is given in Fig. 7.

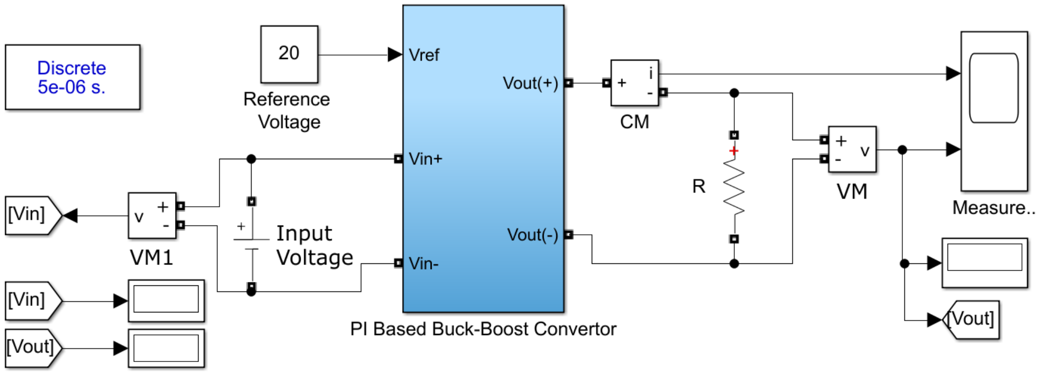


Fig.7 Block diagram of PI controlled buck-boost converter circuit

In this simulation, the gain coefficients in the PI control structure have been determined by the trial and error method as Kp=0.9 and Ki=150. The input voltage value of the converter is applied as 15V. By operating the converter as a boost converter, the output value is required to be 20 V. Graphics showing the output voltage and current values obtained in the simulation are given in Fig. 8.

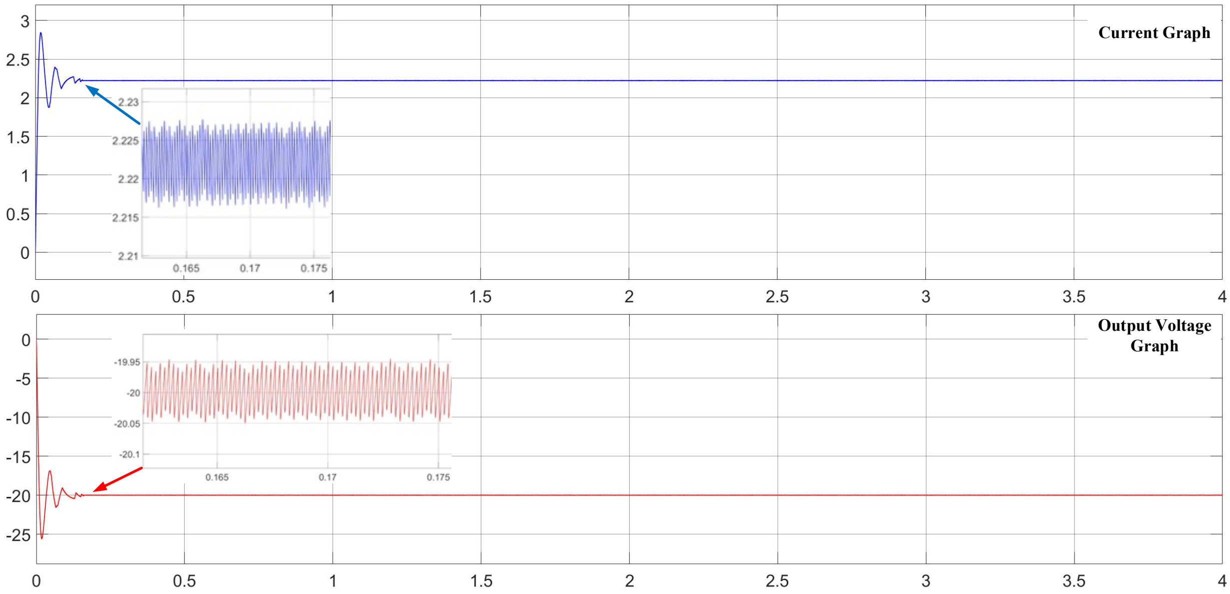


Fig. 8 Current-voltage graph of PI controlled Buck-boost converter circuit (20 Volt Reference)

When the current-voltage graph in Fig. 8 is analyzed, it is seen that the buck-boost converter stabilizes for the desired reference value in about 0.138 seconds. The control process has carried out at an average value of -20 volts with direction changes caused by ± 0.05 V switching. It is seen that the average current value is approximately 2.22 A in the current graph in Fig. 8. The direction changes for the voltage signal are also valid for the current signal of the same magnitude.

B. Optimization of PI Parameters of Buck-Boost Converter Circuit with PSO

The control parameters of the PI-controlled model given in previous section have been optimized with PSO and a simulation study has been carried out. The selected values of parameters for the PSO algorithm are given in Table 2. Thus, the parameters are applied to the PSO algorithm to obtain optimal values of PI controller parameters. The algorithm starts with parameters in Table 2. A random population of particles is initialized and then the PSO algorithm updates their position and velocity. It evolves until the maximum number of iteration. The final value of the objective function obtained in one of the executions of the PSO is best fitness value= 10.57, with the evolution of the fitness illustrated in Fig. 9. Thus, the best particle found by the PSO, that is, the best PI control parameters are obtained using the minimization of the objective function.

TABLE II. Selected values of parameters for the algorithm

PSO parameter	Parameter value
Number of generations	50
Population size	100
Maximum particle velocity	2

Fig. 9 shows the fitness improvement performed to optimize the PI control parameters. The simulation resulted in an optimized Kp=20.7 and Ki=0.06 value.

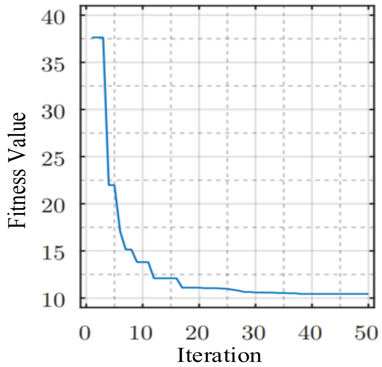


Fig. 9 Best fitness value in each iteration

To demonstrate the control success of the proposed PSO+PI control on the buck-boost circuit and to compare the performance with the PI-controlled buck-boost circuit, control is provided for 5V, 10V, 20V reference output voltage at 15 V input voltage. When the current-voltage graph in Fig. 10 is analyzed, it is seen that the buck-boost converter stabilizes for the desired reference value in about 0.07 seconds. Control operation has carried out at an average value of -20 Volts, with direction changes caused by ± 0.001V switching. When the current graph in Fig. 10 is analyzed, it is seen that the average current value of current value is approximately 2.22 A. The changes in direction for voltage are also valid for currents of the same magnitude.

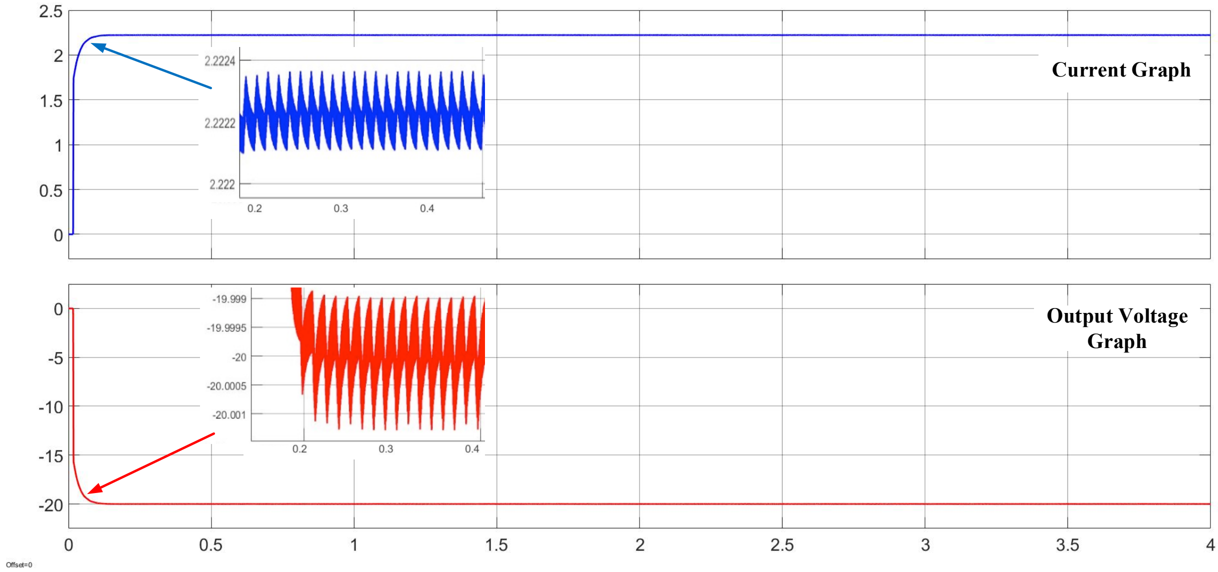


Fig. 10 Current-voltage graph of PSO+PI controlled Buck-Boost converter circuit (20 Volt Reference)

The results of the PI and the proposed PSO+PI controlled buck-boost converter are compared based on transient response properties such as overshoot, undershoot, settling time, rise time, and steady-state transient time in Table 3. The results have been obtained with different output values by operating the converter as both a buck and a boost converter. Accordingly, when the PI and PSO+PI control results are examined in terms of settling time, overshoot amount, and rise time in the buck and boost converter mode, the effects on the converter parameter can be seen if the PI parameters are optimally adjusted. The steady-state performance of the PSO+PI converter is faster than the PI control and no overshoot occurs. It is seen in Table 3 that the proposed PSO+PI control method has a more dynamic structure in terms of settling and rising time of the output parameters of the converter. In the reported results, bold text indicates comparatively the best result.

Table 3. Numerical results of robustness analysis of the Buck-Boost Converter controlled by PSO+PI and PI controller under constant input voltage and variable output voltage conditions.

Method	**Vin(V)**	**Vout (V)**	**I(A)**	**Settling time(s)**	**Overshoot (%)**	**Raise Time(ms)**	**Peak Time(s)**	**Peak Value**
PI	15	20	2.22	0.138	27	7.640	0.018	2.8575
PI	15	10	1.11	0.123	34.038	4.823	0.018	1.439
PI	15	5	0.554	0.142	34.932	7.572	0.02	0.748
PSO+PI	15	20	2.218	**0.07**	**0.342**	**7.290**	**-**	**-**
PSO+PI	15	10	1.112	**0.08**	**0.391**	**7.511**	**-**	**-**
PSO+PI	15	5	0.556	**0.09**	**0.326**	**5.874**	**-**	**-**

V. CONCLUSIONS

This paper presents an approach to design a PI Controller for the buck-boost converter. The tuning of controller gains is performed by minimizing the integral square error between output and the reference voltage of buck-boost converter using the PSO algorithm. It is seen that the proposed PSO+PI approach produces better results than the PI control method, thus increasing the controller performance and improving the dynamic response of the system in terms of performance criteria such as seat time, rise time, and maximum overshoot. In addition, it has been determined that the proposed approach works stably and the system performance does not deteriorate by operating the converter structure as both a buck and a boost converter at different reference values.

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