

Chaos minimization in DC-DC boost converter using circuit parameter optimization

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Abstract: DC-DC converters are prone to several types of nonlinear phenomena including bifurcation, quasi periodicity, intermittency and chaos. These undesirable effects must be controlled for periodic operation of the converter to ensure the stability. In this paper an effective solution to control of chaos in solar fed DC-DC boost converter is proposed. Controlling of chaos is significantly achieved using optimal circuit parameters obtained through Bacterial Foraging Optimization Algorithm. The optimization renders the suitable parameters in minimum computational time. The obtained results are compared with the operation of traditional boost converter. Further the obtained results with BFA optimized parameter ensures the operations of the converter are within the controllable region. To elaborate the study of bifurcation analysis with optimized and unoptimized parameters are also presented.

Nomenclature		VPV	Voltage across PV Panel
L	Inductor	Kd	Proportional constant of controller
C	Capacitor	Ti	Integral tuning constant of controller
R	Load Resistor	Td	Derivative tuning constant of controller
S	Power Switch	Abbreviations	
D	Power Diode	CCM	Continuous Current Mode
V_{in}	Input Voltage	BFA	Bacterial Foraging Algorithm
V_o	Output Voltage	EMC	Electro Magnetic Compatibility
F_s	Switching Frequency		



ID	Diode Current	PWM	Pulse Width Modulation
VD	Diode Forward Bias Voltage	PV Module	Photo Voltaic Module
Ish	Shunt Current	OGY	Ott, Grebogi and Yorke

1. Introduction

Power converters are designed to function in a stable manner in its designed operating region. Outside its defined operating limits the converter experiences phenomenon like period doubling and bifurcations (forking); which may develop into chaos (unpredictability). DC-DC boost converter experiences nonlinear operating conditions when connected to the solar Photo Voltaic system (solar PV) whose output power very often varies with respect to the environmental conditions such as irradiation and temperature. The role of solar energy in distributed power generation system has become inevitable in order to meet the increasing power demands. In addition with zero emission, solar PV converts incident sunlight in to electricity. However, the generated voltage, current and power is unceasingly varying and it depends upon the irradiation and temperature. Further the DC-DC boost converter is an important intermediate power processing unit that plays a vital role in connecting the solar PV to the load [1].

When chaos occurs in DC-DC converter, it causes additional loss, noise ripples, other unwanted outputs and sometimes even leads to catastrophic failure of the converter. In addition instability, spurious oscillations and sub harmonics have been exclusively observed in fast switching power converters when they fail to maintain their normal periodic operation. Hence, chaos in any form should be reduced [2].

Even under certain parametric conditions, due to its inherent nonlinearity, the DC-DC boost converter experiences chaos and leads to collapse in operating mode. Further, a small change or interruption in the system causes above said undesirable complicated chaotic behavior. Therefore, for controlling chaos in nonlinear systems many methods have been proposed [3]. These chaos control methods can be broadly classified into Parametric Variation Methods (method of OGY), Controlling via External Force, Entrainment and Migration Controls, Engineering Control Approaches such as Intelligent Control, Neural Network approach, Synchronization of Chaos and introduction of a controller (classical PI, PID, linear or nonlinear, stochastic etc.). Among the methods proposed, controlling chaos via optimized parameter is the simplest and cost effective solution. Parameter optimization has been given the highest priority since parameters greatly influence converter dynamics and are responsible for chaotic operation [4]. Further, parameters such as R, L, and C in DC-DC boost converter plays a significant role in determining the DC-DC boost converter dynamics and optimizing the above said parameters would further extend the operating range and minimize the occurrence of chaos. Therefore, parameter optimization in DC-DC boost converter assumes significance and it is essential.

In this work parameter optimization of DC-DC boost converter for chaos minimization is carried out by using Bacterial Foraging Algorithm (BFA). The task of identifying the optimal parameter set is framed as an objective function and it is solved using BFA method. Equations pertinent to converter dynamics are evolved and the necessary steps of parameter optimization are explained. Further simulation model developed

using MATLAB/SIMULINK for computing the converter characteristics under different operating conditions. Furthermore, Bifurcation analysis and phase portraits of the simulated results are presented. From the results it is evident that BFA optimized parameters restricts the occurrence of chaos and provides stable operation under wider operating input voltages.

The organization of the paper is as follows, the section 2 explains the closed loop operation of the boost converter and the necessity of optimizing the resistor, inductor and the capacitor. The steps and implementation of BFA algorithm is discussed in section 3. The results of the boost converter with un optimized values are given in section 4 and is followed by the results of the boost converter with optimized values and its bifurcation analysis in section 5. Bifurcation behavior of boost converter for different operating regions is summarized in section 6.

2. Voltage mode controlled boost converter

Generally, DC-DC boost converter forms the front end power converter circuit for solar PV fed applications [5]. This converter provides higher output voltage than the input voltage by periodic switching of the semiconductor devices; since, the power output of the PV array need to be processed before delivering it to the load. The desired output voltage is attained via periodic switching of the converter at fixed frequency. The PWM switching pulse is varied by voltage controlled feedback path designed to provide constant output voltage for varying input voltage conditions. Further, the schematic diagram for the closed loop controlled DC-DC boost converter [1] is shown in Figure 1 where, the DC-DC boost converter is fed from solar PV Module and it comprises of Diode (D), Switch (S), inductor (L), capacitor (C) and load resistor (R). The design equations of boost converter are as follows,

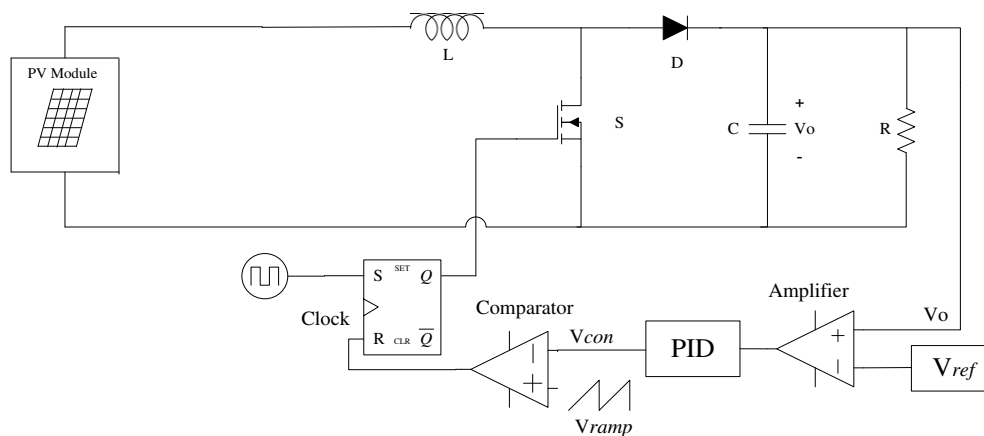


Figure 1. Closed Loop Control of Boost Converter

$$L_{\min} = \frac{D(1-D)^2 R}{2f_s} \quad (1)$$

$$I_L = \frac{V_{in}}{(1-D)^2 R} \quad (2)$$

$$C \geq \frac{D}{R(\Delta V_o/V) f_s} \quad (3)$$

Assuming that the circuit operates in Continuous Conduction Mode, the operating modes of converter can be divided into two (a) When the switch (S) is turned ON, the inductor current rises and energy is stored in it and (b) While the switch (S) is turned OFF, the inductor releases the stored energy to the load [6]. The equations governing the modes of operation are:

When the switch S is turned ON

$$\frac{V_L}{L} = \frac{di_L}{dt} \quad (4)$$

$$\frac{dV_o}{dt} = -\frac{V_o}{RC} \quad (5)$$

When the switch S is turned OFF,

$$\frac{di_L}{dt} = \frac{V_L - V_o}{L} \quad (6)$$

Since the solar PV characteristics are nonlinear in nature, when the converter is connected to the PV panel, its input voltage is not constant. Hence to achieve a constant output voltage, duty cycle of boost converter is controlled by using closed loop voltage mode control [7]. The output voltage to controlling duty cycle transfer function of the DC-DC converter is given as:

$$\frac{V_o(S)}{d(S)} = \frac{(1-D)V_o + (LI_L)S}{LCS^2 + (L/R)S + (1-D)^2} \quad (7)$$

DC-DC boost converters are known as practical nonlinear systems which prone to Electro Magnetic Interference and several types of nonlinear phenomena including bifurcation, quasi periodicity, intermittency and chaos. Various methods used to model this highly non-linear system, are state space, averaging technique, and transfer function modelling. Further, to maintain constant output voltage in DC-DC boost converter, closed loop controllers are employed. These controllers are designed to operate at specific operating point and it regulates the output voltage for sudden change in input and output condition. However, a well-designed PID controller when subjected to continuous change in parameter may lead to chaotic operation of the converter.

To analyse the behaviour of DC-DC boost converter and to show the significance of parameter optimization the input voltage to DC-DC boost converter is subjected to change from 10V to 20V. The system modelled in MATLAB/SIMULINK and it is simulated for the above said operating conditions and the results are analysed. Further, to explicitly showcase the occurrence of chaos; bifurcation analysis and

phase portrait results are also presented. First the input voltage of the DC-DC Boost converter is set to 12V and the output voltage, input current waveforms recorded are shown in Figure 2 Phase portrait under this condition is also presented and it exhibits a single scroll indicating that the converter operation is still stable. Further, the current and voltage waveforms have minimum noises. To extend the analysis input voltage of the converter is continuously changed from 12V to 16V and the corresponding voltage and current waveforms including phase portrait are presented in Figure 3 closer examination on this waveforms reveal that the converter operation swiftly changes towards chaotic operating region via period doubling process from stable operating condition. It is noteworthy to mention that the number of scrolls in phase portrait is an indication of occurrence of chaos. Further, it is Clearly visible that in the above cases the scrolls on phase portrait increase and finally enters into chaos region where infinite number of scrolls occurs as shown in Figure 4.

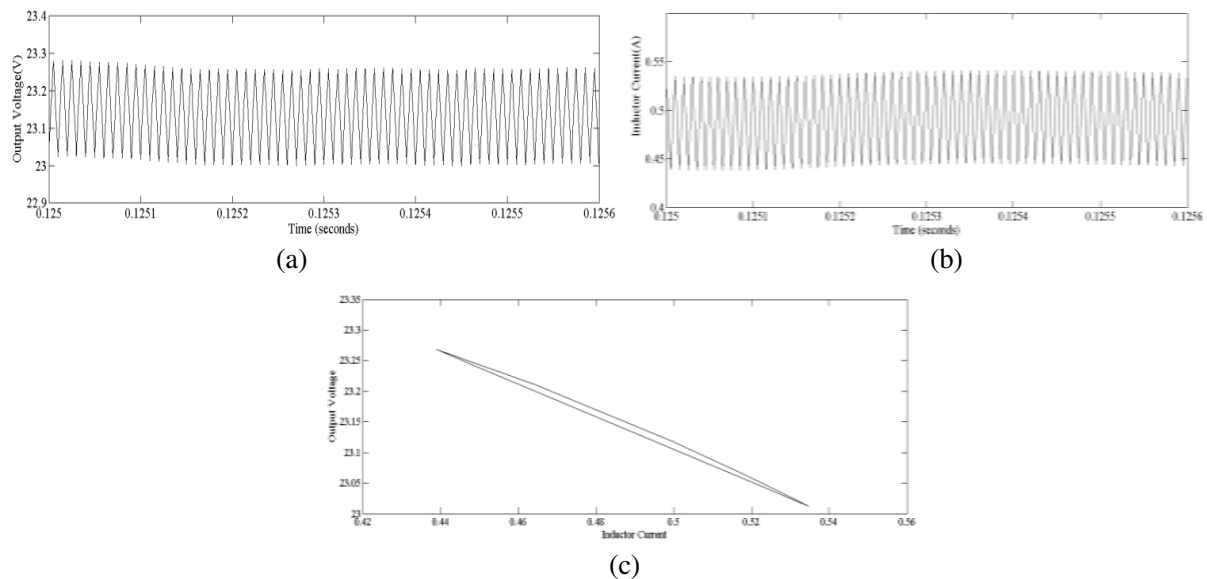
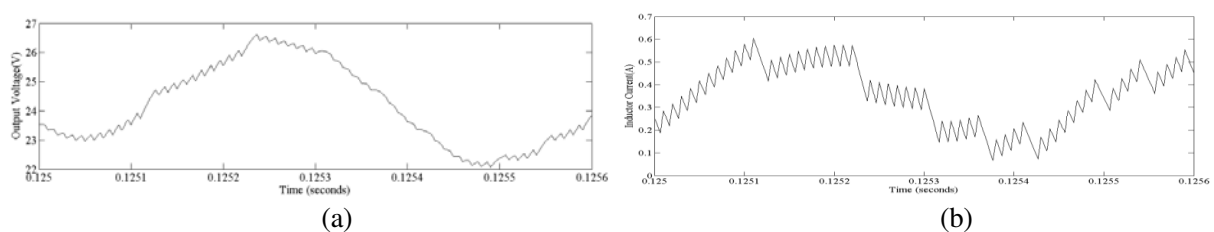
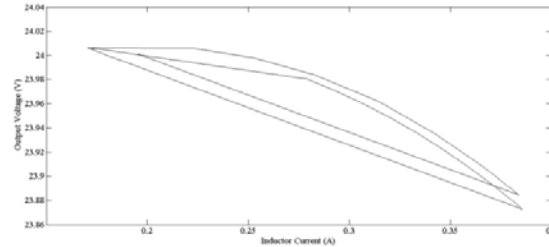


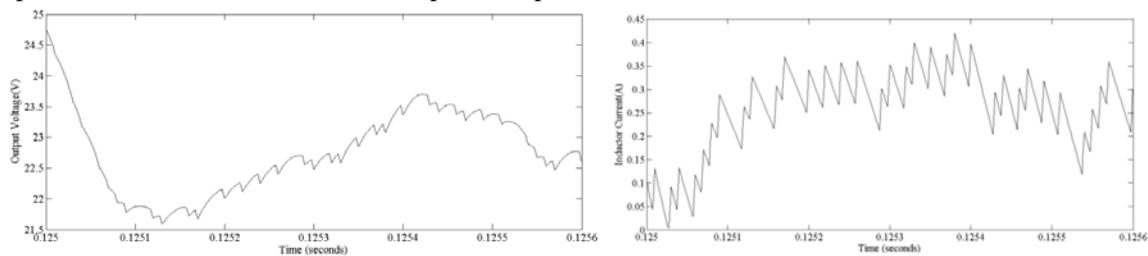
Figure 2. (a)Output voltage waveform (b) Inductor current waveform (c) Phase portrait for Period 1 operation of boost converter with un optimized parameters at $V_{in}=12V$





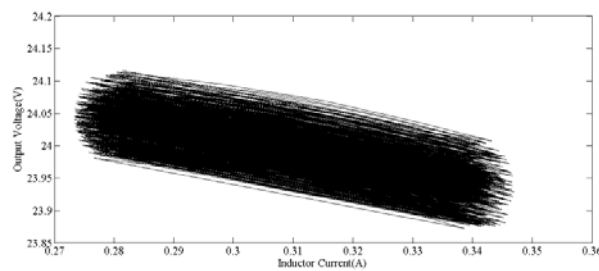
(c)

Figure 3. (a)Output voltage waveform (b) Inductor current waveform (c) Phase portrait for Period 2 operation of boost converter with un optimized parameters at $V_{in}=16V$



(a)

(b)



(c)

Figure 4. (a)Output voltage waveform (b) Inductor current waveform (c) Phase portrait for Chaos operation of boost converter with un optimized parameters at $V_{in} = 20V$

3. BFA based parametric optimization

Bacterial Foraging Algorithm (BFA) was proposed by K. Passino [8] and it belongs to the family of nature-inspired optimization algorithm. The algorithm is based upon the fact that the genes of the fitter species, having successful foraging strategy, are likely to survive and get propagated in the evolution chain. *E. coli* bacteria present in human intestine also undergo a similar foraging strategy. BFA mimics the four principal mechanisms observed in a real bacterial system: chemotaxis, swarming, reproduction, and elimination-dispersal to solve any non-gradient optimization problem. BFA have been successfully applied to variety of engineering problems, such as PID controller, harmonic elimination, transmission loss reduction, antenna parameter calculation, image demonizing, economic load dispatch and machine learning etc. [9-11].

BFA contains population of bacteria which represents a potential solution to the optimization problem. In this work the problem of finding suitable parameter combination for minimization of chaos in DC-DC boost

converter under change in operating condition is formulated as an optimization task and solved using BFA method. The objective function for the problem is given as

$$\begin{aligned} \text{Minimize } f(\phi) &= \sum \left[|e_j| + |\Delta e_j| \right] \\ f(\Phi) &= f([R, L, C]) \end{aligned} \quad (8)$$

Subject to constraints:

$$\begin{aligned} 100 &\leq R < 130 \text{ ohms} \\ 2e - 4 &\leq L < 7e - 4 \text{ Henry} \\ 1e - 6 &\leq C < 5e - 6 \text{ Farad} \end{aligned}$$

Where,

e_j is the error between output voltage and reference voltage.

Δe_j is the error correction at instant j .

The steps involved in the BFA algorithm are explained as follows:

Step 1: Initialize parameters $p, S, N_c, N_s, N_{re}, N_{ed}, P_{ed}, C, \theta^i, i=1,2,3,\dots,S$

Step 2: Elimination–dispersal loop $l=l+1$

Step 3: Reproduction loop $k=k+1$

Step 4: Chemotaxis loop $j=j+1$

- a. For, $i=1, 2, 3, \dots, S$, take chemotactic step for each bacterium.
- b. Compute objective function $J(i, j, k, l)$.
Let $J(i, j, k, l) = J(i, j, k, l) + J_{cc}(\theta^i(j, k, l), P(j, k, l))$
- c. Let $J_{last} = J(i, j, k, l)$, to save the value since we may find a better solution via a run.
- d. Tumble: Generate a random vector $\Delta(i)$, with each element drawn uniformly from $[-1, 1]$.
- e. Move: Let

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C * \phi(i)$$

This results in a step size of $C(i)$ in the direction of the tumble for bacterium i .

- f. Compute $J(i, j+1, k, l)$ and let

$$J(i, j+1, k, l) = J(i, j, k, l) + J_{cc}(\theta^i(j+1, k, l), P(j+1, k, l)) \quad (9)$$

- g. Swim:

- i. Let $m = 0$ (counter for swim length)

- ii. While $m < N_s$
 - Increment $m = m + 1$
 - If $J(i, j + 1, k, l) < J_{last}$ (if doing better), let $J_{last} = J(i, j + 1, k, l)$ and let

$$\theta^i(j + 1, k, l) = \theta^i(j, k, l) + C * \phi(i)$$
 and use the above $\theta^i(j + 1, k, l)$ to compute new $J(i, j + 1, k, l)$ (as we did in step f).
 - Else let $m = N_s$. (This is the end of while statement)
- h. Go to next bacterium $(i + 1)$ if $i \neq S$.

Step5: If $j < N_c$, go to [step 4] in this case continue chemotaxis, since the life of bacteria is not over.

Step6: Reproduction:

- a. For the given k and l , for each $i = 1, 2, 3, \dots, S$, let $J_{health}^i = \sum_{j=1}^{N_c+1} J(i, j, k, l)$

be the health of i^{th} bacterium and sort J_{health} in ascending order

- b. The S_r bacteria with the highest J_{health} values die and remaining S_r bacteria with the minimum values split.

Step 7: If $k < N_{re}$, go to [step 3]. In this case, when the specified reproduction steps are not reached, we start the next generation in the chemotactic loop.

Step 8: Elimination–dispersal: For $i = 1, 2, 3, \dots, S$, a random number is generated and if it is less than or equal to P_{ed} , then that bacterium is dispersed to a new random location else it remains at its original location.

Step 9: If $l < N_{ed}$, then go to [step 2]; otherwise end. Stop and print the result.

4. Results and discussions

To implement BFA based parameter optimization for chaos minimization in DC-DC boost converter which is built for the rating of Input Voltage (Vin) 12V-22V, output voltage (Vo) 24V and switching frequency (f_s) 100kHz, a dedicated software code is written in MATLAB. In order to find the effectiveness of the algorithm, BFA method is tested for various operating conditions and best results are evolved. Since, performance and the convergence speed of BFA algorithm mainly depends on the parameter selection [10] hence the best composition of parameters are arrived via trial and error for different compositions under 15 independent trails. In addition, it is imperative to mention that the parameters elected via above procedure found to satisfy the relation $N_c > N_{re} > N_{ed}$ given in [12]. The selected parameters are listed in Table 1. Simulations are carried out using 2.4 GHz INTEL i3 processor personal computer with 2.0 GB RAM.

To study the effect of the determined parameters, the test performed in section 2 with un optimized parameters are repeated for BFA optimized parameter under various input voltages. Simulated output voltage, inductor current waveforms and their phase portrait (x-axis – inductor current in Ampere, y-axis –

output voltage in Volts) for input voltage values of $V_{in} = 12, 16$ and $20V$ with BFA optimization parameters are shown in Figure.2, Figure.3 and Figure.4 respectively. The input voltages are chosen to show different periods of operation in a DC-DC boost converter.

Table 1. Optimization parameters

Parameter	Value
No. of bacteria	50
Chemotactic step size (N_c)	6
Reproduction Loop size (N_{re})	4
Elimination and dispersal loop size (N_{ed})	2
Dispersal Probability (P_{ed})	0.2
Maximum no of swim length (N_s)	4

For $V_{in}=12V$, It is observed that the phase portrait for un optimized parameters is better than for the optimized values. However, for other cases of $V_{in}=16V$ and $20V$, the system dynamics are considerably disturbed. Analysis with phase portraits is particularly important since it clearly states the occurrence of chaos. Further, the scrolls on phase portrait start increasing and enter into chaos in case of un optimized parameters. This could be attributed to the fact that the L, C parameters are designed for one operating point and may not be suitable for other operating points as well. However, with change in input voltage, the scrolls are within the limits and are controlled for BFA optimized parameters.

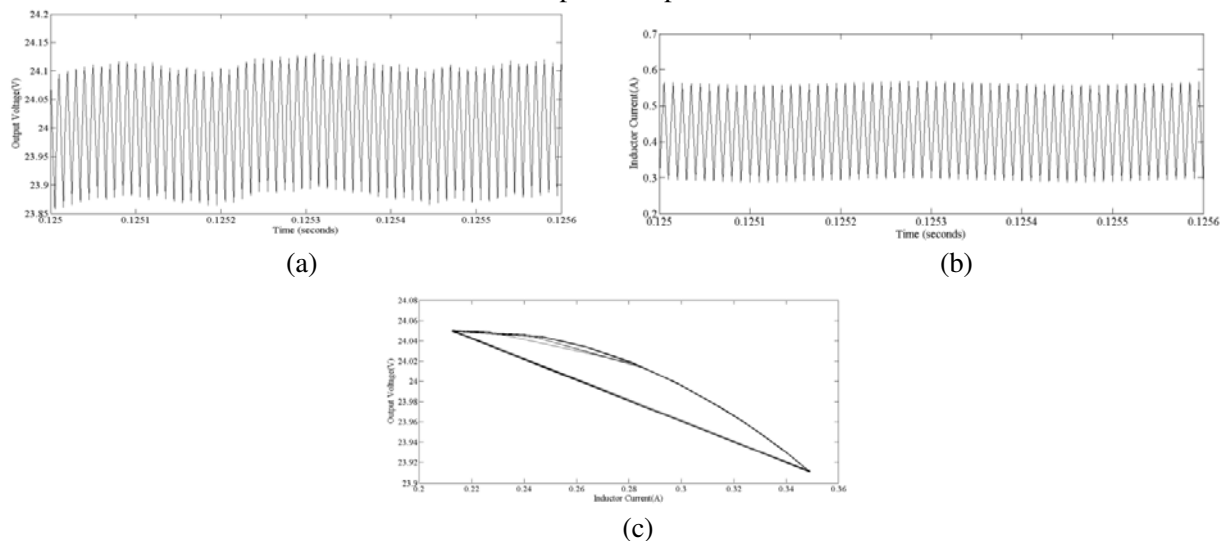


Figure 5. (a) Output voltage waveform (b) Inductor current waveform (c) Phase portrait for Period 1 operation of boost converter after optimization using BFA at $V_{in}=12V$

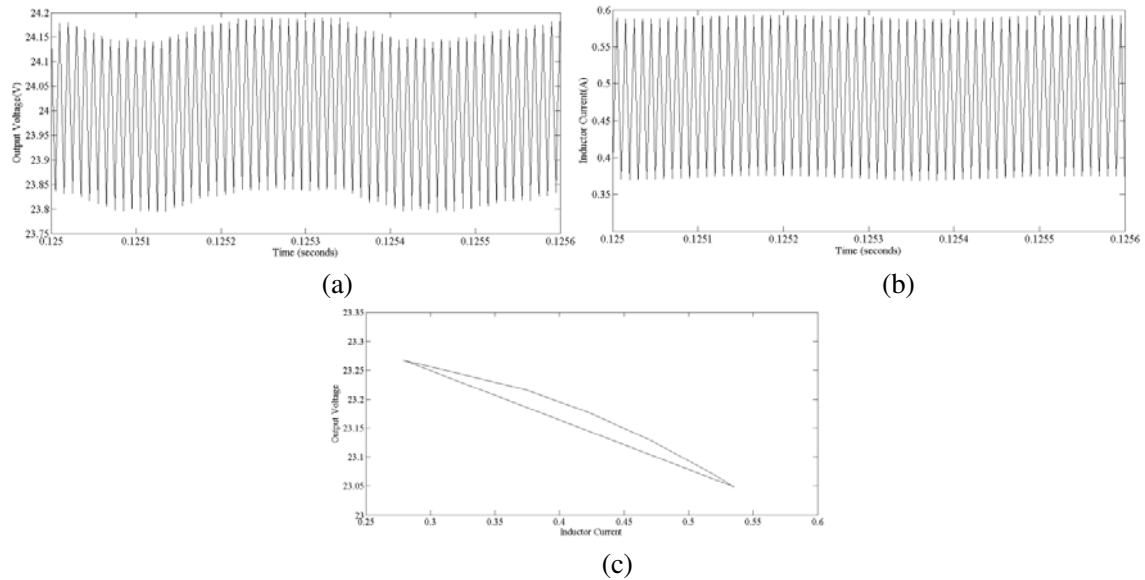


Figure 6. (a) Output voltage waveform (b) Inductor current waveform (c) Phase portrait for Period 1 operation of boost converter after optimization using BFA at $V_{in}=16V$

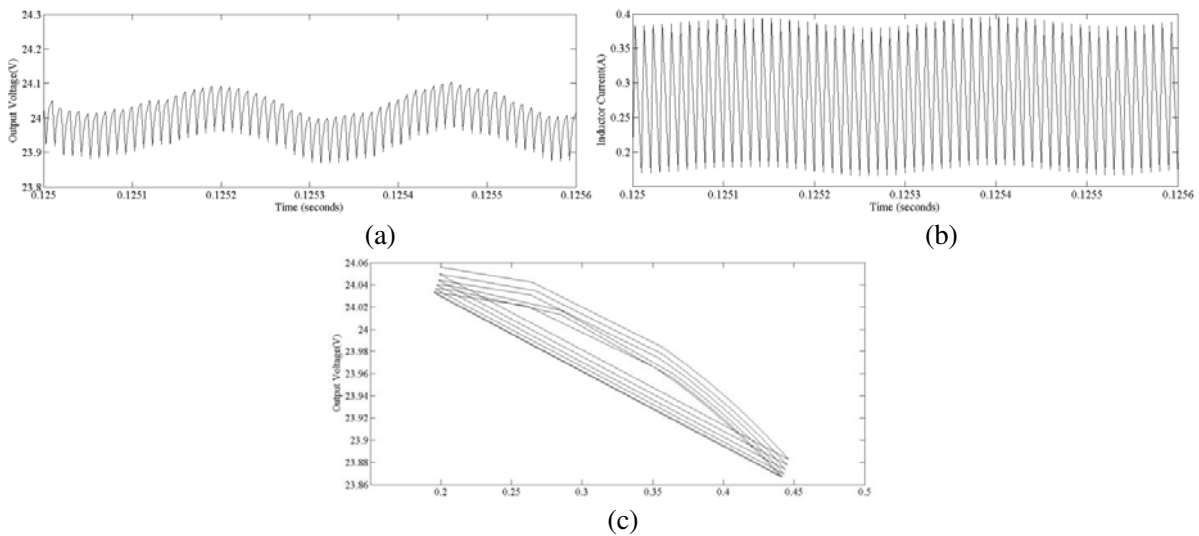


Figure 7. (a) Output voltage waveform (b) Inductor current waveform(c) Phase portrait for Period 4 operation of boost converter after optimization using BFA at $V_{in}=20V$

5. Bifurcation analysis

Bifurcation analysis is the appropriate method to describe the undesirable nonlinear behavior of the system [13]. In which, One parameter (in this case V_{in}) is varied while the output voltage is kept constant. The value of this parameter (V_{in}) is plotted along the x-axis and the asymptotic steady-state behavior of one of the discrete state variables is plotted along the y-axis. This bifurcation plot convey such that the periodic behavior was first transformed to the period-2 sub harmonic, which subsequently led to chaotic regime. Such

a qualitative variation in the system behavior is called a bifurcation [14 -16].

The simplified form of mapping equation describing the chaotic behavior of voltage mode controlled boost converter is as follows [13], and the voltage $V(t)$ waveform shown in Figure 8.

$$x_{n+1} = f(x_n) = \alpha(1 - x_n) \bmod 1, \quad (10)$$

Where,

$$x_n = \frac{t_n}{T_c}, \quad \alpha = \frac{V_o}{V_1} - 1, \quad t_n = \frac{(V_{ref} - V_o)C}{I_c}$$

t_n is the n^{th} switching time interval of the switch, T_c is the clock period, I_c is current through capacitor. V_{ref} is the reference voltage, V_o the voltage across the capacitor C, V_1 the input voltage, and V_o the average output voltage. For $\alpha > 0$, $V_o > V_1$ and in terms of the criterion of Lyapunov exponent for $\alpha > 1$, the sequence $\{x_0, x_1, x_2, \dots, x_n\}$ exhibits chaos within the range of $[0, \alpha]$.

The bifurcation curve of the system before and after optimizing the parameters using BFA are shown in Figure 8 (a), Figure 9 (b). The bifurcation curve is plotted for output voltage with respect to input voltage. It is observed that the system exhibits the period doubling bifurcation. The duration in different bifurcation transition is said as period 1, period 2 and period 4 and so on till the chaos. The comparison of different voltage range for different periods is shown in Table 2. For instance, it is observed that at $V_{in}=17.2\text{V}$, converter operation is in period 4, and period 2 before optimizing and after optimizing using BFA respectively.

Table 2. DIFFERENT OPERATING REGION OF BOOST CONVERTER

Input voltage range	Boost converter operating region	
	With un-optimized parameters	With BFA optimized parameters
10 V - 14 V	Period 1	Period 1
15 V - 17 V	Period 2	Period 1
17.2 V - 17.6V	Period 4	Period 2
17.7 V - 17.9 V	Period 8	Period 2
18V - 20V	Chaos	18V to 19.5V-Period 2 19.6V to 20V-Period 4

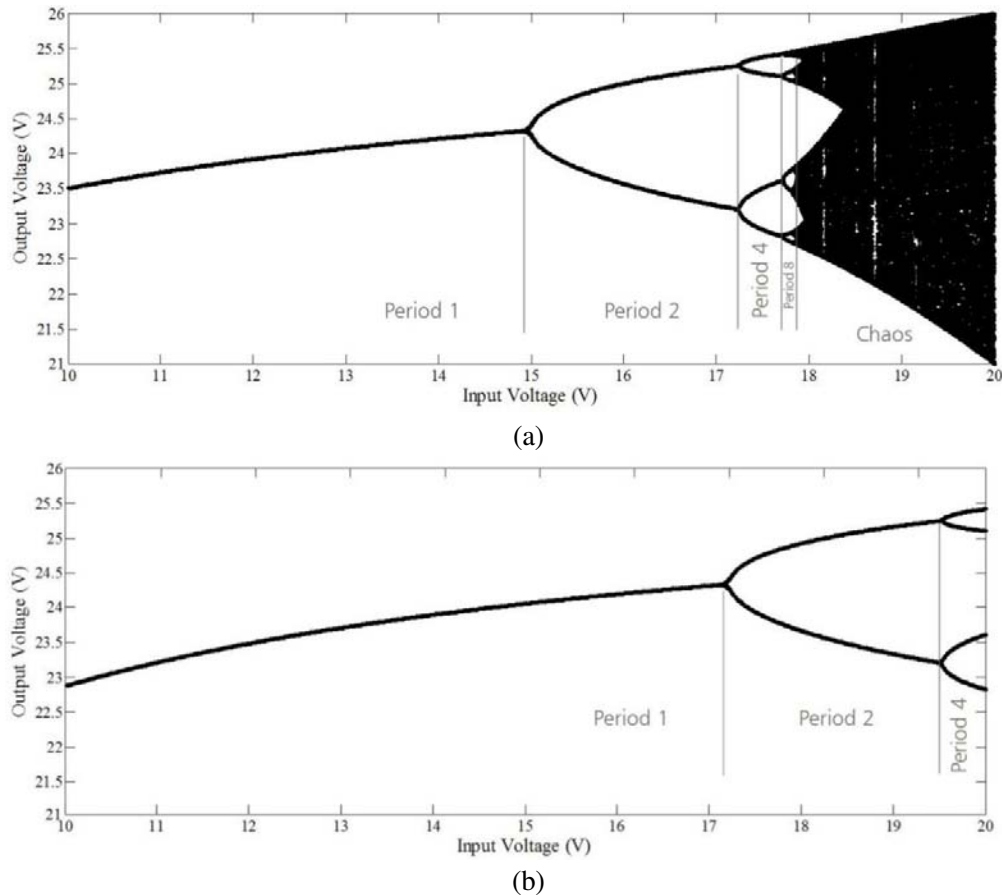


Figure 8. Bifurcation behavior of boost converter with input voltage (V_{in}) as bifurcation parameter for (a) un optimized parameters (b) optimized parameters using BFA

6. CONCLUSION

Controlling of undesirable chaotic behavior in solar fed DC-DC boost converter using optimal parameters are presented in this paper. Well-known Bacterial Foraging Algorithm for optimizing the circuit parameters is carried out. The results obtained using the proposed algorithm is compared with traditional method. From bifurcation analysis and phase portrait it is observed that BFA optimized parameters are profoundly ensures the stable operation of variable input DC-DC boost converter for the reasonable operating region. This indeed shows the increased range of desirable operating spectrum making it suitable for operating voltage. From the work, it is inferred that the proposed strategy replaces the complicated design and dedicated auxiliary circuits involved in chaos control can be for the fast switching DC-DC power converters and thereby the Electro Magnetic Compatibility (EMC) of the converter also improved significantly.

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