Applications of Modern Optimization Methods for Controlling Parallel Connected DC-DC Buck Converters

Ali S. Al-Dmour
Associate Professor in Electrical Engineering Department
Engineering College
Mu'tah University
Mu'tah-Karak
Jordan

Abstract

This paper presents the application of on-line Particle Swarm (PSO) and Ant Colony Optimization (ACO) techniques based-state feedback controllers for adjusting and tuning the output voltage and current of parallel DC-DC buck convectors. The objective of control system is to balance the current of each converter and to highly improve the output voltage performance of the parallel buck converter. Given a system with large variations of input voltage and load, it is necessary to guarantee good performance of the controller for large variations of operating point. The simulation results of PSO and ACO-based controllers systems are compared. The results were obtained show how PSO and ACO can effectively and efficiently optimize the dynamic performance of the adopted converter under variations in load and input voltage as well as in reference voltage.

Keywords: *Particle Swarm Optimization (PSO), state feedback controller, Optimization, Ant Colony Optimization (ACO) , DC-DC converters, parallel buck system.*

1. Introduction

DC-DC converters are electronic devices used to change DC electrical power efficiently from one voltage level to another. These converters are widely used in switched-mode power supplies, adjustable speed drives, uninterruptible power supplies, telecommunication equipment, spacecraft power system, and many other applications to change the level of an input voltage to fulfil required operating conditions. In addition, the converters are usually subjected of large load variations when operated in these applications. Therefore, the main objective of a good control strategy to be developed for such converters must be to achieve an output voltage regulation, under large load variations, as fast as possible without having any stability problem [1]. Usually, the output voltage is regulated by varying the duty cycle of the power MOSFET driving signal. The mode of operation of the converter is simply varied from switch (ON) to (OFF) state and the Kirchhoff's law is applied to obtain the differential equation of each state of the converter [2].

The switching power converters in general are inherently non-linear and time invariant and therefore, the control approach requires effective modelling and analysis of the converters [3]. Controller design for any system needs knowledge about system behaviour. Usually this involves a mathematical description of the relation among inputs to the process, state variables, and output. This description in the form of mathematical equations which describe behaviour of the system (process) is called model of the system.

In recent years, various researches was performed on applying the non-linear methods to control parallel DC/DC converters [4]; however, the controller design approaches based on the linearized state-space average model, due to the simplicity of implementation and generality. Generally, the paralleling of lower-power converter modules offers a number of advantages over a single, high power, centralized power supply. Some of these advantages include higher efficiency, better dynamic response due to a higher frequency of operation, and better load regulation. The major concern of parallel-connected converters is to share the load current among the converters. To do this, some form of control has to be used to equalize the currents in the individual converters. A variety of approaches, with varying complexity and current-sharing performance, have been proposed [4], [5].

Today, many researchers have adopted the intelligent design techniques for different applications which proven success in improving the performance. Among the various techniques of artificial intelligence, the most popular and widely used techniques in control systems are the fuzzy logic, Neural Network (NN) and the Particle Swarm Optimization (PSO) [6], [7], [8]. Such an intelligent controller designed may even work well with a system with an approximate model.

In this paper, the basic circuit and theory is utilized to identify the basic structures and investigate the control problem of parallel buck converter using PSO and ACO methods. This is because of their proved performance in different applications and because of their simplicity, since neither expensive computations nor specialized methods are needed. The parallel-connected converters has been deployed here because of several factors such as growing consumer power demands, importance of dynamic power management, growing requirements for system reliability, and decreasing overall system cost [4]. Consequently, it is widely known that paralleling converters when carefully designed may accommodate the load sharing capability required by the high current applications. However, a conventional controller which incorporates load sharing at any load level suffers the drawback of poor converter's efficiency especially at low output current. Hence, a more advanced controller will be needed to manage the number of converters in parallel required based on the load current which in turn will keep the efficiency of the converter relatively high. It is found that PSO outperforms random search through and at the end of the search process, showing better convergence behaviour and over-fitting avoidance. In addition, the ACO is based on the cooperative behaviour of real ant colonies, which are able to find the shortest path from their nest to a food source. In many practical systems, the objective function, constraints, and the design data are known only in vague and linguistic terms [9]. In this work, the resultant output load voltage and load sharing current of individual converter is analyzed. These results give evidence that the ACO or PSO-based state feedback controllers can work as an any-time method for controlling the switching operation of the DC-DC converters. Consequently, the simulation results of the adopted converter system behaviour and the effectiveness of the controller for optimization and regulation purposes is an important feature of this paper.

2. Small Signal Analysis of the Ideal Converter

The small signal averaged state-space method is a generalized analysis tool which is readily applicable to either simple circuits or complex structures [10]. The linear averaged time-invariant models achieved by using this method are relatively simple, but a lot of mathematical efforts are needed to derive the final results. To obtain such models, the step-by-step procedure proposed in [11], [12], is adapted to our problem.

2.1 Parallel connected buck converters

Paralleled DC-DC converters are used in telecommunication industry widely and operated under closed loop control to regulate the output voltage and allow high current to be delivered to loads without the need to employ devices of high power rating. The design with these standard converter modules influences the costs of development in a positive manner and the system reliability and operational redundancy are improved. In addition, the supply system can be extended quite easily by adding another converter module instead of replacing the converter by a stronger one.

The parallel connection of switch mode converter is a well known strategy. It involves phase shifting of two or more buck converters connected in parallel and operating at the same switching frequency. Two buck converters are connected in parallel feeding a common resistive load with a switching period T and duty cycle D is shown in Figure 1.

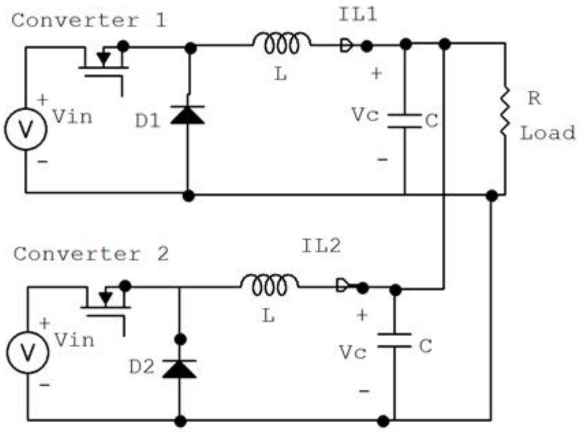

Fig. 1: System containing two parallel connected buck converters

For the purpose to obtain the relation between changes in the converter duty cycle (the switching control signal) and the system states, the following perturbations can be applied [12],[13]:

$D = D + \hat{d}$ for $\frac{\hat{d}}{D} << 1$, $v_{in} = v_{in} + \hat{v}_{in}$ for $\frac{\hat{v}_{in}}{v_{in}} << 1$,

$v_c = v_c + \hat{v}_c$ for $\frac{\hat{v}_c}{v_c} << 1$, and $i_L = i_L + \hat{i}_L$ for $\frac{\hat{i}_L}{i_L} << 1$.

In order to provide examining the response of the converter to load changes, a current source generator I_o is added in parallel with load resistor; therefore, this leads to following assumption:

$$I_o = I_o + \hat{I}_o \quad \text{for} \quad \frac{\hat{I}_o}{I_o} << 1$$

After averaging and applying the perturbations as described in the current section, the state space representation of the open loop two-module parallel connected buck converters is given by:

$$\begin{bmatrix} \frac{d\hat{i}_{L1}}{dt} \\ \frac{d\hat{i}_{L2}}{dt} \\ \frac{d\hat{v}_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{L} \\ 0 & 0 & \frac{-1}{L} \\ \frac{1}{2C} & \frac{1}{2C} & \frac{-1}{2RC} \end{bmatrix} \begin{bmatrix} \hat{i}_{L1} \\ \hat{i}_{L2} \\ \hat{v}_c \end{bmatrix} + \begin{bmatrix} \frac{v_{in}}{L} & 0 & \frac{D_1}{L} & 0 \\ 0 & \frac{v_{in}}{L} & \frac{D_2}{L} & 0 \\ 0 & 0 & 0 & \frac{1}{2C} \end{bmatrix} \begin{bmatrix} \hat{d}_1 \\ \hat{d}_2 \\ \hat{v}_{in} \\ \hat{I}_o \end{bmatrix} \qquad (1)$$

3. Ant colony optimization Algorithm

Ant colony optimization (ACO) is based on the cooperative behaviour of real ant colonies, which are able to find the shortest path from their nest to a food source. The method was developed by Dorigo and his associates in the early 1996s [14], [15]. The ant colony optimization process can be explained by representing the optimization problem as a multilayered object, where the number of layers is equal to the number of design variables and the number of nodes in a particular layer is equal to the number of discrete values permitted for the corresponding design variable. Thus each node is associated with a permissible discrete value of a design variable. The PSO procedure, which is used here for optimizing the state feedback controller gains, is as shown in the flowchart in Figure 2 [16].

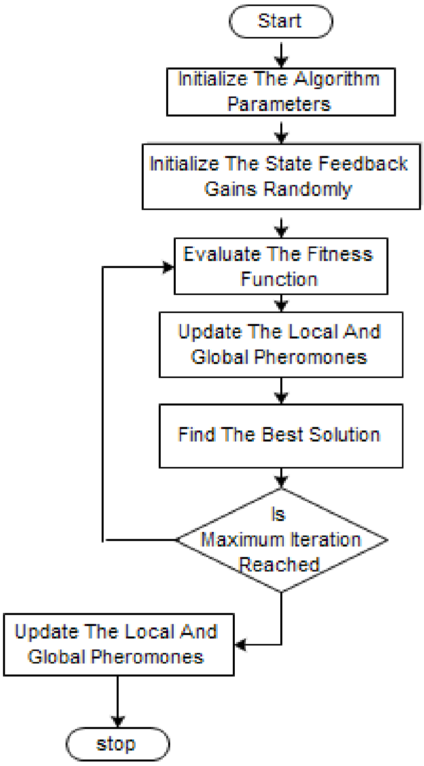

Fig. 2: Flow Chart of ACO Algorithm

The ACO method procedure starts when an ant k, that located at node i, uses the pheromone trail τ_{ij} to compute the probability of choosing the next node j by applying the following probabilistic transition rule:

$$p_{ij}^{k}(t) = \begin{cases} \frac{[\tau_{ij(t)}]^{\alpha}[\eta]^{\beta}}{\sum_{j^{*}\epsilon J_{k(i)}}[\tau_{ij(t)}]^{\alpha}[\eta]^{\beta}} & if\ j\epsilon J_k(i) \\ 0 & otherwise \end{cases} \qquad (2)$$

$J_k(i)$ is a set of nodes which remain to be visited when the ant k is at node i. α and β are two adjustable positive parameters that control the relative weights of the pheromone trail and of the heuristic visibility. After each ant completes its tour, the pheromone amount on each path will be adjusted according to following equation:

$$\tau_{ij} = (1-\rho).\tau_{ij} + \Delta\tau_{ij} \qquad (3)$$

where (1-ρ) is the pheromone decay parameter (0<ρ<1) where it represents the trail evaporation when the ant chooses a node and decides to move.

$$\Delta\tau_{ij} = \begin{cases} \frac{Q}{L_k} & \text{if } (i,j) \text{belongs to the best tour,} \\ 0 & \text{otherwise} \end{cases}$$

where L_k is the length of the tour performed by ant k and Q is an arbitrary constant constant related to the quality of pheromone trails laid by ants.

Here in this work, the algorithm is tested for different values of parameters by simulating the model for different operating conditions. According to the trials, the optimum parameters used for verifying the performance of the ACO-state feedback controller is listed in Table 1.

Table 1: ACO Parameters

ACO Parameters	
Number of ants	100
Number of nodes	2000
Number of iteration	300
Evaporation rate	0.7
α and β	0.7 and 0.2 respectively

4. PSO Algorithm

The PSO algorithm was originally proposed by Kennedy and Eberhart in 1995 [17].The PSO algorithm is an evolutionary computational technique, but it differs from other well-known evolutionary computation algorithms such as the genetic algorithms. Although a population is used for searching the search space, there are no operators applied on the population. Instead, in PSO, the population dynamics simulates a ‘bird flock’s’ behaviour, where social sharing of information takes place and individuals can profit from the discoveries and previous experience of all the other companions during the search for food. Thus, each companion, called particle, in the population, which is called swarm, is assumed to 'fly' over the search space in order to find promising regions of the landscape. Optimization methods based on swarm intelligence are called behaviourally inspired algorithms as opposed to the genetic algorithms, which are called evolution-based procedures.

In the context of multivariable optimization, the swarm is assumed to be of specified or fixed size with each particle located initially at random locations in the multidimensional design space. Each particle is assumed to have two characteristics: a position and a velocity. In addition, it wanders around in the design space and remembers the best position (in terms of the food source or objective function value) it has discovered. The particles communicate information or good positions to each other and adjust their individual positions and velocities based on the information received on the good positions. Thus the PSO model simulates a random search in the design space for the maximum value of the objective function. As such, gradually over much iteration, the birds go to the target (or maximum/minimum of the objective function).

Let x and v denote a particle position and its corresponding flight velocity in a search space, respectively. Therefore, the i^{th} particle is represented as $x^i = (x^{i1}, x^{i2}, \ldots, x^{id})$ in the d-dimensional search space. The best remembered of the i^{th} particle individual particle position is recorded and represented as $pbest^i = (pbest^{i1}, pbest^{i2}, \ldots, pbest^{id})$. The index of best remembered swarm position among all the particles in the group is represented by the $gbest = (gbest^1, gbest^2, \ldots, gbest^d)$. The flight velocity for particle i is represented as $v^i = (v^{i1}, v^{i2}, \ldots, v^{id})$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest^i$ to gbest as presented in the following flow chart shown in Figure 3. The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest^{id}$ to $gbest^d$ as presented in the following formulas [26]:

$$v_{k+1}^{id} = wv_k^{id} + c_1 r_1 (pbest_k^{id} - x_k^{id}) + c_2 r_2 (gbest^d - x_k^{id}),$$

i=1,2,...,n and d=1,2,…,m (5)

$$x_{k+1}^{id} = x_k^{id} + v_{k+1}^{id} \quad (6)$$

where w, $c1$ and $c2 \geq 0$. n is the number of particles in a group; m is the number of members in a particle; w is the inertia weight factor; $c1$ and $c2$ are acceleration constants; $r1$ and $r2$ are two random numbers between 0 and 1; x_k^{id} and v_k^{id} are the velocity and the current of particle i in the d^{th}-dimensional search space at iteration k, respectively.

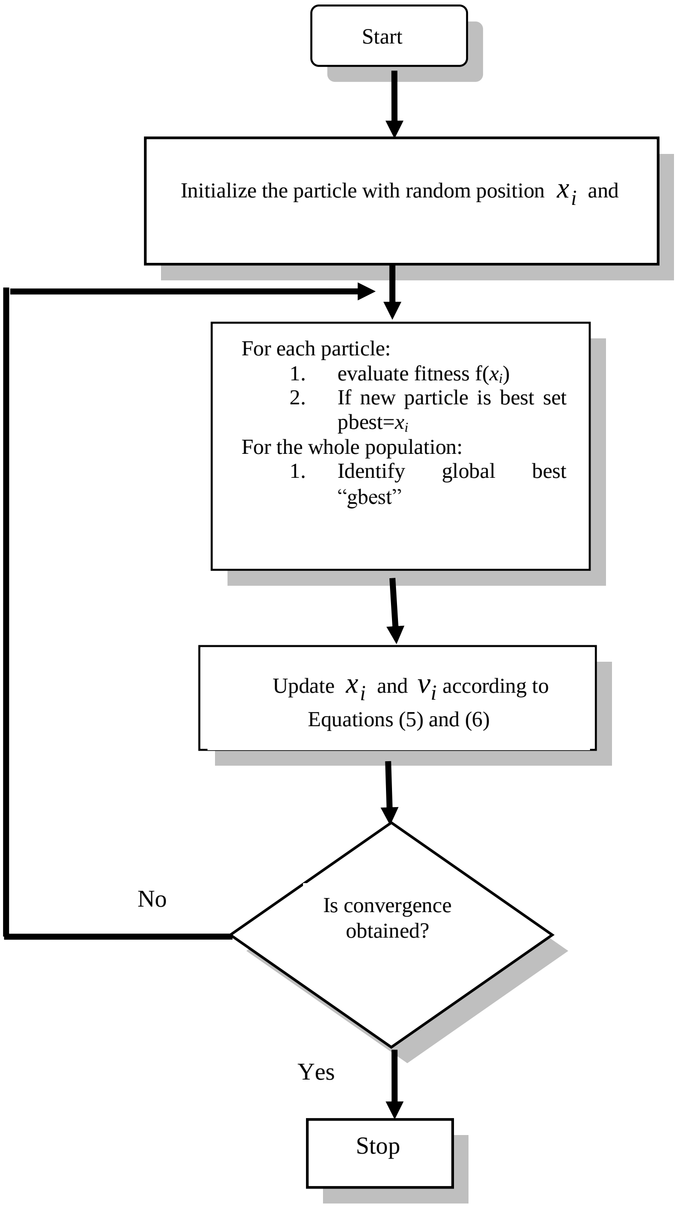

Fig. 3: Flow chart of PSO

In general, PSO shares many similarities with evolutionary computation techniques. The main difference between the PSO and other approaches is that PSO does not have operators and the particles update themselves with the internal velocity; they also have a memory that is important to the algorithm. In addition, the PSO is easy to implement and there are few parameters to adjust. Furthermore, PSO is computationally inexpensive since its memory and speed requirements are low [17].In this work, PSO algorithm is used to find the optimal values of the state feedback gains to improve the behaviour of a Buck converter. The objective of the optimal controller design is to maintain constant output voltage and reduce the overshoots.

To investigate the effectiveness of the PSO-based controller on the performance of the parallel Buck converters, the evolution procedure of PSO Algorithms, which was shown in Fig. 3, has been considered. Moreover, the time responses are chosen as the performance indices to be obtained. Since computational time is one of the important factors to be considered in an optimization process, investigations on the number of individuals/particles were carried out by varying those numbers from 40 to 600. Fewer individuals/particles resulted in high values of errors but faster computational time, while a high number of individuals/particles resulted in smaller values of the mean error with very slow execution time. In order to get compromise values between the mean error and computational time, the best number of individuals/particles was found to be 400 for all algorithms The other parameters considered for PSO algorithm are $C_1 = 2$, and $C_2 = 2$. Moreover, the number of dimensions (Nod) is=5 and the maximum iteration number (Noi) equal 20 and are used for checking termination criterion in this algorithm. Consequently, the inertia weight factor (w) is selected according to the following equation:

$$w = 0.9 - 0.7 * (i / \text{Noi}) \tag{7}$$

where i is the i^{th} iteration.

The decreasing of w through the search process, called adaptive inertia weight is a process similar to that of simulated annealing in which temperature is decreased exponentially, allowing global and local search [18],[19]. As in most search algorithms, in PSO a cost function is needed to evaluate the aptitude of candidate solutions. Generally, the definition of a cost function depends on the problem at hand, but in general should reflect the proximity of the solutions to the optima. The cost function that is adopted in this work is selected to be based on the mean squared error between the system output voltages as well as inductors currents and the related reference values.

5. Simulation results using ACO and PSO algorithms

Simulation results of parallel buck converter are presented in this section where the buck converter parameters are V_{in}=24V, L=69 *m*H, C=220 *u*F, R=13 Ω , witching frequency f_s=100 KHz, and Vo=12. For simulations purposes, the buck converter system was simulated in C++ environment using numerical technique based on forth order Runge-Kutta method with time step size of 20 µsec. The simulation environment is used to test the transient and steady-state response of the system to various disturbances from the input source, reference voltage and load side. The simulation results are then used to compare the open-loop response of the system with the compensated closed-loop responses of the controlled systems with different schemes.

In this work, a linear feedback control law is designed to actively control the behaviour of the converters system. This law is designed using the state vector determined by the state equation (1) of the system described Section 2.1. Since the states are composed of output voltage and inductors currents, the control law will depend on these for various simulations tests. The control signals based on state feedback ideas [20], takes the following form (if two control inputs for both converters are utilised):

$$\begin{bmatrix} u_{c1}(t) \\ u_{c2}(t) \end{bmatrix} = \begin{bmatrix} f_1 & f_2 & f_3 \\ f_3 & f_4 & f_6 \end{bmatrix} \begin{bmatrix} \hat{V}_c(t) \\ \hat{I}_{L1} \\ \hat{I}_{L2} \end{bmatrix} \tag{8}$$

where the scalars $f_1, f_2, \ldots, f_6$ are the feedback gains for the designed control law. Since there is a complete similarity between the two designed converters, it is assumed that, for simplicity, $f_4 = f_1$, $f_5 = f_2$, and $f_6 = f_3$. In the presented work, it is adopted, for the purpose of finding the suitable control law for ACO and PSO controllers, the following command duty ratio algorithm for PWM controller as [5]:

$$D = \frac{V_{ref}}{V_{in}} - \frac{LC}{V_{in}} u_c(k) \tag{9}$$

Actually it is thought when using the off-line optimized parameters (gains) of the state controllers, a rough approximation to the desired control law should be performed first, i.e., direct optimizing. In this manner, the state controller would be capable of driving the system over the operating range without instability problems. Then on-line specialised optimizing would be used to improve the control provided by the state controller. Here, both suggestions is used; the off-line parameters optimizing using the direct manner and a fixed-gain controller so as to stabilise the system and also to provide an approximate control.

In off- line learning, the state controller based-PSO or ACO takes as its inputs either or the system output, or both, and the controller system parameters are optimized to reproduce the needed control signal.

The optimized parameters should then be able to produce the appropriate control signal, making the actual system output approach the reference one. In the other hand, on-line parameters optimization is an iterative procedure, which attempts to minimize the error between the system output, and the reference as data becomes available. Here, the controller parameters are optimized to find the system input that drives the system output to reach the given target. This control system can specifically work in the region of interest, and it may be worked on-line to tune itself while performing the desired work. For successful and accurate working of the controller, the input data must be rich enough to reveal all the important controlled parameters of the system. This is called on-line kind of optimizing as "specialized optimizing" since the ACO or PSO-based state controller is designed to operate in regions of specialization only.

In this work, a parallel buck converter controller using ACO based-state feedback controller was initially applied. The goal of the controller is to maintain the output voltage constant at 12 V in spite of the changes in the load or input voltage. Here, the ACO algorithm is used to optimize the gains values of the state feedback gains K_1, K_2, and K_3 till the desired output is obtained. The values of gains were found to be equal k_1=1.101, K_2=0.02551, and k_3=-0.04327 respectively as illustrated in Figure 4.

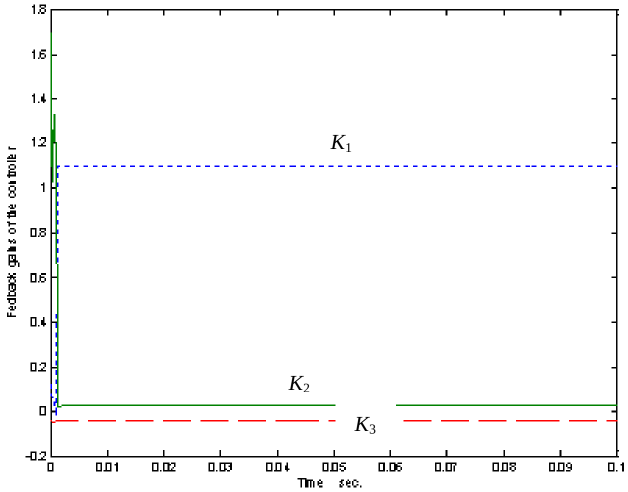

Fig. 4: Feedback gains of the state based-ACO controller

The responses of the open-loop system and the system compensated by an on-line ACO and PSO based-state controller for a 24 V D.C. power source and 0.5 duty cycles using the proposed specialized optimization are illustrated in Figure 5. The response performance parameters of the output voltage results after simulation of open loop and closed loop system are given in Table 2.

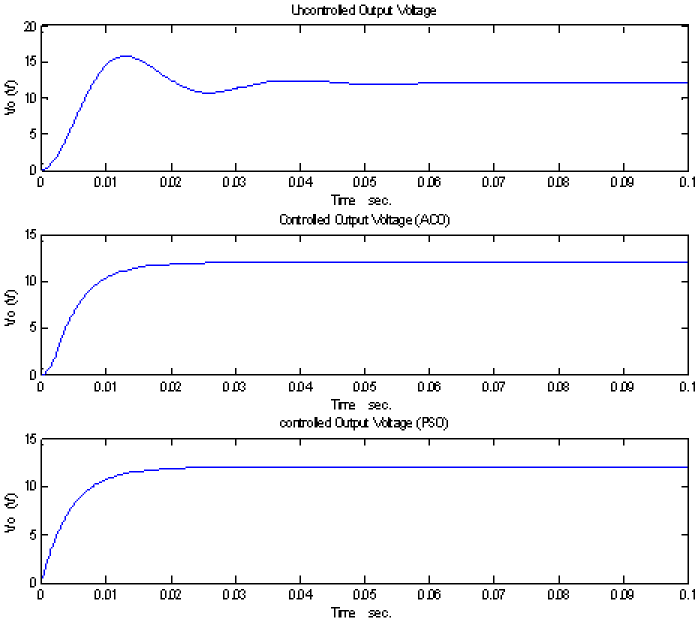

Fig. 5: Time responses of open-loop and closed-loop system to 24 V DC power source

The performance comparison of the controllers is made in terms of peak overshot, rise time, settling time and steady state error. Both controlled responses have slightly zero steady-state error and the open-loop response has a percentage maximum overshoot of 32.07% while the controlled responses nearly have a zero maximum overshoot. In addition, the rise time has been reduced from 3.1 msec to 2.8 msec for ACO and to 2.41 msec for PSO. However, the settling time has been decreased by approximately 60% for both controller schemes from the open loop case.

Table 2: The undisturbed system transient specifications with open loop and closed loop system

Method	Rise Time(*msec*)	Settling Time(*msec*)	Maximum Overshoot %	Steady State Error (V)
Open loop	3.10	43.06	32.07	4.502×10^{-4}
ACO-Based Controller	2.80	18.66	8.82×10^{-6}	1.33×10^{-6}
PSO-Based Controller	2.41	17.28	1.47×10^{-8}	1.76×10^{-9}

In the following, performance of proposed of the ACO and PSO based-controllers in three different conditions including of change in the reference voltage, input voltage, and output load are studied.

5.1 Performance assessment of various algorithms based on system performance

The simulation is initially carried out by varying the output voltage and inductors currents with the variation in the reference voltage using ACO and PSO-based controllers as shown in Figure 6.

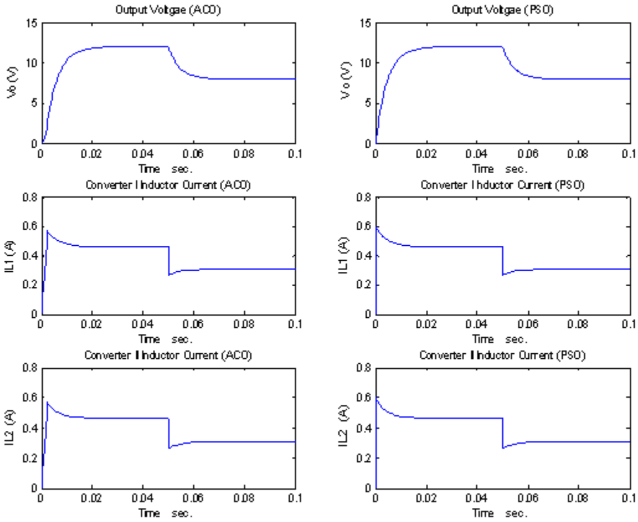

Fig. 6: System responses of ACO and PSO controlled buck converter with the reference voltage is changed from 12V to 8V.

The reference voltage is changed from 12 V to 8 V at moment t= 0.05 sec. where it can be seen that the corresponding output voltage has been changed and followed the reference. In this case, the controller adopts the change in reference, vary the duty cycle of the converter and produce the reference as the output voltage within a fraction of millisecond.

In the present case, the input voltage is varied from 24 to 18V at 0.033 sec and from 18V to 30V at 0.066 sec. The time response of the output voltage and inductor current in a closed-loop system compensated by a ACO and PSO-controller is illustrated in Figure 7. The changes in the input voltage do not make any clear variations in the output voltage and current since the controller adopt the variations in the parameters and continuously track the reference voltage. Consequently, the duty cycle of gate pulse to the MOSFET is changed so that to maintain the output voltage at the same designed value within a fraction of millisecond. This proves the effectiveness and the robustness of the controllers as well as that the controller respond very well under this change.

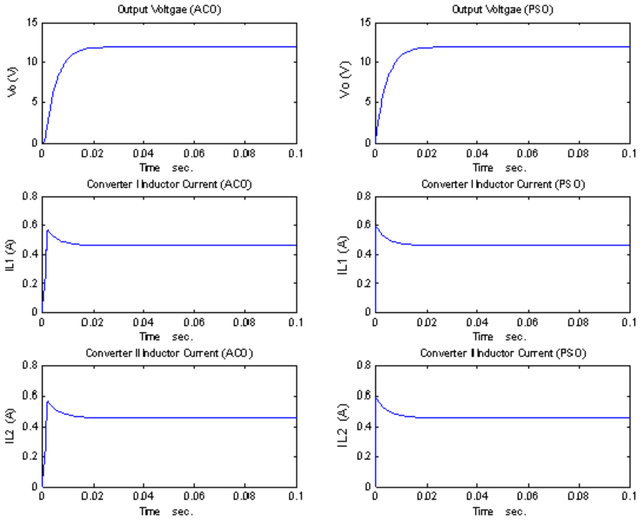

Fig. 7: System responses of ACO and PSO controlled buck converter with the changes in the input voltage

Figure 8 shows the simulation results when the proposed ACO and PSO-based controller are applied to the converter under load variation. The load resistor (R) is suddenly changed from 13 Ω (nominal value) to 9 Ω and again to 16 Ω. By changing the value of resistance load, it has been seen that as load resistance increase, the output voltage is followed the reference value (12V) while the inductors current are changed according to the load values.

Figure 9 shows the behaviour of the controlled system when a failure in one of the converters is occurred after 0.05 sec. from the starting simulation time.

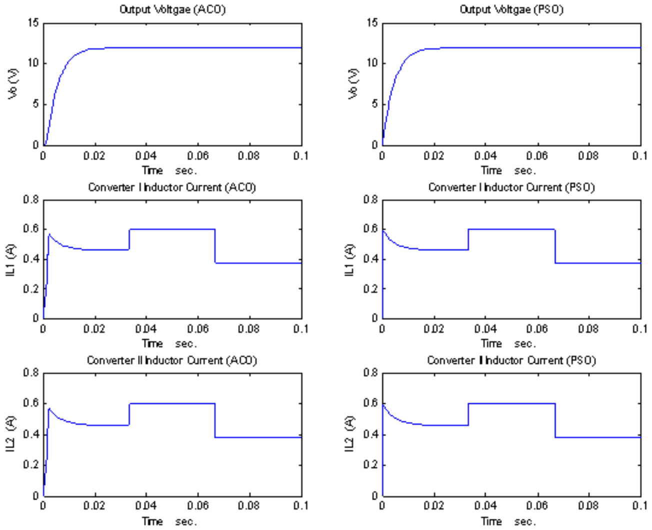

Fig. 8: System responses of ACO and PSO controlled buck converter with the changes in the input voltage

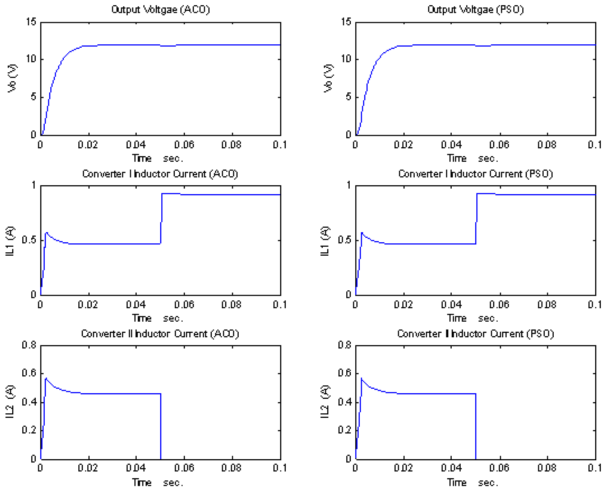

Fig. 9: System responses of ACO and PSO controlled buck converter with sudden failure in converter 2

This Figure illustrates that a satisfactory performance is obtained where the output voltage resumes its reference value (of 12V) immediately after the transient variation caused by the sudden failure in one of the converters. Simulation results verify that the control schemes in this section give stable operation of the power supply and the output voltage and load current can return to the steady state even when it is affected by sudden changes or any failure in the controlled system.

6. Conclusions

The design of on-line ACO and PSO-based state feedback controllers for the parallel converters were adopted as an optimization task and the controller gains are optimized through evolutionary search algorithms. Performance of proposed controllers in different conditions, including of change in reference voltage, the output load and the input voltage as well as the sudden failure in the one of the converters were investigated. By observing the rise time, settling time, and peak overshoot from the step response responses, which are obtained by using the on-line state controllers, it can be concluded that PSO-based parameter optimization is good and robust as compared to other method. The PSO controller gives the better performance and was more robust for model inaccuracies and disturbances in comparison with the ACO-based controller. The obtained simulated results validate the effectiveness of the proposed PSO control strategy. Consequently, the controlled converters systems work fine and behave very well with very less overshoot and settling time. This leads to that the overall speed of the system is increased as seen by the decrease of the settling time when the converter is connected to the power source

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Ali S. Al-Dmour an associate professor in the Electrical Engineering Department at Mutah University in Jordan. He completed his BSc in Electrical Engineering at Mousel University, Iraq, in 1984 and his PhD in Control Systems at Bradford University, UK, in 1996.

His main interest is real-time control application, with particular emphasis on vibration suppression in flexible structures and in controlling electrical machines. In particular, the control laws utilizing intelligent design concepts based on neural networks, fuzzy logic, Particle Swarm Optimization, and genetic algorithms.