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APPLICATION OF ARTIFICIAL BEE COLONY ALGORITHM TO AUTO-TUNING OF STATE FEEDBACK CONTROLLER FOR DC-DC POWER CONVERTER*

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Abstract: The article presents an auto-tuning method of state feedback voltage controller for DC-DC power converter. The penalty matrices employed for calculation of controller's coefficients were obtained by using nature-inspired artificial bee colony (ABC) optimization algorithm. This overcomes the main drawback of state feedback control related to time-consuming trial-and-error tuning procedure. The optimization algorithm takes into account constraints of selected state and control variables of DC-DC power converter. In order to meet all control objectives (i.e., fast voltage response and chattering-free control signal) an appropriate performance index is proposed. Proper selection of state feedback controller (SFC) coefficients is proven by simulation and experimental tests of DC-DC power converter.

Keywords: *artificial bee colony algorithm, state feedback controller, DC-DC power converter, SiC MOSFET*

1. INTRODUCTION

Fast and accurate voltage response is the primary requirement related to control of DC-DC power converters. These are employed in many industrial applications, also in motion control area, as DC motors smooth starters [1] and, as front converters for PMSM and BLDC motors fed by voltage source inverters (VSI) [2], [3]. In the latter case, an additional DC-DC power converter allows the torque ripples to be minimized.

Control task of DC-DC power converter is most often done in cascade control structure with PI type current and voltage controllers [4]. Simple and intuitive tuning methods are the main advantages of this approach, whereas series connection of controllers is responsible for limited bandwidth [4]. The sliding mode control can be em-

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ployed in a cascade control structure to assure robustness of DC-DC power converter against uncertainties and external disturbances [5]. Since new power devices (i.e., SiC JFET and SiC MOSFET transistors) with reduced power losses and switching times provide higher switching frequencies, the time available for execution of the control algorithm decreases. In such a case complex control schemes (e.g., model predictive control, adaptive control, linear matrix inequalities) cannot be easily applied.

Control of DC-DC power converter can also be accomplished by using state feedback controller (SFC). In this approach, all state-space variables (i.e., inductor current and output voltage) are controlled by single device. Since series connection of controllers does not exist in the depicted control scheme, a better dynamic behavior can be achieved in comparison to cascade control structure [6], [7]. The other advantages of SFC are: the possibility of designing robust control system [8] and superior disturbance compensation [6], [7]. On the other hand, introduction of constraints into control system with SFC is more difficult than in cascade control structure, but recently a method based on model predictive approach was proposed to solve the aforementioned problem [6], [7]. Designing process of SFC requires determination of controller coefficients. Contrary to the cascade control structure, all coefficients of SFC are calculated simultaneously. For that reason, proper selection of controller's coefficients is not trivial, especially for complex control system. There are two methods used to determination of state feedback controller coefficients: linear-quadratic optimization and pole placement technique. In the first case, coefficients of the penalty matrices are selected to minimize the quadratic cost function, while in the second approach the pole location is required. In both cases, the trial-and-error procedure is the most often used, but it is challenging and time-consuming, especially if the order of system is high or if its model is not well understood. For that reason, an application of state feedback controller is often limited. Recently, computer-aided optimization algorithms such as: genetic algorithm (GA) [9], particle swarm optimization (PSO) [10] or BAT algorithm [11] have been applied to assign coefficients of SFC. The main requirements related to the optimization algorithms are: fast convergence, low computational effort and simple incorporation of constraint handling method. Since the artificial bee colony algorithm (ABC) proposed by Karaboga [12], [13] exhibits all the features mentioned above, it appears to be a promising approach for determining SFC coefficients.

In this article, the artificial bee colony optimization algorithm is applied to auto-tuning of state feedback controller for DC-DC power converter with SiC MOSFET power devices. The four values of penalty matrices used for determination of SFC coefficients are obtained with the help of the ABC method. In order to meet all control objectives (i.e., fast voltage response and chattering-free control signal) an appropriate performance index is proposed. Constraint handling method is introduced into optimization procedure to limit selected signals of control system. Finally, numerical experiments that prove proper operation of the optimization algorithm and DC-DC power converter are shown.

2. MODEL OF DC-DC POWER CONVERTER

In the proposed approach, state feedback controller was chosen to simultaneously control the coil current and the output voltage of DC-DC power converter with topology shown in Fig. 1.

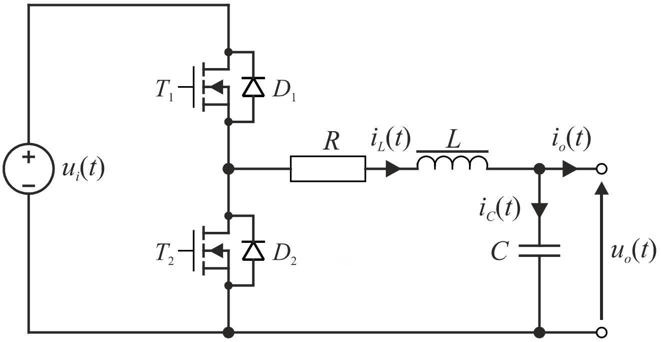


Fig. 1. Topology of DC-DC power converter

In this structure, the T_2 power transistor is used in transient boost mode to provide fast discharging of the output capacitor C. Designing process of SFC requires a state-space representation of the plant

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) + \mathbf{E}d(t), \tag{1}$$

with

$$\mathbf{x}(t) = \begin{bmatrix} i_L(t) \\ u_o(t) \end{bmatrix}, \ \mathbf{A} = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ \frac{1}{C} & 0 \end{bmatrix}, \ \mathbf{B} = \begin{bmatrix} \frac{K_p}{L} \\ 0 \end{bmatrix}, \ u(t) = u_c(t), \ \mathbf{E} = \begin{bmatrix} 0 \\ -\frac{1}{C} \end{bmatrix}, \ d(t) = i_o(t),$$

where $i_L(t)$ – the inductor current, $u_o(t)$ – the output voltage, L, R – inductance and resistance of the inductor, C – the output capacitance, $u_c(t)$ – control signal, K_p – gain of converter, $i_o(t)$ – load current. The following assumptions have been made during model construction:

- Single Operating-Point Approach (SOPA) is applied to model switching DC-DC converter as a linear system working around its operating point [14],
- DC-DC power converter works under continuous current mode,
- the input voltage is constant,
- nonlinearities and dynamics of the converter have been neglected (i.e., power devices have a sufficiently short dead times, modulator operates in its linear range),

- all state variables (i.e., the inductor current and the output voltage) are measured,
- the load current is treated as an unknown disturbance.

3. STATE FEEDBACK CONTROLLER

In this article, state feedback controller is applied to regulate the inductor current and the output voltage of DC-DC power converter. The SFC synthesis procedure requires determination of its structure and coefficients. In order to regulate output voltage without steady-state error, an additional path with integrator has been introduced. In such a case, an augmented model of the plant (1) is as follows

$$\frac{d\mathbf{x}_i(t)}{dt} = \mathbf{A}_i\mathbf{x}_i(t) + \mathbf{B}_i u(t) + \mathbf{F}r(t), \tag{2}$$

with

$$\mathbf{x}_i(t) = \begin{bmatrix} i_L(t) \\ u_o(t) \\ e_u(t) \end{bmatrix},\ \mathbf{A}_i = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} & 0 \\ \frac{1}{C} & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix},\ \mathbf{B}_i = \begin{bmatrix} \frac{K_p}{L} \\ 0 \\ 0 \end{bmatrix},\ \mathbf{F} = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix},\ r(t) = u_{o\,ref}(t),$$

where $u_{o\,ref}(t)$ – reference value of the output voltage. A new state variable $e_u(t)$ represents the integral of the output voltage error

$$e_u(t) = \int_0^t [u_o(\tau) - u_{o\,ref}(\tau)]\,d\tau. \tag{3}$$

In this approach, a discrete SFC will be directly designed to obtain version suitable for implementation in a DSP. For that reason, the discrete version of an additional state variable (3) should be obtained by using, for example, the backward Euler approximation

$$e_u(n) = e_u(n-1) + T_s[u_o(n) - u_{o\,ref}(n)], \tag{4}$$

where T_s – the sampling period, n – the discrete sample time index. The discrete control law for state equation (2) is

$$u(n) = -\mathbf{K}_i\mathbf{x}_i(n) = -\mathbf{K}_x\mathbf{x}(n) - K_e e_u(n), \tag{5}$$

where

$$\mathbf{K}_i = [\mathbf{K}_x \;\; K_e] = [k_{x1} \;\; k_{x2} \;\; k_{e1}] .$$

A block diagram of SFC with discrete integrator is shown in Fig. 2.

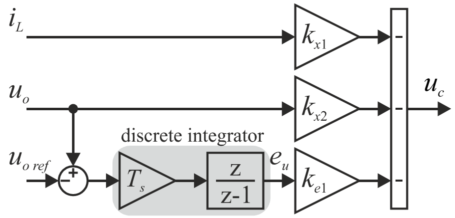


Fig. 2. Block diagram of discrete SFC

The second step of designing procedure concerns determination of SFC coefficients. This could be accomplished by using pole placement technique [15] or linear-quadratic optimization [7]. The latter approach will be employed in this article. In such a case, to minimize the discrete performance index

$$I_{LQR} = \sum_{n=0}^{\infty} [\mathbf{x}_i^{\mathrm{T}}(n)\mathbf{Q}\mathbf{x}_i(n) + u^{\mathrm{T}}(n)Ru(n)], \tag{6}$$

the symmetric and positive (semi-) definite penalty matrices $\mathbf{Q} \geq 0$ and $R > 0$ have to be chosen. Their structures for model (2) with the control law (4) are:

$$\mathbf{Q} = \begin{bmatrix} q_1 & 0 & 0 \\ 0 & q_2 & 0 \\ 0 & 0 & q_3 \end{bmatrix}, \quad R = r. \tag{7}$$

Although only four coefficients have to be selected, depicted task is not trivial and trial-and-error approach seems to be quite time-consuming procedure. For that reason, computer aided optimization algorithm will be employed to find coefficients of the penalty matrices (7).

4. ARTIFICIAL BEE COLONY OPTIMIZATION ALGORITHM

In this article, an artificial bee colony optimization algorithm will be used to obtain coefficients of the penalty matrices. The procedure employed is based on the foraging behavior of honey bees. As a potential solution of optimization problem, the position of a food source is treated. The quality of food sources is determined by the fitness value (FV). Contrary to the popular computer aided optimization algorithms (e.g., PSO), at the beginning of process an artificial colony is divided into employed bees (EB), onlookers (ON) and scouts (SC). Each of these has a different function during optimization procedure. The EB are responsible for visiting food sources and for searching a better one in the neighborhood of current solution. As an indicator of food source quality, the fitness value is used. If a new food source has a greater FV, it is memorized by EB instead of previous one. After all EB tried to find a better solution, these share an information about positions and fitness of food sources with ON. Next, on the basis of FV, the probability is calculated. This is used by ON during selection of a food source to explore. If EB cannot improve the FV of food source, after several attempts this is abandoned and, as a result, the EB becomes an SC. The SC are employed to random search of a new food source.

The main parameter correlated with ABC optimization procedure is the number of colony size *NP*. At the beginning of optimization, values of several parameters (e.g., EB, ON, food sources) are set as half of *NP*. The *D*-dimensional vectors are used to represent the optimized parameters [12]. In order to limit the searching area, the lower (*lb*) and the upper (*ub*) bounds of *D* are also declared. As was mentioned before, the number of attempts to find a better food source during local searching process is restricted. For that reason, the *limit* parameter is introduced. Its value is typically set as a multiple of a food number [12].

4.1. AN APPLICATION OF ABC ALGORITHM TO SFC SYNTHESIS

In order to automatically determine penalty matrices (7) required for computation of SFC coefficients, auto-tuning procedure must be incorporated into optimization algorithm. For that reason, the performance index for a given control problem should be chosen. The main control objective for the DC-DC converter considered is to achieve satisfactory dynamic of output voltage for step variations of $u_{o\,ref}$. This should be accomplished with chattering-free control signal u_c. Control objectives mentioned above lead to the following performance index

$$I_{ABC} = \sum_{n=0}^{N} [\,|e_u(n)|\, nT_s + \alpha \Delta u_c^{\mathrm{T}}(n) \Delta u_c(n)], \tag{8}$$

where α – empirically chosen penalty coefficient, Δu_c – the discrete derivative of control signal, $N = t_{end}/T_{acq}$, t_{end} – the time window applied to evaluate the performance of the system, T_{acq} – data acquisition period ($T_{acq} = T_s/10$).

In order to achieve correct operation of DC-DC power converter, the inductor current and control signal should be limited. Moreover, constraints of selected signals should be included in auto-tuning procedure. For that reason, ABC algorithm will be modified to solve constrained optimization problem. The main modifications are as follows [16]:

- the modification rate (*MR*) control parameter is introduced,
- constraint handling method is employed,
- the *violation* parameter is added,
- scouts production period (*SPP*) parameter is introduced.

The relationship between *MR* parameter and an uniformly distributed random real number $rn \in \langle 0; 1 \rangle$ is used to make a decision on searching new solution in the onlooker bees phase. Constraint handling method based on Deb's rules [17] is employed to perform the selection process of feasible and infeasible solutions. In order to compare two solutions, the tournament selection is used [16], [17]:

- for two feasible solutions, the one with a better objective function is selected,
- any feasible solution (*violation* ≤ 0) is preferred instead of an infeasible solution (*violation* > 0),
- for two infeasible solutions, the one with a smaller constraints violation is chosen.

The *violation* parameter is computed as a maximum value of violations obtained for the inductor current and control signal. In such a case, the boundary values of signals are not exceeded. The last parameter *SPP* introduced defines the predetermined period of cycles beyond which scout is produced if there is an abandoned food source.

On the basis of the performance index (8), the fitness value is calculated

$$fitness_i = \frac{1}{1 + I_{ABC\,i}}. \tag{9}$$

This is used along with *violation* to obtain, the probability value [17]

$$p_i = \begin{cases} \dfrac{1}{2} + \dfrac{fitness_i}{2\sum\limits_{j=1}^{NP} fitness_j} & \text{for feasible solution,} \\ \dfrac{1}{2} - \dfrac{violation_i}{2\sum\limits_{j=1}^{NP} violation_j} & \text{for infeasible solution.} \end{cases} \tag{10}$$

The probability value is used at the beginning of onlooker bees phase to choose the food source for further exploration. The flowchart of constrained ABC optimization procedure employed to auto-tuning of state feedback controller is presented in Fig. 3a. Since some of the procedures occur in each phase, these are shown in Fig. 3b as an evaluation block. The following operations are executed in this block:

- gain values of SFC are calculated by applying *lqrd* function from Matlab,
- simulation of control system is performed by using *sim* function from Matlab,
- performance index I_{ABC} is calculated,
- selection process based on Deb's rules is carried out.

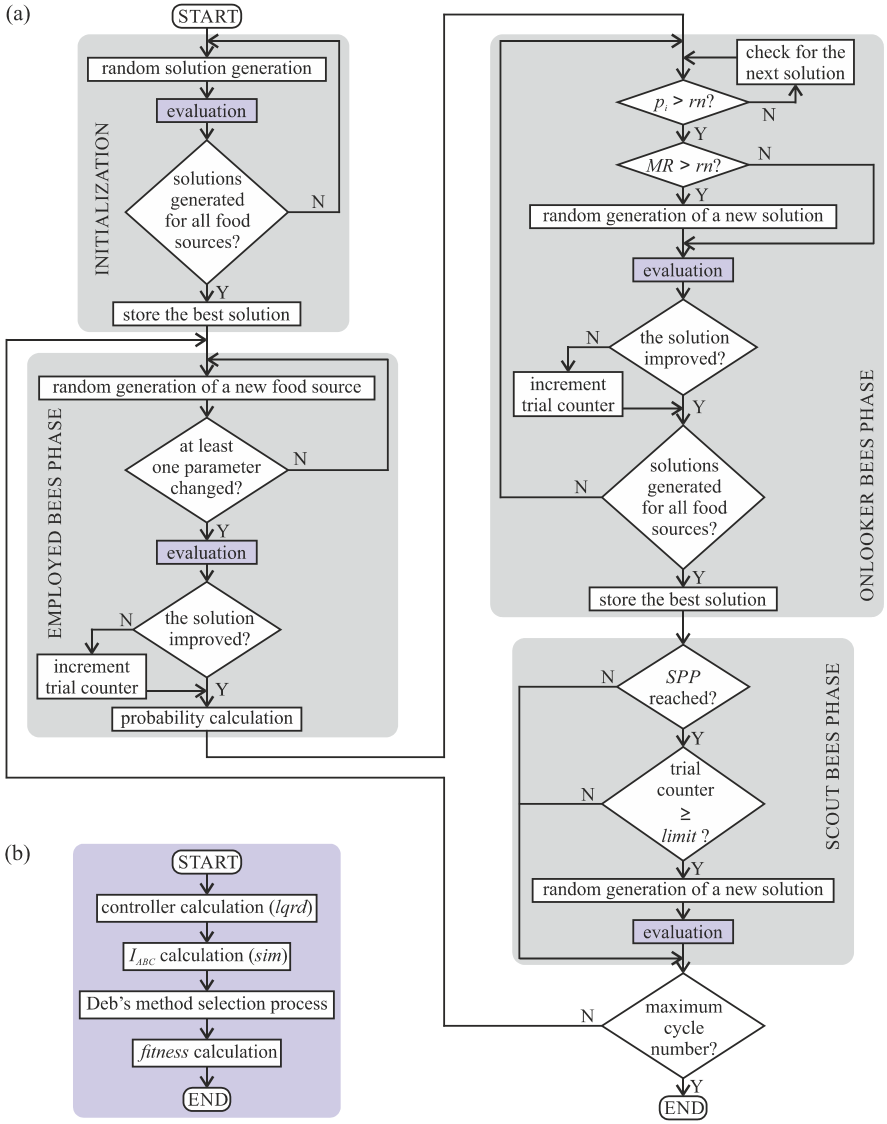


Fig. 3. Flowchart of constrained ABC procedure: (a) general scheme, (b) evaluation block

5. SIMULATION RESULTS

The auto-tuning process of SFC for DC-DC power converter was carried out in Matlab/Simulink/Plecs environment. The main parameters of the plant are summarized in Table 1.

Table 1. Selected parameters of DC-DC power converter

Parameter	Symbol	Value	Unit
Rated power	P_N	600	W
Rated current	I_N	5	A
Rated voltage	U_N	120	V
Switching frequency	f_{PWM}	32	kHz
Inductor resistance	R	0.15	Ω
Inductance	L	3	mH
Capacitance	C	30	μF
Switching period	T_s	31.25	μs

A schematic block diagram of DC-DC power converter with SFC is shown in Fig. 4. In order to assure proper generation of discrete control signal $u_c(n)$, the controller has been implemented in triggered subsystem. Synchronization block guarantees realization of the measurements in the midpoint of the PWM pulse length.

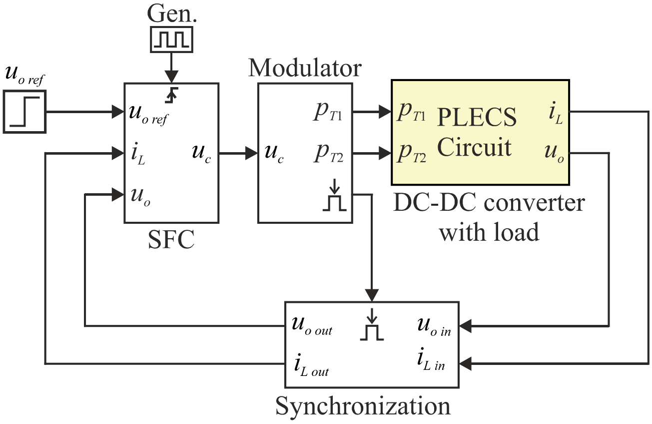


Fig. 4. Schematic block diagram of DC-DC power converter with SFC

Values of ABC control parameters depicted in the previous section have been empirically selected at the beginning of auto-tuning process. Information contained in [18] has been successfully used to set the initial values of most of them. In the next step, after several optimization tests, some values (e.g., *NP*, *MCN*, *SPP* and *limit*) have been manually decreased to reduce the time required for optimization procedure. The final values of control parameters are summarized in Table 2. It should be mentioned that the large searching area defined by the difference between the respective *ub* and *lb* values has been chosen to ensure the free choice of the parameters during optimization procedure. Finally, the value of the penalty coefficient α was manually chosen to provide the trade-off between chattering and dynamics of control signal. For safety reasons, the boundary value of inductor current was set to $I_N = 4$ A.

Table 2. Control parameters of ABC optimization algorithm

Parameter	Symbol	Value
The number colony size	*NP*	20
The number of optimized parameters	*D*	4
The number of food sources	*FN*	*NP*/2
The number of cycles	*MCN*	30
Scout production period	*SPP*	4 × *FN*
Control parameter	*limit*	4 × *FN*
Modification rate	*MR*	0.8
The lower bounds of parameters	$lb_1 \div lb_6$	1×10^{-7}
The upper bounds of parameters	$ub_1 \div ub_6$	1×10^{5}
The penalty coefficient	α	1×10^{-5}

During auto-tuning procedure, the performance index I_{ABC} has been recorded for each iteration and its evolution is shown in Fig. 5a. It should be noted that after 20 iterations, the value of I_{ABC} decreases slightly. The evolution of converter's output voltage during auto-tuning process is presented in Fig. 5b.

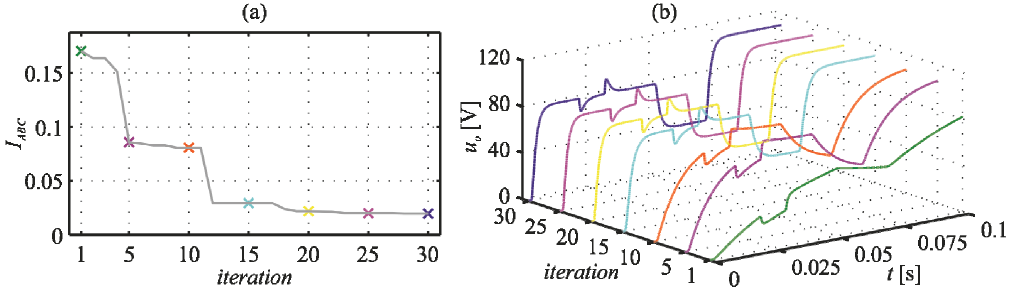


Fig. 5. Evolution of: (a) performance index, (b) output voltage of DC-DC power converter observed during auto-tuning procedure

The following variations of reference voltage have been used: $u_{o\,ref} = 80$ V at 1 ms, $u_{o\,ref} = 40$ V at 50 ms and, $u_{o\,ref} = 110$ V at 70 ms. Perturbations of the output voltage recorded for $t_1 = 20$ ms and $t_2 = 30$ ms are produced by step variations of resistive load (i.e., $R_{o1} = 22\ \Omega$ for $t \in <20; 30>$ ms and $R_{o1} = 33\ \Omega$ for the rest time of run). The final gain values of SFC obtained by using ABC optimization algorithm are

$$k_{x1} = 0.3248, \qquad k_{x2} = 0.0096, \qquad k_{e1} = 14.0739. \tag{11}$$

Simulation responses of DC-DC power converter with SFC coefficients (11) received from auto-tuning process based on ABC optimization algorithm are presented in Fig. 6. From Fig. 6a, it can be seen that output voltage of converter is regulated without steady-state error and overshoot. Transient errors caused by step variations of resistive load at $t_1 = 20$ ms and $t_2 = 30$ ms are eliminated suitably. It should be mentioned that during simulation and experimental tests, the same reference signals, boundary values (i.e., $|i_L < 4|$ A, $|u_C < 1|$ V) and disturbance values are used as for auto-tuning process. Proper operation of constrained optimization procedure is shown in Fig. 6b; the maximum value of inductor current does not exceed the boundary. The last control objective concerning chattering free control signal is also attained (Fig. 6c).

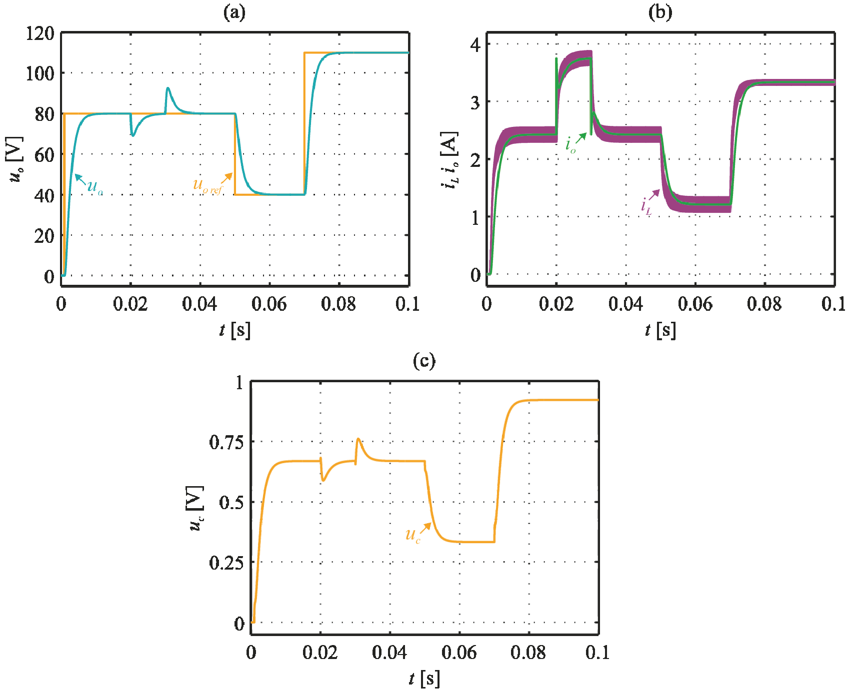
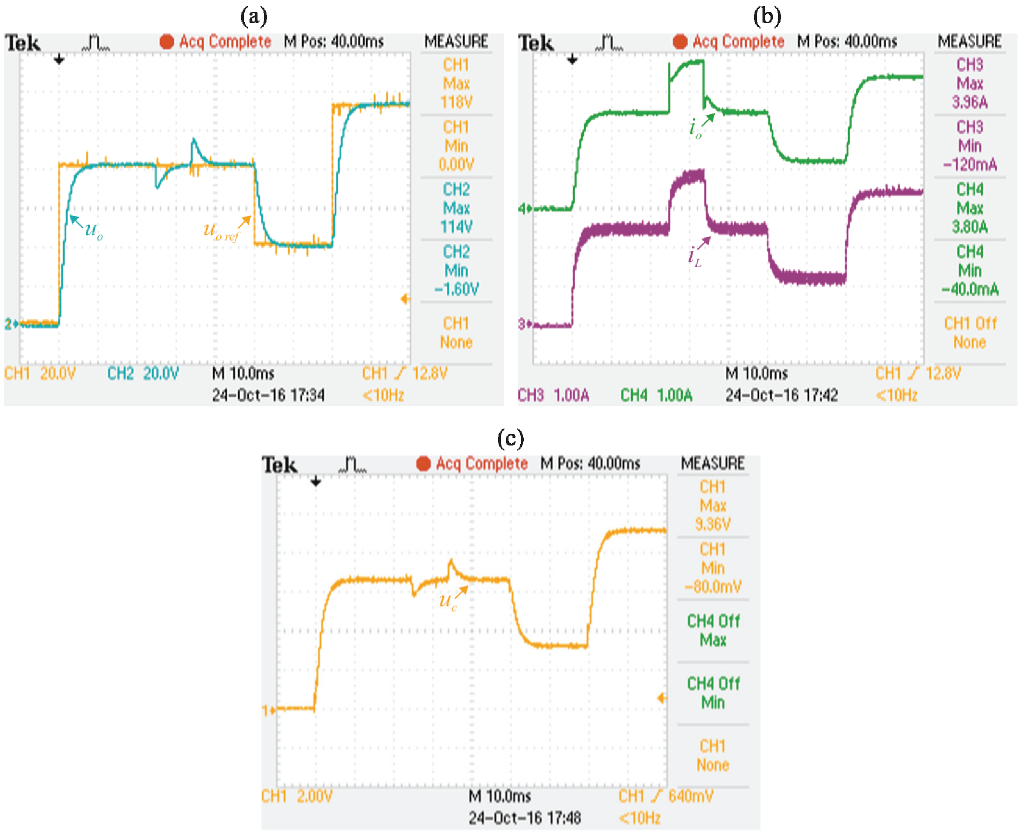


Fig. 6. Simulation responses of DC-DC power converter:
(a) reference and measured output voltages, (b) inductor and load currents, (c) control signal

6. EXPERIMENTAL RESULTS

Finally, the behavior of DC-DC power converter with SFC coefficients obtained from auto-tuning procedure has been investigated in experimental tests. The control algorithm was implemented in DS1104 board. As power devices Cree MOSFETs (C2M0080120D) and Schottky diodes (C4D10120A) were employed. Gate signals for power transistors were generated by using PT62SCMD17 driver. The PWM switching frequency was set at 32 kHz. As voltage and current sensors LV25P and LTS15NP devices manufactured by LEM were applied.


(a)

(b)

(c)

Fig. 7. Experimental responses of DC-DC power converter:
(a) reference and measured output voltages, (b) inductor and load currents, (c) control signal

Experimental responses of DC-DC power converter are shown in Fig. 7 and these coincide well with the simulation responses. From Fig. 7a, proper control of output voltage in the case of step variations of reference signal and resistive load can be observed. It is worth pointing out that the secondary control objectives such as keeping the inductor current and control signal in specified ranges as well as producing smooth control signal are also met.

7. CONCLUSION

In this paper, an application of the artificial bee colony constrained optimization algorithm for auto-tuning of state feedback control for voltage control of DC-DC power converter has been presented. During optimization procedure, four coefficients of penalty matrices required for calculation of SFC were properly selected. Constraint handling method that is based on Deb's selection algorithm was added to ABC procedure to impose limits on selected signals. Simulation and experimental tests prove proper selection of the performance index as well as suitable operation of DC-DC power converter. A comparison of ABC with other optimization algorithms, such as PSO is planned.

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