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DESIGN OF FRACTIONAL ORDER PI CONTROLLER USING METAHEURISTIC ALGORITHMS APPLIED TO DC-DC BOOST CONVERTER- A COMPARISION

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ABSTRACT

In the recent time, fractional order controllers have found wide application in the control of dynamical systems. This work investigates the applications of fractional order proportional and integral controller, to track a commanded output voltage of DC-DC converter and also enhance the transient response. The objective function is to obtain the controller parameters based on the minimization of integral square error (ISE). The indices have been minimized using Queen Bee assist GA (QBGA) optimization technique and it is simulated in MATLAB/Simulink environment. In this paper, we present the comparison of other optimization technique or approaches like GA-FOPI and PSO-FOPI. Simulation results show that the proposed QBGA fractional order PI controller is able to outperform the GA and PSO fractional order PI controllers.

Keywords: boost converter, metaheuristic algorithm, FOPI controller, QBGA.

1. INTRODUCTION

Proportional plus Integral (PI) controllers are widely being used in industries for process control applications. The advantage of using PID controller is due to its simple in design, effective and easily tuned and also good performance including low percentage overshoot and small settling time for sluggish industrial processes [1]. The performance of the feedback PI controllers can be further improved by appropriate settings of fractional Integral action. This paper demonstrates the control behavior of fractional order PI controller for DC-DC boost converter system.

A boost converter must provide a regulated output voltage under varying load and input voltage conditions. The boost converter is non-linear and time variant systems and also exhibits a non-minimum phase system. Hence, control of boost type dc to dc converter is more difficult to compare to the buck converter [2]. Different control algorithms such as linear control theory [3], multi-loop control technique [4] have been applied to regulate dc to dc converter to attain a constant output voltage.

Dynamic characteristic of closed loop boost converter must satisfy certain requirements like good transient response, stable output voltage regulation with input source voltage change and output load variation. To improve the dynamic characteristic of boost converter while preserving the robust characteristics, a fractional order control technique is applied to regulate the converter output voltage.

The main contribution of the present paper is the implementation of fractional order PI controller in regulating the converter output voltage robustness. This work consists mainly in the design of feedback fractional order PI controller in order to get optimal time domain specifications in which integral square error (ISE) has been minimized and hence the controller parameters K_p, K_i and λ are identified. A very important aspect of designing FOPI controllers is to decide upon the values of K_P, K_i and λ. Queen Bee assist Genetic Algorithm is used for tuning the FOPI controller. The development and implementation of the proposed system and controller were done using MATLAB/Simulink.

This paper is organized as follows. Section 2 describes the proposed fractional order PI^{λ} control structure. In section 3, seeks to review DC-DC boost converter. In section 4 describe the objective function of a converter. In section 5 describe the tuning of the controller by QBGA technique. In section 6, simulation results are presented, to demonstrate the advantages of the tuning method. Finally, section 7 draws the conclusions of this work.

2. FRACTIONAL ORDER PI CONTROLLERS

The application of fractional controller in the field of control of dynamical systems is increased. Fractional order control system and controllers are described by a set of differential equations. There are different definitions of Fractional Order differentiations and integrations. Some of the definitions extend directly from integer-order calculus. The well-established definitions include the Grunewald-Letnikov definition, the Cauchy integral formula, the Caputo definition and the Riemann-Liouville definition [5, 6].

Grunewald-Letnikov definition:

$$ {}_aD_t^{\alpha} f(t) = \lim_{h\to 0} \frac{1}{h^{\alpha}} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \binom{a}{j} f(t - jh) \qquad (1)$$

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Where $w_j^{\alpha} = (-1)^j \binom{a}{j}$ represents the coefficients of a polynomial $(1-z)^{\alpha}$

The coefficients can also be obtained from

$$w_0^{\alpha} = 1 \ , w_j^{\alpha} = \left(1 - \frac{\alpha+1}{j}\right) w_{j-1}^{\alpha} \ , \quad j = 1, 2, ... \tag{2}$$

Riemann-Liouville definition:

$$ {}_aD_t^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau) d\tau \tag{3}$$

Where $0 < \alpha < 1$ and a is the initial time instance, assumed to be zero, i.e., α=0;

The differential equation of fractional order PI controller is described as

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) \tag{4}$$

The most common form of a fractional order PI controller is the PI^{λ} controller [7]. The continuous transfer function of FOPI is obtained through Laplace transform, which is given by

$$G_C(S) = \frac{U(S)}{E(S)} = k_p + k_1 \frac{1}{S^{\lambda}}, (\lambda > 0) \tag{5}$$

Where $G_c(S)$ is the transfer function of the controller, E(S) is an error, and U(S) is controller's output. Figure-1 shows the block diagram of FOPI controller.

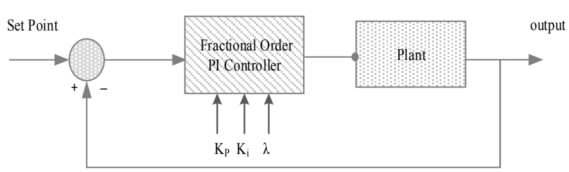

Figure-1. Block diagram of FOPI controller.

A fractional order controller provides an extra degree of freedom due to an incorporation of additional parameter λ. Hence, it gives greater flexibility and possible to improve the performance of conventional PID controller [8].

3. BOOST CONVERTER MODEL

A boost converter is a DC to DC power converter with an output voltage is greater than its input voltage. The average voltage across the load is controlled by varying the duty cycle of the switch. The duty cycle of the boost converter is controlled by fractional order PI controller. The voltage mode control is a common closed loop control method for PWM dc-dc converter due to its simple hardware implementation, good load regulations, and flexibility. The Figure-2 shows circuit implementation of voltage mode control of boost converter.

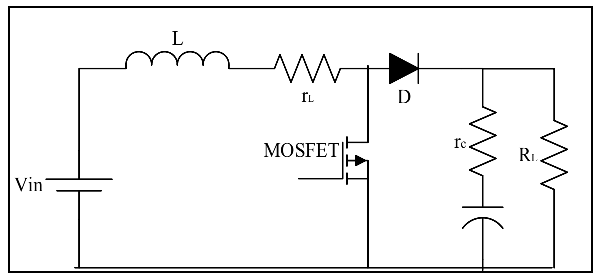

Figure-2. Boost converter controller topology.

To provide optimal performance at all operating conditions of the system FOPI controller is developed to control the duty cycle of the boost converter. Fractional PI controller is designed based on an average state space model of the classical boost DC-DC converter. The differential equation describing the converter behavior during the ON state of the switch is [9].

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \frac{-r_L}{L} & 0 \\ 0 & \frac{-1}{C(R_L + r_c)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{6}$$

The output voltage of DC-DC boost converter during ON state is,

$$v_o = \begin{bmatrix} 0 & \frac{R_L}{(R_L + r_c)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{7}$$

The OFF state of the boost converter is,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\left(\frac{r_1 + R_L / r_c}{L}\right) & -\frac{R_L}{L(R+r_c)} \\ \frac{R_L}{C(R+r_c)} & -\frac{x_2}{C(R_L+r_c)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{8}$$

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The output voltage of DC-DC boost converter during OFF state is,

$$v_o = \begin{bmatrix} r_c / R_L & \dfrac{R_L}{(R_L + r_c)} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (9)$$

In the above, the state variables x_1 and x_2 are inductor current i_L and capacitor voltage v_c, respectively.

4. OBJECTIVE FUNCTION

In the proposed method, the fractional order PI controller parameter is optimally tuned to improve overall boost converter transient behavior. In this study, an integral of squared error is taken as objective function. The objective function is a time domain based given as,

$$\text{Minimize } J_{ISE} = \int_0^T \left(e(t)\right)^2 dt \quad (10)$$

Where $e(t) = \left[V_{ref} - V_0\right]$ is the error signal in a time domain

The aim is to minimize the objective function (10) in order to reduce the boost converter's transient response in terms of rise time, settling time, peak time and steady state error. The optimal value of controller parameters is obtained by evaluating the objective function as specified in (10). The optimization of the fractional order PI controller is carried out using Queen Bee assist GA algorithm (QBGA). The fitness function is

$$fitness\ value = \frac{1}{performance\ index} \quad (11)$$

5. TUNING OF FOPI CONTROLLER BY QBGA

The term queen bee is naturally used to refer to an adult, mated female that lives in a honey bee colony or hive. A new evolution method called queen-bee evolution is proposed for enhancing the optimization capability of genetic algorithms [10-13]. The QBGA is an algorithm based on the interactions of bees in a hive. This queen-bee evolution is similar to nature in that the queen-bee plays a major role in a reproduction process. Basically, there exists a single queen bee with which mates with all other bees, known as drones produced a female bee which ousts the current queen and becomes the new queen. The sequential steps of queen-bee based genetic is described as follows.

a) Generation of bees

b) In the initialization, bees are randomly generated in the feasible search space.

c) Identification of a queen bee

d) Among the randomly generated bees, queen bee is selected as the one which has the best binary structure in minimizing the function (10).

e) Drones mate with the queen, produce two offsprings. Among the two, only the fittest alone survives and the other one is discarded and is equivalent to killing by virgin queen bee.

f) Every virgin queen competes and best competes with a current queen; whichever survives becomes new nest queen.

g) Terminate the program and select the new queen bee as the optimum solution, if termination criterion is reached; else goes to step 3. The termination criterion is taken as 50 iterations.

h) This iteration is repeated several times by regenerating the drones until the best optimal solution is found.

The flow chart for a genetic algorithm with queen bee evolution algorithm is shown in Figure-3. The Table-1 indicates the algorithm parameters for experiments.

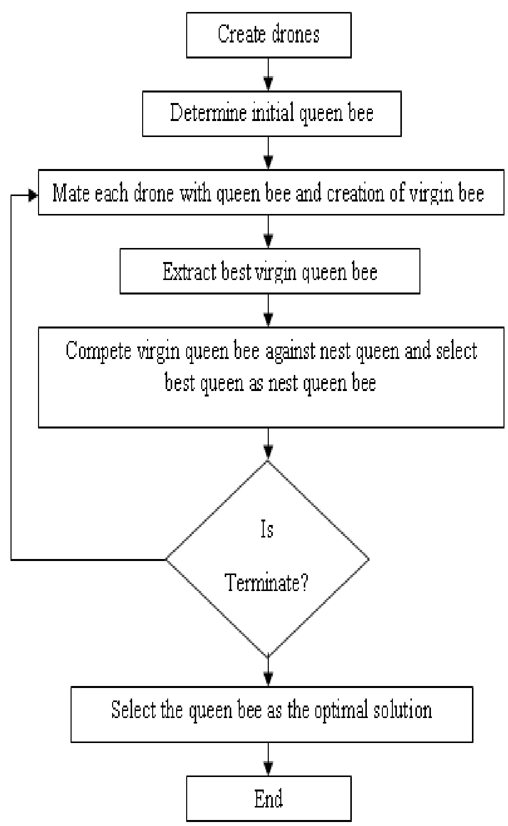

Figure-3. Flow chart of the queen bee GA.

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Table-1. Parameters for experiments.

Parameters	Values
Crossover probability (p_c)	0.6
Mutation probability (p_m)	0.09
Population size	10
Recombination probability (p_r)	0.8
No of iteration	50

At last, the queen-bee evolution makes it possible for genetic algorithms to quickly approach the global optimum as well as decreasing the probability of premature convergence [14].

6. SIMULATION RESULTS

For simulation purposes, the design specifications of the proposed DC-DC boost converter consider in this paper is [9], input voltage, V_{in} = 36V; switching frequency, f_s = 2 kHz; inductance L = 33mH; equivalent resistance of the inductor, r_L = 3Ω; capacitance, C = 1000μF; equivalent resistance of the capacitor, r_c =0.5Ω, and load resistance, R_L = 100 Ω. In the feedback control system, the actual output voltage V_0, and its reference value V_{ref} are fed into the controller. The control voltage e(t), so obtained is processed by the proposed FOPI controller.

To verify the response of the converter, a complete dynamic model of boost converter has been simulated by Matlab environment. The performance of the boost converter controller is carried out using Bees GA. The proposed method employs to solve an optimization problem and look for an optimal set of controller parameters. The optimization of controller parameters is carried out by evaluating the objective function as given in (10). The DC to DC converter has been simulated for variation of load from 100Ω to 200Ω is shown in Figure-5. Similarly, the response of the converter for a step change in input voltage and also change in set point from 80V to 40V and then back to 80V is displayed in Figure-6 and Figure-7. Simulated regulatory response of voltage and current for GA, PSO and Queen Bee based GA tuned FOPI controlled DC-Boost converter at time t=1 sec 10% decrease and time t=2 sec 10% increase is shown in Figure-8.

The boost converter performance measures are verified by using Queen Bee assist GA algorithm. The final values of the optimized controller parameters with the objective function and have been compared with GA and PSO fractional controllers [15]. This can be Table-2 as given by,

Table-2. Dynamic performance analysis of Boost converter.

Controller	K_p	K_i	Lamda	Rise time	Peak Time	Settling time	Steady state error	Minimum of J_{ISE}
GA-FOPI	0.2824	10.2315	0.9172	0.218	0.3755	0.3755	-0.43	1.6649e+07
PSO-FOPI	0.1336	32.5579	0.9839	0.073	0.1285	0.1587	0.22	1.5663e+07
QBGA-FOPI	0.3685	34.0936	1.0215	0.065	0.1098	2.9883	0.15	1.7542e+04

From the Table-2, we conclude that the rise time, peak time and steady state error is reduced as compared to other optimization technique of the genetic algorithm and particle swarm algorithm. The minimization of an objective function is achieved by a queen bee based GA algorithm. It's clear that the QBGA performance is better than GA and PSO algorithms tested for boost converter controller optimization. Simulink results of dynamic response of the closed loop operation are presented in Figure-4.

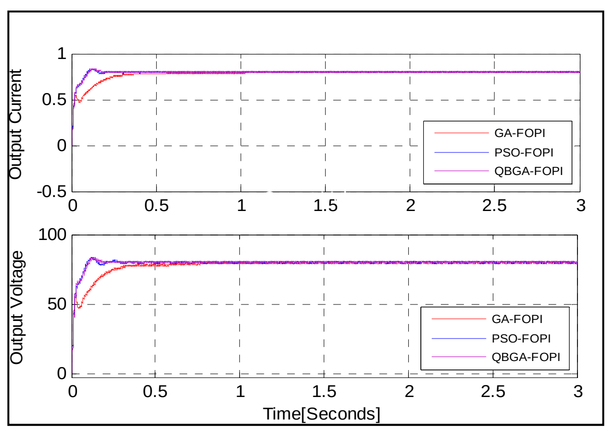

Figure-4. Simulated voltage and current response to GA, PSO and QBGA tuned FOPI controlled boost converter for a set value of 80 V.

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With these optimal values of the controller parameters, the transient response of the boost converter is carried out by applying disturbances to load changes; input source and output voltage of converter are shown in Figure from Figure-5 to Figure-7. The dynamic performance of a converter is compared with GA and PSO optimized controller parameter's response.

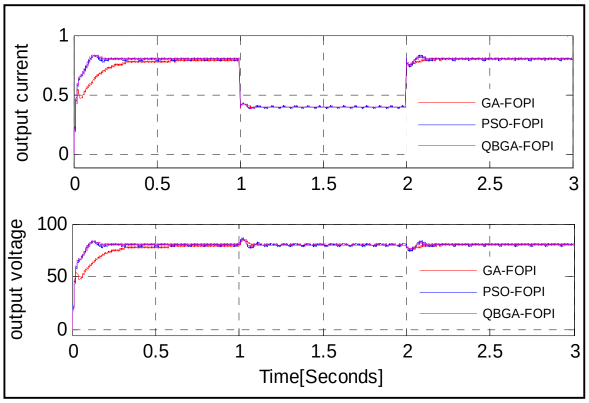

Figure-5. Simulated voltage and current response to GA, PSO and QBGA tuned FOPI controlled boost converter for a change in load from 100 Ω to 200 Ω at time t=1 Sec and 200 Ω to 100 Ω at time t=2 sec.

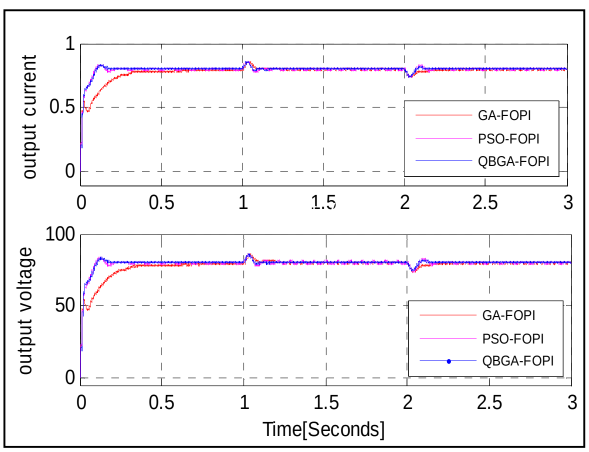

Figure-6. Simulated voltage and current response to GA, PSO and QBGA tuned FOPI controlled boost converter for 10% decrement and increment in supply/input voltage at time t=1 sec and t=2 sec respectively.

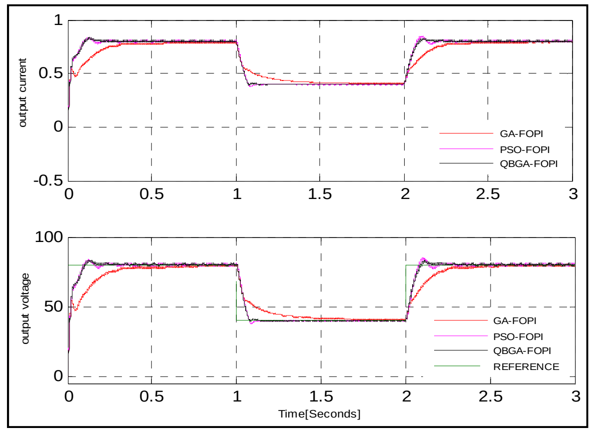

Figure-7. Simulated servo response of voltage and current for GA, PSO and QBGA tuned FOPI controlled boost converter at time t=1 sec 50% decrease and time t=2 sec 50% increase.

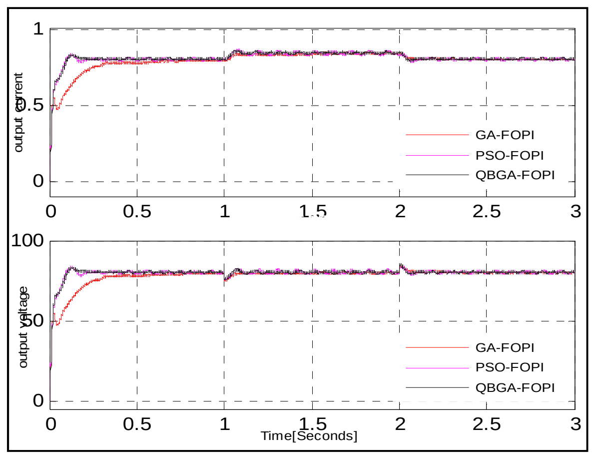

Figure-8. Simulated regulatory response of voltage and current for GA, PSO and QBGA tuned FOPI controlled boost converter at time t=1 sec 10% decrease and time t=2 sec 10% increase.

7. CONCLUSIONS

This paper presented the method of tuning the parameters of FOPI controllers using Queen Bee assist GA algorithm which minimizing the ISE. With the help of fractional order PI controller, the response of boost converter can be designed with more flexibility. Criteria based on system robustness and disturbance rejection were proposed to review the performance of boost converter with fractional order PI controllers. Furthermore, the dynamic response of the converter following step changes of the input and load variations are also simulated and presented. The converter with QBGA-FOPI controller can reduce the time domain performances, rise time, peak time and steady state error as compared to GA and PSO based fractional order PI controllers.

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