Received June 4, 2021, accepted June 17, 2021, date of publication June 24, 2021, date of current version July 7, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3092215

Robust Queen Bee Assisted Genetic Algorithm (QBGA) Optimized Fractional Order PID (FOPID) Controller for Not Necessarily Minimum Phase Power Converters

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This work was supported by the Renewable Energy Laboratory, Department of Communication and Networks, College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia.

This work did not involve human subjects or animals in its research.

ABSTRACT Power electronic converters find application in diverse fields due to their high power conversion efficiency. Converters are often characterized by time response specifications, robustness and stability. Conventionally, converters employ the classic PID controller. The state space average linear time invariant model of a boost converter is known to be a non-minimum phase system. This paper demonstrates that the boost converter with a PID controller using the Queen Bee assisted Genetic Algorithm (QBGA) optimization is not robust to plant parameter variations. A fractional order PID controller based on QBGA optimization proposed here is shown to have improved robustness. The controller proposed here is applicable across converters, viz., buck, boost and buck-boost, equally.

INDEX TERMS Boost converter, non-minimum phase system, QBGA, fractional order PID controller.

I. INTRODUCTION

Power electronic converters are popular in use due to their high efficiency. Under plant parameter variations, closed loop controller design for converters with required regulation poses challenges. DC-to-DC converters often use buck converter, boost converter and buck-boost converter. In practice, design of controllers for converters are based on a simplified average linear time invariant (LTI) model even though the system is piece-wise linear [1]. In the process, the boost converter is represented by a state-space averaged model. Control of buck converters using PID controllers is satisfactory [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Ton Duc Do.

Control of boost converters using PID controller [3] performs well for input voltage and load changes; but not in the presence of plant parameter drifts. This is attributed to the non-minimum phase nature of the boost converter [4]. A few more converters which shows the non-minimum phase nature is provided in [5], that work presents the internal model control based PID tuning to maximize the bandwidth of converters.

General optimal tuning schemes for PID and fractional order PID (FOPID) controllers for unstable and integral plants are reported in [6]. Automatic tuning of optimum PID controllers based on a time-weighted integral performance criterion and integral of time error squared criterion are studied [7]. The Optimal Queen Bee assisted Genetic

Algorithm (QBGA) presented in [8] is used to tune the PID parameters in this paper.

The work of [9] presents the performance analysis of genetic algorithm (GA) and Queen Bee assisted GA tuned PI controller for shunt active power filter connected with complex loads. In which, QBGA tuned PI controller outperforms as compared to other tuning methods. In the present article, the considered plant is of non-minimum phase system and the performance of PID controller with respect to change in plant parameter is not satisfactory [4]. Which leads to explore another type of controller for not necessarily minimum phase power converters.

FOPID controller proposed in [10] provides flexibility and robustness to the system even in the time-delay systems [11] and under plant parameter variations. However the physical realization of FOPID is based on an integer order approximation of the controller transfer function [12], [13]. A procedure for conversion of FOPID to its integer order approximation using the state model is presented in [14]. This approximation is shown to result in a system of increased order, hence increasing the complexity in physical realization. A digital realization of fraction order controller for DC motor control is presented in [15]. There, the Digital FOPID controller for boost converter is used to obtain robustness.

The stability analysis of a fractional order system is based on Matignon's stability theorem [16] and is quite different from that of an integer order system. This paper uses Matignon's stability theorem for stability analysis of the boost converter using FOPID control.

Classical control of boost converter is presented in Section II. Section III comprises FOPID controller for boost converter, and a brief outline of QBGA as used for the optimal tuning of parameters. Simulations are presented and discussed in Section IV. Conclusions are drawn in Section V.

II. CLASSICAL CONTROL OF BOOST CONVERTER

A model for the boost converter and its control based on classical PID controller are discussed here.

The Circuit of boost converter is represented in Fig. 1. Switch S is ideal – short circuit when ON and open circuit when OFF. Diode D is also considered as ideal.

A. THE BOOST CONVERTER MODEL

When S is ON, the governing equations of the boost converter are

$$\left.\begin{aligned} v_i &= L\frac{di_l}{dt} + i_l r_l \\ \frac{dv_c}{dt} &= \frac{1}{C}\left(\frac{0 - v_c}{R_L + r_c}\right) \\ &= \frac{-v_c}{C(R_L + r_c)} \quad \text{and} \\ v_o &= v_c + r_c\left(\frac{-v_c}{R_L + r_c}\right) \\ &= \frac{R_L v_c}{R_L + r_c}, \end{aligned}\right\} \tag{1}$$

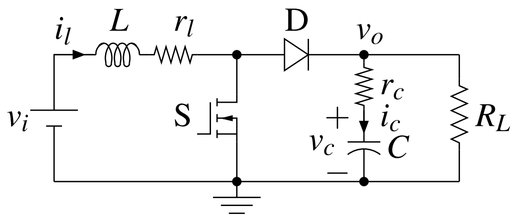

FIGURE 1. The boost converter circuit.

where v_o is the output voltage. With S OFF, the boost converter is described by the following:

$$\left.\begin{aligned} v_c &= -r_c i_c + R_L(i_l - i_c), \\ i_c &= \frac{R_L i_l - v_c}{R_L + r_c} \\ v_i &= L\frac{di_l}{dt} + r_l i_l + r_c\left(\frac{R_L i_l - v_c}{R_L + r_c}\right) + v_c \\ &= L\frac{di_l}{dt} + \left(r_l + \frac{R_L r_c}{R_L + r_c}\right) i_l + \frac{R_L v_c}{R_L + r_c} \\ \frac{dv_c}{dt} &= \frac{1}{C}\left(\frac{R_L i_l - v_c}{R_L + r_c}\right) \quad \text{and} \\ v_o &= r_c\left(\frac{R_L i_l - v_c}{R_L + r_c}\right) + v_c \\ &= \frac{R_L r_c i_l}{R_L + r_c} + \frac{R_L v_c}{R_L + r_c}. \end{aligned}\right\} \tag{2}$$

Let $\mathbf{x} = [i_l \ \ v_c]^{\mathrm{T}}$ be a state vector. Then, from (1) and (2), the piece-wise state-space On and OFF models for the circuit of Fig. 1 are

$$\left.\begin{aligned} \dot{\mathbf{x}} &= A_{ON}\ \mathbf{x} + B_{ON}\ v_i \\ v_o &= C_{ON}\ \mathbf{x} \end{aligned}\right\} \text{ for } \mathrm{T_{ON}} \tag{3}$$

$$\left.\begin{aligned} \dot{\mathbf{x}} &= A_{OFF}\ \mathbf{x} + B_{OFF}\ v_i \\ v_o &= C_{OFF}\ \mathbf{x} \end{aligned}\right\} \text{ for } \mathrm{T_{OFF}}. \tag{4}$$

Here, $A_{ON}, B_{ON}, C_{ON}, A_{OFF}, B_{OFF}$ and C_{OFF} are obtained from (1) and (2) and are given in Appendix.

Then, the average state-space model becomes

$$\left.\begin{aligned} \dot{\mathbf{x}} &= A\ \mathbf{x} + B\ v_i \\ v_o &= C\ \mathbf{x} \end{aligned}\right\} \tag{5}$$

with

$$\begin{aligned} A &= \frac{A_{ON}T_{ON} + A_{OFF}T_{OFF}}{T_{ON} + T_{OFF}}, \\ B &= \frac{B_{ON}T_{ON} + B_{OFF}T_{OFF}}{T_{ON} + T_{OFF}} \quad \text{and} \\ C &= \frac{C_{ON}T_{ON} + C_{OFF}T_{OFF}}{T_{ON} + T_{OFF}}. \end{aligned}$$

The average model of (5) is considered as the plant to design a controller. The simulations, however, are performed with the actual circuit of Fig. 1. The average model of (5) yields the transfer function

$$\frac{V_o(s)}{D(s)} = \frac{\overline{V}_o^2}{\overline{V}_i} \frac{\left(1 + \frac{s}{\omega_{z1}}\right)\left(1 - \frac{s}{\omega_{z2}}\right)}{1 + \frac{s}{\omega_o Q} + \frac{s^2}{\omega_o^2}} \tag{6}$$

where

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}}$$
$$\omega_{z1} = \frac{1}{r_c C}$$
$$\omega_{z2} \approx \frac{R_L}{L}\left(\frac{\overline{V}_i}{\overline{V}_o}\right)$$
$$\omega_o \approx \frac{1}{\sqrt{LC}}\frac{\overline{V}_i}{\overline{V}_o} \quad \text{and}$$
$$Q \approx \frac{\omega_o}{\frac{r_l}{L} + \frac{1}{C(R_L + r_c)}}.$$

$\overline{V}_i$ and $\overline{V}_o$ denote the nominal input and output voltages respectively.

In this paper the model parameters are chosen identical to those in [3] (vide Table 1) to facilitate a comparison of results obtained here with those in [3].

TABLE 1. Nominal plant parameters.

v_i (V)	F_s (kHz)	R_L (Ω)	L (mH)	C (μF)	r_l (Ω)	r_c (Ω)
36	2	100	33	1000	3	0.5

B. DRAWBACKS OF THE CLASSICAL PID CONTROLLER FOR BOOST CONVERTER

This section would like to examine the performance of PID controller for the boost converter deviates from the nominal parameter. The following section presents the results of PID controller proposed in [3] and the next section presents the results of PID controller whose gains are tuned based on Integral Square Error (ISE) optimization.

1) PID CONTROLLER TUNED BASED ON TRANSIENT RESPONSE OPTIMIZATION USING QBGA [3]

Let t_r : rise time, t_s : settling time, M_p : maximum peak over shoot and e_{ss} : steady state error. Also, let K_p, K_i and K_d be the proportional, integral and differential gains of the PID controller respectively. The PID controller proposed in [3] solves the following constrained optimization problem:

$$\begin{aligned}&\text{Minimize } F = (1+t_r)(1+t_s)(1+M_p)(1+e_{ss})\\ &\text{subject to } \ K_p \in [K_{p1},\ K_{p2}],\\ &\qquad\qquad K_i \in [K_{i1},\ K_{i2}],\ \text{and}\\ &\qquad\qquad K_d \in [K_{d1},\ K_{d2}].\end{aligned}$$

In [3], the specifications for the nominal plant taken are $t_r = 60$ ms, $t_s = 1.3$ s, $e_{ss} = 0.6\%$, and $M_p = 0\%$. With a view to make this presentation self-contained, the implementation of QBGA [8] is shown in the flowchart of Fig. 7 in Appendix. Using QBGA, the optimal PID gains obtained are $K_p = 0.326$, $K_i = 8.87$ and $K_d = 0.012$.

Before presenting the simulation results, there is a need to pose and answer the following question: "Why seek robustness to parameter variation?" Significantly, the answer lies in the following as reported in [17]: (i) Temperature rise decreases the equivalent series resistance of an electrolytic capacitor (r_c here); and (ii) Inductor coil resistance (r_l here) increases with increase in temperature. The issue of the need for a robust controller thus settled. In this perspective, the simulation results are reported here.

With values as listed above (taken from [3]), the simulation results are captured in Figure 2. The following observations are of interest:

- The error in response is reasonably small with variations in L. In fact, for $t \in [2, 3]$ s, the maximum output disparity is as small as $\pm$ 0.1 V.
- The disparity in response when r_l drifts in excess of 40% of its nominal value is substantial. For $t \in [2, 3]$ s, the corresponding maximum disparity in output is close to -6.3 V, which is quite large.
- The error oscillates and grows as r_c deviates by more than 40% of its nominal value. For $t \in [2, 3]$ s, it oscillates between $\pm$ 2.8 V.

Clearly, robustness to parameter variations is critical to the controller performance, and that has not been provided by the scheme in [3].

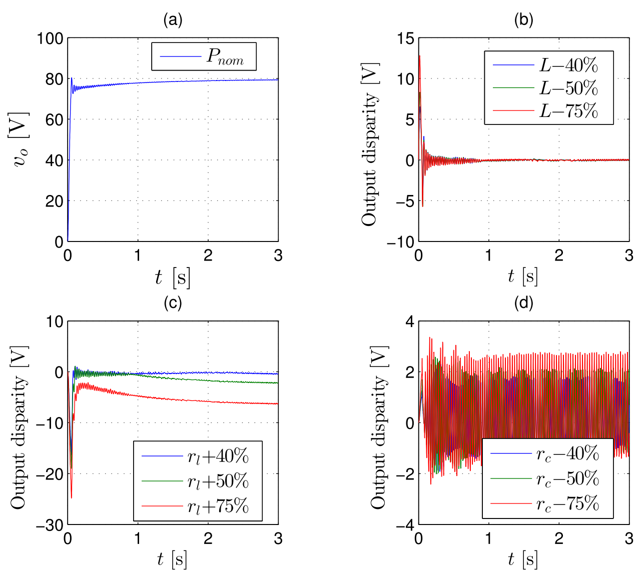

FIGURE 2. Classical PID controller: (a) Plant output with nominal parameters. (b) Output disparity with change in *L*. (c) Output disparity with change in r_l. (d) Output disparity with change in r_c.

2) QBGA BASED ISE OPTIMIZATION FOR PID CONTROLLER

This section would like to examine performance of PID controller whose gains are obtained by optimizing the integral square error. The gains of PID controller parameters are obtained by solving on the following optimization problem using QBGA:

$$\left.\begin{aligned} &\text{minimize} \;\; F = \int_0^\infty e^2(t)dt \\ &\text{subject to} \;\; K_p \in [K_{p1},\; K_{p2}], \\ &\qquad\qquad\;\; K_i \in [K_{i1},\; K_{i2}], \\ &\qquad\qquad\;\; K_d \in [K_{d1},\; K_{d2}]. \end{aligned}\right\} \tag{7}$$

The parameters used to solve the above problem (7) are as follows: (i) Population size: 30; (ii) Bee structure: Binary; (iii) # Iterations: 50; (iv) Gains $K_p \in (0,\ 5]$, $K_i \in (0,\ 15]$ and $K_d \in (0,\ 5]$.

The gains obtained from the above tuning are $K_p = 4.07$, $K_i = 13.5$, and $K_d = 0.099$. The corresponding simulation results are as in Figure 3. The following are the significant observations of the PID controller whose gains are obtained by solving the ISE optimization:

- The error in response is reasonably small with variations in L. In fact, for $t \in [2, 3]$ s, the maximum output disparity is as small as $\pm$ 0.1 V.
- The disparity in response when r_l drifts in excess of 75% of its nominal value is substantial. For $t \in [2, 3]$ s, the corresponding maximum disparity in output is close to -3.7 V, which is large but reduced as compared to result presented in Figure 2.
- The error oscillates and grows as r_c deviates by more than 40% of its nominal value. For $t \in [2, 3]$ s, it oscillates between $\pm$ 1.4 V, which is also reduced as compared to result presented in Figure 2.

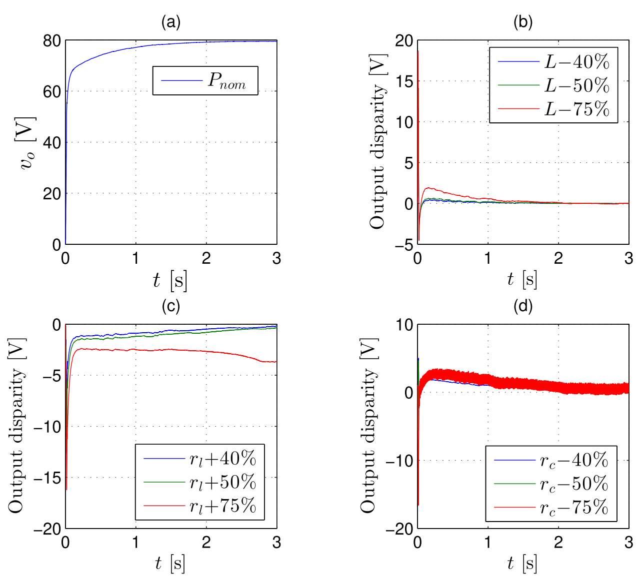

FIGURE 3. QBGA-optimized FOPID controller: (a) Plant output with nominal parameters. (b) Output disparity with change in L. (c) Output disparity with change in r_l. (d) Output disparity with change in r_c.

Slight improvements are observed in the performance of PID controller tuned based on ISE as compared to PID controller tuned based on transient response [3]. However there exist a significant disparity in the output whenever the change in r_l and r_c are significant in boost converter.

III. FOPID CONTROLLER FOR BOOST CONVERTER

To address the problem of lack of robustness of the controller as highlighted in Section II, this section presents the design of FOPID controller [12], [13] for the boost converter. FOPID controller output, $U(S)$, is related to the controller input, $E(s)$, as

$$U(s) = \left(K_p + \frac{K_i}{s^\lambda} + K_d s^\mu\right) E(s), \tag{8}$$

where λ and μ are positive real, thus admitting fractional order as different from the conventional PID control case. In this paper QBGA based optimization is used to tune these parameters, in addition to the PID controller gains.

A. QBGA BASED OPTIMIZATION FOR FOPID

The FOPID control parameters of (8) are obtained by solving on the following optimization problem using QBGA:

$$\left.\begin{aligned} &\text{minimize} \;\; F = \int_0^\infty e^2(t)dt \\ &\text{subject to} \;\; K_p \in [K_{p1},\; K_{p2}], \\ &\qquad\qquad\;\; K_i \in [K_{i1},\; K_{i2}], \\ &\qquad\qquad\;\; K_d \in [K_{d1},\; K_{d2}] \\ &\text{and} \qquad\quad \lambda, \mu \in (0, 1]. \end{aligned}\right\} \tag{9}$$

The QBGA-based optimal tuning of the FOPID parameters to be used in a boost converter is as in the schematic of Figure 4, which is self-explanatory.

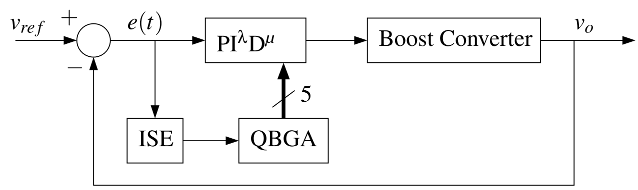

FIGURE 4. Schematic of QBGA-based optimal tuning of FOPID parameters for boost converter.

IV. SIMULATIONS AND DISCUSSIONS

For implementing the QBGA-based optimization for the problem (9), the parameters used in this paper are as follows: (i) Population size: 30; (ii) Bee structure: Binary; (iii) # Iterations: 100; (iv) $K_p, K_i, K_d \in (0,\ 10]$; and $\lambda,\ \mu \in (0, 1]$.

The tuned output values from the QBGA optimization are $K_p = 3.5$, $K_i = 6$, $K_d = 0.001$, $\lambda = 0.8$ and $\mu = 0.3$. The corresponding simulation results are as in Figure 5. The following are the significant observations and comparisons with the results using the classical PID controller:

- The error in response with drift in L not only remains small but has reduced even further; it has been contained between $\pm$ 0.1 V for $t \in [2, 3]$ s.
- The disparity in response when r_l drifts in excess of 40% of its nominal value has greatly reduced. For $t \in [2, 3]$ s, the maximum disparity in output is close to -0.96 V.
- Though the error oscillates as r_c deviates by more than 40% of its nominal value, the oscillations for $t \in [2, 3]$ s

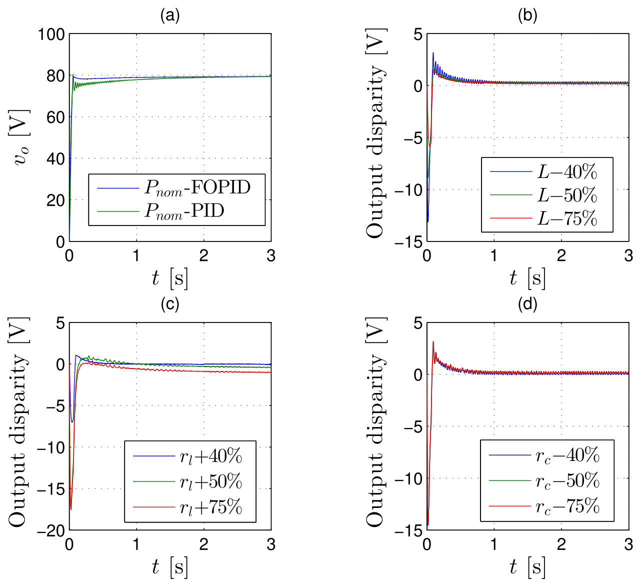

FIGURE 5. QBGA-optimized FOPID Controller: (a) Plant output with nominal parameters. (b) Output disparity with change in L. (c) Output disparity with change in r_l. (d) Output disparity with change in r_c.

are only in the positive side; more importantly, the magnitude is less than 0.27 V.

- The steady state error starts increasing whenever the load resistance falls below 70Ω and the input voltage falls below 30 V. Which is also similar to that of boost converter with PID controller.

A comparison of the maximum absolute disparities in the responses with the classical PID controller and the QBGA based FOPID controller proposed here for the interval $t \in [2, 3]$ s is provided in Figure 6. The percentage of output disparity with respect to desired output at steady state ($t \in [2, 3]$ s) for both PID and FOPID controllers are provided in Table 2. The enhancement in robustness with the present QBGA-based FOPID controller as claimed clearly stands out.

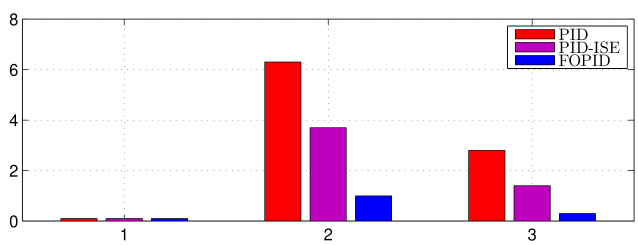

FIGURE 6. Maximum absolute disparity: PID vs. QBGA-based FOPID for $t \in [2, 3]$ s. (1): For variations in L; (2) For variations in r_l; (3) For variations in r_c.

A. NOTE ON PRACTICAL IMPLEMENTATION OF FOPID CONTROLLER

Though the FOPID controller design for the boost controller significantly improves robustness to plant parameter variations in principle, its practical implementation is saddled

TABLE 2. Percentage of output disparity during the time interval $t \in [2, 3]$ s (at steady-state) for the desired output value of 80 V.

Controller \ Plant with	$L + \Delta L$	$r_l + \Delta r_l$	$r_c + \Delta r_c$
PID Controller [3]	0.13%	7.88%	3.5%
PID Controller ISE	0.13%	4.62%	1.75%
FOPID Controller	0.13%	1.25%	0.38%

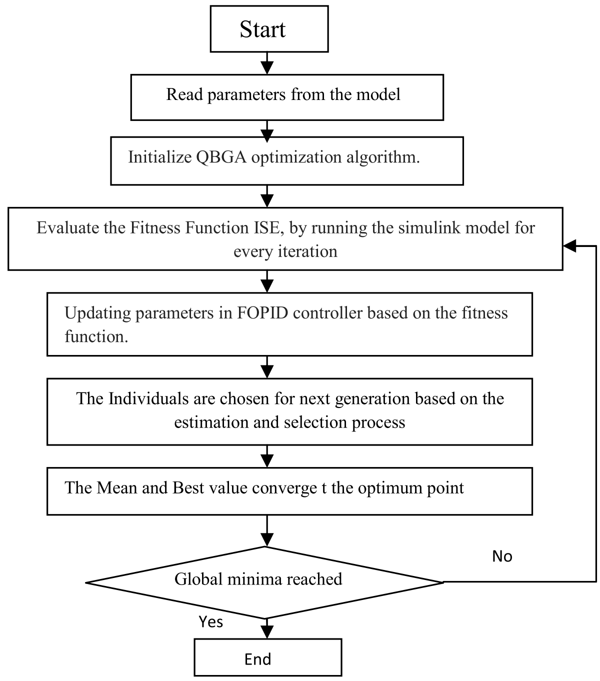

FIGURE 7. Flow chart of QBGA tuning.

with having to 'realise' the fractional order system with an approximate transfer function of high order. This is necessary to match the frequency response in the band of significance by a recursive procedure [12], [13]. In fact, the FOPID controller obtained here corresponds to a transfer function of order 23. Analog implementation of such high order systems is known to be fraught with tolerance effects of individual components. Hence implementation of discrete version of integer order approximated transfer function is necessary. That provides the direction for future work.

V. CONCLUSION

The performance of the classical PID controller for the boost converter falls short in terms of robustness to parameter variations, which are a reality. The non-minimum phase nature of the boost converter causes this infirmity. There is a need for a controller which is agnostic to the plant being minimum phase or non-minimum phase. The fractional order PID controller proposed here is based on optimal tuning of the parameters using a queen bee genetic algorithm optimization. The performance of the classical PID controller for a boost converter is compared with that of the one proposed here.

The robustness of the boost converter with this controller is demonstrated through simulations. Though this paper specifically discusses the design of a robust controller for a boost converter, the controller proposed here works equally well for buck and buck-boost converters too. Practical implementation of a FOPID controller requires a digital implementation; that suggests the vistas for the future.

APPENDIX

$$A_{ON} = \begin{bmatrix} -\frac{r_l}{L} & 0 \\ 0 & \frac{-1}{C(R_L + r_c)} \end{bmatrix}$$

$$A_{OFF} = \begin{bmatrix} -\left(\frac{r_l}{L} + \frac{R_L r_c}{L(R_L + r_c)}\right) & \frac{-R_L}{L(R_L + r_c)} \\ \frac{R_L}{C(R_L + r_c)} & \frac{-1}{C(R_L + r_c)} \end{bmatrix}$$

$$B_{ON} = B_{OFF} = \begin{bmatrix} \frac{1}{L} & 0 \end{bmatrix}^T$$

$$C_{ON} = \begin{bmatrix} 0 & \frac{R_L}{R_L + rc} \end{bmatrix}$$

$$C_{OFF} = \begin{bmatrix} \frac{R_L r_c}{R_L + r_c} & \frac{R_L}{R_L + r_c} \end{bmatrix}$$

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Prince Sultan University for paying the Article Processing Charges (APC) of this publication.

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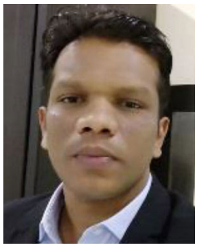

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