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doi:10.15199/48.2022.07.05

Genetic PID and Feedforward Controllers for DC-DC Chopper Converter

***Abstract**. DC voltage choppers such as buck, boost, and buck/boost are widely used in electrical power applications. Since these choppers are connected directly between DC source such as solar photovoltaic PV systems or batteries, a disturbance or dc source fluctuations may occur at the input of chopper circuits. Therefore, the control systems must be designed and developed in order to reduce such an increase or decrease in voltage. In this paper, two control strategies have been studied and analyzed to reduce system disturbance and minimize the error resulted from noise. The first strategy uses both feedback and feedforward controllers, in this strategy the controllers are designed based on linearization system. The second strategy uses genetic algorithm to tune the integrated proportional, integral, and differentiator PID feedback controller parameters directly for the nonlinear system. The results show that, the genetic PID controller has better performance than the Feedforward/Feedback controller. The mathematical model of the chopper-controlled system using both strategies and the simulation results are extracted using Matlab/Simulink 2018.*

***Streszczenie.** Przerywacze napięcia stałego, takie jak buck, boost i buck/boost, są szeroko stosowane w zastosowaniach elektroenergetycznych. Ponieważ przerywacze te są połączone bezpośrednio między źródłami prądu stałego, takimi jak fotowoltaiczne systemy fotowoltaiczne lub akumulatory, na wejściu obwodów przerywacza mogą wystąpić zakłócenia lub wahania źródła prądu stałego. Dlatego też układy sterowania muszą być projektowane i rozwijane w celu ograniczenia takiego wzrostu lub spadku napięcia. W niniejszym artykule zbadano i przeanalizowano dwie strategie sterowania w celu zmniejszenia zakłóceń systemu i zminimalizowania błędu wynikającego z hałasu. Pierwsza strategia wykorzystuje zarówno regulatory sprzężenia zwrotnego, jak i sprzężenia do przodu, w tej strategii regulatory są projektowane w oparciu o system linearyzacji. Druga strategia wykorzystuje algorytm genetyczny do dostrojenia parametrów zintegrowanego regulatora proporcjonalnego, całkowego i różniczkowego ze sprzężeniem zwrotnym PID bezpośrednio dla systemu nieliniowego. Wyniki pokazują, że genetyczny regulator PID ma lepszą wydajność niż regulator sprzężenia zwrotnego/zwrotnego. Model matematyczny systemu sterowanego chopperem wykorzystujący obie strategie i wyniki symulacji są wyodrębniane za pomocą Matlab/Simulink 2018.. (**Genetyczne regulatory PID i Feedforward dla przetwornika choppera DC-DC**)*

Keywords: DC-DC Converter; Feedfarward; Feedback; Genetic Algorithm.
Słowa kluczowe: przekształtnik DC-DC, .algorytm generyczny

1. Introduction

Nowadays, the demand for the power electronics technology has increased due to the importance of its applications in the field of Smart Grids (SG). SG is considered as the state-of-the-art technology which provides more adaptable, stable and sustainable power systems, moreover it integrates many types of power sources effectively such as; Renewable Energy Sources (RES),

Power electronic converters are divided into four types. 1) DC-AC converters: they are known as inverters. Recently, the demand on the renewable energy, such as the solar cells, has been increased. Inverters play significant role to connect between the DC renewable energy sources and the AC grid. Inverters are also widely used in the hybrid vehicle and the air conditioner. 2) AC-AC converters: they are used in speed controlling of machines. 3) AC-DC converters: they are known as rectifiers. One of the main applications for rectifiers is to drive and control speed of DC machines [2].

An example of power system application that uses all types of converters is the DC micro-grid system. The DC micro-grid can be defined as a group of electricity sources and loads within local small area, which usually located far away from cities. In general the DC load applications such as: computers, florescent lights, boilers, coffee makers, electric cookers, washing machines, TVs, radios, CD players, telephones, had experienced a significant consumer demand in the last few years worldwide [4, 5].

The DC-DC chopper plays a crucial role in regulating the DC voltage at the DC main bus. Assuring that, the output voltage remains constant at different operation conditions as possible as it can be without any perturbations. The essential components in the grid structure are shown in Figure 1

Our expectation of any system in our life is to give us a highly efficient output with specific requirements that achieves adequately the main purpose of that system. So, we can conclude that locating the dynamic output behavior is considered as a very substantial part of any system [6,7]. The controller, which is the sub part of any system, is responsible of placement the output based on the user commands. In any controlled system, we need to define the relation between the plant and the controller [8, 9].

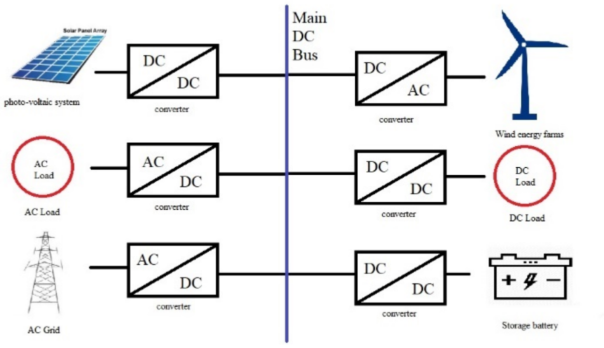

Fig. 1. Grid structure.

The feed-forward controller structure had been used to speed up the process of changing the desired value of the duty cycle and improving the tracking system [10, 11].

The direct pole placement control strategy integrated with feedforward controller was used as a solution that could eliminate steady-state errors and make it equal to zero [12-15].

The input voltage feedforward control has been applied on pulse width modulated (PWM) boost converter [16, 17]. Small signal models have been developed to demonstrate the dynamic nature of the boost converter in continues condition mode, the feed forward technique in this work helped to minify the audio susceptibility.

In [18], the peak voltage modulation feedforward control was applied on pulse width modulated buck converter. The voltage transfer function between the input and output has been derived from small signal model, which has been developed with parasitic parameters such as internal resistance for the MOSFET and the diode. The output voltage deviation has been reduced against the input voltage variation in this work. In the other hand, the feedforward in this scheme has no effective to eliminate the output deviation due to load current changes.

In [19-21], the authors introduced the voltage fluctuation issue at the output of single phase inverter due to the voltage disturbances of the coupling capacitor. The researchers showed that the fluctuation of the DC voltage will affect the input current and thus the maximum power tracking. The control strategy was compensating the voltage and the current of the capacitor bus using two Proportional Integral (PI) controllers. It was tested and verified on 3KW experimental inverter and the obtained results proved the ability of the control technique.

In [22], the researchers proposed the double closed loop control based on ADRC to reduce the generated voltage disturbances and harmonics of voltage source inverter. The adopted approach was compared to the PID control and the achieved results showed that the proposed method provided better performance compared to PID, and accordingly the authors recommended its use in grid connected application.

New upgrade of PI controller was proposed to control the island-mode single-phase inverter [23]. Posicast and repetitive controllers were added to the control loops of proportional and PI respectively. The Posicast controller was used to improve the transient response achieving few oscillations with 21% overdraft. The repetitive controller was used to enhance the disturbance and harmonics rejection achieving total harmonics distortion of 2.64%. The adopted controller was compared to the classical PI controller and the obtained results showed the supremacy of the presented controller.

In [24], the closed loop output impedance was derived by the traditional repetitive voltage and the proposed repetitive capacitor current controllers to enhance the disturbance rejection of single-phase half bridge inverter. The comparison results of the introduced controllers verified that the adopted controller scored minimum output impedance and acquired greater ability to reject the voltage disturbances.

In [25], the authors reviewed two strategies to regulate the output voltage of the grid connected inverters.

In [26-28], the author introduced a full analysis of feedback control system to assist the researchers to have exceptional understanding of various control system. Many aspects were included in the study such as; poles and zeros, Routh-Hurwitz criterion, root locus and bode plot. The mentioned aspects were applied on the proposed control system using MATLAB environment. In [29], the researchers proposed an adaptive feedforward control strategy to solve the jumping disturbance issue at the input voltage of the DC-DC boost converter. The adopted approach combined feedback and adaptive feedforward control techniques. The obtained results showed the effective performance of the explored approach.

In [30], the researchers proposed the feedforward/feedback technique to tune the classical pole placement controller for Single Input Single Output (SISO) system. The control strategy was tested on both mathematical and physical model of the plant. The results showed that the adopted approach achieved excellent responses with zero steady state error under the load variation.

In [31], the combined systems of PI DC bus voltage controller and the feed-forward compensator were presented to regulate the battery/ultra-capacitor storage system for Electric Vehicles (EV). The results showed that the merged control system has the ability to minimize the dynamic load of the vehicle battery with keeping the DC bus voltage at the desired level. Moreover, it will smooth the power transfer to EV under extremely various loads.

The authors presented in [32, 33],a feed forward compensation strategy to improve performance of dc-dc converters such as: Buck, Boost and Buck-Boost. In [34], the author proposed the feed-forward/feedback control strategy depending on the Deep Q-learning Network (DQN) for liquid level regulation under various disturbances. The adopted approach was compared with the traditional PID feedback system. The obtained results showed the supremacy of the proposed strategy.

In [35], the authors introduced a dual control method to regulate the voltage of multi-micro grid inverters. The adopted approach utilized the feed-forward/feedback control structure to enhance the transient response, to reduce the steady state error and to optimize the performance of the controller. The feedback system was converted into an optimization problem with linear objective functions. The experimental results proved the effective performance of the proposed approach in terms of voltage regulation, harmonics rejection and fault condition operation.

In [36—39], the author proposed intelligent controller to manage and predict control parameters to achieve the required tasks such as electric vehicle charging, decision making, V2V communication, and real time estimation.

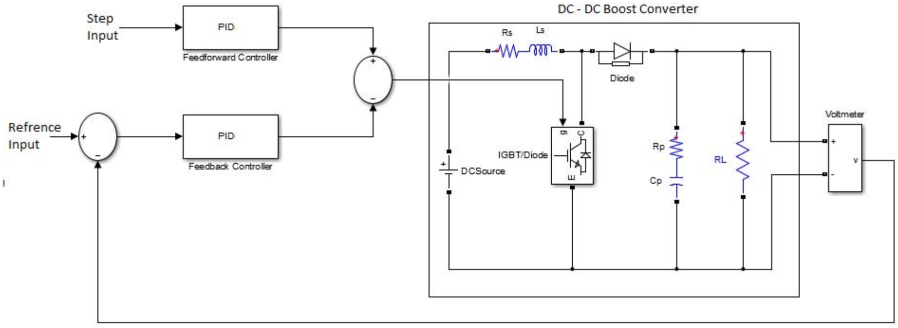

Fig. 2. Boost chopper step up circuit diagram.

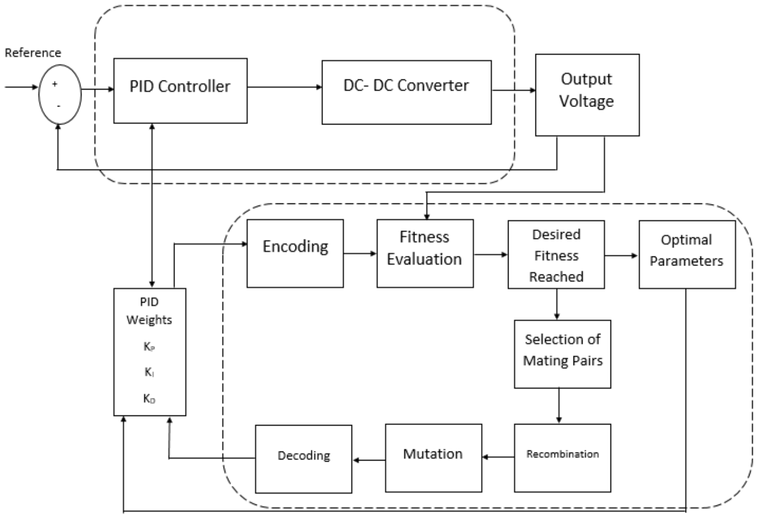

Fig. e 3. Genetic PID Model.

The Developed Methodology

2.1 Controlling the DC-DC System using Feedforward

Figure 2 below shows the boost chopper step up converter circuit diagram. According to on/off (q = 1 and q = 0) switching Pulse Width Modulation (PWM)signal the state differential equations and output equation of the circuit can be derived see [40, 41].

Feedback control system is one of the classical and important types of control in our modern era. Various research works has been undertaken on the study of feedback control systems. It's compensated for any disturbances or changes in the output of the plant, but does not react until the output changes (too late sometimes).

The feedforward control is working in different way comparing to feedback systems. It is compensated only for measured disturbances in the input variables and the knowledge of the system model is required to set the equation of the controller. The feed forward can reduce the disturbances before they affect the controlled variable.

While the feed forward control measures one or more of the process inputs, the feedback estimates the output and the error of the controlled plant. The combined control system can adjust for both inputs and the outputs of the process with delay time. In this work the feed-forward/feedback control system will be used to reduce the disturbances of the DC link at the input of the single-phase voltage source inverter.

PID controller consists of three terms; proportional to the current value of the error (P), the term which reflects the past value of the error using the integrator (I), and the estimator term of the future value of the error using the divertive (D). All PID terms can be controlled using the changeable gain (K).

$$G_C(S) = K(1 + \frac{1}{\tau_i S} + \tau_d S)$$

The boost model after combining both state space and output equations for both on/off (q = 1 with duty

cycle d and q = 0 with duty cycle 1 - d) (PWM) signals will be:

$$\dot{x} = d(A_1x + B_1u) + (1-d)(A_2x + B_2u) = F(d,x,u)y$$
$$= d(C_1x + D_1u) + (1-d)(C_2x + D_2u)$$

According to the system discussed above we have two nonlinear differential equations with two nonlinear inputs (disturbance input voltage u and duty cycle control d). So, the easiest way to control this system is to linearize the model around such point (such as equilibrium point), then apply the standard control strategies to design the controller.

Using linearization, the model of boost converter will be: In order to do that let us define the following:

- Nominal values point of (d, x, u) is $(\bar{d}, \bar{x}, \bar{u})$
- The perturbations $\tilde{d} = d - \bar{d}, \tilde{x} = x - \bar{x}, \tilde{u} = u - \bar{u}$

Find the equilibrium points of the function $\boldsymbol{F}(d,x,u)\ at\ F(\bar{d},\bar{x},\bar{u})$

$F(\bar{d},\bar{x},\bar{u}) = \bar{d}(A_1\bar{x} + B_1\bar{u}) + (1-\bar{d})(A_2\bar{x} + B_2\bar{u}) = 0$

solve for $\bar{x} = \begin{bmatrix} \bar{I}_{Lb} \\ \bar{V}_{Cb} \end{bmatrix}$ at $(\bar{d}, \bar{x}, \bar{u})$

Then the linearization model will be

$$\dot{\tilde{x}} = A\tilde{x} + B_1\tilde{d} + B_2\tilde{u}$$
$$\tilde{y} = y - \bar{y} = C\tilde{x} + \widetilde{D}_1\tilde{d} + \widetilde{D}_2\tilde{d}$$

$$A = \frac{\delta F}{\delta x} \downarrow_{(\bar{d},\bar{x},\bar{u})}$$
$$= \begin{bmatrix} \frac{-1}{L_S}\left\{R_S + \bar{d}\frac{R_P R_L}{R_L + R_P}\right\} & \frac{\bar{d}}{L_S}\left\{\frac{R_P}{R_L + R_P} - 1\right\} \\ \frac{R_L\bar{d}}{C_P(R_L + R_P)} & \frac{-1}{C_P(R_L + R_P)} \end{bmatrix}$$

$$B_1 = \frac{\delta F}{\delta d} \downarrow_{(\bar{d},\bar{x},\bar{u})} = \begin{bmatrix} \frac{1}{L_S}\left\{\bar{V}_{CP} + R_P\frac{(R_L\bar{I}_{LS} - \bar{V}_{CP})}{R_L + R_P}\right\} \\ \frac{R_L\bar{I}_{LS}}{C_P(R_L + R_P)} \end{bmatrix}$$

$$B_2 = \frac{\delta F}{\delta u} \downarrow_{(\bar{d},\bar{x},\bar{u})} = \begin{bmatrix} \frac{1}{L_S} \\ 0 \end{bmatrix} C_P = \begin{bmatrix} \bar{d}\frac{R_P R_L}{R_L + R_P} & 1 - \frac{R_P}{R_L + R_P} \end{bmatrix}$$

$$\widetilde{D}_1 = \begin{bmatrix} \bar{I}_{LS}\frac{R_P R_L}{R_L + R_P} \end{bmatrix}, \widetilde{D}_2 = [0]$$

From the above linearization system, let us define the transfer function with respect to $\tilde{\mathbf{d}}$ as **Q₁(s)** and the transfer function with respect to $\tilde{\mathbf{u}}$ as **Q₂(s).** Where

$$Q_1 = \frac{\tilde{y}(s)}{\tilde{d}(s)} = C(sI - A)^{-1}B_1 + \widetilde{D}_1$$
$$Q_2 = \frac{\tilde{y}(s)}{\tilde{u}(s)} = C(sI - A)^{-1}B_2 + \widetilde{D}_2$$

The output equation with feedforward controller is:

$$Y(s) = \frac{Q_1(s)B_c(s)}{1+Q_1(s)B_c(s)}V_{vef}(s) + \frac{Q_2(s) - Q_1(s)F_c(s)}{1+Q_1(s)B_c(s)}\tilde{U}(s)$$

2.2 Genetic PID Model

The genetic PID model is shown in Figure 3. In this model the PID controller parameters are tuned using genetic algorithm. The genetic algorithm consists of seven stages as shown in Figure 3. It starts by encoding the initial PID parameters, then new parameters are generated by mutation to select the best optimal parameters. This is done through fitness evaluation. Finally, The optimal generated parameters are decoded back to the system.

the output voltage of the DC-DC boost converter is controlled by changing the duty cycle of the switches of the converter. For optimal value of duty cycle under input disturbance and output noise of the system, the smart strategy genetic PID controller improves system performance characteristics such as overshoot, settling time, peak time, and delay time.

2. Experiments and Results

In all the experiments, the GA operates with the configuration shown in Table 1.

Table 1. GA setting

Parameter	Value
Population Size	20
Variable Range	[1, J], j is number of attributes
Maximum Generation	200
Crossover Points	2 points
Crossover Probability	0.75
Mutation Probability	0.005
Elitism	yes
Selection Method	Uniform selection

The proposed model for boost chopper controllers using both genetic PID controller and Feedforward/Feedback controller is tested under different conditions as described in the following examples.

Example 1: In this example, the following parameters of boost chopper-controlled circuit will be used, and then the disturbance in input by 20% around the equilibrium point will be applied. The parameters are $L_S = 1.5\ \mathrm{mH}$, $C_P = 30\ \mu\mathrm{F}$, $R_L = 7.2\ \Omega$, $R_P = 0.01\ \Omega$, $R_s = 0.17\ \Omega$, $\bar{d} = 0.75$.

The step input is shown in Figure 4. The dynamic response of Feedback/Feedforward can be seen in Figure 5. The dynamic response of genetic PID model can be seen in Figure 6.

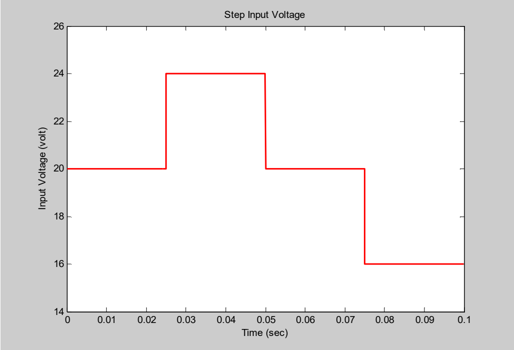

Fig. 4. Step Input Voltage.

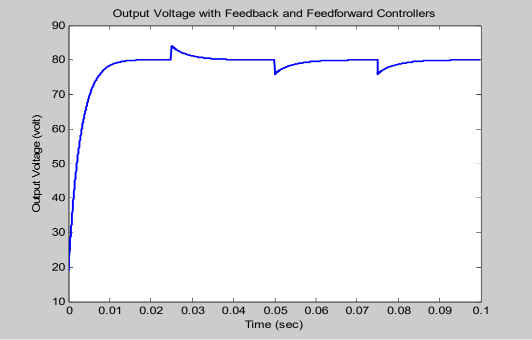

Fig. 5. The dynamic response of Feedback and Feedforward.

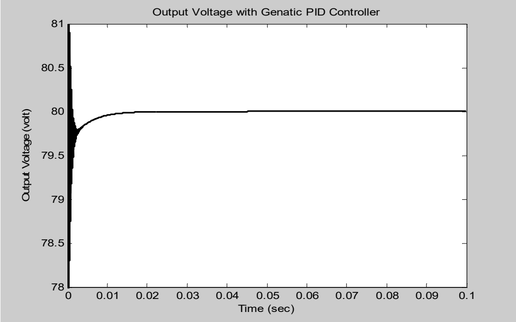

Fig. 6. The dynamic response of genetic PID model.

Figure 4 shows disturbance step input signal with ±20% fluctuation starting from 20 V to 24 at 0.025 sec, then the voltage decreases to 20 V at 0.05 sec, after that a negative fluctuation of 16 V is applied at 0.075 sec for the same duration 0.025 sec. The dynamic response for the first controller strategy Feedforward/Feedback controller is shown in Figure 5, the response shows a small overshoot less than 5% at each disturbance edge for positive and negative and settling time 0.01sec. However, the controller strategy genetic PID improves the dynamic response such that, the settling time 0.002 sec and maximum overshoot to be less than 0.05%.

Example 2: In this example, $\bar{\mathbf{d}}$ from specifications of example 1 is changed to $\bar{\mathbf{d}} = \mathbf{1/3}$. The same controllers used in example 1 will be applied. The dynamic responses for both controller strategy Feedforward/Feedback and genetic PID are shown in Figure 7 and Figure 8 respectively.

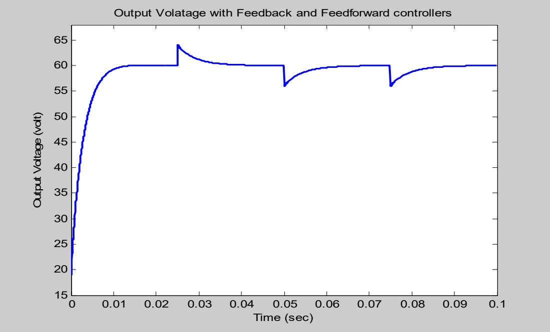

Fig. 7. The dynamic response of Feedback and Feedforward.

The dynamic responses for both controller strategies have not been changed for different duty cycle.

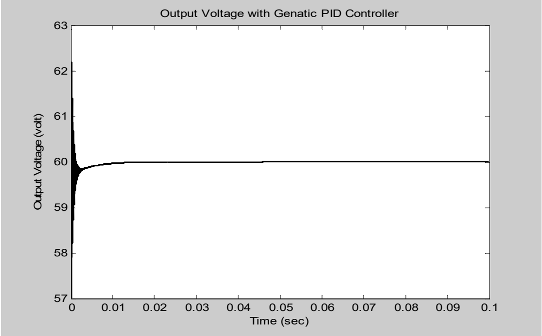

Fig. 8. The dynamic response of genetic PID model.

Example 3: In this example, the parameters from specifications of example 1 are changed as follows: L_S =15 mH, C_P = 0.1 μF, R_L=12 Ω, R_P= 0.1 Ω, R_s= 0.3 Ω, $\bar{d}$= 0.75.

The dynamic responses for genetic PID controller strategy is shown in Figure 9.

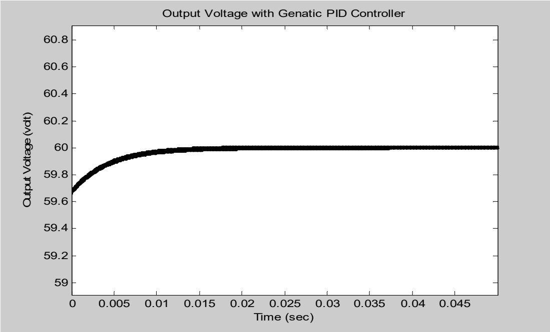

Fig. 9. The dynamic response of genetic PID model with new parameters.

Figure 9 shows that changing the parameters of the system doesn't affect the performance of genetic PID controller strategy.

Example 4:

If Less population in genetic is used compared to example 1, Figure 10 shows the resulted response with Less Population.

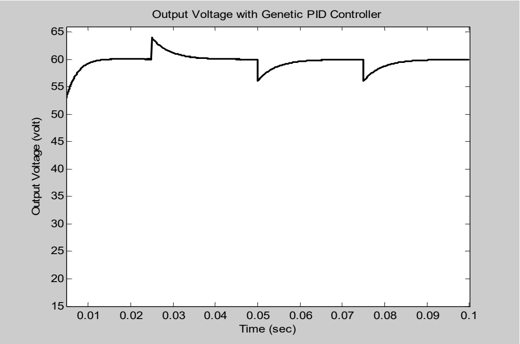

Fig. 10. The dynamic response of genetic PID model

Less population size of genetic algorithm affects the performance of the genetic PID controller and led to bad dynamic response. This emphasizes that, selecting higher population size improves the dynamic response parameter.

3. Conclusion

In this paper, two control strategies for dc chopper-controlled converter are presented. Feedback/Feedforward controller and genetic PID controller are designed to reduce disturbance and steady state error of the system. The results show that, intelligent genetic for tuning PID has better output performance characteristics under different conditions. The simulation results are taken under different scenarios to enhance system performance.

Acknowledgements

Author would like to thank Al-Ahliyya Amman University and Tafila Technical University for the support to conduct this research during aacademic sabbatical year.

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