Genetic algorithm error criteria as applied to PID controller DC-DC buck converter parameters: an investigation

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Abstract. In this paper, the PID controller parameters of a DC-DC buck converter based on error criteria extracted by means of an applied genetic algorithm (GA) are studied. The GA-PID is designed with optimal parameters by minimising integral errors, and the application of these optimal parameters reduces transient response by minimising overshoot, rise time, peak time, and steady state time during step response. The simulation testing was done in MATLAB, and the performance of the proposed GA-PID method was investigated by the simulation of two different plants. The transfer function of the third order system was initially used as a primary simulation for the proposed method, while DC-DC buck converters were used in the second simulation. The results obtained demonstrate the feasibility of employing genetic algorithms to generate optimal parameters for PID controllers for the further development of DC-DC buck converters.

1. Introduction

In various power electronic applications, DC-DC converters are required to generate variable-voltage DC sources from constant voltage DC sources [1]. The advantages of DC-DC converters, including high efficiency, small size, and simple structure, have led to such converters becoming very popular in modern renewable energy and automatic control systems [2-4]. Conventional PID controllers obtain higher performance in the control systems of DC-DC converters through the optimisation of Proportional, Integral, and Derivative values [5]. Managing the transient response of a control system through the application of a PID controller achieves a reduction in the overshoot and the settling time of the system [6, 7]. Moreover, PID controllers are low cost. However, conventional PID controllers offer poor performance during changes of operating points and large load variations, and thus, improvements in this regard is an active area of research [8-10]. Alternative unconventional control techniques are also sometimes used, such as adaptive PID controllers [11], auto-tuning PID controllers [12], PID fuzzy logics [13], PID neural networks [14], and PID genetic algorithms [15]. These smart technologies institute industrial application based on optimal control processes utilise several very important aspects; however, they are not generally easily applied [16-18].

A common feature in many current research activities is the search for a method to apply genetic algorithms to improve the performance of PI controllers and PID controllers in DC-DC converters. Researchers have thus introduced several different methodologies for improving PID controller systems. Bensaadaand developed a new approach to designing sliding mode controllers for buck converters based on genetic algorithms, and the simulation results showed that the new method of
sliding mode control achieved better responses based on output level during load changes [19]. Sundareswaran et al. also proposed a feedback controller method for DC-DC boost converters based on advanced algorithms designed to study the optimisation problem and amend controller parameters on the feedback controller to achieve output voltage regulation [20]. Yuan et al. developed a fuzzy PID controller that employed a genetic algorithm optimisation scheme for buck converters, improving dynamic performance by adjusting the variables of the PID controller to more accurately detect the output voltage level [21]. Abderrezek et al. introduced adaptive terminal synergetic control (ATSYC) as a new control system for DC-DC buck converters, with Genetic Algorithms and Particle Swarm Optimisation algorithms proposed to optimise the controller variables using the Integral Time Absolute Error (ITAE) criterion; the results of their simulation study of buck converters indicated the achievement of an overall implementation of stability as promised through Lyapunov synthesis [23]. Thus, several control optimisation techniques have been proposed to increase the stability and fast transient response of PID controllers, including Fuzzy Logic Controllers (FCL), Artificial Neural Networks (ANN), Particle Swarm Optimisation (PSO), Bacterial Foraging Optimisation (BFO), and Genetic Algorithms (GA) [24].

The objective of this paper is thus to provide a genetic algorithm based PID controller for DC-DC buck converters. Genetic Algorithms are used to improve and evaluate the performance of PID controllers as applied to DC-DC buck converters based on Integral Sum Error (ISE), Integral Absolute Error (IAE), Integral time Absolute Error (IATE), and Mean Square Error (MSE) error criteria. A simple and computationally efficient genetic algorithm is thus employed for the DC-DC buck converter based on the PID controller. Section two presents the DC-DC buck converter model, while section three describes the PID controller. Section four then discusses the requisite genetic algorithm so that section five can offer and discuss the results of testing in more depth. Finally, an evaluation of the GA procedure used in system assessment is offered.

2. DC-DC BUCK CONVERTER MODEL

A buck converter is a category of DC-DC converter that reduces a high voltage level to low voltage level [25]. The conventional buck converter operates by periodically flipping an electronic switch ON and OFF at a rate controlled by varying the duty cycle of the main switches. Such converters basically contain a diode, a transistor, an inductor, a capacitor, and a resistor. The circuit diagram of a basic buck converter is presented in figure 1. This buck converter is composed of a DC input voltage source (V_i), controlled switch (S), diode (D), energy storage element inductor (L), filter capacitor (C), and load resistance (R).

![Figure 1. DC-DC buck converter](image)
which goes through the diode and then through a parallel combination of capacitor and load, such that the capacitor provides energy to the load as explained in figure 2b, these operations deliver high power with low losses in a DC-DC buck converter [9, 10].

![Figure 2. Effects of different switching under dynamic conditions.](image)

The dynamic equations of the buck converter are obtained as follows:

\[
\frac{di_L}{dt} = \frac{1}{L} (\delta V_i - v_o)
\]

\[
\frac{dV_c}{dt} = \frac{1}{C} (i_L - \frac{v_o}{R})
\]

where \( V_i \) is input voltage, \( V_o \) is output voltage, \( t_{on} \) is the ON period, \( t_{off} \) is the OFF period, \( T \) is the switching period and \( \delta \) is the duty cycle.

The best method of ac equivalent circuit modelling for a DC-DC buck converter is state space averaged modelling, which ensures a desired performance objective and provides an accurate model [7, 25]. The state space equations for a DC-DC buck converter during one switch cycle are given by [4, 10]

\[
\begin{bmatrix}
\frac{dL}{dt} \\
\frac{V_o}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & -1/L \\
1/C - 1/RC
\end{bmatrix}
\begin{bmatrix}
i_L \\
v_o
\end{bmatrix} +
\begin{bmatrix}
-1/L \\
0
\end{bmatrix} V_i
\]

The transfer function for a DC-DC buck converter is thus

\[
\frac{V_o(s)}{D(s)} = \frac{(V_i/LC)}{s^2 + \frac{1}{RC} + \frac{1}{LC}}
\]

3. PID Controller

A PID controller is a commonly used control feedback loop mechanism, and these have been applied for decades in industrial control systems [6]. A PID controller tunes controller parameters to emphasise control performance toward zero error \( e(t) \) between desired set-point output and system variables [7]. PID controller parameters are thus the proportional \( (P) \), integral \( (I) \), and derivative \( (D) \) controls, and a PID controller can be parameterised either as in equation 5 or equation 6.

\[
g_c(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}
\]

\[
G_c(s) = K_p + \frac{K_i}{s} + sK_d
\]

where \( k_p \) is proportional gain; \( k_i \) is integral time; \( k_d \) is derivative time; \( G_c(t) \) is the input signal to the plant model; \( e(t) \) is the error signal, defined as \( e(t) = r(t) - y(t) \); and \( r(t) \) is the reference signal input, as seen in figure 3.
In order to achieve acceptable performance, the tuning of the PID controller includes setting the weighted sum of the proportional, integral, and derivative parameters to develop an optimal tuning constant. This setting process is known as tuning the controller [10], and a conventional PID controller does not have an auto-tuning algorithm, as these do not provide accurate control for industrial applications; such systems are tuned using trial and error methods [11,12]. The Ziegler-Nichols open-loop approach for tuning controllers that use proportional, integral, and derivative values has been a common technique since 1940s; however, this approach involves intense manual calculation [18]. Optimisation of PID control with computer software programs now, however, provides an acceptable degree of minimum error and stability.

4. Genetic algorithms

Genetic algorithms (GAs) are efficient tools that were first proposed by John Holland at the University of Michigan in 1970 [26]. GAs are evolutionary computational techniques that differ from other evolutionary computation algorithms, such as the PSO or WCA, due to their selection of an optimal solution in the solution space. GAs start from groups of points, rather than a single point, and are used for solving optimisation problems based on the principles of genetics and natural selection. GAs’ simplicity and robustness in process control systems arise from their parallel, stochastic, and global search methods. GAs can handle a population composed of many individuals based on a random initialised population to get the best possible solution. This solution is represented through creating a chromosome that evolves over generations and under specified selection rules to reach a state that maximises fitness. The basic genetic algorithm procedures are thus

i) Optimisation of the fitness function

ii) Chromosomes population

iii) Selection of chromosomes.

iv) Crossovers to produce the next generation.

v) Random mutation of chromosomes.

The basic components of all genetic algorithms are presented in figure 4 [27].

Figure 3. System controlled by a PID
Figure 4. The basic components of genetic algorithms.

In modern control systems, performance index criteria have motivated the development of genetic algorithms in the quantification of systems performance by error and time. Integral Absolute Error (IAE), Integral time Absolute Error (IATE), Integral Sum Error (ISE), and Mean Square Error (MSE) are the four indices used for the designed PID controller to depict system performance in this work [28]. The objectives of these indices in a GA-PID based tuning are to estimate PID parameters that minimise overshoot time, settling time, steady state error, and referenced tracking error.

The design of a GA based on a PID controller for a DC-DC buck converter using various fitness functions aims to achieve a good system response and to find the optimal parameters $kp$, $ki$, and $kd$ in order to minimise the cost function as shown in figure 5. The first step in generating such a GA is to create the random initial population and check if it satisfies the requirement; a new population is then generated every time the initial population does not satisfy the requirement by crossing over the previous population. The output performance of the optimised controller is then compared with respect to the required steady state error. In the current design, the fourth objective indices reused.
5. Results and discussion

The performance of a PID-GA for a DC-DC buck converter was investigated by analysing and simulating maximum overshoot, rise time, peak time, and steady state time based on ISE, IAE, IATE, and MSE Criteria. Simulation of the results was done via MATLAB, and simulation with two different plants was performed to evaluate the tuning procedure. Equation7 shows a transfer function of the third order system initially used as a primary simulation for the proposed method. The proposed method then used closed loop data to determine the PID controller parameters.

$$\frac{V_o(s)}{D(s)} = \frac{7.95 \times 10^5}{s^3 + 5.5 \times 10^3 s^2 + 6.587 \times 10^4 s + 1000}$$  \hspace{1cm} (7)$$

The responses for output offered by the transfer function with and without PID-GA are shown in figure 6. The performance indices of the PID controllers were compared based on the minimum error integral criteria by calculation of the PID control parameters ($K_p$, $K_i$, $K_d$), maximum overshoot, rise time, peak time, and steady state time, as shown in table 1. The results demonstrate that, for the third order system without any controller, an overshoot of 16.25%, a $tr$ of 0.166 sec, a $tp$ of 0.298 sec and a $ts$ of 0.956 sec are recorded. Introducing PID-GA to the third order system demonstrated an overshoot of 0.91%, a $tr$ of 0.081, a $tp$ of 0.094 sec and a $ts$ of 0.131 sec with respect to MSE criteria.

Figure 5. GA-PID controller design

Figure 6. Step response of the transfer function with and without GA-PID controller for MSE
Table 1. Results of the PID controller parameters, overshoot, rise time, peak time and steady state time for the transfer functions using GA.

|       | ISE   | IAE   | IATE  | MSE   |
|-------|-------|-------|-------|-------|
| $K_p$ | 112.1957 | 299.7125 | 297.6205 | 287.2683 |
| $K_i$ | 82.7567  | 0.4341 | 3.1093 | 0.1725 |
| $K_d$ | 55.0335 | 21.1932 | 3.6813 | 19.6153 |

Overshoot: 1.41, 1.21, 1.19, 0.91
$t_r$: 0.138, 0.082, 0.072, 0.081
$t_p$: 0.195, 0.121, 0.113, 0.094
$t_s$: 0.328, 0.145, 0.134, 0.131

Table 2 shows the DC-DC buck converters’ parameters in the second simulation. The response for the output offered by the DC–DC buck converter with and without PID-GA can be seen in figure 7. Overshoot for the DC-DC buck converter without any controller is 0, $t_r$ is 0.177, $t_p$ is 0.417, and $t_s$ is 0.483 sec, while for DC-DC buck converters with applied PID-GA, overshoot is 1.12, $t_r$ is 0.072 sec, $t_p$ is 0.082 sec, and $t_s$ is 0.123 sec. Table 3 shows the calculated PID control parameters, overshoot, $t_r$, $t_p$, and $t_s$.

Table 2. Parameters of the DC–DC buck converter

| Samples | $V_i$ | $L$   | $C$   | $R$   | $V_o$ |
|---------|-------|-------|-------|-------|-------|
| Values  | 50 V  | 0.48 mH | 1.5 mF | 11.8 Ω | 25 V  |

Figure 7. Step response of DC-DC buck converter with and without GA-PID controller for MSE error.
Table 3. Results of PID controller parameters, overshoot, rise time, peak time, and steady state time for DC-DC buck converter using GA.

|       | ISE    | IAE    | IATE   | MSE    |
|-------|--------|--------|--------|--------|
| $K_p$ | 41.19   | 299.58 | 299.71 | 299.18 |
| $K_i$ | 96.33   | 6.36   | 0.82   | 2.27   |
| $K_d$ | 7.03    | 2.00   | 3.72   | 4.12   |
| Overshoot | 0      | 0.97   | 1.23   | 1.12   |
| $t_r$ | 0.13    | 0.83   | 0.07   | 0.07   |
| $t_p$ | 0.15    | 0.11   | 0.09   | 0.08   |
| $t_s$ | 0.27    | 0.13   | 0.13   | 0.12   |

6. Conclusions

In this paper, GA-PID controllers were designed and simulated for a DC-DC buck converter to achieve optimal controller parameters $K_p$, $K_d$, and $K_i$, and to improve system responses such as overshoot, rise time, peak time, and steady state time. The advantages of genetic algorithms are simplicity and robustness, derived from their parallel, stochastic, and global search methods. Further advantages of genetic algorithms arise from their ability to adapt to changes in operating points. GA-PID controllers were simulated with MATLAB, and the GA optimisation method used to optimise the membership function and gains of the associated PID controller. The performance of the GA-PID in a DC-DC buck converter was investigated by simulating and analysing maximum overshoot, peak time, and steady state time based on ISE, IAE, IATE and MSE Criteria. The simulation results showed better results with the new membership functions.
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