Application of an Intelligent Self-Tuning Fuzzy PID Controller on DC-DC Buck Converter

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Abstract

This paper presents a development of a self-tuning fuzzy PID controller to overcome the appearance of nonlinearities and uncertainties in the system. The self-tuning fuzzy PID controller is the combination of a classical PID and fuzzy controller. The controller is designed based on the expert knowledge of the system. Fuzzy logic is used to tune each parameter of PID controller. Appropriate fuzzy rules are designed to tune the parameter K_p, K_i and K_d of the PID controller, the performance of the buck converter has improved significantly compare to conventional PID controller.

Keywords: *Buck converter, DC-DC converter, Fuzzy controller, PID controller*

1. Introduction

Design and implementation of a control system require the use of efficient techniques that provide simple and practical solution in order to fulfill the performance requirement despite the system disturbances and uncertainties [1]. The occurrence of nonlinear phenomena in DC-DC power converter makes their analysis and control difficult [2]. Classical linear techniques have stability limitations around the operating points. Hence digital and nonlinear stabilizing control methods must be applied to ensure large-signal stability [3].

Fuzzy system can be considered a type of nonlinear function interpolator which was introduced for controlling variable structure systems [3]. Its major advantages are the guaranteed stability and the robustness against parameter, line and load uncertainties. Moreover, being a controller that has a high degree of flexibility in its design choices, the fuzzy controller is relatively easy to implement as compared with other type of nonlinear controllers. Such properties make it highly suitable for control application in nonlinear system such as DC-DC converter.

However, despite being a popular research subject, fuzzy control is still rarely applied in practical DC-DC converters. There are various reason accommodating this, first, unlike PWM controllers, fuzzy controllers are not available in integrated-circuit (IC) forms for power-electronic applications. Second, there is lack of understanding in their design principle by power-supply engineers. No systematic procedure is available for the design of fuzzy controllers. Third, there is strong reluctance to the employment of fuzzy controllers in DC-DC converters because of their inherently high and variable switching frequency, which causes excessive power losses, electromagnetic interference generation, and filter design complication. Fourth, all discussion regarding the usefulness and advantages of fuzzy controllers have been theoretical. The practical worthiness of using fuzzy controllers is generally unproven. In essence, fuzzy controllers are not used in practical DC-DC converter because of the inconvenience of using them, as well as the lack of strong evidence to support the need for using them. These explain why the application of fuzzy controllers in DC-DC converters has only been of academic interest but of little industrial value. Specially, as the theoretical groundwork of fuzzy controller is fairly matured, it is timely to direct more research efforts toward developing practical fuzzy controllers for DC-DC converters. This will enable the industry to truly benefit from the advantages of designing power supplies based on the fuzzy paradigm.

The intent of this study is to design a self-tuning fuzzy PID controller so that a further improved system response performance in both the transient and steady states have been achieved as compared to the system response obtained when either the classical PID or the fuzzy controller has been implemented. Here the fuzzy controller is used to tune the parameter K_p, K_i and K_d of the PID controller. Simulations are performed on Matlab Simulink to illustrate the efficiency of the proposed method.

2. Simulated Model of Buck Converter

Simulated model of buck converter using Matlab Simulink is shown in Figure 1. It consist of 12 V input DC supply, GTO (gate turn on thyristor) as a switch, PWM (Pulse width modulator) generator for providing switching pulses to GTO. The capacitance C is 220 μF, L is 20 μH and R_L is 2 Ω. The parasitic elements RC and RL are estimated to be 30 mΩ and 10 mΩ, respectively [4]. The desired output from this converter is 2 V DC.

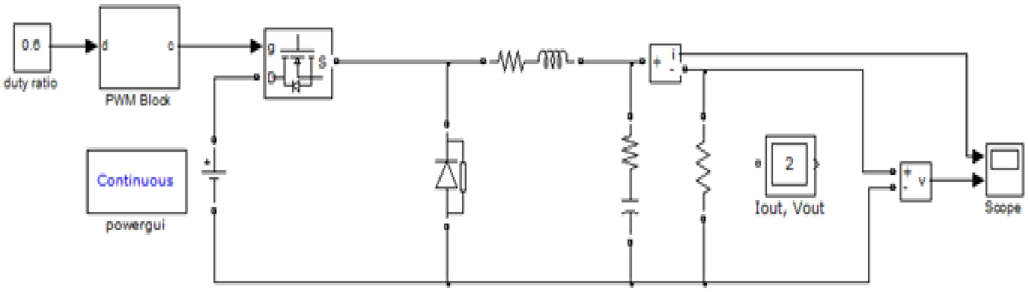

Figure 1. Simulink Model of Buck Converter

3. Overview of Fuzzy PID Controller

Fuzzy PID controllers in literature can be classified into three major categories as direct action type, fuzzy gain scheduling type, and hybrid type fuzzy PID controllers [5]. The direct action type can also be classified into three categories according to number of inputs as single input, double input, and triple input direct action fuzzy PID controllers. The classification of fuzzy PID controllers can be seen in Figure 2.

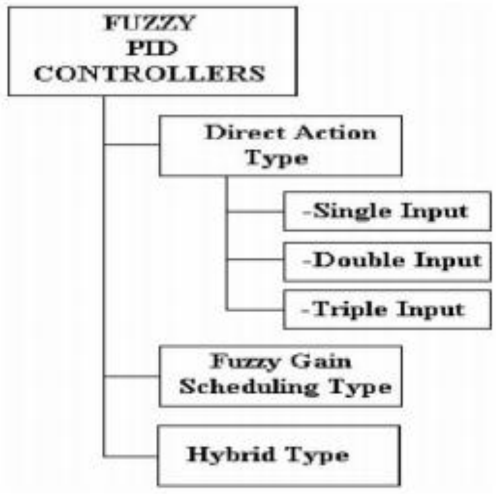

Figure 2. Classification of fuzzy PID controller

4. Single Input Fuzzy PID Controller

This structure uses error as the only input and has a one dimensional rule-base. As it is seen in Figure 3, it is simply a nonlinear mapping of error into fuzzy proportional action cascaded to a conventional PID controller.

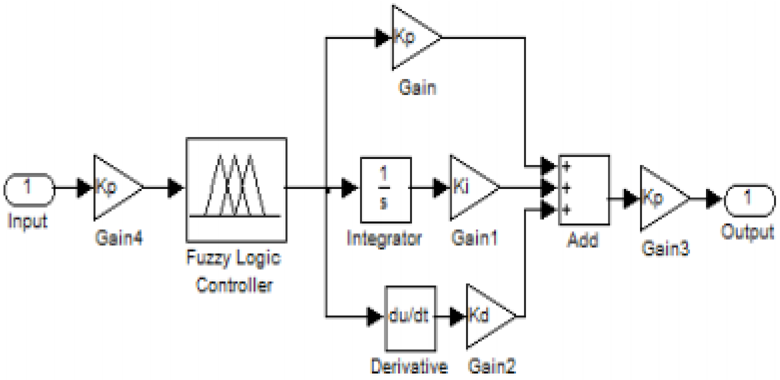

Figure 3. Single Input Fuzzy PID Controller

5. Proposed Self Tunning Fuzzy PID Controller

The proposed controller that is given in Figure 4 is the modified version of the single input fuzzy PID controller. It possesses two main parts: the classical PID and fuzzy controllers. A standard PID controller is also known as the “three-term” controller, whose transfer function is generally written in the “ideal form” as

$$C(S) = K_p + \frac{K_i}{S} + K_d S$$

Where K_p is the proportional gain, K_i the integral gain, K_d the derivative gain. The ‘’three-terms’’ functionality are highlighted by the following;

1) The proportional term is providing an overall control action proportional to the error signal through the all-pass gain factor

2) The integral term is reducing steady-state errors through low-frequency compensation by an integrator
3) The derivative term is improving transient response through high-frequency compensation

In this paper the fuzzy controller will be used to tune the parameter K_p, K_i and K_d of the PID controller, based on certain function of the actuating error signal.

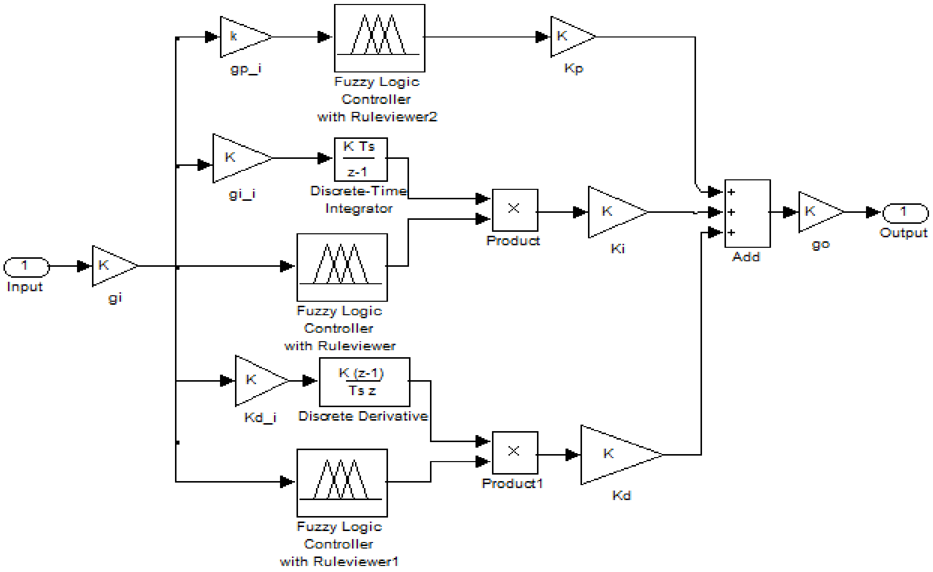

Figure 4. Simulink Model of Self-tuning FPID Controller

6. Controller Development

In this section a self-tuning fuzzy PID controller is developed. The FPID controller consists of three parallel fuzzy sub controllers, namely, fuzzy-based proportional, integral, and derivative controllers. These independent controllers are grouped together to form an intelligent self-tuning fuzzy PID controller. The FPID controller can account for nonlinearity and adaptable to varying operating condition.

6.1 Input Scaling

Since the inference procedure is designed to only operate within the bounds [-1, 1] the input into the fuzzy logic controller is bounded within the universe of discourse between [-1, 1]. The input to the fuzzy controller is directly connected to the output of the ADC. Therefore the input gain gi, should be selected such that $V_{OADC} g_i \in [-1, 1]$.

6.2 Control Gain Coefficient

At the first stage of designing process, discrete model of the conventional PID controller is obtained. Then FPID controller, as shown in Figure 4, is obtained which has six tuning control parameters: $g_{ip,}$ g_{ii}, g_{id}, K_p, K_i, and K_d. In order to simplify the calculations $g_{ip,}$=1 and g_{ii}= g_{id},=T can be considered [6]. A Ziegler-Nichols method is used to determine the initial values of Kp, K_i, K_d for a specific set point.

Since the performance of FPID controller depends on the gains coefficients, it is obvious that the optimization of these parameters will lead to better performance at a particular set point [7].

6.3 Fuzzy-Based Proportional Controller

The first step in designing the controller is to decide which state variables of the system can be taken as the input signal to the controller. The output voltage error e(k) is used as the input to the controller. The output of the fuzzy-based proportional controller is the gain K_p. The universe of discourse of interval spanned by the input variable is partitioned into seven fuzzy subsets of Gaussian shaped membership functions assigning each subset a linguistic value; the various subset are presented as NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big) respectively. The main advantage to employ Gaussian function is that its continuity is usually required for most of conventional gradient-based, either first or second order optimization technique [9].

The second step in the design of the fuzzy sub controller is the determination of the fuzzy IF-THEN inference rules. The number of fuzzy rules that are required is equal to the number of fuzzy sets of the input variable. Thus, a total of seven fuzzy rules are required to relate each possible combination of the input variable to the output membership fuzzy sets. A typical rule can be written as follow. IF e(k) is NB THEN K_p is NB.
The derivation of the fuzzy control rules is heuristic in nature and based on the following criteria [10]:

1) When the output of the converter is far from set point, the change of K_p must be large so as to bring the output to the set point quickly.
2) When the output of the converter is approaching the set point, a small change of K_P is necessary.
3) When the output of the converter is near the set point and is approaching it rapidly, the K_p must be kept constant so as to prevent overshoot.
4) When the set point is reached and the output is still changing, the K_p must be changed a little bit to prevent the output from moving away.
5) When the set point is reached and the output is steady, the K_p remains unchanged.
6) When the output is above the set point, the sign of the change of K_p must be negative, and vice versa.

The next step in the design of the fuzzy sub controller is inference mechanism. The results of the inference mechanism include the weight factor W_I and the change in K_p ci of the individual rule. The weight factor W_I is obtained by Mamdani's min fuzzy implication of μe (e[k]), μe is the membership degrees [9]. Control C_I is taken from the rule base. The change in K_p inferred by the Z_I= Wi * C_I is given by

$$\min \{ \mu_e (e[k])\} * C_i$$

The last step in the design of the fuzzy sub controller is the defuzzification process. The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output obtained is also aggregated fuzzy output. But generally, it is required that the output be a single crisp number. As the aggregated fuzzy set encompasses a range of output values, it must be defuzzified in order to resolve to a single crisp output value from the set. The center of average method is used to obtain the fuzzy controller's output for the control of buck converter.

6.4 Fuzzy based Integral Controller

The same technique applied to the fuzzy-based proportional controller is applied to the fuzzy-based integral controller. The controller has single input the output voltage error e(k). The output of the fuzzy-based integral controller is the gain K_i. Seven fuzzy sets are defined for the fuzzy linguistic variable e(k). After specifying the fuzzy sets of the fuzzy variable, the membership function for these sets are derived. The membership functions are composed of the same fuzzy Gaussian membership functions allocated for the fuzzy based proportional controller. Similarly, the number of fuzzy rules that are required is equal to the number of fuzzy sets that the input variable makes. Therefore, a total of seven fuzzy rules are introduced. The same Mamdani's min fuzzy implication of μ_e (e[k]) is used for the inference mechanism. For the defuzzification process the center of average method is used to obtain the fuzzy controller's output for the control of buck converter.

6.5 Fuzzy-based Derivative Controller

The same process applied to fuzzy-based proportional and integral controller is applied to the fuzzy-based derivative controller. The input signal to the controller is the error signal e(k). The output of the controller is the gain $K_{d.}$ Seven fuzzy sets are defined for the fuzzy linguistic variable e(k). The same fuzzy Gaussian membership functions allocated for the fuzzy based proportional and integral controller are used for these fuzzy sets.

6.6 Output Scaling

Output scaling allows the output of the FPID controller to be adjusted so it has the appropriate amplitude when applied to the DPWM of the buck converter. The FPID controller output is bounded in the universe of discourse between [-1, 1]. The change in duty cycle control ratio of the DPWM is bounded between [-D, 1-D], therefore the output gain must be selected such that $V_{oFPID}g_o \epsilon$ [-D, 1-D], since $V_{oFPID}=a$, it is already bounded between [-D, 1-D] and $g_0=1$.

7. Simulation Results

Simulation results of buck converter are presented in this section. The Matlab Simulink is used to test the transient and steady-state response of the system to various disturbances from the source and load side. The simulation results are used to compare the open-loop response of the system with the compensated closed-loop response of the system.

7.1 Response to 12 V DC Power Source

The response of the open-loop system and the system compensated by a fuzzy logic PID controller for a 12 V DC power source can be seen in Figure 5. Both responses have zero steady-state error since the initial condition of the duty-cycle, D is 0.2891, is chosen so that is met. The open-loop response has a maximum overshoot of 70 percent while the closed-loop response has a maximum overshoot of 6.5 percent. In addition, the settling time has been reduced from 2.75 msec to 1.10 msec. However, the rise time has been increased from 0.2 msec to 0.6 msec.

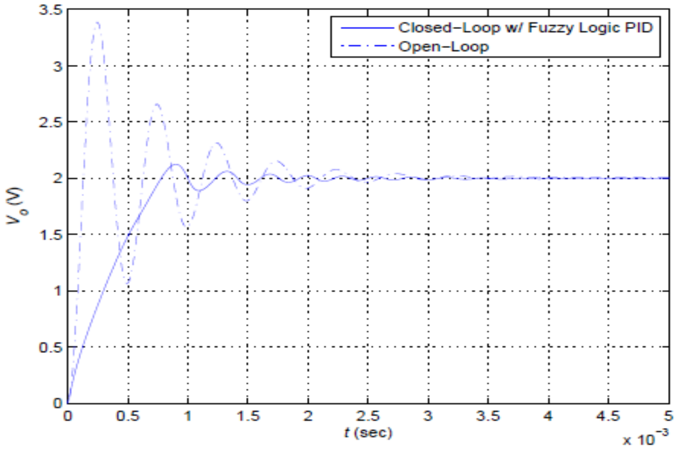

Figure 5. Time Response of Open-loop and Closed-loop System to 12 V DC Power Source

7.2 Response to 1 V Step Change in Power Source

The time response of the open-loop and closed-loop system compensated by a fuzzy logic PID controller for a 1 V step change in the source can be seen in Figure 6. The figure shows that the steady-state error improves from 8 percent to less than 1 percent for the simulation. The steady-state error of the compensated system eventually decreases to zero because of the integral action. In addition, the maximum overshoot improves from 6 percent to less than 1 percent.

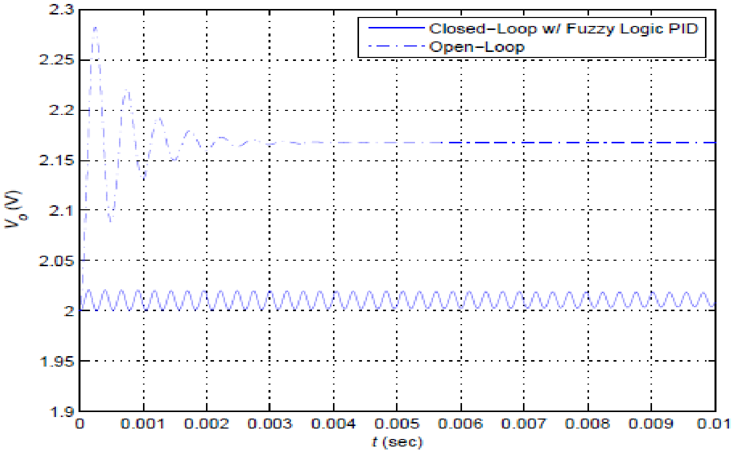

Figure 6. Time Response of Open-loop and Closed-loop System to 1 v Step Change in Power Source

7.3 Response to 1 A step Change in Load Current

The time response of the open-loop and closed-loop system compensated by a fuzzy logic PID controller to 1 A step change in the load can be seen in Figure 7. It can be seen from this figure that the steady-state error decreases from 1 percent to zero. In addition, the maximum undershoot improves from 12 percent to 3 percent and the maximum overshoot improves from 7 percent to 2 percent.

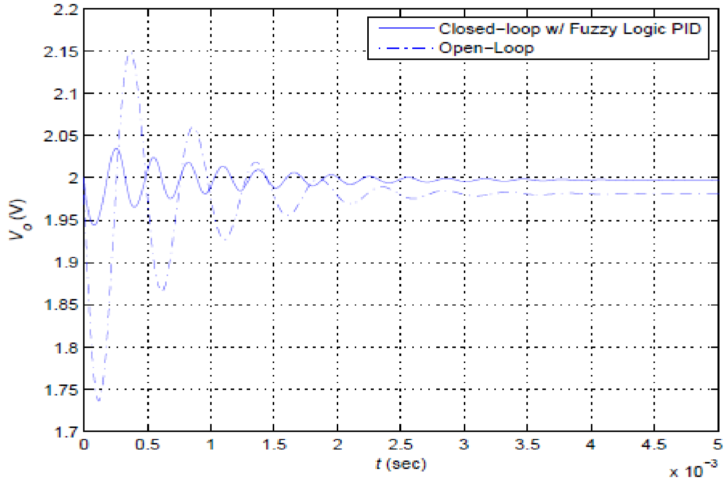

Figure 7. Time Response of Open-loop and Closed-loop System to 1 A Step Change in Load Current

8. Conclusion

One advanced control scheme which can be implemented with microcontrollers is fuzzy logic PID control. Fuzzy logic PID control is a nonlinear control scheme with piecewise linear proportional, integral, and derivative gain to control the duty cycle of the system. Control of the duty cycle, in turn, controls the output voltage of the system. The fuzzy logic controller is designed to implement proportional, integral, and derivative gain when they are appropriate to reduce the error signal of the system. The time-domain response of the closed-loop system with FPID controller is improved with respect to the closed-loop system with PID and fuzzy controller. The overall speed of the system is also increased, as seen by the decrease of the settling time when the converter is connected to the power source.

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