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Oral Presentation

Robust Control of Buck Converter Using PI-Fuzzy Controller

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Abstract

DC-DC converters are widely used in today's world due to their various qualities such as high power density, good response speed, a wide range of output voltage, variable input voltage and a constant output load. It is possible to find numerous types of DC-DC converter topologies. Converter types are classified by their circuit functions based on their input-output voltage levels. Basic DC-DC converter structures are buck, boost and buck-boost converters. Unlike linear circuit topologies, modelling of DC-DC converter circuits are very difficult because of their switched structure. Conventional control systems remain insufficient to control non-linear systems. Fuzzy logic is an alternative approach among non-linear control systems. Fuzzy logic controllers with non-linear conversion functions can successfully control such systems. The performance of these controllers can be improved thanks to the methods used during the design process. In this study, a fuzzy logic based hybrid control topology using conventional PI control was designed for the robust control of a buck type DC-DC converter.
The designed control system was simulated by Matlab/Simulink program. Input voltage, output load and voltage reference of the buck type DC-DC converter were changed to analyze the dynamic performance and robustness of the control system.

Keywords: *Robust Control, Buck Converter, PI-Fuzzy Controller*

1.Introduction

With the developing technology, the requirements for different forms of electrical energy is increasing day by day. Many converters have been developed in parallel with the developments in the field power electronics. DC-DC converters are widely used in various industrial applications to convert DC voltage applied at the input to another DC voltage at a different level (Wu ve ark., 2015 ; Prabhala V.A.K ve ark., 2016 ; Zhang ve ark., 2015). Buck type DC-DC converter is a power electronics circuit that converts input voltage level into a voltage level lower than the input voltage level (Hua ve ark., 1994 ; Calderon ve ark., 2006). Numerous studies focusing on the control of buck type DC-DC converter using different types of controllers can be found in the literature. have been applied to fuzzy logic based control, which is one of the modern control techniques for buck type converters (Yazici ve ark., 2016 ; Singh ve ark., 2015). In this study, a buck converter circuit model was first designed at continuous current mode, and it was analyzed based on switching conditions. Then, a PI-fuzzy controller was designed for the buck type converter, and simulation studies were realized at Matlab/Simulink.

2. Circuit Analysis of Buck DC-DC Converter

The structure of a simplified buck type DC-DC converter is shown in Fig. 1. There are two power switching elements in this circuit as controlled (S) and uncontrolled (D). When S switch is off, the diode is open circuit, and S switch is on, the diode is short circuit (Mohan ve ark., 2002).

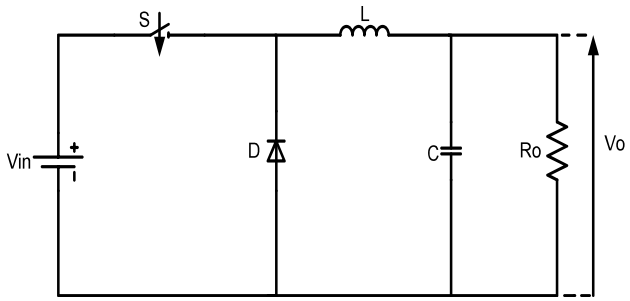


Fig. 1. Buck type DC-DC Converter Circuit

The buck type converter circuit shown in Fig.1 generates a lower average output voltage than the input voltage. Within a certain period, the lower DC voltage than the input voltage is obtained from the semiconductor switch conditions. LC filter is located at the circuit output. While inductance is used to reduce the ripple in the load current, the capacitor is used to reduce the ripple in the converter output voltage. When the switch is on, the inductance feeds the load. Meanwhile, energy is stored on the inductance. When the switch is off, the diode is short circuit. Thus, the energy stored on the inductance is spent on the load. The capacitor at the output of circuit tries to maintain a constant output voltage during the period when the switch is off (Ozdemir ve ark., 2018).The circuit structure for an ideal buck DC-DC converter when S switch is on in Fig. 2.

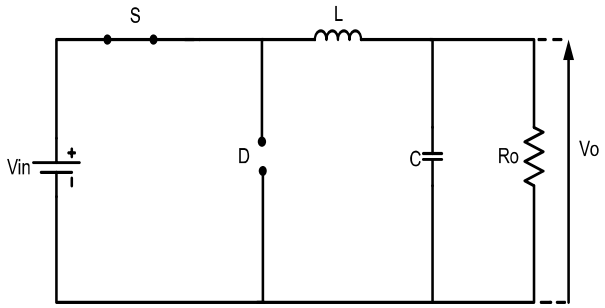


Fig. 2. Converter circuit when S is on.

When S is on, the equations defining the dynamic behavior of the circuit are given in Eqs. 1 and 2.

$$\frac{di_L}{dt} = \frac{V_{in} - V_o}{L} \quad (1)$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{RC} \quad (2)$$

The circuit structure for an ideal buck type DC-DC converter when S switch is off in Fig. 3.

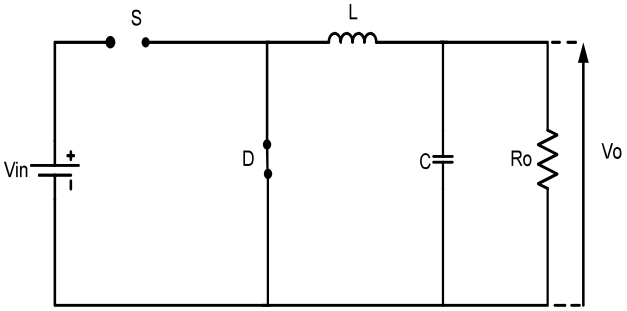


Fig. 3. Converter circuit when S is off.

The equations defining the dynamic behavior of the circuit when S switch is off are given in Eqs. 3 and 4.

$$\frac{di_L}{dt} = -\frac{V_o}{L} \quad (3)$$

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{RC} \quad (4)$$

The relationship between the output and input voltage at steady state for an ideal buck DC-DC converter is defined as given in equation 5.

$$V_o = dV_{in} \quad (5)$$

The duty ratio for a buck DC-DC converter is given in Eq. 6.

$$d = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on} + T_{off}} \quad (6)$$

T_{on} denotes "Logic 1, On" duration of PWM, T_{off} is the "Logic 0, Off" duration of PWM, T represents the period of PWM, and d defines the duty ratio (Erickson R.W., 1997).

3.Fuzzy Logic Control

Fuzzy logic can be defined as a mathematical order to deal with and define uncertainties. It controls a system by relying on the expert's knowledge and predictions about the system to be controlled. In other words, no mathematical model of the system to be controlled is needed. Fuzzy logic control system generally consists of four main units as fuzzification, inference, defuzzification and rule base (Liping ve ark.,2009). The block diagram for fuzzy logic controller is shown in Fig.4.

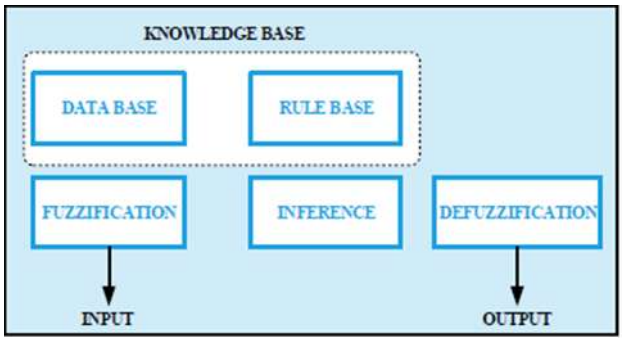


Fig. 4. The block diagram for fuzzy logic controller

Fuzzification unit converts the input data into symbolic values which are linguistic variables. It benefits from membership function to determine the fuzzy sets and degrees of membership for the input data, and assigns linguistic variables to each numerical value such as big, small and etc. Fuzzy inference unit produces fuzzy results by executing the fuzzy values coming from the fuzzification unit to the rules in the rule base. The inputs and outputs are linked by executing the rules in the rule base. The value obtained in this unit is converted to a linguistic expression on the rule table, and sent to the defuzzification unit. The most widely used fuzzy inference method is Mamdani method, which was also used in this study. Defuzzification unit helps obtaining a real and defuzzified value from the fuzzy data sent by the decision unit, which will later be used in the execution. It converts fuzzy data into certain values. Knowledge base consists of a data table where the data about the system are stored. The relationship between input and output is created thanks to the rules in the rule base. Input values that may influence the system output must be determined when a rule base is to be developed for a system (Gani ve ark.,2016). Two inputs, error and change of error, were selected for fuzzy logic controller designed in thus study. Error (e) is the difference between the desired and actual voltage values. Change of error (k) is the difference between the existing error e(k) and previous error e(k-1). k represents the number of iterations in the simulation program, and the definitions of error and change of error are given in Eqs.7 and 8.

$$e(k) = r(k) - y(k) \quad (7)$$

$$de(k) = e(k) - e(k-1) \tag{8}$$

Input and output variables are converted to symbolic expressions during the fuzzification process of a fuzzy logic controller. Linguistic variables of the fuzzy logic controller were used as NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big). Although the membership function of each system input is randomly selected, they can take forms such as triangle, trapezoid, sinusoid, Cauchy, bell curve, sigmoid, and Gaussian, Bell curve membership function was selected as the membership function in this fuzzy logic controller. Bell curve membership functions for error, change of error and output are shown in Fig. 5-7 (Acikgoz ve ark.,2013).

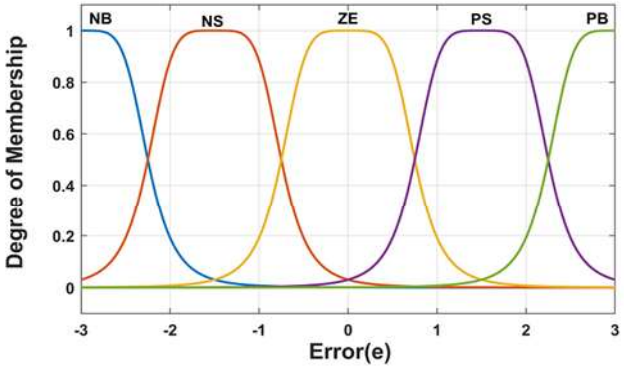


Fig. 5. Bell curve membership functions for error

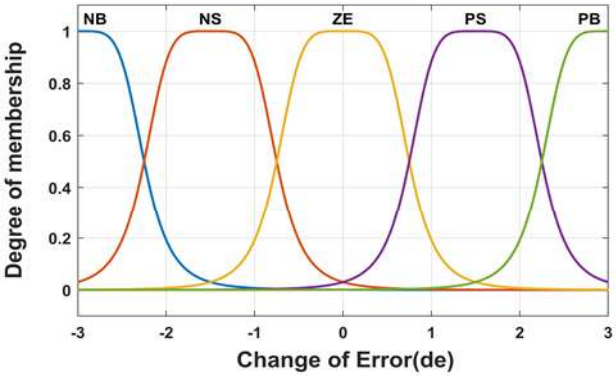


Fig. 6. Bell curve membership functions for change of error

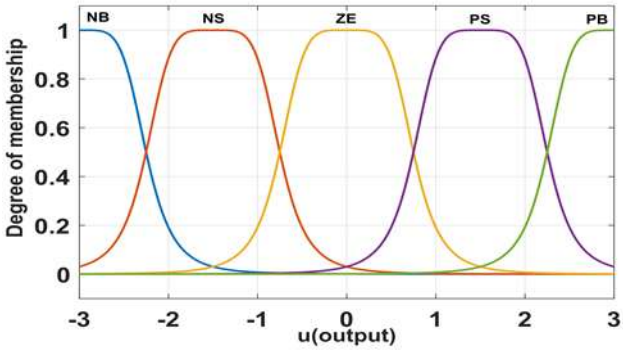


Fig. 7. Bell curve membership functions for output

The equation used for the above mentioned bell curve membership function is given in Eq. 9.

$$A_{bell} = \frac{1}{1+\left|\left(\frac{x-x_T}{d}\right)\right|^{2m}} \tag{9}$$

In the fuzzy inference unit, the relationship between input and output is created based on the rules. AND was used as a fuzzy operator when the rules are written. 25 rules were written in this study. When a controller is executed with more than 25 rules, the system will take longer to respond due to a heavier system load. The rule base is given in table 1.

u		*de*				
		NB	NS	ZE	PS	PB
e	NB	NB	NB	NB	NS	ZE
	NS	NB	NB	NS	ZE	PS
	ZE	NB	NS	ZE	PS	PB
	PS	NS	ZE	PS	PB	PB
	PB	ZE	PS	PB	PB	PB

Table 1. Fuzzy rule base.

Some of the rules are given below.

Rule 5: If e NB and PB, then u ZE

Rule 8: If e NS and ZE, then u NS

Rule 15: If e ZE and PB, then u PB

Rule 22: If e PB and NS, then u PS

In the defuzzification unit, membership weights of error and error of change are found for each rule, and the lowest fuzzy membership weight and respective output membership values (u) are determined. The numerical value obtained at the output of the defuzzification unit is executed on the system.

4.PI-Fuzzy Controller

In a conventional PI controller, K_p is the proportional gain coefficient, and K_i represents the integral gain coefficient. PI-fuzzy control system is a two-input and one output fuzzy control system based on conventional PI control system. Here, K_p is the gain coefficient used with error, and K_i represents the gain coefficient used with error of change. The output equation for PI-fuzzy controller is given in Eq. 10.

$$u(k) = K_p e(k) + K_i T_s [e(k) - e(k-1)] \tag{10}$$

PI-fuzzy controller control model is given in Fig. 8 (Ozcalik ve ark.,2014).

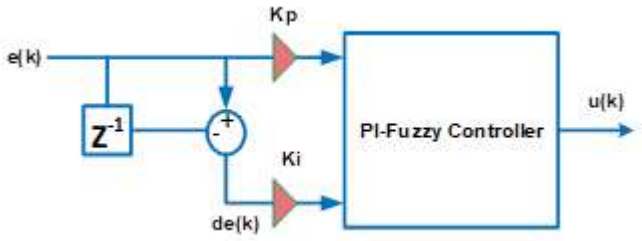


Fig. 8. PI-Fuzzy controller model

5.Simulation Studies

The buck DC-DC converter circuit and PI-fuzzy control system were simulated. The circuit element values of the buck converter are given in table 2.

Parameters	*Symbol*	*Value*
Input voltage	V_{in}	20.875V
Inductance	L	1mH
Capacitance	C	100µF
Resistance	R	7.55Ω
Output voltage	V_o	16.7V
Maximum Power	P_{max}	36.8W
Switching Frequency	f_s	80Khz
Duty Ratio	d	0.8

Table 2. The circuit element values of buck converter

In the simulation, the performance of PI fuzzy controller for reference input tracking expressed as a step function was firstly analyzed. For this purpose, the voltage was increased from 16.7V

to 19.205 V at t=0.1sec. The dynamic response of PI-fuzzy controller analyzed for changes in reference voltage is shown in Fig. 9.

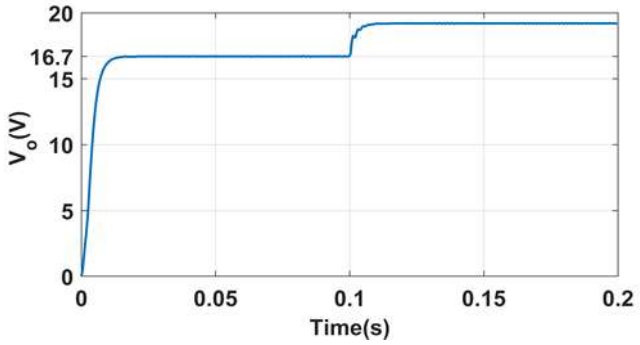


Fig. 9. Dynamic response of PI-Fuzzy controller analyzed for changes in reference voltage

Secondly, the performance of the controllers against the disturbances were analyzed. For this purpose, the input voltage of the buck DC-DC converter operating at a constant load and output voltage was decreased from 20.8V to 17.68 V at t=0.1sec. The dynamic response of PI-fuzzy controller analyzed for changes in input voltage is shown in Fig. 10.

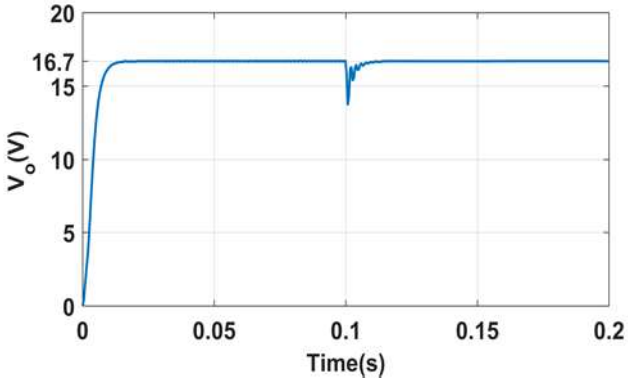


Fig. 10. Dynamic response of PI-Fuzzy controller analyzed for changes in input voltage

Thirdly, the load value of the buck DC-DC converter was increased from 7.55 Ω to 9.815 Ω at t=0.1sec in order to analyze the dynamic response of the PI-fuzzy controller against sudden load change. The dynamic response of PI-fuzzy controller analyzed for sudden load change is shown in Fig.11.

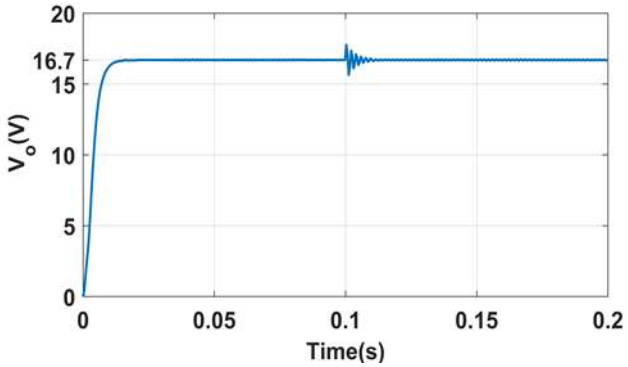


Fig. 11. Dynamic response of PI-Fuzzy controller analyzed for load change

6.Conclusion

In this study, the dynamic performance of a PI fuzzy controller on three different scenarios (reference voltage tracking, input voltage and load change) in terms of controlling a buck DC-DC converter was analyzed. The determination of gain coefficients at the controller output for input membership functions is of vital importance for a stable and effective control system. Therefore, it was aimed to create an effective and robust controller response by setting value ranges of fuzzy logic membership functions in accordance with PI gain coefficients. The simulation demonstrated that PI-fuzzy controller displayed a successful dynamic performance against reference voltage tracking and disturbances (such as input voltage and load change).

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