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Hybrid Control of DC - DC Buck Boost Converter

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Abstract: Optimization of control methods in accordance with their intended use in power electronics applications is a necessity. In this manuscript, a hybrid control approach for DC - DC buck-boost converters consisting of a PI controller and a fuzzy logic controller is presented. The mathematical model has been proposed by determining the parameters of the DC - DC buck-boost converter. PI controller, fuzzy logic controller and hybrid controller are designed and simulated in MATLAB Simulink program. Genetic algorithm is used to select the most suitable PI parameters. Experimental tests are performed to show efficiency of the hybrid method for both buck and boost mode.

***Keywords**:* DC - DC Converter, Fuzzy control, PI control

DA - DA Düşürücü Yükseltici Çeviricilerin Hibrit Yöntem ile Kontrolü

Öz: Güç elektroniği uygulamalarında kullanım amacına göre kontrol yöntemlerinin optimizasyonu bir zorunluluktur. Bu çalışmada, bir PI denetleyici ve bir bulanık mantık denetleyiciden oluşan DA - DA düşürücü yükseltici çeviriciler için hibrit bir kontrol yaklaşımı sunulmaktadır. DA - DA düşürücü yükseltici çeviricilerin parametreleri belirlenerek matematiksel model önerilmiştir. PI denetleyici, bulanık mantık denetleyici ve hibrit denetleyici, MATLAB Simulink programında tasarlanmış ve simüle edilmiştir. En uygun PI parametrelerini seçmek için genetik algoritma kullanılmıştır. Hibrit yöntemin hem düşürücü hem de yükseltici mod için verimliliğini göstermek için deneysel testler yapılmıştır.

***Anahtar kelimeler**:* DA - DA Çeviriciler, Bulanık Kontrol, PI Kontrol

1. Introduction

In some applications of power electronics, it is important to convert a DC voltage to another DC voltage value. DC - DC converters are used for this purpose. DC - DC converters can adjust the input voltage to obtain the desired output voltage. If a converter reduces the input voltage, it is called a buck converter; if it raises the input voltage, it is called a boost converter. If a converter is capable of increasing or decreasing input voltage, it is referred to as buck boost converter. Some control methods are used to control the converters in order to obtain satisfactory results on the output side in terms of output voltage, such as PID control, fuzzy control, and model predictive control. Short settling time, minimal overshoots, fewer oscillations, and a short rise time are some intended specifications of output voltage in many applications [1].

In railway sector, DC - DC converters are used in many applications. For example, AC current which comes from main transformer firstly is converted to DC current and then, DC - DC converters adjust it to desired value. The equipment used in rolling stocks such as radio or windshield wiper, is powered from battery and uses different DC voltage value. To convert voltage parameters come from battery, again DC - DC converters are used.

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Since systems can be managed without mathematical explanations, fuzzy control is a simple and useful tool for control. Instead of mathematical parameters, fuzzy control uses membership functions and a rule table to control the system. As a result, fuzzy control is a convenient and promising approach, particularly for systems with difficult mathematical models to derive. Many control applications for DC - DC converters use fuzzy logic controller (FLC) [1-11]. A fuzzy controller was designed, and a variety of converters were controlled in [2]. The simulation results of a sepic converter and a buck boost converter were demonstrated and compared; decent overshoot and quick response results are obtained. In [3] a FLC design for buck converters was proposed and satisfactory simulation results in terms of overshoot and performance of response were obtained. A multivariable FLC design for buck converter is described in [4]. There were two fuzzy subsets of the membership functions error and change of error: negative and positive. An adaptive fuzzy controller which generated rules and parameters was proposed in [5]. The simulation results were obtained not only for buck, but also boost and buck boost converter.

Variations of PID, such as PI, PD, or PID, are used with fuzzy controller in many applications to enhance performance responses. In [6], the PI – Fuzzy control approach was introduced and compared to the PI control system. For the reduction of the high starting current and well damped output voltage, improved simulation results were obtained. Hybrid control methods were discussed in [7]. The aim of the study was to avoid overshoots and oscillations. In addition, several control approaches were compared considering the system response. A PD – fuzzy like control mechanism was proposed in [8] in order to improve the performance of boost converter. In simulation results, there was small oscillation when the system work under load and it performed reasonably in all operating conditions.

In this manuscript, first, mathematical model of DC - DC buck-boost converter is proposed with the help of formulations in [9]. Then PI controller and a fuzzy logic controller were implemented to control proposed model of buck-boost converter. Following that, experimental tests for both approaches are performed on MATLAB and simulation results are obtained. For fuzzy logic controller, the Sugeno method is employed. The PI controller and the FLC are combined in the last part, and a hybrid control model is proposed. Genetic algorithm is used to find optimum parameters for PI controller. The output voltage for all three methods, considering both buck and boost modes, is demonstrated in the simulation results. The obtained results verify the efficiency of the proposed hybrid control method.

2. Buck Boost Converters

A buck boost converter generates an output in terms of volt which may be larger or smaller than input. The polarity of output is opposite with respect to input voltage. Duty cycle is ratio of on time of PWM signal to period of the signal and it decides to mode of converter is buck or boost. Model of the converter can be shown in Figure 1 and circuit parameters can be seen in Table 1.

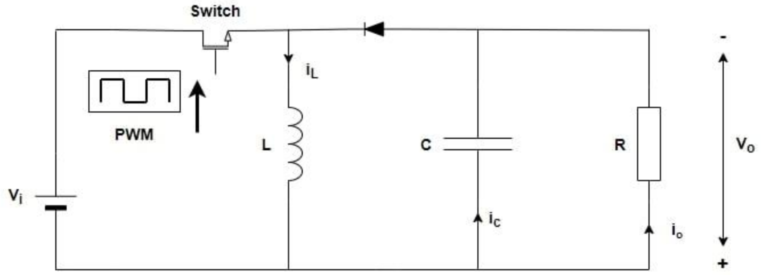

Figure 1. Schematic diagram of buck boost converter

Table 1. Circuit parameters

Parameter	Value
L (inductance)	1,5 mH
C (capacitance)	0,3 mF
R (load resistance)	60 Ω
V_i (input DC voltage)	12 V
f_s (sampling frequency)	10 kHz

The buck-boost converter circuit operates two different modes in one cycle. When switch is on, current flows through inductor and diode is reverse biased. Switch-on situation can be seen in Figure 2. Mathematical model of switch-on circuit can be written as follows:

$$\frac{di_L}{dt} = \frac{V_i}{L} \tag{1}$$

$$\frac{dV_c}{dt} = -\frac{V_o}{RC} \tag{2}$$

When switch is closed with respect to PWM signal, current flows through inductor, capacitor, diode and load resistor. Stored energy in inductor decreases until switch is on because of flowing current. Switch-off situation can be seen in Figure 3.

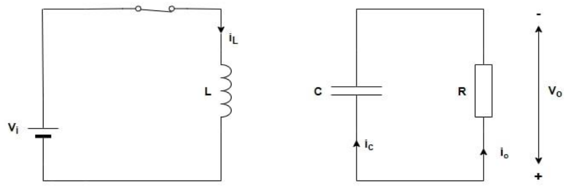

Figure 2. Switch-on mode of buck–boost converter

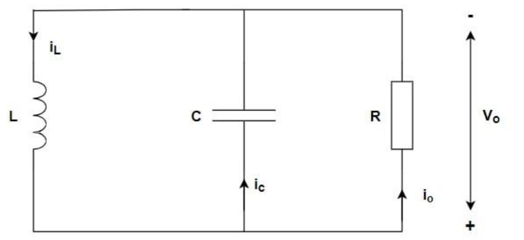

Figure 3. Switch-off mode of buck–boost converter

Mathematical model of switch-off circuit can be written as follows:

$$\frac{di_L}{dt} = -\frac{V_o}{L} \tag{3}$$

$$\frac{dV_c}{dt} = \frac{I_L}{C} - \frac{V_o}{RC} \tag{4}$$

Duty cycle "D" is described as follows:

$$D = \frac{t_{on}}{t_{on} + t_{off}} \quad (5)$$

Switching period T_s is sum of on time and off time and can be written as:

$$T_s = t_{on} + t_{off} \quad (6)$$

If we put together equation (1-4) according to duty cycle and equation 5, following equations are obtained:

$$\frac{di_L}{dt} = D\frac{V_i}{L} - (1-D)\frac{V_o}{L} \quad (7)$$

$$\frac{dV_c}{dt} = (1-D)\,\frac{I_L}{C} - \frac{V_o}{RC} \quad (8)$$

In steady-state, equation 7 and equation 8 can be written as:

$$DV_i = (1-D)V_o \quad (9)$$

$$(1-D)I_L = \frac{V_o}{R} \quad (10)$$

To obtained desired output voltage V_o, duty cycle D must be changed with respect to time. So, relationship between D, V_o and V_i can be found from equation 9:

$$D = \frac{V_o}{V_i + V_o} \quad (11)$$

Duty cycle is calculated with model in Figure 4 with MATLAB Simulink.

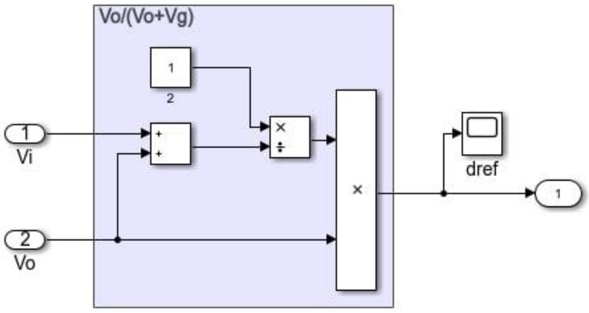

Figure 4. Duty cycle calculator

Duty cycle decides whether converter works in step down mode or step up mode. If D is less than 0,5, converter works in step down mode and if D is larger than 0,5, converter works in step up mode. D must be in range between 0 and 1. Converter model is created MATLAB Simulink. It can be seen in Figure 5.

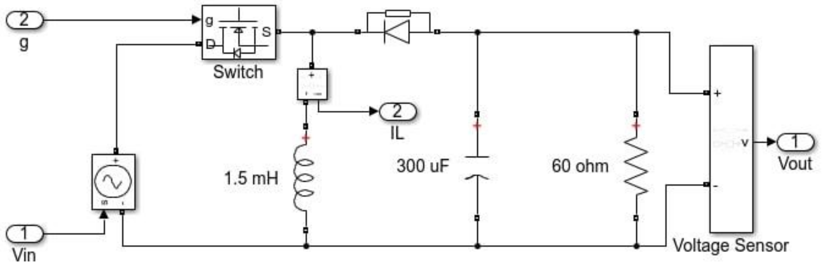

Figure 5. MATLAB simulink model of converter

3. Control of Buck Boost Converter

3.1. PI controller

PID control is mostly used and very popular control methods to control output voltage. PID is an abbreviation for proportional, integral, and derivative respectively. PID can be described as follow [12]:

$$F(s) = \frac{K_d\, s^2 + K_p\, s + K_i}{s} \tag{12}$$
$$F\,(s) = K_p + \frac{K_i}{s} + K_d s$$

where K_d derivative gain, K_i integral gain and K_p proportional gain. Effect of these gain coefficients is summarized in Table 2. In our study, derivative gain is not used. Control schematic of buck boost converter can be shown in Figure 6. Buck boost converter generates an output voltage and this voltage compared with desired output voltage in every loop. PI controller decides duty cycle of PWM signal according to error and this loop continues till reach desired voltage. Coefficients of PI controller are derived with genetic algorithm. MATLAB Simulink genetic algorithm function is used for this purpose.

Table 2. Effect of PID

	Rise Time	Overshoot	Settling Time	Steady State Error
Proportional	Reduce	Raise	Minor Effect	Reduce
Integral	Reduce	Raise	Raise	Eliminate
Derivative	Minor Effect	Reduce	Reduce	Minor Effect

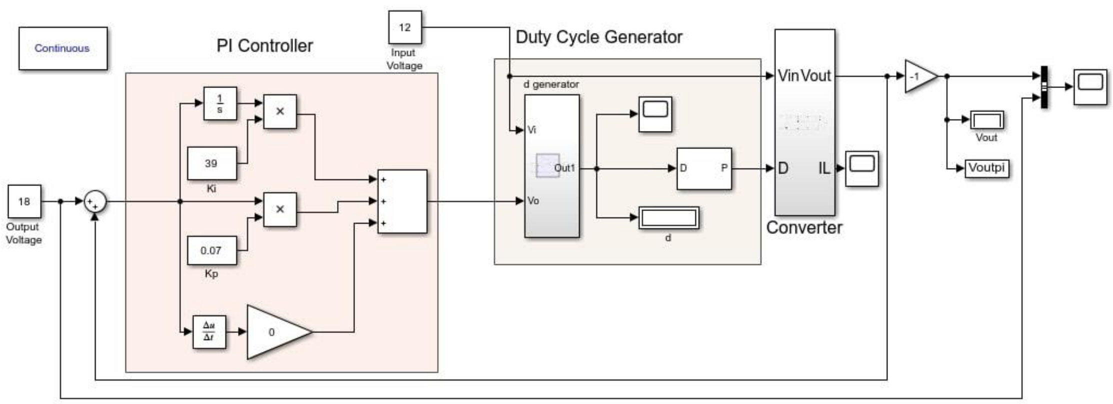

Figure 6. Simulink model of PI controller

3.2. Fuzzy logic controller

Input variables of FLC are output voltage error (Input 1) and change of output voltage error (Input 2). Fuzzy logic controller is presented with diagram in Figure 7. In Figure 8, it can be seen basic design methodology of FLC. For the control output voltage, following rules are used:

1) If the Input 1 is not close to zero, duty cycle should change significantly.
2) If the Input 1 is close to zero, duty cycle modification should be minor.
3) If the Input 1 is close to zero but Input 2 is large, duty cycle should be modified.
4) If the Input 1 is not close to zero but direction of the output is going to zero error, duty cycle change should be medium.

In Table 3, can be seen rule table of fuzzy controller. NB refers to 'negative big', N refers to 'negative', NS refers to 'negative small', NZ refers to 'negative zero', Z refers to 'zero', PZ refers to 'positive zero', PS refers to 'positive small', P refers to 'positive' and PB refers to 'positive big'. Membership functions can be seen in Figure 9 – 10. Sugeno control method is used in FLC.

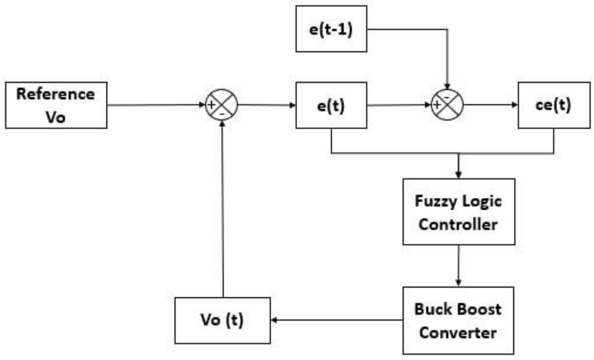

Figure 7. Block diagram of FLC

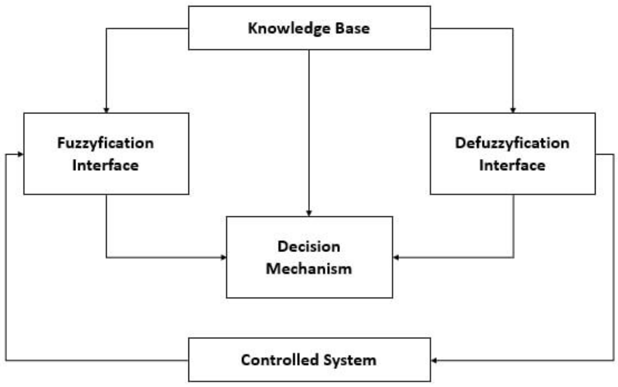

Figure 8. Basic design methodology of FLC

Table 3. Rule table [13]

		Input 2 (change of error)								
		NB	N	NS	NZ	Z	PZ	PS	P	PB
Input 1 (error)	NB	-1,2	-0,23	-0,05	-0.03	-0,03	-0,03	-0,03	0,17	1,15
	N	-1,2	-0,20	-0,02	-0,001	-0,005	-0,002	0,015	0,19	1,18
	NS	-1,19	-0,20	-0,02	-0,003	-0,0005	0,003	0,019	0,2	1,18
	NZ	-1,19	-0,20	-0,02	-0,003	-0,0001	0,003	0,019	0,2	1,18
	Z	-1,19	-0,20	-0,02	-0,003	0	0,003	0,02	0,2	1,19
	PZ	-1,19	-0,20	-0,02	-0,003	0,0001	0,003	0,02	0,2	1,19
	PS	-1,19	-0,20	-0,02	-0,003	0,0005	0,004	0,02	0,2	1,19
	P	-1,18	-0,19	-0,015	0,002	0,005	0,008	0,02	0,2	1,2
	PB	-1,15	-0,17	0,01	0,03	0,03	0,03	0,05	0,23	1,2

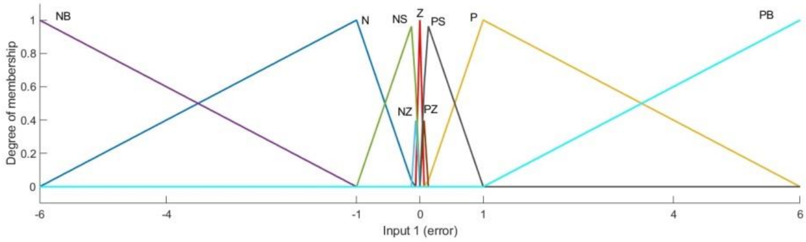

Figure 9. Membership function of input 1(error)

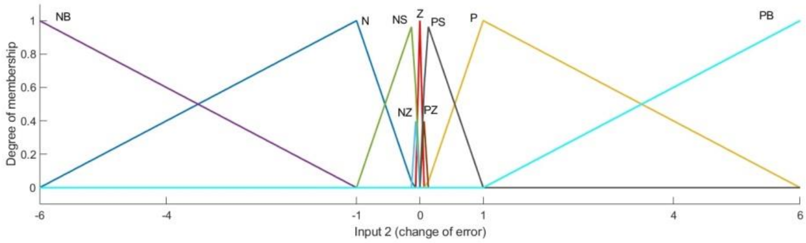

Figure 10. Membership function of input 2 (change of error)

Model of FLC is designed in MATLAB Simulink There are 3 gain coefficients are used to strength output responses of the system. These are error coefficient K_e, change of error coefficient K_{ce} and duty cycle coefficient K_{dc}. These coefficients are defined with genetic algorithm. Model of FLC controller is in Figure 11.

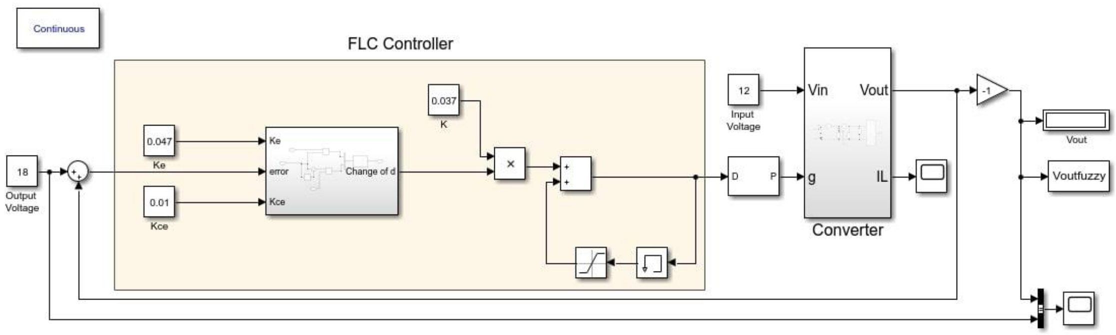

Figure 11. Simulink model of FLC

3.3. PI + fuzzy logic controller

In this hybrid method, both PI controller and FLC are used. Control diagram of the method can be seen in Figure 12. When decided to duty cycle, both control method outputs are combined. With this strategy, it is aimed that to eliminate bad specifics of methods.

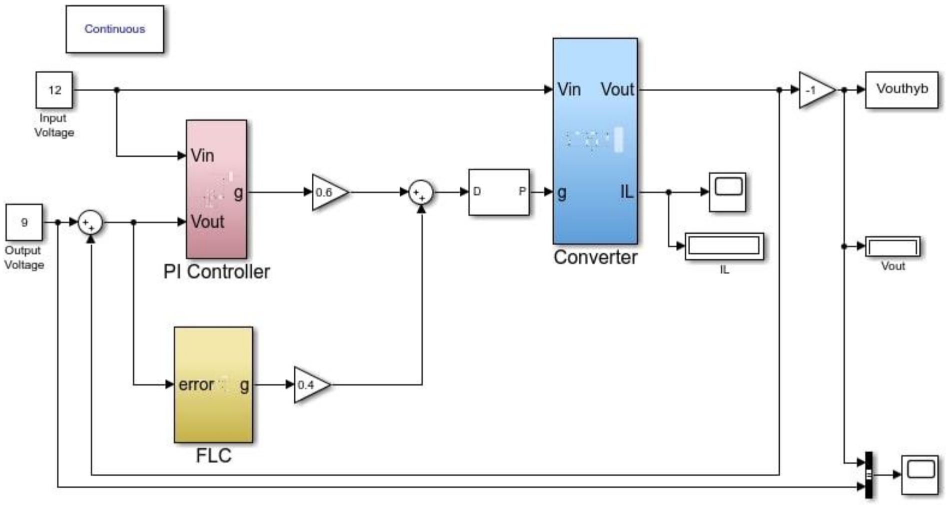

Figure 12. Simulink model of hybrid controller

3.4. Genetic Algorithm

The main aim of the genetic algorithm (GA) is to improve and transfer desired features to next generations. GA uses mutation and crossover operators to transfer features with different selection technics. Most popular selection technics are tournament selection, roulette wheel selection and rank selection. In selection methodology every population member has a fitness value and according to using selection technics population members are chosen by algorithm. Selected members are passed through genetic operators and next generation is created. Selection method is specified according to fitness value of members because it is important to avoid from wrong solution. For instance, if fitness values of population members is so close each other, rank selection method can be chosen; or if one member's fitness value is too greater than others, it should not be chosen roulette wheel selection method to avoid domination of one member in early stage of algorithm process.

In this study, MATLAB Simulink genetic algorithm function is used. For PI controller, to determined K_i and K_p parameters firstly border values are defined and then fitness function is created. Settling time is indicated as achievement criteria. For FLC, to determined K_e, K_{de} and K_{dc} parameters same method is used with PI controller. In FLC settling time and overshoot is used as achievement criteria. When deciding of achievement criteria, general performance of controller methods are considered. For hybrid controller, same parameters are used. Pseudo code of genetic algorithm as follows, where living generation g, population of this generation is $K_1(g)$ and next generation is $K_2(g)$.

Genetic algorithm pseudo code

Start
$g \leftarrow 0$
starting $K_1(g)$
evaluation $K_1(g)$
while stopping criteria is not achieved **do**

reunification $K_1(g) \rightarrow K_2(g)$
evaluation $K_2(g)$
selection $K_1(g)$ and $K_2(g) \rightarrow K_1(g+1)$
$g \leftarrow g + 1$
end

4. Simulation Results

In this section simulation results of three methods are presented. Results are obtained for both boost mode and buck mode. Coefficients which are used are in Table 4.

Table 4. Coefficients

	PI	FLC	Hybrid
K_P	39	-	39
K_i	0,07	-	0,07
K_e	-	0,047	0,02
K_{ce}	-	0,01	0,07
K_{dc}	-	0,037	0,037

Output voltages simulations results can be seen in Figure 13 and 14. Figure 13 presents buck mode of converter (V_i= 12 V and V_o = 9 V) and Figure 14 presents boost mode of converter (V_i= 12 V and V_o = 18 V).

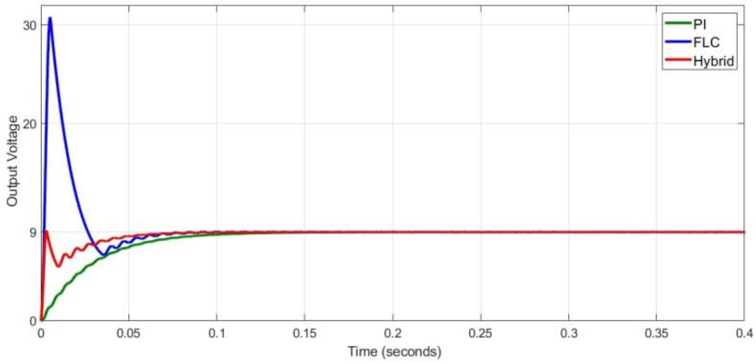

Figure 13. Simulation comparison in buck mode (Vi= 12 V and Vo = 9 V)

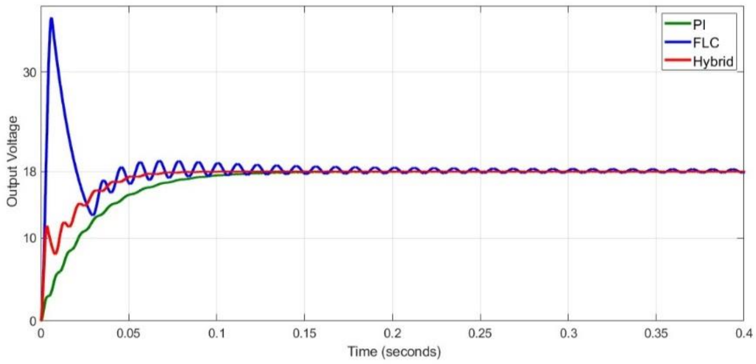

Figure 14. Simulation comparison in boost mode (Vi= 12 V and Vo = 18 V)

Simulation results are given in Table 5. According to results in buck mode with respect to settling time and rise time, best control method is hybrid method. Although there is no overshoot in PI control method, hybrid method has a small overshoot: 0,17 V and FLC has very big overshoot: 21,65 V. Because of the fast response and small overshoot of hybrid control method, it can be said that it is best solution for buck mode. In boost mode, hybrid is the undisputed best solution because of fast response and no overshoot. FLC has big overshoot and oscillations and PI method has small response. In boost mode, rise time of hybrid method is worse than buck mode.

Table 5. Simulation results

	Output voltage = 9 V (buck mode)			Output voltage = 18 V (boost mode)		
	Settling Time	Rise Time	Overshoot	Settling Time	Rise Time	Overshoot
PI	110 ms	60,33 ms	-	152 ms	59,256 ms	-
FLC	85 ms	2,20 ms	21, 65 V	94 ms	1 ms	18,59 V
Hybrid	84 ms	1,78 ms	0,17 V	84 ms	37,133 ms	-

For both buck mode and boost mode, compared results are shown in Figure 12 and Figure 13 respectively. PI controller has no overshoot both buck and boost mode but its settling time and also rise time slower than others method. FLC has very good settling time however, it has very big overshoot both buck and boost mode. FLC has also has very short rise time results. FLC and hybrid method can be seen almost same in settling time results but because of the big overshoot in FLC, hybrid method has better results with respect to settling time. Hybrid controller has better settling time and rise time, no overshoot; so for both buck and boost mode it seems the best control model.

5. Conclusion

In this manuscript a DC - DC buck boost converter is modelled in Simulink/MATLAB and three approaches such as PI, FLC, and a hybrid model that combines PI control and FLC are applied to obtain desired output level. In order to verify the efficiency of proposed model, simulations are performed for each control method. Then the performance of the methods are compared in terms of the step information of the output signal. The results demonstrate that PI method outperforms FLC when the output overshoot is taken into account. However, FLC outperforms PI method in terms of rise time and settling time. Aside from these results, the hybrid model outperforms both the PI and FLC methods in terms of overshoot, settling time, and rise time. Consequently, hybrid model has improved the performance of converter in comparison to other approaches. As a future study, different control methods such as Model Predictive Control (MPC) can be integrated to proposed hybrid model.

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Resume

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Ethics Statement:
Authors confirm that the article is original, there is no plagiarism issue.
All authors contributed equally.