Fuzzy Sliding Mode Control of DC-DC Boost Converter

Zeynep Bala Duranay
EEE Department
Firat University, Technology Faculty
Elazig, Turkey
zbduranay@firat.edu.tr

Hanifi Guldemir
EEE Department
Firat University, Technology Faculty
Elazig, Turkey
hguldemir@firat.edu.tr

Servet Tuncer
EEE Department
Firat University, Technology Faculty
Elazig, Turkey
stuncer@firat.edu.tr

***Abstract*—A sliding mode fuzzy control method which combines sliding mode and fuzzy logic control for DC-DC boost converter is designed to achieve robustness and better performance. A fuzzy sliding mode controller in which sliding surface whose reference is obtained from the output of the outer voltage loop is used to control the inductor current. A linear PI controller is used for the outer voltage loop. The control system is simulated using Matlab/Simulink. The simulation results are presented for input voltage and load variations. Simulated results are given to show the effectiveness of the control system.**

Keywords-boost converter; DC-DC converter; FLC; fuzzy logic; sliding mode

I. INTRODUCTION

Voltage-mode control and current-mode control are two methods used to control DC-DC converters [1]. The voltage-mode control is robust to disturbances, but slow. Current-mode control has a fast transient response but is more complex than voltage mode control. Classical PI and hysteretic controllers are the most used controllers for DC-DC converters. The linearized converter model around an operating point obtained from the state space average model [2] is used for conventional linear controllers. The classical controllers are simple to implement but the effect of variation of system parameters cannot be avoided, due to the dependence of linearized model parameters on the converter's operating point [3]. The controller for DC-DC converters must account the nonlinearity and parameter variations. It should maintain stability and provide fast response in any operating condition. Classical control methods for DC-DC converters are not much efficient in achieving the desired performance [4-5]. A nonlinear control technique developed in [6] derived from variable structure control theory is called sliding mode control (SMC) has advantages of simple implementation, robustness and fast transient response [7]. SMC is used to maintain the output voltage of the converter to be independent of parameters, input and load variations [8]. It provides invariant system dynamics to uncertainties when controlled in the sliding mode [9]. SMC has a problem of chattering. Chattering is undesirable oscillations having finite amplitude and frequency due to the presence of unmodeled dynamics or discrete time implementation [10]. Some methods such as equivalent control and boundary layer approach are used to reduce the chattering. Equivalent control based methods cannot be used to reduce chattering because of their finite number of output values. The boundary layer approach has a problem of reaching sliding mode due to the replacement of the discontinuous control action with a continuous saturation function [10]. Fuzzy sliding mode control (FSMC) is another method used to avoid the chattering problem [11]. Fuzzy logic control is a non-conventional and robust control technique which is suitable for nonlinear systems characterized by parametric fluctuation or uncertainties [12-13]. FSMC has the advantage of not being directly related to the mathematical model of the controlled systems as the SMC. FSMC combines fuzzy logic and SMC to control the DC-DC converter to achieve better performance. In FSMC, the fuzzy system is used to estimate the upper bound of the uncertain disturbances to reduce the chattering. Fuzzy logic controller (FLC) has an increased level of efficiency regarding nonlinear converters. In this method, the control action is generated by linguistic rules which do not require an accurate mathematical model of the system, hence the complexity of the nonlinear model is decreased [14-15]. FLC overcomes the deficiency resulting from using linearized small signal models and improves the dynamic behavior.

II. DC-DC BOOST CONVERTER MATHEMATICAL MODEL

The output voltage of a boost type DC-DC converter is higher than the input source voltage. This is achieved by periodically opening and closing the switching element in the converter circuit. The DC-DC boost converter is shown in Figure 1. The switching period is T. The switch is kept open for time (1-D)T and is kept closed for time DT. The analysis is done by examining voltage across and current through the capacitor for both times, when the switch is open and when the switch is closed. Continuous conduction mode (CCM) will be assumed in which the inductor current will have a nonzero value due to load variations. When the switch is closed, the diode in the circuit is reverse biased and becomes open circuit as shown in Figure 2(a). Then the voltage across the inductor is:

$$v_L = V_s = L\frac{di_L}{dt} \quad (1)$$

and the current through the capacitor is:

$$i_c = C\frac{dv_c}{dt} \quad (2)$$

If the switch changes to off position as shown in Figure 2(b), the inductor current cannot change suddenly and the diode becomes forward biased providing path for inductor current. Then the voltage across the inductor becomes:

$$v_L = V_s - v_c = L\frac{di_L}{dt} \quad (3)$$

the current through the inductor is:

$$i_L = i_c + i_R = C\frac{dv_c}{dt} + \frac{v_c}{R} \quad (4)$$

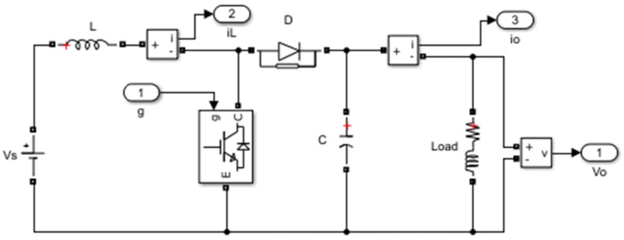
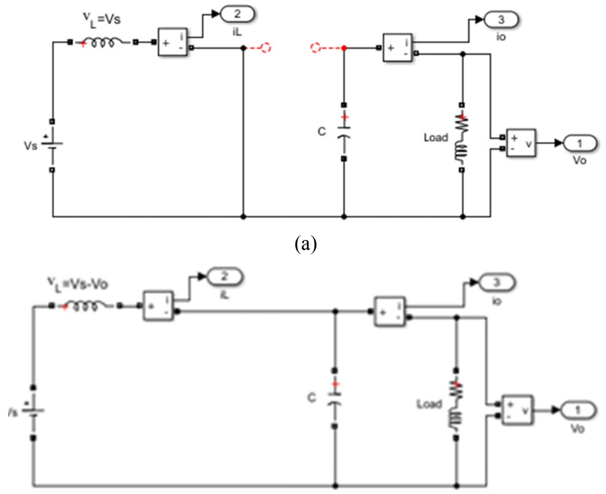


Fig. 1. Boost converter.



(a)

(b)

Fig. 2. Boost converter operation (a) Switch closed (b) Switch open.

Rearranging (1)-(4) and representing them as state equations by taking the voltage across the capacitor and the current through the inductor as state variable and combining (1), (3) and (2), (4) with u which is the control input taking the values 0 and 1 representing the switch position (switch is closed when u=1 and switch is open when u=0) then we have:

$$\frac{\mathrm{di_L}}{\mathrm{dt}} = -(1-\mathrm{u})\frac{\mathrm{v_c}}{\mathrm{L}} + \frac{\mathrm{V_s}}{\mathrm{L}} \quad (5)$$

$$\frac{\mathrm{dv_c}}{\mathrm{dt}} = (1-\mathrm{u})\frac{\mathrm{i_L}}{\mathrm{C}} - \frac{\mathrm{v_c}}{\mathrm{RC}} \quad (6)$$

Taking x_1=$\mathrm{i_L}$ and x_2=$\mathrm{v_c}$, then the state equations become,

$$\mathrm{x}_1 = -(1-\mathrm{u})\frac{1}{\mathrm{L}}\mathrm{x}_2 + \frac{\mathrm{E}}{\mathrm{L}} \quad (7)$$

$$\mathrm{x}_2 = (1-\mathrm{u})\frac{1}{\mathrm{C}}\mathrm{x}_1 - \frac{1}{\mathrm{RC}}\mathrm{x}_2 \quad (8)$$

III. SLIDING MODE CONTROL

The SMC theory uses a high speed switching strategy to force the system trajectory to move and stay on a path called sliding surface in the state space. The system trajectory before reaching the sliding surface is called reaching mode and the regime of control system on the sliding surface is known as sliding mode. In sliding mode, the system response remains insensitive to parameter variations and disturbances. Assuming we have the state equation in state space form,

$$x(t) = f(x,t,u) \quad (9)$$

where x is the state vector, u is the control input and f is a function vector. If the function vector f is discontinuous on a surface S(x)=0 then,

$$f(x,t,u) = \begin{cases} f^{+}(x,t,u^{+})\ if\ S > 0 \\ f^{-}(x,t,u^{-})\ if\ S < 0 \end{cases} \quad (10)$$

The aim is to find a control action u such that the state vector x tracks a desired trajectory x* that is,

$$S(x) = x - x^{*} \quad (11)$$

even with the model uncertainties and disturbances. The required control input is given by (12):

$$u = \begin{cases} 1\ for\ S > 0 \\ 0\ for\ S < 0 \end{cases} \quad (12)$$

Since the aim is to force the system states to reach the sliding surface and slide towards the origin, the control strategy should ensure the stability and the following inequality must be fulfilled [16]:

$$S\dot{S} \leq \eta|S| \quad (13)$$

where η is a positive constant that guarantees the system trajectories hit the sliding surface in finite time [17].

IV. SLIDING MODE CONTROLLER DESIGN

Sliding mode controller design procedure and the necessary equations governing the controller were derived and presented in [18-19]. The performance of the sliding mode controller was also presented against input voltage and load variations. The main objective in sliding mode control is to force the error to reach the switching surface and stay on that surface [20]. Using the state equations for boost converter given in (3) and (4), the steady state output voltage should be the desired voltage V*. That is,

$$x_2 = V^{*} \quad (14)$$

$$\dot{x_2} = \dot{V}^{*} = 0 \quad (15)$$

The sliding function is formed by the state variable error, defined as,

$$S = x_1 - x_1^{*} = 0 \quad (16)$$

The reference value x_1^* is obtained from the output of the linear voltage controller as

$$x_1^* = \frac{v^2}{RV_S} \tag{17}$$

In order to force the system states to the sliding line S=0, the control signal is

$$u = \frac{1}{2}(1 - sign(S)) \tag{18}$$

To guarantee the state trajectory to reach the sliding line and slides over it, the reaching law condition,

$$S\dot{S} < 0 \tag{19}$$

should be satisfied. Since,

$$\dot{S} = \dot{x_1} - \dot{x_1^*} \tag{20}$$

and state variables are constant and coincide with the reference values at the steady state, $\dot{x_1^*} = 0$

Solving the inequality given in (19) by replacing (17) we get the existing condition of sliding mode,

$$x_2 > V_S \tag{21}$$

Thus the output voltage should be higher than the source voltage for sliding mode to exist.

V. FUZZY LOGIC CONTROL

The most important feature of fuzzy logic is that it uses linguistic variables rather than numerical variables [14]. Values of linguistic variables are sentences in a natural language, such as big and less, and represented by fuzzy sets. Fuzzy logic control is closer to human thinking and natural language. It consists of a set of linguistic control rules. The FLC converts the linguistic control rules based on expert knowledge into an automatic control strategy. FLC is used with systems whose processes are too complex for analysis by conventional techniques [21]. A fuzzy logic controller for a boost converter consists of fuzzification, inference and defuzzification as shown in Figure 3.

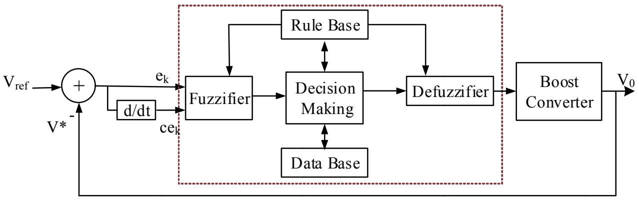


Fig. 3. Fuzzy logic controlled boost converter.

Input data are converted into linguistic values by the use of membership functions in the fuzzifier. Using the knowledge and the linguistic variables definition, fuzzy rules are evaluated and then controller action is obtained. Defuzzification stage is used to convert the fuzzy results to control action. The error e(k) which is the difference between the reference and measured current values is used as input to the fuzzy controller. The output of the fuzzy controller is the change in duty cycle $\Delta d[k]$, which is used to obtain the PWM signal for the switch in the converter. A Mamdani type fuzzy logic control architecture is the one in which max–min and center of gravity methods are used in the inference engine and defuzzification. Minimum and maximum functions are used to describe the AND and OR operators respectively in the control rules. Sum–product composition method has been used to change the qualitative action to a quantitative action. Weighted average of the centroids of all output membership functions is used to obtain the crisp output. The design of a fuzzy logic controller starts with the definition of membership functions for the inputs. The input resolution increases with the increasing number of fuzzy levels. The triangular membership function due to its simplicity is chosen for the controller input. The degree of membership for a given input is determined in the fuzzifier interface. The control rules for the designed fuzzy controller are determined from the DC–DC boost converter behavior. Input and output membership functions are given in Figures 4 and 5. Values of the input membership functions are determined from the maximum current flowing through the inductor. The values of the output membership functions are determined by considering the duty ratio interval which is between 0 and 1. The fuzzy rules are given in Table I, in which S is the error (e) and $\dot{S}$ is the change of error (ce). The fuzzy control rules are obtained based on the following criteria:

1. If the error between the reference and measured current is big meaning that the output of the converter is far from the reference point, then Δd should be big to take the output to the reference value quickly.
2. If the output of the converter is near the desired reference, a small change in duty cycle is needed.
3. If the desired reference is achieved and the output is steady, there should be no change in the duty cycle.

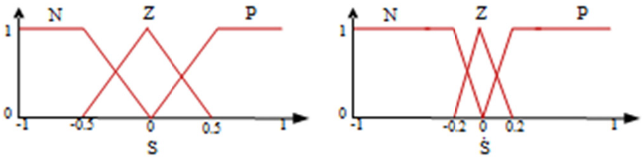


Fig. 4. Input membership functions.

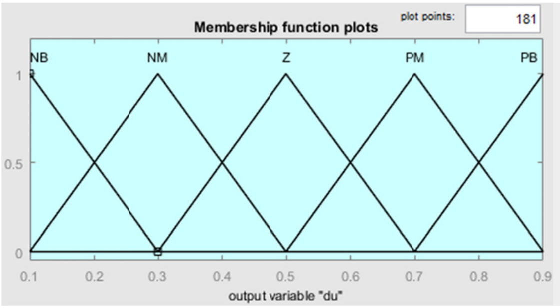


Fig. 5. Output membership functions.

Surface view of the rules of the fuzzy logic control is presented in Figure 6. The rules are derived from the combinations of the inputs which are the error and change in error for a function of output. Fuzzy logic based controller design procedure is presented for DC-DC [22], buck [16], boost [23] and buck-boost converters [24]. The performance of the fuzzy controller was also presented against input voltage and load variations. It is found that fuzzy controlled system is highly reliable and robust to change in circuit parameters and external disturbances [16].

TABLE I. SMF RULE TABLE

ce e	N	Z	P
N	NB	NM	Z
Z	NM	Z	PM
P	Z	PM	PB

e: error,
ce: change of error

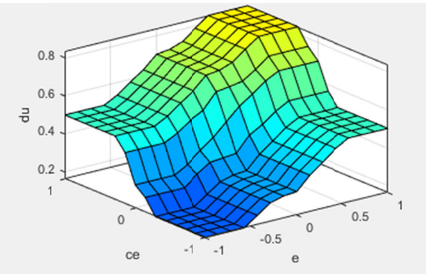


Fig. 6. Surface view of the fuzzy rules.

VI. FUZZY SLIDING MODE CONTROLLER

Fuzzy logic is a robust technique that has been very successfully applied to stability analysis and control system design for uncertain nonlinear systems [25-28]. It is a model free technique based on heuristics methods. It provides an approach for collecting human knowledge and dealing with nonlinearities or uncertainties. It is used for modeling and control of uncertain systems that cannot be easily controlled by conventional techniques. Fuzzy controller design is based on expert knowledge of the system besides the mathematical model. Sliding mode and fuzzy logic control are combined to control the DC-DC boost converter to achieve better performance and to improve robustness. Lyapunov stability criteria ensure the stability of the FSM controlled system. Fuzzy system is used to reduce the chattering of the converter by estimating the bound of the uncertain disturbances. It enhances the system robustness [21]. Sliding surface, obtained by the difference of measured current and reference inductor current which is obtained by the output of a PI controller connected to the error between reference and measured output voltages is used as the input to the fuzzy controller. The fuzzy control input is determined by a set of fuzzy rules expressed as a form of the conditional statements. The duty cycle is obtained as the controller output. The duty cycle is obtained by adding the scaled output $\Delta d[k]$ by h and the previous sampling period's duty cycle $d[k-1]$. So, the fuzzy controller output is:

$$d[k] = d[k-1] + h\Delta d[k] \tag{22}$$

This represents a discrete time integration of the fuzzy controller output. Integrating the fuzzy controller's output reduces steady-state error. The block diagram of the duty cycle calculation is given in Figure 7. The pulse width modulated control signal u is obtained by comparing the signal d with a triangular carrier signal. The Simulink representation of the designed overall FSM controller is given in Figure 8.

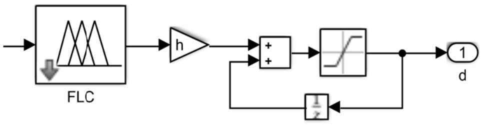


Fig. 7. Duty cycle calculation.

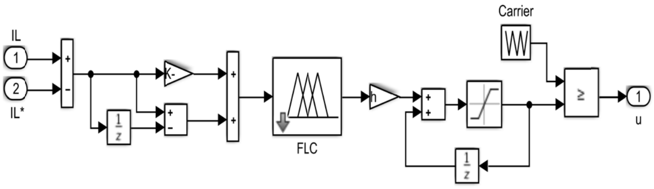


Fig. 8. FSM controller.

VII. SIMULATIONS

The aim is to implement a robust controller with a good dynamic performance even with input voltage variations and load changes. That system should have an invariant dynamic performance under different operating conditions. A cascade PI control and FSM control approach is implemented to improve both the disturbance rejection and tracking performance. The output voltage loop controller is a linear PI type controller. Since the dynamics of the current is much faster than that of the output voltage, a fuzzy sliding mode controller is used in the inner current loop. The output voltage of DC-D boost converter is controlled by the duty ratio of the switch used in the converter circuit. FSM controller is used to obtain the desired output voltage. Figure 9 shows the block diagram of the FSM controlled boost converter. The performance of the FSM controlled DC-DC boost converter is monitored with different reference voltages, under input voltage variations, and load variations. A boost converter with the parameters given in Table II is used for the simulations.

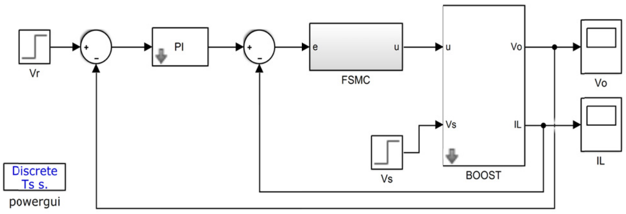


Fig. 9. Simulink block of the FSM controlled boost converter.

TABLE II. PARAMETERS OF BOOST CONVERTER

Vs (V)	L (mH)	C (μF)	R (Ω)
20	4	1200	200

The performance of the FSM controlled boost converter is first tested for the reference voltage change. The output voltage and current waveforms are shown in Figure 10 for a step change in the desired reference voltage from 30V to 40V at time t=0.5s. Load variation is applied to the FSM controlled boost converter to test its robustness under load variation. Figure 11 shows the voltage and current waveforms when the load resistance is changed from R=200Ω to R=100Ω at time t=0.5s. 30 V output voltage is maintained during the load change. Test for the input voltage change is also made to see the effects of the input voltage variations on the output voltage. A step change in input voltage is made when the converter is at steady state with a 30V output voltage. The performance of the controlled system is shown in Figure 12 and Figure 13 when a change in input voltage from 20V to 15V and 20V to 25V occurs at the time t=5s. In Figure 12, a decrease in input voltage occurs and in Figure 13, an increase in input voltage occurs at t=0.5s. Figures 10-13 prove the robustness of the FSM control against changes in the load and input voltage. The recovering feature of the FSM controlled boost converter can be clearly seen.

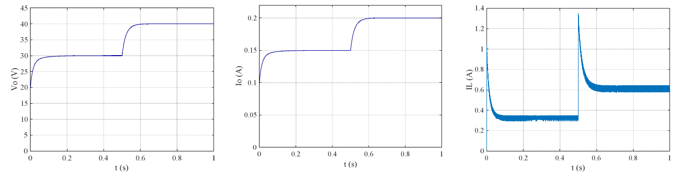


Fig. 10. Output voltage and output and input current waveforms for step change in reference voltage.

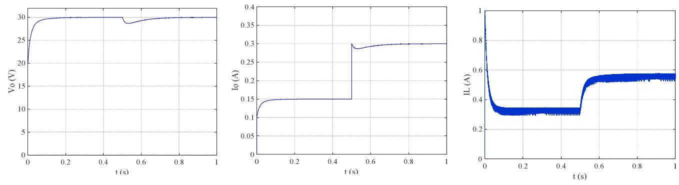


Fig. 11. Output voltage and output and input current waveforms for step load variations.

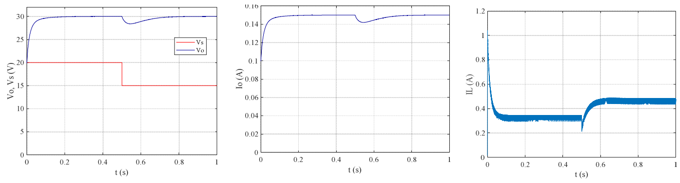


Fig. 12. Output voltage and output and input current waveforms when input voltage decreased from 20V to 15V.

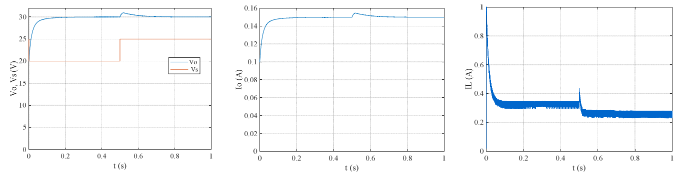


Fig. 13. Output voltage and output and input current waveforms when input voltage increased from 20V to 25V.

VIII. CONCLUSIONS

A sliding mode fuzzy controller designed and simulated for a DC-DC boost converter to improve the performance and achieve robustness. The error obtained from the load current and the reference current which is the sliding surface and its derivative are used as inputs to the fuzzy controller which controls the duty ratio of the signal driving the switch in the converter circuit. Matlab/Simulink programming environment is used for the simulations. The obtained results show that the controlled system is robust against load and input voltage variations. A good dynamic performance is also achieved.

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