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Comparative Analysis of PI and Sliding Mode Control Methods for Cascade DC/DC Boost Converters

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Abstract – In this study, a single switch cascade DC/DC boost converter has been preferred instead of conventional cascade DC/DC boost converter to reduce cost and provide simple system control. High-performance controller design for DC/DC converters is the most important problem of power electronics. To solve this problem, PI (proportional-integral) and SMC (sliding-mode control) are used for the purpose of control the voltage at the cascade DC/DC boost converter output. The advantages and disadvantages of these two control methods have been discussed in the study. Furthermore, the cascade DC/DC boost converter circuit is designed by connecting two boosters in succession. The simulation results of the control methods applied to this converter circuit have been analyzed and the most efficient controller has been determined to overcome the disadvantages of the system. Moreover, since the number of circuit elements in the proposed cascade DC/DC boost converter is less than in the conventional boost converter, both the cost has decreased and the output voltage has been more easily controlled.

Keywords – Cascade DC/DC boost converter, PI controller, sliding mode control, power electronics

I. INTRODUCTION

With the technology advancing in a dizzy manner, the need for DC/DC converters is greatly increased. DC/DC converters are a very important component of energy conversion in developing renewable energy applications [1], [2]. The DC/DC converters are power electronics components that provide constant voltage to the outputs [3]-[5]. However, cascade DC/DC boost converters are used to achieve a higher voltage [6], [7].

In order to obtain the high output voltage value in the conventional DC/DC boost converter, the duty cycle value must be kept high. This will adversely affect the converter's performance. The cascade boost DC/DC converter can be used to minimize this negative effect. Using the cascade boost DC/DC converter, it is possible to increase the output voltage ratio without increasing the duty cycle value [8], [9]. Thus, the disadvantage of the DC/DC conventional boost converter can be overcome. In addition, this cascade structure needs to be checked accurately and efficiently. Different controllers are used for this purpose. In this study, the PI controller and sliding mode controller have been used. However, the different outputs of these two controllers are compared in the study.

The PI control system consists of a combination of proportional (P) and integral (I) control. The PI control system is a method that produces a control signal that varies proportionally with the magnitude of the difference between the input and output signal and the integral of the error [10], [11]. Permanent state error that can occur in the system is eliminated by the integral effect added to the proportional effect [12]. However, this process causes the response speed to decrease under the same stability conditions. Increasing the speed of the integral effect gain and increasing the gain value can lead to instability. PI control generally cannot give the desired results against external disturbances and modeled dynamics. The block diagram of a PI controller is shown in Fig. 1.

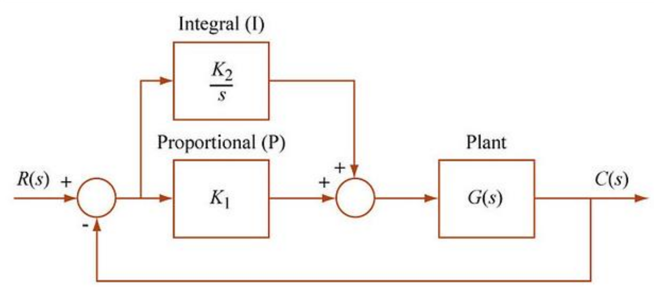

Fig. 1. Block diagram of PI controller

In the sliding mode control method, a linear or nonlinear system is drawn onto the surface defined in the state space and held on the surface using infinite switched feedback control [13], [14]. This surface consists of state variables and the “sliding surface” is defined. Once the system reaches the sliding surface, its behavior becomes independent of controlled system parameter changes and disturbing effects [15], [16].

The reaching and sliding phases in the sliding mode control are shown in Fig. 2. If the system is in zone 1, it reaches zone 4. If the system is in zone 3, it reaches zone 2, after which the sliding phase takes place. As a result, the error reaches zero.

However, the sliding mode control is a robust control because it is insensitive to system-related parameter uncertainties and disturbance magnitudes, and by changing the sliding function the dynamic behavior of the system can be changed [17].

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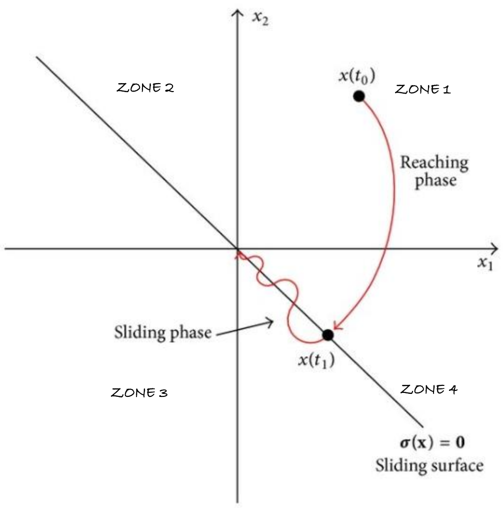


Fig. 2. Reaching and sliding phases in SMC

In this study, DC/DC cascade boost converter which has a higher voltage gain than conventional DC/DC boost converters is used. Thanks to the DC/DC cascade boost converter, the output voltage of the source with low input voltage is easily regulated to the desired level more efficiently. The PI and SMC controllers have been used together to control the cascade DC/DC boost converter. The results obtained have been compared and analyzed.

II. MATERIALS AND METHOD

In this study, the cascade DC/DC boost converter circuit is designed and 40 VDC voltage is applied to the input of this circuit. In addition, the PI controller and SMC controller have been created with the appropriate parameters and applied to the circuit. Thus, a constant 200 VDC voltage has been obtained at the output of the circuit. The effect of these two control methods on the system response has been investigated. In addition, the control methods applied to the system have been compared and their effects on system performance have been analyzed.

By connecting two DC/DC boost converters in series, the two-switches classic cascade DC/DC boost converter circuit has been obtained as in Fig. 3.

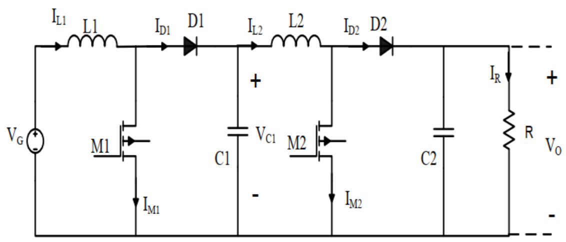


Fig. 3. The conventional cascade DC/DC boost converter circuit

The conversion ratio of the obtained converter for each layer is the same as the conversion ratio of the DC/DC boost converter. The conversion ratio between the V_{C1} voltage and the V_G input voltage on the first floor of the conventional cascade boost converter is as follows.

$$\frac{V_{C_1}}{V_G} = \frac{1}{1-d} \tag{1}$$

The conversion rate on the second layer has been calculated as follows.

$$\frac{V_0}{V_{C_1}} = \frac{1}{1-d} \tag{2}$$

When these two equations are compared, the conversion ratio of the cascade DC/DC boost converter is found as in equation (3).

$$\frac{V_0}{V_G} = \frac{1}{(1-d)^2} \tag{3}$$

The biggest advantage of the cascade DC/DC boost converter is its high gain. However, despite this advantage, the increase in the number of successively connected boost converters reduces the overall gain. In order to overcome this situation, a single-switch cascade DC/DC boost converter is designed with a lower cost and fewer circuit elements. The conversion rate of this circuit is the same as the conventional cascade DC/DC boost converter.

The M1 and M2 switches used in the conventional cascade DC/DC boost converter circuit have been transformed into a single-switch by designing a new cascade DC/DC boost converter as in Fig. 4. Thus, system control is simpler and the cost of the system is cheaper.

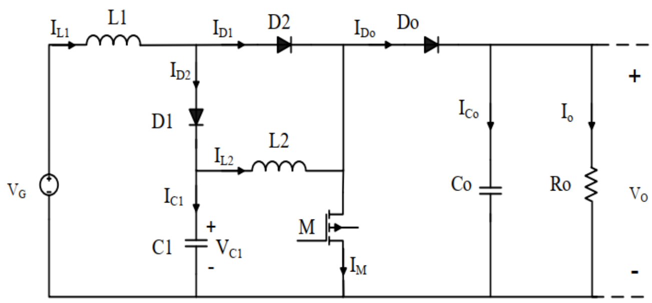


Fig. 4. Designed cascade DC/DC boost converter circuit

In this study, the input voltage of the cascade DC/DC boost converter is 40 VDC and the output voltage is 200 VDC and the output power is 1 kW. For this purpose, the circuit elements have been appropriately selected. Then the output value of the system was compared with the reference value. The error value resulting from the comparison was passed through the PI controller and the system was controlled with the generated control signal. The control mechanism of the cascade DC/DC boost converter with the PI controller is shown in Fig. 5.

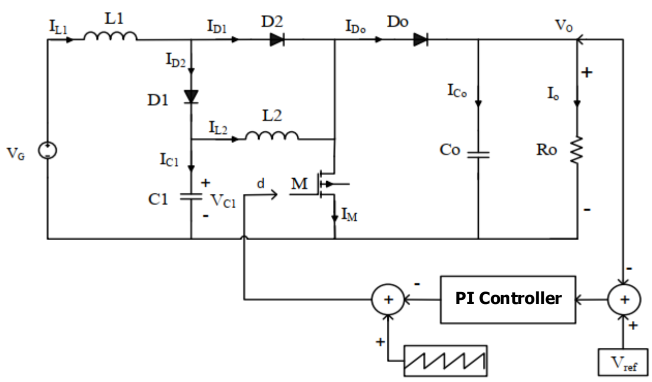


Fig. 5. Cascade DC/DC boost converter circuit with PI controller

Another control mechanism applied to the designed cascade DC/DC boost converter is sliding mode control. After determining the system parameters, an appropriate sliding surface has been selected and the sliding mode controller has been included in the system. The circuit formed by applying the SMC method, which is insensitive to external disturbances and fast, to the cascade DC/DC boost converter is shown in Fig. 6.

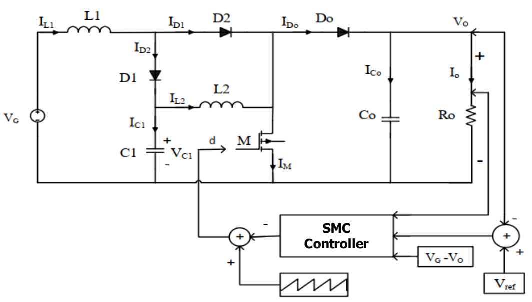


Fig. 6. Cascade DC/DC boost converter circuit with SMC controller

III. Results and Discussion

Necessary circuit elements with appropriate values have been determined in order to obtain the desired output value against the given input. The semiconductor circuit elements are suitably connected to each other. The characteristics and equivalent circuit parameters of the cascade DC/DC boost converter are given in Table 1.

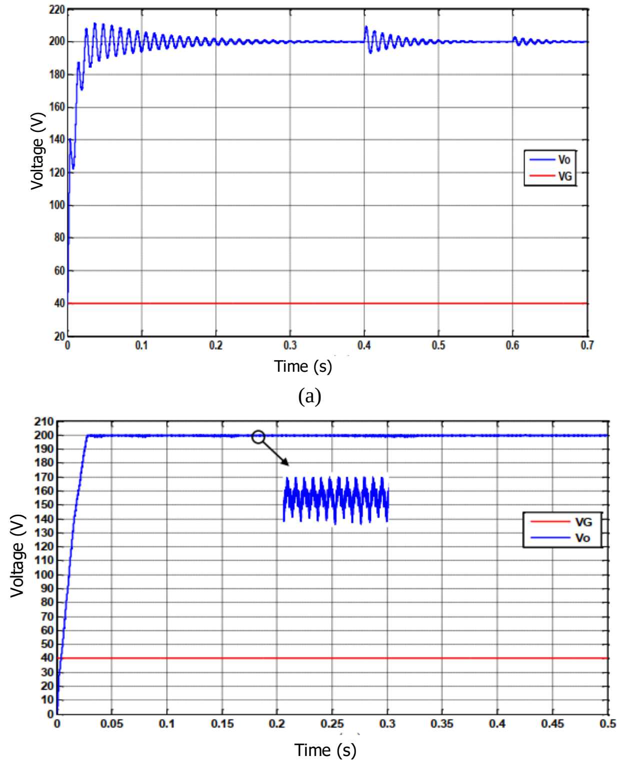
Table 1. Cascade DC/DC boost convertor parameters

Parameters	Values
Input Voltage (V_G)	*40 VDC*
Output Voltage (V_0)	*200 VDC*
Switching Frequency	*50 kHz*
Output Power (P_0)	*1 kW*
L_1	*0.55 mH*
L_2	*0.47 mH*
C_0	*47 uF*
C_1	*22 uF*
R_0	*40 Ω*

These parameters were applied to the cascade DC/DC boost converter model created in the MATLAB/Simulink environment together with PI and SMC controller. The advantages and disadvantages of both controllers are discussed in this section. In the simulations, the input voltage was kept constant and the response of the system was examined by changing the output resistances. In addition, the input voltage value was changed by keeping the output resistance constant and the response of the system was analyzed. All simulation results were able to keep the output voltage of the system constant at 200 VDC.

Fig. 7(a) shows the input and output voltage graph of the system in the circuit under which PI control is performed. In contrast, the input-output voltage graph of the SMC controlled circuit is as in Fig. 7(b).

As shown here, when the control of the cascade DC/DC boost converter is provided by SMC, the output voltage quickly reaches the desired value. With SMC, the transition of the system to the steady state is faster than the system with PI control. In addition, the dwell time and settlement time of the system are very short.

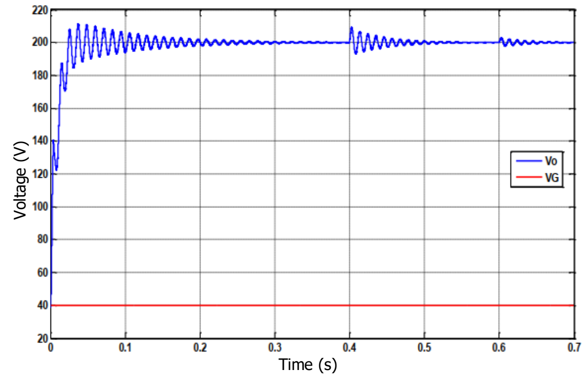


(a)

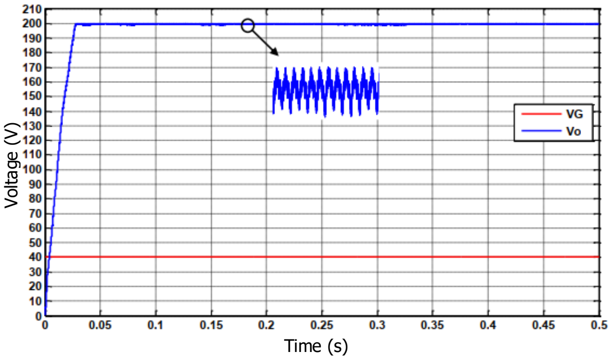
(b)

Fig. 7. System input and output voltage graph for (a) PI controlled circuit (b) SMC controlled circuit

Three different loads were tested at the output of the system. The output loads used herein are R_1=40Ω, R_2=80Ω and R_3=120Ω, respectively. Fig. 8(a) shows the output voltage at variable output loads of the PI controlled circuit and Fig. 8(b) shows the output voltage at variable output loads of the SMC controlled circuit.



(a)

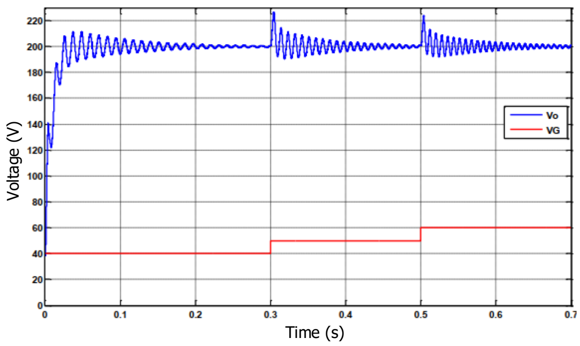


(b)

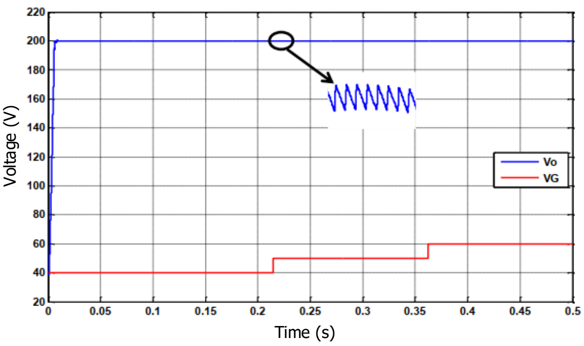
Fig. 8. Output voltage at variable output loads of (a) PI controlled circuit (b) SMC controlled circuit

In SMC controlled systems, the sliding surface is reached when the reaching phase is over. Thus, the output voltage will not be affected by the change of parameters and external disturbances. As shown in Fig. 8, no matter how much the output loads of the system change, the output voltage is kept constant. Furthermore, SMC responds very quickly to changes made compared to the PI control, and there is no deviation.

After examining the cascade DC/DC boost converter under different loads, this time, as shown in Fig. 9, the system with variable input voltages applied was examined. The input voltages were applied as 40-50-60 VDC respectively. Fig. 9(a) shows the PI controller applied system and Fig. 9(b) shows the SMC applied system.



(a)



(b)

Fig. 9. Output voltage at variable input voltages of (a) PI controlled circuit (b) SMC controlled circuit

All the simulation results showed that after the system became stable, the changes in the parameters did not cause any change in the output voltage of the system. Accordingly, the changes in the system controlled by the SMC controller were detected very quickly and the system response was very fast. In contrast, the system with the PI controller was able to detect these changes later and the system response was slower. Furthermore, the biggest advantage of SMC is that there is no deviation from the current state as the system's states are on the sliding surface when any changes occur in the system. This makes SMC superior to the PI controller.

IV. CONCLUSION

The cascade DC/DC boost converter is used to increase the output voltage ratio without increasing the duty cycle of conventional DC/DC boost converters. However, the two switching elements in these converter circuits both make control difficult and increase the cost. In order to prevent this problem, a single-switch cascade DC/DC boost converter has been used in the study. PI and SMC control methods have been used to obtain the desired voltage at the output of this converter. When the system is controlled by the PI controller, the time taken to reach the desired output values and to keep these values constant is high. In order to reduce these times, SMC control method was applied to the system. SMC is an effective control method that is insensitive to parameter changes and external disturbances in the system and quickly reaches the desired result.

As a result of the study, the most efficient cascade DC/DC boost converter circuit in terms of system parameters was designed and the desired output voltage values were obtained. In order to achieve the desired values, PI and SMC control methods were compared. Consequently, it has been observed that the most appropriate control method is SMC in order to reduce the time it takes to properly adjust the output voltage of the system and to minimize the disadvantages of the controller and the system.

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