

## A Quadratic Cascade DC/DC Boost Converter Design

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**Abstract** – This study includes the design of quadratic cascade DC/DC boost converter with PI controller. Two or more cascade boost converters have been used to increase system efficiency. Advantages of the proposed converter compared to the conventional boost converter are less current fluctuations and output voltage, the prolongation of system life by dividing the input current, and the less number of semiconductor elements used. What makes this converter more advantageous than others is that it only works with a single controller circuit by adding a diode, capacitor and inductor. The mathematical equations of the system have been obtained by the equivalent circuit analysis and thus the control circuit has been designed. The purpose of the generated control circuit is to keep the output voltage of the system constant due to the power sources that produce different voltages. The controller realizes this by applying to the power switches after generating different pulse widths at variable loads. The proposed quadratic cascade DC/DC boost converter has not caused any change in the output voltage despite the variable load and input voltage values. As a result, the proposed system is longer lasting compared to the conventional boost converters.

**Keywords** – *Boost converter, quadratic cascade boost converter, control strategy, power electronics*

### I. INTRODUCTION

One of the most common types of DC/DC converters is the boost converters. This converter increases the input DC voltage at a certain level to a higher DC voltage level. Boost converters are especially used excessively in power electronics applications. Boost converters are indispensable especially in renewable energy applications because they regulate the variable voltage and raise low input voltage values. Applications using DC/DC boost converters are automotive applications, power amplifier applications, adaptive control applications, battery power systems, consumer electronics, and communication applications [1], [2].

Nowadays, renewable energy sources such as solar energy, wind energy, wave energy, and fuel cell have become an alternative energy source with the increasing damage caused by fossil fuels to the environment [3], [4]. However, the current and voltage characteristics of these renewable energy systems are always variable [5]. It is, therefore, necessary to use three-phase power electronics converters in these renewable generation systems. Among the proposed topologies, three-phase DC/DC boost converters are used for energy conversion in systems consisting of renewable power sources because they can offer high efficiency and low electromagnetic interference emissions [6], [7]. The performance of these converters in terms of efficiency depends on the applied control structure. To improve the amplifier performance, different control strategies have been presented in the literature using pulse width modulation (PWM), space vector modulation, soft switching, nonlinear and adaptive control methods [8]-[13]. These methods are used to control the system in applications involving renewable power systems and to make the system less affected by the variable parameters.

In this study, the DC/DC boost converter with a PI controller is designed as a cascade. This approach is based on the principle of increasing the performance and efficiency of the system by using two or more cascade boost converters at the same time. It is aimed to extend the life of the structure by dividing the current at the system entrance. In addition, the total number of semiconductor elements in the system is less than that of conventional boost converters. The PI controller block used in the design minimizes the fluctuations in the output voltage by controlling the voltage generation by changing the pulse widths applied to the MOSFETs in the converter.

### II. MATERIALS AND METHOD

The basis of this study is the quadratic boost converter with voltage gain 4 when the pulse width is 0.5. The advantages of the structure are that thanks to the cascade connections do not increase the number of the power switch, only the addition of new inductor, capacitor and diode are sufficient and it can operate with only one controller circuit. The control circuit is designed by analyzing the mathematical equations of the circuit. The main purpose of the control circuit is to apply it to power supplies that produce different voltages and to keep the output voltage constant. In addition, since the load values connected to the circuit can change at any time, the control circuit generates different pulse widths and applies them to the power switch to keep the output voltage of the circuit stable.

The PI controller design is based on the dynamic model of the circuit. The circuit diagram is shown in Fig. 1 with the switch closed in the quadratic cascade boost converter. According to this diagram, inductor and capacitor equations are as follows.

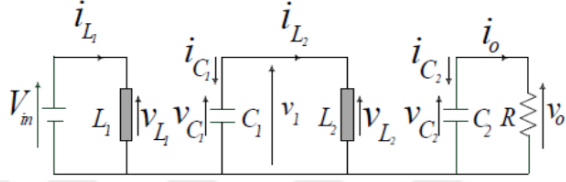


Fig. 1. Quadratic cascade boost converter (switch off)

$$L_1 \frac{di_{L1}}{dt} = V_{in}, L_2 \frac{di_{L2}}{dt} = v_{c1}, C_1 \frac{dv_{c1}}{dt} = -i_{L2}, C_2 \frac{dv_{c2}}{dt} = -\frac{v_0}{R} \quad (1)$$

Thanks to these equations, we can easily obtain the state space equations of the system.

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1}, \frac{di_{L2}}{dt} = \frac{v_{c1}}{L_2}, \frac{dv_{c1}}{dt} = -\frac{i_{L2}}{C_1}, \frac{dv_{c2}}{dt} = -\frac{v_0}{C_2 R} \quad (2)$$

The circuit diagram is shown in Fig. 2 with the switch on in the quadratic cascade boost converter. According to this diagram, inductor and capacitor equations are as follows.

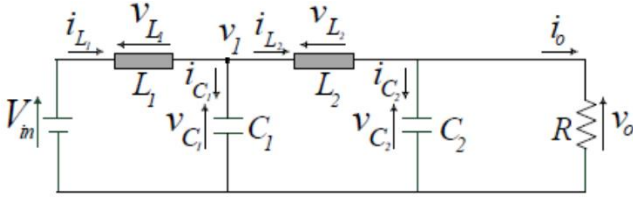


Fig. 2. Quadratic cascade boost converter (switch on)

$$\begin{aligned} L_1 \frac{di_{L1}}{dt} &= V_{in} - v_{c1}, & L_2 \frac{di_{L2}}{dt} &= v_{c1} - v_0 \\ C_1 \frac{dv_{c1}}{dt} &= i_{L1} - i_{L2}, & C_2 \frac{dv_{c2}}{dt} &= i_{L2} - \frac{v_0}{R} \end{aligned} \quad (3)$$

What is important for the PI controller design is to calculate the correlation between inductor currents or derivatives of capacitor voltages. According to this;

$$C_2 \frac{dv_{c2}}{dt} + \frac{v_0}{R} = (1 - d)i_{L2} = u \quad (4)$$

correlation is obtained. In this equation, u is the output of the PI controller. When the equation (4) is arranged; the equation

$$d = 1 - \frac{u}{i_{L2}} \quad (5)$$

is obtained. The closed-loop transfer function of a PI controller is expressed as follows:

$$G_F = \frac{G_0}{1+G_0} = \frac{\frac{1}{C_2}(k_p+k_i)}{s^2 + \left(\frac{1+Rk_p}{RC_2}\right)s + \frac{k_i}{C_2}} \quad (6)$$

If we edit this obtained equation;

$$G_F = \frac{\frac{1}{C_2}(k_p s + k_i)}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \quad (7)$$

is obtained. Finally, when the equations are compared, the coefficients  $k_p$  and  $k_i$  are calculated as follows.

$$k_p = 2\zeta\omega_0 C_2 - \frac{1}{R}, \quad k_i = \omega_0^2 C_2 \quad (8)$$

As a result of the equations and calculated parameters, the voltage control scheme of the quadratic cascade boost converter is shown in Fig. 3.

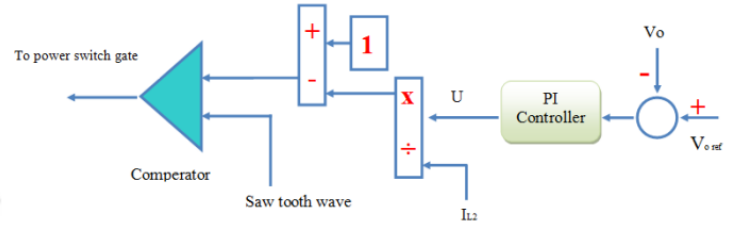


Fig. 3. Voltage control diagram of the quadratic cascade boost converter

### III. RESULTS AND DISCUSSION

In this section, it is compared that the traditional boost converters and the proposed quadratic cascade boost converters. The circuit diagram of the designed quadratic cascade boost converter is shown in Fig. 4.

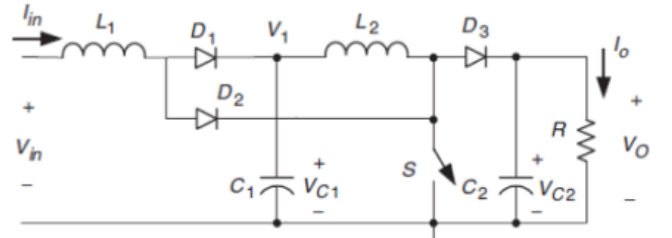


Fig. 4. Designed quadratic cascade boost converter circuit diagram

Then, the PI controller circuit is added to the designed circuit to evaluate the performance of the structure. The system parameters have been calculated as  $k_p = 0.002$  and  $k_i = 2.54$  when placed in Eq. (8). The best results have been obtained with these values. The purpose of using the PI controller in the system is to obtain a constant voltage at the output by controlling the changes in the input voltage of the system or sudden changes of the loads at the system output. Usually, the output voltage in the controller circuits is compared to a reference voltage and the resulting signal is applied to the controller as input. The controller circuit designed in this study takes the inductor current on the second floor of the cascade circuit as an example. This reveals the difference between the designed controller from the other controllers.

The block diagram of the proposed design is shown in Fig. 5. Accordingly, using low-power converters in parallel instead of high-power converters has several advantages. Some of these advantages are; higher efficiency, better dynamic response time, better load regulation, higher reliability, easier maintenance, and smaller energy storage devices. The majority of losses in the system are directly related to the currents passing through the inductors. Therefore, the converters are connected in parallel to reduce these currents as much as possible and achieve fewer loss values. In this way, the current at the system input is divided on parallel paths. By increasing these paths, the current flowing through each floor decreases to a lesser value and transmission and switching losses on the elements are reduced and system efficiency is increased.

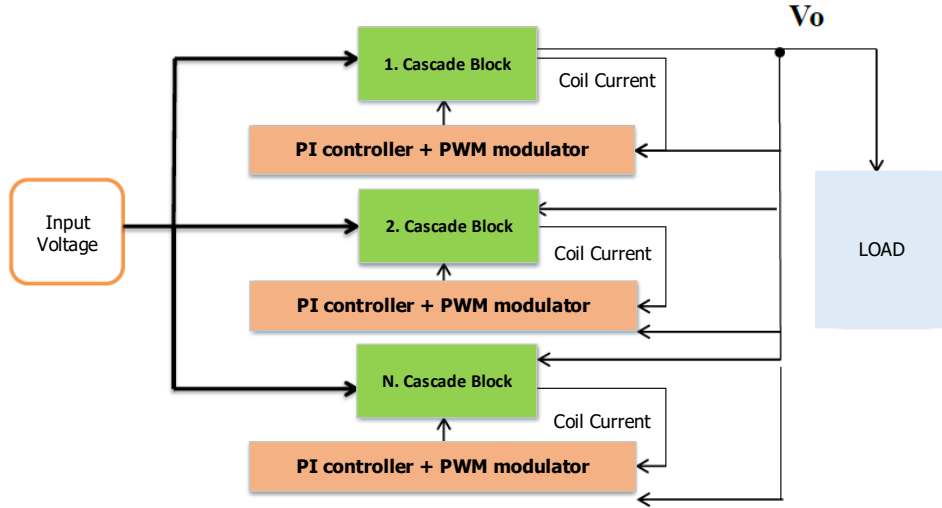


Fig. 5. Block diagram of the proposed design

In the system, two or more cascade boost converters have been connected as parallel with the PI controller and PWM modulator at the input and output of the system. The power value that can be transferred increases with the increase of the floors. At higher power ratings, it is necessary to increase the number of floors in order for the circuit to operate with safe and low current values.

The proposed quadratic double-floor cascade boost converter is more advantageous than a single-floor boost converter. In particular, if any of the circuits fails, at least one circuit continues to generate a voltage. The output voltage fluctuation is very small. Current fluctuations of the inductors at the input are below 5%. Furthermore, one of the characteristics of the boost converter circuit is that the output voltage is not affected too much even if the load at the output changes. Fig. 6 shows the voltage changes at the system output for different output load values.

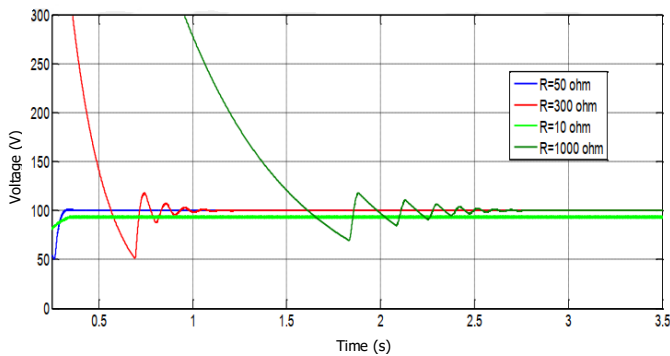


Fig. 6. System output voltages at different loads

Accordingly, the output voltages have remained constant when the output load changes. The load values have been changed to 10Ω, 50Ω, 300Ω and 1000Ω respectively. In contrast, the output voltages have been conveniently fixed to 100V. In a well-controlled boost circuit, the output voltage remains constant, no matter how much the input voltage changes. However, as a result of the input voltage changes while the output load is constant, the voltage graph at the system output is shown in Fig. 7. Input voltage values have been changed to 15V, 21V and 35V respectively. Despite these

changes, the system output voltage increased to 80V and remained constant around 80V.

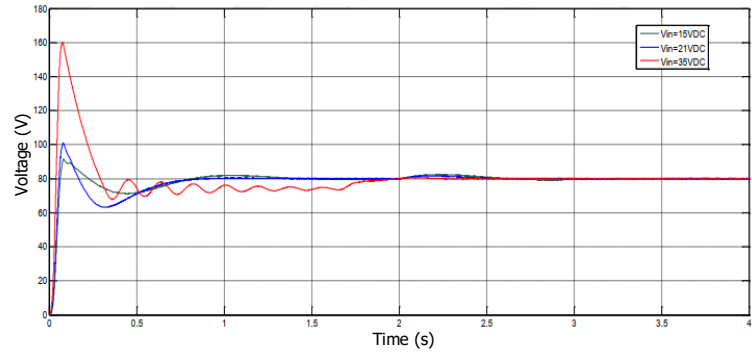


Fig. 7. System output voltages at different input voltages

The elements used in the designed circuit are given in Table 1. Accordingly, the proposed cascade boost converter and the conventional structure have compared. Under the same conditions (input voltage, load, frequency and pulse width), the voltage gain of the proposed cascade circuit has been determined to be higher. Considering fluctuation rates, this ratio is acceptable level in both structures.

Furthermore, the comparison of the proposed structure and the conventional structure at different output powers is shown in Fig. 8. According to these results, it is observed that the proposed structure is more efficient at high values of output power.

Table 1. The proposed structure and conventional structure values

Proposed	Conventional
$L_1=3\text{ mH}$	$L_1=7\text{ mH}$
$L_2=3\text{ mH}$	$L_2=3\text{ mH}$
$C_1=33\text{ }\mu\text{F}$	$C_1=33\text{ }\mu\text{F}$
$C_2=330\text{ }\mu\text{F}$	$C_2=330\text{ }\mu\text{F}$
$RL_1=0.3\text{ }\Omega$	$RL_1=0.7\text{ }\Omega$
$RL_2=0.3\text{ }\Omega$	$RL_2=0.3\text{ }\Omega$
$V_{in}(DC)=30\text{ V}$	$V_{in}(DC)=30\text{ V}$
$R=450\text{ }\Omega$	$R=450\text{ }\Omega$
$M_{1,2}\text{ Duty-cycle}=0.5$	$M_{1,2}\text{ Duty-cycle}=0.5$
$\text{Frequency}=10\text{ kHz}$	$\text{Frequency}=10\text{ kHz}$

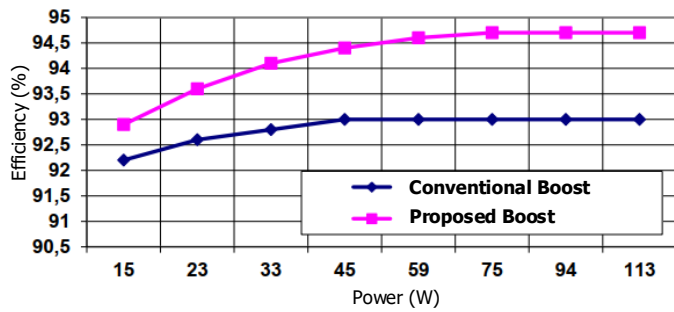


Fig. 8. Comparison of the efficiency of two structures at different output powers

The simulation results obtained by changing the load values at the system output between 50 Ω and 450 Ω and the input voltage between 18 V and 45 V are given in Fig. 9.

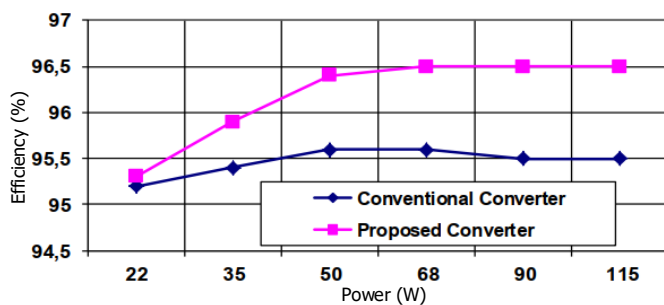


Fig. 9. Efficiency comparison between parallel proposed and parallel conventional boost converters according to the system output power

Accordingly, 50 V voltage and 2% THD (Total Harmonic Distortion) were obtained at the output of the proposed structure. Fig. 9 shows the efficiency comparison of these two structures relative to the output power values. As a result, a quadratic cascade boost converter designed in the study has been understood to be more efficient than conventional boost converters.

#### IV. CONCLUSION

In this study, a new model is presented by using a PI controller and PWM technique for cascade DC/DC boost converters. Quadratic DC/DC boost converter has been used for each floor. More than two parallel floors have been used for power transfer, depending on the system input power or the boost converter capacity used on each floor. Thanks to the designed PI controller, the system has operated with stable and high efficiency at different input voltages and output loads. The main advantage of the proposed structure is that by dividing the input current in parallel paths, less current flows in the circuit elements and switches, thus providing longer life and higher efficiency of the system. In addition, the proposed structure can be easily applied to all renewable energy sources because the input currents of the floors have a very small fluctuation rate.

In future applications of this structure, studies in the higher powers can be done. In addition, different boost structures can be used on the floors. Furthermore, applications with different loads can be realized by converting the generated DC voltage to AC values with different inverter structures.

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