

## Modeling and Simulation of DC-DC Converters

Evren ISEN<sup>1\*</sup>

<sup>1</sup>Department of Electrical Engineering, Faculty of Engineering and Natural Sciences, Bandirma Onyedü Eylül University, Bandirma, Turkey

**Abstract:** DC-DC converters are used in many types industrial applications. They are used to change the DC source voltage level to higher or lower level. In recent years, as the use of photovoltaic systems increases, DC-DC converters have got more important. In this study, the basic DC-DC converters, named boost, buck and buck-boost converters, are modeled and simulated in Matlab/Simulink. The detailed circuit equations and derived models from that equations for each switching modes are presented in the study. The obtained results from converter models are verified with electrical simulations that is utilized Simulink blocks. Closed-loop control is used in both methods. Both simulations are realized in the same conditions, such as controller parameters, circuit parameters and simulation options in Simulink. Transient-state with load change and steady-state response of both methods are compared in the study. The output voltages of each methods and difference waveforms are given in the results. They show that the presented models can be used for simulation of these converters.

**Keywords:** Boost Converter, Buck Converter, Buck-Boost Converter, Converter Modeling

### DC-DC Dönüştürücülerin Modellenmesi ve Simülasyonu

**Özet:** DC-DC dönüştürücüler birçok endüstriyel uygulamada kullanılmaktadır. DC kaynak gerilim seviyesini arttırmak veya azaltmak için kullanılırlar. Son yıllarda fotovoltaik sistemlerin kullanımının artmasından dolayı DC-DC dönüştürücülerin kullanımı daha fazla önem kazanmıştır. Bu çalışmada, yükseltici, düşürücü ve düşürücü-yükseltici dönüştürücü olarak adlandırılan temel DC-DC dönüştürücüler Matlab/Simulink ortamında modellenmiş ve simülasyonları yapılmıştır. Her bir anahtarlama modu için ayrıntılı devre denklemleri ve bu denklemlerden türetilmiş modeller çalışmada sunulmuştur. Dönüştürücü modellerinden elde edilen sonuçlar, Simulink bloklarının kullanıldığı elektrik simülasyonları ile doğrulanmıştır. Her iki yöntemde de kapalı çevrim kontrol kullanılmıştır. Simulink ortamında her iki simülasyon da, kontrolör parametreleri, devre parametreleri ve simülasyon seçenekleri açısından aynı koşullarda gerçekleştirilmiştir. Çalışmada her iki yöntemin yük değişimli geçici durum ve kararlı durum cevabı incelenmiştir. Her yöntemin çıkış gerilimleri ve gerilim farkları sonuçlarda verilmiştir. Elde edilen sonuçlar sunulan modellerin bu dönüştürücülerin simülasyonu için kullanılabileceğini göstermektedir.

**Anahtar Kelimeler:** Yükseltici Dönüştürücü, Düşürücü Dönüştürücü, Düşürücü-Yükseltici Dönüştürücü, Dönüştürücü Modelleme

Reference to this paper should be made as follows

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### 1. Introduction

Switched-mode DC-DC converters can be produced lighter and smaller than linear converters. Therefore, they are utilized in portable consumer electronics as well as industrial electronics. DC-DC converters are widely used in different applications such as uninterruptable power supply [1], battery charging [2], [3], photovoltaic (PV) systems [4], [5], wind power systems [6], [7]. They are used in wide range of power. Isolated [8] and non-isolated [9] topologies are preferred depending on the application requirement. Nowadays, due to the increase in the use of renewable energy sources and electric vehicles today, the use of DC-DC converters has also increased.

DC-DC converters have an important role in PV systems. Because the output voltage of a PV panel is DC, the DC-DC converters are used at the output of PV panel. Depending on the panel voltage, DC bus voltage level and isolation requirement, different types of DC-DC converters are used.

\*Corresponding author; [eisen@bandirma.edu.tr](mailto:eisen@bandirma.edu.tr)

Boost, buck and buck-boost converters are basis, and most used types of non-isolated converters. The efficiency and control are important as PV panels have low efficiency. Therefore, many researches are done on DC-DC converters [10], [11]. A quadratic boost converter is improved to increase the power conversion efficiency [12]. The efficiency and voltage gain are increased with the modified topology of bidirectional DC-DC converter with four switches. It is developed for the applications that have low output voltage with a high current [13]. With switched-capacitor structure and sliding mode control, DC voltage gain increases, and the voltage stress is decreased on the power switch. It provides longer off-time for switch in continuous current mode, thus losses of the switch decreases [14].

The modeling of converter is used to design the converter control. Using the two different digital controllers on a boost converter model, performance of the converter is presented [15]. Signal flow graph method is used to extract the model of buck-boost converter, and the controller is used on the model [16]. Boost and Cuk converters are modelled, and their MPPT performances are compared using the models [17]. Sliding mode and fuzzy logic MPPT techniques are applied on a boost converter to present the performances of the techniques [18].

In this study, non-isolated DC-DC converters called boost converter, buck converter and buck-boost converter are modelled in Matlab/Simulink. The results of the model are verified with the electrical simulation results. The presented models can be applied in m-file with code to analyze the converters for many different types of parameters fast.

## 2. Modeling and Simulation of the Converters

The converters are modeled in Matlab/Simulink in the study. The mathematical model is applied in Simulink by mathematical blocks. The obtained model results are compared with electrical simulation results to verify the models. The same circuit and control parameters are used in two methods. The used circuit parameters are given in Table 1.

**Table 1.** Circuit parameters

Converter type	$v_i$	$v_o$	P	L	C	f
Boost converter	24 V	48 V	480 W	300 $\mu H$	250 $\mu F$	20 kHz
Buck converter	48 V	24 V	480 W	300 $\mu H$	12.5 $\mu F$	20 kHz
Buck-boost converter	48 V	24 V	480 W	600 $\mu H$	500 $\mu F$	20 kHz

The boost, buck and buck-boost converters are inductor-based converters. This type of converters work based on energy transfer from inductor to output. Depending on the controlled switch, two state occurs in the converters. In the first state that the switch is *ON*, the energy that is drawn from input is stored in the inductor. In the second state, the switch is *OFF*, and stored energy in the inductor is transferred to the output. Two different equivalent circuits exist depending on the switching state. In each state, differential equations of the circuit occur, and they are used for converter modeling. The advantageous of modeling is to be applicable in different software.

### 2.1 Boost Converter

In the non-isolated applications if the DC voltage must be increased, boost converter is used to increase the input DC voltage to higher DC output voltage [19]. The converter consists of an input inductor, a semiconductor switch, a diode and an output capacitor as seen in Figure 1 [20].

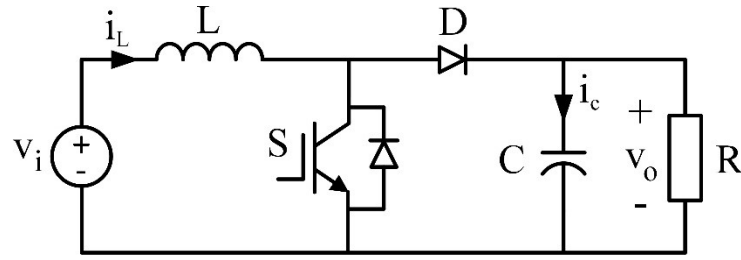


Figure 1. Boost converter topology

In the boost converter, semiconductor switch is turned *ON* and *OFF* during a switching period. Two different operation modes occurs in a switching period as seen in Figure 2. The *ON* state topology that the controlled switch is closed, is given in Figure 2a. In this mode, input voltage is applied to inductor directly, and inductor current increases. Inductor voltage and current equations are given in (1). Output capacitor feeds the load and discharges, simultaneously while inductor stores energy. The equations of the capacitor seen in (2).

The second mode that switch is *OFF* in, is seen Figure 2b. In this mode, the energy stored in the inductor is transferred to the output so the inductor current decreases. The load is fed, and the capacitor charges. The equations of the mode are seen in (3) and (4). The differential equations depending on the switching function (*S*) obtained by combining differential equations in (1)-(4). The mathematical model can be applied in Simulink by (5) and (6). In the equations, *S* function takes value 0 and 1.

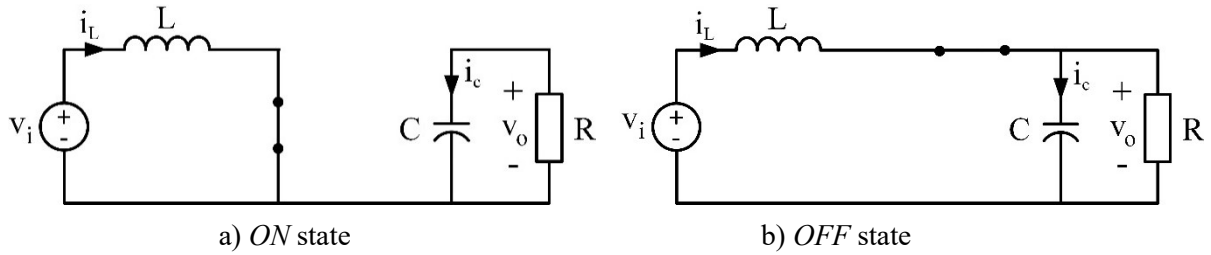


Figure 2. Operation modes of boost converter

$$\left. \begin{aligned} v_L &= v_i \\ \frac{di_L}{dt} &= \frac{v_i}{L} \end{aligned} \right\} S = 1 \quad (1)$$

$$\left. \begin{aligned} i_C &= -\frac{v_o}{R} \\ \frac{dv_o}{dt} &= -\frac{v_o}{RC} \end{aligned} \right\} S = 1 \quad (2)$$

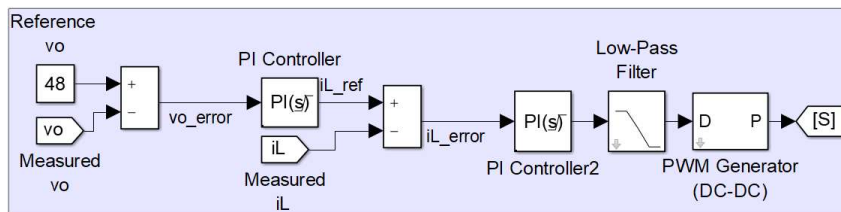
$$\left. \begin{aligned} v_L &= v_i - v_o \\ \frac{di_L}{dt} &= \frac{v_i - v_o}{L} \end{aligned} \right\} S = 0 \quad (3)$$

$$\left. \begin{aligned} i_C &= i_L - \frac{v_o}{R} \\ \frac{dv_o}{dt} &= \frac{i_L}{C} - \frac{v_o}{RC} \end{aligned} \right\} S = 0 \quad (4)$$

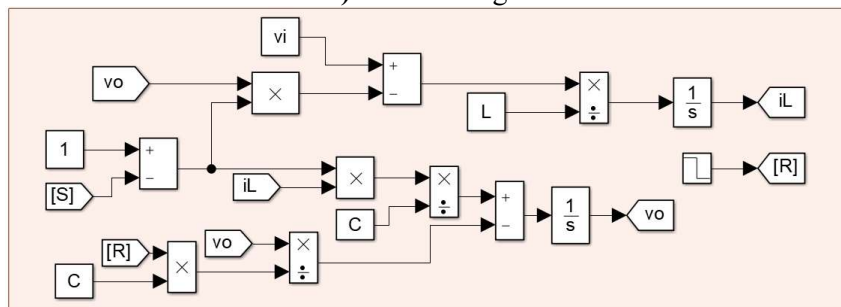
$$\frac{di_L}{dt} = \frac{v_i - v_o(1-S)}{L} \tag{5}$$

$$\frac{dv_o}{dt} = \frac{i_L(1-S)}{C} - \frac{v_o}{RC} \tag{6}$$

Figure 3 shows the Simulink model of the boost converter. Closed-loop control algorithm and mathematical model of the converter are given in Figure 3a and Figure 3b. In the control algorithm, the output voltage error is calculated by reference and measured values. The error is applied to PI regulator, and the output of the regulator gives the inductor current reference. Using this value and measured inductor current value, current error is calculated, and it is applied to PI regulator to calculate duty cycle. The duty cycle signal is filtered with low-pass filter to stabilize the variation. At the end of the algorithm, the duty cycle is given to DC-PWM generator to create PWM signals. The outputs of the mathematical model are output voltage and inductor current. PWM signals that control the converter define with  $S$  function. Changing with  $S$ , inductor current and output voltage occurs.



a) Control algorithm



b) Mathematical model of the converter

Figure 3. Simulink model of the boost converter

In order to verify the results of the model, electrical simulation is realized in Simulink that is shown in Figure 4. The same control algorithm that is seen in is Figure 3a used in the simulation. The output voltage waveforms of two methods and difference between them are given in Figure 5. The output voltage waveforms are so similar as seen in Figure 5a and Figure 5b. The difference voltage waveform is very small as seen in Figure 5c. It shows the suitability of the model.

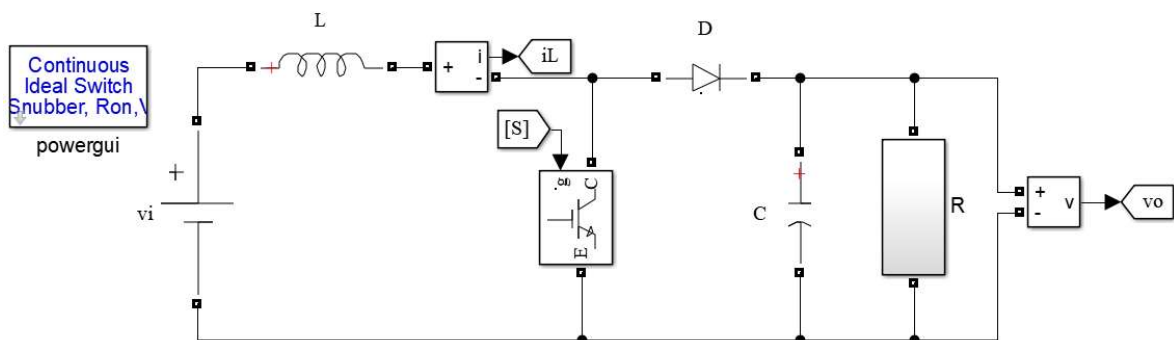


Figure 4. Simulink circuit of the boost converter

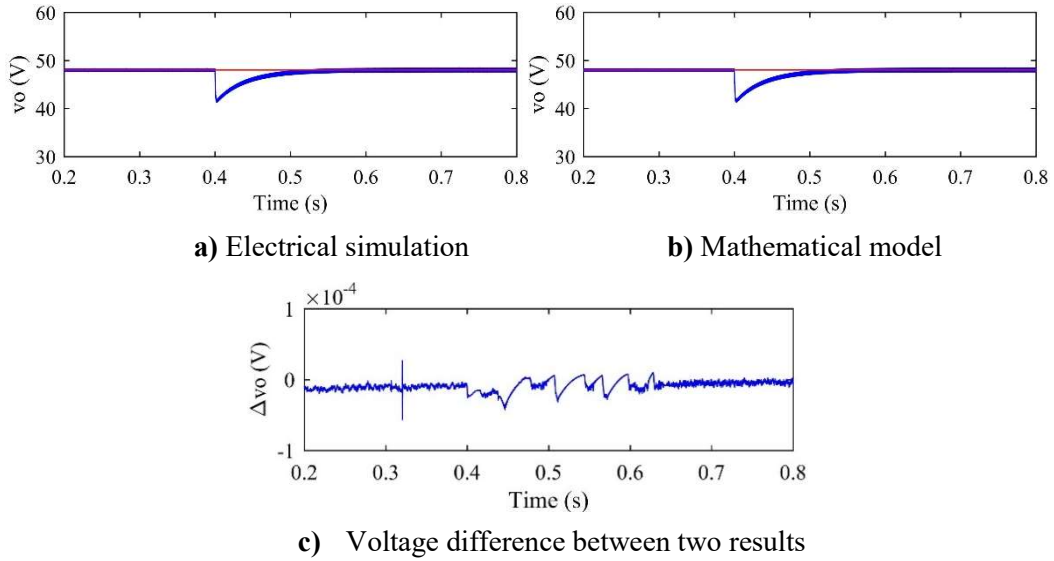


Figure 5. Output voltages and difference voltage waveforms

### 2.2 Buck Converter

This type of converter is used to decrease the input DC voltage to lower DC voltage at the output [21]. It consists of the same components with boost converter. The difference between two topologies is location the components. Inductor places in the output of the converter. Therefore, input current is discontinuous unlike boost converter [22]. Figure 6 shows the buck converter topology.

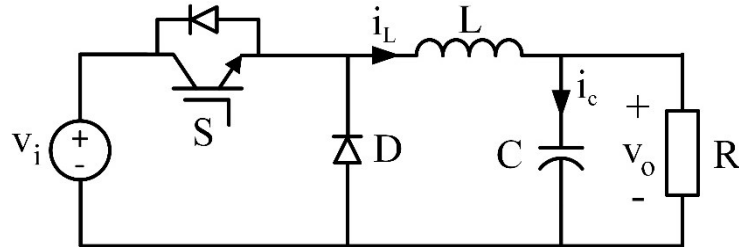


Figure 6. Buck converter topology

The operation modes that occur depending on the switching state, are shown in Figure 7. In the first mode, the switch is *ON*, and input supply feeds the output. The inductor stores energy in this interval. The topology is seen in Figure 7a. In the *OFF* mode, the diode is *ON*, and the current continues flowing through the diode as seen in Figure 7b.

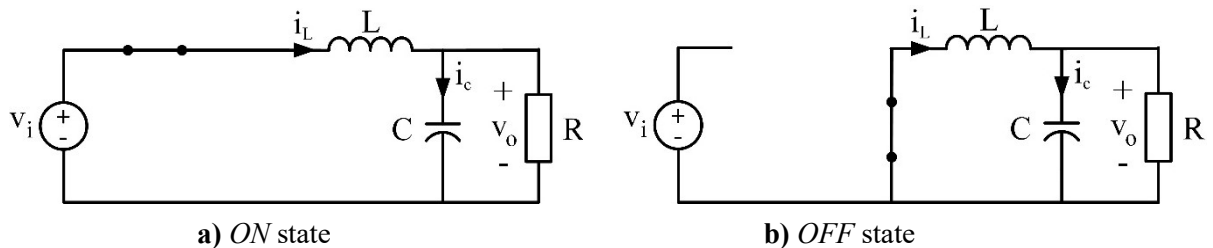


Figure 7. Operation modes of buck converter

The circuit equations of the converter for both modes are given in (7)-(9). Combining the equations and using the  $S$  function, the equations (10) and (11) are obtained. The differential equations are used for modeling the converter.

$$\left. \begin{aligned} v_L &= v_i - v_o \\ \frac{di_L}{dt} &= \frac{v_i - v_o}{L} \end{aligned} \right\} S = 1 \quad (7)$$

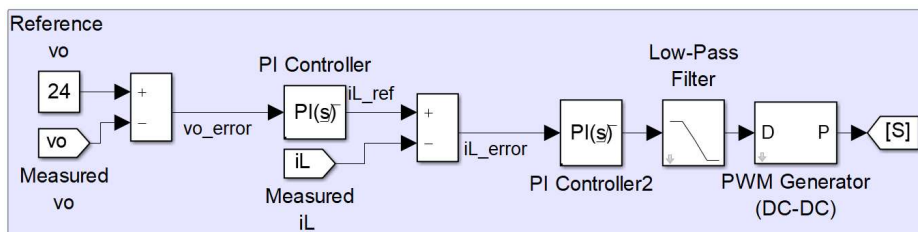
$$\left. \begin{aligned} i_C &= i_L - i_o \\ \frac{dv_o}{dt} &= \frac{i_L - \frac{v_o}{R}}{C} \end{aligned} \right\} S = 1, 0 \quad (8)$$

$$\left. \begin{aligned} v_L &= -v_o \\ \frac{di_L}{dt} &= -\frac{v_o}{L} \end{aligned} \right\} S = 0 \quad (9)$$

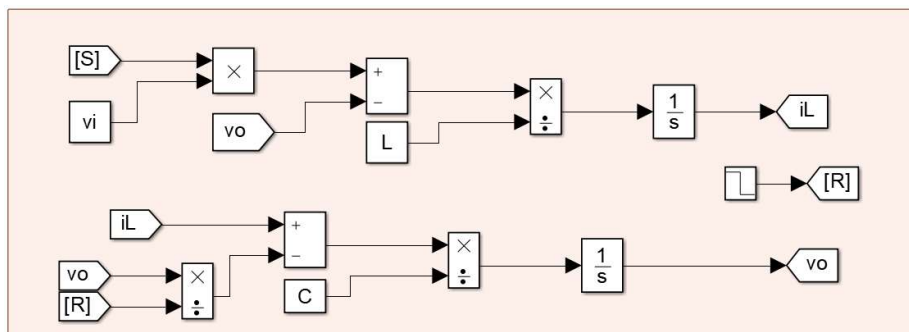
$$\frac{di_L}{dt} = \frac{Sv_i - v_o}{L} \quad (10)$$

$$\frac{dv_o}{dt} = \frac{i_L - \frac{v_o}{R}}{C} \quad (11)$$

The mathematical model and control algorithm of the buck converter is seen in Figure 8. The closed-loop control algorithm is given in Figure 8a. Based on the equations (10) and (11), the mathematical model of the circuit is created as seen in Figure 8b.



a) Control algorithm



b) Mathematical model of the converter

Figure 8. Simulink model of the buck converter

The Simulink electrical circuit of the buck converter is given in Figure 9. Unlike boost converter, inductor is placed at the output. As the controlled switch is placed in the input side, input current is discontinuous. The control algorithm is the same with model control algorithm that is given in Figure 8a.

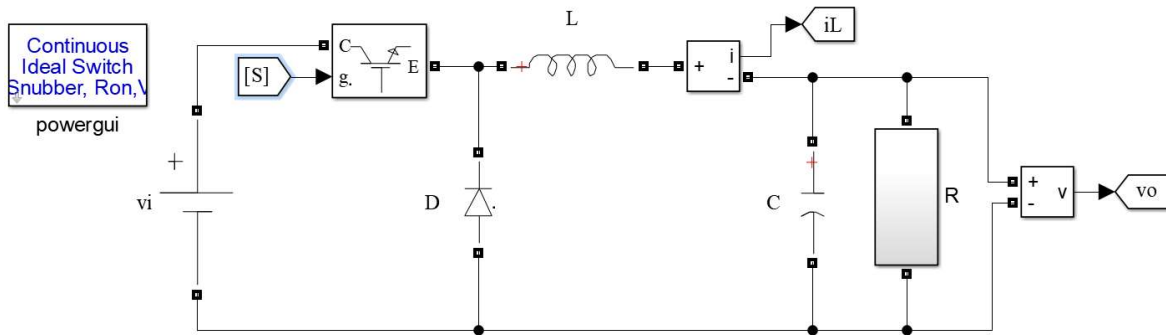


Figure 9. Simulink circuit of the buck converter

The model and electrical simulation results are given in Figure 10. Electrical simulation and mathematical model output voltage waveforms are seen in Figure 10a and Figure 10b, respectively. As seen in Figure 10c, there is a very small difference between each results only in transient-state. The waveforms show the effectiveness of the model.

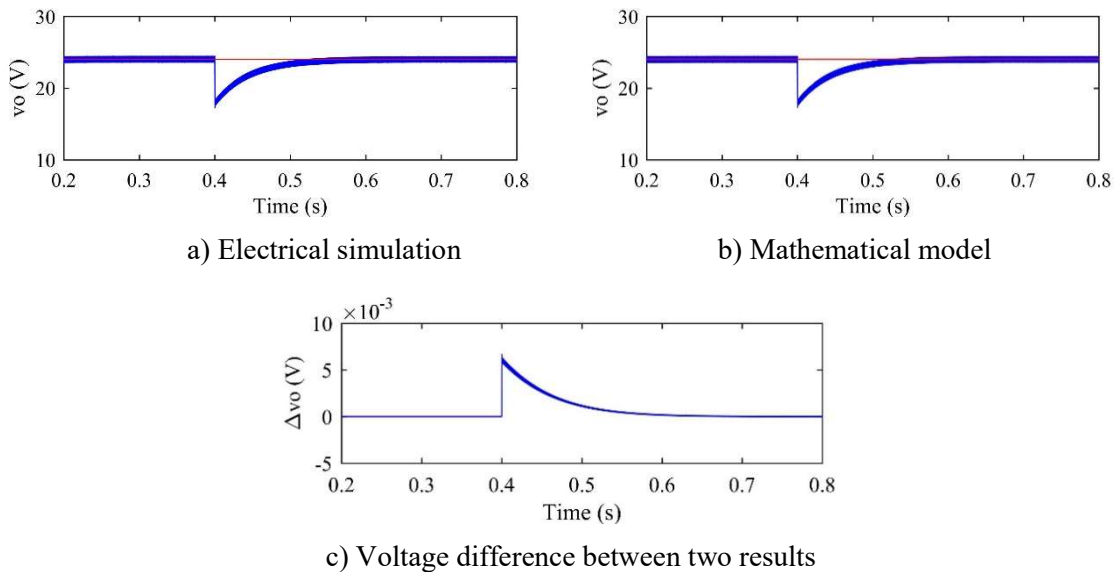


Figure 10. Output voltages and difference voltage waveforms

### 2.3 Buck-Boost Converter

The converter has a capability to decrease or increase the input DC voltage. It is a converter of a combination of boost and buck converter [23]. The main difference of the converter from the others is output voltage polarity [24]. The topology of the converter is seen in Figure 11. In the converter, controlled switch is connected to input as buck converter. When the switch is *ON*, the inductor is connected to input supply directly, and energy is stored in the inductor while the capacitor feeds the load. As the diode is reverse polarity, it isolates the input and output sides of the converter. In the *OFF* state, the diode starts flowing current, and the stored energy is transferred to the output. The state topologies are given in Figure 12.

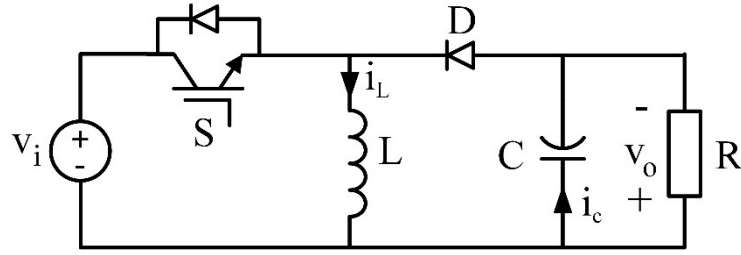


Figure 11. Buck-boost converter topology

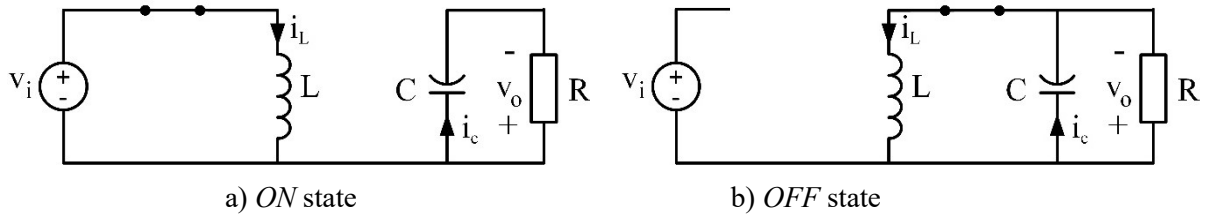


Figure 12. Operation modes of buck-boost converter

In order to derive the differential equations of the model, the required circuit equations are given in (12)-(15) for two states of the  $S$  function. The derived model by combining the equations with  $S$  is seen in (16) and (17). The Simulink model that is seen Figure 13 is derived based on the model.

$$\left. \begin{aligned} v_L &= v_i \\ \frac{di_L}{dt} &= \frac{v_i}{L} \end{aligned} \right\} S = 1 \quad (12)$$

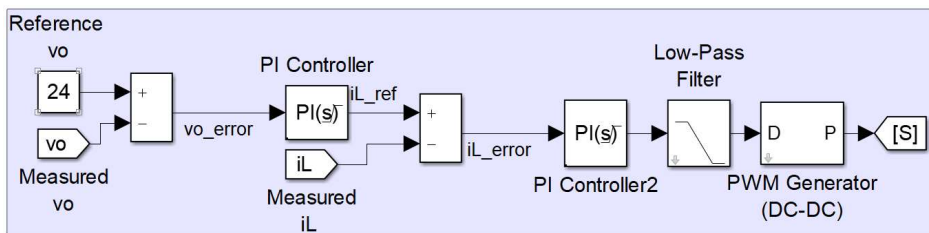
$$\left. \begin{aligned} i_C &= -\frac{v_o}{R} \\ \frac{dv_o}{dt} &= \frac{v_o}{RC} \end{aligned} \right\} S = 1 \quad (13)$$

$$\left. \begin{aligned} v_L &= -v_o \\ \frac{di_L}{dt} &= -\frac{v_o}{L} \end{aligned} \right\} S = 0 \quad (14)$$

$$\left. \begin{aligned} i_C &= i_L - i_o \\ \frac{dv_o}{dt} &= \frac{i_L}{C} - \frac{v_o}{RC} \end{aligned} \right\} S = 0 \quad (15)$$

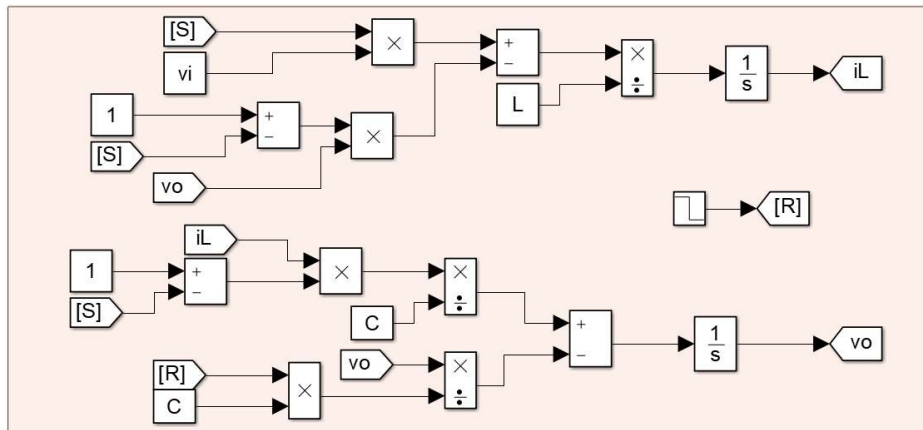
$$\frac{di_L}{dt} = \frac{Sv_i - (1-S)v_o}{L} \quad (16)$$

$$\frac{dv_o}{dt} = \frac{(1-S)i_L}{C} - \frac{v_o}{RC} \quad (17)$$



a) Control algorithm

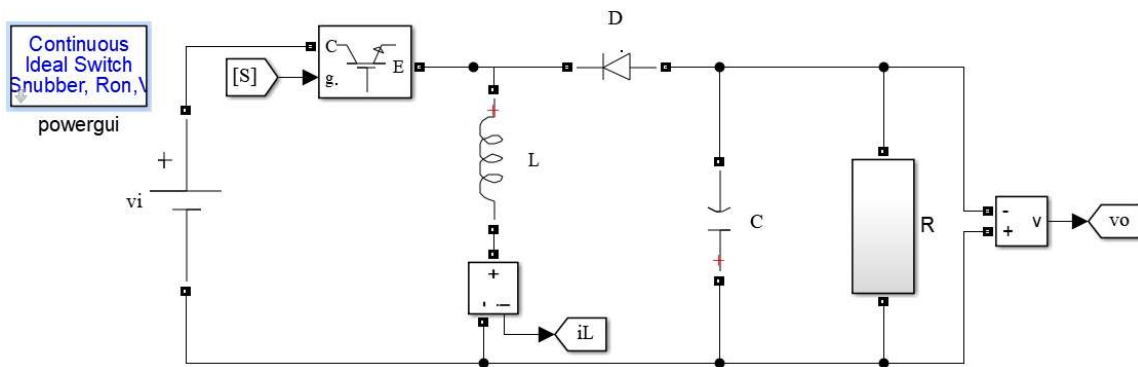




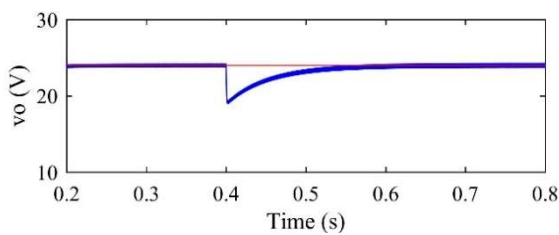
b) Mathematical model of the converter

**Figure 13.** Simulink model of the buck-boost converter

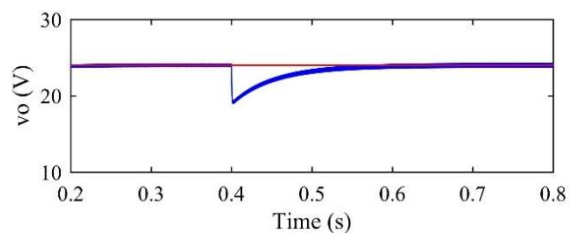
The electrical simulation model in Simulink, and results of both methods are seen in Figure 14 and Figure 15, respectively. Both methods have a good steady-state response and transient response as seen in Figure 15a and Figure 15b. As seen in Figure 15c, the difference between two results is very small and negligible. It verifies the effectiveness of the mathematical model.



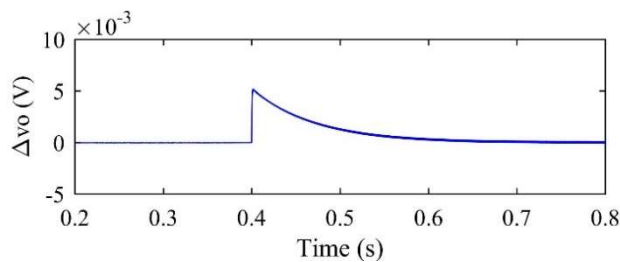
**Figure 14.** Simulink circuit of the buck-boost converter



a) Electrical simulation



b) Mathematical model



c) Voltage difference between two results

**Figure 15.** Output voltages and difference voltage waveforms

### 3. Discussion

The mathematical models of the three converters are given in Table 2 in order to overview the results. In the models, capacitor voltage  $v_o$  and inductor current  $i_L$  are state variables. The models run depending on the  $S$  switching function. It defines the PWM signal. It takes values zero and one. In the electrical simulation, it corresponds *ON* and *OFF* states. The output voltage of converters is obtained depending on the models.

The main advantageous of converter modeling is that total simulation real time is shorter than the electrical simulation that is done by Simulink blocks. Table 3 shows the real running time of electrical simulations and models. As seen in the table, model simulation real time is shorter than electrical simulation in three converters. In boost converter, the model simulation time is shorter of 32.6% than electrical simulation. Similarly, in buck and buck-boost converters, model simulation time is shorter of 41.1% and 45.3%, respectively. The Table 3 shows effectiveness of modeling on simulation real time. If the simulated system is more complex, the difference time gets higher.

**Table 2.** Mathematical model

Converter type	Inductor current	Output voltage
Boost converter	$\frac{di_L}{dt} = \frac{v_i - v_o(1-S)}{L}$	$\frac{dv_o}{dt} = \frac{i_L(1-S)}{C} - \frac{v_o}{RC}$
Buck converter	$\frac{di_L}{dt} = \frac{Sv_i - v_o}{L}$	$\frac{dv_o}{dt} = \frac{i_L - \frac{v_o}{R}}{C}$
Buck-boost converter	$\frac{di_L}{dt} = \frac{Sv_i - (1-S)v_o}{L}$	$\frac{dv_o}{dt} = \frac{(1-S)i_L}{C} - \frac{v_o}{RC}$

**Table 3.** Real running time of simulation

	Simulation (sec)	Model (sec)	Δt%
Boost Converter	7.722246	5.203678	32.614
Buck Converter	7.887231	4.642952	41.133
Buck-Boost Converter	9.306722	5.089458	45.314

### 4. Conclusion

The DC-DC converters are widely used in many industrial applications. As renewable energy sources became more popular, the use of converters have got more important. Therefore, three-types of DC-DC converters, such as boost, buck and buck-boost converter, are investigated in this study. The electrical simulation software simulates circuits, successfully. However, simulations may take long time especially if the circuit is complex and have more switching devices. Therefore, mathematical model of converter is used to shorten the simulation time and to analyze the system for many parameters fast. In the study, the models and electrical simulation circuit of three converters presented in detail. Mathematical model and electrical circuit are compared for steady-state and transient-state. The results show that models are verified with electrical simulations. The model can be used in code for many parameter analyses fast.

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