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Araştırma Makalesi -Research/ Article

Sliding-Mode Control Techniques of SEPIC Converter in Continuous Current Mode

SEPIC Dönüştürücünün Sürekli Akım Modunda Kayan Kipli Kontrolü

Mehmet Yılmaz[1*], Muhammet Emin Kalçık[2], Muhammet Fatih Çorapsız[3]

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ABSTRACT

Nowadays, direct current (DC) voltage is required for the operation of the machines used in many industrial applications. DC voltage generating photovoltaic (PV) panels or other DC voltage generators need to be converted from the voltage level produced by the DC voltage levels required for the operation of the machines. The conversion of a DC voltage to a different DC voltage is performed by DC-DC converters. The most commonly used DC-DC converters in the literature are buck, boost, buck-boost, CUK and SEPIC converter. In this study, different control methods are used in order to reach the desired voltage level of the output voltage of the equivalent series resistance and ideal SEPIC converter in continuous current mode. Conventional Proportional-Integral (PI) and Sliding Mode Control (SMC) methods are used to ensure that the converter reaches the desired voltage level. PI controller parameter values are calculated according to trial and error method. In order to compare the performances of the controller used in the case ideal and equivalent series resistance cases, the controller parameters are taken the same. SMC is shown to perform better in ideal and equivalent series resistance SEPIC converter compared to the traditional PI controller from simulation results. Besides, modeling and controller applications of SEPIC converter are realized by using MATLAB / SIMULINK program.

Keywords- DC-DC Converter, SEPIC Converter, Sliding Mode Controller, PI Controller and Voltage Control

ÖZ

Günümüzde birçok endüstriyel uygulamalarda kullanılan makinaların çalışması için doğru akım (DC) gerilime ihtiyaç duyulmaktadır. DC gerilim üreten fotovoltaik (PV) paneller ya da diğer DC gerilim üreteçlerinin ürettikleri gerilim seviyesinden makinaların çalışması için gerekli farklı DC gerilim seviyelerine dönüştürülmeleri gerekmektedir. Bir DC gerilimi farklı bir DC gerilime dönüştürülmesi işlemi DC-DC dönüştürücüler tarafından gerçekleştirilmektedir. Literatürde en sık kullanılan DC-DC dönüştürücüler; alçaltıcı, yükseltici, alçaltıcı-yükseltici, CUK ve SEPIC dönüştürücüdür. Bu çalışmada sürekli akım modunda eşdeğer seri dirençli ve eşdeğer seri dirençsiz SEPIC dönüştürücünün çıkış geriliminin arzu edilen gerilim seviyesine ulaşması için farklı kontrol yöntemleri kullanılmıştır. Dönüştürücünün arzu edilen gerilim seviyesine ulaşmasını sağlamak için geleneksel Oransal-İntegral (PI) ve Kayan Kipli Kontrolcü (KKK) kullanılmıştır. PI kontrolcü parametre değerleri deneme-yanılma yöntemine göre hesaplanmıştır. İç dirençli ve iç dirençsiz durumda kullanılan kontrolcü performanslarını kıyaslamak amacıyla kontrolcü parametreleri aynı alınmıştır. Elde edilen simülasyon sonuçlarından kullanılan kontrolcüler

[1]*Corresponding author contact: mehmet.yilmaz@atauni.edu.tr (https://orcid.org/0000-0001-7624-4245)
Department of Electrical and Electronics Engineering, Atatürk University, Faculty of Engineering, Erzurum, Turkey
[2]Contact: mekalcik@agri.edu.tr (https://orcid.org/0000-0001-8601-1269)
Department of Electronics and Automation, Ağrı İbrahim Çeçen University, Patnos Vocational School, Ağrı, Turkey
[3]Contact: corapsiz@atauni.edu.tr (https://orcid.org/0000-0001-5692-8367)
Department of Electrical and Electronics Engineering, Atatürk University, Faculty of Engineering, Erzurum, Turkey

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kararlı durum hatası, yerleşme zamanı ve yükselme zamanı gibi başarım parametreleri açısından kıyaslanmıştır. KKK hem dirençli hem de iç dirençsiz SEPIC dönüştürücüde geleneksel PI denetleyiciye oranla daha iyi sonuç verdiği görülmüştür. Simülasyon çalışmaları MATLAB/SIMULINK programı kullanılarak yapılmıştır.

Anahtar Kelimeler- DC-DC Dönüştürücü, SEPIC Dönüştürücü, Kayan Kipli Kontrolcü, PI kontrolcü ve Gerilim Kontrolü

I. INTRODUCTION

Before the advances in modern power electronics technology, DC-DC conversion was carried out by the operation of 2 DC machines as motors and generators. The voltage value desired by the load was obtained by adjusting the parameters of the DC machine operating as a generator [1]. After technological advances in power electronics, these structures have been replaced by DC-DC converters. DC-DC converters are circuit topologies that provide power to the DC voltage load below or above the desired voltage level [2]. Converters in DC systems increase or decrease the voltage which is done by the transformer in alternating current (AC) systems [3]. While the desired voltage values were adjusted with the generator parameters before the technological developments, semiconductor switches are now used to adjust voltage values after the technological developments. Semiconductor switches, such as MCT, SCR, MOSFET and IGBT are generally used for power control in DC-DC converters [2]. By adjusting the transmission and cutting times of the switch, the desired output voltage is applied to the load side at the desired level. Figure 1 shows the DC-DC converter block diagram.

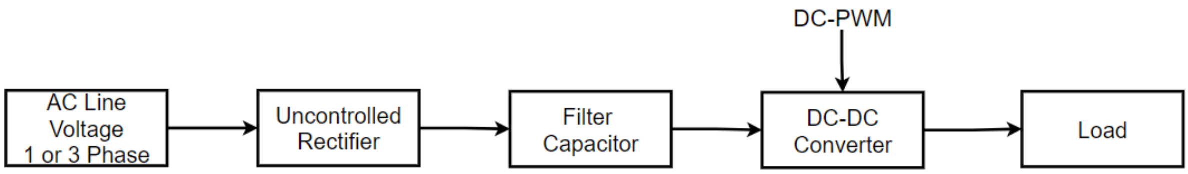

Figure 1. DC-DC converter block diagram

There are 2 different situations between the source voltage (V_{in}) and the output voltage (V_{out})of the DC-DC converters.

- $V_{in} < V_{out}$
- $V_{in} > V_{out}$

Buck and boost converters are considered as basic converters. In some circuits, the buck-boost, CUK and SEPIC converter topologies are used with the combination of these two basic converters. The difference of CUK converter from buck-boost and SEPIC converter is that it has reverse polarity between output voltage and input voltage. DC-DC converters are operated in 2 different time modes;

- Continuous Current Mode (CCM)
- Discontinuous Current Mode (DCM)

Current modes vary depending on the inductor size. If the inductor current is reset during the cutting of the semiconductor switching element the DCM occurs, the CCM occurs, otherwise. In general, converters are designed to operate in CCM. DC-DC converters are generally used in mobile phone chargers, photovoltaic systems and car audio systems.

There are many studies in the literature about SEPIC converter. For example, SEPIC led driver is designed by Sehirli E. et al. [4]. In the study, the design of the converter has been realized and applied by determining the values of the SEPIC converter circuit elements through the input voltage, power and output voltage of the drive. Kesik E. P. [5] designs SEPIC battery charger hardware for automotive photovoltaic applications. SEPIC converter topology is examined in detail and all necessary parameters of the components are calculated using the relevant theoretical equations in line with the design goals. As a result of these calculations, the most suitable switching frequency is determined. Consequently, SEPIC converter circuit is designed and simulated with LTspice circuit simulator. Simulation studies were carried out in real time and verified by performing the required experiments. Sel A. [6] applies the SMC to the SEPIC converter in a discrete time environment. The state space model of the SEPIC converter to be controlled is obtained using the state space mean method. Then, the system model

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requiredfor the controller is calculated by considering the small signal model of the converter. As a result of the simulation studies carried out, the controller's robustness is illustrated.Khateb A. E. et al. [7] design a SEPIC converter based fuzzy logic controller (FLC) for maximum power point tracking (MPPT) of a PV system.The performance of the proposed controller is compared to conventional PI-based converters.They observed that the proposed controller performance from simulation and real-time results is better than traditional PI based controllers.Chiang and Shieh [8] study the modeling and control of PV charging system.In the first part of the study, the authors provide a dynamic model of the SEPIC converter.Also, the adaptive MPPT controller is designed and aprototype (80-W) system is installed.The effectiveness of the suggested methods is proven by the help of simulation with extensive experimental results.The proposed system has been shown to be effective both in MPPT and power balance control.Zhao and Kwasinski [9] examine a multi-input DC-DC converter model with the help of SEPIC converter topology.The simulation of this converter structure is made by conducting basic dynamic equations and small signal analysis in CCM.As a result of the analysis, it is observed that the input current is almost constant and makes the proposed topology more flexible than multiple input topologies.Jaafar A. et al. [10] design a DC-DC SEPIC converter that operates in CCM.In the first part of the study, various aspects of the modes of operation of the SEPIC converter are analyzed.Transient time and frequency responses are compared with the help of the average state space model and small signal analysis.Later, simulations for transient time and frequency responses are confirmed by experimental studies.PI control method is used to control the designed SEPIC converter output voltage.The simulation and experimental studies indicate that the performance of the controller is robust.Alternatively, Mamarelis et al. [11] design a SEPIC converter for PV systems.The authors use a SMC to get maximum power from the PV system.As a result of simulation and experimental studies, it is observed that the SMC produces very robust results. There are also several topologies in the literature based on the SEPIC converter [12-15].

SEPIC converters are circuits that transmit the DC input voltage to the output at a lower or higher level.SEPIC converters basically consist of 1 switching element, 2 inductors, 1 diode, 2 capacitors and 1 load resistor.The output voltage of these converters has the same polarity as the input voltage has in the buck-boost converters.SEPIC converters are preferred more frequently than other converters because of their overcurrent limitation, easier control of the controlled semiconductor switch that helps to reduce the fluctuation in the input current by reduce the filter requirement [16].SEPIC converter equivalent circuit diagram is shown in Figure 2.

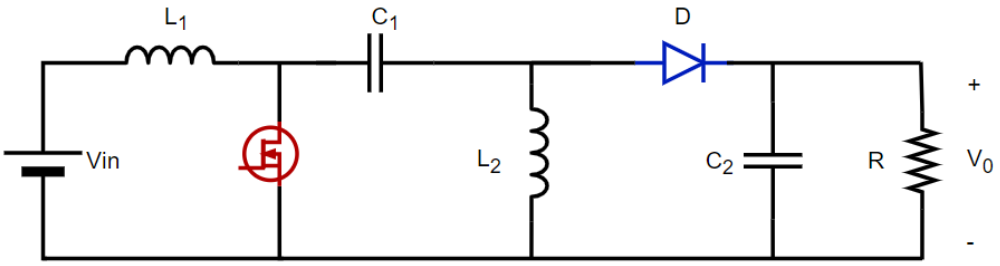

Figure 2. SEPIC converterbasiccircuit

II. DYNAMIC ANALYSIS OF SEPIC CONVERTER

Dynamic analysis of SEPIC converter is examined for two cases; in the first one the switching element is open and it is closed in the second one. The state space equations of the ideal and equivalent series resistor SEPIC converter in CCM are given in the following;

Before beginning, we give the nomenclature used in the equations here:

- V_{in} *Input Voltage, V*
- V_o *Output Voltage, V*
- V_{C1} *Average Capacitor Voltage, V*
- i_{L1} *Inductor Current, A*
- i_{L2} *Inductor Current, A*
- R *Load Resistance, Ω*

- C_1 *Capacitor, F*
- L_1 *Inductor, H*
- C_2 *Capacitor, F*
- L_2 *Inductor, H*

A. Ideal SEPIC Converter when the Switching Element is Closed

When the switching element is closed, the equivalent circuit given in Figure 3 is obtained. While the switch is closed, the i_{L1} main arm current supplies energy to the L_1 inductor, also, the C_1 capacitor is discharged and transfers its energy to the L_2 inductor.The current of the L_2 inductor energized thanks to the C_1 capacitor increases linearly.On the other hand, the C_2 capacitor continues to energize the load.Consequently, the dynamic analysis equations are as in equations (1), (2), (3) and (4).

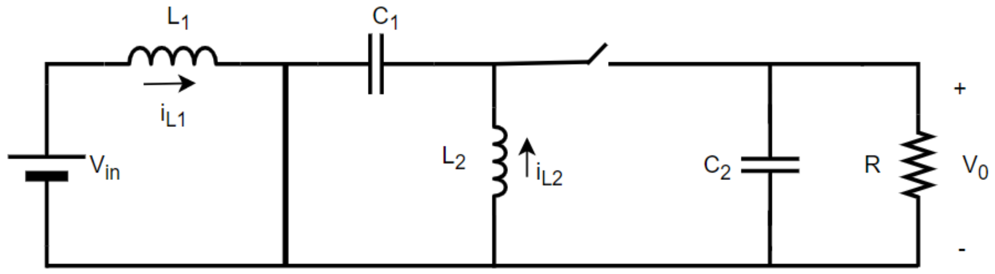

Figure 3. Switching element is closed

$$L_1\dot{i}_{L1} = V_{in} \tag{1}$$

$$C_1\dot{V}_{C1} = (-i_{L2}) \tag{2}$$

$$L_2\dot{i}_{L2} = V_{C1} \tag{3}$$

$$C_2\dot{V}_0 = (\frac{V_0}{R}) \tag{4}$$

B. Ideal SEPIC Converter when the Switching Element is Open

When the switching element is open, the equivalent circuit given in Figure 4 is obtained. The diode D is closed while the switching element is open. The C_1 capacitor is charged through the L1 inductor and Vin. Also, the C_2 capacitor is charged through $V_{in,}$ L_1 and L_2 inductors, energizes the load. Hence, the dynamic analysis equations are as in equations (5), (6), (7) and (8).

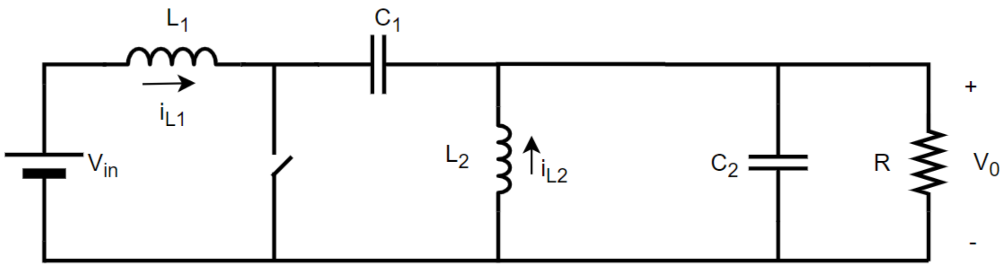

Figure 4. Switching element is open

$$L_1\dot{i}_{L1} = (V_{in} - V_{C1} - V_0) \tag{5}$$

$$C_1\dot{V}_{C1} = i_{L1} \tag{6}$$

$$L_2\dot{i}_{L2} = (-V_0) \tag{7}$$

$$C_2\dot{V}_0 = (i_{L1} + i_{L2} - \frac{V_0}{R}) \tag{8}$$

C. Equivalent Series Resistor SEPIC Converter when the Switching Element is Closed

Equivalent series resistance SEPIC converter is the circuit topology that behaves closest to the operation of the SEPIC converter in real-time applications. In this topology, the circuit components are not considered ideal and the circuit components used have series resistor. In Figure 5, equivalent series resistance SEPIC converter circuit topology is shown when switching element is closed. In such circumstances, the dynamic analysis equations are as in equations (9), (10), (11) and (12).

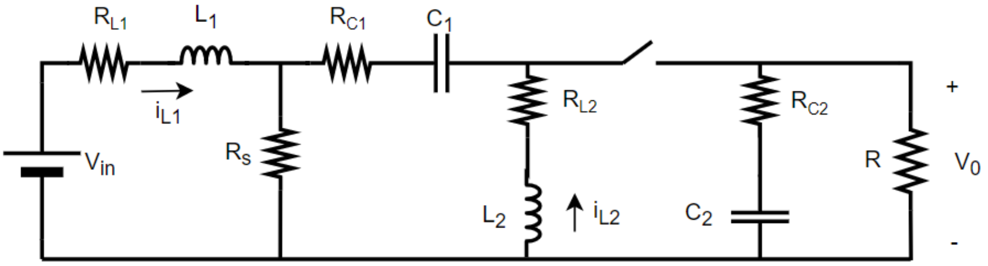

Figure 5. Switching element is closed

$$L_1\dot{i}_{L1} = V_{in} - R_{L1}i_{L1} \tag{9}$$

$$C_1\dot{V}_{C1} = (-i_{L2}) \tag{10}$$

$$L_2\dot{i}_{L2} = V_{C1} - i_{L2}(R_{C1} + R_{L2}) \tag{11}$$

$$C_2\dot{V}_0 = (-\frac{V_0}{R + R_{C2}}) \tag{12}$$

D. Equivalent Series Resistor SEPIC Converter when the Switching Element is Open

In Figure 6, equivalent series resistance SEPIC converter circuit topology is shown when switching element is open. The dynamic analysis equations in this scenario are as in equations (13), (14), (15) and (16).

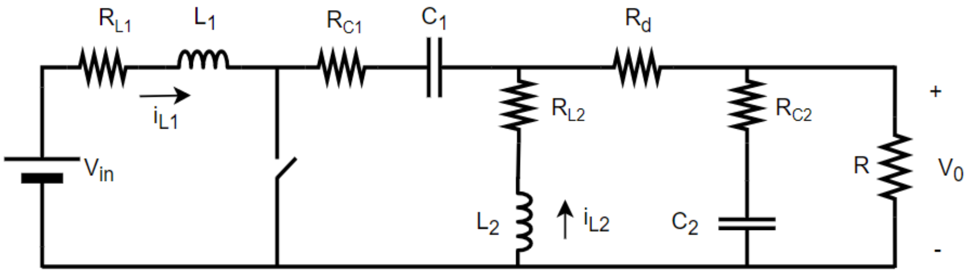

Figure 6. Switching element is open

$$L_1\dot{i}_{L1} = V_{in} - (R_{L1} + R_{C1} - R_a R_{C2})i_{L1} + (R_a R_{C2})i_{L2} - V_{C1} - V_{C2}R_a \tag{13}$$

$$C_1\dot{V}_{C1} = i_{L1} \tag{14}$$

$$L_2\dot{i}_{L2} = -V_{C2}R_a - (R_{L2} + R_a R_{C2})i_{L2} - (R_a R_{C2})i_{L1} \tag{15}$$

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$$C_2\dot{V}_0 = i_{L1}R_a + i_{L2}R_a - \frac{V_0}{R+R_{C2}} \quad (16)$$

$$R_a = \frac{R}{R+R_{C2}} \quad (17)$$

III.PI CONTROLLER

The PI controller, formed by the combination of proportional (P) and integral (I) controllers, is one of the most frequently used controller types in the control of linear systems [17]. The transfer function of this controller is given in equation (18).

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (18)$$

Here, K_i represents the integral gain and K_p is used for the proportional gain. The block diagram of the PI controller is given in Figure 7. In Figure 7, *R(s)* is equal to the reference voltage and the output voltage is equal to $V_0(s)$. The controller is tuned optimally by using a trial and error method, and gains are found as $K_p = 0{,}001$ and $K_i = 0{,}2$.

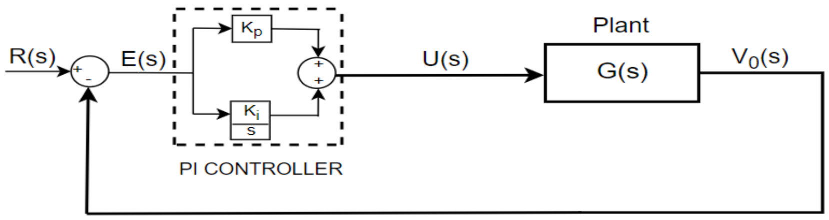

Figure 7. PI Controller

IV.SLIDING MODE CONTROLLER

SMC is a frequently preferred control method for the management of nonlinear systems. The most important advantage of this method is that it is not necessary to know the mathematical model of the nonlinear system. The idea of SMC first introduced by Emelyanov in 1950 [18]. In the SMC method, using the infinite switching feedback control, the linear or nonlinear system is drawn and held on the surface defined in the state space [19]. This surface consists of state variables and is selected according to the desired system response shape and called as the "sliding surface". Once the system reaches the sliding surface, its behavior becomes independent of the controlled system parameter changes and disruptive effects, which indicates that a robust controller structure is obtained. There are many studies in the literature about the SMC, which is frequently preferred for the solution of nonlinear systems [20,21]. The SMC method consists of access and sliding phases with 3 basic rules for the access phase [22]:

Constant change access rule:

$$\dot{s} = -p\,sign(s) \quad (19)$$

Constant-Proportional alternating access rule:

$$\dot{s} = -p\,sign(s) - K_S \quad (20)$$

Exponential alternating access rule:

$$\dot{s} = -p|s|^a\, sign(s) \quad (21)$$

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V. SIMULATION RESULTS

Simulation studies are examined in 2 different ways; the SEPIC converter is set to the ideal status in the first one, and it is set to series resistor status in the second case.

A. Ideal SEPIC Converter

The design parameters of ideal SEPIC converter controlled by SMC and PI control methods are given in Table 1. Design parameters are calculated by obtaining *12V* output voltage from *20V* input voltage. The simulation model of the SEPIC converter, which is expressed with dynamic equations, are realized with MATLAB / SIMULINK program.

Table 1. IdealSEPIC converterdesignparameters

InputVoltage	20 V
OutputVoltage	12 V
CapacitorValuesC_1& C_2	2µF & 800µF
Inductor Values L_1& L_2	134µH & 134µH
Switching Frequency	100 kHz
Load Resistance	5 Ω

In Figures 8 and 9, ideal SEPIC converter simulation model controlled by PI control method and ideal SEPIC converter simulation model controlled by SMC method are shown, respectively.

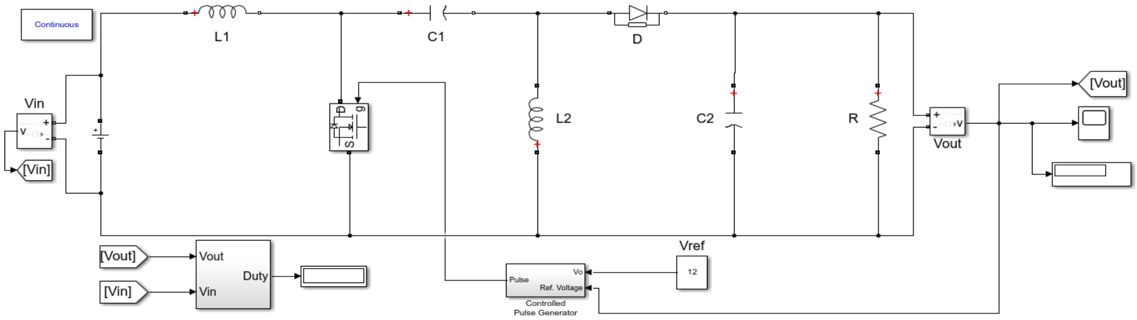

Figure 8. SEPIC converter simulation model controlled with PI controller

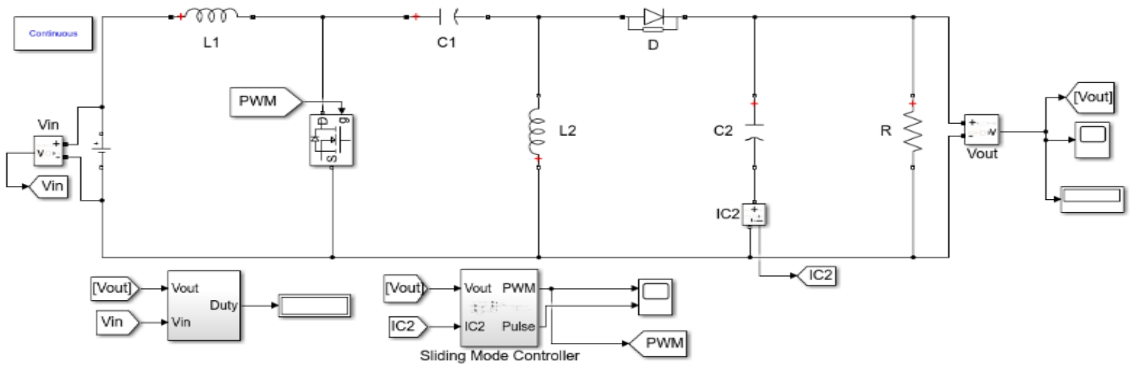

Figure 9. SEPIC converter simulation model controlled with SMC

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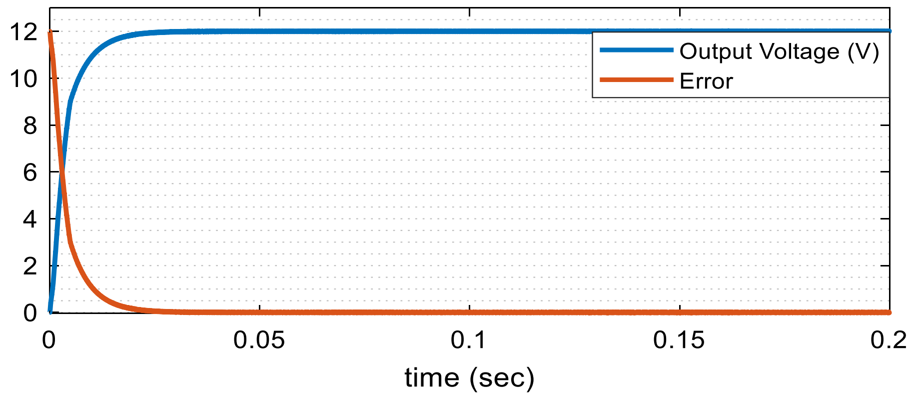

Figure 10. Output voltage and error with PI controller

Figure 10 shows the time-dependent variation of the SEPIC converter output voltage controlled by the PI controller. It is observed that the output voltage of SEPIC converter reaches the desired output voltage *12V* after *0,02s.* Also Figure 10 shows the time-dependent variation of the error in the SEPIC converter controlled by the PI controller. It is observed that the error of output voltage reaches the lowest value after approximately *20 ms.*

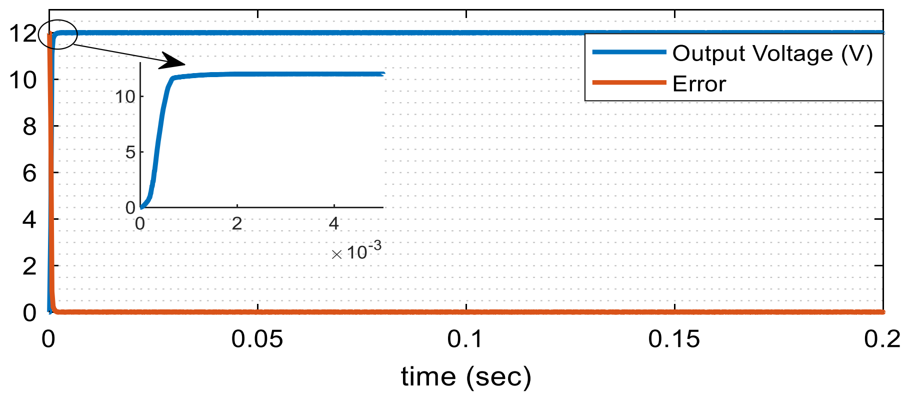

Figure 11. Output voltage with SMC

The change of output voltage of SEPIC converter controlled by SMC shows in Figure 11. It can be observed that the output voltage reaches the reference value after approximately *0,001s.* Moreover, Figure 11 shows the error of the output voltage. It can be seen that the error dropped to a minimum value after about *1ms.*

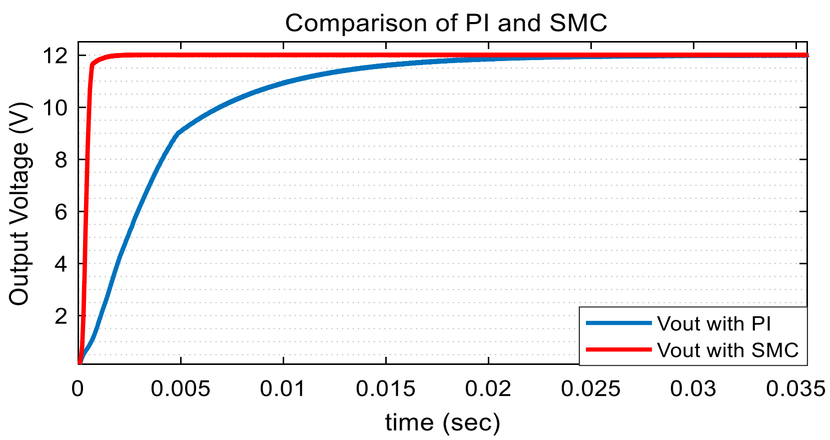

Figure 12. Comparison of output voltage of SEPIC converter

In Figure 12, the comparison of the output voltages of ideal SEPIC converter controlled by two different control methods is provided. It can be observed that the SMC reaches the desired reference value in much shorter time compared to the PI controller.

B. Equivalent Series Resistance SEPIC Converter

The design parameters of the equivalent series resistance SEPIC converter controlled by SMC and PI control methods are given in Table 2. As a result of the simulation studies, the output voltage and the error in the output voltage are shown for different control methods of ideal SEPIC converter and sketched in the figures which are given in the following.

Table 2. Equivalent series resistance (ESR) SEPIC converter design parameters

InputVoltage	20 V
OutputVoltage	12 V
CapacitorValuesC_1& C_2	2µF & 0.08µF
Inductor Values L_1& L_2	134µH & 134µH
Switching Frequency	100 kHz
Load Resistance	5 Ω
ESR of capacitors R_{C1} & R_{C2}	0.01Ω & 0.01Ω
ESR of inductors R_{L1} & R_{L2}	0.03Ω & 0.03Ω

In Figures 13 and 14, equivalent series resistance SEPIC converter simulation model controlled by PI control method and equivalent series resistance SEPIC converter simulation model controlled by SMC method are given respectively.

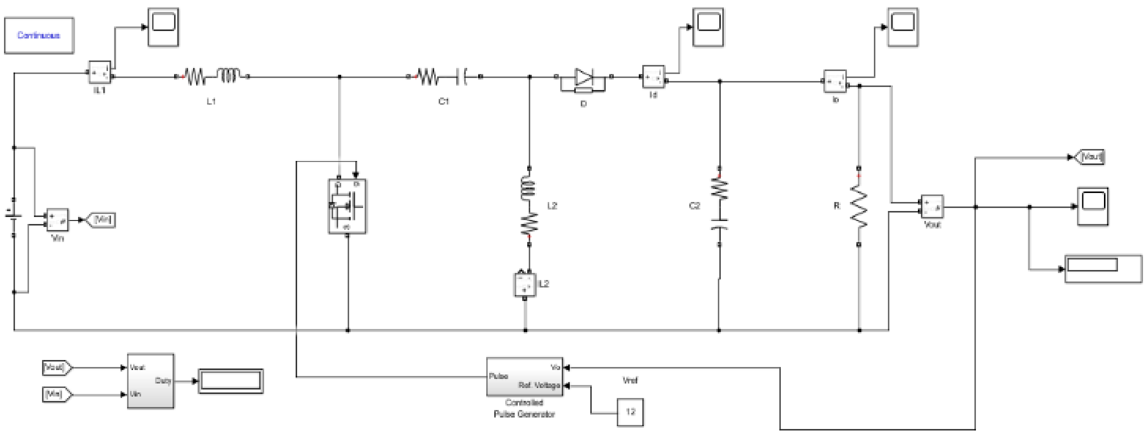

Figure 13. SEPIC converter simulation model controlled with PI controller

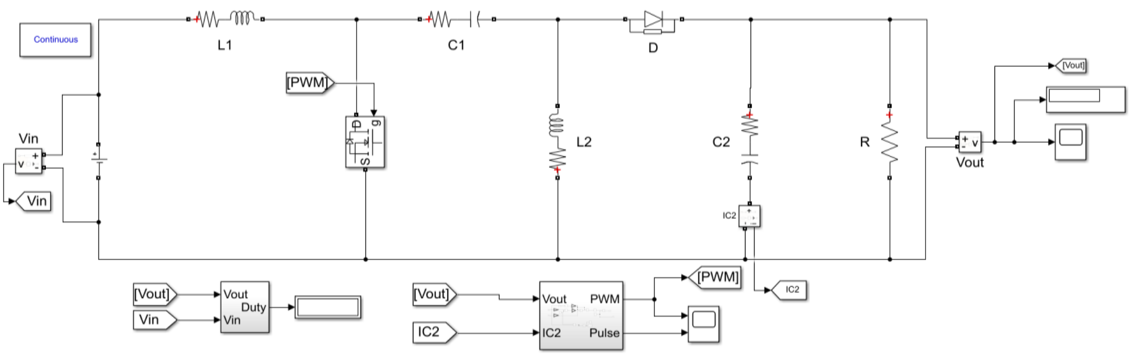

Figure 14. SEPIC converter simulation model controlled with SMC

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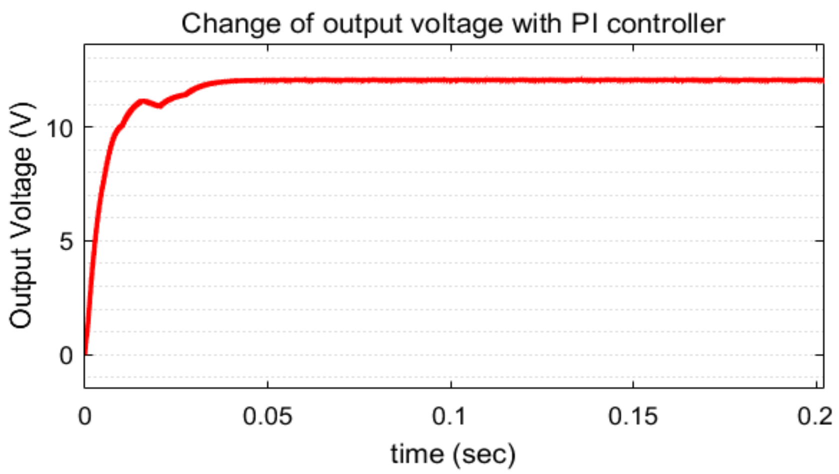

Figure 15. Output voltage with PI controller

The change of the output voltage based on time-dependent of the equivalent series resistance SEPIC converter is shown in Figure 15. The output voltage of the converter controlled by the PI controller reaches the reference value after *0,04 s.*

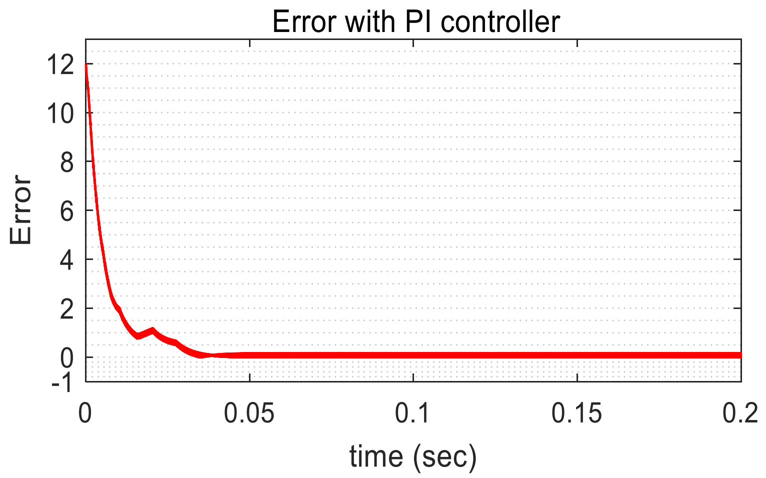

Figure 16. Error with PI controller

It can be seen in Figure 16 that the error in the output voltage of the SEPIC converter controlled by the PI controller drops to minimum values after *40 ms*.

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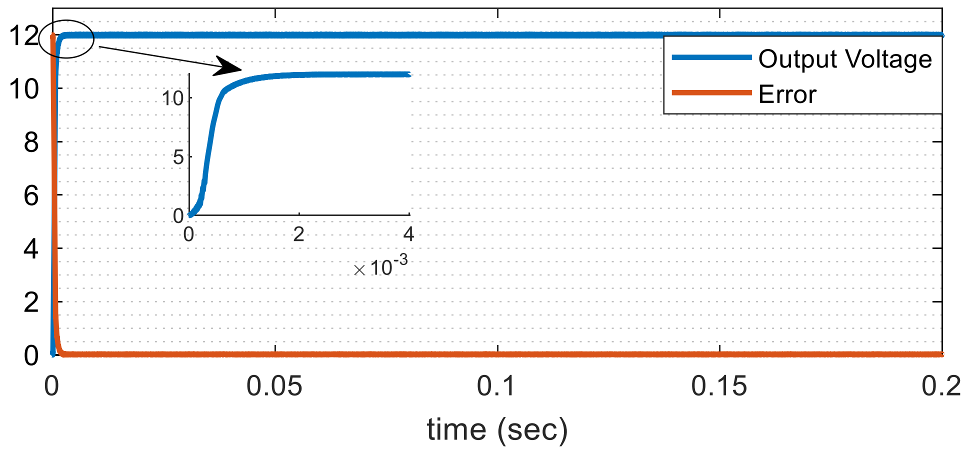

Figure 17. Output voltage with SMC

Figure 17 shows that the output voltage of the equivalent series resistance SEPIC converter controlled by SMC reaches *12V* after approximately *0,002s.* Also, the value of the error in the output voltage indicates the controller performance. Figure 17 shows the error in the equivalent voltage resistance SEPIC converter output voltage controlled by SMC.

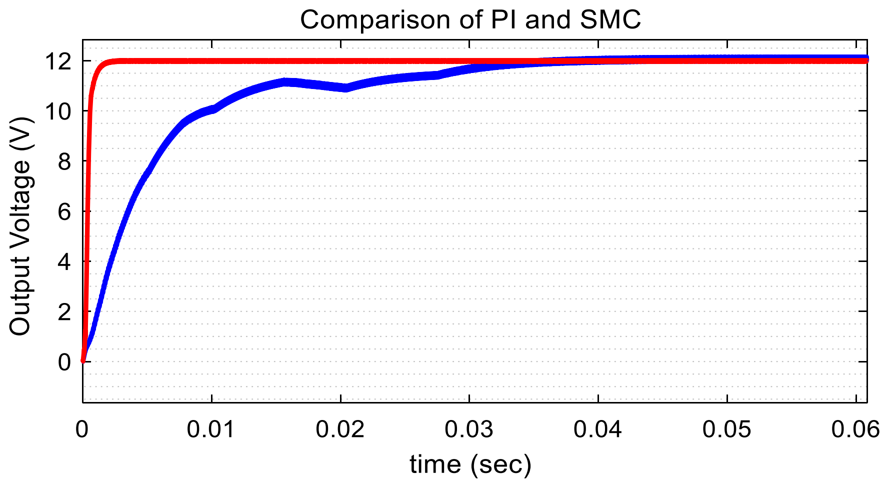

Figure18. Comparison of output voltage of SEPIC converter

In Figure 18, the comparison of the output voltages of the equivalent series resistance SEPIC converter controlled by two different control methods is shown. It can be seen that the SMC reaches the desired reference value in much shorter time compared to the PI controller.

Table 3. Comparison of controller

Controller	**PI**	**SMC**	**PI(ESR)**	**SMC(ESR)**
Settling time	0,02 s	0,001 s	0,04 s	0,002
Rise time	0.0008 s	0,00035 s	0,006 s	0,00046 s
Overshoot	% 0,372	% 0,259	%0,6	% 0,4
Error (ITAE)	0.0003652	*0.000191*	*0.0008412*	*0.0004127*

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VI.CONCLUSION

In this study, the analysis and modeling of the SEPICconverter isperformed using the MATLAB/SIMULINK program. In the first part of the study, the sliding mode and the PI controller are used in order to reach the desired reference ideal SEPIC converter. PI controller parameters are calculated asK_p= *0,001* and K_i = *0,2* with the help of trial and error method. When the PI control method is applied, the output voltage reached the reference after approximately *0,02s,* while the sliding mode controller method followed the reference after *0,001s.* It is observed that the error in the output voltage is the lowest value after *20 ms* for the PI control method and *1ms* for the SMC. In the second part of the study, the sliding mode and PI controller are used in order to follow the desired reference of the equivalent series resistance SEPIC converter. The PI controller parameters are taken to be the same as the $K_p$and $K_i$values in the ideal SEPIC converter for comparison. When the PI control method is applied, the output voltage reached the reference after approximately *0,04s*, and when the SMC method is used, the output voltage followed the reference after *0,002s*. When comparing the two different states, it is observed that fluctuation occurred in the output voltage in the equivalent series resistance case and the settling time increased. This study can be used to obtain a new dc voltage by adjusting the voltage produced from photovoltaic panels in proportion to the needs of the load. SEPIC converters are preferred more frequently than other converters because of their overcurrent limitation, easier control of the controlled semiconductor switch that helps to reduce the fluctuation in the input current by reduce the filter requirement. As a future research, real-time implementation of the SEPIC converter can be performed and its control with different controllers is considered.

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