STABILITY ANALYSIS OF SEPIC CONVERTER USING MATLAB/SIMULINK

1SIDHARTH SABYASACHI, 2PRATYUSHA MOHANTY

1,2Electrical & Electronics Engineering Department Centurion University of Technology and Management (CUTM) Odisha, India
Email: sidharth.mana@gmail.com, pratyushamohanty0@gmail.com

Abstract: DC-DC converter is a converter where we are regulating the input voltage to get the desired output voltage which is either greater than or equal to or less than the input voltage with positive or negative polarity. A lot of dc-dc converters are available in the world out of which SEPIC (Single-Ended Primary-Inductor Converter) converter is one of them. To analyse the converter, a lot of techniques are available. This paper presents the use of MATLAB/SIMULINK to study the stability of the converter. The state space technique is applied to this higher order converter and converted into transfer function. The reduced order technique is applied to the system and compared with the higher order system which gives approximate results for all type of analysis.

Keywords: DC-DC Converter, SEPIC Converter, Transfer Function, State Space Analysis, Stability Theory, Reduced Order Technique, MATLAB/SIMULINK.

I. INTRODUCTION

A lot of dc-dc converter has been designed for different application purpose such as buck converter, boost converter, buck-boost converter, flyback converter, push-pull converter, forward converter etc. The converters are designed based on the switching operation which helps to transfer the energy from load to source. The SEPIC converter is one of the dc-dc converter which gives higher or lower output voltage as compare to the input voltage with the help of switching operation and energy storage elements like inductor and capacitor. The operating mode of the converter depends upon the flow of the load current which can be continuous or discontinuous. So the converter can be operated as Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode (DCM) which depends whether the load is heavy or light. The switching operation takes place at a higher frequency which increases the response of the system. While designing any converter, we have to consider the source, switching elements, filter elements and loads. The filtering elements are mainly the energy storage elements which decide the order of the system. For lower order converters, it is easier to design the converters which can operate in the stable mode and controller design is also simple. For higher order converters, it is very difficult to design the controller which can operate the converter in the stable mode. The SEPIC converter is a 4th order converter where two inductors and two capacitors are used. Since the system is nonlinear, the controller design is very difficult. So to analyze the system behavior, the order of the system has to be reduced using well defined methods. In this paper, we are using small signal analysis including the equivalent series resistance for inductor and capacitor. The average model is designed and with the help of state space analysis, the system is converted in the form of transfer function. The different stability theory has been used to verify the operating mode. Depending upon the energy state of each state variables, the system order is reduced which helps to analyze the system better. The higher order as well as the reduced order system behavior has been compared which gives approximate results.

II. STATE SPACE ANALYSIS OF SEPIC CONVERTER

2.1. State Space Model of SEPIC Converter

The state space analysis is of the method by which the converter can be analyzed. In this method, the converter is converted into mathematical differential equation. The number of equation is equal to the number of energy storage elements present in the converter. These equations are converted into matrix form. The converter can operate in CCM mode as well as DCM mode. When CCM mode is considered, depending upon the switching operation, the converter operation can be divided into two modes of operation i.e. switch ON operation and switch OFF operation. The equivalent circuit diagram for SEPIC converter including equivalent series resistance for inductor and capacitor is shown in fig.1. The equivalent circuit diagrams during switch on condition and switch OFF condition are shown in fig.2 and fig.3 respectively.

The state space equation by taking the average of each state variables, the state space equation is

\[ x(t) = Ax(t) + Bu(t) \] (Eq.1)

\[ y(t) = Cx + Du(t) \]
In this converter, there is no direct connection between input and output. So Du(t) is absent.

\[
A = A_1d + A_2(1-d)
\]

\[
B = B_1d + B_2(1-d)
\]

where

- \( A \) = 4x4 System Matrix
- \( B \) = 4x1 Control Matrix
- \( d \) = Duty Cycle
- \( C_1, C_2 \) = Output Matrix

For switch ON and \( d \) for switch OFF condition.

The state vector \( x \) and \( y \) is the output vector.

The average model is created for this converter in MATLAB by using the linear differential equation. In average model, ripple is neglected and it is used for steady state analysis. The model is shown in fig. 6. The output voltage waveform is shown in fig. 4 with duty cycle 0.5. It is shown that the converter is giving 10 V and the steady state is achieved approximately at 0.03 sec. The circuit parameter is given in table 1.

### Table 1. Converter Parameter

<table>
<thead>
<tr>
<th>Circuit Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage (Vs)</td>
<td>10V</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>0.5</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>10V</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>100kHz</td>
</tr>
<tr>
<td>Load R</td>
<td>1Ω</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>100( \mu )H</td>
</tr>
<tr>
<td>( r_{L1} )</td>
<td>1m( \Omega )</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>100( \mu )H</td>
</tr>
<tr>
<td>( r_{L2} )</td>
<td>1m( \Omega )</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>800( \mu )F</td>
</tr>
<tr>
<td>( r_{C1} )</td>
<td>3m( \Omega )</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>3000( \mu )F</td>
</tr>
<tr>
<td>( r_{C2} )</td>
<td>1m( \Omega )</td>
</tr>
</tbody>
</table>

**2.2. Variation of Voltage gain with Duty Cycle**

For ideal converter, when no equivalent series is considered, the output voltage is related to the input voltage by duty cycle.

\[
V_o = \frac{V_{in}d}{1-d} \quad \text{(Eq.3)}
\]

By varying the duty cycle from 0 to 1, the output voltage can be varied. The equation 3 is rearranged to convert into voltage gain \( V_o/V_{in} \). The graph is taken between voltage gain and duty cycle which is shown in fig. 7. When the duty cycle is 0, the voltage gain is 0. By increasing the duty cycle, the voltage gain increases, and at duty cycle of 0.5, the voltage gain is 1. That means the duty cycle below 0.5, the converter steps down the input voltage. At 0.5, the output voltage is equal to the input voltage. Duty cycle above 0.5, the voltage gain increases above 1 and since the derivation is for ideal converter, when duty cycle is 1, the voltage gain is infinity.

The equation (3) is not valid for practical converter. That’s why the equation is modified by including the internal resistances for inductor and capacitor. In ideal converter, the output voltage does not depend upon the load resistance whereas in practical converter, the output voltage depends on both load resistance and equivalent series resistance.
The output voltage for practical converter is

\[
V_o = \frac{V_i}{1 - d + \frac{d \times r_1}{d - 1} \frac{1 - d \times r_2}{d \times r_2} \frac{2d - 1}{R \times R} (1)\text{Eq.4)}
\]

By rearranging the equation, the voltage gain is calculated and it is drawn against the duty cycle. The figure 5 shows the variation of voltage gain with respect to duty cycle for different load. It is shown that when the load resistance increases, the maximum voltage gain is also increases. In this figure, R is varied from 1 to 10 \(\Omega\) and it is observed that upto duty cycle 0.8, there is no change of voltage gain, but when it is more than 0.8, the voltage gain is different for different value of R which is increasing for increasing of R.

**Figure 5: Voltage gain Vs Duty Cycle with variable load**

2.3 State Energy

The fig. 8 shows the state energy graph for the state variables. The converter has four state variables. The contribution of energy for each state variable is calculated by using Hankel Singular values and it is shown that the energy contribution by two state variables are larger as compare two other two state variables and the system is operating in the stable mode. So the converter can be easily converted from 4th order to 2nd order system and other two state variables can be neglected. The responses of both the systems are compared and it is observed that both the responses are approximately equal.

**Figure 8: State energy**

III. STABILITY ANALYSIS

3.1. Simulation of the Converter

The converter is derived by converting into mathematical equation. The parameters are defined in the program. The averaging state space model in matrix form is defined in the program. With the help of programming language, the state space model is converted into transfer function which is a 4th order function.

\[
H(s) = \frac{4.99s^3 + 1.665 \times 10^5 s^2 + 7.284 \times 10^7 s + 1.041 \times 10^{12}}{s^4 + 3.93s^3 + 7.93 \times 10^3 s^2 + 2.319 \times 10^6 s + 1.045 \times 10^{10}}
\]

Now the converter is reduced into 2nd order by using model order reduction technique which is decided from state energy graph. The 2nd order transfer function is

\[
H_2(s) = \frac{3.515s + 1.664 \times 10^6}{s^2 + 362.8s + 1.671 \times 10^6}
\]

Here, the duty cycle is taken 0.5. The output voltage is \(V_o=9.994\) V which is calculated for practical converter and we have observed form the voltage gain graph that at 0.5, the change in voltage gain is very small. That’s why the output voltage nearly to 10 V.

3.2. Step Response

The step response of the both the model i.e. original model and reduced order model are drawn with the help of simulation. It is observed that the peak amplitude for both the model is 1.63 and overshoot is 64%. The rise time and the settling time for both the model are almost equal. So we can conclude that the system can be analyzed by reducing the order of the system which is easier than higher order system. The figure 8 shows the step response of both the model. The figure 9 shows the step response of the original model. The peak amplitude, rise time, settling time are shown in the figure itself. From figure 8, both the step response are overlapping with each other, which shows equal response.

**Figure 8: Step Response of both the model**
3.3. Bode Plot of the Converter
The bode plot of the converter is compared for both the model which is shown in figure 10. There is a slight change in the 2nd order which can be neglected for stability analysis. The bode plot for the original model with phase margin and gain margin is shown in figure 11. It is observed that gain margin is infinity and phase margin is 23.1°. So this system is inherently stable. In reduced order model, gain margin is infinity and phase margin is 23.2°. So this system is also showing the stability of the system.

The figure 12 shows the pole zero map of both the model. It is observed that the locations of zeros are in the left half of the s-plane in both the model. So the system is stable.

3.5. Root Locus Plot of the System

The root locus for both the system is shown in figure 13. For both the system, the damping is 1 and overshoot is 0%. So the system is critically damped.

3.6. Nyquist Diagram

3.4. Pole Zero Map of the System
The Nyquist diagram for both the model is shown in the figure 14 which shows the closed loop system is stable for both the model.

### 3.7. Nichols Chart

![Nichols Chart](image)

**Figure 15: Nichols Chart for both the Model**

The stability can also be checked by using Nichols chart which is shown in figure 15. It is observed from the figure that the closed loop system is stable. And both the diagram is approximately same.

### CONCLUSIONS

It is observed that the system can be analyzed with the reduced order model. The stability of the system can be checked by using different method with the help of MATLAB. All the plots are draw by writing the code in the m.file. So it will be easier for designing the controller of the system. In this paper, the converter is reduced to the 2nd order model. The energy of state variables are observed and only 2 out of 4 variables are contributing more energy. So we are neglecting the energy of other two variables. We are comparing the both the models by different plots and it is concluded that both the system giving same responses.

![Average Model of the SEPIC Converter](image)

**Figure 6: Average Model of the SEPIC Converter**

### REFERENCES


