Effect of pole zero location on system dynamics of boost converter for micro grid

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Abstract. Green clean energy like photo voltaic, wind energy, fuel cell can be brought together by microgrid. For low voltage sources like photovoltaic cell boost converter is very much essential. This paper explores the dynamic analysis of boost converter in a continuous conduction mode (CCM). The transient performance and stability analysis is carried out in this paper using time domain analysis and frequency domain analysis techniques. Boost converter is simulated using both PSIM and MATLAB software. Furthermore, state space model obtained and the transfer function is derived. The converter behaviour when a step input is applied is analyzed and stability of the converter is analyzed from bode plot frequency for open loop. Effect of the locations of poles and zeros in the transfer function of boost converter and how the performance parameters are affected is discussed in this paper. Closed loop performance with PI controller is also analyzed for boost converter.

1. Introduction

Nowadays with the development in the field of smart grid, the main objective is to provide secure, efficient, reliable power to the consumer. In this context micro grid plays an important role in integrating green clean energy like photo voltaic, wind energy, fuel cell, etc. Figure 1 shows the typical structure of micro grid. The micro grid concept is clearly explained with the help of the diagram shown. Renewable energy sources are connected to the utility grid through the microgrid. There are two types AC and DC micro grid. Many researchers are still working to resolve the problems due to micro grid. There is no need for inverter in case of DC micro grid and therefore the issues caused by AC micro grid are reduced to a large extend, with this type of micro grid network[1].

Due to the low output voltage in renewable power sources, like PV and fuel cell boost converters are required to improve the voltage profile of the system [2]. Non isolated dc-dc converters are available in compact size they are used in most negative ground application in vehicles for various DC powered

Figure 1. Typical Structure of a micro grid
appliances and equipment. Without transformers, the overall size of the power electronics interface is reduced therefore losses due to transformers is also reduced and the power is not wasted has more advantages higher efficiency, lower cost, compact in size, better performance compared to conventional isolated converter with transformer.

2. Boost Converter
Boost converter is a non isolated dc-dc converter which increases the dc input voltage [3],[4]. It consists of one inductor, one MOSFET switch and a diode. When the switch is in ON state energy is stored in the inductor and the capacitor connected across the load delivers energy to the load. The energy stored in inductor during ON state is transferred to load during OFF state of the switch. More than one input can also be given to the multi input boost converter [5] for integrating more than one renewable energy source.

In boost converter the input dc power is transferred to the output when the switch is in OFF state

![Non Isolated Boost Converter](image)

**Figure 2. Non Isolated Boost Converter**

![Modes of Operation](image)

**Figure 3. On state and Off state of the switch**

When the switch is in ON state, the voltage across the inductor,

\[ V_L = V_g \]  \hspace{1cm} (1)

Current through the capacitor,

\[ I_C = -I_0 \]  \hspace{1cm} (2)

When the switch is in OFF state, the voltage across the inductor,

\[ V_L = V_g - V_0 \]  \hspace{1cm} (3)

Current through the capacitor

\[ I_C = I_L - I_0 \]  \hspace{1cm} (4)

At steady state, Applying inductor volt-second balance

\[ V_g D + (V_g - V_0)(1 - D) = 0 \]

\[ V_g = V_0 (1 - D) \]  \hspace{1cm} (5)

Thus the voltage gain of the boost converter is given by,
\[
\frac{V_0}{V_g} = \frac{1}{(1-D)} \quad (7)
\]

Using capacitor current –balance equation,
\[
-I_0 D + (I_L - I_0)(1 - D) = 0 \quad (8)
\]

Applying KCL, we get
\[
I_C = I_g \quad (9)
\]
\[
I_0 = I_g(1 - D) \quad (10)
\]

Thus the relation between input and output current is given by,
\[
\frac{I_g}{I_0} = \frac{1}{(1 - D)} \quad (11)
\]

3. **State model of Boost converter**

In a Boost Converter, we can classify the modes of operation into two modes

3.1. **Mode 1**

When switch S is in On state, the voltage across the inductor,
\[
V_L = V_g \quad (12)
\]

The two energy storage elements are inductor and capacitor in this converter. Therefore the voltage across inductor and current through capacitor are the state variables in this state space modelling.

\[
L \frac{di_L}{dt} = V_g \quad (13)
\]
\[
\frac{di_L}{dt} = \frac{1}{L} (V_g) \quad (14)
\]

Similarly, current through the capacitor is determined applying KCL,

\[
L \frac{di_L}{dt} = V_g \quad (15)
\]
\[
\frac{di_L}{dt} = \frac{1}{L} (V_g) \quad (16)
\]
\[
L \frac{di_L}{dt} = V_g \quad (17)
\]
\[
\frac{di_L}{dt} = \frac{1}{L} (V_g) \quad (18)
\]

The State Space model representation during on state operation,
\[
\begin{bmatrix}
    i_L \\
    v_C
\end{bmatrix} =
\begin{bmatrix}
    0 & 0 \\
    0 & -\frac{1}{RC}
\end{bmatrix}
\begin{bmatrix}
    i_L \\
    v_C
\end{bmatrix} + \begin{bmatrix}
    1 \\
    0
\end{bmatrix} V_g \quad (19)
\]

3.2. **Mode 2**

When switch S is in OFF state, Voltage across the inductor,
\[
V_L = V_g - V_0 \quad (20)
\]
\[ L \frac{di_L}{dt} = V_g - V_0 \quad (21) \]
\[ V_0 = V_C \quad (22) \]
\[ \frac{di_L}{dt} = \frac{V_g}{L} - \frac{V_C}{L} \quad (23) \]

Current through the capacitor,
\[ i_C = i_L - I_0 \quad (24) \]
\[ C \frac{dv_C}{dt} = i_L - \frac{V_0}{R} \quad (25) \]
\[ V_0 = V_C \quad (26) \]
\[ \frac{dv_C}{dt} = \frac{i_L - V_C}{C} \quad (27) \]

The State Space model representation during on state operation,
\[ \begin{bmatrix} i_L \\ v_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{LRC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_g \quad (28) \]

3.3. Transfer Function

Combining both the ON and OFF state of the boost converter, the state space model can be represented as follows,
\[ A = A_1 + A_2 (1 - D) \quad (29) \]
\[ D' = (1 - D) \quad (30) \]
\[ A = \begin{bmatrix} 0 & -\frac{D'}{L} \\ \frac{D'}{C} & 1 \end{bmatrix} \quad (31) \]
\[ B = \frac{1}{L} \quad (32) \]
\[ v_0 = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} V_g \quad (33) \]
\[ C_1 = C_2 = C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (34) \]
\[ D_1 = D_2 = D = \begin{bmatrix} 0 \end{bmatrix} \quad (35) \]

The transfer function can be determined using the following equation,
\[ [SI - A]^{-1} = \begin{bmatrix} S & -\frac{D'}{L} \\ \frac{D'}{C} & S + \frac{1}{LRC} \end{bmatrix}^{-1} \quad (36) \]
\[
[S - A]^{-1} = \begin{bmatrix}
1 & -D' \\
S + \frac{1}{RC} & \frac{1}{S} \\
1 & \frac{1}{S}
\end{bmatrix}
\] (37)

C and B matrix are multiplied to get the final output as shown in equation 19

\[
\frac{v_0(s)}{v_g(s)} = C[S - A]^{-1}B
\] (38)

\[
\frac{v_0(s)}{v_g(s)} = \begin{bmatrix} 0 & 1 \\ S + \frac{1}{RC} & \frac{1}{S} \end{bmatrix} \begin{bmatrix} 1 \\ \frac{1}{S} \end{bmatrix}
\] (39)

\[
\frac{v_0(s)}{v_g(s)} = D' \frac{S^2}{S + \frac{1}{RC} + \frac{D^2}{LC}}
\] (40)

Input to output transfer function of DC-DC Boost Converter can be determined using the following equation,

\[
\frac{v_0(s)}{v_g(s)} = \frac{D'}{S^2 + \frac{1}{RC} + \frac{D^2}{LC}}
\] (41)

\[
= -\frac{1}{(1 - D)} \left[ \frac{S^2LC}{D^2R^2} + \frac{S}{D^2R} + 1 \right]
\] (42)

Control to output transfer function can be determined from the following equation,

\[
\frac{v_0(s)}{d(s)} = \frac{V_g}{(1 - D)} \left[ \frac{1}{\frac{S^2LC}{D^2R^2} + \frac{S}{D^2R} + 1} \right]
\] (43)

4. Simulation Results

Boost converter is simulated [6] using PSIM software and output voltage, switch voltage waveforms, etc., are obtained. PSIM simulated circuit is shown in Fig 4.

Figure 4. Boost converter PSIM circuit

Figure 5 shows the output voltage of the circuit. With an input voltage of 12v, we get an output of 24v.
Figure 5. Output Voltage

Figure 6 shows the switch voltage waveforms. It is compared with the output voltage waveform. The voltage ripple corresponds to the switch voltage.

Figure 6. Switch voltage waveforms

Step input is given as the input and the change which occurs in the output is shown using the time response graph. The transient step response helps to determine the stability of the system in open loop as well as closed loop. It is very important characteristic response to analyze the stability of any converter.

Fig 7 shows the step response of boost converter in MATLAB. This clearly shows the prevailing peak overshoot, more settling time, and the characteristics of time response of conventional boost converter.

Figure 7. Step response of boost converter
Frequency response using bode plot technique gives more information about the converter characteristic compared to the time response hence this converter is analyzed both for time response and frequency changes. Figure 8 shows the Bode plot of boost converter simulated using MATLAB with the transfer function of the converter. Characteristics like gain margin, phase margin, resonant peak, resonant frequency, bandwidth can be determined for a frequency response and these parameters are yardstick allows a quantitative measure of the stability of the boost converter.

![Bode plot of boost converter](image)

**Figure 8. Bode plot of boost converter**

### 5. Performance Analysis of Boost Converter

The open loop response of the Boost converter is shown below with the time domain specifications like rise time, overshoot and settling time for the given unit step input. Figure 9.

![Step response of boost converter](image)

**Figure 9. Step response of boost converter with time domain specifications**

By observing the behaviour of the plot, behaviour of the boost converter and its stability of the converter is determined. Boost converter considered is relatively more stable when the settling time of the converter is less compared to other non-isolated dc-dc converters. Settling time varies inversely to the real part of the roots. Addition of zeros to the open loop transfer function increases bandwidth reduces rise time, increases the settling time and time constant increases for higher values of time period.
Addition of poles to the open loop transfer function decreases the bandwidth and increases the rise time of the converter system resonant peak becomes larger and settling time decreases. Step response of boost converter after adding a pole /zero at different locations shown in Fig [10][11][12].

Figure10. Step response of boost converter after adding a pole

Figure 11. Step response of boost converter after adding a pole at location 2

Relative stability is improved when the converter closed loop poles of the transfer function moves away from the imaginary axis [7]-[10]
The analysis of the boost converter using Ziegler-Nichols method is given below:
After applying step input to the boost converter and analyzing the output, the following parameters are determined in Table 1.

Table 1: Parameters obtained from Ziegler Nichols method

| PI Controller | Ku | Tu  | Kp  | Ti   |
|---------------|----|-----|-----|------|
|               | 0.5| 5 msec | 0.2 | 4e-3 |

Substituting the parameters obtained using Ziegler Nichols method, the following PI controller transfer function is determined [7]. Transfer function of PI controller is shown in equation (44)

\[ G_{pl}(s) = \frac{0.2s + 50}{s} \]  

(44)

Design values for simulation are given in Table 2.

Table 2: Parameters considered for simulating boost converter

| Vg   | Vo   | D   | Fs      | P    | Io   | Ro   | L   | C   |
|------|------|-----|---------|------|------|------|-----|-----|
| 12 V | 24 V | 0.5 | 60 kHz  | 40 W | 1.66 A | 15 Ω | 0.015 mH | 10 μF |

Boost converter with PI controller is simulated using MATLAB software. The following table gives the details about the open loop and closed loop performance of boost converter and shows the overshoot got reduced after implementing PI controller and converter open loop to closed loop.

Table 3: Comparison of open loop and closed loop performance of boost converter

|                | Max overshoot | Setting time (s) |
|----------------|---------------|------------------|
| Open loop      | 77.3 %        | 0.00117          |
| Closed loop    | 0 %           | 0.05             |
Closed loop response of the boost converter and the reduced overshoot from 77.3% to zero percentage is shown in figure 13 and the values are tabulated in Table 3.

6. Conclusion
The design and the performance of Boost converter is accomplished in continuous conduction mode and simulated using MATLAB/ Simulink. The performance parameters of the Boost converter under consideration are rise time, settling time and maximum peak overshoot. This paper analyzed the closed loop control performance of boost converter using Ziegler-Nichols method and also when the location of poles and zeros varies the behaviour is also shown.

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