Abstract – This paper deals with controlling DC-DC boost converter by average sliding controller (ASC) cascaded with PI voltage controller. In the study after modeling of circuit configuration, the cascaded PI-ASC controller is applied to the DC-DC Boost converter. The output value of PI voltage controller is used as a reference current value for ASC which is used for current controller. The topology is modeled and simulated in MATLAB/Simulink program under variable load. Then the simulation results of the PI-ASC controller are compared to that of PI-PI controller.

I. INTRODUCTION

Nowadays, the rapid increase in technology ensures the use of new products for consumers. On the other hand, the rapid of increasing generalizes the use of DC. The need for small and efficient power electronics system rises [1]. There are many applications which are used for DC-DC converters have been published for last two decades [2]. The technology of DC-DC converters has been progressed very quickly. DC-DC converters are very important for applications in the industry. They are particularly used for dc motor drivers, communication furnishing, power supplies, mobile phones, and laptops, un-interrupted power supplies (UPS), renewable energy et al. DC-DC converters have a non-linear character in nature. The engineers who study in control and power electronics field face some difficulties when they want to design a converter that has high performance for industrial applications [3]-[4].

There are many kinds of DC-DC converter which use for industrial application e.g. boost, buck, flyback, buck-boost et al. they can be used for getting desired voltage or current from converter output. DC-DC boost converters are used for applications that require higher output voltage than source voltage. The control method used for DC-DC boost converter must overcome its non-linearity, the variation of voltage and load; provide stability for all conditions [3]. To get desired output voltage which is higher than source voltage some control methods are used.

In this study, PI controller is used for controlling output voltage to get desired voltage. ASC is used for controlling boost inductor current to get desired current. The output value of PI voltage controller is used as a reference current value for ASC which is used for current controller under variable load.

II. DC-DC BOOST CONVERTER

A classical DC-DC boost converter (Fig.1) which consists of five external components provide higher output voltage than input voltage and this feature makes it so important in many applications such as communication, industry, renewable energy, mobile phones, un-interrupted power supply (UPS) etc.

The DC-DC boost converter has two different conditions which depend on switch (S) position. The circuit topology changes according switch position. When S is at ON state the related equations are given in (1) and (2). \( R_m \) is the internal resistance of the output capacitor and it is neglected. The combined matrix form of (1) and (2) is given in (3).
\[ \frac{di}{dt} = \frac{1}{L} V_o \]  
\[ \frac{dv}{dt} = \frac{1}{C} \left( \frac{v}{R} \right) \]  
\[ \begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_z \\ v \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_o \] 
\[ \text{(3)} \]

When switch S is at OFF state the related equations of the circuit are given in (4) and (5). The combined matrix form of (4) and (5) is given in (6).

\[ \frac{di}{dt} = \frac{1}{L} (V_o - v) \]  
\[ \frac{dv}{dt} = \frac{1}{C} (i_z - v) \]  
\[ \begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_z \\ v \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_o \] 
\[ \text{(6)} \]

ON-OFF state of DC-DC boost converter’s matrix form is given in (3) and (6) respectively. By combining (3) and (6) a new equation which is given in (7) shows state space average model. D is duty cycle for converter.

\[ \begin{bmatrix} \frac{di}{dt} \\ \frac{dv}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-D}{L} \\ (1-D)C & 0 \end{bmatrix} \begin{bmatrix} i_z \\ v \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_o \]  
\[ \text{(7)} \]

The voltage conversion rate for converter with D is given in (8).

\[ \frac{di}{dt} = \frac{1}{L} V_o \]  
\[ \text{(8)} \]

III. PI-ASC CONTROL STRATEGY OF DC-DC BOOST CONVERTER

DC-DC boost converter is controlled by different current controllers. In this study ASC is used for current control to get desired dynamic behavior. As seen from Fig.2, The ASC reference current is ensured by PI controller’s output value. The output voltage of converter is measured and compared the reference voltage which is determined before and the result of this comparison is as input for PI controller. Close loop control of converter with PI has zero steady-state error thanks to integral effect. The appropriate \( K_p \) and \( K_i \) coefficients can be determined by Ziegler-Nichols.

The sliding-mode controller (SMC) is a robustness controller and insensitive to disturbances. It ensures good regulation properties in different operating conditions. Also it is a good candidate for non-linear controller [5]. But because of its theoretical complexity, the choosing of parameters for SCM is hard. The parameters must be selected to give satisfactory result and stability conditions. Variable switching frequency brings high sensitivity for SCM to noise [6]. There are some control methods to eliminate the disadvantage of having variable frequency for switching. One of these control methods is ASC that operates with constant frequency. ASC fixes the variable switching frequency to its signal and its signal is ramp. After fixing the frequency, the frequency of switching is constant. The duty cycle (D) changes by variation of the control signal; but by using ASC it is not important because the switching frequency is constant [7]. The application which ASC is used as a controller is robust, stable and good regulator in spite of variable operating conditions.

\[ x_1 = -\frac{(1-D)}{L} x_1 + \frac{1}{L} V_o \]  
\[ x_2 = -\frac{(1-D)}{C} x_1 + \frac{1}{RC} x_2 \]  
\[ x_1 = i_z \quad \text{and} \quad \dot{x}_1 = \frac{di}{dt} \]  
\[ x_2 = v_o \quad \text{and} \quad \dot{x}_2 = \frac{dv}{dt} \]  
\[ \text{(9)} \]

\[ \text{(10)} \]

To control DC-DC boost converter with PI and average sliding controller, \( K_p \) and \( K_i \) coefficients are determined for PI controller and for sliding control a sliding surface is defined by \( x_2=V_{ref} \) in stat-space.

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{L} \\ \frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_z \\ v \end{bmatrix} - \lambda \begin{bmatrix} i_z - x_1 \\ v - x_2 \end{bmatrix} \]  
\[ \text{(12)} \]

Figure 2. Boost converter controlled with PI-ASC controller.
\( i_{\text{ref}} \) is PI controller output signal and \( \lambda \) (Lamda) is sliding surface coefficient [6]. ASC is used for current so (9) is used for (12). Equation (13) is obtained by this way.

\[
D = \frac{V_r - V_o}{V_o} + \lambda L \left( \frac{i_\text{ref} - i_l}{V_o} \right)
\]

(13)

IV. SIMULATION MODEL AND RESULTS
DC-DC boost converter and its controller are modeled and simulated in MATLAB/Simulink program. After modeling DC-DC boost converter which needs a MOSFET for switching, a resistor as load, a diode, an inductor and a capacitor, the PI voltage controller is modeled. The input value of the PI controller (shown in Fig.3) is difference between desired voltage (V\(_r\)) and output voltage (V\(_o\)). Input voltage of the topology is multiplied with the output of the PI controller for input feed forward.

The output signal of PI controller is reference current (\( i_{\text{ref}} \)) for ASC. The input signal of ASC is difference between \( i_{\text{ref}} \) and measured output current of circuit. The ASC for current is given in Fig. 4.

The performance of the DC-DC boost converter that controlled with cascaded PI-ASC controller under different loads is compared. The proposed circuit simulation diagram in MATLAB/Simulink is shown in Fig. 5. and the parameters used in the simulation program are given with Table-I.

### Table I. System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>( V_i )</td>
<td>40V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>( V_o )</td>
<td>200V</td>
</tr>
<tr>
<td>Load Resistance</td>
<td>R</td>
<td>40-80( \Omega )</td>
</tr>
<tr>
<td>Capacitance</td>
<td>C</td>
<td>470( \mu F )</td>
</tr>
<tr>
<td>Inductance</td>
<td>L</td>
<td>470( \mu H )</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>( f_s )</td>
<td>50kHz</td>
</tr>
</tbody>
</table>
The simulation results related to output voltage and output current of the controlled topology are shown in Fig. 6 and Fig. 7 respectively. The simulations have been done for 1000 W load (full load) at input voltage of 40 V. Then the load is decreased to 500 W to observe the dynamic behavior of the output voltage. Fig. 8 shows the inductor current value under different load. As it is seen the circuit is controlled under continuous conduction current mode.

The dynamic behaviors of the output voltage of the topology which are shown in Fig 9 are observed under PI-PI controller and PI-ASC controller. As seen from the figure, when the PI-ASC controller is applied the output voltage ripple is less than the output voltage ripple when the PI-PI controller is applied. Also, the settling time of the output voltage is small under PI-ASC controller.

Figure 9. Output voltages at load change (PI+PI and PI+ASC)

V. CONCLUSION

In the study the cascaded PI voltage-ASC current controller is applied to the DC-DC Boost converter. The controlled topology is modeled and simulated in MATLAB/Simulink program under variable load. Then the simulation results of the PI-ASC controller are compared to that of PI-PI controller. First the topology is controlled by PI controller which has zero steady-state error. This PI controller output signal is used as a current reference for current AS controller. The response of controller is improved in sensitive implementation by using ASC. ASC has simple mathematical model so it is easy method for applications. The systems controlling AS controller have stability under variable condition. Under variable loads, the input and output currents and output voltage are observed. It is observed that when the PI-ASC controller is applied the output voltage ripple is less than the output voltage ripple when the PI-PI controller is applied. Also, the settling time of the output voltage is small under PI-ASC controller.

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