Design, Control and Modelling of a Novel Multi-Input-Multi-Output Boost Converter Hub

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***ABSTRACT*- This paper reports on the design, control and modelling of a novel Multi-Input-Multi-Output Boost Converter topology. The converter hub can integrate renewable energy sources such as wind turbines, photovoltaic arrays, fuel cells, etc. for provision of different output voltage levels. The advantage of energy sources integration is that the required output voltage levels could be made up from a range of sources. The designed converter has the advantages of a simple configuration, fewer components, high conversion ratio and high efficiency.**

The regulated output voltage levels are achieved via classical PID controllers which utilise the concept of closed-loop voltage mode control. Design of the converter control system requires comprehensive knowledge of the converter structure, its operation principle and the small-signal model for continues conduction operation mode. The validity of the converter's control performance is demonstrated through software simulation.

Index Terms: DC-DC Converter, IGBTs, Multi-Input-Multi-Output(MIMO), Renewable energy, small signal modelling, state space averaging.

I. INTRODUCTION

Recently, the number of applications which require more than one power source or more than one kind of energy source is increasing. Generating Multi Input converters, having the capability of diversifying different energy sources, will provide improved reliability and the system flexibility.

Many control methods are used for controlling DC-DC converters where the simple and low cost controller structure is always in demand for most industrial and high performance applications [1]. Most used technique to control switching power supplies is Pulse Width Modulation [2].

When boost converter is employed in open loop mode, it exhibits poor voltage regulation and unsatisfactory dynamic response, and hence, this converter is provided with closed loop control for output voltage regulation. Hence, various close loop techniques had been proposed such as PID controller, Fuzzy logic and other techniques, as well as many other researchers came out with new designs to be controlled with appropriate control technique such as [3] using soft switching technique, and [4] presented high frequency power switches design and robust controller.

In controlling the DC-DC converters a voltage mode control or current mode control could be applied simply by closing a feedback loop between the required output voltages and switching device's duty ratio signal [2]. Due to nonlinearity of current mode control dynamics the difficulties of obtaining the small signal model is achieved, furthermore in current mode control an additional inner feedback loop is needed to control the inductor current and then regulate the output voltage indirectly [5], thus the current mode control is more complex to implement than voltage mode control.

Within close loop system, PID control is considered as a traditional linear control method commonly used in many applications [6]. The PID controller is a popular control feedback used in industrial area due to its flexibility and easy implementation in real applications, furthermore, if the system is complex, the PID can be designed to track an error and assume the system as a black box. A PID controller calculates an error value as the difference between the measured value and the desired reference value [7]. So the PID controller has to adjust three parameters k_p, k_i, k_d of the system which would affect the transient response, rise time, settling time and steady state error, over shoot and stability. Thus, it is not necessary for the system to get the three actions P, I and D it may use one or two actions to improve the system dynamic response.

In this paper a voltage mode control using a PID controller is presented to obtain the closed loop three Input Double Output DC-DC boost converter topology structure as shown in figure 1, where different input sources connected in such a way to integrate the available input sources to provide a high conversion ratio [8].

This paper organised as follow: section II presents the proposed Multi-Input-Multi-Output (MIMO) DC-DC boost converter topology and its operation principle. The dynamic modelling of the DC-DC boost converter for three input source Double output is presented in section III including the MATLAB simulation results. Finally, the conclusion of this study is summarised in section IV.

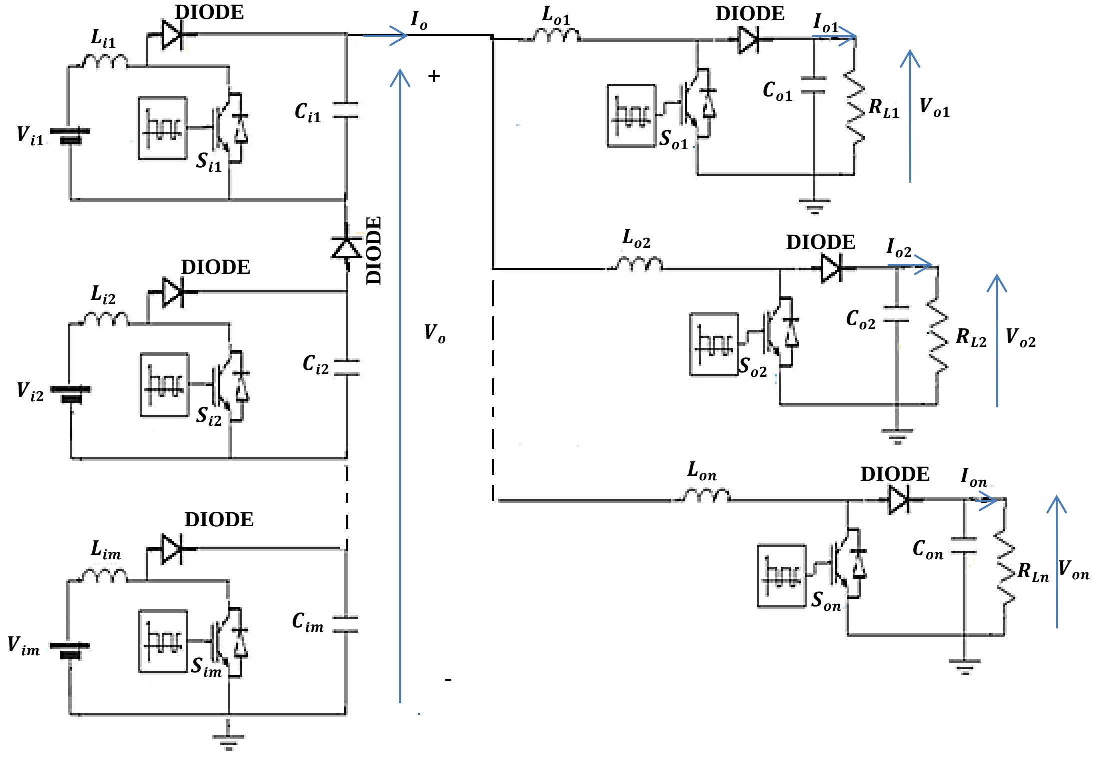

Figure.1. Proposed Multi-Input-Multi-Output DC-DC boost converter topology

II. CONVERTER STRUCTURE AND OPERATION PRINCIPLES

A new efficient MIMO DC-DC Boost converter is proposed with the specifications of high conversion ratio and lower number of components with comparison to the available MIMO Boost converter topologies.
In this design the stepping up voltage occurs in two stages; where the output voltage of the first stage (V_o) acts like the input DC voltage to the next stage, so that means higher conversion ratio, which is important in high DC voltage applications.

The mathematical equations of the proposed (MIMO) Boost converter have been derived assuming that the system is lossless (ideal components):

$$V_{o1} = \left[\frac{V_1}{1-D_1} + \frac{V_2}{1-D_2} + \frac{V_3}{1-D_3} + \cdots + \frac{V_m}{1-D_m}\right]\left[\frac{1}{1-D_{o1}}\right] \tag{1}$$

$$\therefore V_{on} = \left[\sum_{k=1}^{k=m} V_m \frac{1}{1-D_m}\right]\left[\frac{1}{1-D_{on}}\right] \tag{2}$$

V_{on} : The output DC voltage.

V_m: The DC input voltage.

D_m: Duty cycle of the input IGBT switches.

D_{on}: Duty cycle of the output IGBT switches.

In this paper a three input sources V_{i1}, V_{i2}, V_{i3} are responsible for supplying the loads. The converter designed to operate in Continues Conduction Mode as the inductors current will never goes to zero. In this mode the five switches are active. For each switch, a specific duty ratio is considered. Here, S_{i1} is active to regulate the first input source V_{i1} current to desired value. In the same time S_{i2}, S_{i3} are active to regulate V_{i2}, V_{i3} respectively, by controlling the input inductor currents I_{Li2} and I_{Li3}. Regulating the DC bus voltage $V_o = V_{ci1} + V_{ci2} + V_{ci3}$ to

desired value are duty ratios of the three input switches. Also, the output voltage V_{o1} is controlled by the output power switch S_{o1} and $V_{o2}$is controlled by S_{o2}. According to switches states, there are four different switching states in one switching period as shown in figure 2. For each state the inductor and capacitor equations have been investigated as follows:

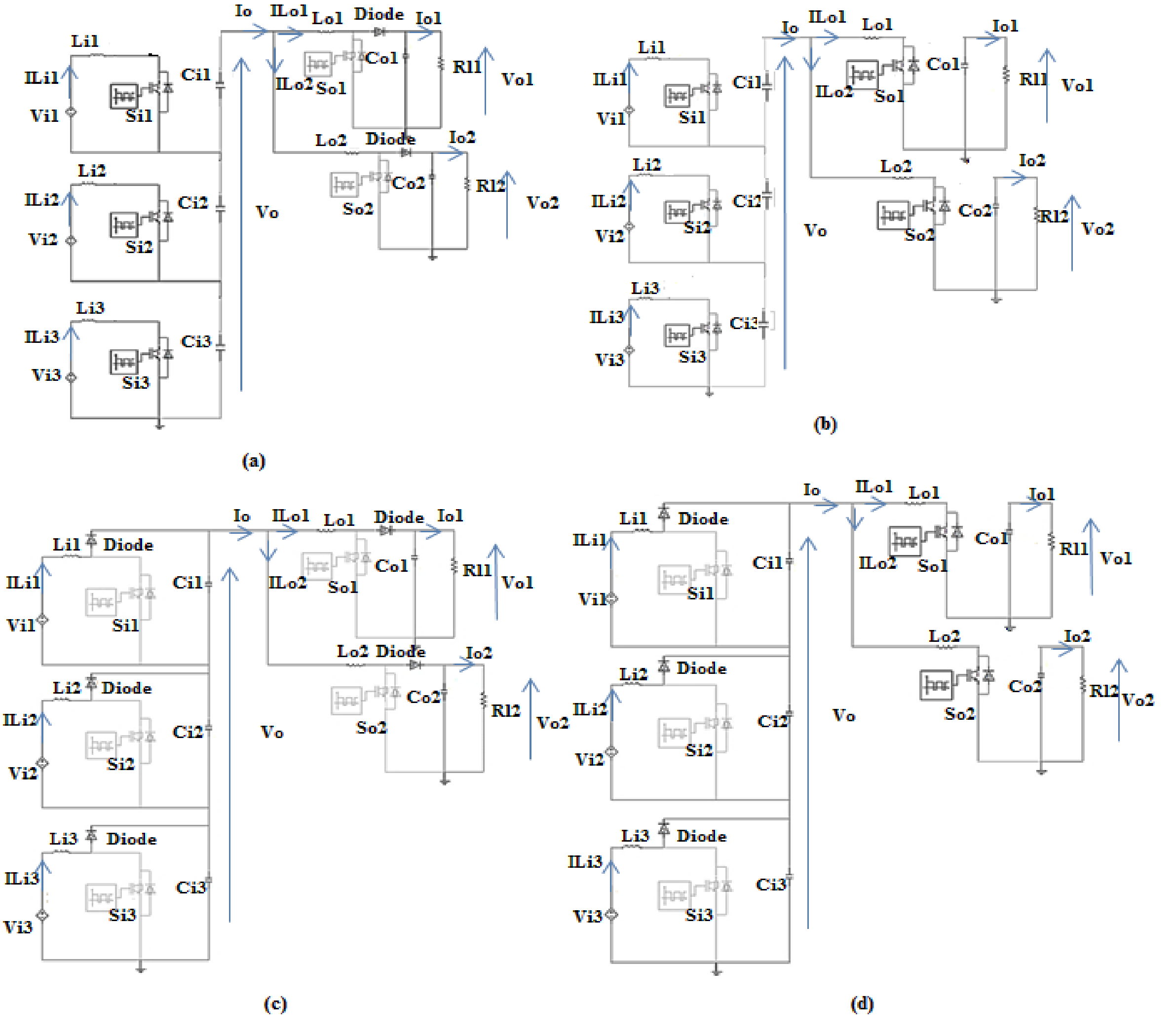

Figure.2. Equivalent circuit of Boost converter switching mode, (a) switching state 1, (b) switching state 2, (c) switching state 3, (d) switching state

a) Switching state 1: In this state, the input power switches S_{i1}, S_{i2}, S_{i3} are turned ON, while the output switches S_{o1} and S_{o2} are turned OFF. When the input switches are ON the input stage diodes are reversely biased, so S_{o1} and S_{o2} are OFF. Assuming that the output capacitors are fully charged, thus the power will deliver to the load R_{L1}, R_{L2}. Equivalent circuit of proposed converter in this state is shown in figure 1(a). In this state, V_{i1}, V_{i2}, V_{i3} charge the inductors L_{i1}, L_{i2}, L_{i3} respectively, so the inductors current increases and the output capacitors are discharged.

The inductors and capacitors equations in this mode are as follows:

$$\begin{cases} L_{i1}\frac{di}{dt} = v_{i1} \\ L_{i2}\frac{di}{dt} = v_{i2} \\ L_{i3}\frac{di}{dt} = v_{i3} \\ C_{i1}\frac{dv_{ci1}}{dt} = -i_o \\ C_{i2}\frac{dv_{ci2}}{dt} = -i_o \\ C_{i3}\frac{dv_{ci3}}{dt} = -i_o \\ L_{o1}\frac{di}{dt} = v_o - v_{co1} \\ L_{o2}\frac{di}{dt} = v_o - v_{co2} \\ C_{o1}\frac{dv_{co1}}{dt} = i_{Lo1} - \frac{v_{o1}}{R_{L1}} \\ C_{o2}\frac{dv_{co2}}{dt} = i_{Lo2} - \frac{v_{o2}}{R_{L2}} \end{cases} \tag{3}$$

b) Switching state 2: In this state, the input power switches S_{i1}, S_{i2}, S_{i3} are still ON, and the output switches S_{o1} and S_{o2} are turned ON. When the input switches are ON the input stage diodes are reversely biased. Assuming that the output capacitors are fully charged, thus the power will deliver to the load R_{L1}, R_{L2}. Equivalent circuit of proposed converter in this state is shown in figure 1(b). In this state, V_{i1}, V_{i2}, V_{i3} charge the inductors L_{i1}, L_{i2}, L_{i3} respectively, as well as the output inductors L_{o1}, L_{o2} charges from the capacitors C_{i1}, C_{i2}, and C_{i3} so the inductors current I_{Lo1}, I_{Lo2} increases. In addition, capacitors C_{o1}, C_{o2} are discharged. The inductors and capacitors equations in this mode are as follows:

$$\begin{cases} L_{i1}\frac{di}{dt} = v_{i1} \\ L_{i2}\frac{di}{dt} = v_{i2} \\ L_{i3}\frac{di}{dt} = v_{i3} \\ L_{o1}\frac{di}{dt} = v_o \\ L_{o2}\frac{di}{dt} = v_o \\ C_{i1}\frac{dv_{ci1}}{dt} = -(i_{Lo\,1} + i_{Lo\,2}) \\ C_{i2}\frac{dv_{ci2}}{dt} = -(i_{Lo\,1} + i_{Lo\,2}) \\ C_{i3}\frac{dv_{ci3}}{dt} = -(i_{Lo\,1} + i_{Lo\,2}) \\ C_{o1}\frac{dv_{co1}}{dt} = \frac{-v_{o1}}{R_{L1}} \\ C_{o2}\frac{dv_{co2}}{dt} = \frac{-v_{o2}}{R_{L2}} \end{cases} \tag{4}$$

c) Switching state 3: In this state, the input power switches S_{i1}, S_{i2}, S_{i3} are turned OFF, and the output switches S_{o1} and S_{o2} are turned OFF. When the input switches are OFF the input stage diodes are forward biased. In this state the stored energy in the input inductors will deliver to charge the capacitors C_{i1}, C_{i2}, and C_{i3}. In addition, the stored energy in the output inductors will deliver to charge the output capacitors C_{o1}, C_{o2}, as well as to deliver the stored energy to the loads R_{L1}, R_{L2}. Equivalent circuit of proposed converter in this state is shown in figure 1(c). In this state, the inductors current I_{Li1}, I_{Li2}, and I_{Li3} decreases and the capacitors C_{i1}, C_{i2}, and C_{i3} charged. The inductors and capacitors equations in this mode are as follows:

$$\begin{cases} L_{i1}\frac{di}{dt} = v_{i1} - v_{ci1} \\ L_{i2}\frac{di}{dt} = v_{i2} - v_{ci\,2} \\ L_{i3}\frac{di}{dt} = v_{i3} - v_{ci\,3} \\ L_{o1}\frac{di}{dt} = v_o - v_{co1} \\ L_{o2}\frac{di}{dt} = v_o - v_{co2} \\ C_{i1}\frac{dv_{ci1}}{dt} = i_{Li\,1} - i_o \\ C_{i2}\frac{dv_{ci2}}{dt} = i_{Li\,2} - i_o \\ C_{i3}\frac{dv_{ci3}}{dt} = i_{Li\,3} - i_o \\ C_{o1}\frac{dv_{co1}}{dt} = i_{Lo1} - \frac{v_{o1}}{R_{L1}} \\ C_{o2}\frac{dv_{co2}}{dt} = i_{Lo2} - \frac{v_{o2}}{R_{L2}} \end{cases} \tag{5}$$

d) Switching state 4: In this state, the input power switches S_{i1}, S_{i2}, S_{i3} are still OFF, and the output switches S_{o1} and S_{o2} are turned ON. When the input switches are OFF the input stage diodes are forward biased. In this state the stored energy in the input inductors keep charging the capacitors C_{i1}, C_{i2}, and C_{i3}. In addition, the stored energy in the input inductors will deliver to L_{o1} and L_{o2} through the switches S_{o1}, S_{o2} respectively. So the inductors current I_{Li1}, I_{Li2}, and I_{Li3} keep decreasing, while I_{Lo1}, I_{Lo2} increases. In addition, the capacitors C_{o1}, C_{o2}, will discharge through the loads R_{L1}, R_{L2}. Equivalent circuit of proposed converter in this state is shown in figure 1(d). In this state, and the capacitors C_{i1}, C_{i2}, and C_{i3} charged. The inductors and capacitors equations in this mode are as follows:

$$\begin{cases} L_{i1}\frac{di}{dt} = v_{i1} - v_{ci1} \\ L_{i2}\frac{di}{dt} = v_{i2} - v_{ci\,2} \\ L_{i3}\frac{di}{dt} = v_{i3} - v_{ic\,3} \\ L_{o1}\frac{di}{dt} = v_o \\ L_{o2}\frac{di}{dt} = v_o \\ C_{i1}\frac{dv_o}{dt} = i_{Li\,1} - i_o \\ C_{i2}\frac{dv_o}{dt} = i_{Li\,2} - i_o \\ C_{i3}\frac{dv_o}{dt} = i_{Li\,3} - i_o \\ C_{o1}\frac{dv_{co1}}{dt} = \frac{-v_{o1}}{R_{L1}} \\ C_{o2}\frac{dv_{co2}}{dt} = \frac{-v_{o2}}{R_{L2}} \end{cases} \tag{6}$$

III. DYNAMIC MODELING OF THE DC-DC BOOST CONVERTER

As mentioned before the proposed converter is controlled by switches S_{i1}, S_{i2}, S_{i3} and S_{o1}, S_{o2}. Each switch has its own specific duty cycle. By proper regulation of switches duty cycles, outputs voltage V_{o1} and V_{o2} are adjustable. To design the closed loop controller for the converter, first dynamic model must be obtained. As stated before in section II to control the output voltage; regulating the bus DC voltage V_o is also needed. In addition, as each input has its own power switch and different parameters value, different controller need to be designed.

Small signal model is the basis for optimised controller design. Especially, for MIMO converters, an effective model will be helpful to realise closed-loop control, and to optimise the converter dynamics [1]. Unlike the conventional SISO converter, the MIMO converter is a high order system, thus the symbolic derivation of the transfer function of each plant is boring; therefore, it is difficult to obtain values of poles and zeros for analysis.

The dynamics of the plant can be described in a matrix form; then computer software is used to plot the bode graph of different transfer functions. Based on small signal modelling method [2], the state variables and duty ratios, input voltages contains two components, dc values (X, D, V) and disturbance values ($\hat{x}, \hat{d}, \hat{v}$). It is assumed that the perturbations are small and do not vary significantly during one switching period. So the proposed converter equations are as follows:

$$\begin{cases} i_{Li}(t) = I_{Li} + \hat{\imath}_{Li}(t) \\ i_{Lo}(t) = I_{Lo} + \hat{\imath}_{Lo}(t) \\ v_{o1}(t) = V_{O1} + \hat{v}_{o1}(t) \\ v_{o2}(t) = V_{O2} + \hat{v}_{o2}(t) \\ d_{i1}(t) = D_{i1} + \hat{d}_{i1}(t) \\ d_{i2}(t) = D_{i2} + \hat{d}_{i2}(t) \\ d_{i3}(t) = D_{i3} + \hat{d}_{i3}(t) \\ d_{o1}(t) = D_{o1} + \hat{d}_{o1}(t) \\ d_{o2}(t) = D_{o2} + \hat{d}_{o2}(t) \end{cases} \tag{7}$$

Where $i_{Li}(t)$, $i_{Lo}(t)$ the input/output inductors current and output capacitor voltage $v_{o1}(t), v_{o2}(t)$ are state variables. Substitutes (7) into (3)-(6), apply the averaging model and multiplied with its duty cycle value. So the system can be represented in a matrix form using a state space averaging model. The state space model takes the following form:

$$\begin{cases} \frac{dX}{dt} = AX + BU \\ Y = CX + DU \end{cases} \tag{8}$$

Where X is a matrix containing the state variables, U is a matrix containing the control inputs $d_{i1}(t), d_{i2}(t), d_{i3}(t), d_{o1}(t), d_{o2}(t)$ and Y is a matrix containing the system outputs $v_o(t), v_{o1}(t), v_{o2}(t)$.

Matrixes X, Y, U takes following form:

$$X = \begin{bmatrix} \hat{\imath}_{Li1}(t) \\ \hat{v}_{ci1}(t) \\ \hat{\imath}_{Li2}(t) \\ \hat{v}_{ci2}(t) \\ \hat{\imath}_{Li3}(t) \\ \hat{v}_{ci3}(t) \\ \hat{\imath}_{Lo1}(t) \\ \hat{v}_{co1}(t) \\ \hat{\imath}_{Lo2}(t) \\ \hat{v}_{co2}(t) \end{bmatrix}, Y = \begin{bmatrix} \hat{v}_{ci1}(t) \\ \hat{v}_{ci2}(t) \\ \hat{v}_{ci3}(t) \\ \hat{v}_{o1}(t) \\ \hat{v}_{o2}(t) \end{bmatrix}, U = \begin{bmatrix} \hat{d}_{i1}(t) \\ \hat{d}_{i2}(t) \\ \hat{d}_{i3}(t) \\ \hat{d}_{o1}(t) \\ \hat{d}_{o2}(t) \end{bmatrix}$$

The transfer function matrix of the converter is obtained from the small signal model from matrices A, B, C and D as follows:

$$G = C(SI - A)^{-1}B + D \tag{9}$$

The rank of transfer function matrix depends on the control variables; so according to the number of control variables as mentioned before, rank of transfer function matrix G is 5×5

Where

$$y = Gu \tag{10}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} & g_{15} \\ g_{21} & g_{22} & g_{23} & g_{24} & g_{25} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix}$$

Using MATLAB software the transfer functions of the controller can be written as follows:

$$g_{11} = \frac{\hat{v}_{ci1}}{\hat{d}_{i1}} = \frac{V_{i1}}{\left((1-D_{i1})(1+\frac{Li1Ci1}{(1-Di1)^2})S^2\right)} \tag{11}$$

$$g_{22} = \frac{\hat{v}_{ci2}}{\hat{d}_{i2}} = \frac{V_{i2}}{\left((1-D_{i2})(1+\frac{Li2Ci2}{(1-Di2)^2})S^2\right)} \tag{12}$$

$$g_{33} = \frac{\hat{v}_{ci3}}{\hat{d}_{i3}} = \frac{V_{i3}}{\left((1-D_{i3})(1+\frac{Li3Ci3}{(1-Di3)^2})S^2\right)} \tag{13}$$

$$g_{44} = \frac{\hat{v}_{o1}}{\hat{d}_{o1}} = \frac{V_O(1-\frac{L_{O1}}{(1-D_{O1})^2 R_{L1}}S)}{\left((1-D_{O1})(1+\frac{(1-D_{O1})^2 R_{L1}\sqrt{\frac{C_{O1}}{L_{O1}}}}{\sqrt{L_{O1}C_{O1}}})S+\frac{L_{O1}C_{O1}}{(1-D_{O1})^2}S^2\right)} \tag{14}$$

$$g_{55} = \frac{\hat{v}_{o2}}{\hat{d}_{o2}} = \frac{V_O(1-\frac{L_{O2}}{(1-D_{O2})^2 R_{L2}}S)}{\left((1-D_{O2})(1+\frac{(1-D_{O2})^2 R_{L2}\sqrt{\frac{C_{O2}}{L_{O2}}}}{\sqrt{L_{O2}C_{O2}}})S+\frac{L_{O2}C_{O2}}{(1-D_{O2})^2}S^2\right)} \tag{15}$$

In this paper the simulation results for three different input DC sources chosen within these ranges ($V_{i1} = (200-500)V$, $V_{i2} = (350-875)\ V\ and\ V_{i3} = (250-625)\ V$) and tow output DC voltages are obtained using PID controller. As the values of the converter parameters the inductors L and the capacitors C have been sized to achieve a constant DC output voltage where $V_o = 4\ kV, V_{o1} = 8\ kV\ and\ V_{o2} = 11\ kV$. So by controlling the bus DC voltage V_o through the PID controllers on the first stage of the designed converter to adapt itself as these inputs changes, thus the next stage will provide controlling the output DC voltages as the load changes. Figure 3 depicts the simulation result using MATLAB software of three input tow output DC-DC boost converter including the load and input sources variations to test the performance of the closed loop control.

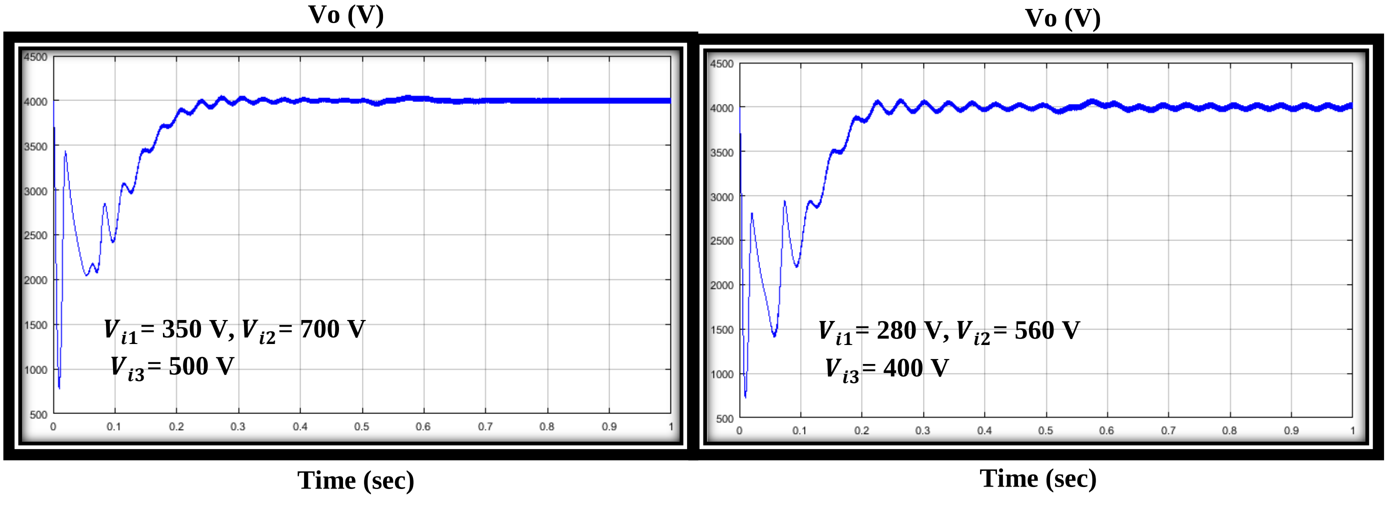

Figure (3.a) Input sources variation (less than 20% of the original input values)

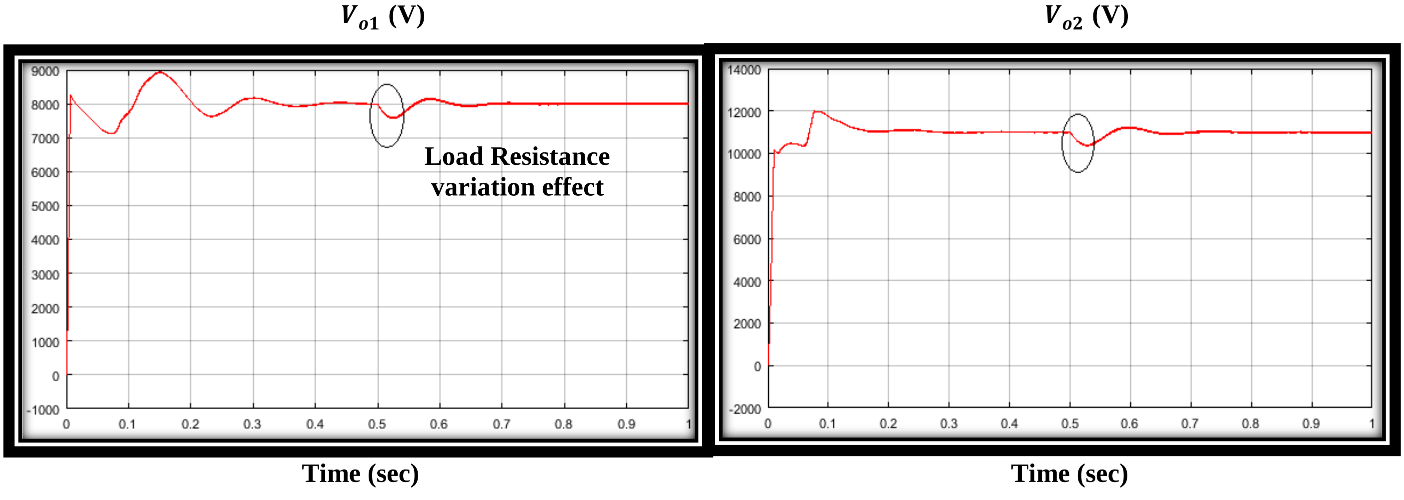

Figure (3.b) Load variation at t=0.5s where$R_L$changed from 1kΩ to $R_L = 500\ \Omega$

Figure 3 depicts the proposed converter output DC voltage results $V_o = 4\ kV, V_{o1} = 8\ kV, V_{o2} = 11\ kV$

IV. CONCLUSION

In this study, a new Multi Input Multi Output DC-DC Boost converter with the advantages of simple configuration, fewer components and high conversion ratio for medium to high voltage applications is proposed. The operation principles and the switching states with the dynamic modelling of the proposed converter have been provided. To verify the performance of the converter MATLAB simulations have been performed.

The presented Boost converter achieves a constant 8 kV, 11 kV for the two outputs from three DC input sources at an operating frequency of 1 kHz. As a whole, the results prove the effective integrated operation of input sources which will provide a reliable and flexible system, as well as the simplicity of designing the controller to achieve a constant DC output voltage in different scenarios when the inputs or the load changes.

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