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A Two Input- One Output DC-DC Converter for DC Sources*

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***Abstract*— Modeling and simulation of a DC-DC converter is performed in this paper that is suitable in distributed generation systems and petrochemical industry. In this paper, a two input converter is proposed and the switch's duty cycles are employed as control freedom to achieve desired output voltage and power. Furthermore, a linear controller is utilized to regulate the output voltage. Finally, the presented dynamic model was tested by simulation results and in continuous the simulation results confirm its suitable operations.**

Keywords*— *Two input converter; Linear controller.

I. INTRODUCTION (*HEADING 1*)

Recently, the worldwide energy crisis is aggravated by rapid increasing economy and great demand of energy. Then to have this energy, most of the customers are used renewable energy sources. These sources need converters to regulate output voltage and power. Some of these sources have a DC voltage and we can use them for DC loads. But if the loads voltage is not equal to sources voltage, the converters could regulate their voltage to loads voltage. In [1 and 2] an one input-output DC-DC converter is proposed which consists of High-Frequency Transformer (HFT) and a half bridge converter at input port and a rectifier converter at the secondary side of HFT. In [3 and 4] a DC-DC converter is implemented for wind turbine supplied DC loads. Switches of

These converters are transistor where they are expensive than diodes, but these converters are bidirectional. In [5] the DC-DC converter has HFT but the number of diodes is more than our converters.

The conventional DC-DC converters have not transformer, then they cannot increase or decrease the output voltage of sources to load voltage. Because these converters cannot change the voltage in a large amount. Therefore, nowadays the High- Frequency Transformers (HFT) is used. High frequency causes major features like high efficiency, low volume, high power density and high turn ratio (i.e., n).

In this paper a DC-DC converter with a HFT, two half bridge converters at input ports and two rectifier converters at the secondary side of HFT are used. This converter is analyzed step to step to show its performance.

II. CIRCUIT CONFIGURATION AND OPERATION PRINCIPLE

Fig. 1 shows the circuit configuration of the proposed converter which is suitable for DGs (e.g., Fuel Cell, …). In this unidirectional structure, two HFTs are improvised to reduce volume of the converter, increase the efficiency and lead to reduce the cost of converter design.

In this paper, the output voltage can be controlled by duty cycle D_1 and D_2. Switches S_{11}, S_{21} have *180º* phase shift to S_{31}, S_{41}. This matter is continuing as S_{12}, S_{22} rather than S_{32}, S_{42}. The switching period ($T_s=1/f_s$) is divided to 6 modes as principle modes are considered.

[*] This paper is extracted from the Master's (Msc) thesis.

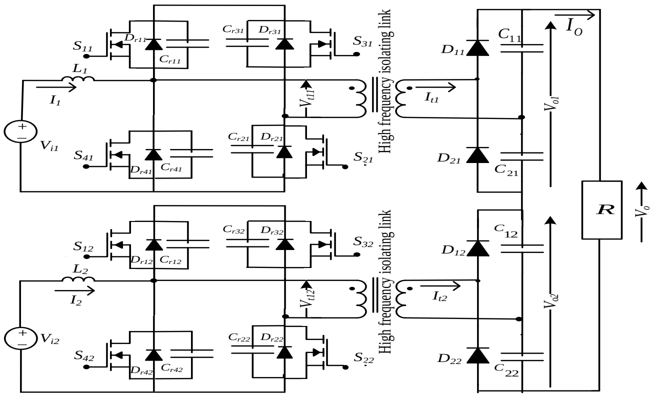


Fig. 1. Two inputs/one output DC-DC converter scheme.

Fig. 2 shows the HFT model of the converter with its turn ratio (i.e., n) where L_s is the leakage inductance of the the transformer. All impedances, currents and voltages are moved to output side with turn ratio (i.e., *n*).

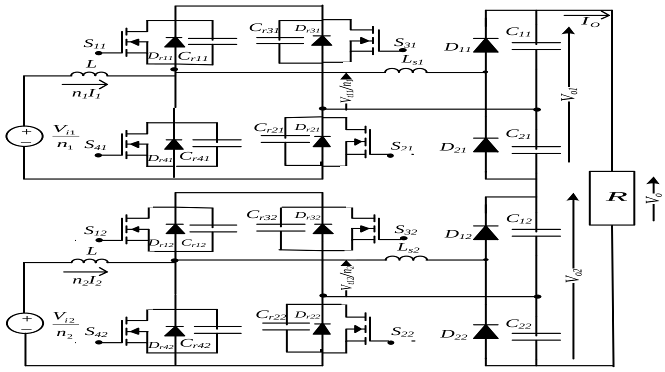


Fig. 2. HFT topology schematics of the studied converter.

The switching period (T_s=$1/f_s$) is divided to 6 stages as listed in Table I.

TABLE I. SWITCHING INTERVAL

Interval	*From-To*	*Description*
1	t_0- t_1	S_{11}, S_{21}, S_{31}, S_{41}, S_{12}, S_{22}, S_{32}, S_{42}: on
2	t_1- t_2	S_{11}, S_{21}, S_{31}, S_{41}, S_{12}, S_{22}, D_{12}: on
3	t_2- t_3	S_{11}, S_{21}, S_{12}, S_{22}, D_{11}, D_{12}: on
4	t_3- t_4	S_{11}, S_{21}, S_{31}, S_{41}, S_{12}, S_{22}, S_{32}, S_{42}: on
5	t_4- t_5	S_{11}, S_{21}, S_{31}, S_{41}, S_{32}, S_{42}, D_{22}: on
6	t_5- t_6	S_{31}, S_{41}, S_{32}, S_{42}, S_{12}, D_{21}, D_{22}: on

The simulation results of key waveforms for a specific operating point are shown in Fig. 3, where the energy is transferred from the input side to the output side.

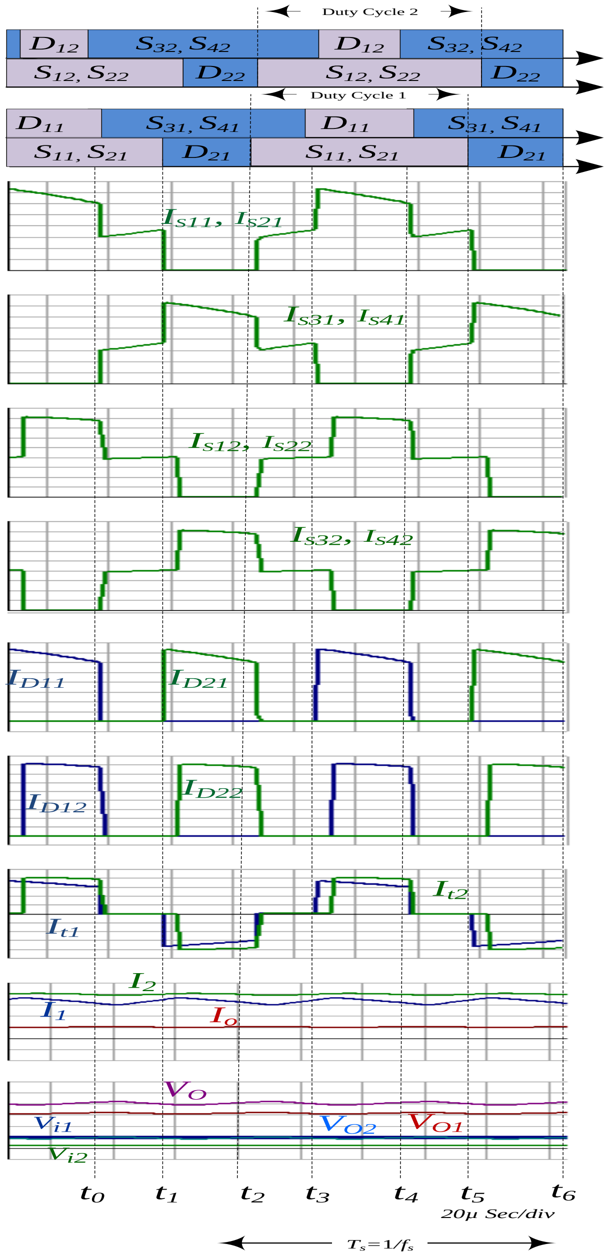


Fig. 3. Principal curves during a commutation sequence.

Fig. 3, exhibits main waveforms of the converter during a commutation sequence. In this figure I_{S11}, I_{S21}, I_{S41}, I_{S42}, I_{S12}, I_{S22}, I_{S42} and I_{S42} are the currents of input port switches. As shown in figure, when the switches are off, their currents are zero. Duty Cycle of each input ports (D_1 and D_2) determine the duty cycle of each diode in output port, where their currents are shown in figure (I_{D11}, I_{D12}, I_{D21} and I_{D22}). I_{t1} and I_{t2} are the currents of HFTs in second side in this figure and I_1, I_2 and Io are input ports and output port currents respectively. $V_{i1}=48\ V$, $V_{i2}=24\ V$, $V_{O1}=150\ V$, $V_{O2}=50\ V$ and $V_O=200\ V$ (*i.e.*, $V_{o1}+V_{o2}$) are input voltages, each output voltage and total output voltage respectively (as shown in Fig. 1), where $V_{O1}=V_{C11}+V_{C21}$ and $V_{O2}=V_{C12}+V_{C22}$.

III. ANALISIS OF STEADY-STATE OPERATION

In this paper the state-space averaging model is used to design the linear controller for voltage regulation. Then the 6 intervals models are shown in Fig. 4 to extract the state-space averaged equations.

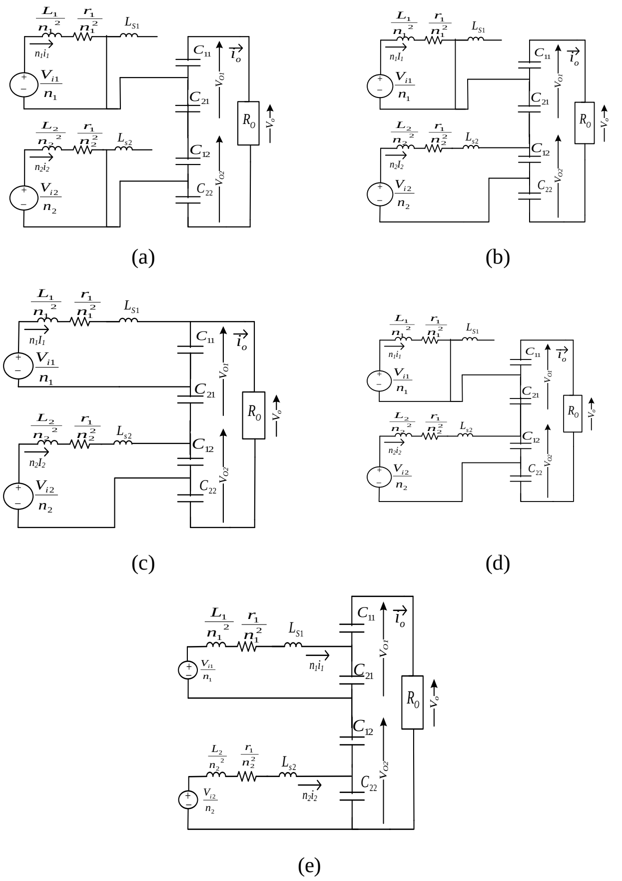


Fig. 4. (a) Active components of Mode 1 and 4.
(b) Active components of Mode 2. (c) Active components of Mode 3.
(d) Active components of Mode 5. (e) Active components of Mode 6.

The state-space averaged equations of this converter are derived as the following equation:

$$\begin{bmatrix} i'_1 \\ i'_2 \\ v'_{O1} \\ v'_{O2} \end{bmatrix} = A \begin{bmatrix} i_1 \\ i_2 \\ v'_{o1} \\ v'_{o2} \end{bmatrix} + B \begin{bmatrix} V_{i1} \\ V_{i2} \end{bmatrix} \tag{1}$$

$$A=\begin{bmatrix} \frac{-r}{L_1}(2D_1-1)-\frac{r(2-2D_1)}{L_1+n_1^2L_{S1}} & 0 & \frac{-(1-D_1)n_1}{L_1+n_1^2L_{S1}} & 0 \\ 0 & \frac{-r_2}{L_2}(2D_2-1)-\frac{r_2(2-2D_2)}{L_2+n_2^2L_{S2}} & 0 & \frac{-(1-D_2)n_2}{L_2+n_2^2L_{S2}} \\ \frac{2n}{C}(1-D_1) & 0 & \frac{-2}{RC} & \frac{-2}{RC} \\ 0 & \frac{2n_2}{n}(1-D_2) & \frac{-2}{RC} & \frac{-2}{RC} \end{bmatrix} \tag{2}$$

$$B=\begin{bmatrix} \frac{2D_1-1}{L_1}+\frac{2-2D_1}{L_1+n_1^2L_{S1}} & 0 \\ 0 & \frac{2D_2-1}{L_2}-\frac{2-2D_2}{L_2+n_2^2L_{S2}} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3}$$

Using the equation $X=-A^{-1}BU$, $Y=-C^TA^{-1}BU$ and assuming $r_1=0$, $r_2=0$, therefore the DC part of steady-state equation can be written, as equation (4). Due to the fact that L_{S1} and L_{S2} are very small, the equation (4) commutates as written as following equation:

$$\begin{bmatrix} i_1 \\ i_2 \\ V_{O1} \\ V_{O2} \end{bmatrix} = \begin{bmatrix} \frac{V_{i1}}{n_1^2(D_1-1)^2R}+\frac{V_{i2}}{n_1n_2(D_1-1)(D_2-1)R} \\ \frac{V_{i1}}{n_1n_2(D_1-1)(D_2-1)^2}+\frac{V_{i2}}{n_2^2(D_2-1)^2R} \\ \frac{V_{i1}}{n_1(1-D_1)} \\ \frac{V_{i2}}{n_2(1-D_2)} \end{bmatrix} \tag{5}$$

Based on equation (5), the output voltage are as functions of the duty cycle D_1 and D_2, which is written by:

$$V_{O1}=\frac{V_{i1}}{n_1(1-D_1)} \tag{6}$$

And:

$$V_{O2}=\frac{V_{i2}}{n_2(1-D_2)} \tag{7}$$

IV. DERIVATION METHODOLOGY OF CONTROL SCHEME

In this section, the liner controller of the proposed converter is presented. Due to the fact that proposed converter is formed of two oneinput-oneoutput unidirectional converters with different amount of input voltages, one controller is improvised for per output voltage, V_{o1} *and* V_{o2}. In fact, the load and input voltages can be variable. Therefore to apply their influence, input currents, duty cycles and output voltages should be considered variable too, as equation (8).

$$\begin{bmatrix} i_1 \\ i_2 \\ V_{O1} \\ V_{O2} \end{bmatrix} = \begin{bmatrix} -\dfrac{C^2(L_1+L_{S1}n_1^2)(\frac{-1+2D_1}{L_1}+\frac{2(1-D_1)}{L_1+L_{S1}n_1^2})(\frac{4n_2-4D_2n_2}{RC^2})V_{i1}}{4(1-D_1)(-1+D_1)(1-D_2)n_1^2n_2} - \dfrac{C^2(L_2+L_{S2}n_2^2)(\frac{-1+2D_2}{L_2}-\frac{2(1-D_2)}{L_2+L_{S2}n_2^2})(\frac{4n_2-4D_2n_2}{RC^2})V_{i2}}{4(1-D_1)(1-D_2)(-1+D_2)n_1n_2^2} \\ \dfrac{C^2(L_1+L_{S1}n_1^2)(\frac{-1+2D_1}{L_1}+\frac{2(1-D_1)}{L_1+L_{S1}n_1^2})(\frac{-4n_1+4D_1n_1}{RC^2})V_{i1}}{4(1-D_1)(-1+D_1)(1-D_2)n_1^2n_2} + \dfrac{C^2(L_2+L_{S2}n_2^2)(\frac{-1+2D_2}{L_2}-\frac{2(1-D_2)}{L_2+L_{S2}n_2^2})(\frac{-4n_1+4D_1n_1}{RC^2})V_{i2}}{4(1-D_1)(1-D_2)(-1+D_2)n_1n_2^2} \\ -\dfrac{(L_1+L_{S1}n_1^2)(\frac{-1+2D_1}{L_1}+\frac{2(1-D_1)}{L_1+L_{S1}n_1^2})}{(-1+D_1)n_1}V_{i1} \\ -\dfrac{(L_2+L_{S2}n_2^2)(\frac{-1+2D_2}{L_2}-\frac{2(1-D_2)}{L_2+L_{S2}n_2^2})}{(-1+D_2)n_2}V_{i2} \end{bmatrix} \quad (4)$$

$$\begin{aligned} i_1 &= I_1 + \tilde{i}_1 \\ v_{i1} &= V_{i1} + \tilde{v}_{i1} \\ v_{o1} &= V_{O1} + \tilde{v}_{o1} \\ D_1 &= D_1 + \tilde{D}_1 \\ i_2 &= I_2 + \tilde{i}_2 \\ v_{i2} &= V_{i2} + \tilde{v}_{i2} \\ v_{o2} &= V_{O2} + \tilde{v}_{o2} \\ D_2 &= D_2 + \tilde{D}_2 \\ R &= R + \tilde{R} \end{aligned} \quad (8)$$

Where: I_1, I_2, V_{i1}, V_{i2}, V_{o1}, V_{o2}, D_1, D_2 and R are DC parts of converter, While $\tilde{i}_1$, $\tilde{i}_2$, $\tilde{v}_{i1}$, $\tilde{v}_{i2}$, $\tilde{v}_{o1}$, $\tilde{v}_{o2}$, $\tilde{D}_1$, $\tilde{D}_2$ and $\tilde{R}$ are their AC perturbation components. By placing (8) in (1) and neglecting of all DC terms and keeping only the AC terms with the power of one, the AC state-space equations have been written as:

$$\begin{bmatrix} \tilde{i}_1' \\ \tilde{i}_2' \\ \tilde{v}_{o1}' \\ \tilde{v}_{o2}' \end{bmatrix} = \tilde{A} \begin{bmatrix} \tilde{i}_1 \\ \tilde{i}_2 \\ \tilde{v}_{o1} \\ \tilde{v}_{o2} \end{bmatrix} + \tilde{B} \begin{bmatrix} \tilde{v}_{i1} \\ \tilde{v}_{i2} \\ \tilde{D}_1 \\ \tilde{D}_2 \\ \tilde{i}_o \end{bmatrix} \quad (9)$$

Where $\tilde{A}$ *and* $\tilde{B}$ are as equations (10) and (11). Assuming $X(s) = (SI - A)^{-1} BU(s)$, the equation (9) can be solved to obtain the AC terms of the output voltages (V_o, V_{o2}) as equations (12) and (13).

$$\tilde{v}_{o1} = G_{vo1vi1}(s) \cdot \tilde{v}_{i1} + G_{vo1D1}(s) \cdot \tilde{D}_1 + G_{vo1io}(s) \cdot \tilde{i}_o \quad (12)$$

$$\tilde{v}_{o2} = G_{vo2vi2}(s) \cdot \tilde{v}_{i2} + G_{vo2D2}(s) \cdot \tilde{D}_2 + G_{vo2io}(s) \cdot \quad (13)$$

The block diagrams of the controller are exhibited in Fig. 5. According to equation (12) and (13) to have a desired output voltage, the duty cycle should be regulated by the controllers $G_{C1(S)}$, $G_{C2(S)}$. Considering the Figure 5, the controllers G_{C1} and G_{C2} should be designed and V_{O1} and V_{O2} can be regulated by duty cycles with these controllers. Fig. 6 shows the bode diagrams of the duty cycle to output voltages transfer functions (i.e., $G_{vo1D1}(s)$ and $G_{vo2D2}(s)$) and the compensated functions, $G_{vo1D1}(s) \cdot G_{C1}$ and $G_{vo2D2}(s) \cdot G_{C2}$.

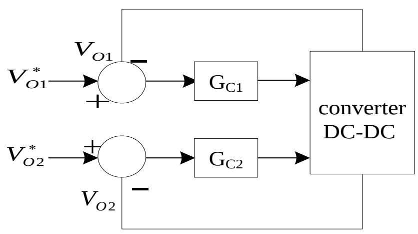
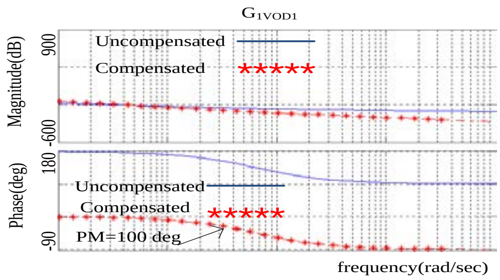


Fig. 5. Schematic of the linear controllers block diagrams.

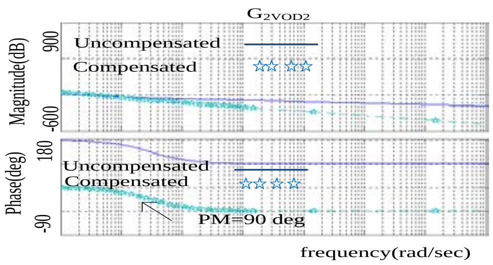
As shown in this Fig, it is obvious that the compensated transfer functions are more stable than the uncompensated ones. Because their phase margins are positive e and they are 100 deg and 90 deg respectively.

$$\tilde{A}=\begin{bmatrix} -\frac{(-1+2D_1)r_1}{L_1}-\frac{2(1-D_1)r_1}{L_1+n_1^2L_{S1}} & 0 & \frac{(-1+D_1)n_1}{L_1+n_1^2L_{S1}} & 0 \\ 0 & -\frac{(-1+2D_2)r_2}{L_2}-\frac{2(1-D_2)r_2}{L_2+n_2^2L_{S2}} & 0 & \frac{(-1+D_2)n_2}{L_2+n_2^2L_{S2}} \\ \frac{2(1-D_1)n_1}{C} & 0 & 0 & 0 \\ 0 & \frac{2(1-D_2)n_2}{C} & 0 & 0 \end{bmatrix} \quad (10)$$

$$\tilde{B}=\begin{bmatrix} \frac{-1+2D_1}{L_1}+\frac{2(1-D_1)}{L_1+L_{S1}n_1^2} & 0 & \frac{-2i_1r_1+2V_{i1}}{L_1}+\frac{-2V_{i1}+2i_1r_1+n_1V_{O1}}{L_1+L_{S1}n_1^2} & 0 & 0 \\ 0 & \frac{2(1-D_2)}{L_2+L_{S2}n_2^2}+\frac{-1+2D_2}{L_2} & 0 & \frac{-2i_2r_2+2V_{i2}}{L_2}+\frac{2V_{i2}+2i_2r_2+n_2V_{O2}}{L_2+L_{S2}n_2^2} & 0 \\ 0 & 0 & -\frac{2i_1n_1}{C} & 0 & -\frac{2}{C} \\ 0 & 0 & 0 & -\frac{2i_2n_2}{C} & -\frac{2}{C} \end{bmatrix} \quad (11)$$



(a)



(b)

Fig. 6. Transfer functions of duty cycles to output voltages with and without compensations:
(a) VO1 (b) VO2

Fig. 7, presents simulation results in mentioned converter and with the parameters listed in Table II.

Where V_o *(i.e.,* $V_{o1}+V_{o2}$) and p_o *(i.e.,* p_1+p_2) are output voltage and power respectively. With a controller that is designed and as shown in simulation results, with a load varying in *t=0.08 Sec* from *400 KW* to *100 KW*, the output voltage is constant and equal to *200 V* where $V_{O1}=150$ *V* and $V_{O2}=50$ *V*.

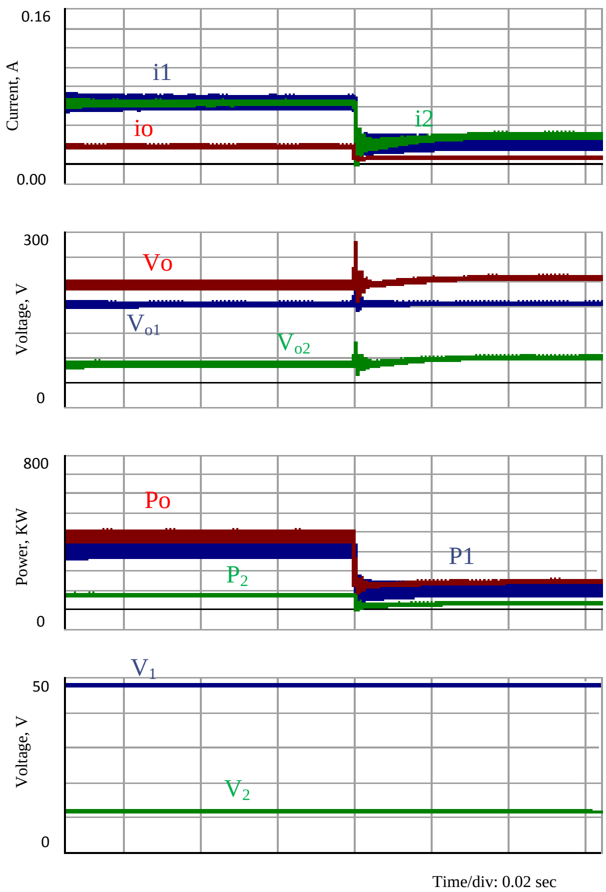


Fig. 7. Waveforms of simulation results.

TABLE II
THREE-PORT CONVERTER PARAMETER

Converter parameters	**Value**
Switching frequency, f_s	10000 HZ
L_1 , L_2	1 mH
L_{S1} , L_{S2}	0.05 μH
C_{11}, C_{21}, C_{12}, C_{22}	100 μF
input voltage, V_{i1}	48 V
input voltage, V_{i2}	12 V
Output voltage, V_o	200 V
winding ratios, n_1 ,n_2	1

V. CONCLUSION

In this paper, a low volume two input port DC-DC converter with two HFTs, is analyzed step to step. This converter is controlled with the switch duty cycles to achieve a desired output voltage. The unidirectional proposed structure has two HFTs, two half bridge converters at primary side and two rectifier converters at output side of the HFTs. The simulation results have proved the theoretical analysis. The proposed converter is very suitable for DC output renewable energy sources, such as Fuel Cells and PVs.

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