EE -665 Power Electronics System For Electrical Vehicles

Semester Project : - DUAL ACTIVE BRIDGE CONVERTER

Design , Control and Operation of Dual Active Bridge Converter

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Under Guidance

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1. Origin Of Dual Active Bridge Converter

In the area of high power density, low power dc/dc converters, there has been a expantion of resonant, quasi-resonant, multi-resonant and resonant transition converters which offer the advantages of soft switching and high switching frequencies.

However, Schwarz was the first one to recognize the profit of resonant switching for the realization of high power dc/dc converters rated in kilowatts. while series and parallel resonant converters have been used in various high power applications, they rather demand a significant penalty in terms of device and component VA stresses.

The dual active bridge converter, proposed by Rik W. De Doncker in 1988, is a dc/dc converter that utilizes two identical primary and secondary side H bridges and a high frequency isolating transformer. It uses active devices on both the input and output sides to realize a minimal topology which has no extra reactive components,low device stresses and it uses the transformer leakage inductance as the main energy transfer element. It allows bidirectional power flow with additional advantages in terms of low ripple current levels in the output and input filter capacitors. This Circuit also allow higher frequency operation with the help of zero voltage switching.

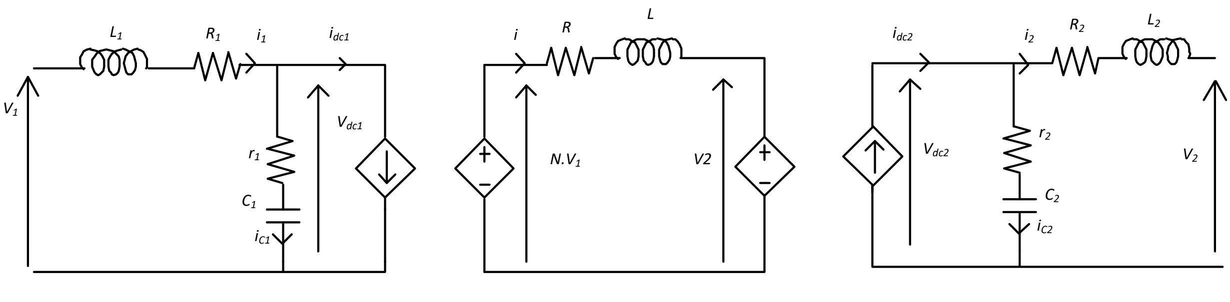

Fig. 1: Electrical network representation of Dual Active Bridge Converter

2. Dual Active Bridge Converter

A Dual Active Bridge converter is DC/DC bidirectional converter where input voltage and output voltage both are DC.

When power is flowing from the DC side to the converter, this circuit acts as a inverter and then it feed it to the transformer and transformer to the second part of the circuit , the second half of the circuit behave like as rectifier , we are using high frequency transformer for high efficiency with electrical insulation.

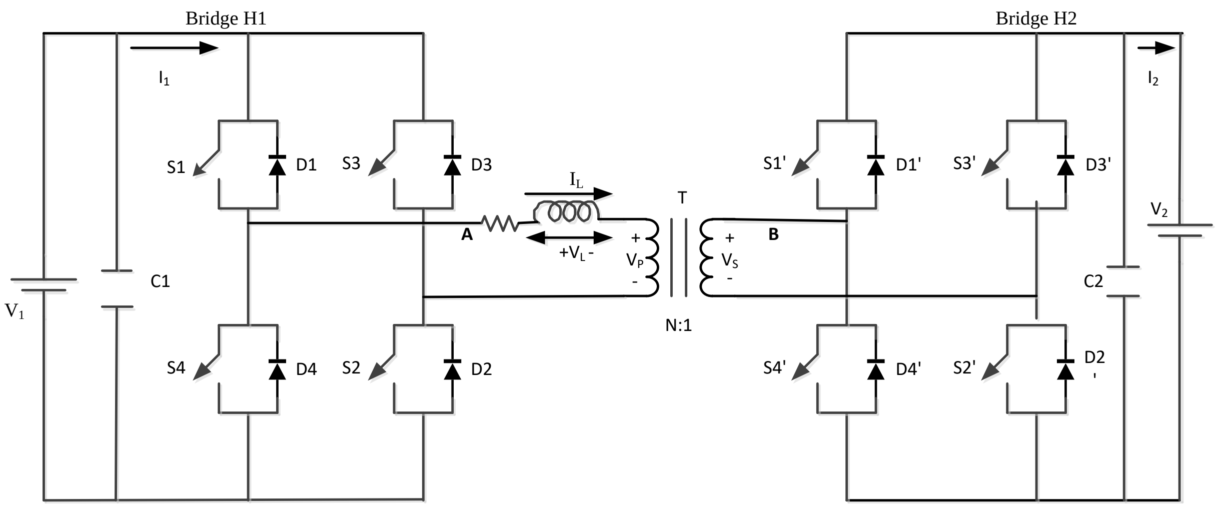

Fig. 2: Dual Active Bridge Converter

One major advantage of such a converter is the bidirectionally of power flow and ability to control the reactive power of the Grid.

3. Fundamental analysis of DAB

$$V_{a1} = V_1\angle\Delta_1 V_{b1} = V_2\angle\Delta_2 \tag{1}$$

$$I_1 = \frac{V_1\angle\Delta_1 - V_2\angle\Delta_2}{xL\angle 90} \tag{2}$$

$$I_1 = \frac{V_1\angle(\Delta_1 - 90)}{xL} - \frac{V_2\angle(\Delta_2 - 90)}{xL} \tag{3}$$

if single freuencey is present then

$$S = V_o * (I_O)^*, P = VIcos\theta, Q = VIsin\theta \tag{4}$$

$$S = P + iQ \tag{5}$$

$$S = V_2\angle\Delta_2 * (I_1)^* \tag{6}$$

$$S = V_2\angle\Delta_2 * (\frac{V_1\angle(\Delta_1 - 90)}{xL}) - \frac{V_2\angle(\Delta_2 - 90)}{xL})^*$$
$$S = (\frac{V_1 * V_2\angle(90 - \Delta_1 + \Delta_2)}{xL} - \frac{(V_2)^2\angle 90}{xL} \tag{7}$$

$$P_L = \frac{V_1 * V_2 * cos(90 - (\Delta_1 - \Delta_2))}{xL} \tag{8}$$

$$P_L = \frac{V_1 * V_2 * sin(\Delta_1 - \Delta_2)}{xL} \tag{9}$$

$$Q_L = \frac{V_1 * V_2 * cos(\Delta_1 - \Delta_2)}{xL} - \frac{(V_2)^2}{xL} \tag{10}$$

From equation (9) we can see that for power to flow from a to b there must a phase difference between Vp and Vs and hence switching pulses of two H-bridges must have a phase difference. This phase shift controls the amount of power flow, from one dc voltage source to the other. This allows a Constant frequency, square wave mode of operation, and utilization of the leakage inductance of the transformer as the main energy transfer element. The resonant converter is not utilized because of high VA stresses.

4.1 Forward Operation

in forward operation mode converter takes supply from voltage source It is working on bipolar switching SPWM at a pulse two diagonally opposite switches are in conduction mode for converter 1 switches (S1 , S2) for converter 2 (S1' , S2') working in charging mode , at a time 4 switches will in conduction mode .

the Power follow sequence in forward mode .

1. Bridge 1 = V_1 →S_1 → Inductor → Transformer →S_2
2. Bridge 2 = Transformer →S_1' → Battery →S_2' → Transformer

4.2 Backward Operation

in backward operation mode operation mode we take power form battery than to switches switches belongs to converter 2 (S3' , S4') and switches belongs to converter 1 (S3 , S4) are in conduction. for a current flow in a circuit at a time 4 switches must in the conduction mode.

the Power follow sequence in Reverse mode .

1. Bridge 2 = Battery →S_3' → Transformer →S_4' → Battery
2. Bridge 1 = Transformer → S_3 → V_1 →S_4 → Transformer

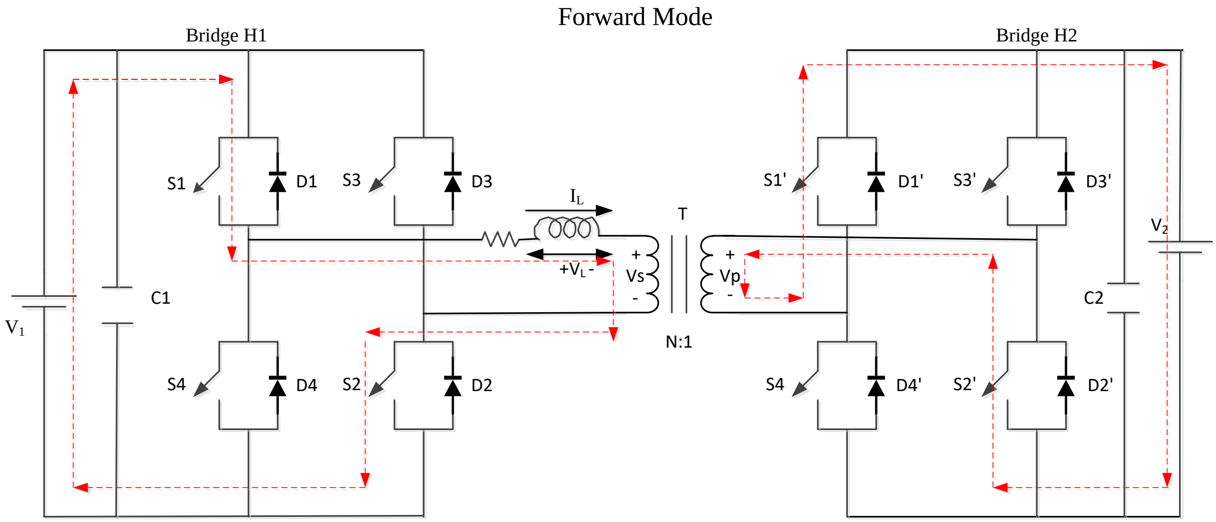

Fig. 3: Forward Mode

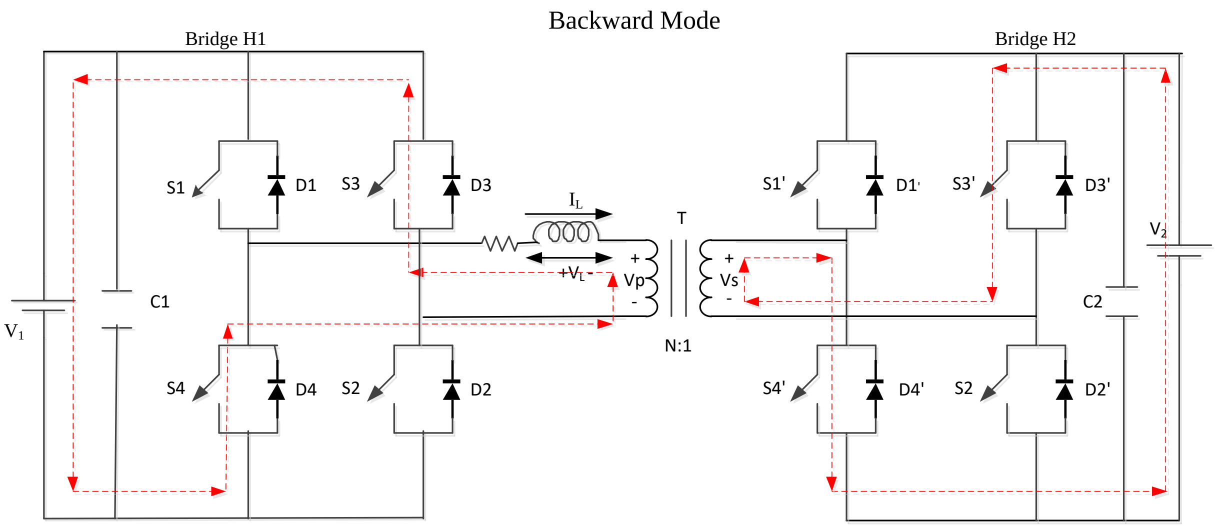

Fig. 4: Backward Mode

5. Inductor Current Characteristic

From the above inference obtained from equation (9), we have seen that there must be phase difference in the voltages across the inductor. Now we intend to analyse the inductor current behaviour.

Let us consider,

$V_{in} > V_o$

Also for our convenience, let us consider a unity turns ratio for the isolation transformer in Fig2.

Now, the voltage across the inductor is given by $V_L = V_{an} - V_{bn}$

During the period t_1 when S1,S2 and S3',S4' are ON in the 1st and 2nd H bridge respectively,

$V_L = V_{in} + V_o$ in magnitude and the hence the inductor current is having a higher gradient given by $\frac{V_L}{L}$.

During the period t_2 when S1,S2 and S1',S2' are ON in both the 1st and 2nd H bridges respectively, $V_L = V_{in} – V_o$ in magnitude and the hence the inductor current is having a less gradient given by $\frac{V_L}{L}$ compared to t_2 .

During the period t_3 when S3,S4 and S1',S2'are ON in the 1st and 2nd H bridge respectively,$V_L = -V_{in} - V_o$ and the hence the inductor current is having a negative gradient in this interval.

During the period t_4 when S3,S4 and S3',S4' are ON in both 1st and 2nd H bridge respectively, $V_L = -V_{in} + V_o$ and the hence the inductor current is again having a negative gradient in this interval but it is less than t_3 .

During the period t_5 when S1,S2 and S3',S4' are ON in both 1st and 2nd H bridge respectively, $V_L = V_{in} + V_o$ and the hence the inductor current is now having a positive gradient in this interval. Thus we obtain the inductor current characteristic as shown in the figure.

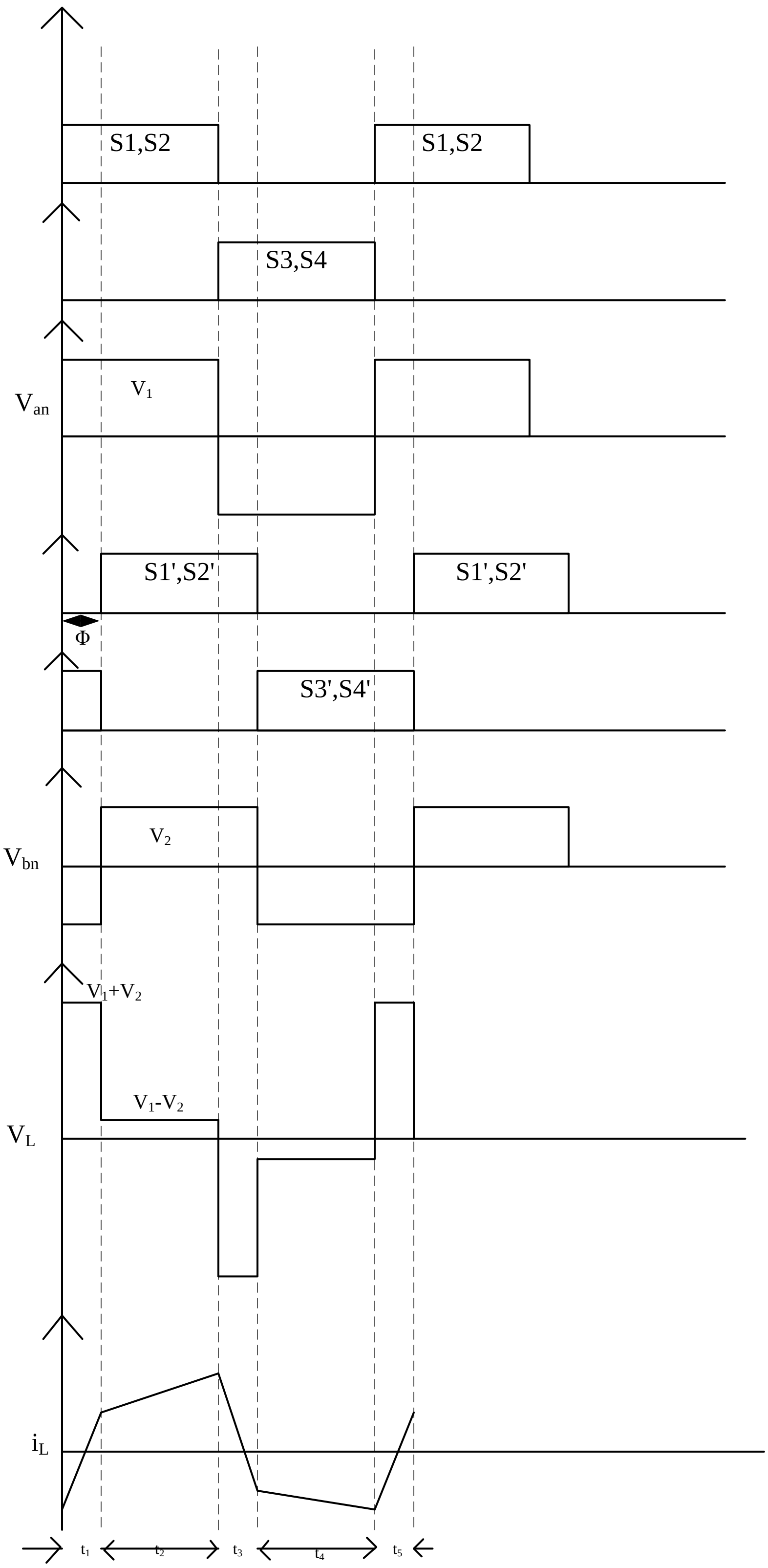

Fig. 5: Inductor Current

6 Mathematical expression of Dual Active Bridge Converter

during interval $t_o - t_1$

$$i_L(t_1) = i_L(t_0) + (V_1 + V_2) * \frac{DT_S}{L_S} \tag{11}$$

during interval $t_1 - t_2$

$$i_L(t_2) = i_L(t_1) + (V_1 - V_2) * \frac{(1-D)T_S}{L_S} \tag{12}$$

during interval $t_2 - t_3$

$$\Delta I_{L_S} = (V_1 + V_2) * \frac{-DT_S}{L_S} \tag{13}$$

here we find the value of I_{to}

$$i_L(t_0) = \frac{(1-2D)V_2 - V_1}{4 * f_s * L_S} \tag{14}$$

maximum value of inductor current

$$i_L(t_1) = I_L(max) = \frac{-(1-2D) * V_1 + V_2}{4 * f_s * L_S} \tag{15}$$

average value of inductor current

$$I_L(avg) = \frac{D * (1-D)v_2}{2 * f_s * L_S} \tag{16}$$

input power

$$P_{in} = n * V_1 * I_L(avg) = n * V_1 * \frac{D * (1-D)V_2}{2 * f_s * L_S} \tag{17}$$

input power is a DC power as Dual Active Bridge is DC -DC bidirectional converter so output power also DC power$P_{in} = p_{out} = \frac{(V_2)^2}{R}$

as form the power balance we can find the output voltage V_2

$$V_2 = n * V_1 * R_L \frac{D * (1-D)V_2}{2 * f_s * L_S} \tag{18}$$

7. State Space Analysis of Dual Active Bridge Converter

7.1 Need of State Space Analysis

State space analysis can be applied to any dynamic system. Transfer function method is defined for LTI systems. It neglects the initial conditions. We can know the behaviour of a system to a particular input if its transfer function is known which is quite complex for non LTI systems. Thus state space analysis is done which has many advantages: -

1. It can be used for linear or nonlinear, time-variant or time-invariant systems.

2. It is easier to apply where Laplace transform cannot be applied such as for differential equations with unknown constants.

3. The nth order differential equation can be expressed as 'n' equation of first order.

4. It is a time domain method therefore it is suitable for digital computer computation.

7.2 State Space Analysis of DAB

the transformer primary side voltage V_p have only two states: (a) $+V_1$ when switches S1 and S2 are on; (b)$-V_1$ when switches S3 and S4 are on , same as at output bridges transformer secondary voltage is Respectively

$$V_p(t) = S_1(t)V_{in}(t) \tag{19}$$

$$V_s(t) = S_2(t)V_s(t) \tag{20}$$

Let current flowing from Inductor I_L and voltage across capacitor V_o , so the state variable will be Respectively

$$\frac{di_L(t)}{dt} = \frac{-R_t}{L_t} I_L(t) + \frac{S_1(t)}{L_t} V_{in}(t) - \frac{S_2(t)}{L_t} V_O(t) \tag{21}$$

$$\frac{dV_O(t)}{dt} = \frac{-1}{RC_O} V_O(t) + \frac{S_2(t)}{C_O(t)} I_L(t) - \frac{I_O}{C_0} \tag{22}$$

As equation (21) and equation (21) both are non linear and time variant we change them into linear and time invariant by using state space averaging . here we are using Fourier series for state space averaging where subscript R and I for real and Imaginary part Respectively .

$$\begin{aligned}\frac{d\langle I_L\rangle_0}{dt} =& \frac{-R_t}{L_t}\langle I_L\rangle_0 + \frac{1}{L_t}\langle V_{in}\rangle_0\langle S_1\rangle_0 + \frac{2\langle S_1\rangle_{1R}}{L_t}\langle V_{in}\rangle_{1R} + \frac{2\langle S_1\rangle_{1I}}{L_t}\langle V_{in}\rangle_{1I} \\ &- \frac{1}{L_t}\langle V_O\rangle_O\langle S_2\rangle + \frac{2\langle S_2\rangle_{1R}}{L_t}\langle V_O\rangle_{1R} + \frac{2\langle S_2\rangle_{1I}}{L_t}\langle V_O\rangle_{1I}\end{aligned} \tag{23}$$

$$\frac{d\langle V_0\rangle_O}{dt} = \frac{-1}{C_O}\langle I_O\rangle_O + \frac{-1}{RC_O}\langle V_O\rangle_O + \frac{\langle S_2\rangle_O}{C_O}\langle I_L\rangle_O + \frac{2\langle S_2\rangle_{1R}}{C_O}\langle I_L\rangle_{1R} + \frac{2\langle S_2\rangle_{1I}}{C_O}\langle I_L\rangle_{1I} \tag{24}$$

In case of Input voltage and the load Current , the dynamic behaviour is much slower than output voltage variation of DAB converter so $0th$ Component of Input Voltage and Load Current is zero . the $1st$ order component component of $S_1(t)$ and $S_2(t)$ are

$$\langle S_1\rangle_{1R} = 0$$

$$\langle S_1\rangle_{1I} = \frac{-2}{\pi}$$

$$\langle S_2\rangle_{1R} = \frac{-2cosd\pi}{\pi}$$

$$\langle S_2\rangle_{1I} = \frac{-2cosd\pi}{\pi}$$

Now we compare Equation with standard state space form where X(t) are State vector and u(t) are input

$$\frac{dX(t)}{dt} = A_1X(t) + B_1u(t)$$

$$Y(t) = C_1X(t) + D_1u(t)$$

$$\mathrm{A} = \begin{bmatrix} \frac{-1}{RC_O} & \frac{-4sin(d\pi)}{\pi C_O} & \frac{-4cos(d\pi)}{\pi C_O} & 0 & 0 & 0 \\ \frac{2sin(d\pi)}{\pi L_t} & \frac{-R_t}{L_t} & \omega_s & 0 & 0 & 0 \\ \frac{2cos(d\pi)}{\pi L_t} & -\omega_s & \frac{-R_t}{L_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-R_t}{L_t} & \frac{4sin(d\pi)}{\pi L_t} & \frac{4cos(d\pi)}{\pi L_t} \\ 0 & 0 & 0 & \frac{-2sin(d\pi)}{\pi C_O} & \frac{-1}{RC_O} & \omega_s \\ 0 & 0 & 0 & \frac{-2cos(d\pi)}{\pi C_O} & -\omega_s & \frac{-1}{RC_O} \end{bmatrix}$$

$$\mathrm{B} = \begin{bmatrix} 0 & 0 & \frac{-2}{\pi L_t} & 0 & 0 & 0 \\ \frac{-1}{C_O} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$\mathrm{X} = \begin{bmatrix} V_{ao} & I_{t1R} & I_{t1I} & I_{to} & V_{o1R} & V_{o1I} \end{bmatrix}^T$$

$$u = \begin{bmatrix} V_{in} & I_L \end{bmatrix}^T$$

because of zero initial value assumption, I_{t0}, V_{O1R}, V_{O1I} are all zero. so the dynamic state space wiil be

$$\frac{d}{dt}\begin{bmatrix}\Delta V_{O0}\\ \Delta I_{t1R}\\ \Delta I_{tI1}\end{bmatrix} = \begin{bmatrix}\frac{-1}{RC_O} & \frac{-4sin(d\pi)}{\pi C_O} & \frac{-4cos(d\pi)}{\pi C_O}\\ \frac{2sin(d\pi)}{\pi L_t} & \frac{-R_t}{L_t} & \omega_s\\ \frac{2cos(d\pi)}{\pi L_t} & -\omega_s & \frac{-R_t}{L_t}\end{bmatrix} * \begin{bmatrix}\Delta V_{O0}\\ \Delta I_{t1R}\\ \Delta I_{tI1}\end{bmatrix} + \begin{bmatrix}0 & \frac{1}{C_O}\\ 0 & 0\\ \frac{-2}{\pi L_t} & 0\end{bmatrix} * \begin{bmatrix}V_i\\ I_L\end{bmatrix} \tag{25}$$

8 . Control Techniques

Majorly we used four types of control principal in Dual Active Bridge Converter , in control techniques we mainly control the phase shift between the output voltage of two bridge convertes so the power flow can be possible from the leakage inductance of transformer as we know that in AC system power flow one end to other end when it is change in voltage angle

8.1 Single Phase Shift (SPS)

In single phase shift control technique , in convertert 1 the opposite leg switches in going in conduction mode and we give the phase shift in 2nd bridge converter for the power flow in from one end to other end , as it is easiest and most useable technique in DAB the disadvantage of this technique is as power flow depend on leakage inductance so circulating current so we dont have full range of ZVS and get the 2 level output voltage . In SPS method, the phase shift is given only between the corresponding switches of two active bridges having gate signals with 50% duty cycle. Thus, the voltage present at the transformer terminals is two level ac square wave and can be modified by adjusting the phase shift. The power flowing through the converter can be regulated by controlling the current passing through the leakage inductor which depends on the voltage across the terminals of the transformer. SPS modulation is easy to implement and soft-switching can be achieved. In single phase shift modulation, the steady state operation of DAB can be segregated into four intervals based on the operation of switches as discussed in the section Inductor current characteristics.

9. Open Loop Simulation of Dual Active Bridge Converter

Given Data $v_{in} = 400V$, $V_{out} = 360V$, Output Power= $22KW$, Switching Frequency = $10KHz$ Now we calculate the value of R , L ,C

9.1 Calculation of R

$$
\begin{aligned}
R &= \frac{(V_o^2)}{R} \\
R &= \frac{(3600^2}{22 * 10^3} \\
R &= 5.891\Omega
\end{aligned}
\tag{26}
$$

9.2 Calculation of L

For Calcultion of inductor we have to find the values of D or either we have to decide the phase shift which is given to Bridge 2 let the duty ratio D = 0.1 Relation between D and θ ,

$$
\begin{aligned}
D &= \frac{\theta}{\pi} \\
0.1 &= \frac{\theta}{180^\circ} \\
\theta &= 18^\circ
\end{aligned}
\tag{27}
$$

so the phase differnce between the Bridge H1 and Bridge H2 is 18°

$$
\begin{aligned}
P_{out} &= n * V_1 * \frac{D * (1 - D)V_2}{2 * f_s * L_S} \\
L &= \frac{(400)^2 * 0.1 * 0.9}{2 * 10000 * 22 * 10^3} \\
L &= 29.45\mu H
\end{aligned}
\tag{28}
$$

9.3 Calculation of Output Capacitor

$$
C_{out} = \frac{I_o * D}{\Delta V_o * f_s}
\tag{29}
$$

value of output current is $I_o = \sqrt{\frac{P_O}{R}} \Longrightarrow \mathrm{I}_o = 61.1A$

in partically we assume there is approximate 5% in Output Voltage the value of $\Delta V_O = 18V$

$$
\begin{aligned}
C_{out} &= \frac{I_o * D}{\Delta V_o * f_s} \\
C_{out} &= \frac{61.1 * 0.1}{18 * 10^4} \\
C_{out} &= 33.94\mu F
\end{aligned}
\tag{30}
$$

10. Simulation

In simulation we use the single phase control techniques .

In single phase shift control technique , in convertert 1 the opposite leg switches in going in conduction mode and we give the phase shift in 2nd bridge converter for the power flow in from one end to other end , as it is easiest and most useable technique in DAB the disadvantage of this technique is as power flow depend on leakage inductance so circulating current so we dont have full range of ZVS and get the 2 level output voltage .

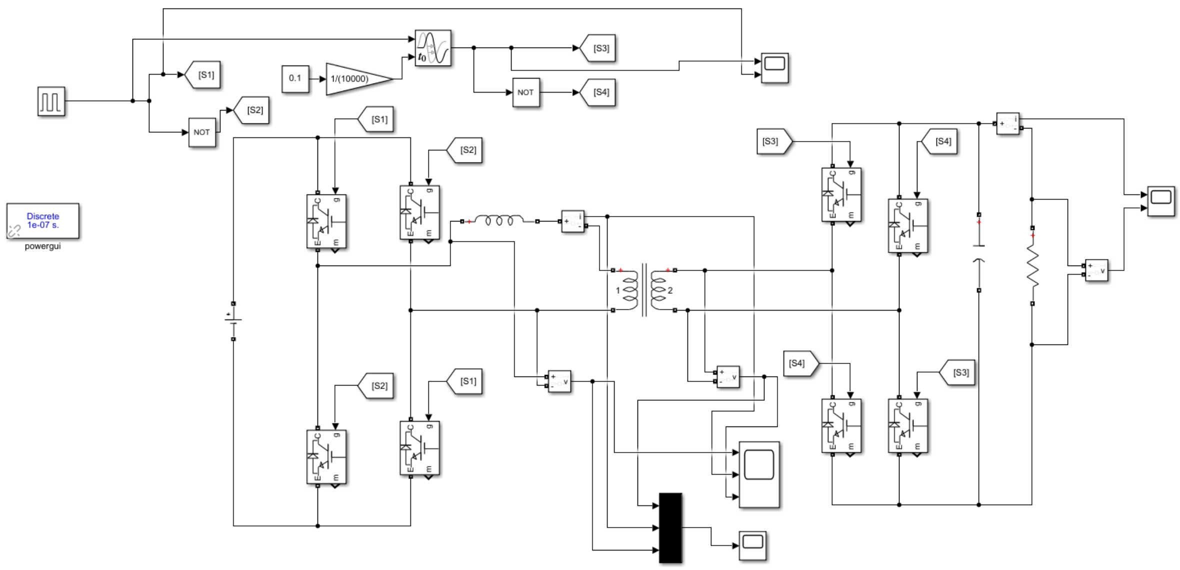

Fig. 6: Simulation Circuit of Dual Active Bridge Converter

11. Simulation Result

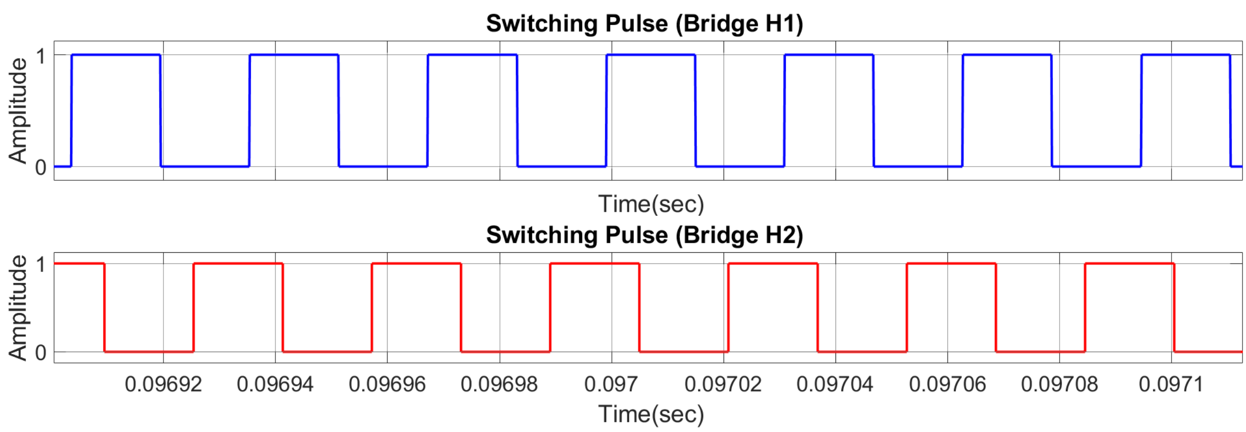

Fig. 7: Switching Pulse

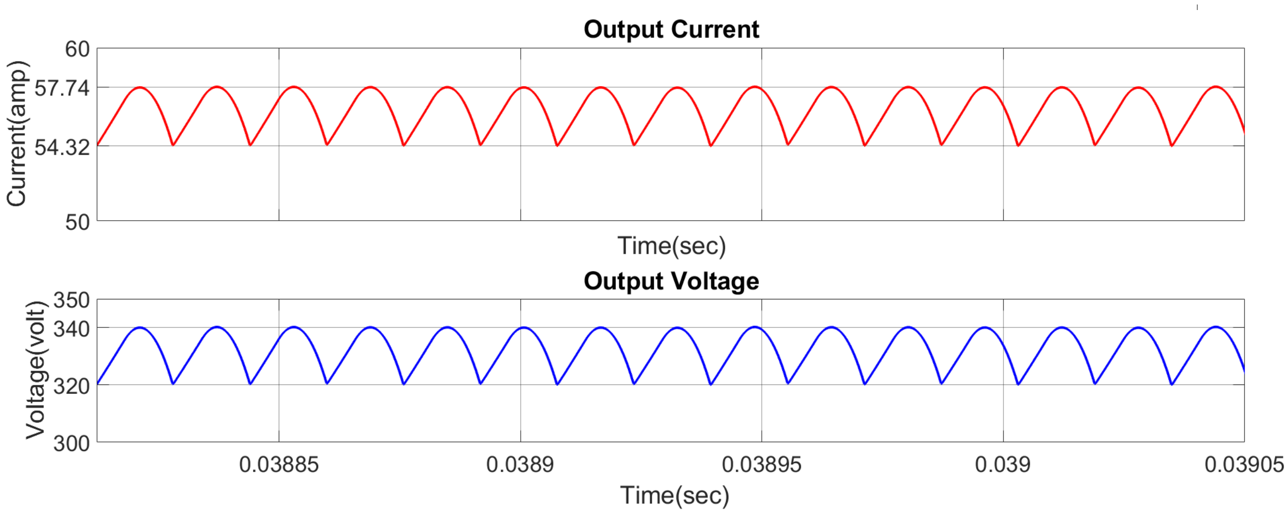

Fig. 8: Output Voltage and Output Current

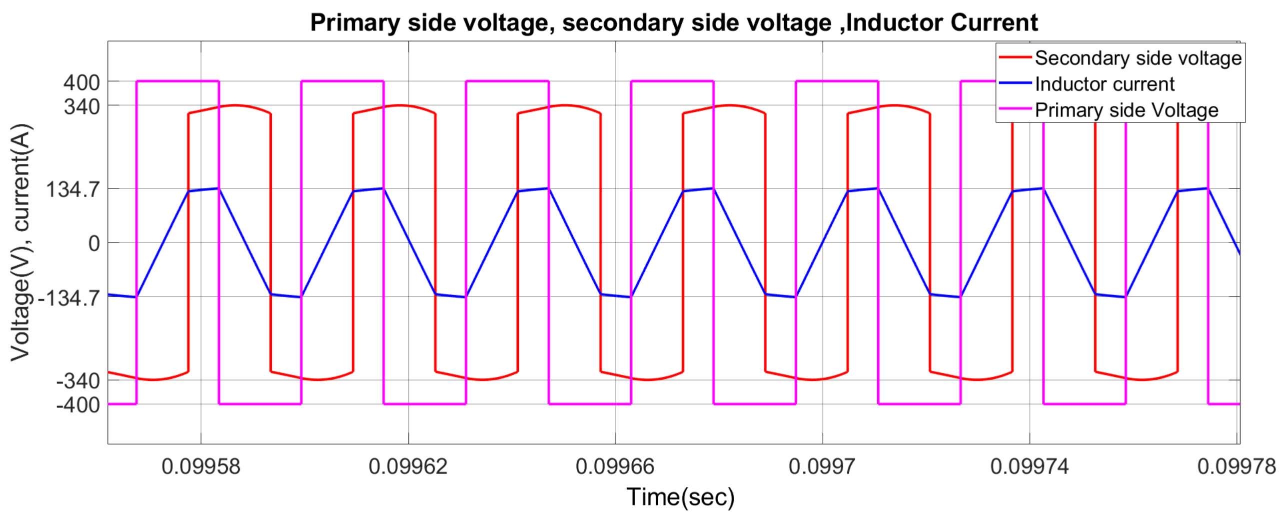

Fig. 9: Primary Side Voltage , Inductor Current , Secondary side Voltage

12. Conclusion and Discussion

The simulation results are obtained using the single phase shift (SPS) control technique where the phase difference between the bridges H1 and H2 is taken as 18°.

The primary voltage is the square wave output voltage of bridge H1 of 400 V. The secondary voltage obtained is of two level due to the SPS control technique. The ripple in the output voltage waveform is 5.88 %of its peak value where the minimum voltage is 320 V and maximum voltage is 340 V. The output current also has a ripple of 5.9 % and is plotted alongside the output voltage. The inductor current obtained in the simulation is having the desired nature and thus the Dual Active Bridge DC-DC converter has been designed and simulated using the widely used SPS control technique.

13. References

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