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Performance Evaluation of Dual-Bridge High Frequency Resonant DC/DC Converter

G. K. Gaidhane[1], A. S. Sindekar[2]

PG Student [EPS], Department of Electrical Engineering, Government College of Engineering, Amravati, India[1]

Associate Professor and HOD, Department of Electrical Engineering, Government College of Engineering, Amravati, India[2]

ABSTRACT:A bidirectional dual-bridge high-frequency isolated resonant DC-DC converter is gaining more attention in renewable energy system due to its high power density, small size, reducing stress and removing electromagnetic interference noise. In this paper the simulation of dual bridge LCL resonant converter is carried out for battery load. The simplified steady state analysis using complex ac analysis is given and conditions for zero voltage switching are presented accordingly.

KEYWORDS: DC-DC converter, renewable energy sources, isolated transformer, zero -voltage switching (ZVS).

I. INTRODUCTION

With the increasing demand for electric power in future automobiles, telecom and computer system, hybrid vehicle system and aviation system, people have recognized the key importance of renewable energy sources to these systems [1]-[3]. The bidirectional dc-dc converter plays an important role to interface between high voltage bus where energy generation device such as photovoltaic panel or other sources installed, and a low voltage bus, where generally energy storage devices such as a battery or super capacitor is connected. The input to this converter is generally variable dc voltage sources like fuel cell, photovoltaic or ac sources with both changing in magnitude and frequency. The output of this converter is dc which can be fed to dc load or fed to utility through an inverter. The power level of such type of converter is generally less than 100 kW [4]. A dual bridge converter (DBC) is generally consisting of two active bridges linked by high frequency transformer and power transfer inductor. The operating frequency of DBC is very high which offers many advantages like smaller size and light weight of reactive components, power supply with faster transient response [5]. Compare to traditional dc-dc converter the bidirectional dual-active bridge (DAB) have many advantages, like electrical isolation, high reliability ease of soft switching control and bidirectional power flow [6].

Various topologies variations for DC-DC converters of high power applications with bidirectional power transfer have been proposed and developed through the last four decades. For the development of the efficient power, dc-dc converter they use either resonant [7], soft switch achieved by controlling phase shift [8-9], or hard pulse width modulation (PWM) [9]. Even though PWM and soft switched achieved by controlling phase shift converters have their own advantages but they have also limitations to use for middle power bidirectional dc-dc converters. These converter topologies aren't efficient to use for middle bidirectional dc-dc converters due to the following drawbacks;

- large number of switches
- large components
- limited range of satisfactory for high frequency
- Complex power and control circuit etc.

As high power applications, medium and low power bidirectional dc-dc converters are based on hard switching [10], soft switching or resonant switching type [11]. Most of these dc-dc converters are well suited for a particular application even though they have their own drawback. Their limitations can be described as;

- lack of isolations
- high component stresses
- large ripple current through the filtering inductors
- At high frequencies the converter designed to operate under resonance and soft switching may suffer from hard switching of the devices.

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The dual active bridge resonant converter is a combination of two active bridges with resonant tank as shown in fig. 1. Two active bridges are linked by a HF transformer and resonant tank. The resonant tank is either series resonant or parallel resonant or combination of both. Z_p and Z_s are parallel and series resonant tanks respectively. They can be capacitor inductor, series combination of LC or parallel combination of LC. Z_p could be put on any side of transformer. The series resonant converter has drawback of voltage regulation at light load while parallel resonant converter cause low efficiency at reduced load due to circulating current. Series-parallel LC-L resonant converters overcome the most of the limitations of series and parallel resonant converters. The magnetizing and leakage inductance of a HF transformer could be utilized as part of series resonance tank Z_s and parallel resonance tank Z_p respectively [12]. The power flow through the resonant tank can be controlled by controlling phase shift between the gating signals of the two bridges.

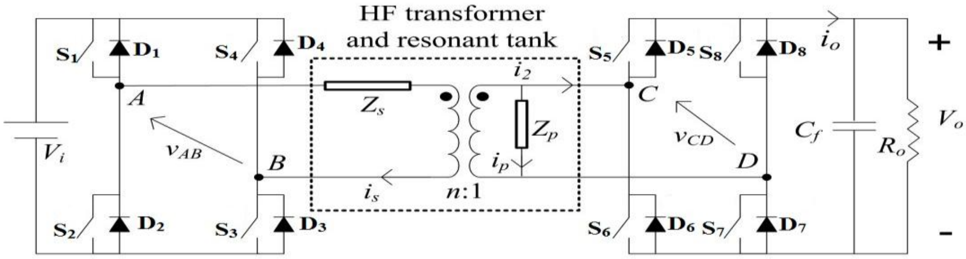

Fig. 1. A dual-bridge converter with a generalized resonant tank

A number of resonant converter configurations have been analyzed and designed in literature [12]. Basically three methods are available for analyzing resonance converters in steady state.

1. **Approximate analysis using complex circuit analysis method [6].**

   In this method the fundamental components of waveform are used as voltages and currents. It is quite simple for analysis.

2. **State space or differential equation approach [13]**

   This method is accurate but analysis is very difficult to use.

3. **Fourier series or frequency domain analysis approach [14]**

   In this method, all harmonics are taken into account and classical AC analysis technique is used to analyze the converter.

In this paper the approximate analysis using complex circuit analysis method is used to analyze the converter and accordingly conditions for ZVS is derived for both bridges. Simulation results for Full and half load (resistive) load are included for the purpose of validation.

II. SYSTEM DEVELOPMENT

In complex ac analysis approach, only fundamental component of voltages and currents are consider while all other harmonics are neglected. It is assumed that all switches, diodes and transformer are ideal [14]. The leakage and magnetizing part of transformer are used as a part of series and parallel resonant tank by proper arrangement [12]. The effect of snubber circuit is also neglected. All the parameters on secondary side of HF transformer have been taken to primary side and are denoted by superscript " ' ". The reactances of Z_P and Z_S are defined as X_P and X_S respectively. With equivalent impedance, the equivalent circuit of converter in phasor domain can be drawn as shown in fig. 2.

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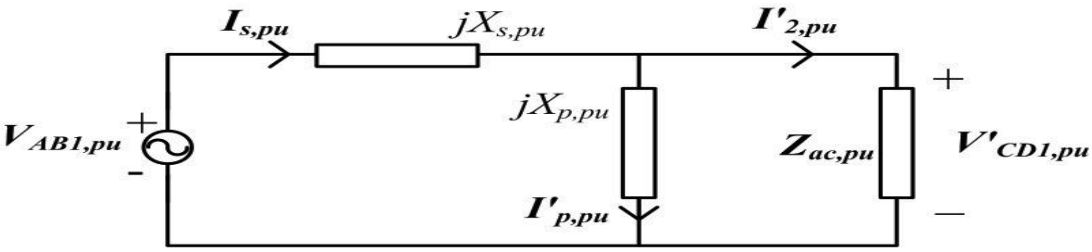

Fig. 2. The phasor domain equivalent circuit of the dual-bridge resonant converter.

For convenience the base values are taken as bellow:

$$V_B = V_1; Z_B = R_F'; I_B = V_B / Z_B \tag{1}$$

Where $R_F' = {n_t}^2 * ({V_0}^2/P_0)$ is the primary side reflected load resistance, R_F' is the full load resistance, n_t is transformer turns ratio.

The normalized frequency F is given by;

$$F = \omega_s/\omega_r = f_s/f_r \tag{2}$$

Where $\omega_r = 1/2\pi\sqrt{L_s C_s}$ is a frequency of a resonant tank. The normalized values of all the reactances are given by:

$$X_{s,pu} = X_s/Z_B \tag{3}$$

$$X_{p,pu} = X_p'/Z_B \tag{4}$$

Where X_s is a reactance of series resonant tank and $X_p' = n_t^2 X_p$ is a primary side reflected reactance of parallel resonant tank.

$V_{AB1,pu}$ and $V_{CD1,pu}'$ are the normalized fundamental phasor components of square-waves V_{AB} and V_{CD}'. The normalized fundamental components of V_{AB} and V_{CD}' in phasor domain are:

$$V_{AB1,pu} = \frac{4}{\pi} e^{j(\omega_s t - \frac{\pi}{2})} \tag{5}$$

$$V_{CD1,pu}' = \frac{4M}{\pi} e^{\left(\omega_s t - \emptyset - \frac{\pi}{2}\right)} \tag{6}$$

Here ω_s is switching angular frequency, $\emptyset$ is phase angle between primary side voltage $V_{AB1,pu}$ and secondary side voltage $V_{CD1,pu}'$. M is a converter gain which is given as:

$$M = \frac{V_0'}{V_i} \tag{7}$$

By means of principle of superposition, the three current phasor can be evaluated as:

$$I_{s,pu}(t) = \frac{4}{\pi X_{s,pu}} \left(M e^{-j\emptyset} - 1\right) e^{j\omega_s t} \tag{8}$$

$$I'_{2,pu}(t) = \frac{4}{\pi X_{s,pu}} [M(1+K)e^{-j\emptyset} - 1)] e^{j\omega_s t} \tag{9}$$

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$$I'_{p,pu}(t) = -\frac{4M}{\pi X_{p,pu}} e^{j(\omega_s t-\emptyset)} \tag{10}$$

The resonant current in time domain can be obtained as:

$$i_{s,pu}(t) = \frac{4[M\cos(\omega_s t-\emptyset)-\cos(\omega_s t)]}{\pi X_{s,pu}} \tag{11}$$

$$i'_{2,pu}(t) = \frac{4[M\cos(\omega_s t-\emptyset)(1+K)-\cos(\omega_s t)]}{\pi X_{s,pu}} \tag{12}$$

.

$$i_{p,pu}(t) = -\frac{4M\cos(\omega_s t-\emptyset)}{\pi X_{p,pu}} \tag{13}$$

Where:

$$K = \frac{w_s\ L_s - (1/\omega_s C_s)}{\omega_s L_p} = \frac{L_s}{L_p}\left(1-\frac{1}{F^2}\right) \tag{14}$$

The switch peak current on both sides of the HF transformer is:

$$I_{sp,pu} = \frac{4\sqrt{M^2+1-2M\cos\emptyset}}{\pi\,|X_{s,pu}|} \tag{15}$$

$$I'_{2p,pu} = \frac{4\sqrt{(M+MK)^2+1-2M(1+K)\cos\emptyset}}{\pi\,|X_{s,pu}|} \tag{16}$$

From fig. 2 converter gain M can also be given as:

$$M = \left|\frac{Z_{ac,pu} \parallel jX_{p,pu}}{X_{s,pu} + Z_{ac,pu} \parallel jX_{p,pu}}\right| = f(\theta) \tag{17}$$

Where

$$Z_{ac,pu} = \frac{Z_{ac}}{R'_F} = \frac{8R'_o\cos\theta}{\pi^2 R'_F} = \frac{8\ \cos\theta}{\pi^2} H \tag{18}$$

Where $R_o{}'$ is a output load resistance while θ is an angle between I'_2 and $V'_{CD,pu}$. $H=R_o{}'/R'_F$ is normalized load resistance and H $\in [1,\infty]$ as load goes on decreasing from full load to zero load.

From equation (17) it is concluded that M is function of θ, which is difference of angle between $V_{AB1,pu}$ and $I'_{2,pu}$. Here θ is not a controllable parameter; hence M can be controlled by controlling another angle β, which is a difference between $V_{AB1,pu}$ and $I'_{2,pu}$ given as:

$$\theta = \beta - \emptyset \tag{19}$$

Where,

$$\beta = tan^{-}\left(\frac{(1+K)Z_{ac,pu}\ sin\theta}{(1+K)Z_{ac,pu}\ cos\theta - X_{s,pu}}\right) \tag{20}$$

Hence from equations (17), (19) and (20) M can be expressed as:

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$$M = \frac{8\,H \sin \emptyset}{\pi^2\, X_{s,pu}} \tag{21}$$

The soft switching conditions for two bridges are:

$$i_{s,pu}(0) < 0 \text{ for the primary bridge} \tag{22}$$

$$i'_{2s,pu}\left(\frac{\emptyset}{\omega_s}\right) > 0 \text{ for the secondary bridge} \tag{23}$$

With the help of equations (15) and (16) the conditions can be re-written as:

$$\frac{4[M\cos(\emptyset)-1]}{\pi X_{s,pu}} < 0 \tag{24}$$

$$\frac{4[M(1+K)-\cos(\emptyset)]}{\pi X_{s,pu}} > 0 \tag{25}$$

The series resonance is consisting of series connection of LC which is operating above the resonance so $X_{s,pu}$ is positive. The solution to realize zero voltage switching of two bridges is:

$$\cos\emptyset < \min\left\{\frac{1}{M}, M(1+K)\right\} \tag{26}$$

To satisfy equation (24) it is better that both *1/M* and *M (1+K)* are greater than 1 because maximum value of cos Ø is 1. For this *M* should be less than one so that the soft switching of primary bridge is possible and once $M \leq 1$ soft switching of secondary bridge is possible by properly selecting the value of *K*.

So many resonant tanks have been analyzed in [6] and it is concluded that LC-L series parallel resonant converter has more zero voltage switching range for secondary bridge compared to other resonant converters. The analysis results of ZVS conditions are concluded in Table I.

TABLE I
DIFFERENT ZVS CONDITIONS IN DUAL-BRIDGE RESONANT CONVERTER

Tank type	Primary bridge	Secondary bridge
(LC)	$\cos\emptyset < \frac{1}{M}$	$\cos\emptyset < M$
(L)(C)		$\cos\emptyset < M(1-F^2)$
(LC)(L)		$\cos\emptyset < M\left[1+\frac{L_s(1-1/F^2)}{L_p}\right]$
(LC)(C)		$\cos\emptyset < M\left[1+\frac{c_p(1-F^2)}{Cs}\right]$
(LC)(LC)		$\cos\emptyset < M\left[1+(F^2-1)(\frac{F^2L_p}{L_s}+\frac{C_s}{L_p})\right]$

III. SIMULATION RESULTS

The simulation of dual bridge LCL resonant converter is carried out in Simulink. The dual-bridge LCL converter is assumed to work at the following conditions:

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$V_1 = 200V$, $V_o = 48V$, $F = 1.09$, $K = 0.3$. $f_s = 100$ kHz.

The resonant tank components can be taken as:

$L_s = 87.54\mu H, C_s = 35nF, L_p = 50.42\mu H$

The capacitive filter connected at output side is given by

$$C = \frac{1}{4\sqrt{3}\, f_s\, \gamma\, R_L} = 70\mu F \qquad (27)$$

The full load (200 W) and half load (100 W) operations are presented in fig. 3 and fig. 4 respectively. The ZVS operation is confirmed from the converter current vs. time plot of switches. The current though parallel inductor placed on secondary side of HF transformer I_p is depends on output voltage and it is independent of load level. The output current of secondary bridge is i_o whose average value is output dc current. The negative part of i_o accounts only for small portion of period which indicates low circulating current and high efficiency.

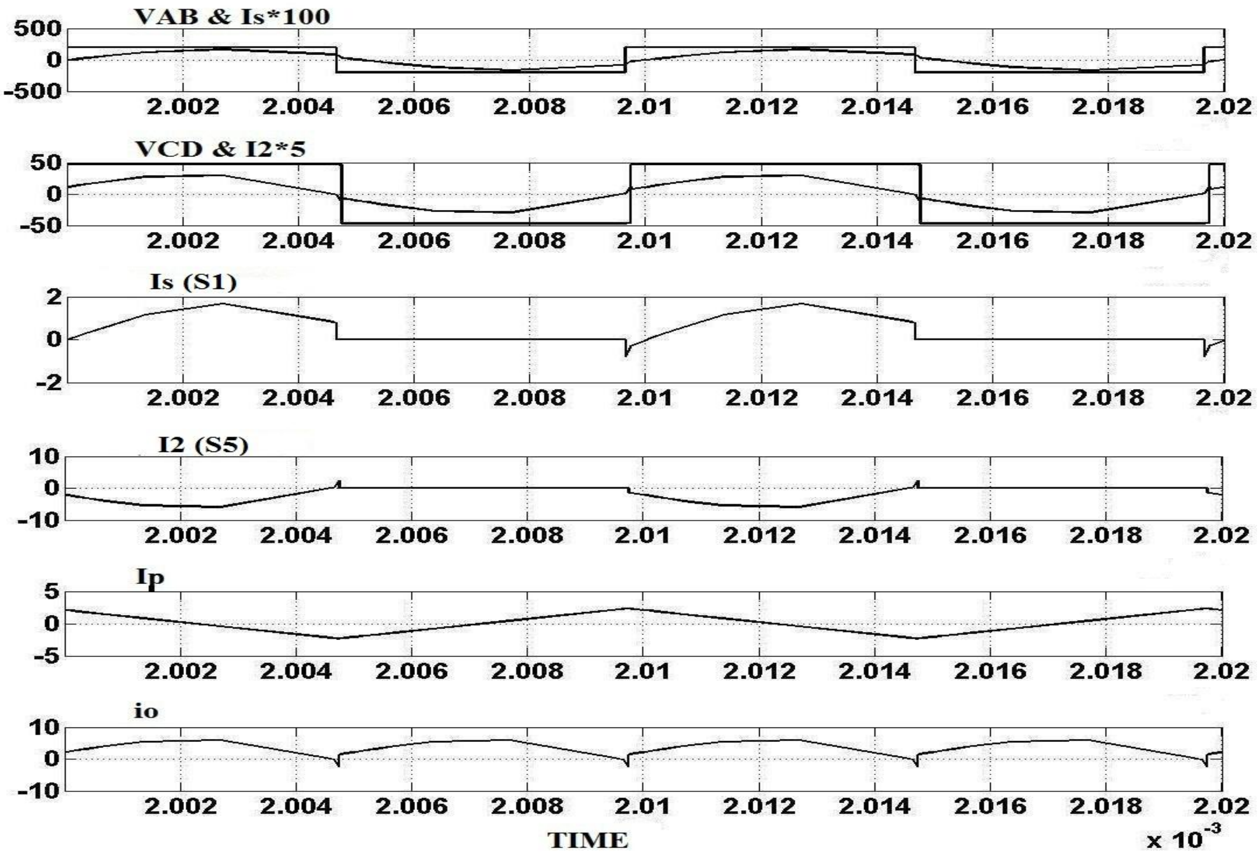

Fig. 3. Simulation results of a dual-bridge LCL resonant converter at $P_o = 200\ W$, $V_o = 48\ V$

Fig. 3 and fig. 4 follows the ZVS conditions mention in equations (21) and (22), hence this converter is best suitable for minimizing converter losses by carrying ZVS during conversion for multipurpose medium power application.

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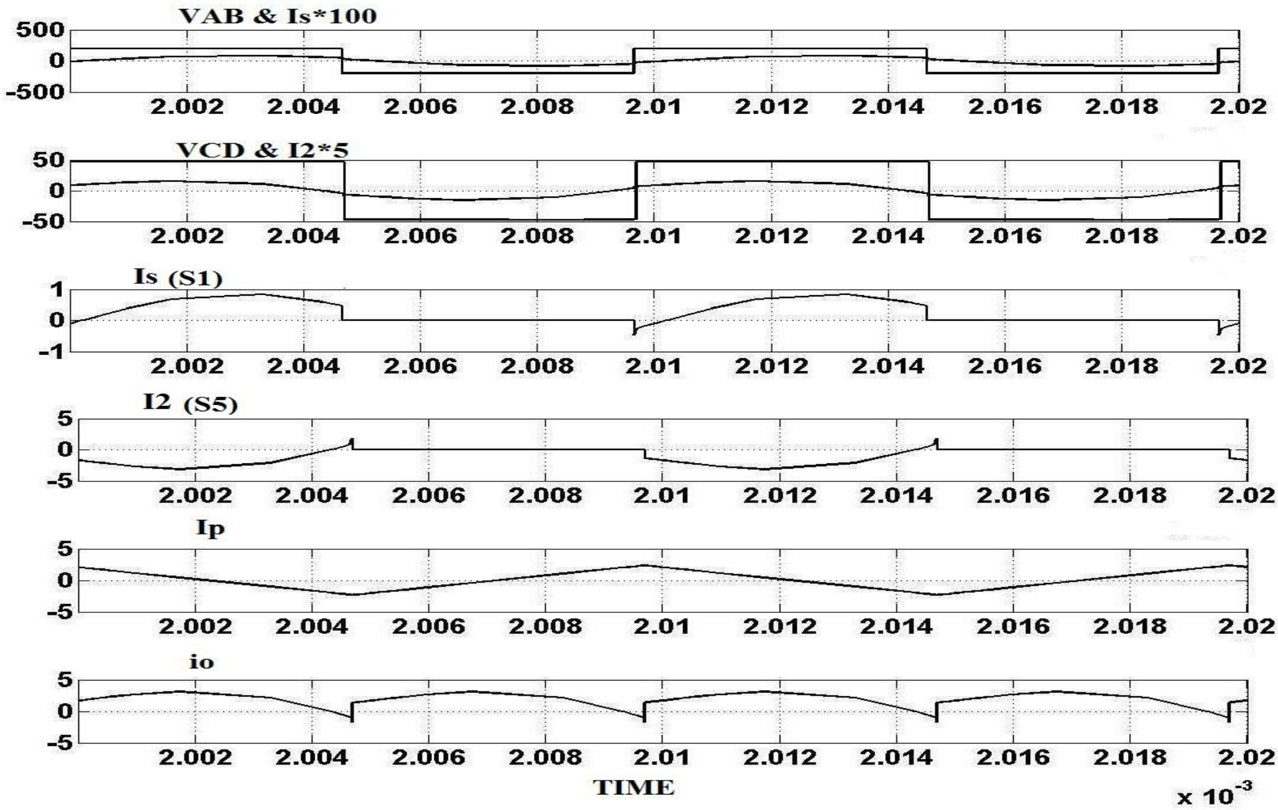

Fig. 4. Simulation results of a dual-bridge LCL resonant converter at $P_o = 100\ W, V_o = 48\ V$

Comparison between Simulated and calculated values of various parameters is given in following Table II. Most of values show reasonable match. The parallel inductor current actually shows a triangular form instead of the assumed sinusoidal form, which is the main reason of the mismatch shown in the tables. At heavy load, the parallel current I_p does not affect I_2 too much. However, the effect of I_p on I_2 becomes apparent at light load. The mismatch of the phase-shift angle is due to the necessary dead-gap in the gating signals of each pairs of switches in one leg and voltage drop in switches.

TABLE II
COMPARISON OF SOME PARAMETERS OF DBRC FOR $V_I = 200V$, $V_O = 48V$ AND $f_S=100kHz$.

Load Level	Parameters	Simulated Value	Calculated value
Full Load 200W	M	0.9761	0.9792
	I_s	1.64A	1.45A
	I_2	6A	7.5A
	Ø	3.6°	3.3°
Half Load 100W	M	0.9792	0.95
	I_s	0.84A	0.76A
	I_2	3.2A	3.16A
	Ø	1.8°	1.6°

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IV. CONCLUSION

In this paper the analysis of dual bridge high frequency series parallel LCL resonant converter is carried out with modified complex ac analysis approach. The simulation carried out in Simulink gives the detail view of all operational parameters. The simulation plot validates the theoretical analysis. From simulation it is observed that the ZVS is carried out in both converters.

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