A Novel Resonant Topology for High Frequency Isolated Bidirectional Dual-Active-Bridge DC-DC Converter for Power Conversion Systems

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Abstract – Power conversion Systems (PCSs) using high frequency (HF) isolated bidirectional dc-dc converters (IBDCs) results in high power density, reduced weight, size and low noise without compromising efficiency, cost and reliability. The core circuit of these HF-PCSs is Dual-Active-Bridge (DAB) - IBDC. Large scale practical applications of DAB-IBDC for high frequency link (HFL) PCSs is expected with the recent advances in solid-state semiconductors, magnetic materials, capacitive materials and microelectronic technologies. In DAB-IBDC, soft switching solution is a research direction to improve the performance which includes improvement of HFL resonant tank circuits. The research necessary regarding the soft switching solution in DAB-IBDC includes ease of realizing soft switching by taking different topologies into consideration. A set of topologies have been considered which can be reduced to a generalized form for consideration with mathematical analysis as well as power throughput derivation. On the basis of this, a novel resonant topology has been proposed which is a combination of series and parallel resonant circuits and can be worked out on the basis of these generalized forms. In comparison to conventional DAB topologies, proposed resonant converter topologies reduce bridge currents thus lowering both conduction and switching losses. Results show that this topology offers higher efficiency over wide range of both input voltage and load conditions.

Index Terms – Dual-Active-Bridge (DAB), Power conversion systems (PCSs), High Frequency (HF), High Frequency Link (HFL), Isolated bidirectional dc-dc converter (IBDC).

1. INTRODUCTION

We are depleting our conventional or non-renewable energy resources day by day, so it's time to focus on the non-conventional or renewable energy resources more and more. By considering the atmospheric conditions like global warming, we have no other option than non-conventional or renewable energy resources to be used. People have recognized a big potential of renewable energy resources. An inherent feature of all these renewable energy resources is that the available energy varies randomly which results in a wide variation in the available output power and voltage which makes a power converter, a necessary part of all such generation systems.

Generation of all these renewable energy resources is connected to the Grid and to reduce the transmission losses, we had to move towards Distributed Generation systems which will result in micro or local Grids to function independently at remote places to cater the local requirement. As having the drawback of dependence on atmospheric conditions this requires some type of storage at the time when there is an abundance of energy and utilizes the same when there is scarcity of that, in the form of bank of storage batteries or super capacitors. For this, there is need of IBDCs which can be interfaced between the DC bus and the storage batteries.

An overview of DAB-IBDC for HFL-PCSs [1] shows some research subjects like basic characterization, control strategy, soft-switching solution and variant as well as hardware design and optimization. So, by considering soft-switching solution as the research subject, various topologies of the resonant tank circuit are required to be considered.

We are using resonant tank networks for the HF - IBDCs which has certain disadvantages like insignificant currents which may circulate through tank elements, even when load is disconnected, leading to poor efficiency at light load. In addition, where the resonant converters are modulated under variable frequency operation, the range of switching frequencies can be very large which will increase the complexity of the control structure as well as the filter requirement**.** Among many IBDCs, Dual-bridge phase-shifted dc/dc converter or DAB converter is a preferred option as having small component count, high frequency operation, offering galvanic isolation, allowing high power operation and accommodating a wide range of voltage levels which may operate in buck as well as boost modes. In this, there is only one component which is inductor and that can be utilized as the energy transfer device placed between the two bridges along with the high frequency transformer. This inductor may include the leakage inductance of the transformer. The net power with its direction is controlled by the phase-shift angle of two bridges on two sides of the HF transformer. But in this DAB, regardless of the control and resonant schemes, it draws a large reactive current component and therefore results in reduced efficiency.

There are different resonant circuit topologies available in the literatures which are competing to achieve soft switching over the entire operation range. In [2], an analysis of dual-bridge series resonant dc/dc converter (DBSRC) is given with two simple modified ac equivalent circuit analysis methods for both voltage source load and resistive load and proved that these two methods result in the same solutions and same analysis can be used for both the cases where only the fundamental components of the voltages and currents are considered. All switches may work in either ZVS or ZCS for a wide variation of voltage gain. DBSRC have some similarities with the standard full-bridge dc/dc series resonant converter (SRC) but having unique feature of bidirectional power flow capability due to the secondary side active bridge. In DAB converter, the performance depends on the leakage inductance of the transformer which is used for power transfer and it should be as small as possible. So, if DAB converter is used for applications with wide input/output voltage variations, ZVS of primary side converter may be hard to achieve. In DBSRC, leakage inductance is used as part of the resonant tank and has low possibility of transformer saturation due to series capacitor. In [3], it presented a CLLC resonant topology which is an asymmetric topology, where both directions of power flow are modulated under the variable frequency modulation (FM) above resonance. ZVS for input inverting choppers and ZCS for output rectifier switches achieved regardless of the direction of power flow for a wide variation of voltage gain. Its main features are snubberless, fully soft switched and no additional soft-switching auxiliary circuit and with very wide input voltage range capability. In [4], a bidirectional full-bridge CLLC resonant converter using a symmetric LLC-type resonant network, having zero-voltage switching capability for primary power switches and soft commutation capability for output rectifiers. The power conversion efficiency in any directions is exactly the same. In [5], it presented a bidirectional dc-dc converter which is composed of two class-E resonant converters and bidirectional power flow is controlled by changing the transistor control pulse frequency. Its advantages are high operation frequency and zero value of the transistor switching losses. In [5-7], a set of topologies using resonant DAB for reducing the reactive power drawn by the two bridges are presented and thus lowering the bridge currents, losses with increase in efficiency. Similarly, there are some other topologies available in the literature which is having three or more elements in their resonant tank circuits for achieving soft switching. A diversity in the available topologies gives a designer the freedom to choose the most suitable for the given application.

The paper is organized in a manner that in Section 2, there is review of topologies with different elements in their resonant tank network. Section 3 gives the proposed topology for consideration and validation purpose while in Section 4, there are results and discussion. In section 5, there is conclusion of the work.

2. REVIEW OF TOPOLOGIES

There are different topologies in [6] which use immittance conversion concept for its utilization in resonant converters. An immittance converter is an abbreviation of impedance-admittance converter, where the input impedance is proportional to the load admittance connected across the output terminals. The resonant converters whose resonant networks exhibit immittance conversion characteristics are termed as resonant immittance converters (RIC). In RIC, there is relation between the input-output voltages and currents as shown in fig.1, such that the output current is proportional to input voltage and output voltage is proportional to input current.

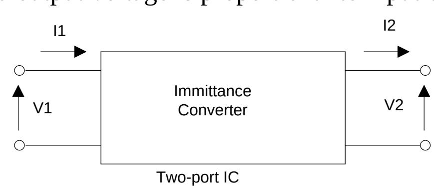

Figure1 A two-port resonant Immittance Converter

This relationship will be helpful in achieving the goal of lowering the bridge currents by reducing reactive current component and thus lowering the total losses with increase in efficiency. The resonant converters which do not exhibit immittance conversion characteristics or non-RIC topologies are also usable but for other applications e.g. they may be used with a high-frequency sinusoidal source, which is more difficult to generate than a square-wave source. The topological structures with one or two branches in their resonant tank network do not exhibit immittance conversion characteristics while with three branches in their resonant network, there are two topological structures, i.e. tee-network and pi-network which exhibit immittance conversion characteristics which have been utilized in the research papers as resonant DAB [7]-

[9]. As the parasitic components of a practical resonant converter circuit elements force to behave as a higher order resonant converter, so these parasitic components can be gainfully utilized as a part of their resonant DAB. So, these can be extended to higher order branches in their resonant network exhibiting immittance conversion characteristic. In this, each branch can be constrained to be composed of maximum of two reactive elements so as to restrict the maximum number of reactive elements in a network to be four. Research papers in literature which considered resonant DAB topologies from these set of RIC topologies are [7] and [8], where consider a tee-network of LCL as a resonant DAB converter and a tuned network. In [9], a tee-network of CLC is considered as a resonant DAB and in [10], there is increase in the power density by using a tuned CLLC structure with decreased number of magnetic components and with decreased transformer magnetizing inductance by using coupled inductors with relatively low coupling factor. This results in high leakage inductances on both the primary and secondary sides of the HF transformer. As by using coupled inductors with a low coupling factor, rather than a transformer and discrete inductors, only one magnetic component needs to be designed and manufactured which could decrease the overall cost of the converter.

The topologies in [7]-[9] are tee-network having three elements with the symmetric structure as shown in fig.2.

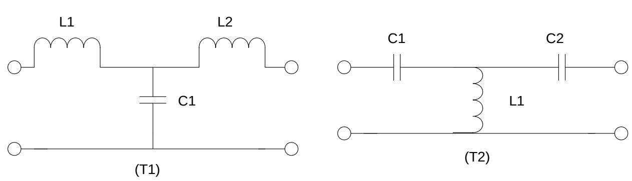

Figure 2 A tee-network having three elements

Other possible combinations for resonant DAB converters topologies [6] having four elements network structures which can be reduced to above LCL or CLC symmetric tee-network structure are shown in fig.3.

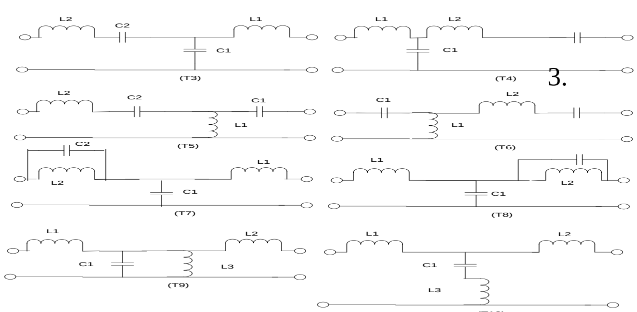

Figure 3 Four elements network structures

Similarly, another group of topologies having symmetric structure of pi- network of CLC or LCL with three elements and can be transformed to above tee-network structure by using delta to wye transformation are shown in fig.4.

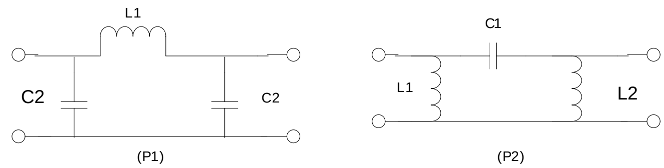

Figure 4 A pi-network having three elements

Other possible combinations or arrangements of resonant DAB converter topologies [6] having four elements network structures which can be reduced to above CLC or LCL symmetric pi-network structure are shown in fig.5.

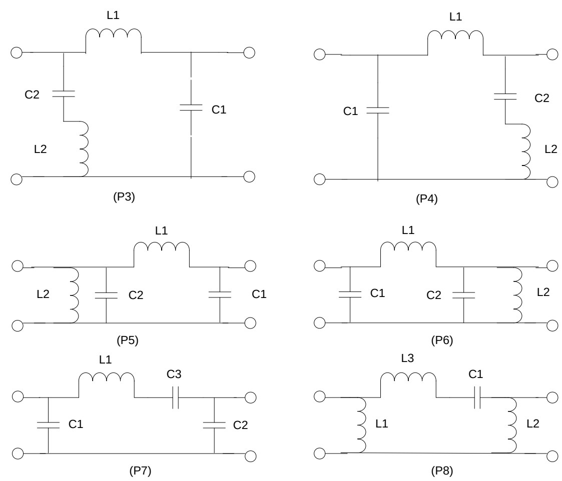

Figure 5 Four elements network structures

These are the topologies which can be used as resonant DAB converters to lower the bridge currents by reducing reactive power and so reducing losses with increase in efficiency on the pattern of topologies [7]-[10] which gives the designer a freedom to choose the most suitable topology for a given application by gainfully utilizing the parasitic components of practical circuit.

In some of these RIC topologies, namely T7 & P4-P7, a capacitor directly appears across the input, so a square wave voltage cannot be connected at their input port and they are excited with square-wave current source. They are suitable for conversion of a current source into a voltage source and thus suitable for voltage source inverter applications. Remaining topologies can be excited with a square-wave voltage source. Similarly, there are other higher order RIC topologies which may work as resonant DAB converters having more than four elements in their resonant tank network which are not considered in this work and considered in future work. These higher order resonant converters have the advantages like they will remove the inherent limitations of lower order resonant converters, offer steeper fall of the gain with frequency, exhibiting better controllability against wide line and load variations with smaller frequency variation. Also a properly designed higher order resonant converter has an overall smaller volt-ampere rating of a resonant network and achieves better efficiency. The following analysis is done to generalize the set of topologies as

- Mathematical Analysis
- Power Calculation

2.1. Mathematical Analysis

The circuit is analyzed in frequency domain under steady state conditions. The two voltage sources on either side of the resonant tank network are square wave voltage sources and by using fundamental component analysis only the fundamental components are analyzed as tuned network which presents high impedance to harmonics generated by converters and so effects of these harmonics on the operation will be insignificant. A common mathematical analysis for all these mentioned topologies are summarized into the following two groups.

- For LCL tee-network and LCL pi-network.
- For CLC tee-network and CLC pi-network.

2.1.1. For LCL tee-network and LCL pi-network

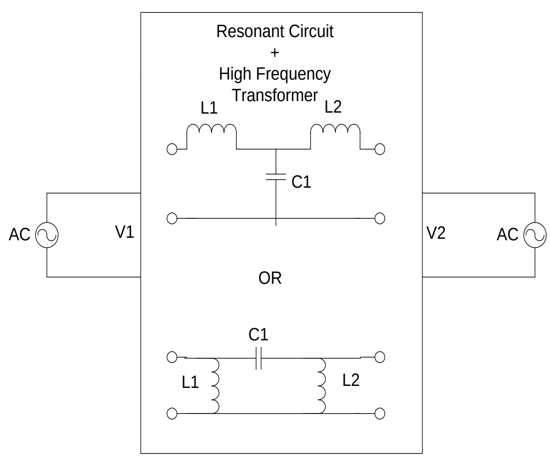

Figure 6 Equivalent circuits of LCL tee-network and LCL pi-network

The reactance of $L_1, C_1 \& L_2$ are considered to be equal at fundamental switching frequency. Voltages V_1 and V_2 are in the form of pulse-width-modulated square waves. Therefore, it comprises of sinusoids of diminishing amplitudes at odd multiples of f_S. If $L_1C_1L_2$ is tuned to f_s, then it will result as equation (1)

$$L_1C_1 = L_2C_1 = \frac{1}{(w_s)^2} = \frac{1}{(2\pi f_s)^2} \quad (1)$$

The fundamental phasors are shown in fig.7. In LCL tee-network, by application of superposition theorem, the voltage across capacitor C_1 is equal to the vector sum of v_1 and v_2. Voltage across L_1 is v_2 and that across L_2 is v_1, so that i_1 is proportional to v_2 and i_2 is proportional to v_1. Thus, each end of LCL network behaves as a current source with amplitude dependent on the voltage on the opposite sides.

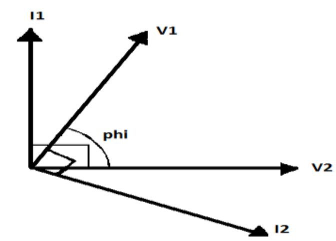

Figure 7 Phasor Diagram of LCL tee-network and LCL pi-network

When the phase difference phi (Φ) between v_1 and v_2 is 90°, there is no reactive power and so minimizing bridge currents, which are significantly smaller than those of a conventional DAB converter for which the bridge voltage and current phasors do not align. Similar will be the case for LCL pi-network, which can be transformed to the LCL tee-network.

2.1.2. For CLC tee-network and CLC pi-network.

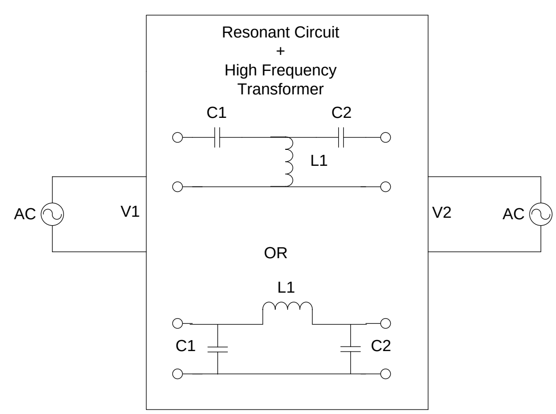

Figure 8 Equivalent circuits of CLC tee-network and CLC pi-network

Similarly, as the reactance of $C_1, L_1 \& C_2$ are equal at fundamental switching frequency so the Voltages V_1 and V_2 are in the form of pulse-width-modulated square waves. Therefore, it comprises of sinusoids of diminishing amplitudes at odd multiples of f_S. If $C_1L_1C_2$ is tuned to f_s, then it will result as equation (2)

$$L_1C_1 = L_1C_2 = \frac{1}{(w_s)^2} = \frac{1}{(2\pi f_S)^2} \quad (2)$$

The fundamental phasors are shown in fig.9. In CLC tee-network, by application of superposition, the voltage across capacitor L_1 is equal to the vector sum of v_1 and v_2. Voltage across C_1 is v_2 and that across C_2 is v_1, so that i_1 is proportional to v_2 and i_2 is proportional to v_1. Thus, each end of CLC network behaves as a current source with amplitude dependent on the voltage on the opposite sides.

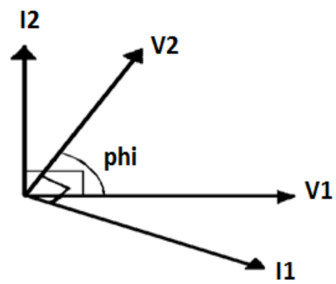

Figure 9 Phasor Diagram CLC tee-network and CLC pi-network

Thus, there is no reactive power and so minimizing bridge currents, which are significantly smaller than those of a conventional DAB converter for which the bridge voltage and current phasors do not align. Similarly, the case for CLC pi-network, which can be transformed to the CLC tee-network. In a conventional DAB converter for which the bridge voltage and current phasors do not align as shown in Fig.10.

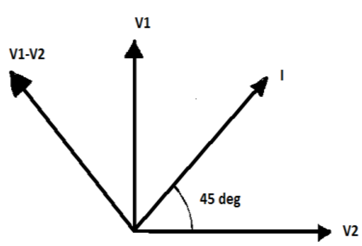

Figure 10 Phasor Diagram of a Conventional DAB converter

2.2 Power Calculation

A common analysis for the power transfer calculation for the two cases is considered from where the power calculation of all other mentioned topologies can be obtained. The different cases are

- For the case, i.e. LCL tee-network and LCL pi-network.
- For the cases, i.e., CLC tee-network and CLC pi-network

2.2.1. LCL tee-network and LCL pi-network.

Voltages and currents of the system are derived in the frequency domain under steady-state conditions. Voltage sources v_1 and v_2 are represented by Fourier series expansions as in equation (3) and (4)

$$v_1 = \frac{4V_{DC1}}{\pi}\sum_{a=1,3,5\ldots}^{\alpha}\frac{1}{a}\cos(aw_s t + a\Phi)\sin(\frac{a\alpha_1}{2}) \quad (3)$$

$$v_2 = \frac{4nV_{DC2}}{\pi}\sum_{b=1,3,5\ldots}^{\alpha}\frac{1}{b}\cos(bw_s t)\sin(\frac{b\alpha_2}{2}) \quad (4)$$

Where 'n' is transformer turns ratio and 'Φ' is the phase lead of the fundamental component of v_1 with respect to that of v_2. The magnitude of the power transferred has been quantified as [7] & [8] shown in equation (5)

$$P= \frac{8n}{\pi^2 X}V_{DC1}V_{DC2}\sin(\Phi)\sin(\frac{\alpha_1}{2})\sin(\frac{\alpha_2}{2}) \quad (5)$$

Power throughput of the system for any given α_1 *and* α_2 will be dictated by system parameters as operating frequency and supply voltages. Here, majority of the power was transferred at the fundamental frequency of the tuned resonant network. The direction of power flow can be controlled by setting Φ to either 90^0 for positive power transfer values and -90^0 for negative power transfer values while magnitude of power flow in either direction can be controlled by modulating the magnitudes of v_1 and v_2 with α_1 and α_2 respectively between 0 and 180^o. Under such conditions, bridge converters produce minimal reactive power as their fundamental voltage and current components are either in phase or in antiphase.

2.2.2 CLC tee-network and CLC pi-network

Voltages and currents of the system are derived in the frequency domain under steady-state conditions. Voltage sources v_1 and v_2 are represented by Fourier series expansions as in equation (6) and (7)

$$v_1 = \frac{4V_{DC1}}{\pi}\sum_{a=1,3,5\ldots}^{\alpha}\frac{1}{a}\cos(aw_s t)\sin(\frac{a\alpha_1}{2}) \quad (6)$$

$$v_2 = \frac{4nV_{DC2}}{\pi}\sum_{b=1,3,5\ldots}^{\alpha}\frac{1}{b}\cos(bw_s t + b\Phi)\sin(\frac{b\alpha_2}{2}) \quad (7)$$

Where 'n' is transformer turns ratio and $'\Phi'$ is the phase lead of the fundamental component of v_2 with respect to that of v_1. The magnitude of the power transferred has been quantified [9] as shown in equation (8)

$$P=\frac{8n}{\pi^2 X} V_{DC1} V_{DC2} \sin(\Phi) \sin(\frac{\alpha_1}{2}) \sin(\frac{\alpha_2}{2}) \qquad (8)$$

Power throughput of the system for any given α_1 *and* α_2 will be dictated by system parameters, operating frequency and supply voltages. Here, majority of the power was transferred at the fundamental frequency of the tuned resonant network. The direction of power flow can be controlled by setting Φ to either 90^0 for positive power transfer values and -90^0 for negative power transfer values while magnitude of power flow in either direction can be controlled by modulating the magnitudes of v_1 and v_2 with α_1 and α_2 respectively between 0 and 180^o. Under such conditions, bridge converters produce minimal reactive power as their fundamental voltage and current components are either in phase or in antiparallel.

3. Proposed Topology for consideration and validation

One such proposed topology is undertaken for consideration of the derived generalized form for validation purpose as shown in fig.11 (T4).

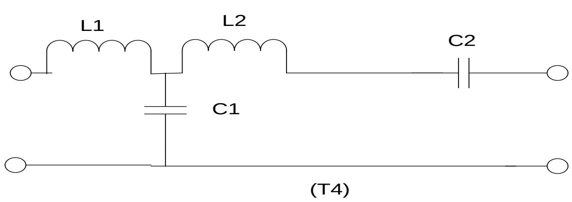

Figure 11 Resonant circuit of the proposed topology

In this, a novel resonant topology is proposed which is a combination of series and parallel resonant circuits placed on the either sides of the high frequency isolated transformer. Its main feature is that it is not drawing the reactive power from the mains from either side. This will result in reduced bridge currents which reduce the switching as well as conduction losses in the converter and also the reduced VA rating of the bridges.

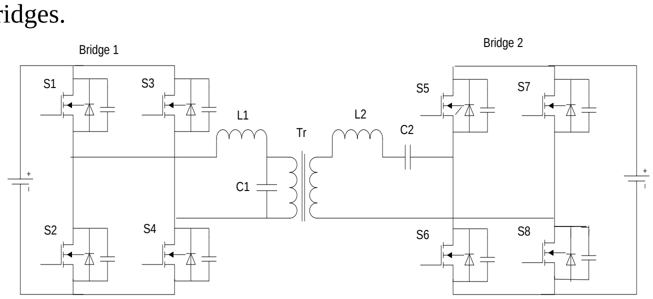

Figure 12 Circuit Diagram of the proposed topology

In fig.12, two active bridges are separated by an isolation transformer and a resonant circuit. The function of the isolation transformer is to get isolate the two full bridge voltages for safety reason and match the voltages on either sides of the transformer. The function of the resonant circuit is to get convert the square voltages available at the output of the bridge to its fundamental sine component so as to ease the process of switching from hard switching to soft switching by reducing the switching losses. This resonant circuit which is also a filter circuit have the advantage of selecting only the fundamental component at the input i.e., square wave and ignoring other harmonics without affecting the results. So, these topologies rely on the basis of fundamental harmonic analysis of the converters. These are PWM modulated converters having three degrees of freedom, i.e., one phase shift angle between the two legs of first bridge, second phase shift angle between the two legs of the second bridge and the third phase shift angle between the two bridges. By controlling the first and second phase shift angles, the amount of power flow in forward and backward directions are controlled. While the third phase shift angle is controlled for the direction of power flow and its magnitude determines the angle in degrees by which the second bridge voltage is phase shifted from the first bridge voltage.

By applying superposition theorem, voltage across C_1 is $v_1 + v_2$, which will result in voltage across L_1 and L_2 with magnitude v_2 and v_1 respectively. The phasor diagram showing different quantities like v_1, v_2, i_1, i_2 and Φ, i.e., phase shift angle between v_1 and v_2 is shown in fig.13.

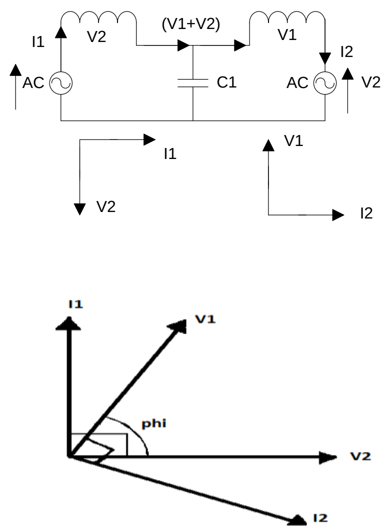

Figure 13 Equivalent circuit for analysis using the fundamental component of voltages V_1 and V_2 and their phasor diagram

The purpose is to get lower the bridge currents which are generally drawn in addition as the reactive power from the mains. This can be minimized if the phase difference between v_1 and i_1 and similarly between v_2 and i_2 are reduced to zero, i.e. in phase with each other and means no reactive power drawn from the mains on each side. These are tuned networks which are tuned to the resonant frequency and PWM modulation is used instead of frequency modulation which requires a large range of frequencies which will be difficult for the control as well as filter action. The control scheme required for this is simple having equal PWM for each bridge while maintaining a phase shift of 90^0 or -90^0 between the bridges. Equal PWM of the bridge voltages with α_1 and α_2 is used to control the magnitude of the power flow.

The schematic of the proposed resonant DAB converter is shown in Fig.13, where S_1 - S_8 are semiconductor switches which are taken as MOSFETs. Load on the secondary side is active and taken as V_{DC2} which may be a battery which is used for storing or retrieving energy. Primary and secondary bridges full-bridges are operated at a fixed frequency f_s and convert dc supply voltages V_{DC1} and V_{DC2} to a three-level pulse-width-modulated ac voltage sources v_1 and v_2 respectively. These two ac voltage sources are connected together through an isolation transformer and a $L_1C_1L_1$ network which is tuned to f_s . In this, the magnitude of power flow is regulated by controlling the pulse width of voltages of v_1 and v_2, while keeping the phase shift between them constant, i.e. 90^0 or -90^0. So, depending on the direction of the power flows switches S_1 and S_2 of Bridge 1 are operated in antiphase at switching frequency f_s with duty cycle of 50% to generate v_1. Switches S_3 and S_4 are operated in the similar way except v_{S4} lags v_{S2} by a displacement of α_1 degree.

4. RESULTS AND DISCUSSIONS

The simulation results of one such topology. i.e., LCL tee-network considered as Model 1 which is available in the literature [8] are observed and compared with the results of the proposed model which is considered as Model 2, by using MATLAB Simulink and shows improvement in the results in comparison. The working conditions of both the models are same while the values of different components in case of model 2 are shown in Table 1 when referred to the primary side of high frequency transformer.

Parameter	Theoretical Value
Rated power	2.5KW
V_{DC1}	380V
V_{DC2}	50V
Turns Ratio	7.6
f_S	50 KHZ
L1	155.35microH
L2	200microH
C1	65.2nF
C2	226.85nF

Table 1 Design Parameters of the Topology

The scenarios under which the results of both the models are compared include:

- Variation of Input Voltage (V_{dc1})
- Variation of output voltage (V_{dc2}), i.e. State of Charge (SOC) of Battery on output side
- Variation in Efficiency at different modulation angles under the condition $\alpha_1 = \alpha_2$

4.1. Variation of Input Voltage (V_{dc1})

In this case, the input voltage is varied from 10% of rated input voltage (380V) to 100% of rated input voltage while output voltage/Battery Voltage/State of Charge (SOC) is 80% of rated voltage (48V) and simulation time is 0.01 sec in all the cases. The Modulation angles, i.e. α_1 and α_2 are equal to its maximum value of 180^0.

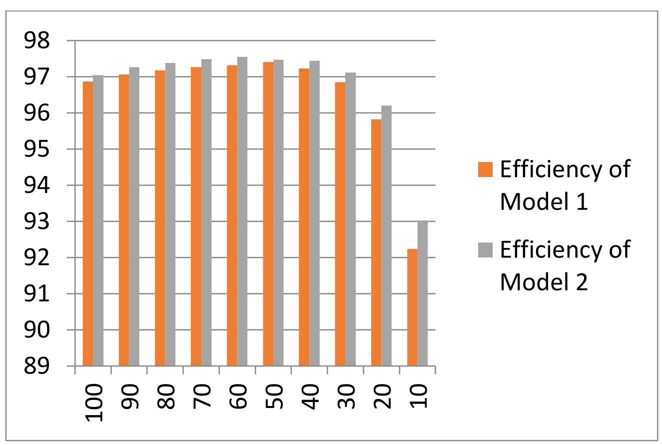

Figure 14 Percentage efficiency of Model 1 and Model 2 with percentage variation of input voltage (V_{dc1})

4.2 Variation of output voltage (V_{dc2}), i.e. State of Charge (SOC) of Battery on output side

In this case, input voltage is fixed (380V) and its output voltage or battery voltage (SOC), V_{dc2} is varied from 10% to 100% of rated voltage (48V). The simulation time is 0.01 sec in all cases and the modulation angles, i.e. α_1 and α_2 are equal to its maximum value of 180^0.

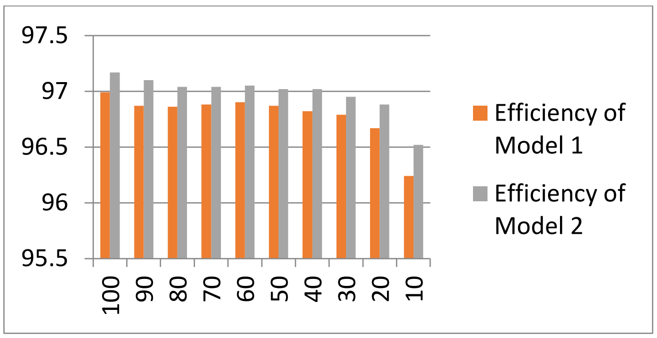

Figure 15 Percentage efficiency of Model 1 and Model 2 with percentage State of Charge (SOC) of battery, i.e. variation of output voltage (V_{dc2})

4.3. Variation in Efficiency at different modulation angles under the condition $\alpha_1 = \alpha_2$

In this case, input voltage is fixed (380V) and its output voltage or battery voltage (V_{dc2}) is fixed at 80%. The simulation time is 0.01 sec in all cases. Now at rated voltage (48V), the modulation angles, i.e. α_1 and α_2 are equal and its value varies from 10% to 100% of its maximum value (180^0)

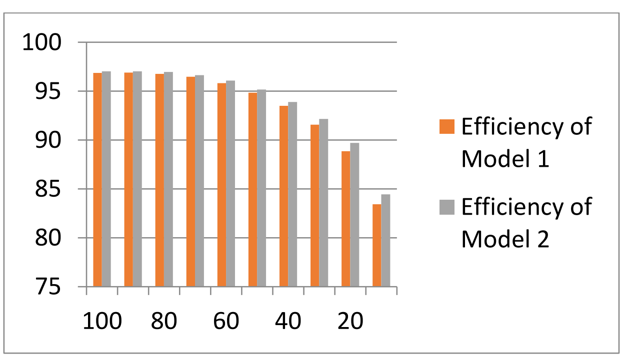

Figure 16 Percentage efficiency of Model 1 and Model 2 with percentage of modulation angle of 180^0 (i.e. $\alpha1 = \alpha2$)

The simulation results shown above indicate that the efficiency of Model 2 which is proposed have good performance in comparison to Model 1 in all the conditions considered above.

5. CONCLUSION

The various resonant tank circuit topologies taken under consideration are with three or four elements in their resonant tank circuits which can be reduced to three elements resonant tank circuit topology. This resonant tank circuit topology have the advantages in comparison to conventional DAB converter topologies, i.e. reduced bridge currents and thus lowering both conduction and switching losses with increase in efficiency. One such topology is proposed to validate the mentioned generalized forms and thus offerring higher efficiency over wide range of both input voltage and load conditions.

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