A Review on Topologies of Dual Active Bridge - Isolated Bidirectional DC-DC Converters for High Frequency Power Conversion Systems

[1]Vikram Kumar,[2]Vipan Kakkar

[1]Research Scholar,[2]Associate Professor
[1]School of Electronics and Communication Engineering,
[1]Shri Mata Vaishno Devi University, Jammu, India.

Abstract: Dual active bridge (DAB) isolated bidirectional DC-DC converters (IBDCs) are the core circuits of high frequency power conversion systems. These have the advantages of high power density with reduced weight and size but without compromising the cost, efficiency and reliability of the system. This paper provides a comprehensive review of different types of topologies of DAB-IBDCs. This paper also deals with different variants of DAB-IBDCs and thus enabling the integrated solutions for their increased performance in terms of efficiency for variation in supply voltages and load conditions. As far as modeling and optimization of the DAB-IBDCs in power conversion systems are concerned, state-of-the-art topologies are trending as the research direction which has been discussed here. The advances in the semiconductor devices, electromagnetic materials as well as electronic technologies have increased their expectations in various applications.

***Index Terms* - Dual-Active-Bridge, Isolated bidirectional DC-DC converter, High frequency link, Power conversion systems.**

I. Introduction

We are moving increasingly towards non-conventional/renewable energy resources due to the depletion of available conventional/non-renewable energy resources. Environmental issues such as global warming are also responsible for these changes. These problems are becoming the burning issues which need to be addressed soon. The only way to tackle with these issues is to use the available energy resources economically and efficiently. Moreover, we have to depend largely upon the non-conventional/renewable energy resources instead of the conventional/non-renewable energy resources like coal, gas, petroleum etc.

The basic feature of all such available renewable energy resources is that the energy available from these energy resources is varying with time and thus resulting in wide variations of power generation. A power converter is a necessary component of all such generation systems by which the excess power is stored in energy storage systems like batteries and super capacitors which can be retrieved or utilized whenever required. This energy storage will be helpful in reducing the renewable energy/power curtailment and thereby achieving full utilization of available renewable energy resources in distributed power generation systems. These power converters will help in stabilizing the output and fulfilling the requirement of power conversion from one form to another as per the requirement.

In these power conversion systems with high frequency isolation, the DAB-IBDCs are the essential components. The other applications of high frequency DAB-IBDCs include electric vehicles, implantable medical devices etc. In applications like electric vehicles and implantable medical devices, it requires wireless power transfer between two inductively placed solenoids. While in wired or conducting power transfer, it requires two inductively placed coils with an iron core between them or simply a transformer. The electric vehicles in transportation have become an indispensable and thus the wireless power transfer process can shift the gasoline-dependent vehicles to electric vehicles which create less dependency on gasoline products and rare impact on the environment. Similarly, in implantable medical devices applications, the high frequency DAB-IBDCs are used for powering the implants placed in the human body.

B. Zhao et al (2015) presented various research subjects in DAB-IBDCs for high frequency power conversion systems which include its basic characterization, control strategy, soft switching solution, variants, hardware design and optimization with typical application schemes like battery energy storage systems and uninterrupted power supplies. The researchers also suggested their design recommendations and future trends [1].

The high frequency DAB-IBDCs appear earlier in 1990s in the literature [2-4] but due to the performance limitation of power semiconductor devices, magnetic materials and capacitive materials, the power losses of these DAB-IBDCs were quite high and so their efficiency was suboptimal. As the technology improves with time, these DAB-IBDCs were appeared again in the literature. The practical applications of DAB-IBDC in power conversion systems are possible with the recent advancements and developments in solid-state semiconductors devices, magnetic materials, capacitive materials and technologies [1].

In comparison to Si based power semiconductors, the SiC and GaN power semiconductors have superior characteristics like ultra low loss, high speed devices, and high voltage ratings. These power devices are wide-band-gap semiconductors which have the ability to operate at higher temperatures [5]. There is an improvement in switching time transitions of SiC/GaN based power semiconductor devices in comparison to their Si based counterparts which allow them to operate at higher switching frequencies. With all these abilities like operation at higher temperature, higher frequencies and higher voltages, it results in higher power densities of DAB-IBDCs. So, these devices are highly interesting for their use in future electronic systems. In addition, these devices require smaller cooling devices such as heat sinks and fans. Based on the comparison as stated, the properties of SiC/GaN are found to be highly exciting to the designers for providing substantial performance improvements over their Si based counterparts. F. Xue et al (2016) focussed on the use of GaN devices in building a highly efficient bidirectional DC-DC converter for getting higher power density in battery energy storage system applications. The special package of the available GaN devices requires a PCB layout method by taking into consideration the thermal design along with the switching loop inductance. It presented the design considerations of GaN based DAB-IBDCs in terms of switching noise, thermal relief and gate-drive power supply for optimizing the layout which have minimal loop inductance along with good heat dissipation [6].

Since 1974, the magnetic materials like Fe-rich amorphous alloys including (Fe, Co)-Si-B and (Fe, Co, Ni)-(Cr, Mo, W)-C which have good soft magnetic properties were used in transformer cores for their lower core loss applications. Later, the Fe-based alloys having nanocrystalline structure such as FINEMET and NANOPERM were developed which exhibit superior soft-magnetic properties over amorphous structures [7]. Similarly, there have also been advancements in capacitive materials and microelectronic technologies with time which thereby poses a great challenge for power electronic scientists and engineers to work in this field.

For considering the DAB-IBDCs in medium-voltage power conversion systems, the transformers would impose limitations on the overall power density. In power conversion systems, the use of low frequency transformers results in bulky, heavy and noisy systems. The low frequency transformers are used for achieving the required galvanic isolation and voltage matching between two different voltage level circuits. By replacing these low frequency transformers with high frequency transformers, the features like low volume, light weight and low cost of the converter can be achieved. The high frequency power conversion systems based on high frequency transformers avoid voltage and current waveform distortions which are caused by the core saturation as in the case of low frequency transformers. Moreover, switching/operating frequency operation above 20 kHz results in great reduction of power conversion systems noise [1]. Thus, these high frequency DAB-IBDCs have the advantages of higher frequency operation, high power density, small size, light weight and higher efficiency.

With all these advancements in the semiconductor switching devices, electromagnetic materials as well as nano-electronic technologies, there is a lot of work in the field of DAB-IBDCs with respect to their topologies for improving the overall power conversion efficiency. There are various topologies of DAB-IBDCs in the literature which require a review on the topologies for the study purpose to put them in real life applications.

This paper is organized as follows. The DAB-IBDCs are discussed in section II. The resonant converter topologies are discussed in section III while its variants are discussed in section IV. The conclusion is discussed in section V.

I. **DAB-IBDCs**

The name dual-active-bridge (DAB) of the converter is derived from the circuit topology while the original term isolated bidirectional dc-dc converter (IBDC) relates to its functionality. Thus, the DAB can be considered as an isolated bidirectional DC-DC converter namely DAB-IBDC as shown in Fig.1 with its basic structure, where converter A and B are both active full-wave bridges converting first DC-to-AC and then AC-to-DC respectively in Mode A-B operation for forward power transfer. The power flows in reverse direction during Mode B-A operation. The bidirectional power flow is shown by Mode A-B and Mode B-A operations respectively. Here, V_A and V_B are two DC bus voltages carrying currents i_A and i_B respectively on the two sides of the DAB-IBDC along with a high frequency transformer with turn ratio n:1.

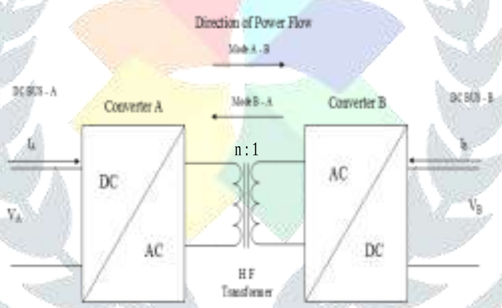

Fig.1 Basic Structure of DAB-IBDC

These DAB-IBDCs are of two types: resonant as well as non-resonant type DAB-IBDCs. The conventional DAB-IBDC converter [8] is of non-resonant type DAB-IBDC which has only one inductor, L as shown in Fig. 2.

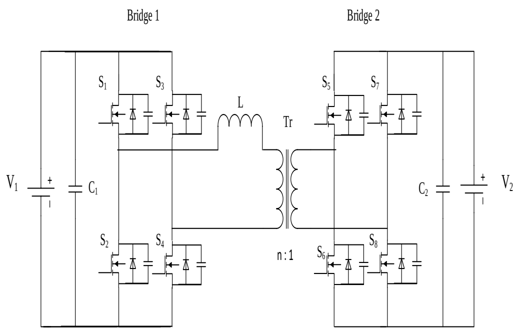

Fig.2 Conventional DAB-IBDC converter

The resonant type DAB-IBDC consists of at least one pair of inductor (L) and capacitor (C) components for the resonance purpose and accordingly named as series resonant converter (SRC), parallel resonant converter (PRC) or there may be a combination of both SRC and PRC. These resonant type DAB-IBDCs have different topological configurations in addition to one pair of L and C with multiples of each or both for different resonant converter topologies.

These resonant converters may have either voltage source or current source at their input for getting different topological configurations. In voltage source resonant converters, the current passing through the resonant components is nearly sinusoidal and its frequency can be adjusted to either above, below or at the resonant frequency of the LC resonant tank network. Thus, the output voltage of the converter is regulated by adjusting the switching or operational frequency to either above or below that resonant frequency, as by varying the frequency of operation, the impedance of the resonant components vary. When the operation is at the resonant frequency of LC tank network, some other means for controlling the output voltage are required. The weight and volume of these additional reactive components in resonant converter is not negligible. Sometimes we prefer to employ non-resonant type DAB-IBDC converters for considering the power density issue.

In non-resonant DAB-IBDC as shown in Fig. 2, there are two full-wave bridges as Bridge-1 and Bridge-2 which are separated by an isolated transformer 'Tr'. There are two DC bus voltages as V1 and V2 on either side of the conventional DAB-IBDC converter. The active switches (S1-S8) in two bridges and the filtering capacitors (C1, C2) are shown in Fig. 2. This high frequency transformer provides the necessary galvanic isolation and voltage matching between two electric circuits of different voltage levels. The inductor, L acts as an instantaneous energy storage device which may be the leakage inductance of the transformer or an additional inductor in the circuit. In a DAB-IBDC converter, the performance is heavily dependent on the leakage inductance of the transformer. The value of this inductor plays a important role in the efficient functioning of DAB-IBDCs. S. Saeed et al (2021) presented a DAB-IBDC with variable inductor for extending the optimal switching region to achieve high efficiency over wide range compared to the traditional solutions [9].

The DC output power can be controlled by adjusting the phase shift angle (Φ) between two full-wave active bridges and is given by:

$$P = \frac{n\, V_1 V_2}{2\, \pi\, f_s\, L}\, \Phi(\pi - \Phi) \tag{1}$$

Where 'f_s' is the operating/switching frequency and the transformer turns ratio is given by n: 1. In a DAB-IBDC, the rating of switching elements depends relatively on the DC power source voltage and the load current. Thus, with higher voltage and current specifications of DAB-IBDC converter, its physical size becomes larger and simultaneously the conduction and switching losses also increases which results in reduction of overall power conversion efficiency. T. Hirose et al (2010) proposed a DC-DC converter which lowers both the rated voltage of switching elements and load current by sharing the dc power source voltage between two converters. This is possible with two bridge-type converters which are linked through superposition in the additive polarity and in series. Thus, the capacity of HF transformer decreases which results in more efficient and smaller dc-dc converter [10]. The features of DAB-IBDC include its bidirectional power transfer capability, modular and symmetric structure along with ease of realizing soft-switching in semiconductor switching devices.

The topological configurations of DAB-IBDC converter may vary depending on the type of AC-DC converter as well as DC-AC converter used on both sides of the high frequency transformer. These may be half-bridge or full-bridge type converters. Y. P. Chen et al (2019) presented a structurally reconfigurable resonant DAB-IBDC for achieving full-range soft-switching and enhanced light-load efficiency. The DAB-IBDC operates in full-bridge mode for 50% to 100% load for achieving soft-switching in all switches with an independence from input to output voltage ratio. Below 50% load, the DAB-IBDC is reconfigured to operate in half-bridge mode [11]

The DAB-IBDC may have either non-isolated or isolated resonant converter topologies but the step-up/step-down ratio is limited in case of non-isolated ones. The advantages of non-isolated converter topologies include lower magnetic bulk, higher efficiency and compactness. I. Alhurayyis et al (2020) presented a review on isolated and non-isolated DC-DC converters for medium voltage DC networks as the research on isolated converters is in its infancy which is limited by the conversion ratio and component ratings [13]. The isolation in HF bidirectional dc-dc converter topologies has been introduced for voltage matching as well as safety reasons which may be resonant or non-resonant type converter topologies.

For applications requiring sufficient step-up/step-down ratio in non-isolated bidirectional dc-dc converters, A.K. Rathore et al (2016) proposed a solution which have overall high voltage gain without using any transformer. Its key features include high step-up/step-down ratio, high efficiency, low device voltage stress, soft-switching including ZVS turn-on for all switches and ZCS turn-on/off for all diodes in both buck and boost modes of operation. But all these features are gained at the cost of efficiency which is limited to an approximate value of 95%. This is a current-fed LCL resonant dc-dc converter having current-fed half-bridge boost converter at the front-end followed by a voltage doubler at the output for enhancing the gain to double value as shown in fig.3. Similarly in buck operation, the high voltage is first divided to half with a capacitor divider for gaining higher step down ratio [13].

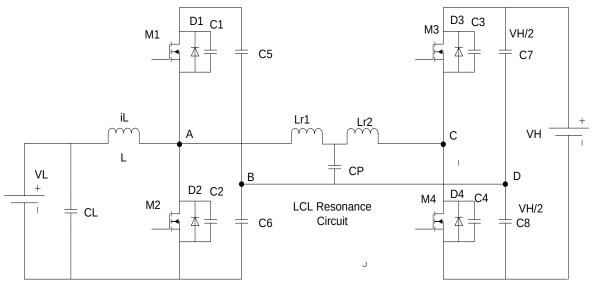

Fig. 3. Non-isolated Bidirectional current-fed LCL resonant dc-dc converter

There are different methods for analysing these resonant converters which includes time domain analysis, state-plane analysis and frequency-domain analysis. In time domain analysis, the steady-state operation is derived by using differential equations in each state which becomes cumbersome for solving higher order resonant converter solutions. The state-plane analysis is based on linear models and it is difficult to linearize the models of higher order resonant converter topologies. The frequency domain analysis will be the only practical tool for analyzing higher order resonant converter topologies which can be applied by using fundamental harmonic approximation (FHA). The resonant tank network acts as a pass filter which removes the harmonics of the fundamental components of the current/voltage generated by the switching networks at its output. Thus the fundamental sinusoidal component of voltage and current are arriving at the winding inputs. Utsab Kundu et al (2016) presented an analytical design approach by using frequency domain analysis to derive the characteristic equations of DAB series resonant converter (DABSRC) in normalized form and later by using these characteristic equations as described, the appropriate steps for converter design are presented [14]. This approach ensures zero voltage switching (ZVS) of both active bridges during the bidirectional power transfer.

In resonant converters, the resonant tank network is followed by an effective ac load resistance or equivalent ac resistance (Rac) which is the ratio of fundamental component values of voltage and current at the resonant tank network terminals. This can be achieved by replacing the rectifier, filter and load resistor with an equivalent ac resistance. The equivalent ac resistance for the resonant converter using an inductor output filter is given by

$$R_{ac} = \frac{\pi^2}{8} R_L \qquad (2)$$

Similarly, the equivalent ac resistance for the resonant converter using a capacitive output filter is given by

$$R_{ac} = \frac{8}{\pi^2} R_L \qquad (3)$$

This approach gives us an approximate analysis but it is good enough for simple design purposes. Thus, the DAB-IBDC is the core circuit of HFL-PCSs with resonant circuit topologies using L and C components in their resonant tank circuits and depending upon the arrangement of these L and C combinations in the resonant tank networks, there are different types of resonant converter topologies available in the literature.The overall power loss, PLoss in the DAB-IBDC is given by

$$P_{Loss} = P_S + P_{Con} + P_{Cu} + P_I + P_U \qquad (4)$$

Where PS ,PCon , PCu , PI and PU are the switching, conduction, copper, iron and unknown losses in the DAB-IBDCs. The unknown losses mainly include line-resistor losses, copper losses caused by skin and proximity effects and so on.

There is a contribution of different types of power losses which are occurring in DAB-IBDCs. H. Akagi et al (2014) proposed a simple and practical method for power-loss distribution of an IBDC by using SiC-MOSFET/SBD dual modules. It was observed that the sum of iron and copper losses due to magnetic devices was around 30% of overall power loss. This was nearly equal to either conduction loss or switching loss produced by the SiC modules. While, the remaining 10% of the overall power loss were considered as unknown losses. The maximal conversion efficiency from the dc-input to dc-output terminals was approximately 98.7% at partial load operation, which was calculated from an accurately measured overall power loss by excluding gate-drive and control circuit losses. While at rated power, the efficiency was observed as 97.9% [15]. This breakdown indicates that it is important to reduce conduction as well as switching losses produced by the SiC modules and the copper as well as iron losses in the transformer and auxiliary inductors for improving the overall power efficiency.

The switching loss and conduction loss are the major losses of interest occurring in DAB-IBDCs which can be overcome by using SiC-based power semiconductor devices. S. Inoue et al (2007) carried out the loss analysis for determining the effectiveness of using SiC-based power semiconductor switching devices. It shows that SiC-based power semiconductor devices will reduce both conduction as well as switching losses, thereby increasing the overall efficiency to 99% or higher against the power devices used in 2005 which were Trench-Gate Si-IGBTs. The core material used in the transformer was FinemetTM (Nano-crystalline soft-magnetic material manufactured by Hitachi Metals) and the efficiency achieved was approximately 97% by excluding the gate drive and control circuit losses from the overall power loss. While in 1991, the power semiconductor devices used were First-Generation Si-IGBTs, the core material was Ferrite and the efficiency achieved was approximately 91%. This finding shows how the efficiency continually improved with time. This loss analysis encouraged the introduction of SiC power semiconductor devices in dc-dc converters for significantly reducing the power losses and thus proved a significant contribution in increasing the power density of PCSs [16].

Thus, the DAB-IBDC is the core circuit of HFL-PCSs with resonant circuit topologies using L and C components in their resonant tank circuits and depending upon the arrangement of these L and C combinations in the resonant tank networks, there are different types of resonant converter topologies available in the literature which are discussed in next section.

II. Resonant Converter topologies

A resonant converter (RC) with high frequency operation in electronic circuit applications results in soft switching of semiconductor switching devices which results in high efficiency and small size of DC-DC converters. The series resonant converter (SRC) and parallel resonant converter (PRC) are the basic resonant converter topologies having two reactive elements in their resonant tank circuit. The SRC is a step-down converter which requires an additional transformer for stepping-up the voltage. The SRC can be used as an alternative to the well-known conventional DAB converter which has bidirectional power flow capability. This will be possible if the conventional SRC adds the features of both stepping-up and stepping-down the voltage. S. Hu et al (2019) presented a DAB-IBDC with series resonant converter for minimizing the tank current over wide ZVS range for enhancing the overall system efficiency [17].

In [18], the results indicate that this technique achieves better efficiency in comparison to the conventional phase-shift DAB converter over wide power range along with smaller currents in comparison to conventional DABs at light load conditions. This SRC exhibits similar efficiency during higher power transfers and higher efficiency during light load conditions.

The SRC and PRC with two reactive elements are second-order resonant converters which have the merits of simple configuration but they still have certain limitations for further applications. The higher order resonant converter topologies are considered because of the inherent limitations of second-order resonant converter topologies. These higher order resonant converters offer a steeper fall in gain with frequency and thus exhibiting better controllability over wide line and load variations with small variations in frequency. A properly designed higher order resonant converter has an overall smaller volt-ampere rating of the resonant network and also achieving better efficiency [19]. In addition, the practical circuit elements have their inherent parasitic components which deduce the available second-order resonant converter topology to a higher order resonant converter topology. Thus these parasitic components are gainfully utilized as a part of the resonant tank network. Moreover, the diversity in the available resonant converter topologies gives the designer a freedom to choose the most suitable or appropriate topology for a given application. The authors has discussed the DAB-IBDC by incorporating the transformer non-idealities in the topology [20]. The lumped elements along with high voltage transformer model are shown in Fig. 4.

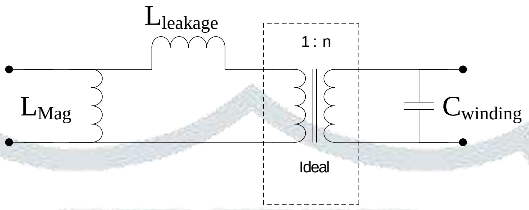

Fig.4 Lumped element high voltage transformer model

While considering combination of series-parallel resonant converter topologies, the Type-4 and Type-11 LLC resonant tank circuits have very similar behavior over the switching frequency. These have the same number of resonant stages in a given switching cycle and also same operation modes for leading and lagging power factor. The Type-4 LLC converter has been considered as band filter with series-parallel type of resonant tank network. The Type-11 LLC converter has also been considered as a series parallel resonant tank network but with different location of extra parallel resonant inductor which is developed from the basic LC series resonant converter. The Type-4 LLC converter is similar to the conventional LC series resonant converter, because during the LC resonant stage, the load is in series with the resonant tank. Similarly, the Type-11 LLC converter is similar to the conventional CL parallel resonant converter and the load is in parallel with the resonant tank during the LLC resonant stage. Hence, similar to the difference associated with the dc gain between PRC and SRC, the voltage gain of Type-11 LLC converter is higher than that of Type-4 LLC converter at same switching frequency [21].

In making a comparison between series-resonant, parallel resonant and combinational series-parallel resonant converter topologies in low output voltage power supply applications, it has been observed that the combinational series-parallel resonant converter topology exhibit the characteristics of both series and parallel resonant converter topologies. The combinational topology removes the main disadvantages of series and parallel resonant converter topologies. These can operate over wide input voltage range along with large load range i.e. from no-load to full-load conditions, while maintaining excellent efficiency [22]. The technique used for the comparison is based on classical ac complex analysis approach.

In a comparative analysis of isolated bi-directional dc-dc converter topologies with wide input/output voltage [23], which had considered four IBDC topologies including DAB, SRC and each one of these operated in two stage operation based on the combination of an isolation stage and a non-isolated voltage converter. In all these topologies, a bidirectional battery charger is considered which interfaces a low voltage battery with a high voltage DC bus operating under wide input and output voltage ranges. Thus, depending upon the mathematical and simulation results, the most efficient topology found for this specific converter application is two-stage series resonant converter with an efficiency of 90% at rated power with an operation range as shown in Fig. 5, where the battery voltage ranges from 11V to 16V on LV side and bus voltage ranges from 220V to 447V on HV side.

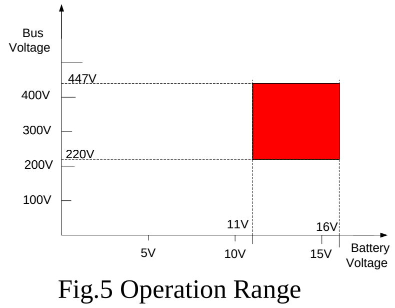

Fig.5 Operation Range

A similar comparison in resonant converter topologies like series resonant converter, parallel resonant converter and hybrid of series and parallel resonant converter is done in [24] for high voltage dc applications. Of all these, the parallel resonant converter topology leads to lowest peak switch current stress along with most ideal behaviour.

M. Borage et al (2009) presented a series-parallel type of resonant tank circuit by considering LCL-T resonant converter and the effect of transformer winding capacitance. It results into an LC-LC type resonant converter and thus converting the topology from third-order to a fourth-order topology. Under given design conditions, this LC-LC resonant converter exhibit as a constant output current source with in-phase source voltage and current under all load conditions. Thus, the transformer leakage inductance and winding capacitance are gainfully captured as a part of the resonant tank network with improved output characteristics. Thus we can say that the LC-LC RC retains the characteristics of LCL-T RC while gainfully utilizing the transformer leakage inductance and winding capacitance [25].

From the study of various topologies of resonant tank circuit, it has been observed that as the number of reactive components increases in resonant tank network, the characteristics/features of the resonant tank network improves in comparison to the resonant tank network with lower number of reactive components. In [26], the different parameters of dc-dc converter like input impedance, voltage gain and efficiency are derived for various topologies like SRC, PRC, LLC, LCC and LCLC along with their merits and limitations. In case of three element resonant tank networks like LLC type, the peak gain depends on the value of the inductance ratio of two inductors. Similarly, in LCC, the peak gain depends on the value of the capacitance ratio of two capacitors. In case of four element resonant tank networks like LCLC topology, it combines the features of both LCC and LLC resonant converters. In case of two elements resonant tank networks such as SRC, the voltage gain cannot be more than unity and it will be unitary when the switching frequency is equal to the resonant frequency which is independent of load. Under light load conditions, it remains nearly equal to one for switching frequency approximately equal to the resonant frequency, thus the output voltage cannot be regulated over a wide range by adjusting the switching frequency operation. If the output voltage has to be regulated under light load conditions, a large range of switching frequency is required in comparison to high load conditions. In case of PRC, during light load conditions where switching frequency is approximately equal to the resonant frequency, the output voltage rises to a very high value. Thus in comparison to SRC, by changing the switching frequency in case of PRC,, the output voltage can be stepped up or down significantly.

All types of basic topologies dedicated to type-4 LLC series resonant converter with varying input/output structures and different isolation requirements are discussed in [27]. Many studies favour Type-4 LLC resonant converters due to its advantages like high conversion efficiency, ZVS for all semiconductor switches, ZCS for all rectifier diodes with wide input voltage range when working in boost mode. There are different variations or modifications in circuit configuration of Type-4 LLC resonant converter which suit different practical requirements for achieving their optimal performance under each application. According to the variety of input/output structures like full bridge/half bridge/central tapped and the isolation types like none/input/output/both, there are different relationship among these components for different combinations. Accordingly, there are different modifications which are suitable for different practical applications including high input voltage, low input voltage, high output voltage, high output current, high power rating, isolation and their suitability for magnetic integration. These resonant converters are also suitable for ultra-high input applications which results in high voltage stress on the circuit switches. This problem can be solved by using a three-level converter which limits the voltage stress of each switch to half of its input voltage and thus improving the power conversion efficiency. In multi-output application, the rectifier diode's operation under ZCS condition is achieved when the converter working under Boost mode is full-bridge full-wave rectifier. It is suitable for HV and high power output applications. For much higher boost rate, a half-bridge full-wave rectifier or a voltage doubler is preferable. For medium to ultra low voltage, a full-wave centre-tapped rectifier is suitable and for ultra low power rating systems, a half-wave rectifier is favourable. All the available topologies of Type-4 LLC series resonant converter with varying kinds of input/output structures and locations of isolation maintain the same characteristics and merits as the original one.

H. Karshenas et al (2011) investigated common medium-power and soft-switched IBDC topologies which are increasingly used for interfacing purpose in different applications like renewable energy resources, hybrid electric vehicles and UPS system. The different configurations of IBDC are classified into few families which provide the insight into the basic operation of each family by investigating the working principle of the representative member of each family. This helps to compare different characteristics of each family and thus understanding their advantages and disadvantages for given applications [28].

Resonant converter topologies also include resonant immittance converter (RICs) topologies. These are the topologies in resonant networks that exhibit immittance conversion characteristics, i.e. conversion of a constant voltage source to a constant current source and vice versa. The resonant converters whose resonant network exhibit immittance conversion characteristics are termed as RICs. These are discussed in next section.

III. Resonant Immittance Immittance Converter

A two-port resonant immittance converter is shown in Fig. 6. M. Borage et al (2011) presented twenty-four resonant immittance converter (RIC) topologies with three and four reactive elements in their resonant tank network. It also mentioned the operating point and design conditions under which these topologies exhibit immittance conversion characteristics. These are lumped-element RIC topologies representing the transmission parameters of various topological structures of the electrical networks. These are useful in many power electronic applications. This research specifically aimed towards the identification of RIC topologies. Other RC topologies or non-RIC topologies are also useful which are popularly used for other applications. Non-RIC topologies require a HF sinusoidal source, which is more difficult to generate than a square-wave source. M. Yaqoob et al (2020) presented a fifth-order resonant immittance network based DAB converter [29].

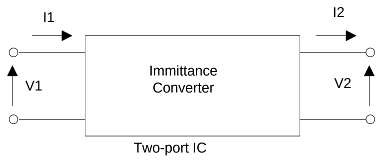

Fig.6 Two-port Immittance Converter

A.K.S. Bhat et al (1991) presented a unified or generalized approach for the steady-state analysis of resonant converters with the help of a generalized tank circuit scheme as shown in fig.7. This generalized tank circuit scheme will be helpful for obtaining the converter gain and design equations of higher order resonant tank circuit and thus good features can be exploited in the practical designs. Different resonant tank circuit configurations are obtained from this unified or generalized tank circuit scheme. This unified approach will be helpful in the analysis of different schemes separately, where the results for a particular scheme can be obtained by opening or shorting the non-required tank circuit components of the generalized scheme in a computer program. The effect of high frequency transformer and other parasitic components can also be considered in the analysis. In this, an attempt is made for the generalized approach using steady-state analysis of the resonant inverter where the load presented to the tank circuit is RL type. This equivalent impedance can present both the leading and lagging power factor. A leading power factor facilitates the use of fast thyristors or asymmetric SCR's and the converter operates in below resonance mode. If switches are capable of gate or base turn-off then the converter can operate in above resonance mode or lagging power factor mode [30]. The general purpose simulation software-application PSPICE can be used for the ac analysis of resonant converters [31].

Z. Khan et al (2019) presented the DAB-IBDC with a three-phase resonant immittance network for achieving unity power factor operation at both AC links which mitigate the reactive power loss. The power flow through the converter is controlled by modulating either internal or both internal and external phase-shift angles; thus, providing two degrees of freedom [32].

Y. Zhang et al (2004) proposed a systematic modelling method of the resonant converter for developing a low frequency d-q model of the resonant converter. For a given resonant tank, its orthogonal counterpart is constructed. Then by combining these two orthogonal tanks, a complex circuit is obtained which subsequently can be expressed in d-q form circuit, where every variable can be treated as a rotating vector with its envelope modulated by a low frequency function [33].

There are different topologies with two or more reactive elements in the resonant tank circuit available in the literature which can be utilized for different application. A comparison of different topologies is there in the literature for its easy understanding. These resonant tank circuits will help in achieving soft switching of power semiconductor switching devices for their use in high frequency operation for achieving higher power density.

IV. Variants of DAB-IBDC

Depending upon the applications of DAB-IBDCs, the traditional DAB-IBDCs are required in many variants like three-phase DAB-IBDC and multiport converters.

A. Three-phase DAB-IBDC converter

The operation of three-phase DAB-IBDC converter is similar to the single-phase DAB-IBDC with a few changes. It has three-phase converter by using full-bridges which operate in six-step mode in comparison to the two-level mode operation for single-phase DAB-IBDC. The three-phase DAB-IBDC is shown in Fig. 7.

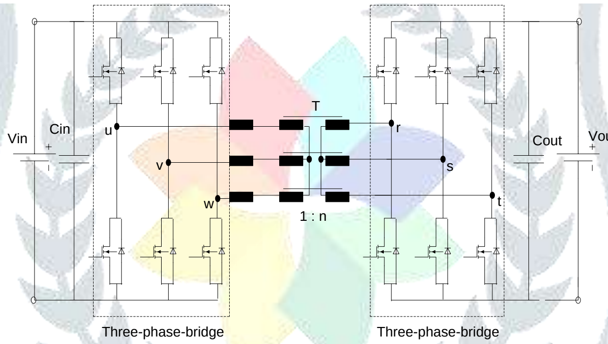

Fig.7 A three-phase DAB-IBDC converter

R. De Doncker et al (1991) presented a three-phase soft-switched dc-dc converter having higher power density in high power applications. These three-phase dc-dc converter topologies are suitable for high-power density and higher power applications like single-phase phase-shifted dc-dc converters. In this, the single-The single-phase DAB DC-DC converter and three-phase DAB DC-DC converter are presented which operate in soft-switched manner with reduced switching loss and increased switching frequency. The three-phase DAB converters have most favourable characteristics in comparison to single-phase ac-link DC-DC converters like lower turn-off peak current in power devices, lower rms current ratings of both input and output filter capacitors and smaller filter element values due to high frequency content in both input and output waveforms. By using a three-phase symmetrical transformer instead of single-phase transformers, a better utilization of the available apparent power of transformer (as a consequence of the controlled output inverter) can be made which increases the power density. The main disadvantage lies in the practical realization of three-phase symmetrical transformer and identical leakage inductance in each phase and moreover, it requires two additional devices in each bridge [2].

B. Multiport DAB-IBDC converter

A DC-DC converter can connect any number of ports and accordingly linking multiport in multi-individual DC-DC conversion stages by using a common link where energy from all the ports can be exchanged. In multiport DAB-IBDC converter, there is a multiport transformer. In multiport transformer, there is one core which is shared by different windings. A multi-port DAB-IBDC converter with three-port transformer is shown in Fig. 8.

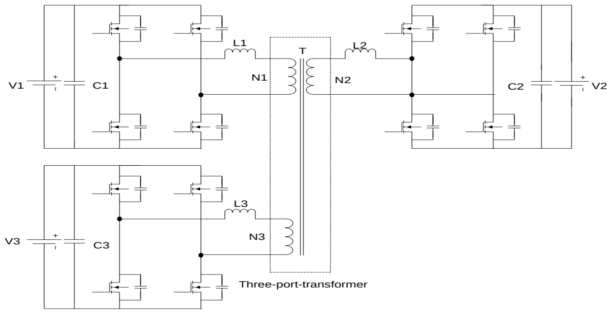

Fig.8 Multiport converter.

W. Qingshan et al (2016) presented the design of HF transformer IBDC modules which are connected in module-cascaded solid-state transformer (SST). The bidirectional DC-DC converter is a crucial element for power transmission in SSTs. The proposed DAB converter consists of two three-leg bridges along with a high frequency transformer with winding shunt taps. By changing the number of primary winding turns, its leakage inductance can be adjusted on a large scale which enables the possibility of reduction of overall loss over wide load range. The efficiency improves at both light and heavy load conditions in comparison to conventional DAB converter along with higher power density. In addition, the additional bridge arm structure along with the flexible control schemes provides high-level fault tolerance capability [34].

H.V. Hoeket al (2013) proposed an enhanced modulation strategy in three-phase DAB converters with boost in the efficiency of electric vehicle. The triangular as well as trapezoidal modulations for three-phase DAB improve the load efficiency at partial load conditions. Typically, the three-phase DAB DC-DC converters are avoided in lower power applications, especially in wide voltage and power range applications although three-phase DABs reduces filter cost and volume in comparison to single-phase DABs. The proposed schemes are compared with two conventional DAB concepts i.e. single-phase DAB with combined modulation and three-phase DAB with classical phase-shift modulation. It has been found that the efficiency of three-phase DAB increased substantially. Therefore, the modulation strategy which is hybrid of two proposed modulation schemes along with phase-shift modulation is the ideal one as it boosts the efficiency in addition to inherent low filter volume [35].

J.Walter et al (2003) presented a three-phase DAB converter (DAB3) which converts power between 42V (automobile Powernet) and 300V (fuel-cells). This is high-power and galvanically isolated DC-DC converter topology for future automobile applications. The DAB3 has been selected in this application after comparing different topologies like serial resonant converter (SR), single-phase DAB (DAB1) and three-phase DAB (DAB3). All these circuits are investigated for their operation in soft-switching manner that enables the reduction in device switching loss with increase in switching frequency. All these having the key features of galvanic isolation, reduced cooling cost and capability of transferring energy over wide voltage range. The final design is a mixture of theoretical analysis, simulation results and practical experiences. The DAB3 converter topology is the best with lower filter stress and thus requiring dc capacitors for apparent power in transformer and it will reduce the cost of passive components with simultaneous increase inthe reliability of the converters [36].

D. Segaran et al (2008) presented a comparative evaluation of two back-to-back converters for their use in bidirectional power transfer application. These two alternatives are studied in terms of their operating characteristics and losses which provide the basis for selection of two topologies in any particular operating context. This paper considers their control strategies and the anticipated converter losses. This comparison allows to a considerable choice between two alternatives for any particular application [37].

N. Soltau et al (2012) derived different modelling approaches while covering the dynamic behaviour of three-phase DAB. Of all, the first approach utilizes the state-space averaging method in conjunction with state-variable averaging and the second approach utilizes the first harmonic approximation. A control design method is developed based on these models and evaluated for different converter parameters. It is finally implemented by using a DSP controller in laboratory prototype of the converter. This control structure can be applied easily in any three-phase DAB independent of power level and applications [38].

S.P. Engel et al (2012) presented the dynamic behaviour of three-phase high power DAB DC-DC converters in DC-Grid applications. It also analyzed them with dynamic control strategy. It also implemented a compensation technique for compensating the unbalanced transformer phase currents which are caused due to asymmetric leakage inductances. Both state-space averaging and first harmonic approximation models for the steady-state and transient analysis are developed for describing the dynamic behaviour of three-phase DAB. A unique control method is also presented which settles the transformer currents within one-third of the switching period, because when the transferred power in the DAB changes fast, the transformer currents become balanced leading to oscillations in output current. In addition, these transformer currents will remain symmetrical and avoids the oscillations. Based on this fast current control, an outer voltage controller is also designed. In comparison to conventional quasi steady-state control, this fast current control has some potential advantages under dynamic conditions. But in practice, it is difficult to achieve complete symmetrical short-circuit impedance in high-power medium-voltage transformer. This scheme can be extended to compensate any unbalance in the transformer which enables its effectiveness in balancing the three-phase currents [39].

Hauke van Hoek et al (2013) presented an enhanced modulation strategy for three-phase DAB to boost the efficiency of electric vehicle converter. The triangular and trapezoidal modulations in three-phase DAB converter are proposed for addressing the poor partial load efficiency problem. It is found that the efficiency of three-phase DAB converter has increased substantially. Moreover, the three-phase DAB converter filter requirement is smaller than that of the single-phase DAB converter. It has been concluded that the modulation strategy obtained by combining the two proposed modulation schemes along with phase-shift modulation is the ideal one, because it boosts the efficiency along with inherent low filter volume. It offers promising solution for miniaturization of galvanically isolated DC-DC converters in electric vehicles using three-phase DABs [40].

J. Walter et al (2003) presented a 2 kW three-phase DAB (DAB3) converter to interface 42V and 300V power supplies that can be easily scalable to 20 kW. This is high-power and galvanically isolated DC-DC converter topology for future automobile applications. The DAB3 has been selected for this application after comparing different topologies like serial resonant (SR) converter, single-phase DAB (DAB1) and DAB3. All these having the key features of galvanic isolation, reduced cooling costs and capability of transferring energy over a wide voltage range. These circuits are investigated for their operation in soft-switching manner and thus enabling the reduction in device switching loss with increase in their switching frequency [41].

So, there are different variants of DAB-IBDCs which are available in literature like three-phase DAB-IBDCs and multiport converters mentioned above and thus proving their requirement as DAB-IBDCs in the field of DC-DC converters.

V. CONCLUSION

The isolated bidirectional DC-DC converters in high frequency power conversion systems serving as their core circuits had been discussed. It had different advantages like high power density, reduced weight and size along with low noise without compromising the efficiency, cost and reliability of the system. For modelling of bidirectional dc-dc converter with high frequency isolation in power conversion systems, the soft switching techniques along with their modulation techniques are the research topics. These are discussed here along with their different soft switching and resonant converter topologies. Moreover, their variants are also discussed here. These high frequency operated DAB-IBDCs with new advancements help in applications which require highly efficient resonant converter topologies with reduced switching losses over wide operation range. This can be used as a platform to start with and explore DAB-IBDC more and more for efficient use in various applications like distributed generation systems, EVs, IMDs etc. In future, the design and performance optimization of DAB-IBDC using latest devices, and the system-level solutions of DAB-IBDC for HFL PCSs is definitely seen as a promising research trend

REFERENCES

[1] Zhao, B. Song , Q. Liu, W. and Sun, Y. 2014. Overview of Dual-Active Bridge Isolated Bidirectional DC-DC Converter for High Frequency-Link Power-Conversion System. IEEE Transactions on Power Electronics, 29 (8):4091–4106.

[2] De Doncker, R. Divan,D. and Kheraluwala, M. 1991. A three-phase soft switched high-power-density dc/dc converter for high-power applications. IEEE Trans. Ind. Appl., 27(1) : 63–73.

[3] Kheraluwala, M.H. and De Doncker,R. 1991.Single phase unity power factor control for dual active bridge converter. Industry Applications Society Annual Meeting, 2: 909-916.

[4] Kheraluwala, M. Gascoigne, H.R.W. Divan, D.M. and Baumann, E.D.1992. Performance characterization of a high-power dual active bridge dc-to-dc converter. IEEE Trans. Ind. Appl., 28(6):1294–1301.

[5] Biela, J. Schweizer, M. Waffler, S and Kolar, J.W. 2011. SiC versus Si-Evaluation of potentials for performance improvement of inverter and dc-dc converter systems by SiC power semiconductors. IEEE Trans. Ind. Electronics, 58 (7):2872–2882.

[6] Xue, F. Yu, R and Huang, A.Q. 2016. Design considerations of an isolated GaN Bidirectional DC-DC converter. IEEE Energy Conversion Congress and Exposition (ECCE):1-7.

[7] Lee, M.C. Lin, C.Y. Wang, S.H. and Chin, T.S. 2008. Soft-magnetic Fe-based nano-crystalline thick ribbons. IEEE Trans. Magn., 44 (11): 3836–3838.

[8] Kheraluwala, M.H. and Doncker, R.W.D. 1993. Single phase unity power factor control for dual active bridge converter. Proc. IEEE Ind. Appl. Soc. Annu. Meet : 909–91.

[9] Saeed, S, Garcia, J and Georgious. 2020. Dual-Active-Bridge Isolated DC-DC Converter with Variable Inductor for Wide Load Range Operation. IEEE Transactions on Power Electronics.

[10] Hirose, T and Matsuo, H. 2010. A consideration of bidirectional superposed dual active bridge dc-dc converter. Proc. 2nd IEEE Int. Symp. Power Electron. Distrib. Generation System, pp: 39–46.

[11] Chan, Y.P. Loo, K.H. Yaqoob, M and Lai, Y. M. 2019. A Structurally Reconfigurable Resonant Dual-Active-Bridge Converter and Modulation Method to Achieve Full-Range Soft-Switching and Enhanced Light-Load Efficiency. IEEE Transactions on Power Electronics, 34 (5): 4195-4207.

[12] Alhurayyis, I. Elkhateb, A. and John Morrow, J. Isolated and Non-Isolated DC-to-DC Converters for Medium Voltage DC Networks: A Review. IEEE Journal of Emerging and Selected Topics in Power Electronics.

[13] Rathore, A.K.. Patil, D.R. and Srinivasan, D. 2016. Non-isolated Bidirectional Soft-Switching Current-Fed LCL Resonant DC/DC Converter to Interface Energy Storage in DC Microgrid. IEEE Transactions on Industry Applications, 52 (2): 1711–1722.

[14] Kundu, U. Sikder, S. Kumar, A. and Sensarma, P. 2016. Frequency Domain Analysis and Design of Isolated Bidirectional Series Resonant dc-dc Converter. IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES).

[15] Akagi, H. Yamagishi, T. Tan, T, Kinouchi, I. Miyazaki, Y. and Koyama, M. 2014. Power-loss breakdown of a 750-v, 100-kw, 20-khz bidirectional isolated dc-dc converter using sic-mosfet/sbd dual modules. Proc. Int. Power Electronics Conference: 750–757.

[16] Inoue, S. and Akagi, H. 2007.A Bidirectional Isolated DC-DC Converter as a Core Circuit of the Next-Generation Medium-Voltage Power Conversion System. IEEE Transactions on Power Electronics, 22 (2): 535–542.

[17] Hu, S. Li, X. and Bhat, A.K.S. 2019. Operation of a Bidirectional Series-Resonant Converter With Minimized Tank Current and Wide ZVS Range. IEEE Transactions on Power Electronics, 34 (1) : 904-915.

[18] Martin Ibanez, F. Martin Echeverria, J. Vadillo, J, and Fontan,L. 2015. A step-up bidirectional series resonant dc/dc converter using a continuous current mode. IEEE Trans. Power Electronics, 30 (3): 1393–1402.

[19] Borage, Nagesh, M.K..Bhatia, M. and Tiwari, S. 2011.Resonant immittance converter topologies. IEEE Trans. Ind. Electronics, 58(3): 971– 978.

[20] Johnson, S. D. Witulski, A.F. and Erickson, R.W. 1987. A comparison of resonant topologies in high voltage DC applications. Applied Power Electronics Conference and Exposition, IEEE, San Diego, CA USA: 145-156.

[21] Chen, W. Rong, P. and Lu, Z.Y. 2010. Snubberless bidirectional DC-DC converter with new CLLC resonant tank featuring minimized switching loss. IEEE Trans. Ind. Electronics, 57(9): 3075–3086.

[22] Steigerwald, R.L. 1981. A comparison of half-bridge resonant converer topologies. IEEE Trans. Power Electronics, 3 (2): 174-182.

[23] Borage, Nagesh, M.K.V. M. Bhatia, M.S. and Tiwari, S. 2009. Design of LCL-T resonant converter including the effect of transformer winding capacitance. IEEE Transactions on Inddustrial Electronics, 56 (5): 1420–1427.
[24] Outeiro, M.T. and Buja, G. 2015. Comparison of resonant power converters with two, three, and four energy storage elements. Proc. 40th IEEE Ind. Electron. Soc. Annu. Conf. (IECON): 1406–141.
[27] Chen, W and Lu, Z. 2008. Investigation on topology for Type-4 LLC resonant DC-DC converter. Proc. IEEE PESC, Jun. 15–19, 2008: 1421–1425.
[28] Karshenas, H. Daneshpajooh, H. Safaee, A. Bakhshai, A. and Jain, P. 2011. Basic families of medium-power soft-switched isolated bidirectional dc–dc converters. Proc. IEEE Power Electron, Drive Syst. Technol. Conf., Tehran, Iran, 2011: 92–97.
[29] Yaqoob,M. Loo, K. Chan, Y.P. and Jatskevich, J. 2020. Optimal Modulation for a Fifth-Order Dual-Active-Bridge Resonant Immittance DC–DC Converter. IEEE Transactions on Power Electronics, 35 (1): 70-82.
[30] Bhat, A.K.S. 1991. A unified approach for the steady-state analysis of resonant converters. IEEE Trans. Ind. Electronics, vol. 38 (4): 251–259.
[31] Borage,and M. Tiwari, S. 2012. AC Analysis of Resonant Converters Using P Spice –A Quicker Approach. Asian Power Electronics Journal, 6 (2).
[32] Khan,A.Z Loo, K.H. and Lai, Y.M. 2019. Design, Analysis, and Performance Characterization of Dual-Active-Bridge DC–DC Converter Utilizing Three-Phase Resonant Immittance Network. IEEE Transactions on Power Electronics, 34 (2): 1159-1180.
[33] Zhang, Y. and Sen, P.C. 2004. D-Q models for resonant converters, Proc. PESC, 2004: 1749–1753.
[34] Qingshan, W. and Liang, D. 2016. Research on loss reduction of dual active bridge converter over wide load range for solid state transformer application. 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER): 1-9.
[35] Hoek, Neubert, M. and Doncker, R.W.D. 2013. Enhanced modulation strategy for a three-phase dual active bridge—boosting efficiency of an electric vehicle converter. IEEE Trans. Power Electronics, 28 (12): 5499–5507.
[36] Walter, J. and Doncker, R.W. D. 2003. High-power galvanically isolated dc/dc converter topology for future automobiles. Proc. IEEE 34th Annual Power Electron. Special Conf., 1: pp. 27–32.
[37] Segaran, D. Holmes, D.G. and McGrath, B.P. 2008. Comparative analysis of single and three-phase dual active bridge bidirectional dc–dc converters. Proc. AUPEC, Sydney, NSW, Australia, Dec. 2008: 1–6.
[38] Soltau, Siddique, N.H. and Doncker, R.D. 2012. Comprehensive modeling and control strategies for a three-phase dual-active bridge. Proc. Int. Conf. Renewable Energy Res. Appl., 2012: 1–6.
[39] Engel, S.P. Soltau, N. Stagge, H. and Doncker, R.W.D. 2012. Dynamic and balanced control of three-phase high-power dual-active bridge DC/DC converters in DC-grid applications. IEEE Trans. Power Electronics, 28 (4): 1880–1889.
[40] Hoek, H.V. Neubert, M.and Doncker, R.W.D. 2013. Enhanced modulation strategy for a three-phase dual active bridge—Boosting efficiency of an electric vehicle converter. IEEE Trans. Power Electronics, 28(12): 5499–5507.
[41] Walter, J. and Doncker, R.W.De. 2003. High-power galvanically isolated DC/DC converter topology for future automobiles. IEEE 34th Annual Conference on Power Electronics Specialist, 2003. PESC '03., Acapulco, Mexico, 2003,1: 27-32.