A Review on Soft Switching Solutions of Dual Active Bridge-Isolated Bidirectional DC-DC Converter for High Frequency Power Conversion Systems

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Abstract: Dual active bridge-isolated bidirectional DC-DC converters (DAB-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 on soft switching solutions for 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 modelling and optimization of the DAB-IBDCs with high frequency isolation in power conversion systems are concerned, state-of-the-art soft switching techniques is trending as the research direction which has been discussed here. The advances in the semiconductor devices, electromagnetic materials as well as nano-electronic technologies have increased their expectations in various applications.

***Index Terms* - Dual-active-bridge, Isolated bidirectional DC-DC converter, Soft switching techniques, Power Conversion System.**

I. INTRODUCTION

We are moving increasingly towards non-conventional/renewable energy resources due to 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 or 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 are 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, 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 the 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 its design recommendations and future trends [1].

High Frequency DAB-IBDCs were seen 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 sub optimal. 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 microelectronic technologies [1].

In comparison to Si 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 the 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.

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 Finemet TM (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. The test circuit used for this purpose was simple where the dc output terminals were connected back to the dc input terminals for regenerating dc output power back to the dc voltage source. This is used for accurately measuring the overall power loss in the dc-dc converters. 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 [6].

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% [7]. 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.

Fie Xue et al (2016) focused on the use of GaN devices in building a highly efficient DAB-IBDCs 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 optimising the layout which have minimal loop inductance along with good heat dissipation [8].

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 [9]. 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 system 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, the electromagnetic materials as well as nano-electronic technologies, there is a lot of work in the field of DAB-IBDCs with respect to its improvement in overall power conversion efficiency. There are various soft-switching solutions and soft-switching techniques of DAB-IBDCs in the literature which require a review for the study purpose to put them in real life applications.

This paper is organized as follows. A brief overview of DAB-IBDC is given in section II. The concept of soft switching is discussed in section III. The different soft switching techniques are discussed in section IV. The conclusion is given in section V

II. DAB-IBDC

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.

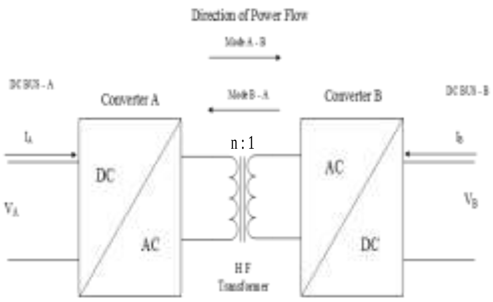

Fig.1 Basic Structure of DAB-IBDC

Thus, the dual-active-bridge (DAB) can be considered as an isolated bidirectional dc-dc converter (IBDC) namely DAB-IBDC as shown in Fig.1 as its basic structure, where converter A and B are both active full-wave bridges converting DC-to-AC and 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 features of DAB-IBDC include its bidirectional power transfer capability, modular and symmetric structure along with ease in realizing soft-switching of semiconductor switching devices. The bidirectional power flow is shown by Mode A-B and Mode B-

A. Here, V_A and V_B are two DC bus voltages carrying currents i_A and i_B respectively on the two sides of DAB-IBDC along with a HF transformer with turn ratio n:1.

The DAB-IBDCs are of two types: non-resonant as well as resonant type DAB-IBDCs. The conventional DAB [10] is of non-resonant type DAB-IBDC having only one inductor (L) as shown in Fig.2. In this non-resonant DAB-IBDC, 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 V_1 and V_2 on either side of the conventional DAB DC-DC converter. The active switches (S_1-S_8) in the two bridges and the filtering capacitors (C_1, C_2) 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 DC output power can be controlled by adjusting the phase shift angle (Φ) between two full-wave active bridges and is given by:

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

Where ‘f_s’ is the operating/switching frequency and the transformer turns ratio is n:1

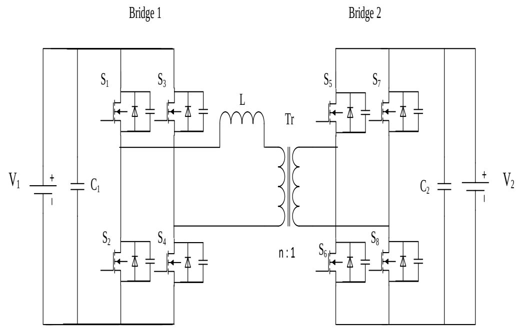

Fig.2: Conventional DAB DC-DC converter

While resonant type DAB-IBDC consists of at least one pair of L and C elements for the resonance purpose and accordingly named as series resonant converter (SRC), parallel resonant converter (PRC) or it may be a combination of both SRC and PRC. These resonant type DAB-IBDCs have different topological configurations with at least one pair of L and C and additional options of multiples of each or both for different resonant converter circuit topologies. 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.

There are different methods for analyzing 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 [11]. 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 (R_{ac}) 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.

III. Soft switching

The soft switching in the power semiconductor switching devices is the required feature in different resonant power converter topologies for reducing the switching loss so that they can operate at higher frequencies and thus achieving higher power density. The switching power loss (P_{sw}) in a DC-DC converter is given by

$$P_{sw} = k\, I_{sw} V_{sw}\, f\, (t_{on} + t_{off}) \qquad (4)$$

where k is a constant, Isw and Vsw be the current through and voltage across the switching device during the transition period respectively, 'f' is the frequency of operation while ton and toff be the on and off times of the switching period respectively. As frequency of operation 'f' increases for increasing the power density, Psw also increases. This can be controlled by decreasing either Isw or Vsw without affecting the terms ton and toff. While the on and off times (ton and toff) of the switching transition period have been improved to the order of several nano seconds as in the case of SiC/GaN based power semiconductor devices. This is in contrast to the Si based power semiconductor devices which have the value of the order of few hundreds of nano seconds.

The voltage across and the current through the switching devices during the commutation period mainly depend on both the characteristics of the switch and the circuitry connected to them. There is a finite commutation time period in the semiconductor switches which are associated with concurrent occurrence of both the voltage across and the current through the semiconductor switches. This leads to hard switching which results in increased switching power and electrical stresses. Thus, to minimize or completely diminish the switching power losses, different soft switching techniques have been developed.

In hard switching, there is a considerable overlap time period during the transition between the voltage and current waves which can be improved by soft switching. This soft switching can be achieved by either zero voltage switching (ZVS) or zero-current-switching (ZCS) in the DC-DC converters. The soft switching converters are classified according to the differences in their operating principles as quasi-resonant converters (QRCs), multiresonant converters (MRCs), resonant transition converters (RTCs) and resonant power converters (RPCs). All these methods make use of auxiliary devices for achieving the soft switching. Out of all these, RPCs are the most popular because of their high performance in terms of power density and efficiency. In RPCs, the auxiliary devices are inserted in cascade to the converters as a resonant tank network with two or more reactive elements.

There are different resonant tank circuit topologies available in the literature which can be utilized for achieving soft switching to operate at higher switching frequencies for increasing the power density of DAB-IBDCs. The resonant tank circuits of these topologies offer different resonant impedances and accordingly different output voltages as per the requirement of voltage gain and power at the output.

Li Wang et al (2015) presented an isolated bidirectional dc-dc converter for medium voltage application by combining LLC resonant converter with a DAB converter. In normal conditions, it operates as an LLC resonant converter for achieving ZVS turn-on at the primary side and ZCS turn-off at the secondary side. However, during over current conditions, the converter will automatically switch over to resonant and DAB mixed mode operation where the switching can be accomplished by measuring output voltage to realize the duty cycle modulation for limiting the output current below the chosen value. Thus, the cycle-by-cycle current limitation is guaranteed when over current occurs or during the start up process. It operates at fixed resonant frequency. Thus, it not only maintains the high efficiency characteristic of LLC resonant converter but also enhances its reliability by solving the over current protection issue [12].

The soft switching requirement of resonant converter topologies is necessary for operating them at higher frequencies. This soft switching requires a control strategy which includes different modulation techniques for controlling the power throughput and the voltage gain.

IV. Soft Switching Techniques

Several research papers had proposed different circuitry arrangements for modifying the current and voltage waveforms of the switches during their commutation period which helps to eliminate or at least mitigate the hard switching and their ill effects by increasing their soft switching range over wide operating conditions. These developed circuitry arrangements force to zero either the voltage across the switch when they are turned on or the current through the switch when they are turned off. Such a way of commutating the switch is collectively known as soft switching and accordingly termed as ZVS and ZCS depending on the electrical quantity which is kept at zero during the transition time. The different soft switching solutions in different applications appearing in the literature tried its best to improve the range of soft switching operation.

A. Soft switching solutions in Distributed Generation

In distributed generation systems, the available input voltage from the renewable energy resources may be varying depending upon the environmental conditions. Similarly, the load may also be varying depending upon the load conditions or state of charge of storage batteries. A conventional DAB converter has limited range of operation over which ZVS can be attained as at lower load conditions, the ZVS of left-leg switches is lost because the energy stored in the leakage inductance of the transformer is insufficient to discharge the switch and transformer capacitances. There are some soft switching solutions which enhance the soft switching range for achieving higher efficiency over wide operation range.

M. Kasper et al (2016) discussed ZVS conditions of power MOSFETs by determining that whether a ZVS condition is achieved for a given operating point or not by considering the stored charge within the MOSFETs. This paper concludes that in the analysis of complete ZVS switching, the conditions derived depends on the charge-equivalent capacitance and not on the energy equivalent capacitance. This paper first analytically derived the conditions and then experimentally verified the non-zero losses in incomplete soft-switching. It addressed the issues of non ideal soft-switching behaviour of Si super junction MOSFETs. The ZVS range can be extended intentionally by increasing the transformer leakage inductance and/or with an additional series inductance but this is possible at the cost of loss of effective duty cycle, reduction in transformer turns ratio and higher switch current as well as conduction losses [13].

Yao-Ching Hsieh et al (2015) presented a soft-switched isolated bidirectional full-bridge DC-DC converter where the leakage inductance can achieve ZCS in current-fed step-up mode and ZVS in voltage-fed step-down mode. In step-up mode, the secondary side active switches are suitably controlled for providing zero-current transition conditions to the primary side switches. While in step-down mode, an additional capacitor-diode combination is used for reducing the voltage stress during transition period. In step-up mode, the efficiency achieved is 95% while in step-down mode; the conversion efficiency reaches to 94%. All the conversion efficiencies are higher than 91% even at light load conditions [14]. A comparison of different soft-switching topologies in the literature is shown in Table 1.

M. Borage et al (2005) proposed an auxiliary circuit which is an add-on to the conventional full-bridge ZVS (FBZVS) PWM converter without any alteration in the main power circuit. The topology achieved ZVS over entire conversion range by using a passive and simple auxiliary circuit in full-bridge PWM converter by using phase shift control. The stored energy in the auxiliary circuit is minimal under full-load condition which increases progressively as the load current decreases and thus having minimum conduction loss penalty. The results show that the efficiency improves at light load conditions as it mainly depends on the switching loss. In some techniques, the range of ZVS operation is extended at the expense of increased conduction loss [15].

M. Pahlevani et al (2016) proposed a series-parallel current-driven (SPCD) full-bridge DC-DC converter which processes and deliver the power efficiently over wide range of load conditions without using any type of auxiliary circuit. So, it eliminates the need of extra auxiliary circuit which provides the reactive current for achieving soft-switching in light load conditions. It will fully eliminate the voltage spikes across the output diodes by providing smooth and lossless commutations in the output diodes. This is an efficient and reliable solution for variety of applications having features like high switching frequency, high output voltage and high power density. Moreover, it has the ability to integrate all the magnetic components into an integrated transformer for achieving higher power density which can be thoroughly analyzed by using ANSYS HF structure simulator [16].

X. Li et al (2010) presented a fixed frequency DBSRC where the switching frequency is set higher than the resonant tank frequency while the converter is working only in CCM mode. All switches may achieve either ZVS or ZCS for wide variation in voltage gain and during all load conditions. Out of different design objectives like achieving soft-switching in all switches, lower resonant current and small tank size for a converter for varying input/output voltage, the realization of soft switching is put on the priority which mainly depends on the converter gain. In comparison to the traditional DAB-IBDC, this can be operated at higher switching frequency and thus having higher efficiency. It has additional resonant component in comparison to a conventional DAB which bring extra size and cost. This LC type resonant DAB-IBDC shares some similarities with the traditional series resonant unidirectional full-bridge dc-dc converter but still have some unique features due to its secondary-side bridge which have the capability of bidirectional power flow. This DBSRC has low possibility of transformer saturation because of having series capacitor which can be split into two parts and placed on both sides of the transformer. The transformer magnetizing inductance is assumed to be infinity while its leakage inductance is considered as part of the resonant inductance [17].

W. Chen et al (2010) presented a CLLC-type resonant tank network which has features of ZVS in input inverting choppers and ZCS in output rectifier switches which is regardless of the direction of power flow. This converter will have minimum switching loss if all the main switches are MOSFETs. It is fully soft-switched and totally snubberless. This DC-DC converter has wide input voltage range that can be fully exploited in energy storage devices. The power flow in both directions is modulated by variable frequency modulation (FM) scheme whose value is above the resonant frequency. This is an asymmetric resonant topology of DAB-IBDC which has different operation states during forward and backward power conversion modes. It is because of the transformer's asymmetric turn numbers and asymmetric structures of the resonant tank networks. The highest efficiency achieved in this exceeds 96% [18].

J.H. Jung et al (2013) presented a symmetric LLC-type resonant tank network for low voltage DC distribution systems. It presented its operating principle, gain characteristic and design methodology which have ZVS capability for primary side power switches and soft-commutation capability for output rectifier diodes. It also analyzed the design of resonant tank network of the converter where power flow directions change softly. The small magnetising inductance guarantees ZVS operation in the primary side switches but this small magnetising inductance will also increase the conduction loss in the MOSFETs, transformer windings and in the output rectifiers. So, bigger the value of this magnetising inductance smaller will be the conduction loss which improves the power conversion efficiency of the converter. But at the same time, the large magnetising inductance reduces the gain which is below the unity. In this, the transmitted power and output voltage are modulated under variable frequency modulation scheme. There is no requirement of snubber circuit for reducing the voltage stress in the switching devices because the switch voltage of the primary and secondary powering stages is confined to the input and output voltages respectively. The power conversion efficiency is same in each direction and the maximum efficiency achieved is 97.8% [19].

In addition to voltage-fed converters, current-fed DAB-IBDC can also be considered for soft-switching solution. S. Jalbrzykowski et al (2011) proposed a DAB-IBDC which is composed of two current-sourced class-E resonant converters. Being the two converters employed in the system as current sourced, therefore the parasitic inductances of the connection is of no importance here. The bidirectional power flow is controlled by changing the transistor control pulse frequency with a constant break between the succeeding pulses as in quasi-resonant converters. Therefore, in both boost and buck mode converter operations, bidirectional power flow depends on mutual relation between the control pulses of the transistor pairs located diagonally in the converter bridges. Its advantage includes high frequency operation (200 - 450 KHz) and zero value of transistor switching loss [20].

TABLE 1. COMPARISION OF DIFFERENT SOFT-SWITCHING TECHNIQUES

Topology	Application	Efficiency	Soft Switching Type	Soft switching Range	Features
Passive auxiliary circuit [13]	For full-bridge pulse-width modulated (FBPWM).	-	-	ZVS over entire conversion range.	Minimum conduction loss under full-load conditions.
Series-Parallel Current-Driven [18]	For high output voltages with wide range of load variations.	-	Soft switching for input power semiconductors and smooth commutation for output diodes.	Soft-switching for wide-range of operating conditions.	No need for extra auxiliary circuits to provide reactive current for soft-switching at light loads.
Dual-bridge series resonant dc/dc converter [4]	-	-	All switches may work in either ZVS or ZCS.	-	For all load and input/output voltage conditions.
CLLC Resonant tank [5]	-	Highest efficiency 96%.	ZVS for input inverting choppers and ZCS for	-	Fully soft-switched and totally snubberless.

		.	output rectifier switches.		
Resonant Class-E converters [9]	For high operation frequency 200-450 KHz.	-	-	Zero value of transistor switching losses.	Bidirectional power flow controlled by transistor control pulse frequency changes.
Symmetric LLC-type resonant converter [6]	For low-voltage DC power distribution system.	Maximum efficiency is 97.8% at 0.8 FL.	ZVS for primary power switches and soft commutation capability for output rectifiers.	-	No requirement of clamp circuits and snubbercircuits .
A tuned LCL network [8]	-	Efficiency of 96% at FL.	-	Higher efficiency over a wide range of both input voltage and load.	Reduced Bridge currents in comparison to conventional DAB topology.
A tuned CLC Network [10]	-	Efficiency 95% at FL.	-	Lower both conduction & switching losses and improving the bridge power factors.	Reduced Bridge currents in comparison to conventional DAB topology.
Bidirectional-switch-based isolated resonant converter [21]	Voltage regulation capability of the converter through simple fixed-frequency PWM control.	Peak Efficiency of 98.3% and 98% at nominal input voltage.	ZVS and low-current switching of primary Side switches, ZCS of output diodes.	High efficiency over a wide input voltage range and highly efficient.	It has low circulating currents. It provides voltage regulation through basic fixed-frequency PWM control.
Current-fed push-pull dc-dc converter [22]	Full soft-switching operation at a fixed switching frequency.	Peak Efficiency is 96.3%	-	Full-soft-switching of all transistors in a wide range of input voltage and power.	It used an active voltage doubler rectifier controlled by the switching sequence synchronous to that of the input-side switches. No requirement of clamping circuit.
A topology of full-bridge dc-dc converter [16]	Output is adjustable over a wide range and load resistance is fixed and for high power applications.	-	ZVS operation and low at higher duty ratio	ZVS of active switches over the entire conversion range.	An adaptive auxiliary current.
Passive auxiliary circuit [13]	For full-bridge pulse-width modulated (FBPWM).	-	-	ZVS over entire conversion range.	Minimum conduction loss under full-load conditions.
Series-Parallel Current-Driven [18]	For high output voltages with wide range of load variations.	-	Soft switching for input power semiconductors and smooth commutation for output diodes.	Soft-switching for wide-range of operating conditions.	No need for extra auxiliary circuits to provide reactive current for soft-switching at light loads.

In soft switching solutions of tuned resonant tank networks operating at the resonant frequency of tank network, the control scheme is simple where each bridge is driven with equal PWM while maintaining the phase shift between two full-bridges to a fixed value of 90^0 or -90^0 for regulating the magnitude and direction of power flow respectively. This will help to minimize the converter reactive power as this tuned (resonant) network offers high impedance to the harmonics generated by the converters.

Control and ZVS range is almost independent of DC voltage ratio, component values and power levels. The small harmonic content in the transformer results in reduced losses. The transformer efficiency will improve as a consequence of current waveforms which are more sinusoidal and having smaller high frequency harmonic contents. Due to phase alignment between bridge's output voltage and resonant tank current, the full-bridge currents are smaller by a factor $\sqrt{2}$ times than those in a standard conventional DAB, where the angle between these two is 45^o [23]-[26].

R.P. Twiname et al (2014) presented a DAB converter for bidirectional high-power transfer by using a tuned LCL network to minimize the converter reactive power. It has a resonant DAB converter with ZVS operation of half of its switches at all times and the efficiency achieved is 96% at rated power. It achieves higher efficiency over wide range of input voltage and load conditions. It significantly improves the efficiency and having smaller currents in semiconductor switches and transformer which in turn results in significant reduction of copper and switching loss in the system. So, the rms and peak values of bridge currents are significantly smaller than those of a conventional DAB converter operating under similar conditions. Due to smaller rms currents in the converter, there are smaller heating losses and device stresses in comparison to a conventional DAB converter. The combined VA rating of the magnetic components is less than those in a comparable conventional DAB converter. It has the ability to transfer power bidirectional at high efficiency over wide range of power and supply voltages. The total VA rating of the inductors is approximately the same in each case but the transformer VA rating is approximately 30% smaller [23], [24].

R.P. Twiname et al (2015) presented a resonant DAB topology by using a tuned CLC network. It considers fundamental components of voltages and currents which are dominant in power calculation. It makes use of magnetizing as well as leakage inductances of the isolation transformer by using a loosely coupled transformer. In this, the bridge currents are approximately sinusoidal and in-phase with their respective voltages which indicate near zero reactive power transfer between two full-bridges. In comparison to conventional DAB, it reduces bridge currents which lower both the conduction loss as well as switching loss by improving the bridge power factors. Here, the magnitude and direction of power flow can be controlled through either relative phase angle or by using PWM of the voltages produced by two bridges. In this, equal PWM for each bridge is used for controlling the magnitude of power flow by fixing the phase shift between these two bridges to either 90^0 or -90^0 according to the direction of power flow. Thus, high efficiency over wide range of dc supply voltages and power throughput is observed with an efficiency of 95% at the rated output power [25].

W.L. Malan et al (2016) proposed a linear state-space model of phase-controlled resonant DAB which uses a tuned CLLC network along with coupled inductors with relatively low coupling factor which have high leakage inductance in both primary and secondary sides of the HF link. This resonant DAB converter is modulated with small switching frequency range as compared to series resonant DAB which is modulated by same FM scheme. In series resonant DAB, a wide switching frequency range is required for modulating the power transfer which complicates both the control and filter design requirement. By using this derived model and decoupled control scheme with three PI controllers, the resonant tank currents are controlled in this. Therefore, the magnitude of power transfer is controlled by controlling the angle between two full bridges for improving the soft switching range of the controller [26].

Lin R.L. et al (2010) presented the design criterion of resonant tank in LLC DC-DC resonant converter which has high efficiency within wide range of input voltage and also ensures the high power factor of LLC resonant tank circuit. The value of parallel resonant inductor is determined by considering load matching and also ensuring optimal efficiency. The inductance ratio of series to parallel resonant inductors is designed as per the voltage gain and input power factor of LLC resonant tank circuit. A required hold-up time of 20ms is considered in dc-bus capacitor of DC-DC converter for discharging its stored energy to the load within this hold-up time after the input voltage source blacks out. For having high efficiency within this wide dc-bus voltage range, the design criteria considers load matching, voltage gain and input power factor of the LLC resonant tank for optimal efficiency [27].

Zhe Zhang et al (2016) focussed the analysis and design of high frequency ac inductor which acts as a power interfacing component in DAB converter or DAB's derivative topologies for transforming energy between primary and secondary side. The design difficulty of ac inductor in DAB converter which operates under wide input voltage range, have been pointed out and analyzed. The DAB converter in an isolated bidirectional DC-DC converter topology is the most critical part of power conversion systems like SSTs. The operating principle and corresponding voltage/current stresses over ac inductor are analyzed for DAB converter. Here, six diverse winding arrangements are studied for the design purpose which has lowest ac resistance and core loss. The core loss is first calculated and then compared by using both GSE and IGSE methods. The input and output voltage mismatch is evaluated by calculating the core loss by using this IGSE approach. Based upon the finite element method (FEM) simulation, the winding losses are also investigated. Finally, the case where both core loss and winding loss are almost equal is selected as an optimal point. It is found that ac inductor with single-turn winding configuration achieves the lowest overall loss [28].

Roman Kosenko et al (2016) proposed a bidirectional current-fed push-pull DC-DC converter topology which has active voltage doubler rectifier controlled by the switching sequence that is synchronized to the input-side switches. This control algorithm provides soft-switching in all the transistors at fixed switching frequency operation over wide range of input voltage and power without any requirement of snubbers or resonant switching. This converter has considerably high step-up voltage ratio in comparison to the traditional current-fed converters. This is due to the utilization of circulating energy in stepping-up mode of input voltage [29].

M. Borage et al (2008) proposed a topology for full-bridge DC-DC converter having features of ZVS in the active switches over entire conversion range. This is possible without any significant increase in full load conduction loss in applications requiring adjustable output over wide range along with fixed load resistance. In this, the stored energy in the auxiliary inductor is minimal under full-load condition which increases progressively as the load current decreases. So, the auxiliary current is adaptive which have high value at lower duty ratio for assisting the ZVS operation. Its value is low at higher duty ratio and thus minimizing the additional conduction loss. It finds application in high-power rating full-bridges where ZVS operation is desired but without any penalty of additional losses at full-load. It not only reduces the switching loss but also assist the reliable operation by eliminating the current and voltage stresses in the devices as well as EMI which generally results from non-ZVS operation [30].

There are certain topologies in literature which are developed for certain specific applications. L. Costa et al (2017) from Germany proposed a fault-tolerant series-resonant DC-DC Converter (FT-SRC) topology. The SRC has wide applications in power supply telecommunication, wireless power transfer systems in electrical vehicles and HV power supplies. It also finds its application in solid-state transformers (SSTs) where fault tolerance is the highly desired feature which can be obtained through redundancy. This letter proposed a reconfiguration scheme for SRC in the case when there is failure of one semiconductor and thus reducing the need of redundancy. By using this proposed scheme, the full-bridge based SRC can be reconfigured to half-bridge topology and thus keeps the converter operational even during the failure. The failure may be open circuit (OC) or short circuit (SC) of one switch. The reasons which imply this OC fault are bond-wire lift off or rupture and failure in the gate drive circuit. Similarly, the reasons which imply SC fault includes result of an overvoltage, static or dynamic latch up, second breakdown or energy shock. The drawback of this technique is that the output voltage drops to half of its original value. In this novel reconfigurable rectifier which is based on voltage-doubler topology is a solution for keeping output voltage constant even after the fault has been occurred. The main advantages of the proposed converter include post fault operation, simpler implementation, reduced number of additional components and no efficiency deterioration. However, the resonant capacitor must be designed for higher ratings as during failure modes of operation, the values are twice than in normal mode operation. This solution is in comparison to other methods of FT-SRC which requires significant amount of extra hardware (such as semiconductors/leg redundancy or series connection of fuses/switches to isolate the fault). It increases the cost and also compromises with the efficiency of system. In the proposed fault-tolerant solution, it has minimum additional hardware and having no impact on the efficiency of SRC converter along with the advantage of inherent fault-tolerant capability of the topology [31].

M. Borage et al (2007) proposed an LCL-T resonant converter which has the characteristic of constant-current (CC) source when operated at resonant frequency. It requires additional constant-voltage (CV) limit for introducing its use in open-load conditions of converter which is commonly experienced in CC power supplies. So, this LCL-T resonant converter has built in CC-CV characteristics having CV limit by using two diodes which clamps the primary voltage of isolation transformer to input dc supply voltage and thus removing the requirement of complex feedback controls [32].

W.L. Malan et al (2016) presented that a LCL resonant converter (RC) which has inherent constant current characteristics when it is operated at tuned resonant frequency of the circuit. This makes the LCL-RC topology useful for capacitor and battery charging applications [33].

M. Borage et al (2005) presented an LCL-T resonant converter (RC) which behaves like a current source when operated at resonant frequency. It has advantages like easy parallel operation and low circulating currents at light load conditions. Also with appropriate phase-shifts in the paralleled modules, the peak-peak ripple in output current is reduced. Moreover, the increase in ripple frequency reduces the filter requirement. These are suitable in capacitor charging of power supplies [34].

M. Borage et al (2006) presented a high frequency half-bridge LCL-T resonant converter topology which has constant-current and constant-voltage for capacitor charging power supply (CCPS) applications. A CCPS has charging mode, refresh mode and discharging cycle. So it requires an elaborate and intricate feedback control and timing circuit. The requirement of sensing the output current/voltage and the feedback control circuit is eliminated in this. The changeover from CC to CV mode or vice-versa is automatic and smooth. This converter have an inherent CC characteristic while the characteristic of CV limit is achieved by using two diodes for clamping the primary voltage of the isolation transformer to input DC supply voltage. So, this converter has in-built CC-CV characteristics. The converter operates in CC mode while the energy-storage capacitor is being charged and operates in CV mode when the voltage across the capacitor is changing [35].

Yogesh Jaiswal et al (2015) presented a fourth order Resonant Immittance Converter (RIC) topology as RIC is a new family of RCs which can convert a voltage source into a current source and thus making them suitable for constant current (CC) power supply applications. The analysis and design of this fourth order RIC topology is used in CC power supply applications. It also elaborated the procedure of performing the converter optimization that leads to closed-form expressions for calculating the component values and ratings. This converter behaves as a CC power supply while maintaining high efficiency under part-load conditions. This can be considered as an alternative topology for application requiring a CC power supply [36].

S. Bansal et al (2012) presented the design of an isolated DC-DC converter topology for photovoltaic solar systems, which regulates the constant output voltage under various operating conditions of the photovoltaic cell. The role of DC-DC converter is to match the load with PV source by continuously adjusting the voltage and current levels by moving the operating point. It is phase-shifted full-bridge converter where the phase-shifting control algorithm is performed by using PI controller. This PI controlled isolated full-bridge DC-DC converter for photovoltaic (PV) system can be used as a standalone power source in remote areas [37].

There are certain topologies which overcome the drawbacks of conventional DC-DC converters like EMI, which is the basic characteristic of any switching circuit. The features of resonant converter include low EMI, low dv/dt and less ringing currents due to smooth switching transitions. The common mode (CM) conducted EMI and the parasitic capacitance of the circuit component are associated with high dv/dt. As the switching frequency of circuit increases, the noise spectrum extends further on higher side which subsequently becomes difficult to filter. So, with the advent of resonant and soft-switching converters, the rate of rise of voltage (dv/dt) is reduced and the HF oscillations or ringing are minimized. These reduced CM-EMI generations lower the switching loss.

M. Borage et al (2003) presented a common-mode noise source and its passive cancellation in full-bridge resonant converter. This is possible with the systematic investigation and identification of the dominant source in CM noise generation in case of full bridge resonant converter. Basically, it is small mismatch in the apparently symmetrical circuit which results in large CM injection. It mathematically analyzed the predicted dominant CM current injection and its cancellation by simple passive technique. The mismatch of the parasitic capacitances is identified to be the primary cause for this EMI [38]. As for EMI compliance, a common-mode filter is generally used to suppress the CM injection and also the leakage current into the ground plane which is limited to small values for safety reasons. So, the filter capacitor is normally limited to lower values of the order of thousands of picofarads which require a large CM choke for obtaining requisite attenuation when the windings of CM choke carry full load current and hence becomes bulky.

There are certain topologies of DAB-IBDC DC-DC converters for solid state transformer applications. H. Qin et al (2009) presented an AC-AC DAB converter for solid state transformer while investigating its application in solid state transformer which is controlled by phase-shift modulation. For obtaining the bidirectional ac power flow, the MOSFETs are replaced by four-quadrant switching cells in conventional DAB DC-DC converter. Out of different topologies in SST, one is multi-stage AC-DC-AC-DC-AC SST having maximum controlling flexibility but with complex circuit configuration. It has large passive components and hence requiring a trade-off for reducing the number. The other topology is single-stage direct AC-AC power conversion SST which has fewer conversion stages with minimum passive components. It reduced the conduction loss with increased reliability. It described the operating modes in both power flow directions and also analyzed its zero-voltage switching criteria. One design example is given with its simulation results for the verification purpose [39].

L. Li et al (2008) compared two kinds of AC/AC converters which have high frequency link. These are voltage mode based forward converter and current mode based flyback converter. A comparison is done between the configurations, topologies, control strategies, principle characteristics, design criteria of key circuit parameters and principle prototypes of the two kinds of converters. In comparison to voltage mode converters, the current mode converters have different characteristics like more concise circuit topologies, wide range of input voltage, higher quality of output waveforms, higher reliability, lower cost, lower conversion efficiency and thus more suitable for small power conversion fields. This provides the technical foundation for new types of electronic transformers which are regulated by sinusoidal AC power supplies and AC regulators [40].

H. Fan et al (2011) presented the design of HF IBDC modules which are connected in input-series-output-parallel (ISOP). It provides higher efficiency over wide load range. This modular structure enables the use of LV MOSFETs having low on-state resistance which results in low conduction loss in medium input voltage applications. It also employed phase-shift DHB converter for achieving HF galvanically isolated bidirectional power flow along with ZVS in all switching devices. It leads to low switching loss even at HF operation. It also proposed adaptive inductor as an energy transfer element in phase-shift DHB converter for optimizing the circulating energy to maintain ZVS under light load conditions. It minimizes the conduction loss during heavy loads resulting in high efficiency over wide load range and higher power density. The current stress of the switching devices can also be reduced in this [41].

S. Inoue et al (2007) addressed a bidirectional DC-DC converter which is suitable for energy storage systems like electric double layer capacitor (EDLCs) or Lithium Ion batteries. This DC-DC converter charges the capacitor bank from zero to its rated value without any external precharging circuit. The power loss depends not only on the power transfer but also on the DC output voltage. Thus, when the output voltage drops along with the discharge in energy storage device, the power loss increases for given power transfer. This DC-DC converter continues its operation in discharge mode when the voltage across the energy storage device drops although power loss and peak current impose limitations on the permissible DC-voltage range [42].

B. Soft switching solutions in EVs

In inductive WPT applications, two coils namely transmitter coil and receiver coil are placed at some distance which are weakly coupled to each other. In this, when one capacitor is added on each side of transmitter coil (TC) and receiver coil (RC), four basic types of compensation networks or topologies are obtained named as S/S, S/P, P/S and P/P. Here, 'S' and 'P' represents series and parallel connections respectively. Out of all these, S/S and S/P are very common in use. The S/S topology provides higher efficiency than S/P topology over wide range of load resistance. Moreover, parallel-compensated network has large reactive current in pickup coil which is reflected back to the primary side. The S/S compensation is generally the preferred choice in battery charging applications. The selection of inverter type depends on the type of TC tank network. When the TC side tank network is series type (S/S, S/P), the inverter used is VSI whereas the inverter is CSI when TC side tank network is of parallel type (P/S, P/P). The P/S and P/P compensation networks are realized with CSI in the inversion stage. The DC link inductor in CSI is an extra bulky component and so the work on P/S and P/P compensation networks were quite limited to low powers only. But in applications, where stiff current is readily available, these compensation topologies are comparatively more suitable than S/S and S/P topologies. The DC input to the current source inverter is required to be stiff that can be acquired from the output of solar cell. It eliminates the need of extra inductor which is required in current-fed topology. Otherwise a DC link inductor is required for CSI source because the previous power factor correction (PFC) output stage provides a stiff voltage source. In high power applications, the CSI switch voltage rating is high because high amplitude of current passes through parallel capacitors in P/S and P/P tank networks.

S. Samanta et al (2015) presented an inductive WPT solution in EV battery charging. It consists of current-fed (C) (LC) (LC) topology using current fed converters. The resonance in transmitter coil side is C-C-L type while in the receiver side; it is series L-C type. The required high transmitter coil current circulates through the parallel resonating capacitor which leads to higher inverter output voltage. The reactive power delivered by the capacitor is proportional to the square of its voltage and this issue is resolved by adding a capacitor in series with the TC circuit. This capacitor in series with the transmitter coil also reduces the voltage rating of inverter switches. Moreover, in this current fed topology, the inductor placed in the dc-link also provides the necessary short-circuit protection during inverter fault. It provides stiff current at the input that limits the inverter switch current stress to peak DC inductor current. The resonant converter provides soft-switching during device turn-off and reduces the switching losses along with soft recovery of bridge rectifier by eliminating the diode reverse recovery loss. It reduces inverter switch stress to half the value as in case of conventional (L) (C) parallel resonant tank network [43] & [44].

S. Samanta et al (2016) presented an inductive WPT topology by using current-fed half bridge CLC type transmitter and LC type receiver configuration. This is in comparison to conventional IPT circuit topology employing parallel L-C resonant tank/compensation network in transmitter coil side for transferring power effectively through the air-gap. The voltage stress across inverter switches is considerably high due to high reactive power consumption by the loosely coupled coils. During G2V operation, the power flow is controlled by variable switching frequency modulation to achieve extended ZVS in inverter switches. Here, TC side converter is current-fed half bridge topology and RC side converter is voltage doubler topology. The impedance of TC is high due to high leakage inductance and it needs to be reduced significantly by adding a series capacitor. So, the parallel capacitor needs to supply only a fraction of total reactive power demand by keeping all the merits of current fed converter like low current stress at inverter switches and low harmonic content in coil currents. Similarly in RC side, a capacitor is connected in series with RC for compensating the reactive power absorbed in the coil to compensate the effect of high leakage inductance of the receiver coil. Finally, the power in receiver network is rectified through the voltage doubler circuit and then supplied to the load. The operating power factor of the output half bridge current fed inverter is considered to be lagging to achieve ZVS at device turn-on. However, soft switching at device turn-off is also possible if this power factor becomes leading [45].

S. Samanta et al (2016) presented a comparison and performance evaluation of L-C and C-C-L type compensation schemes in CSI based inductive WPT applications. There are many IPT topologies which are based on power electronics, reactive power compensation network and wireless pad. The performance of C-C-L type compensated network is comparatively better in terms of inverter switch voltage stress, overall cost and efficiency with the expense of one extra capacitor. In C-C-L type network, the overall converter gain can be adjusted by selecting appropriate capacitors, whereas this facility is not available in parallel L-C type network. In C-C-L type tank network, the overall converter gain can be adjusted by selecting appropriate value of series capacitor. Thus, the parallel L-C type tank is the preferred choice in low output to input voltage gain applications. In medium power applications with relatively higher output to input voltage gain, the C-C-L type resonant tank network based IWPT topology will be the preferred choice. The transmitter and receiver coil voltage and current magnitudes are same for given output power. When a suitably designed capacitor is added in series with TC, it improves the performance significantly. Because both the inverter switch voltage and inverter output volt-amp are reduced approximately to half by using this C-C-L type resonant tank network [46].

S. Samanta et al (2016) presented the concept study and feasibility analysis of current-fed power electronics in medium power WPT systems. The possible IPT systems with CSI topology includes current-fed push-pull, half-bridge and full-bridge converters. The possible compensation or resonant tank networks for transmitter side are parallel LC or CCL types with series LC type receiver side tank network to keep minimum number of components on board [47].

S. Samanta et al (2016) presented a WPT technology by using full-bridge current-fed topology in medium power applications like EV's battery charging. In such applications, both inverter switch current stress and short-circuit protection during inverter fault are very important which can be achieved by using stiff DC current at the input of the inverter. The resonance circuit in TC side is parallel LC type and in RC, it is series LC type. These resonant converters facilitate soft-switching during turn-off of the transmitter switches and soft-commutation of rectifier diodes by reducing reverse recovery loss. The maximum efficiency of DC-DC WPT stage is close to 90% having coefficient of coupling of the order of 18%. This is suitable in applications like solar-to-vehicle, opportunistic charging and slow single-phase residential charging. The extra DC inductor can be removed in applications where stiff DC current is readily available like solar output [48].

S. Samanta et al (2016) presented the performance comparison between current-fed full-bridge and half-bridge topologies having CCL type transmitter and LC type receiver tank configuration in wireless IPT applications. The full-bridge topology provides slightly better efficiency in comparison to half-bridge topology while the overall component cost in full-bridge topology is higher due to higher component count [49].

S. Samanta et al (2016) presented a bidirectional WPT topology which uses current-fed half-bridge CLC type transmitter and LC type receiver configuration in medium power applications. During both grid to vehicle and vehicle to grid operations, the power flow is controlled by variable switching frequency operation to achieve extended ZVS range of inverter switches. In this, the soft switching at turn-on of inverter switches is always ensured irrespective of the load change by keeping inverter output power factor in lagging condition [50].

S. Samanta et al (2017) proposed a ZVS IPT topology in EV's battery charging application by powering the transmitter side resonant tank network through a current-fed half-bridge inverter to achieve both ZVS turn-on and turn-off in all inverter switches. The receiver side converter used is of voltage doubler topology to achieve high voltage gain with reduced number of component count on board. The transmitter side tank network is (C) (LC) type whereas the receiver side tank network is chosen as series LC type to keep least number of component counts in EVs. The power is controlled by varying switching frequency while keeping the duty cycle of inverter switches constant to 50%. The inverter switching frequency is selected in such a way that the inverter output power factor is kept at unity, by which all the switches experience ZVS during both turn-on and turn-off time. Also, the unity power factor at the receiver side rectifier ensures zero reverse recovery loss [51].

C. Soft switching solutions in IMDs

Modern implantable neuro-stimulation devices can significantly improve the quality of life for patients by partially restoring the lost sensory and motor functions by running reliably and efficiently over long periods of time, often decades. In this, power needs to be supplied inductively by using near-field resonant coupling. To power implantable electronic systems is a critical challenge in the area of IMDs especially for life-saving medical devices like cardiac or neural bio-implants. For providing energy to power IMDs, it usually requires batteries, supercapacitors and other energy harvestings solutions with transcutaneous energy transmission (TET). Among different TET technologies like radio frequency (RF) transmission and electromagnetic induction, the ultrasonic TET (UTET) is the most promising one. The ultrasonic waves traversing in biological tissues result in phenomenon such as cavitations, mechanical stimulation and temperature rise. So, depending on the power of wave and its duration of exposure, different health hazards may arise. For these, the FDA regulates the acoustic wave power emission and defines the safety limits in ultrasound transmissions for medical applications.

E. Gamez et al (2014) presented improved efficiency in WPT for implantable biomedical devices having ferrite based negative permeability metamaterial design. The metamaterial is used for enhancing the coupling in near-field inductive wireless power transfer systems. These are designed for exhibiting the desired electromagnetic response in certain operating frequency range. The properties of metamaterial are not present in nature like negative refractive index. Left handed metamaterial has simultaneous negative permittivity and permeability which can be used to focus and enhance the evanescent waves [52].

Raffaele Guida et al (2016) presented a 700 kHz ultrasonic link in transferring power from external acoustic transmitter to in-body deeply implanted medical devices wirelessly. This ultrasonic wave is the promising technology which has some benefits in comparison of radio frequency like safe and efficient charging. It discussed the design of wireless energy transfer link in deeply implanted IMDs, where the receiver is able to harvest energy from an ultrasonic transmitter to charge its supercapacitor [53].

Veeraiyah Thangasaamy et al (2015) presented WPT for on-chip inductor in class-E power amplifier for IMD applications. The popular use of biomedical implants is in pacemakers and emerging retina prostheses, together with brain-computer interfaces. Other popular uses include drug delivery and smart orthopaedic implants. The avoidance of batteries or piercing of wirings has made the wireless powering in these implantable devices a highly attractive solution [54].

Y. Yan et al (2021) presented the complete ZVS analysis in DAB-IBDC. It quantifies the minimal initial inductor energy to complete the ZVS transient process for enhancing the efficiency of DAB-IBDC [55]. Similarly, S. Shao et al (2019) presented a review on the causes of circulating current and loss of ZVS in a DAB-IBDC [56]. B.Liu et al (2021) presented ZVS range calculation for a DAB-IBDC which is based on nonlinear characteristic of the output capacitance of the power device i.e. C_{OSS}-V_{DS} profile [57].

There are different solutions which are available in the literature that improve the soft switching range for getting higher efficiency over entire operation range. Moreover, there are different variants of DAB-IBDCs like three-phase DAB-IBDCs and multiport converters which are available in literature and are required to be studied.

VI. CONCLUSION

The DAB-IBDCs in high frequency power conversion systems serving as their core circuits has 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 solutions are the research topics. These are discussed here along with their different soft switching techniques. These high frequency operated DAB-IBDCs with new advancements help in applications which require highly efficient soft switching solutions 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.

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