A Review on Control Strategies 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 the control strategies for DAB-IBDCs. It deals with different modulation techniques 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 control strategies as modulation 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, single-phase-shift modulation, extended-phase-shift modulation, double-phase-shift modulation, triple-phase-shift modulation, 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 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.

Fie Xue et al (2016) focused on the use of GaN devices in building a highly efficient DAB-IBDC 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].

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. 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 [7].

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% [8]. 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.

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, electromagnetic materials as well as nano-electronic technologies, there is a lot of work in the field of DAB-IBDCs with respect to the improvement in overall power conversion efficiency. There are various control strategies of DAB-IBDCs in the literature which require a review on their control solutions for 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 control strategies are discussed in section III. The single-phase-shift (SPS) modulation technique is discussed in section IV while the extended-phase-shift (EPS) modulation technique is discussed in section V. The dual-phase-shift (DPS) modulation technique is discussed in section VI. The triple-phase-shift (TPS) modulation technique is discussed in section VII. The conclusion is given in section VIII.

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.

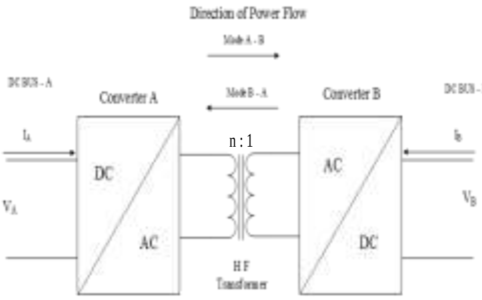

Fig.1 Basic Structure of DAB-IBDC

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 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 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 high frequency 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 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

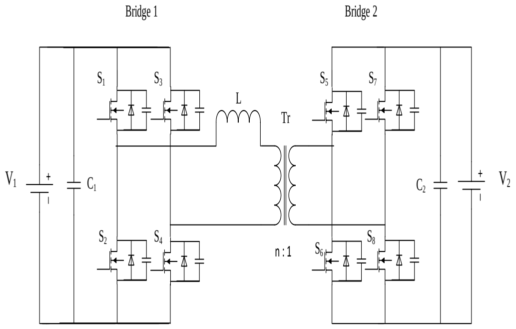

Fig.2 Conventional DAB dc-dc converter

The 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. Similarly, the DAB-IBDCs 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. N. Hou et al (2020) presented an overview and comparison of modulation and control strategies for non-resonant single-phase DAB-IBDC [11].

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 [12]. 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.

III. Control Strategies

The control strategy is the research topic for regulating the output of DAB-IBDCs. It includes different modulation techniques in resonant converters like switching frequency modulation (FM), resonant frequency (RF) modulation, pulse-width modulation (PWM) and phase-shift (PS) modulation. In PWM converters, the output is regulated by modulating the pulse width of gating signals of the power semiconductor switching devices. At low pulse width or low duty cycle the peak values of voltage and current in the circuit increases which results in increased stresses on the switching semiconductor devices. In other modulation techniques for regulating the output of resonant converters, the pulse width or the duty cycle is kept constant and high which includes switching frequency modulation and phase-shift modulation. This phase shift may be either between the two bridges itself and/or between the two legs of any one or both bridges of the DAB-IBDCs.

M. M. Jovanovic et al (1992) classified resonant and soft-switching PWM techniques based on their operating principle and origin. And the general properties of most of the prominent families are summarized along with their merits and limitations with an objective to define the most suitable for given area of application [13]. Using FM modulation technique, the output voltage becomes the function of the reactance of resonant tank. Thus, the output voltage can be controlled by controlling this reactance i.e. by controlling the switching/operating frequency. This variation in frequency has a large range of operation for modulating the output voltage. When the range of frequency is notably high, the size of reactive components primarily depends on the lowest frequency chosen. Ganj Liu et al (2016) reduced this operating range of switching frequency which is required for modulating the output voltage in isolated bidirectional series-resonant DC-DC converter. It is controlled by using a combination of variable switching frequency control and delay-time control of secondary-side rectifier switches which are replaced by diode rectifiers. This delay-time control is implemented in the modulation of secondary-side switches which assists the conventional variable switching frequency control in the primary switches. In this, a sufficient reduction in switching frequency range is observed [14].

Z. Pavlovic et al (2012) proposed a modulation technique for high power isolated DC-DC converters which have two stages of non-isolated as well as isolated topologies. The first stage is DAB series resonant converter (SRC) with pulse modulation technique and the second one is boost converter which regulates the terminal voltage of DAB SRC. It requires frequency variation for controlling the delivered power. Another control variable is the intermediate bus voltage and by changing this bus voltage, the control frequency band can be narrowed down. Its main feature is the elimination of switching loss in active devices so as to allow them to operate at higher switching frequency of the order of 500 kHz in the DAB SRC. The resonant inductor is entirely composed of transformer leakage inductance. In other words, the second non-isolated stage is required for regulating the intermediate bus voltage while the proposed DAB SRC provides the necessary electrical isolation [15].

In phase shift (PS) modulation, there is a phase-shift either between two full-bridge converters itself or between the two legs of one full-bridge converter or both. B. Hua et al (2008) from USA discussed the short-time-scale transient process in case of HV and high power IBDCs having phase-shift control. It includes dead-band effect and phase-shift error, which are two important factors that affect the operation and control of HV and high power converters. The Dead-band effect affects the steady-state as well as transient commutating processes. It has been found that Dead-band effect is more significant in high-power and HV based DAB-IBDC converters than in conventional low-voltage and low-power converters. The relationship between power and phase-shift angle affected by the effects of dead-band and phase-shift error can be reduced by selecting proper value of inductance. It had given the concept of energy dead-band by describing the conditions, where no energy flows from source to load or load to source as it only flows from the leakage inductance to load [16]. Several modulation methods have been proposed for reducing the conduction and switching losses in DAB-IBDCs like internal phase-shift with in primary or secondary side full-bridges of DAB-IBDC for controlling power and also extending the ZVS operation region. The ZCS or unity power factor is required at the secondary side of DAB-IBDC because the ZVS increases conduction loss, especially at low output voltage. Some representative parts of these phase-shift control methods include single phase-shift (SPS) control, extended phase-shift (EPS) control, dual phase-shift (DPS) control and triple phase-shift (TPS) control. For improved topologies and the variants of DAB-IBDC, the control methods may be different but all are derived from these methods.

IV. SPS Modulation Technique

The SPS control is the most widely used control method in DAB-IBDC where the cross-connected switch pairs of both the full bridges are switched in turn to generate the phase-shifted square waves with 50% duty ratio on the transformer's primary and secondary sides. By adjusting this phase shift angle (Φ) between two square wave voltages, the voltage across the transformer's leakage inductance will change. The gate pulses to the gate signals of different switching devices are as shown in Fig. 3.

The power flow direction and magnitude can be controlled by changing the phase shift (Φ) angle between two square wave voltages. It had some advantages like small inertia, highly dynamic and ease in realizing soft-switching control. Here, the control of power flow depends on transformer's leakage inductance which results in circulating power when the voltage amplitude on the two sides of the transformer does not match. It results in increase of rms and peak currents values. Moreover, the converter cannot operate with ZVS condition in whole power transfer range in addition to higher power losses [1].

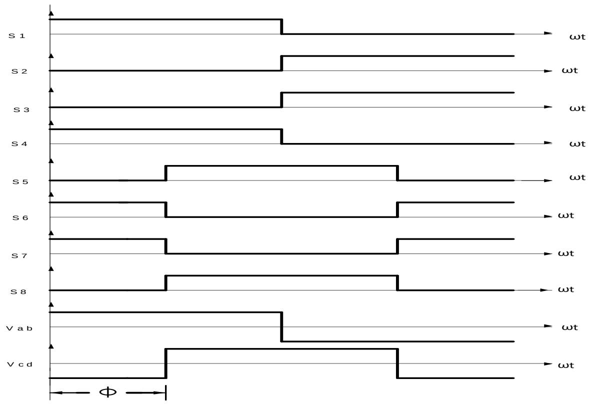

Fig. 3: SPS Modulation

M. M. Kheraluwala et al (1993) used SPS control for single-phase unity power factor control of DAB converter which addressed the design, control and performance issues of the proposed high power factor power supply. It is an AC line fed switching power supply with a single power converter stage having high input power factor while maintaining good regulation at the desired output dc voltage. This DAB converter receives a rectified ac line voltage through a diode-bridge rectifier which is connected to a small, HF filter capacitor. The two active bridges generate edge-resonant square waves which are approximately phase-shifted from each other. It simultaneously performs the high frequency dc output regulation while maintaining UPF at the ac input. So, this DAB converter shows high performance in terms of overall power factor, efficiency and its dynamic response under load and line disturbances [10].

A conventional DAB converter using single phase shift (SPS) control has large reactive power which stresses its switching elements and thus resulting in increase of power losses with reduction in efficiency. It draws a large reactive power component at low operating power levels, which increases the converter conduction losses. So, if DAB-IBDC is used for applications with wide input and output voltage variations, the ZVS for primary side converter may be hard to achieve.

T. Mishima et al (2011) proposed a power control scheme for ZVS-PWM in dc-dc converters having SPS with active rectifier. It achieves soft commutation in all power semiconductor devices under wide range of output power. This scheme is effective for medium and high output voltage applications, where output power control is based on small phase-shift angles. It results in reduction of idling power in primary-side inverter and a snubberless rectification in secondary-side rectifier with circulating current flowing in the secondary-side rectifier [17]. In primary side phase-shift (PPS) control scheme, there is severely limited soft-switching range for active switches in primary side leg of the FB inverter. The idling power loss due to the circulating current appears in inverter legs under the condition of large phase-shift angle or light load power ratings. Also, turn-off commutations of diodes in the secondary-side rectifier are performed by hard-switching mode, which trigger voltage surges and thus reducing the converter efficiency. Thus, by comparing ZVS-PWM dc-dc converter with a secondary side phase-shift (SPS) as a counterpart of ZVS-PWM dc-dc converter with PPS, a guideline for effective utilization of the PS schemes can be clarified.

V. EPS Modulation Technique

In EPS control, the cross-connected switch pairs of one full bridge converter are switched in turn while the switch pairs in other full-bridge converter are switched with an inner phase-shift ‘D’. The phase shift ratio between two square wave voltages is ′Φ′as shown in Fig. 4. It result in output ac voltages having one bridge output as a three-level wave while the other one is two-level, 50% square wave.

During the time intervals of zero voltage in three-level voltage wave, the backflow power becomes zero and thus the circulating power decreases. In comparison to SPS control, the EPS control not only improves the efficiency but also expands the ZVS range and thus reducing the current stress and enhancing the regulating flexibility. In comparison to SPS control, there is an inner phase shift ratio control in addition to the outer phase shift ratio control. The outer phase-shift ratio is used for controlling the power flow direction and magnitude while the inner phase-shift ratio is used for decreasing the circulating power and thus expanding the ZVS range. In case of EPS control, when voltage conversion states are changed from boost to buck or vice versa, the operating states of two bridges are required to be exchanged for achieving the proper operation [1]

G.G. Oggier et al (2011) proposed an EPS control for operating the DAB converter under soft-switching in entire operating range. It imposed a certain modulation index in one of the two bridges which is in addition to the phase-shift between transformer primary and secondary voltages. This reduces the reactive power drawn and lowers the converter conduction loss. It improves the overall efficiency of DAB converter which is up to 20% in comparison to the conventional SPS control. An algorithm for implementing this EPS control is also proposed in it [18].

Huiqing Wen et al (2016) proposed the power flow characteristics of DAB converter by analyzing its backflow power expression. This back flow power is minimized by adopting EPS control. It shows that EPS control provides better performance in terms of output power regulating capability, peak current and backflow power. This paper also shows experimentally that backflow power and peak current were reduced largely by using EPS control and thus improving the system efficiency [19].

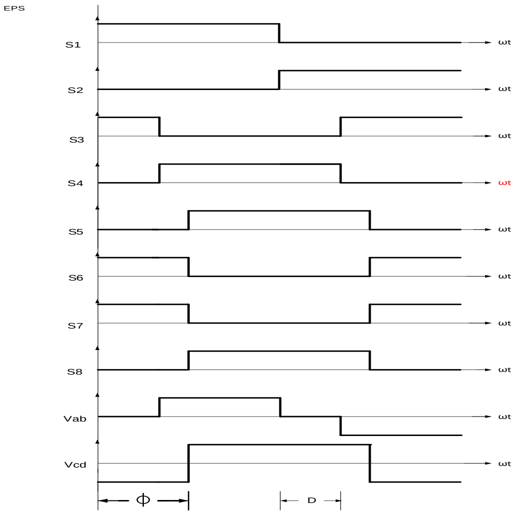

Fig.4: EPS Modulation

VI. DPS Modulation Technique

The DPS control is different from EPS control in the sense that in DPS control, the cross-connected switch pairs of both full bridges are switched with an inner phase-shift ‘D’ while the phase shift ratio between two square wave voltages is ′Φ′. The output ac voltages of both bridges are three-level waves as shown in Fig. 5.

In DPS control, it has the advantage of decrease in current stress while achieving steady-state current. This improves the efficiency by expanding the ZVS operation range by minimizing the output capacitance in comparison to SPS control. While in comparison to EPS control, the operating states of two bridges in DPS control are same during the voltage conversion states or power flow directions. So, it is easier to implement the DPS control with excellent dynamic performance [1].

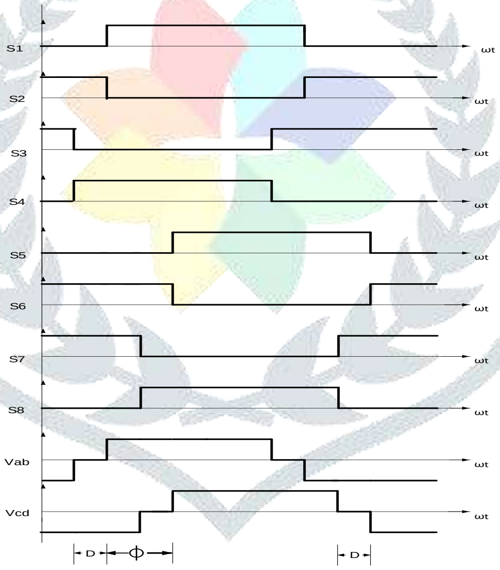

Fig.5: DPS Modulation

H. Bai et al (2008) from USA eliminated the reactive power in IBDC and thus increasing the system efficiency by using DPS control. This is achieved by adjusting the phase-shift between primary and secondary voltages of the isolation transformer in addition to the phase-shift between the gate signals of diagonal switches in each H-bridge. It shows an excellent dynamic and static performance in comparison to the traditional SPS control. The corresponding equations regarding reactive power in IBDC are derived. It shows that the reactive power in traditional SPS control is inherent and it is the main factor for contributing large peak current and hence large system losses. So, the DPS control can eliminate the reactive power in IBDC which decreases the peak inrush current and steady-state current and thus improving the system efficiency by minimizing the output capacitance in comparison to the traditional SPS control [20].

Zhao et al (2012) from China [21] presented the power characterization of an isolated bidirectional DAB dc-dc converter by using DPS control along with detailed theoretical and experimental analysis of the transmission power in IBDC. So, in comparison to the traditional SPS control, DPS control significantly improves the performance of IBDC. It also pointed out some wrong information about the transmission power of an IBDC under DPS control [20] in two control methods, which are SPS and DPS. There is same global maximum power in both cases.

VII. TPS Modulation Technique

The TPS control is similar to the DPS control where the cross-connected switch pairs in both full bridges are switched with an inner phase-shifts as shown in Fig.6. But these inner phase-shifts are unequal while these are same in DPS control. So, the TPS control has three degrees of freedom for the controlling action and the research on TPS control generally focussed on the optimization of its control. The TPS control scheme appears in the literature after the SPS, EPS and DPS controls, so it can be considered as a unified form of phase-shift control.

The EPS & DPS controls can be regarded as the special cases of the unified form of phase-shift control which is TPS control. The SPS control have only one control degree, the EPS and DPS controls have two degrees of control while there are three degrees of control in TPS control. Of all these controls, the TPS control is the most difficult to implement and there is not a single implement strategy or standard for implementing this [1].There are also some other modulation techniques available in the literature which may be a hybrid of different modulation schemes depending on the different conditions of power transfer stages.

H. Zhau et al (2009) presented a hybrid modulation scheme for DAB converter with an extended power range for ultra capacitor applications. It enables an increase in operational power range from 100% to 16.67% instead of 100% to 58.33%. It is almost 100% increase in power transfer range as compared to the conventional phase-shift modulation. This hybrid modulation is a combination of conventional phase-shift modulation (PSM) and proposed triangular modulation (TRM) which is PTRM. So, the triangular shape of current in PTRM will introduce higher rms currents both in transformer as well as switches which results in higher peak currents. It will increase the copper loss in transformer and conduction loss in the switches. So, PTRM is not suitable for high power transfers and it is used solely for lower power transfer ranges while PSM works in higher power range and thus forming a hybrid combination of these two [22].

D. Xu et al (2004) proposed a PWM plus Phase-Shift (PPS) control for bidirectional DC-DC converters by combining both PWM and phase-shift controls together for reducing the current stress, conduction loss and switching loss in the switching devices. The ZVS conditions are also achieved for large load variations. In phase-shift (PS) bidirectional DC-DC converter, the duty cycles of the switches are kept at maximum and when the amplitude of equivalent input voltage is not equal to the equivalent output voltage, the peak and RMS values of currents in the converter become much higher. It also increases the reactive power transferred between the converters which leads to higher current stress on the switching devices along with higher conduction losses. Therefore, the converter can't achieve ZVS conditions during light-load. In PPS control of bidirectional DC-DC converters, the PWM control in the duty cycles acts as an electric transformer between the equivalent input and output voltages, thus both the positive and negative amplitudes of the equivalent input voltage are equal to that of equivalent output voltage. So, in comparison to PS control, the PPS control reduces the current stress and RMS values of the currents in the converter. It reduces the losses in the converter and also, achieves the ZVS conditions under large load variations [23].

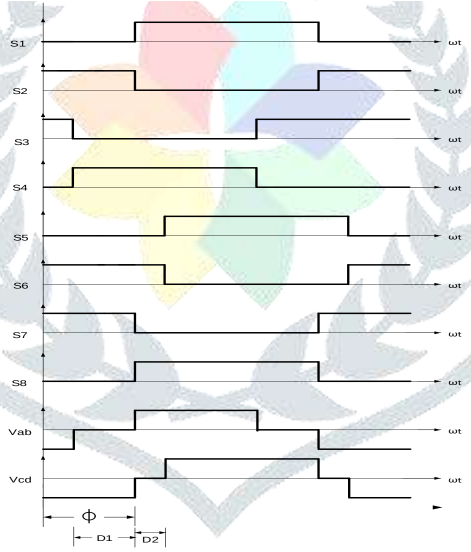

Fig.6: TPS Modulation

B. Zhao et al (2015) presented the fundamental-optimal strategy and also developed a universal steady-state model for the analytical relations of HFL electrical quantities in the DAB-IBDC using PWM plus phase-shift controls. There is universal reactive power interaction among different HFL electrical quantities. On the basis of this, a practical HFL fundamental-optimal strategy (FOPS) is proposed for decreasing the circulating current and increasing the power efficiency. The dead-band must be set to prevent the short circuit between the two switches in the same leg and this will affect the change in switching characterization. There are different dead-band control methods for the expansion of soft-switching ranges which also increases the efficiency of IBDCs [24].

W. Choi et al (2016) presented an optimal modulation strategy for minimizing the current conduction in a given DAB converter. It is based on fundamental component analysis (FCA) or fundamental duty modulation (FDM). This FDM of DAB converter over wide operation range is the optimal modulation scheme for which the DAB converter has reduced values of rms currents over wide range of operating conditions. The operating principle of proposed FDM is based on the fundamental component analysis (FCA) of DAB converter where by modulating the PWM signals in the fundamental component domain; the minimum level of the circulating current can be acquired by using a single control variable. An optimal operation is employed by using a simpler controller structure and thus there is not any requirement of operating mode classification, off-line calculation or current information. This controller structure is simpler which maintains high efficiency over entire operating region with the computational complexity of only 1.8 times that of the conventional PSM scheme. The proposed FDM achieves higher efficiency under wide operating conditions due to the reduced conduction level and wide ZVS range. The efficiency improves in this proposed FDM from 10% to 38% at light load condition as compared to the conventional modulation methods [25].

The output of resonant converter depend not only upon the switching frequency but also on the resonant frequency as well. For example, the output of a voltage-fed series resonant converter is determined by the ratio of switching frequency to the resonant frequency. This fact implies that besides the switching frequency modulation method, there is another method known as resonant frequency modulation for modulating or controlling the output. In resonant frequency modulation, it is required to modulate the value of inductor or capacitor in the resonant tank circuit. So, this is another class of modulation technique which is known as resonant frequency modulation for regulating the resonant converters or a new family of resonant converters which are modulated or regulated at fixed switching frequency operation. It uses a switch controlled inductor (SCI) or switch-controlled capacitor (SCC) in its resonant circuit. The switching losses in these SCI and SCC are very low due to zero-current or zero-voltage switching respectively. Here, the equivalent inductance of the SCI or the equivalent capacitance of the SCC is modulated over a wide range by the external signal. The SCC is much better than SCI in high frequency applications. W.J. Gu et al (1988) presented a steady-state analysis of class-E resonant converter which is regulated by using a SCC [26].

M. Yaqoob et al (2016) presented a DAB-IBDC which is regulated by changing the ratio of switching to resonant frequency of the resonant tank. A modified LCL resonant tank comprising of switch-controlled inductor (SCI) is presented for realizing a tuneable resonant tank. It ensures ZVS in the primary side and ZCS in the secondary side of the DAB-IBDC under wide range of output voltage and charging current of super-capacitor. In SCI, there is change in its equivalent inductance by changing SCI's firing angle and the value of equivalent inductance of SCI can be modulated in the range from infinity to its own value. An efficiency of 94.23% is achieved in this case. The firing angle of SCI is selected in such a way that it keeps ZCS at the secondary side for avoiding excessive ringing in the voltage and current because of the parasitic inductances in the switches [27]-[28].

There are some other control strategies which are available in the literature with some improved results. S. Dutta et al (2013) presented several predictive current mode controls in single-phase DAB DC-DC converter by using current control strategies. These various current control strategies include average current control, peak current control and predictive current mode control. A comparison of all these proposed controllers with the traditional average based current control is presented along with a proposal of power based predictive controller [29].

T. Labella et al (2014) presented an additional secondary-side bidirectional ac switch to isolated series resonant converter. It provides voltage regulation by using basic fixed-frequency pulse width modulation (PWM) control in a hybrid of series resonant and PWM boost converter. Therefore, by adding a secondary side bidirectional ac switch, the benefits of highly efficient LLC and series-resonant converters will remain there but with an additional feature of voltage regulation capability in the converter through this simple fixed-frequency PWM control [30].

J.M. Zhang et al (2001) presented an improved DAB DC-DC converter by using a novel control scheme. It eliminates the large feedback energy problem. There is no circulation of energy which flows back from the output to the input as in case of conventional DAB. Also, the soft-switching in all switches different load conditions is achieved termed as ZVZCS along with low sensitivity of the parasitic parameters. It eliminates the circulation energy by altering the switching sequence of the switches in the output bridge. Both efficiency as well as output capacitor current ripple is improved. It used a synchronous rectifier at the output for getting higher power efficiency. This scheme is attractive for high power and high frequency applications [31].

The control and gate drive circuits of DAB-IBDC in the literature that are used for implementing different types of modulation schemes have its own features. Seon Hwan Hwang et al (2013) proposed distributed digital control architecture for modular SST by using DSP and FPGA. The topology is three-stage SST based on modular structure for superior controllability and it requires digital implementation for higher performance. This digital control platform is achieved by using a floating-point DSP and an FPGA. The main control algorithms are performed by using DSP and the simple logical processes are implemented in FPGA for synthesizing suitable gating signals to control the external devices accordingly. So, with this proposed method, it enables high switching frequency operation along with multitasking for achieving flexible design of modular-based SST [32].

Jiang T.Y. et al (2015) proposed a bidirectional LLC resonant converter topology along with a new control scheme which automatically switches between forward mode and backward mode transitions. It is quite attractive solution for energy storage system applications in achieving soft-switching of all switches. All switches in primary and secondary sides turn-on and turn-off with same switching frequency, but with different pulse widths based on the requirement of voltage gain. The switching frequency is used for regulating the output power. An auxiliary inductor is added for making this topology symmetrical in different operating modes. The magnitude and direction of power flow changes automatically and continuously in energy storage systems to balance energy while keeping the dc-bus voltage constant. In comparison to traditional IBDCs like DAB converter, the reverse energy and turn-off loss are reduced dramatically, which improves the overall power conversion efficiency. The efficiency achieved in this case is above 97% at full load [33].

S. Mondal et al (2008) proposed an analog ZVS controller for bidirectional high frequency galvanically isolated DC-DC converter. The power flow scheme is based on the comparison between closed-loop power demand and the reference power generated from phase-shift angle in dual active full-bridge (DAFB) PWM converter. This is simple and cost effective solution for providing steady state and transient performance in comparison to other complex bidirectional DSP based controllers which requires extra software development cost. The measurement will also be fast as no ADC or DAC conversions are involved [34].

The predictive controller is an attractive solution for controlling power converters which provides faster mode of control during load transients. Ideally, a predictive controller should be able to latch over to the desired reference value within in one cycle. But in actual practice, the action of controller heavily depends on the accuracy of sensors as well as the values of passive elements in the circuit.

S. Dutta et al proposed a predictive control algorithm for bidirectional DAB DC-DC converter, which will be a faster alternative of the classical PI based phase-shift controller. This mode of control removes the dc bias in isolation transformer and hence preventing the transformer from saturation. There are three versions of controller. First is predictive phase shift control where there is a phase shift between primary and secondary converters. Second is duty cycle mode control where the duty cycle of secondary-side switches is controlled in a predictive fashion. Third is equal area criterion duty mode controller where the value of transformer leakage inductance is an important parameter as the incorrect value introduces dc bias in the current [35].

S. Talbi et al (2017) presented PI-Fuzzy control in bidirectional DAB DC-DC converter. The PI-fuzzy controller (PIFC) is a closed loop fuzzy control system which is used for an energy storage application in aerospace, where battery is fed by isolated bidirectional DAB DC-DC converter. The stability analysis has been carried out by using Lyapunov's method which shows sufficient stability conditions when proper values of PIFC parameters are chosen and thus providing a stable and high level control. The main advantage of fuzzy controller is that there is no requirement of any prior knowledge of system parameters [36].

P. Wang et al (2021) presented both large-signal average-value modeling as well as small-signal average-value modeling of DAB-IBDC with TPS modulation [37]. F. Wu et al (2019) presented cooperative TPS control for DAB-IBDC for eliminating the dual-dc side flow back currents improving the current characteristics [38].

The different types of control strategies along with modulation techniques used in DAB-IBDCs are discussed here. Some specified modulation techniques which are used in some particular conditions are also available in literature which mentioned their control and gate drive circuits. Further, the different types of soft switching solutions which are available in the literature are also discussed that helps in improving the soft switching conditions of DAB-IBDCs.

VIII. CONCLUSION

The control strategies as different modulation techniques of isolated bidirectional DC-DC converters in high frequency power conversion systems serving as their core circuits had been discussed. The DAB-IBDCs have 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 DAB-IBDCs with high frequency isolation in power conversion systems, the control strategies along with their modulation techniques are the research topics. 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, electric vehicles, implantable medical devices 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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