A Comprehensive Study of Modulation Techniques and Efficiency Improving Schemes for Non Resonant 1-Φ DAB Dc-Dc Converter

D.Srinivasa Rao[1] | Dr. Anupama A. Deshpande[2]

[1]Research Scholar, Department of Electrical Engineering, Shri JJTUniversity, Jhunjhunu, Rajasthan, INDIA
[2]Professor, Department of Electrical Engineering, Shri JJTUniversity, Jhunjhunu, Rajasthan, INDIA

Abstract: The non resonant single-phase dual-active-bridge (NRSPDAB) dc–dc converter technique has been widely applied for the isolated dc–dc power converter which operates at high frequency finds many applications in MVDC and LVDC systems. During the last decade the NRSPDAB converters are also finds applications in solid state transformers, automotive energy storage systems and aerospace applications. During the last decade considerable research has been done to overcome the hurdles in developing the various modulation techniques for NRSPDAB Dc-Dc converter. The objective of this paper is to present, analyze, and compare the various current modulation techniques associated with NRSPDAB converter. All the possible phase shift methods are presented. The relative possible analysis of the phase shift methods are also carried out for NRSPDAB Dc-Dc converter. Overview and comparison of efficiency improving schemes are also carried out. Finally efficient modulation techniques and efficiency improving schemes are proposed for various applications associated with the proposed converter.

KEYWORDS: Dual active bridge (DAB) converter, High Frequency, Modulation techniques, Efficiency improving schemes, Solid state transformer

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I.INTRODUCTION

The non resonant single-phase dual-active-bridge (NRSPDAB) dc–dc converter was first proposed by the end of 20th century for realizing high-efficiency and high-power-density dc–dc power conversions. In recent years, the use of high-frequency (HF) transformers in place of traditional LF transformers is considered to be the developing trend of next-generation dc-dc power conversion[1]-[4]. High-frequency-link (HFL) power conversion systems based on HF transformers can also avoid voltage and current waveform distortion caused by the core saturation of LF transformers. In recent years, the advances in new power devices and magnetic materials (especially the development of silicon carbide (SiC) - and gallium-nitride (GaN)-based power devices and iron-based Nano crystalline soft magnetic) also have made NRSPDAB feasible for eliminating bulky and heavy LF transformers from power conversion systems. Thus, NRSPDAB has regained the attention of numerous researchers. The NRSPDAB dc–dc converter, which can form series and parallel connections has become one of the most attractive isolated dc–dc power conversion topologies for inter connection of dc grids, solid-state transformer (SST), automobile applications, Battery energy storage system, and aerospace application. The NRSPDAB dc–dc converter is a very attractive choice for electrical vehicle (EV) battery charger, The NRSPDAB -based SST, has been regarded as one of the main emerging techniques in DC power distribution systems (MVDC/LVDC). Moreover, based on the NRSPDAB dc–dc converter, the back-to-back (BTB) system has been investigated to resolve the problems of power flow balancing between ac grids, which can also be employed to replace the line frequency transformer[5]-[8]. In addition, to match different dc grids at different voltage levels, the modular multilevel dc-link solid-state transformer (MMDCT) system with NRSPDAB dc-dc converters is proposed. The MMDCT not only has the same modularity and flexibility but also has good fault handling capacity [9]-[10]. Fig.1 and 2 shows basic topology and its equivalent circuit of a NRSPDAB dc-dc converter simultaneously.

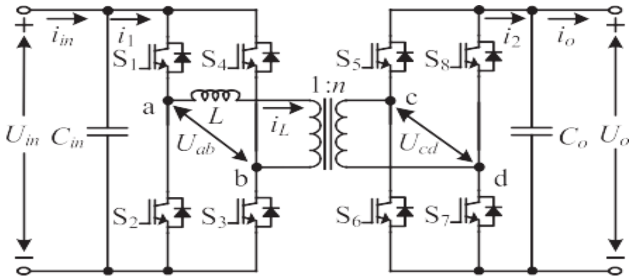


Fig.1. Topology of a NRSPDAB dc–dc converter

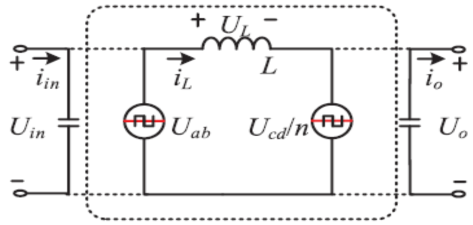


Fig.2. Equivalent circuit of an NRSPDAB dc–dc converter

Fig.3 shows the application of NRSPDAB dc–dc converter in EV battery charger and Fig. 4 depicts a phase of ac-ac SST to regulate Ac power at distribution level [11]-[12].

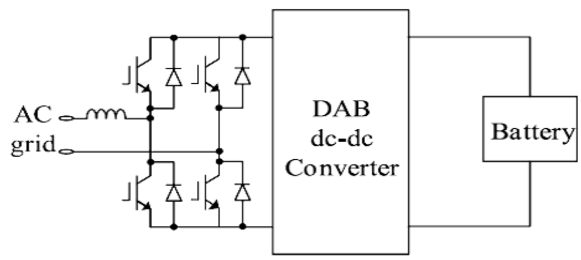


Fig.3.Block diagram of a NRSPDAB -based EV battery charger

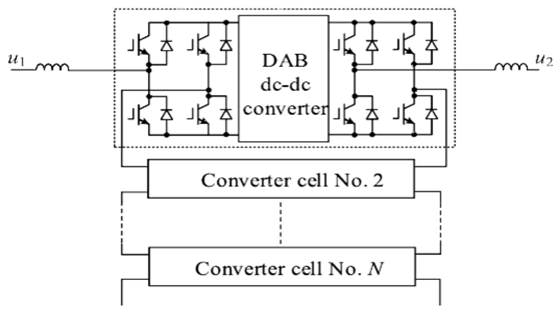


Fig.4. A phase of BTB system

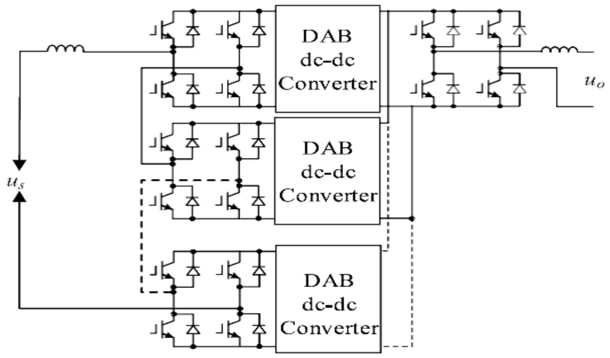


Fig.5. MMC based three-stage SST topology

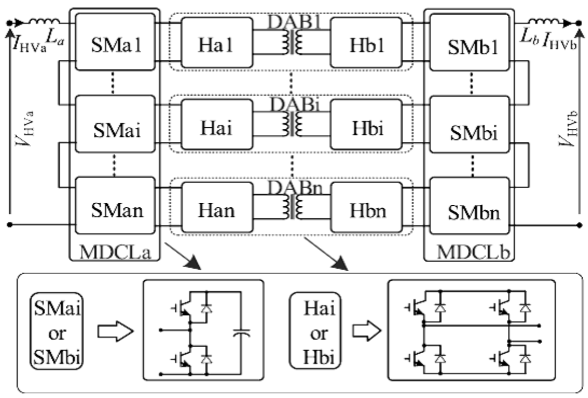


Fig.6. MMC based dc-link SST system

Fig. 5 shows NRSPDAB dc–dc converter, the back-to-back (BTB) system has been applied to solve the problem of power flow balancing between ac grids, which can be used to replace the line frequency transformer and Fig. 6 shows NRSPDAB dc–dc converter employed in modular multilevel dc link solid state transformer (MMDCT) [13]-[14]. Significant efforts toward dealing with the technical challenges for the efficiency optimization and the dynamics improvement of the NRSPDAB dc–dc converter is made previously. However, so far there is a lack of comprehensive analysis and comparison of various operation strategies, making it difficult to decide which method to adopt under different circumstances [15]-[16]. Therefore, the main intention of this paper is to provide a better understanding of the NRSPDAB converter control and operation in terms of various modulation methods, the static and dynamic performance, and reviews the most recent advancements on the phase-shift modulations, efficiency optimization techniques, and dynamic-improvement techniques of the NRSPDAB dc–dc converter [17]-[18]. A detailed comparison of different control methods are also presented in this paper to decide which method to use for different applications [19]-[20].

The rest of sections of this paper are organized as follows. Section II introduces the typical phase-shift modulation methods for the NRSPDAB dc–dc converter. To provide a better understanding of the phase-shift modulation, all possible phase-shift patterns are presented. Section III presents the analysis of the typical phase-shift modulation methods. Section IV presents a thorough review of latest methods for the efficiency-improvement for the NRSPDAB dc-dc converter. Finally, efficient modulation techniques are presented and simulated for various conditions associated with NRSPDAB dc –dc converter is presented in Section V, with verification results. The concluding remarks are presented in Section VI.

II. TYPICAL PHASE-SHIFT MODULATION METHODS

Generally, the phase-shift modulations are the most attractive modulation techniques for the NRSPDAB dc–dc converter.

A. SPS Modulation Method

The single-phase-shift (SPS) modulation method, as shown in Fig. 7 (where *D* is the phase-shift ratio), is presented originally when the NRSPDAB dc–dc converter is proposed.

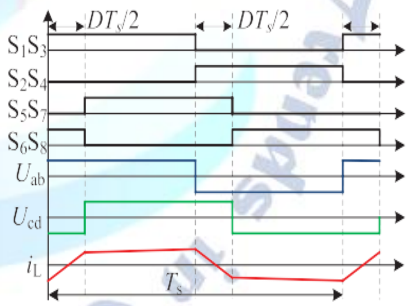


Fig. 7.Waveforms for SPS modulation method

S_1–S_4 and S_5–S_8 are square-wave gate signals with 50% duty ratio for the corresponding switches in Fig.1 U_{ab} and U_{cd} are the equivalent ac output voltages of full-bridges H_1 and H_2 respectively, and i_L is the current of inductor *L*. In SPS control, the cross-connected switch pairs in both full bridges are switched in turn to generate phase-shifted square waves with 50% duty ratio to the transformer's primary and secondary sides. Only a phase-shift ratio (or angle) *D* can be controlled. Through adjusting the phase-shift ratio between U_{ab} and U_{cd} , the voltages across the transformer's leakage inductor will change. Then, the power flow direction and magnitude can be simply controlled.

The performance characteristics of the NRSPDAB converter under SPS control are reasonably good with less device and component stresses, small filter components, reduced switching losses, bidirectional power flow, buck–boost operation, low sensitivity to parasitic parameters. Even though, the NRSPDAB dc–dc converter can achieve a good efficiency under the SPS modulation when both side voltages are matched. The SPS modulation method will always result in high-circulating power and limited zero-voltage-switching (ZVS) range when both side voltages are mismatched and decreases the efficiency of an NRSPDAB dc–dc converter.

B. DPS Modulation Method

The DPS modulation method is an improved phase-shift modulation method for the NRSPDAB dc–dc converter. As shown in Fig. 8, different from the SPS modulation scheme, an inner phase-shift ratio D_{D1} is added to both side H bridges under the DPS modulation method, and the another phase-shift ratio D_{D2} determines the relative position between the output voltages of the input side and the output side H bridges.

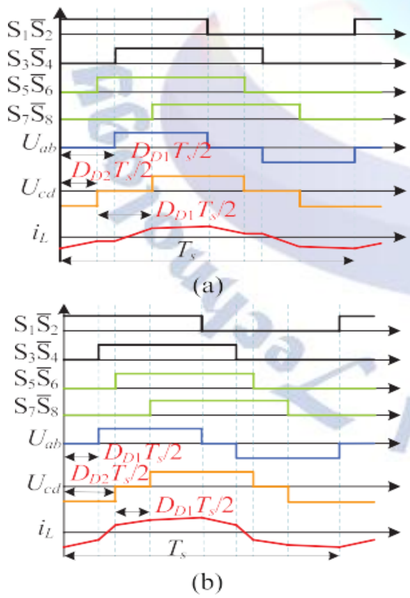


Fig. 8.Waveforms for DPS modulation method (a) $0 \le D_{D2} \le D_{D1} \le 1$ (b) $0 \le D_{D1} < D_{D2} \le 1$

As shown in Fig. 8, the DPS modulation usually has two different conditions according to relationship of D_{D1} and D_{D2}. When $0 \le D_{D2} \le D_{D1} \le 1$, waveforms for the DPS modulation are shown in Fig.8 (a), and when $0 \le D_{D1} < D_{D2} \le 1$, waveforms for the DPS modulation are shown in Fig.8 (b). Compared with the SPS modulation method, the DSP modulation method can be employed to decrease the current stress, expand the ZVS operation range, and reduce the reactive power of the NRSPDAB dc–dc converter. Under certain operation conditions, dead band compensation can also be implemented easily in the DPS control without a current sensor.

C. EPS Modulation Method

Different from the DPS modulation, an inner phase-shift ratio D_{E1} is added to the input-side H-bridge or the output-side H-bridge. Therefore, there are also two conditions of the EPS modulation according to the position of the inner phase-shift ratio. When D_{EP1} is added to the primary-side H-bridge, waveforms for the EPS modulation are shown in Fig. 9(a), and when D_{ES1} is added to the secondary-side H-bridge, waveforms for the EPS modulation are shown in Fig. 9(b).

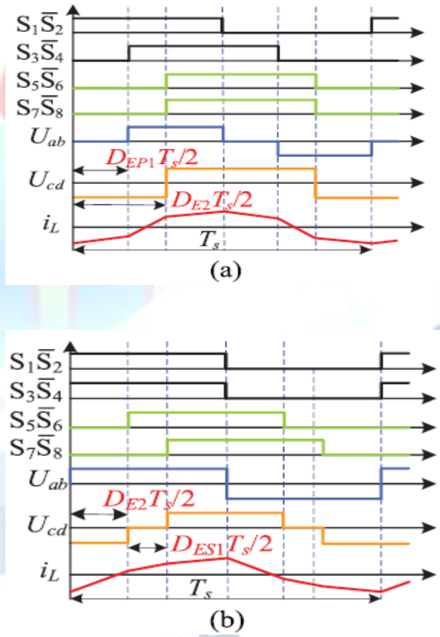


Fig. 9.Waveforms for EPS modulation method (a), (b) D_{E1} at I/P and O/P side of H-bridge

Similar to the DPS modulation method, the EPS modulation method can also be used to decrease the current stress, expand the ZVS operation range, and reduce the reactive power. Different from the DPS modulation method, when the voltage conversion states are changed between the boost and buck states and the power flow directions are changed between the forward and reverse power flow, the operating states of the two bridges are needed to be exchanged to decrease the circulating power.

D. TPS Modulation Method

The waveforms for TPS modulation method are shown in Fig. 10, where i_0, i_1, i_2, i_3, i_4, i_5, i_6, and i_7 are the boundary inductance currents of the NRSPDAB dc–dc converter (these boundary inductance currents will be used to determine ZVS performances in the next section). Similar to the DPS modulation method, both sides of the H bridge output voltages contain the inner phase-shift ratios, but these two-inner phase-shift ratios may be different. With three phase-shift ratios D_1, D_2, and D_3 for the NRSPDAB converter, the TPS modulation method can obtain the minimum current stress, minimum conducting losses, minimum power losses, and maximum ZVS range. In fact, the TPS method was proposed after SPS, EPS, and DPS methods; it is a unified form of phase-shift methods. SPS, EPS, and DPS methods can also be regarded as special cases of TPS method. From the view of implementation, SPS method requires only one control degree; the EPS and DPS method require two control degrees, and three control degrees are needed for TPS method. Hence, TPS control is the most difficult to implement. For EPS control, the operating states of the two bridges should be changed when the voltage conversion states or power flow directions are changed. Apart from the above four versatile modulation methods, a variable-frequency modulation technique is also a viable choice for the NRSPDAB dc–dc converter, especially when wide power range is required. For NRSPDAB dc–dc converter, lower switching frequency allows the transfer of higher power. A variable-frequency modulation method for the NRSPDAB dc–dc converter is proposed to ensure ZVS over a wide power range with lower reactive power. If the selected switching frequency range does not affect converter filter design and components choices, then variable-frequency modulation can be used to extend power transfer range of the NRSPDAB dc–dc converter.

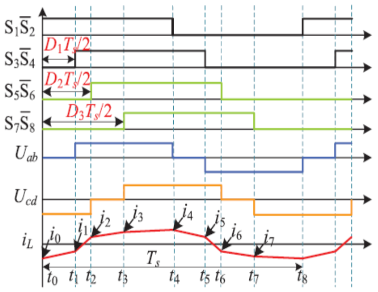


Fig. 10.Waveforms for TPS modulation method

III. ANALYSIS OF THE TYPICAL PHASE-SHIFT MODULATION METHODS

In order to acquire a better understanding of the phase-shift modulation used for the DAB dc–dc converter, the comprehensive analysis of all possible phase-shift modulation modes for the NRSPDAB dc–dc converter is provided here. For the NRSPDAB dc–dc converter, the principle for determining a modulation mode is that the transferred power can be obtained uniquely and expressed by the phase-shift ratios directly. Generally, there are only three possible phase-shift ratios for an NRSPDAB converter, including one for the input-side H-bridge, one for the output-side H-bridge, and one between these two H-bridges. In addition, the output side and the input side of the NRSPDAB converter can be changed equivalently because of its symmetrical structure,D_1,D_2, and D_3 can be replaced by $D_1^{'}$, $D_2^{'}$, $D_3^{'}$ respectively for reversal of power flow. Moreover, the defined positive direction of the inductance current i_L should also be reversed. The NRSPDAB dc–dc converter is a symmetrical structure.

The phase-shift modulation modes based on the phase-shift ratios D_1,D_2, and D_3, which have the same reference S1, are obtained, and the obtained results are also suitable for the phase-shift modulation modes based on the phase-shift ratios $D_1^{'}$, $D_2^{'}$, $D_3^{'}$ According to Fig.10 D_1,D_2, and D_3 should meet the conditions as

$$\begin{cases} 0 \leq D_1 \leq 1 \\ 0 \leq D_3 - D_2 \leq 1 \\ 0 \leq D_2 \leq 2 \\ 0 \leq D_3 \leq 2 \end{cases} \quad (1)$$

According to Fig.10, U_{ab} and U_{cd} are symmetric three-level waveforms, and based on Fourier series, U_{ab} and U_{cd} can be expressed as

$$U_{ab} = \sum_{m=1,3,5\ldots}^{\infty} \frac{4U_{ab}}{m\pi} \cos\left(\frac{m\pi\ D_1}{2}\right) \sin(2\pi f_s m t)$$

whereU_{ab}=U_{in}

$$U_{cd} = \sum_{m=1,3,5\ldots}^{\infty} \frac{4U_{cd}}{m\pi} \cos\left(\frac{m\pi\ (D_3-D_2)}{2}\right) \sin[\,2\pi m\left(f_s t - \frac{D_3+D_2-D_1}{2}\right)] \quad \text{where } U_{cd} = U_0$$

(2)

Then, the transferred active P and the reactive power Q determined by U_{ab} and U_{cd} with the same frequency of the NRSPDAB dc–dc converter can be shown as

$$P=\sum_{m=1,3,5\ldots}^{\infty}\frac{4U_{in}}{nf_sL\pi^3m^3}U_0\cos\left(\frac{m\pi\ D_1}{2}\right)\cos\left(\frac{m\pi\ (D_3-D_2)}{2}\right)\sin\left(\frac{m\pi\ (D_3+D_2-D_1)}{2}\right)$$

$$Q=\sum_{m=1,3,5\ldots}^{\infty}\frac{4U_{in}}{nf_sL\pi^3m^3}U_0\cos\left(\frac{m\pi\ D_1}{2}\right)\cos\left(\frac{m\pi\ (D_3-D_2)}{2}\right)\cos\left(\frac{m\pi\ (D_3+D_2-D_1)}{2}\right) - \frac{4U_0^2}{n^2f_sL\pi^3m^3}\cos^2\left(\frac{m\pi\ (D_3-D_2)}{2}\right) \quad (3)$$

According to the equation 3 the transferred power of the NRSPDAB dc–dc converter is mainly formed by the first-order voltage of U_{ab} and U_{cd}. Then, the transferred power P and the reactive power Q can be further expressed as

$$P = 4U_{in}U_0\cos\left(\frac{\pi\ D_1}{2}\right)\cos\left(\frac{\pi\ (D_3-D_2)}{2}\right)\sin\left(\frac{\pi\ (D_3+D_2-D_1)}{2}\right)/\ nf_sL\pi^3$$

$$Q = 4U_{in}U_0\cos\left(\frac{\pi\ D_1}{2}\right)\cos\left(\frac{\pi\ (D_3-D_2)}{2}\right)\cos\left(\frac{\pi\ (D_3+D_2-D_1)}{2}\right)\ /\ nf_sL\pi^3 - 4U_0^2\cos^2\left(\frac{\pi\ (D_3-D_2)}{2}\right)/n^2f_sL\pi^3 \quad (4)$$

To transfer power from the input side to the output side, P should be positive, and the relationship between D_1,D_2, and D_3 can be obtained as

$$0 \le \frac{\pi\ (D_3+D_2-D_1)}{2} = \Phi \le \pi \quad (5)$$

According to (4), when φ is from 0 to $\pi/2$, the maximum power range of the NRSPDAB dc–dc converter can be obtained, and when $D_1 = 0$ and $D_2 = D_3 = 0.5$, the maximum power transfer can take place. In addition, the reactive power Q can also be expressed as

$$Q = Q_1 - Q_2 \quad (6)$$

Where

$$Q_1 = 4U_{in}U_0\cos\left(\frac{\pi\ D_1}{2}\right)\cos\left(\frac{\pi\ (D_3-D_2)}{2}\right)\cos(\Phi)/\ nf_sL\pi^3$$

$$Q_2 = 4U_0^2\cos^2\left(\frac{\pi\ (D_3-D_2)}{2}\right)/n^2f_sL\pi^3 \quad (7)$$

From (1), (5), and (7), Q_2 is always positive, and the sign of Q_1 is depends on the value of φ. When φ is larger than $\pi/2$, Q_1 is negative. When φ is smaller than $\pi/2$, Q_1 is positive. To avoid large Q for low-conducting losses, the signs of Q_1 and Q_2 must be the same. Thus, φ should be smaller than $\pi/2$. According to (4), D_1 and $(D_3 - D_2)$ are usually determined as 0 for high power transmission of the NRSPDAB dc–dc converter. However, when D_1 and $(D_3 - D_2)$ are close to zero in these phase-shift modulation modes, $(D_3 + D_2 - D_1)$ is always close to two. As a result, P is close to zero. Thus, these phase-shift modulation modes are not very suitable for power transmission.

Even though some advanced phase-shift modulation methods, including the EPS modulation method and the DPS modulation method, are proposed first for boosting the efficiency of the NRSPDAB dc–dc converter, the TPS modulation method can always provide the best efficiency. The reason is that the EPS and DPS modulation methods can be said as the special cases of the TPS modulation method, which are shown in Fig.11.

From Fig.11, when D_1 of the TPS modulation method is equal to zero, or D_2 of the TPS modulation method is equal to D_3, the EPS modulation method can be obtained by using the TPS modulation method. Similarly, when D_1 is equal to $(D_3 - D_2)$, the TPS modulation method equals to the DPS modulation method. Moreover, when D_1 and the difference between D_2 and D_3 are equal to zero, the SPS modulation method can be obtained. Therefore, since the SPS, DPS, and EPS modulation methods are contained in the TPS modulation method, the TPS method can always provide the best efficiency for the NRSPDAB dc–dc converter. Considering efficiency optimization, the recommendation for selecting phase-shift modulation modes will be given in the following section.

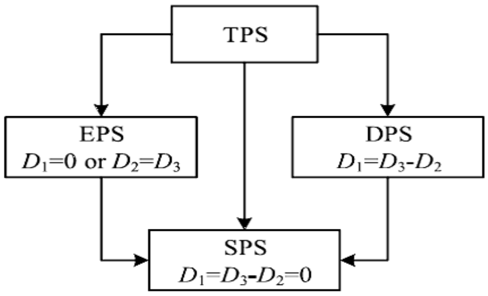


Fig. 11.Relation Diagram of typical phase shift methods

IV. REVIEW OF LATEST METHODS FOR EFFICIENCY-IMPROVEMENT

For the NRSPDAB dc–dc converter, the power losses mainly consists of switching losses and conduction losses in switching devices, copper and core losses in transformer and inductor. When wide-band gap semiconductors, such as SiC-based switches and GaN-based switches are used, then the switching losses of the NRSPDAB dc–dc converter can be reduced significantly, and the efficiency of the NRSPDAB dc–dc converter can also be improved by using efficiency optimization methods. Generally, there are four control methods to boost the efficiency of the NRSPDAB dc–dc converter. Power-loss-model-based optimization method, reactive power optimization method, inductor current optimization method, ZVS range optimization method.

A. Power-Loss-Model-Based Optimization Method

Generally, total power losses of the NRSPDAB dc–dc converter can be divided into five categories: switching losses, conduction losses, copper losses, iron losses, and unknown losses, as shown in Fig. 12. Unknown losses are mainly composed of line-resistor losses, copper losses due to skin and proximity effects, ohmic losses in the dc-link capacitors etc. Generally, unknown losses are a small portion of overall power losses and can be neglected. Generally, the procedure for implementing power-loss-model-based optimization method can be divided into four steps. First, the phase-shift modulation methods, such as the DPS, EPS, or TPS methods should be selected. Then, based on different power-loss elements, the corresponding power-loss model can be obtained. Moreover, according to the certain working condition, including input voltages, output voltage, and power requirement, minimum power loss for the NRSPDAB dc–dc converter can be obtained by using an enumeration method of different phase-shift ratios in the mathematical software, such as MATLAB and Math cad. Finally, the optimized phase-shift ratios for different conditions are to be stored in a digital controller or a signal processor for practical implementation.

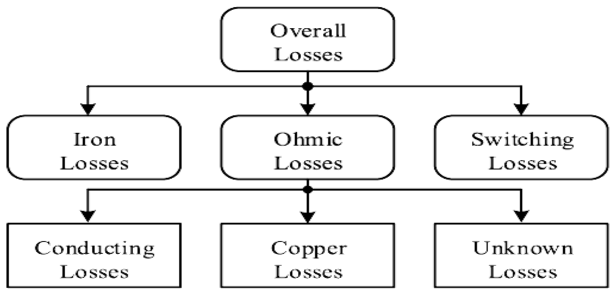


Fig.12. Classifications of losses in NRSPDAB dc–dc converter

B. Reactive Power Optimization Method

The reactive power also called as reverse power in NRSPDAB operation, and this reverse power may be the main factor contributing to large peak current and large system losses under the SPS modulation method. Waveforms for SPS modulation method with reverse power can be shown in Fig.13 (a), where dark areas of the inductor current have opposite direction to the primary-side H bridge output voltage. Therefore, to compensate this reverse power, the transferred power, which should be more than the load requirement, will be drawn from the input side that will affect the efficiency of a NRSPDAB dc–dc converter. To reduce this reverse power, some advanced phase-shift modulation methods such as the DPS modulation method [see Fig. 13(b)] can be employed, where smaller back power is generated. The reverse power characteristics in both sides of the NRSPDAB dc–dc converter are thoroughly analyzed under buck or boost modes, and a minimum- reverse power scheme with the EPS modulation method is proposed to reduce reverse power and to improve the efficiency of the converter. According to the general definition of reactive power of ac system, a minimum-reactive-power method is proposed to reduce the reactive power for NRSPDAB dc–dc converter on the input side with the TPS modulation method. Similarly, based on the extended TPS modulation method, a minimum-reactive-power scheme with simplified theoretical calculations and implementation is adopted. It is proposed to boost the efficiency of a NRSPDAB dc–dc converter. Especially, the reactive power optimization strategy increases the efficiency by indirectly reducing the rms and average value of the inductor current.

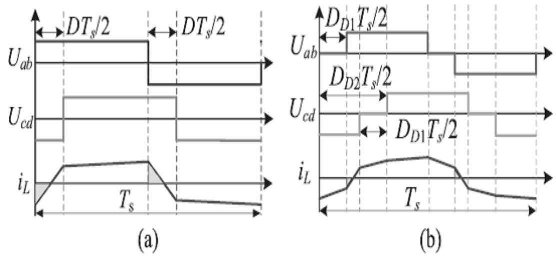


Fig.13. Waveforms for phase-shift modulation methods with reactive power. (a) SPS modulation. (b) DPS modulation

C. ZVS Range Optimization Method

ZVS optimization can be achieved by using the parallel parasitic capacitance or by adding a parallel capacitor for each switch to reduce switching losses of switches and boost the efficiency. Generally, ZVS switching performance is achieved by charging or discharging these parallel capacitors to ensure the switches turn ON at zero voltage. Generally, there are two types of ZVS conditions, including upper switch and lower switch for the NRSPDAB dc–dc converter, which are shown in Fig.14. ZVS processes of S1 and S2 are shown here as examples for the NRSPDAB dc–dc converter.

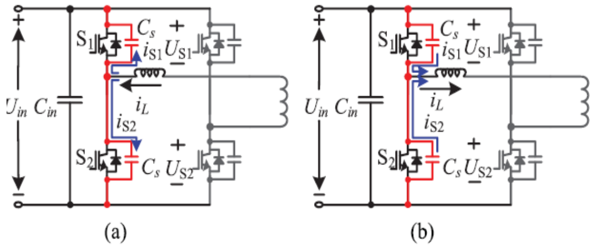


Fig.14. ZVS performances for the NRSPDAB dc–dc Converter (a) ZVS for upper switch (b) ZVS for lower switch

The corresponding switching signals, current, voltage waveforms of S_1 and S_2 are illustrated in Fig.15. As shown in Fig. 14(a), to implement ZVS for the upper switch S_1, the negative inductance current is required to charge the parallel capacitor of S_2 and discharge the parallel capacitor S_1; and when $US1$ becomes negative, the switch S_1 will turn ON at zero voltage, as shown in Fig.15 (a). Similarly, the positive inductance current is required to charge the parallel capacitor of S_1 and discharge the parallel capacitor of S_2 [Fig.14 (b)], becomes negative, the switch S_2 will turn ON at zero voltage, as shown in Fig. 15(b). Therefore, ZVS performances of the NRSPDAB dc–dc converter are determined by the direction of the inductance currents, and combining Fig.10 and 14, the required directions of the inductance currents to implement ZVS performance of each switch are S_1, S_3, S_6, S_8 = negative(i_0, i_1, i_6, i_7); S_2, S_4, S_5, S_7 = positive(i_2, i_3, i_4, i_5).

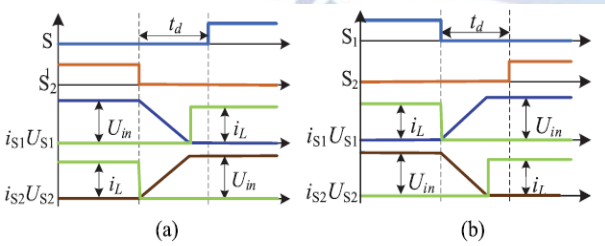


Fig.15.States of S1 and S2 during ZVS Signals for (a) upper-switch (b) lower-switch

D. Inductor Current Optimization Method

Conduction losses, copper losses, and iron losses, which are the main power losses of the NRSPDAB dc–dc converter, can be determined by the rms or the average absolute value of the inductance current. Small rms value or average value of the inductance current leads to the minimum conduction and copper losses for the NRSPDAB dc–dc converter. In order to reduce the conduction loss of the NRSPDAB dc–dc converter, a solution based on the minimum conduction loss modulations for low-power, medium-power, and high-power levels is proposed to boost the efficiency of an NRSPDAB dc–dc converter. However, this method is suitable only when a numeric table is used for calculation. When the input voltage is much larger or smaller than the output voltage, the waveform of the inductance current is close to a triangle as shown in Fig.16. The rms value I_{LRMS} and average absolute value I_{LAV} of the inductor current is calculated as

$$I_{\mathrm{LRMS}} = \sqrt{\frac{2(t_1+t_2)}{3T_s}}\, i_p \;,\; I_{LAV} = \frac{2(t_1+t_2)}{T_s}\, i_p \qquad (8)$$

To transfer large amount of power, the sum of t_1 and t_2 is always equal to a half of switching time T_s. The rms value and average value can be reduced by decreasing the peak-current of the inductance current.

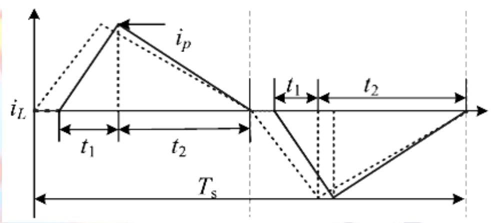


Fig.16. Inductance current when both side voltages are not matched

V. SIMULATION OF EFFICIENCY IMPROVEMENT METHODS

The power-loss-model-based optimization method and the ZVS range optimization method are not suitable for online optimization since offline calculations are necessary and the implementation is complicated. Moreover, the ZVS soft-switching boundary for the NRSPDAB dc–dc converter is also a little difficult to determine, when the minimum inductance current for charging the parallel capacitor of switches is considered.

Reactive power optimization method boosts the efficiency by indirectly reducing the rms current of inductor because the reactive power can be calculated as the integral part of the output voltage of H-bridge and the inductor current. The inductor current is always flowing though the transformer and the four switches, where the power loss is mainly generated. Thus, it is necessary to reduce the inductor current directly for boosting the efficiency of the NRSPDAB dc–dc converter. Reactive power optimization method and inductor current optimization method are considered separately for further analysis and simulation.

Voltage conversion ratio k is defined as

A. $K = n\frac{U_{ab}}{U_{cd}}$ (9)

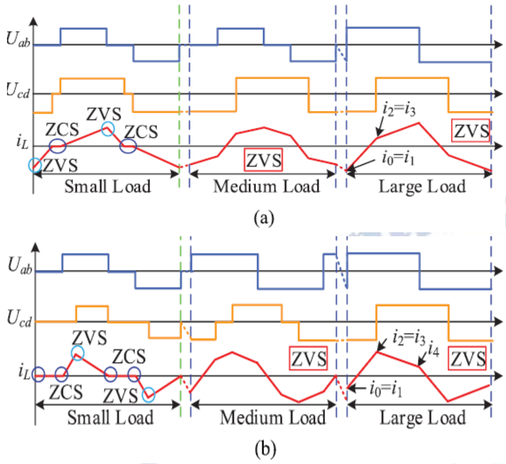


Fig.17. Phase-shift modulation methods used for MRMSC scheme under different voltage conditions. When (a) $k > 1$(b) $k < 1$

From Figs.17 and 18, the Minimized rms current (MRMSC) scheme and the Minimum Current-stress-optimized (MCSO) strategy use the same phase-shift modes from light-load condition to medium-load condition.

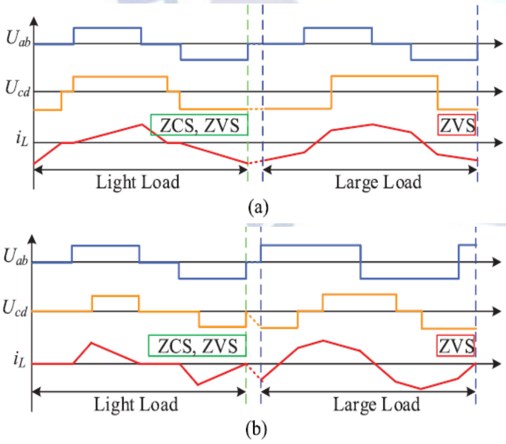
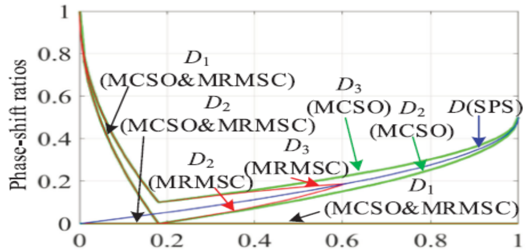


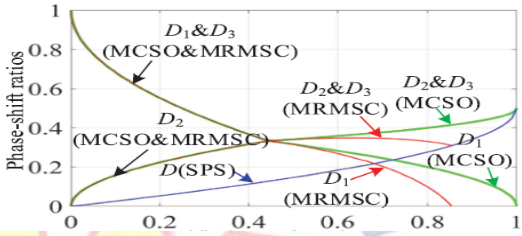
Fig.18.Phase-shift modulation methods for MCSO scheme under different voltage conditions. When(a) $k > 1$. (b) $k < 1.5$

From Figs.17 and 18, the Minimized rms current (MRMSC) scheme and the Minimum Current-stress-optimized (MCSO) strategy use the same phase-shift modes from light-load condition to medium-load condition. When the transferred power is close to the maximum transferred power of the NRSPDAB dc–dc converter, the EPS modulation method is still employed under the MCSO strategy, but the SPS modulation method is adopted under the MRMSC scheme.

The waveforms of the phase-shift ratios D_1, D_2, and D_3 versus p under different strategies with different k values are shown in Fig.19, and the phase-shift ratio D under the SPS modulation method is also presented.



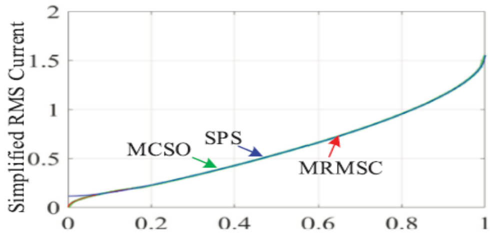
(a). Transferred power p



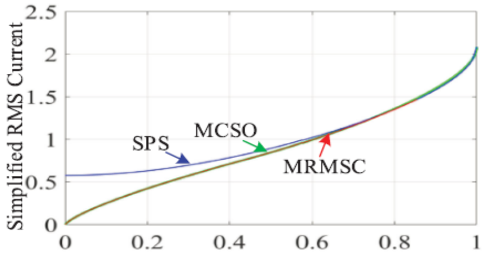
(b). Transferred power p

Fig.19. Phase-shift ratios versus p under different modulation methods with different k. (a) $k = 0.9$. (b) $k = 1.5$.

When k is close to one, the phase-shift ratios D_2, and D_3 of the MRMSC strategy and MCSO strategy are similar to the phase-shift ratio D of the SPS modulation method because the SPS modulation method is the best choice under matching side voltages for the NRSPDAB dc–dc converter. But in heavy-load situation, the SPS modulation method is selected in the MRMSC scheme. It is worth mentioning that the optimized solutions of D_1, D_2, and D_3 under MCSO strategy and MRMSC strategy are very close, and gradually become closer with the increase of k when $k > 1$ and the decrease of k when $k < 1$ as shown in figure 19.



(a). Transferred power p



(b). Transferred power p

Fig.20. Simplified rms current versus p under different modulation methods with different k (a) $k = 0.9$. (b) $k = 1.5$.

The MCSO scheme is shown in Fig. 20. Compared to SPS modulation method, the MRMSC scheme and MCSO scheme can reduce the rms value of the inductor current for the NRSPDAB dc–dc converter, especially when k is further away from one. But the MCSO scheme can achieve very similar performances as MRMSC strategy, and when p is close to one, the MRMSC strategy can achieve a slightly better performance than MCSO strategy to reduce the rms value of the inductor current.

VI. CONCLUSION

This paper offers a comprehensive overview of modulation methods, efficiency-optimization schemes for the NRSPDAB dc–dc converter, and thorough comparisons of different optimization methods are discussed in detail.

1. The typical modulation methods, including the advanced phase-shift modulation and the variable-frequency modulation methods, are presented in this paper. Based on all possible modulation methods, SPS, DPS, EPS, and TPS modulation schemes are selected for NRSPDAB dc–dc converter and analyzed in detail. Moreover, the relative analysis of typical phase-shift modulation methods, including the SPS, DSP, EPS, and TPS modulation methods, is illustrated, which can explain why the TPS modulation method can always provides the best efficiency for an NRSPDAB dc–dc converter.

The TPS control mode is simplified as the conventional DPS, SPS, and EPS modes are the special conditions such as SPS ($D_1 = 0$ and $D_2 = D_3$), DPS ($D_1 = D_3 - D_2$), EPS ($D_3 - D_2 = 0$ or $D_1 = 0$). An overview of efficiency-optimization schemes for an NSDAB dc–dc converter, including power-loss model based optimization methods, reactive power optimization method, inductance current optimization method, ZVS range optimization schemes are presented in detail. The performance and simulations verifies the MCSO strategy with simple operation is suitable for all load conditions.

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