A Novel Dual Phase Shift Modulation for Dual-Active- Bridge Converter

Song Chi
State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology
Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology
Tianjin, China
chis@hebut.edu.cn

Peng Liu
State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology
Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology
Tianjin, China
liupeng135615@163.com

Xue Li
State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology
Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology
Tianjin, China
lixue@hebut.edu.cn

Mochen Xu
State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology
Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology
Tianjin, China
greatmcxu@126.com

Shanhu Li
State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology
Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology
Tianjin, China
shanhuli@hebut.edu.cn

***Abstract*—The isolated dual active bridge (DAB) dc-dc converter with conventional dual-phase-shift (DPS) modulation exhibits large variations of currents under a small change of phase shift ratio at light load and larger peak current and reactive power at non-heavy load. To solve this problem, this paper proposes a novel dual phase shift (NDPS) modulation method based on two degrees of freedom under non-heavy load conditions. By redefining the constraints of two inner phase shift ratios and one outer phase shift ratio, NDPS modulation achieves a wider phase shift adjustment range at non-heavy load, and basically eliminates reactive power. By establishing mathematical models of transmission power, the paper introduces and analyzes the operating principle of the NDPS modulation in detail, and provides the operation mode analysis of the converter. Finally, the effectiveness of the proposed method is verified by experimental result.**

Keywords—Dual active bridge (DAB), Reactive power, Novel dual phase shift (DPS), Transmission power, Non-heavy load

I. INTRODUCTION

The dual active bridge (DAB) converter is a bidirectional DC-DC converter which possesses the advantages of simple structure, symmetry, high power density, galvanic fault isolation, and easy implementation of soft switching[1]. In recent years, it has important applications in the field of new energy, such as electric vehicles, uninterruptible power supplies, new energy power generation and DC power distribution [2-4].

Fig. 1 shows the circuit schematic of the isolated DAB converter. Traditional phase-shift modulation strategy for the DAB converter is called single phase shift (SPS) modulation. This phase-shift modulation method is accompanied by a large power reflow and a large current stress, and when the voltage ratio of the two sides is not equal to 1, the full range of zero-voltage-switching (ZVS) cannot be realized [5]. In [6], a dual phase shift (DPS) modulation method was proposed, which can effectively eliminate a large amount of power reflow, reduce current stress, broaden the range of soft switching, and increase the efficiency of the converter. Since there are two degrees of freedom, DPS modulation is simple and flexible [7]. Paper [8] and paper [9] respectively model the current stress and the reflow power functions, and apply mathematical methods to obtain the optimal performance under DPS modulation. The triple phase shift modulation is proposed in reference [10], it further improves the overall performance of the converter and makes the control more flexible. However, because of its three degrees of freedom, triple phase shift has the complexity of modulation. Therefore, the phase-shifting modulation based on two degrees of freedom is more simple and easy to implement [11,12]. Nevertheless, there are still partial reactive power in conventional DPS modulation under non-heavy load conditions. Besides, conventional DPS modulation method has a small adjustment range of phase shift ratio when transmitting the same power under light load conditions, and the change of phase shift ratio causes a relatively large inrush current which impact on the switches and compromise the safe operation of the converter [13,14]. All the possible phase-shifting modulation strategies of DAB converter are described in reference [15], but one of them is not elaborated in detail.

This work supported by 1. Research on High Frequency Power Electrionic Technology and Application. "100 People Plan" Funding for Introducing Overseas High-level Talents of Hebei Province, No.E2015100007.

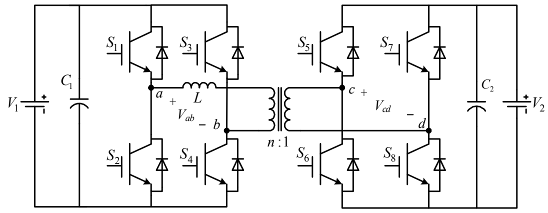


Fig. 1: Circuit schematic of the isolated DAB converter

According to the previous discussion, to solve the problem of reactive power and large inductor current with conventional DPS under non-heavy load condition, this digest proposes a novel dual phase shift (NDPS) modulation method. The modulation principle of NDPS is to redefine constraint relationship between two inner shift ratios and outer shift ratio, which are the outer shift ratio and the inner shift ratio of primary H bridge as one freedom degree of the NDPS, and the inner shift ratio of secondary H bridge as another freedom degree. The NDPS modulation is especially suitable for non-heavy load power transmission. It has a wide adjustment range of phase shift at the same low power transmission, low variations of currents, eliminates a large amount of reactive power, and increases the efficiency of the converter. By comparing the power characteristics of the traditional DPS and the novel DPS, it is concluded that the NDPS has excellent performance under the condition of non-heavy load.

II. CONVENTIONAL DPS MODULATION

For the convenience of analysis, the base power value P_b and the per unit of transmission power $P_{out[p.u.]}$ can be expressed as

$$P_b = \frac{nV_1V_2}{8f_sL} \quad (1)$$

$$P_{out[p.u.]} = \frac{P_{out}}{P_b} \quad (2)$$

Where n is the transformer turns ratio, V_1 is the input voltage, V_2 is the output voltage, f_s is the switching frequency, L is the inductance of primary bridge, P_{out} is the transmission power. If $P_{out[p.u.]}$ is less than 0.67, it can be defined as a non-heavy load.

The traditional DPS modulation includes two phase shift ratios: phase shift ratio between the primary and secondary side of the transformer D_2 (outer phase shift ratio) and phase shift ratio between the gate signals of the diagonal devices in the same side D_1 (inner phase shift ratio), the inner shift ratio D_1 includes $D_{1\text{-}1}$ in primary H bridge and $D_{1\text{-}2}$ in secondary H bridge, D_1=$D_{1\text{-}1}$=$D_{1\text{-}2}$ with conventional DPS. Fig. 2 shows the waveforms of DPS modulation. The product of the primary side voltage V_{ab} and inductor current i_L is the instantaneous power P. The portion where the instantaneous power is negative represents the reactive power. Due to the addition of the inner phase shift ratio D_1, the waveform of the primary side voltage V_{ab} contains zero level and the existence of zero level eliminates the part of reactive power. Form Fig. 2, it still contains the reactive power of the transmission power with the DPS modulation.

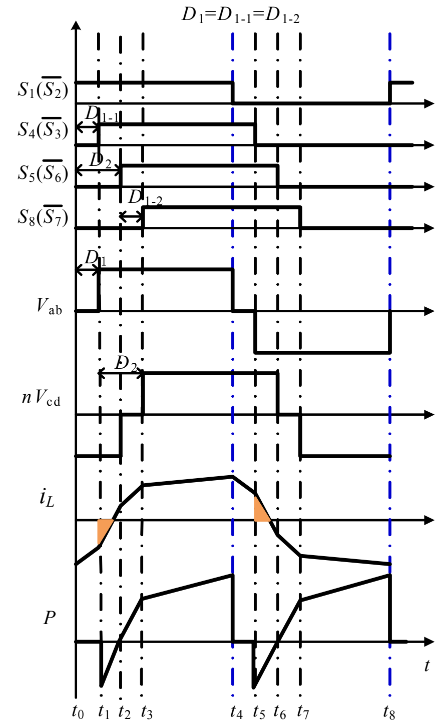


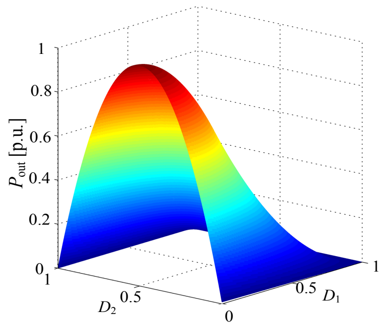
Fig. 2: Waveforms of DPS modulation (case II: $D_2 > D_1$, $D_1+D_2 < 1$)

According to different combinations of inductor voltages with D_1 and D_2, by neglecting the losses of converter, the transmission power of DPS modulation is shown in Table I. From Table I, the transmission power can be divide into four cases with DPS modulation.

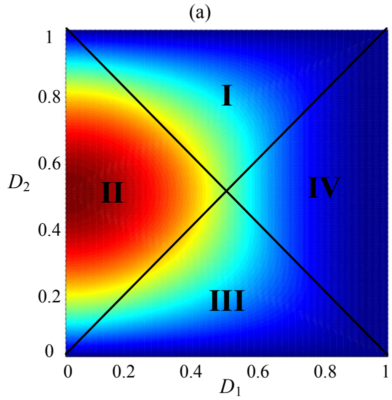
Fig. 3 show the 3-D model and 2-D model of the DPS transmission power with $D_2 \in [0, 1]$ and $D_1 \in [0, 1]$. As shown in Fig. 3(a), the maximum transmission power $P_{out[p.u]}$ is obtained under $D_1 = 0$ and $D_2 = 0.5$ with DPS modulation and its value is 1. As shown in Fig. 3(b), the case IV represents the light load region. Light load region only accounts for a quarter of total region, so the adjustment ranges of traditional DPS light load phase shift angle is relatively small.

TABLE I. OUTPUT POWER (P.U.) OF DAB CONVERT WITH DPS

Case	Boundary	P_{out}(p.u.)
I	$D_2 > D_1, D_2 + D_1 \geq 1$	$2(1-D_2)(1+D_2-2D_1)$
II	$D_2 > D_1, D_2 + D_1 < 1$	$-2D_1^2 - 4D_2^2 + 4D_2$
III	$D_2 \leq D_1, D_2 + D_1 < 1$	$2(2-2D_1-D_2)D_2$
IV	$D_2 \leq D_1, D_2 + D_1 \geq 1$	$2(1-D_1)^2$



(a)



(b)

Fig. 3: Transmission power of DAB converter by using DPS modulation with D_1 and D_2. (a) 3-D model. (b) 2-D model.

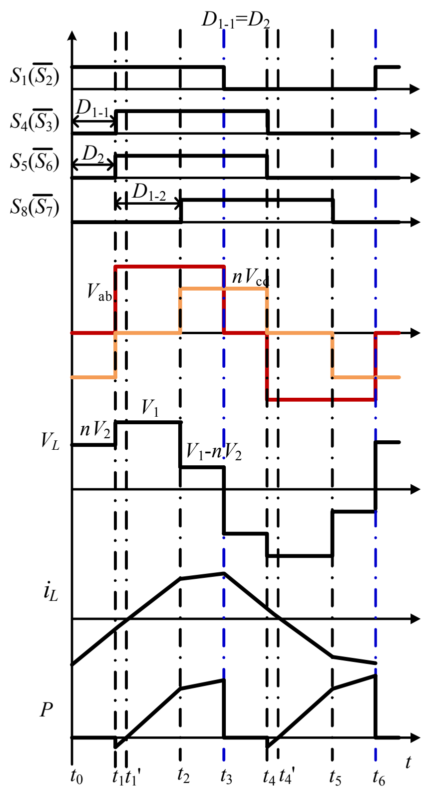
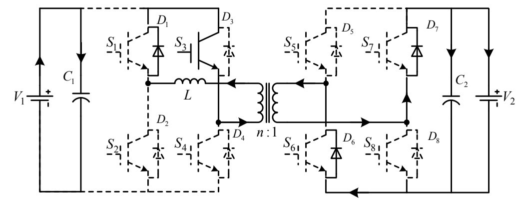
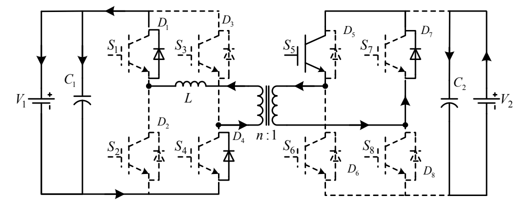


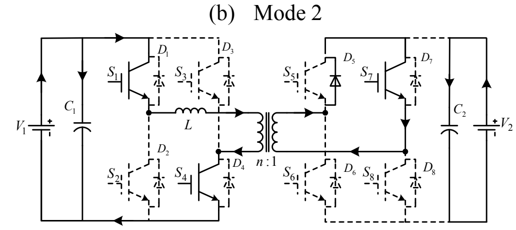
Fig. 4: Waveforms of NDPS modulation (case I: $D_{1\text{-}2}+D_2 < 1$)



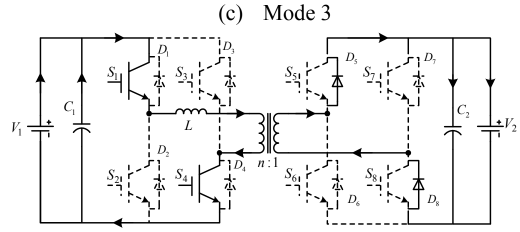
(a) Mode 1



(b) Mode 2



(c) Mode 3



(d) Mode 4

Fig. 5 Operation modes of the converter with NDPS modulation

III. NDPS MODULATION FOR DAB CONVERTER

A. The principle of NDPS modulation

In order to solve the problem of reactive power under non-heavy load condition and current large variation with change of phase shift ratio under light load condition, a novel DPS is proposed. The main waveforms of NDPS modulation are shown in Fig. 4. In the NDPS modulation, the novel constraint relationship is that the outer phase shift ratio D_2 and the inner phase ratio in primary H bridge $D_{1\text{-}1}$ are simultaneously as a freedom of degree (ie. $D_2 = D_{1\text{-}1}$), and the inner phase shift ratio in secondary H bridge $D_{1\text{-}2}$ is the other freedom of degree. As can be seen from Fig. 4, the driver of signals of S_4 and S_5 are the same, which is remarkable feature of the NDPS modulation.

In Fig. 4, compared to the waveforms of DPS, the reactive power of the transmission power is basically eliminated under the NDPS modulation, and the peak current is smaller than that of DPS.

B. Operation Modes of DAB Converter in NDPS

To simplify the process of the analysis, we assume that the converter has reach steady operation states. According to the principle waveforms in Fig. 4, the operation mode of converter can be divided into eight states. However, due to the volt-second balance principle of inductor, the switching waveform has half-period symmetry. Therefore, this paper only introduces four operation states in the half-period as shown in Fig. 5. The inductance current $i_L(t)$ at any time can be expressed as

$$\frac{di_L(t)}{dt}=\frac{V_{ab}-nV_{cd}}{L} \tag{3}$$

1) Mode 1(t_0-t_1): Fig. 5(a) shows the equivalent circuit for the mode 1. Just before t_0, S_2 and S_3 are conducting. The current i_L is in negative direction, the current flows through D_1 and S_3. The secondary full bridge current flows to source V_2 through D_6 and D_7. At this mode , the V_{ab} is zero, and the inductance current can be expressed as

$$i_L(t_1)=i(t_0)+\frac{nV_2}{L}(t-t_0) \tag{4}$$

2) Mode 2(t_1-t_1'): Fig. 5(b) shows the equivalent circuit for the mode 2. If current i_L is still in negative direction at t_1 then at t_1, S_3 and S_6 are turned OFF and S_4 is turned ON at zero current, i_L is carried from inductor L to source V_1 by D_1 and D_4, V_{ab} is equal to the supply power voltage V_1; secondary side current flows through S_5 and D_7, so V_{cd} is equal to zero. The inductance current decays negatively until t_1' time is zero, and the inductance current can be expressed as

$$i_L(t)=i_L(t)+\frac{V_1}{L}(t-t_1) \tag{5}$$

3) Mode 3(t_1'-t_2): Fig. 5(c) shows the equivalent circuit for the mode 3. During the t_1'-t_2 time, all the switch drive signals were not changed. At time t_1', inductor current becomes positive, it flows to the transformer through S_1 and S_4. On the secondary,the current becomes free flow through S_7 and D_5, and V_2 charges to C_2 at this time. The inductor current expression is the same as (5).

4) Mode 4(t_1'-t_2): Fig. 5(d) shows the equivalent circuit for the mode 4. Before time t_2, S_8 does not flow current, and at time t_2, S_7 turns off , S_8 is turned on at zero current. Since the driver signal of the left full-bridge switchs do not change, the state of the primary circuit is the same as that of mode 3, and the secondary current becomes power supply to V_2 through D_5 and D_8, and the inductor current value continues to increase. At this mode, V_{ab} is equal to V_1, V_{cd} is equal to V_2, and the inductor current is expressed as

$$i_L(t)=i_L(t)+\frac{V_1-nV_2}{L}(t-t_2) \tag{6}$$

After the above analysis, the voltage V_{ab} is zero in the t_0-t_1, and the V_{ab} is also zero in the t_3-t_4, therefore a large reactive power can be reduced.

C. Transmission Power of NDPS modulation

According to the analysis of operation modes in section B, assuming t_0 =0, the switching period is T, and the switching frequency is f_s=1/T. The average current of the inductor over one switching period should be zero in steady state. In the range of $D_{1\text{-}2}$+D_2<1, $D_2\in$ [0, 1] and $D_{1\text{-}2}\in$ [0, 1], from (4) to (6), currents of inductor can be derive as

$$\begin{cases} i_L(t_0)=-\dfrac{nV_2}{4f_sL}\left[k(1-D_2)+2D_2+D_{1-2}-1\right] \\ i_L(t_1)=-\dfrac{nV_2}{4f_sL}\left[k(1-D_2)+D_{1-2}-1\right] \\ i_L(t_2)=-\dfrac{nV_2}{4f_sL}\left[k(1-D_2-2D_{1-2})+D_{1-2}-1\right] \end{cases} \tag{7}$$

where k= $V_1/(nV_2)$ is the voltage conversion ratio, and we assume k ≥1 in the paper, the other condition k <1 can be analyzed similarity. When the power flows from V_1 to V_2, the transmission power is

$$\begin{aligned} P_{\text{out}} &= \frac{2}{T}\int_0^{\frac{T}{2}} V_{ab} i_L(t)\,dt = \\ &\frac{nV_1V_2}{4f_sL}\left[D_{1-2}(1-D_{1-2})+D_2(1-D_2-D_{1-2})\right] \end{aligned} \tag{8}$$

The transmission power unit value is

$$P_{\text{out[p.u.]}}=2D_{1-2}(1-D_{1-2})+2D_2(1-D_2-D_{1-2}) \tag{9}$$

According to different combinations of inductor voltages with $D_{1\text{-}2}$ and D_2, by neglecting the losses, the transmission power with NDPS modulation can be expressed in Table II.

TABLE II. OUTPUT POWER (P.U.) OF DAB CONVERT WITH NDPS

Case	Boundary	P_{out}(p.u.)
I	$D_{1-2}+D_2\le 1$	$2D_{1-2}(1-D_{1-2})+2D_2(1-D_2-D_{1-2})$
II	$D_{1-2}+D_2>1$	$2(1-D_{1-2})(1-D_2)$

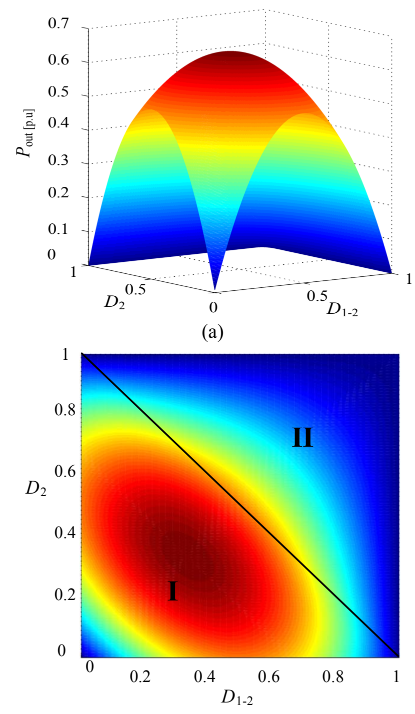


Fig. 6 Transmission power of DAB converter by using NDPS modulation with $D_{1\text{-}2}$ and D_2. (a) 3-D model. (b) 2-D model.

There are two cases of transmission power in the NDPS modulation. Comparing light load region of DPS and NDPS from Table I and Table II, the equation of case IV with DPS only has one variable, however, there are two variables in the equation of case II with NDPS. Consequently, the adjustment of light load region with NDPS is more flexible than that of DPS. Therefore, when transmitting the same power, there is less variation of current under the NDPS.

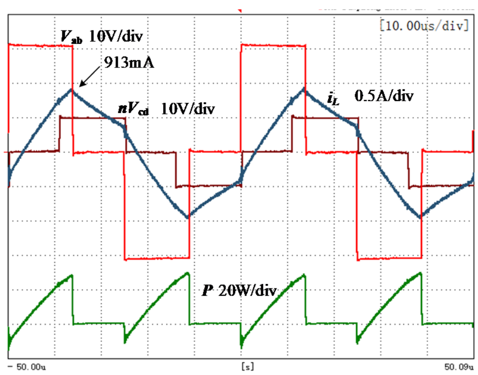
Fig. 6 show the 3-D model and 2-D model of the NDPS transmission power with $D_2 \in [0, 1]$ and $D_{1\text{-}2} \in [0, 1]$, It can be seen that, the NDPS has a wide range of phase shift ratio adjustments compared to the light load operation of the traditional DPS, and the maximum transmission power $P_{out[p.u.]}$ with NDPS modulation is 0.67.

IV. EXPERIMENTAL RESULT

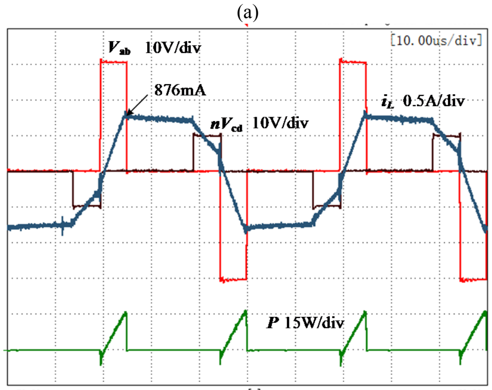
In order to verify the aforementioned analysis, a laboratory prototype is construed based on TMS320F28335 DSP controller. Table III shows the main parameters of converter. The experimental results were obtained under the NDPS and DPS modulation.

TABLE III. MAIN PARAMETER OF PROTOTYPE

Parameter	Value
Primary dc voltage V_1	30V
Secondary dc voltage V_2	10V
Switching frequency f_s	20kHz
Transformer turn n	1
Sum of inductance L	155μH
Voltage of conversion ratio k	3

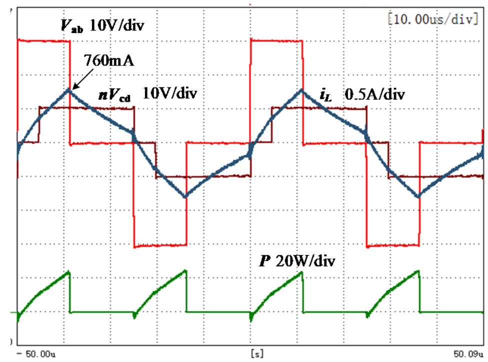


(a)

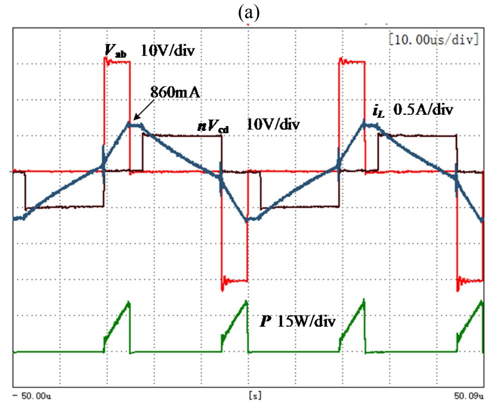


(b)

Fig. 7 Experimental waveforms of DPS modulation '(a) non-heavy load ($P_{out\,[p.u.]}$= 0.6) (b) light load. ($P_{out\,[p.u.]}$= 0.1)



(a)



(b)

Fig. 8 Experimental waveforms of NDPS modulation '(a) non-heavy load ($P_{out\,[p.u.]}$= 0.6) (b) light load. ($P_{out\,[p.u.]}$= 0.1)

Fig. 7 and 8 show the experimental waveforms of two H bridge voltages, inductance current and instantaneous transmitting power with the DPS and the NDPS modulation, respectively. As can be seen form Fig. 7 (a) and Fig. 8 (a), the NDPS eliminate reactive power and reduce the peak inductance current under the non-heavy load. Comparing Fig. 7 (b) and Fig. 8 (b), the NDPS also has no reactive power under light load. These results show the correctness of the theoretical study.

V. CONCLUSION

This paper proposed a novel dual phase shift modulation. The theoretical and experimental results demonstrate that the novel dual phase shift modulation has excellent performance, such as eliminate reactive power under non-heavy load, smaller peak current of inductance than that of conventional DPS. Under light load condition, NDPS modulation expands regulating range of transmission power and enhances regulatingflexibility. Besides, NDPS modulation is simple in principle and easy to implement.

REFERENCES

[1] R. W. A. A. De Doncker, D. M. Divan and M. H. Kheraluwala, "A three-phase soft-switched high-power-density DC/DC converter for high-power applications," in *IEEE Transactions on Industry Applications*, vol. 27, no. 1, pp. 63-73, Jan.-Feb. 1991.

[2] S. Inoue and H. Akagi, "A Bidirectional DC–DC Converter for an Energy Storage System With Galvanic Isolation," in *IEEE Transactions on Power Electronics*, vol. 22, no. 6, pp. 2299-2306, Nov. 2007.

[3] S. Inoue and H. Akagi, "A Bidirectional Isolated DC–DC Converter as

a Core Circuit of the Next-Generation Medium-Voltage Power Conversion System," in *IEEE Transactions on Power Electronics*, vol. 22, no. 2, pp. 535-542, March 2007.

[4] F. Krismer and J. W. Kolar, "Efficiency-Optimized High-Current Dual Active Bridge Converter for Automotive Applications," in *IEEE Transactions on Industrial Electronics*, vol. 59, no. 7, pp. 2745-2760, July 2012.

[5] H. Bai, Z. Nie and C. C. Mi, "Experimental Comparison of Traditional Phase-Shift, Dual-Phase-Shift, and Model-Based Control of Isolated Bidirectional DC–DC Converters," in *IEEE Transactions on Power Electronics*, vol. 25, no. 6, pp. 1444-1449, June 2010.

[6] H. Bai and C. Mi, "Eliminate Reactive Power and Increase System Efficiency of Isolated Bidirectional Dual-Active-Bridge DC–DC Converters Using Novel Dual-Phase-Shift Control," in *IEEE Transactions on Power Electronics*, vol. 23, no. 6, pp. 2905-2914, Nov. 2008.

[7] B. Zhao, Q. Song and W. Liu, "Power Characterization of Isolated Bidirectional Dual-Active-Bridge DC–DC Converter With Dual-Phase-Shift Control," in *IEEE Transactions on Power Electronics*, vol. 27, no. 9, pp. 4172-4176, Sept. 2012.

[8] B. Zhao, Q. Yu and W. Sun, "Extended-Phase-Shift Control of Isolated Bidirectional DC–DC Converter for Power Distribution in Microgrid," in *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4667-4680, Nov. 2012.

[9] B. Zhao, Q. Song, W. Liu and W. Sun, "Current-Stress-Optimized Switching Strategy of Isolated Bidirectional DC–DC Converter With Dual-Phase-Shift Control," in *IEEE Transactions on Industrial Electronics*, vol. 60, no. 10, pp. 4458-4467, Oct. 2013.

[10] K. Wu, C. W. de Silva and W. G. Dunford, "Stability Analysis of Isolated Bidirectional Dual Active Full-Bridge DC–DC Converter With Triple Phase-Shift Control," in *IEEE Transactions on Power Electronics*, vol. 27, no. 4, pp. 2007-2017, April 2012.

[11] H. Wen and W. Xiao, "Bidirectional dual-active-bridge DC-DC converter with triple-phase-shift control," *2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, 2013, pp. 1972-1978.

[12] J. Huang, Y. Wang, Z. Li and W. Lei, "Unified Triple-Phase-Shift Control to Minimize Current Stress and Achieve Full Soft-Switching of Isolated Bidirectional DC–DC Converter," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4169-4179, July 2016.

[13] L. Zhu, A. R. Taylor, G. Liu and K. Bai, "A Multiple-Phase-Shift Control for a SiC-Based EV Charger to Optimize the Light-Load Efficiency, Current Stress, and Power Quality," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 4, pp. 2262-2272, Dec. 2018.

[14] B. Zhao, Q. Song, W. Liu and Y. Zhao, "Transient DC Bias and Current Impact Effects of High-Frequency-Isolated Bidirectional DC–DC Converter in Practice," in *IEEE Transactions on Power Electronics*, vol. 31, no. 4, pp. 3203-3216, April 2016

[15] B. Zhao, Q. Song, W. Liu and Y. Sun, "Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System," in *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4091-4106, Aug. 2014.