DC Bias Abatement in Dual Active Bridge Converter using Covalent Active and Passive Components

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***Abstract*—The Dual Active Bridge (DAB) converter is the most attractive bidirectional DC-DC converter topology in the distribution network. However, the DC bias is the most common issue in the dual active bridge converter due to the sudden change in internal or external phase shift angles to regulate the power signal. Consequently, it will increase conduction losses, a core saturation problem of High-Frequency Transformer (HFT), and loss of Zero Voltage Switching (ZVS) operation. Therefore, this paper presents the DC bias abatement in the DAB converter using covalent active and passive components to alleviate these problems. The proposed method employs the series capacitor in the windings of HFT as the passive component. Whereas the DAB converter's control variables are used as the active component, which modulates the power signal. Thus, the detailed control strategy along with covalent active and passive components to mitigate the DC bias problem is presented in this paper. The experiential results validate the performance of the proposed control method in terms of wide-range of voltage regulation and soft-switching operations**.

Keywords—DC-DC converter, Solid State Transformer, Dual Active Bridge Converter, Steady state DC bias, Transient DC bias, Co-ordinate control.

I. Introduction

Due to the advent of smart technology, there is a revolution in the power architecture of distribution networks. Consequently, the demand for high power density DC-DC converters has been proliferated in recent years. In the literature, the number of isolated, non-isolated, and resonant DC-DC converter topologies [1] are presented with their significant features for various applications in the distribution network. Among these, Dual Active Bridge (DAB) converter

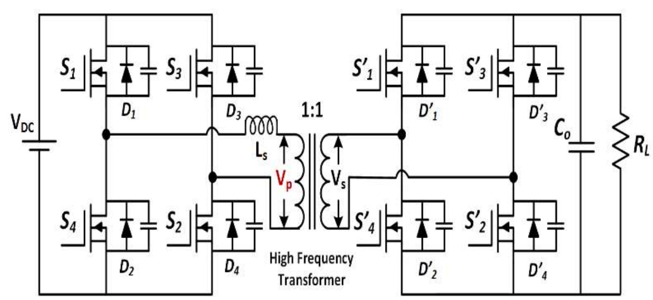

Fig. 1. Dual Active Bridge Converter.

[2]–[4] is the most attractive DC-DC converter topology for high power application due to its high power density operation, bidirectional power flow feature, and high-frequency galvanic isolation.

The two active bridges on both the sides of the High-Frequency Transformer (HFT) are used in the DAB converter, as shown in Fig.1. Both the bridges are phase-shifted from each other by the phase shift angle ϕ. As a result, it controls the amount of power being transferred on either side of HFT. Further, it enables the square wave input voltage and leakage inductance of HFT as the main power transfer components. Therefore, the output power equation as the function of control variable ϕ is evaluated as,

$$P_{out} = \left(1-\frac{\phi}{\pi}\right)\frac{V_p\ V_s\ \phi}{2\pi f_s L_s} \tag{1}$$

Where the V_p and V_s are the primary and secondary sides voltages of HFT, L_s is the leakage inductance, and f_s is the switching frequency of the DAB converter. The voltage equation for the square wave input voltage and its reflected current in the primary winding of HFT are evaluated as,

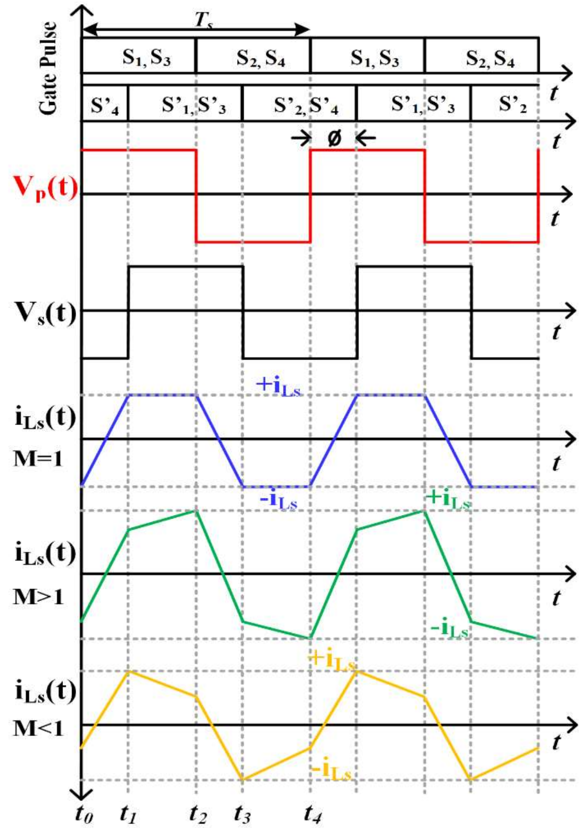

Fig.2. Key waveforms of Dual Active Bridge Converter [17].

$$V_p(t) = \sum_{1,3,5..}^{\infty}\left[\frac{4V_{DC}}{n\pi}\sin\left(n\omega t\right)\sin\left(\frac{\delta}{2}\right)\right] \tag{2}$$

$$i_{Ls}(t) = \sum_{1,3,5..}^{\infty}\left[\frac{4V_{DC}}{n\pi Z_{eq}}\sin\left(n\omega t-\alpha\right)\sin\left(\frac{\delta}{2}\right)\right] \tag{3}$$

$$V_s(t) = \sum_{1,3,5..}^{\infty}\left[\frac{4V_{DC}}{n\pi}\sin\left(n\omega t-\phi\right)\sin\left(\frac{\delta}{2}\right)\right] \tag{4}$$

Where δ is the duty cycle, Z_{eq} is the equivalent input impedance, and its corresponding angle α refers to the primary side of HFT, and G is the gain achieved on the secondary side of HFT. Fig.2 shows the annotated steady-state key waveforms of the DAB converter. It shows that the shape of the inductor current is highly influenced by the HFT's turn ratio, i.e., M.

The single-phase shift (SPS) angle of the DAB converter is abruptly changed to regulate the output voltage during a step load change. Consequently, the transient DC bias [5], [6] is occurred in the winding current. It leads to the violation of peak values of inductor current based on the turn ratio of HFT. It is the most common and serious issue in the DAB converter. Moreover, the discrepancy in the pulse width from the driving control circuit, the discrepancy between the characteristics parameters of switches, and the device's on-state voltage drop also lead to the transient DC bias in the inductor current.

This transient DC bias causes (i) DC offset in the HFT's current waveform, (ii) increased current stress in the active devices, (iii) core saturation of HFT, and (iv) overshoot or undershoot in the winding current may affect the reliability of DAB converter, and (v) affects dynamic response. Hence, the various control techniques are employed to alleviate the transient DC bias. [7] method employs the active flux balancing control technique to eliminate the transient DC bias. In this method, the duty cycle of both the active bridges is adjusted independently to balance the magnetic flux. However, the corresponding duty cycle calculations make the control algorithm cumbersome.

Further, [8] employs the two control loop flux balancing method in which one control loop monitors the magnetizing current, whereas the other control loop keeps the average current zero through the primary and secondary windings of HFT. The magnetic ear method [9] to eliminate transient DC bias uses an additional coil, flux sensor, and air gap placement inside the core to control the excitation current. This will affect the structure aspects of the DAB converter and its effectiveness. On another side, various phase shift control methods, [10]– [13] are employed in which dissociate transitional periods are added to modulate the power flow. Consequently, it exacerbates the non-linearity of the system and complicates the closed-loop control design.

Beside this, the transient DC bias problem is also solved on the hardware side using DC blocking capacitor in [14]. Also, the structure of topology, i.e., Half Bridge (HB) or Full Bridge (FB), used in the DAB converter affects its gain, i.e. (G) [15], [16]. Hence, this effect needs to be considered while providing the solution to alleviate the transient DC bias in the winding current.

Therefore, in the view of the above-mentioned concerns regarding the solutions to alleviate the Transient DC bias in the DAB converter, the proposed solution is presented in this paper. In the proposed method, the transient DC bias is eliminated using the covalent active and passive components. The proposed method utilizes the structural behavior and prevailing control variables to alleviate the transient DC bias in the winding current. Further, the behavior of the proposed solution is validated in terms of bidirectional power flow feature, output voltage regulation, soft-switching operation, and ease of implementation.

This paper follows as, Section II describes the evaluation of the proposed method. It covers the ease and implementation of the proposed control method based on the different aspects. Section III validates the effectiveness of the proposed method in alleviating transient DC bias through the simulation and experimental results. Section IV provides the conclusion.

II. Proposed Control method

In the DAB converter, transient DC bias is the design challenge due to the volt-second imbalance of the high frequency transformer. It results in DC offset in the current signal of HFT and series inductor L. The main objective of the proposed control method is to alleviate transient DC bias in the current signal of HFT and enhance its dynamic response. Hence, the DC blocking capacitor as the passive component is placed symmetrically on the primary as well as the secondary winding of HFT. Whereas the phase shift angle and switching frequency of the DAB converter are employed as the active components in the proposed method.

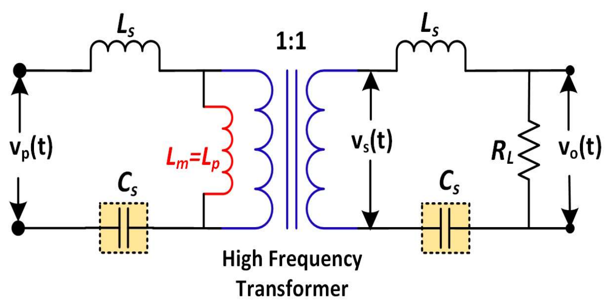

Fig. 3. DAB converter's equivalent circuit.

Fig.3 shows the DAB converter's equivalent circuit. It indicates that the DC blocking capacitors (Cs) are connected in series with the primary and secondary sides of HFT. Further, the leakage inductance of primary and secondary sides of HFT also acts as the series elements. Hence, series-parallel LLC resonant tank circuits are realized in the DAB converter by intervening in the parasitic inductance of HFT.

The capacitors Cs block the DC offset occurs due to the transient DC bias in the DAB converter. Further, it assists in the soft-switching operation. Hence, the gain of the resonant tank circuit is evaluated as,

$$G = \frac{v_s{}^F}{v_p{}^F} = \frac{Z_p}{Z_p + Z_s} \tag{5}$$

$$\begin{aligned} Z_s &= j\left(X_{Leakage} + X_{Ls}\right) - jX_{cs} \\ Z_p &= \frac{jX_p\ R_{ac}}{jX_p + R_{ac}} \\ Z_{eq} &= Z_s + Z_p \end{aligned} \tag{6}$$

The series and shunt branch element's impedances are denoted as Z_s and Z_p, respectively.

$$G = \frac{\left(j\omega L_p\right) \| \left(R_{ac}\right)}{\left(j\omega L_p\right) \| \left(R_{ac}\right) + j\omega L_s - \dfrac{1}{j\omega C_s}} \tag{7}$$

$$G = \frac{k}{\sqrt{\left(1 + k + \dfrac{1}{f_n^2}\right)^2 + Q^2 k^2 \left(f_n - \dfrac{1}{f_n}\right)^2}} \tag{8}$$

$$k = \frac{L_p}{L_s}, \quad Q = \frac{1}{R_{ac}}\sqrt{\frac{L_s}{C_s}}, f_n = \frac{f_s}{f_r}$$

$$X_{Ls} = \omega_s L_s,\ X_{Lp} = \omega_p L_p, \quad X_{Cs} = \frac{1}{\omega_s C_s}$$

From (8), the gain of the resonant tank circuit is found to be a function of the switching frequency fs, as well as the AC equivalent resistance R_{ac}. Therefore, the current stress is evaluated based on the voltage gain and control variable (ϕ) as,

$$i_{\text{stress}} = \int \frac{V_p - V_s}{L_s}\, dt \tag{9}$$

From (4)-(9), it is observed that the current stress is the function of gain and phase shift angle ϕ. Further, the gain is varied according to the structure of topology, i.e., FB or HB, employed in the DAB converter. The large change in the outer phase shift angle increases the current stress during the step load change. This sudden change in the large phase shift angle strikes the undershoot or overshoot in the current signal of HFT. As a result, it creates a volt-second imbalance and magnetic flux imbalance in the core of HFT. This will lead to the core saturation of HFT due to the DC components, and it is expressed as,

$$i_{DC} = i_{pDC} - i_{sDC} \tag{10}$$

Where i_{pDC} and i_{sDC} are the DC components in the primary and secondary windings of HFT. Further, its dynamic response is also assessed using the DC bias's attenuation velocity. However, the DC bias is decayed exponentially with the time due to the *Ls* and *R*, and it is expressed as,

$$i_{TDC} = I_{TDC}\, e^{\frac{-t}{\tau}} = I_{TDC}\, e^{\frac{-Ls}{R}t} \tag{11}$$

Where I_{TDC} denotes the peak value of the DC component decided by the transient DC bias, and τ denotes the decay time constant.

On the other side, the use of only the control variable (ϕ) in the DAB converter required a significant value of phase shift angle during the step load change, resulting in a high DC component in the winding current. Hence, the DAB converter's switching frequency is added as another control variable in conjunction with the phase shift angle. It is employed to decrease the switching frequency and increase the phase shift angle when the load is varied from 100% to light load conditions. Thereby, the required value of phase shift angle decreases during step load change. Further, it will reduce the transient DC bias and DC component in the winding current of HFT due to reduced phase shift angle.

Nevertheless, the transient bias is occurred due to the small change in the phase shift angle employed by the proposed method. However, it is then compensated by the series resonant capacitor connected in series with both the winding of HFT. Further, the dual control variables in the proposed method improved the performance of the DAB converter in terms of voltage regulations within the narrow range of switching frequency, zero voltage switching operation under light load conditions, and ease of implementation.

III. VALIDATION OF THE PRIOPOSED METHOD

A. Simulation Results:

The DAB converter having the power rating of 5kW is modeled and simulated in the PSIM software. Table-I shows the simulated and experimental parameters of the DAB converter. A 400V DC is given as the input to the DAB converter, and output is maintained constant at the 400V DC under different loading conditions. Fig.4 shows the various signals of the conventional DAB converter during the step load change. In Fig.4(a), it is observed that the change in the phase shift angle takes to modulate the power flow at the step moment of 0.25. The phase shift angle increases after the step moment as the load increases from 1.8 kW to 3.2 kW. The transient DC bias that occurs in the winding current during the step moment is shown in Fig.4(b) and Fig.4(c).

Further, the DAB converter is simulated by employing the proposed solution for the same power rating as the conventional DAB converter in Fig. (4). In the proposed method, both the control variables, i.e., phase shift angle and switching frequency, is employed during the step load change. Fig.5 shows the simulated response of various signals in the proposed method.

Fig.5 (b) shows that the transient occurs in the winding current of HFT during the load change at the step moment. Further, it shows that the transient pattern is symmetrical along the X-axis. Thus, it reveals that the DC components are blocked out by the series resonant capacitors employed on both sides of HFT. As a result, it reduces the current stresses and balances the magnetic flux along the core of HFT.

TABLE I
SPECIFICATION DETAILS OF THE PROPOSED SYSTEM

Components		Description
Power Output (Simulation)		5 kW
Power Output (Experimentation)		2 kW
Input and Output voltages		DC 400V
DAB	Switching frequency	102 kHz
	Resonant frequency	100 kHz
	Series inductor of tank circuit Ls	42 µH
	Turns ratio	1:1
	Series Capacitor of tank circuit Cs	56 nf
	Magnetizing inductor of HFT Lm	56 µH
	DC link capacitor Co	200 µf

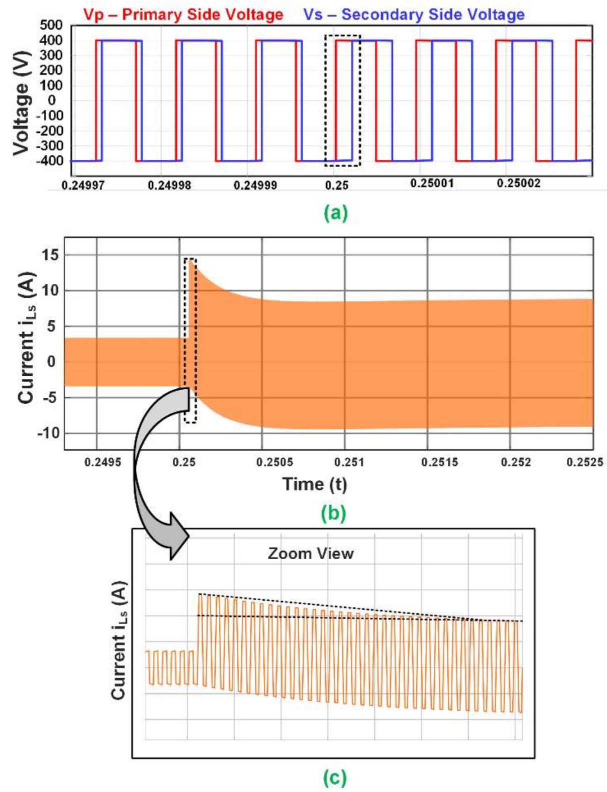

Fig. 4. Voltage and current through the windings of high frequency transformer, during step load change in the conventional DAB converter.

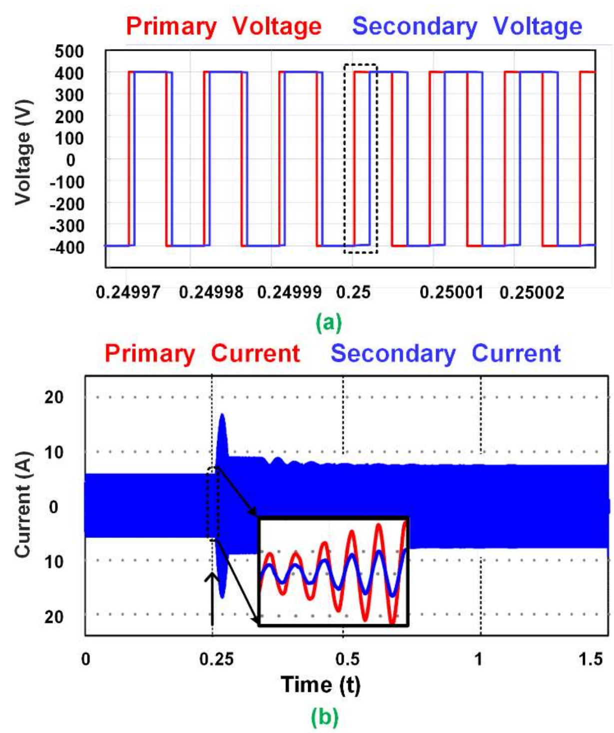

Fig. 5. Voltage and current through windings of high frequency transformer during sudden load change against proposed control method.

B. Experimental Validations:

The hardware prototype of the proposed 2 kW modified DAB converter is built up in the laboratory. All the magnetic components such as resonant inductor and high-frequency transformer are designed referring to [18]. The series branch element manifests the leakage inductance of HFT, whereas the parallel branch element manifests the magnetizing inductance of HFT. The values of required series and parallel branch elements are calculated using (5)-(8). Thus, the calculated values of all elements are shown in Table-I. The film capacitor, double metalized polypropylene, automotive grade, i.e., R76UN256050H4J, is selected. The calculated value of series resonant capacitors is connected in series with both the windings of HFT. This will benefit to eliminate the transient DC bias during the bidirectional power flow.

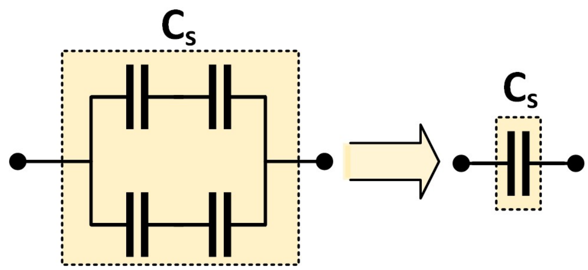

Fig. 6. Realization of series resonant capacitor.

Furthermore, a single capacitor cannot supply the required voltage and current demand. Hence, according to Fig.6, the two capacitors are linked in series to fulfill the voltage demand, while two sets of series connections are connected in parallel to meet the current demand.

Initially, the hardware model is loaded at full load condition. Afterward, increasing the switching frequency and decrease in the phase angle are employed from 100% load to light load conditions to regulate the output voltage. The experimental results during the step load change with the

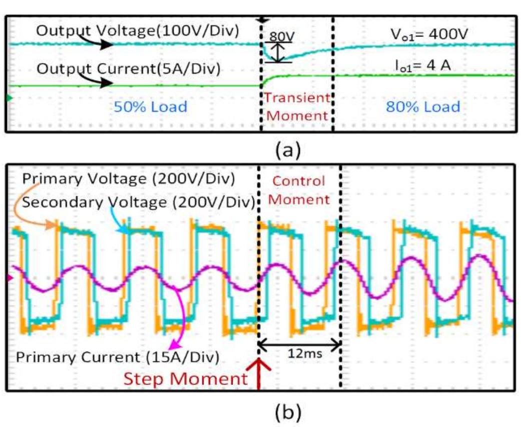

Fig. 7. Response of current and voltage across the high frequency transformer in the proposed method.

proposed method are shown in Fig.7. It shows that the load changes quickly from 50% to 80% of full load. As a result, the undershoot occurs in the output voltage during the transient moment, as shown in Fig.7(a). Further, Fig.7(b) shows that the change in the phase shift angle is taken at the step moment to maintain the constant output voltage. Thus, the output voltage is maintained constant by employing the dual degree control variables.

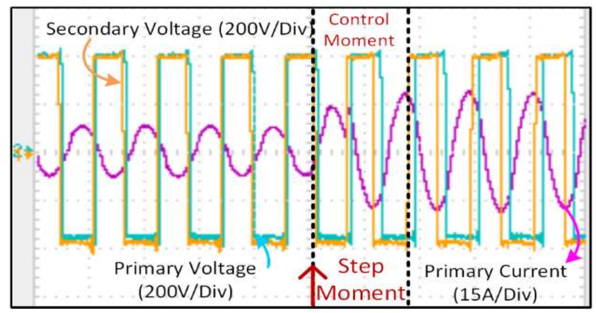

Fig. 8. The proposed method's transient response during a reverse power flow.

Nevertheless, transient DC bias, which occurs in the current of HFT due to the sudden change in the control variables, is blocked by the series resonant capacitor. Hence, the power signals of HFT are symmetrical along the X-axis, as shown in Fig.7(b). Thus, Fig.7(b) reveals that transient DC bias is eliminated using the proposed method during the control moment.

Similarly, the response of the proposed method against the transient DC bias while transmitting power in the reverse direction is analyzed experimentally. Fig.8 shows the transient response of the proposed method during the power flow in the reverse direction. It shows that the current direction is negative with respect to the square wave input voltage. Also, the current signal is symmetric along the X-axis, and there is no DC component in the winding current of HFT. Thus, the proposed method using the covalent active and passive components alleviate the transient DC bias problem in the DAB converter.

Further, the soft switching operations are monitored by evaluating the value of angle α from (3). The positive value of α before and after the step load change reveals that the proposed method achieves the zero voltage switching in the active devices. Moreover, this value of α is always lagging behind the input voltage of HFT in the soft-switching operation. Thus, the proposed method ensures the soft switching operation is realized under various loading conditions.

Thus, in the proposed method, by employing the series resonant capacitor and dual degree control variable, the performance of the DAB converter is improved concerning the wide range of voltage regulation, soft switching operation, and ease of implementation under the different loading conditions. Furthermore, the use of a dual degree control variable improves the control flexibility while transferring power in both directions. In addition to this, the proposed control method is able to maintain the volt second balance in the core of HFT irrespective of the transformer turns ratio.

In the comparison of the proposed control method with the other method to alleviate transient DC bias, the Triple Phase Shift (TPS) and Optimized Phase Shift (OPS) modulation scheme are employed to alleviate the transient DC bias. But these control methods require intense calculations to determine various internal and external phase shift angles. So, it is highly complicated to implement. On the other side, magnetic flux control methods are also employed to eliminate the transient DC bias. However, these methods require magnetizing current measurement, and the extraction of magnetizing current is difficult for practical applications. Nevertheless, the proposed method better performs to mitigate DC bias in the DAB converter concerning the experimental results.

IV. CONCLUSION

This paper presented the proposed method to alleviate the transient DC bias in the Dual Active Bridge (DAB) converter using the covalent active and passive components. In the proposed method, the series resonant capacitors employ as the passive component, which blocks the DC component in the winding current. Also, it assists in the soft-switching operation by acting as part of the resonant circuit. Further, the dual degree control variable is employed as the active component, which reduces the required phase shift angle for voltage regulation. As a result, it reduces the current stress on the switching devices. The proposed control method's active and passive components maintain the power waveform's symmetry during the sudden load change. It demonstrates that the proposed solution keeps the magnetic flux balance in the core of the high-frequency transformer. Therefore, it prevents the core saturation and heating problems. Further, the proposed control method is verified in the simulation and hardware model. Its effectiveness is demonstrated by simulation and experimental results during sudden load change.

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REFERENCES

1) R. L. Steigerwald, R. W. De Doncker and H. Kheraluwala, " A comparison of high-power DC-DC soft-switched converter topologies," in IEEE Transactions on Industry Applications, vol. 32, no. 5, pp. 1139-1145, Sept.-Oct. 1996, doi: 10.1109/28.536876.
2) M. N. Kheraluwala, R. W. Gascoigne, D. M. Divan and E. D. Baumann," Performance characterization of a high-power dual active bridge DCto-DC converter," in IEEE Transactions on Industry Applications, vol. 28, no. 6, pp. 1294-1301, Nov.-Dec. 1992, doi: 10.1109/28.175280.
3) 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, doi: 10.1109/TPEL.2012.2189586.
4) W. Choi, K. Rho and B. Cho, "Fundamental Duty Modulation of Dual-Active-Bridge Converter for Wide-Range Operation," in IEEE Transactions on Power Electronics, vol. 31, no. 6, pp. 4048-4064, June 2016, doi: 10.1109/TPEL.2015.2474135.
5) 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, doi: 10.1109/TPEL.2015.2445831.
6) Q. Bu, H. Wen, H. Shi and Y. Zhu, "A Comparative Review of High-Frequency Transient DC Bias Current Mitigation Strategies in Dual-Active-Bridge DC–DC Converters Under Phase-Shift Modulations," in IEEE Transactions on Industry Applications, vol. 58, no. 2, pp. 2166-2182, March-April 2022, doi: 10.1109/TIA.2021.3136498.
7) Wang, Z., Chai, J. and Sun, X. (2018), Method to control flux balancing of high-frequency transformers in dual active bridge dc–dc converters. The Journal of Engineering, 2018: 1835-1843. https://doi.org/10.1049/joe.2018.8338
8) Y. Panov, M. M. Jovanovi´c and B. T. Irving, "Novel transformer-flux balancing control of dual-active-bridge bidirectional converters," 2015 IEEE Applied Power Electronics Conference and Exposition (APEC), 2015, pp. 42-49, doi: 10.1109/APEC.2015.7104330.
9) G. Ortiz, J. M¨uhlethaler and J. W. Kolar, "Magnetic Ear"-basedbalancing of magnetic flux in high power medium frequency dual active bridge converter transformer cores," 8th International Conference on Power Electronics - ECCE Asia, 2011, pp. 1307-1314, doi: 10.1109/ICPE.2011.5944377.
10) B.Zhao, Q.Song and W.Liu, "Power Characterization of Isolated Bidirectional Dual-Active-Bridge DC–DC Converter With Dual-Phase-Shift Control," IEEE Transactions on Power Electronics, vol. 27, no. 9, pp. 4172-4176, Sept. 2012, doi: 10.1109/TPEL.2012.2189586.
11) Y. Tang et al., "Reinforcement Learning Based Efficiency Optimization Scheme for the DAB DC-DC Converter with Triple-Phase-Shift Modulation," IEEE Transactions on Industrial Electronics (Early Access), 10 July 2020, doi: 10.1109/TIE.2020.3007113.
12) G.Xu, L.Li, X.Chen, Y.Liu, Y.Sun and M.Su, "Optimized EPS Control to Achieve Full Load Range ZVS with Seamless Transition for Dual Active Bridge Converters," IEEE Transactions on Industrial Electronics (Early Access), 11 August 2020, doi: 10.1109/TIE.2020.3014562.
13) J. Hu, S. Cui, D. v. d. Hoff and R. W. De Doncker, "Generic Dynamic Phase-Shift Control for Bidirectional Dual-Active Bridge Converters," in IEEE Transactions on Power Electronics, vol. 36, no. 6, pp. 6197-6202, June 2021, doi: 10.1109/TPEL.2020.3039348.
14) Z. Qin, Y. Shen, P. C. Loh, H. Wang and F. Blaabjerg, "A Dual Active Bridge Converter with an Extended High-Efficiency Range by DC Blocking Capacitor Voltage Control," in IEEE Transactions on Power Electronics, vol. 33, no. 7, pp. 5949-5966, July 2018, doi: 10.1109/TPEL.2017.2746518.
15) D. Atkar, P. Chaturvedi, H. M. Suryawanshi, P. Nachankar, D. Yadeo and S. Krishna,"Solid State Transformer for Electric Vehicle Charging Infrastructure," 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020), 2020, pp. 1-6.
16) R. L. Steigerwald, "A comparison of half-bridge resonant converter topologies," in IEEE Transactions on Power Electronics, vol. 3, no. 2, pp. 174-182, April 1988, doi: 10.1109/63.4347.
17) X. Li and Y. -F. Li, "An Optimized Phase-Shift Modulation For Fast Transient Response in a Dual-Active-Bridge Converter," in IEEE Transactions on Power Electronics, vol. 29, no. 6, pp. 2661-2665, June 2014, doi: 10.1109/TPEL.2013.2294714.
18) M. K. Kazimierczuk, "High-Frequency Magnetic Components". 2nd ed.Chichester, U.K.: Wiley, 2014.