Sensorless Phase Shift Control for Phase Shifted DC- DC converters for Eliminating DC Transients from Transformer Winding Currents

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***Abstract*—The paper presents a two phase shift control strategy for Dual Active Bridge(DAB) and Triple Active Bridge(TAB) converter to eliminate the dc transients from the high frequency transformer winding currents during operating phase angle change from one cycle to the next cycle. The proposed two phase shift method controls the alternating nature of high frequency current in transformer windings in one switching cycle without using any high frequency current sensor. The proposed control strategy applies two different phase shift angles during positive and negative half cycles in order to eliminate the dc transients from transformer winding currents during steady state phase angle change. The control strategy is analyzed and applied for power flow direction reversal of Dual Active Bridge Converter and for changing power flow mode from three port scenario to two port scenario in case of Triple Active Bridge converter. The proposed control strategy study has been verified by performing experimental study on a hardware prototype.**

***Index Terms*—Phase Shifted Converter Control, DAB, TAB, Current Control, DC Transient, Duty Cycle, Mode Change**

I. INTRODUCTION

Large scale integration of Renewable Energy Sources(RES) and Energy Storage Systems(ESS) into ac or dc grid requires galvanic isolation between different electrical sources, which is often realized by using transformer isolated dc-dc converters. Transformer isolated phase shifted dc-dc converters[1]-[19] has been a popular topic of research, as it provides numerous advantages like wide operating range of Zero Voltage Switching(ZVS) during device turn-on, galvanic isolation, high efficiency, bidirectional power flow capability, wide dc voltage variation etc. The transformer isolated phase shifted Dual active Bridge(DAB) and Triple Active Bridge(TAB) converters employ a high frequency transformer which is the key power transferring element. In DAB and TAB converters, the power flow is regulated using phase shifts among the different winding voltages[1]-[5]. The leakage inductance of the transformer or any other external series inductor connected to the transformer terminals act as the energy transfer element[1]-[5]. The schematic circuit diagrams for a Dual Active Bridge (DAB) converter and a Triple Active Bridge Converter are shown in figures 1 & 2.

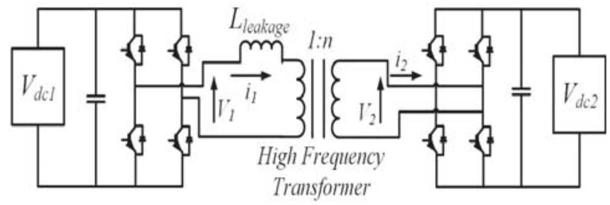

Fig. 1: Two Port Dual Active Bridge Converter

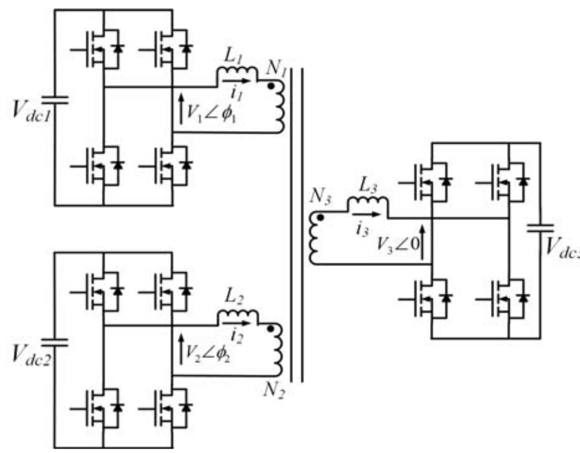

Fig. 2: Three Port Triple Active Bridge Converter

The conventional phase shift control method of DAB or TAB converters produce a large dc transients in transformer winding currents during operating phase angle change. The developed dc transient in transformer winding currents take quite a few number of cycles to dissipate the dc transients depending on winding resistances. For continuous phase angle change operation, the transformer develops huge dc offsets in winding currents and magnetizing flux and can cause transformer saturation leading to converter failure. Figures 3 and 4 show the dc transients that is observed in transformer winding currents due changes in phase angle for DAB and TAB converters. In order to reduce effects of dc transients, techniques like controller bandwidth reduction and introducing air-gaps in transformer cores are used to avoid saturation during transients. Phase shifted DC-DC converter current control methods, proposed in [6]-[8], has not addressed transformer saturation phenomenon. Direct current control methods proposed in [9]-[11][19], employ current sensors for implementing the current control of phase shifted converters, and are sensitive to leakage inductances.

A two phase shift method is discussed in this paper, which uses two different phase shift angles during transients for each half cycle to eliminate or reduce the dc transient currents to a minimum level. In this paper, the two phase shift method is applied to DAB and TAB converter transient operation for

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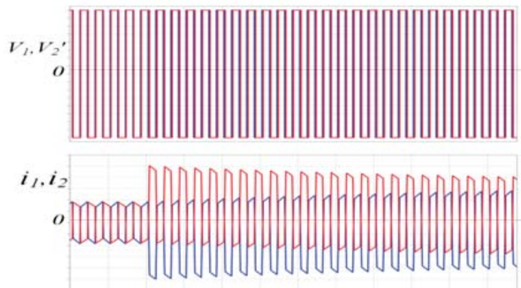


Fig. 3: Equivalent Circuit for DAB Transformer

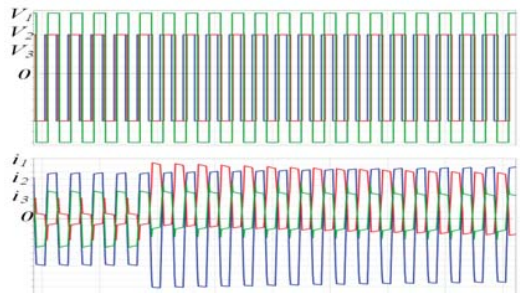


Fig. 4: Transformer Currents During Transients in TAB Converter

square wave winding voltages and quasi-square wave voltages. The two phase shift method is also applied for power reversal of DAB converter without dc transient currents, operating mode change from three port operation to two port operation and back for TAB converter. The two phase shift method is verified using a laboratory hardware prototype made of 1200V and 1700V SiC Mosfets using a ferrite core based high frequency transformer. The DAB converter operation is tested at 400V/400V for V_{dc1} and V_{dc2} with a high frequency transformer. The three port TAB converter operation is tested at 400V/400V/600V voltage levels for V_{dc1}, V_{dc2} & V_{dc3}. The power level for two phase shift control method is tested around 4kW-5kW power level for DAB & TAB converter with operating switching frequency of 25kHz.

II. Proposed Two Phase Shift Method for Dual Active Bridge(DAB) Converter

A. Two Phase Shift Method for Square Wave Voltages for DAB

In the proposed two phase shift method, the PWM generator of the controller uses two different phase shift angles during any change command in operating phase angle. The two phase shifts are applied during positive & negative half cycles of reference voltage. The two phase shift angles for any switching cycle are generated prior to the switching cycle and updated in the PWM generator. In order to derive and explain the two phase shift method, the equivalent circuit of DAB converter, neglecting magnetizing inductance of the transformer, is used which is given in figure 5. The proposed two phase shift method is explained in figure 6, where ϕ_{old} is the steady state phase angle for switching cycle $(n-1)$. When the command for steady state phase angle value occurs, the controller generates an intermediate phase angle ϕ_k for positive half cycle, which changes the transformer current to the steady state value of ϕ_{new}.

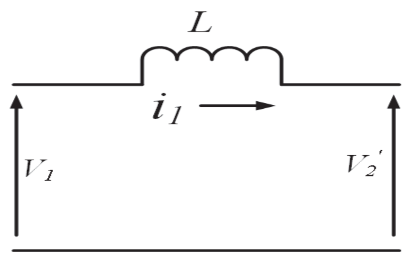


Fig. 5: Transformer Currents During Transients in TAB Converter

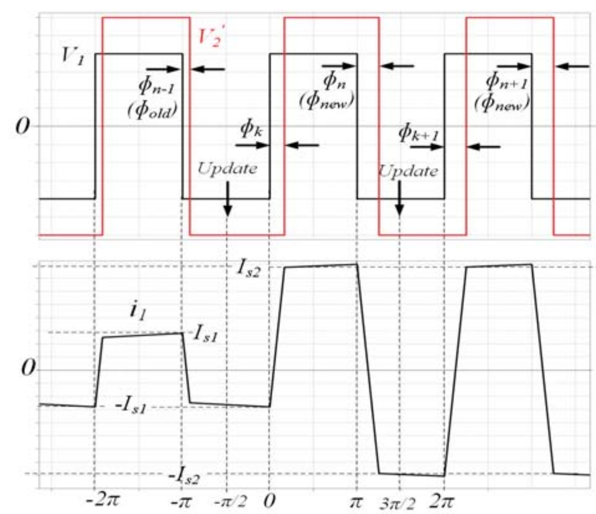


Fig. 6: Two Phase Shift Method in DAB Converter

In figure 6, the phase angle for the next switching cycle is updated in the PWM generator at the midpoint of each negative half cycle of V_1, i.e. at $\frac{n\pi}{2}$ instant, where $n = -1, 3, 7$ etc. In this method, two phase angles are used between primary and secondary voltages. ϕ_k is the phase shift between the negative to positive transition($-V_{dc}$ to $+V_{dc}$) and ϕ_{new} is the phase shift between positive to negative transition($+V_{dc}$ to $-V_{dc}$). I_{s1} is the steady state peak line current at $m\pi$(m=odd) instants when phase angle is ϕ_{old}, and I_{s2} is the steady state peak line current at $m\pi + \phi_{new}$(m=even) instant, when phase angle is ϕ_{new}. If phase angle needs to be changed in n^{th} switching cycle from ϕ_{old} to ϕ_{new}, the peak line current must reach from I_{s1} at $\omega t = 0$ to $+I_{s2}$ at $\omega t = \phi_{new}$. The intermediate phase shift ϕ_k is the required phase angle to eliminate dc transient effect in winding current. Clearly the angle ϕ_k can be expressed as a function of ϕ_{old} and ϕ_{new}, which is derived below. From DAB operation, currents -I_{s1} and +I_{s2} are expressed as shown in (1) and (2). The currents -I_{s1} and +I_{s2} can be related to each other, as given in (3). Solving ϕ_k from (1)-(3), the expression for ϕ_k is given in (4). Following this method, the phase angle ϕ_{k+1} at $(n+1)^{th}$ switching cycle is equal to ϕ_{new}, as given in (5). The proposed control thus settles the winding current within one switching cycle during phase angle change.

$$-I_{s1} = -\frac{V_{dc1}}{\omega L}(\frac{\pi}{2}) + \frac{V_{dc2}{}'}{\omega L}(\frac{\pi}{2} - \phi_{old}) \quad (1)$$

$$I_{s2} = -\frac{V_{dc1}}{\omega L}(\frac{\pi}{2} - \phi_{new}) + \frac{V_{dc2}{}'}{\omega L}(\frac{\pi}{2}) \quad (2)$$

$$I_{s2} = \frac{V_{dc1} + V_{dc2}{}'}{\omega L}(\phi_k) - I_{s1} \quad (3)$$

$$\phi_k = \frac{V_{dc1}\phi_{new} + V_{dc2}{}'\phi_{old}}{V_{dc1} + V_{dc2}{}'} \quad (4)$$

$$\begin{aligned} \phi_{k+1} &= \frac{V_{dc1}\phi_{n+1} + V_{dc2}{}'\phi_n}{V_{dc1} + V_{dc2}{}'} \\ &= \frac{V_{dc1}\phi_{new} + V_{dc2}{}'\phi_{new}}{V_{dc1} + V_{dc2}{}'} = \phi_{new} \end{aligned} \quad (5)$$

The proposed two phase shift method is verified using a laboratory hardware prototype for a 400V:400V 2 port DAB converter at 25kHz. Figure 7 shows the transformer winding voltages and currents without using two phase shift method control. Figures 8 and 9 show the transformer winding voltages and current waveforms during transient using two phase shift method. In order to verify the robustness of the method, the phase shift is varied as a low frequency sinusoid with a dc value, as $\phi = \phi_{dc} + \phi_{ac} sin(\omega t)$. Figure 10 shows the transformer winding voltages and currents for continuously varying phase shift.

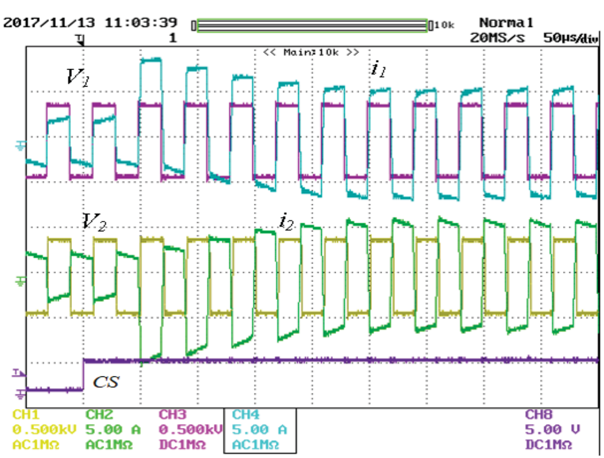


Fig. 7: DC Transients in Transformer Currents without Two Phase Shift Control

Using the two phase shift method it can be observed that the winding currents reach the new steady state within one switching cycle. There is a very small dc offset present which is due to the resistance of the winding, since the derived equations are based on ideal inductive circuit. In this paper, all the derivations are based on ideal inductive circuit for DAB converter.

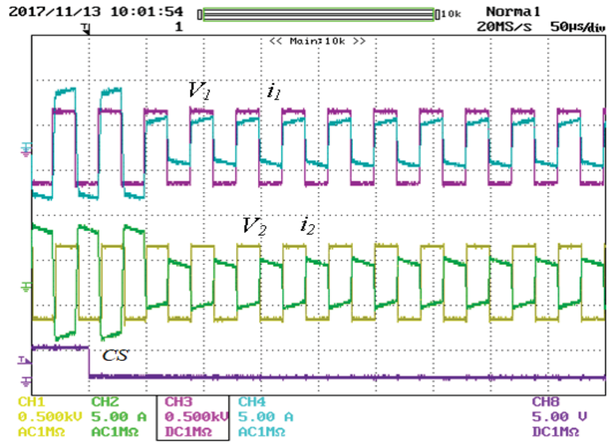


Fig. 8: Transients in Transformer Currents Using Two Phase Shift Control

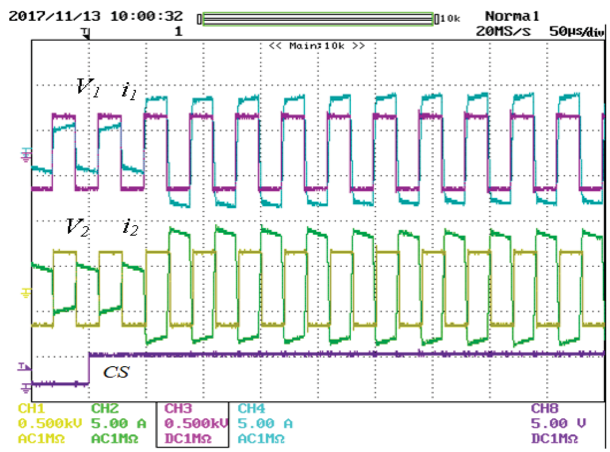


Fig. 9: Transients in Transformer Currents Using Two Phase Shift Control

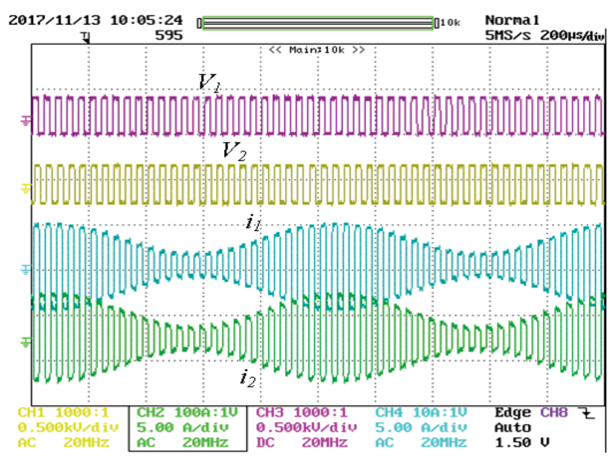
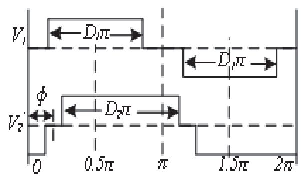


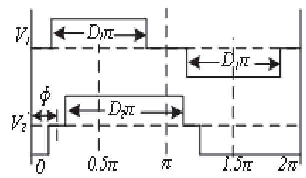
Fig. 10: Transformer Currents with Varying Phase Shift Angle

B. Two Phase Shift Method for Quasi-Square Wave Voltages for DAB

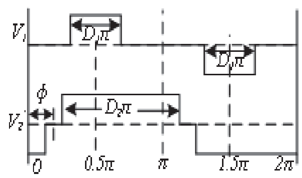
The aforementioned two phase shift method is extended to duty cycle modulated quasi-square wave voltages, i.e. square wave voltages with a zero duration. The quasi square wave voltage is necessary for DAB operation mainly to improve the soft-switching region for DAB converter and achieve higher efficiency at low power oeprating regions[12]. The number of control parameters for DAB converter using quasi square wave voltages, changes from $1(\phi)$ to $3(\phi, D_1, D_2)$. Figures 11(a)-11(f) show the six possible cases for duty cycle and phase shift combined modulation.



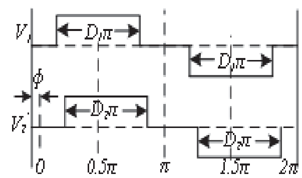
(a) Case1: $0 < 0.5(1-D_1)\pi < \phi - 0.5(1-D_2)\pi < \phi + 0.5(1-D_2)\pi$



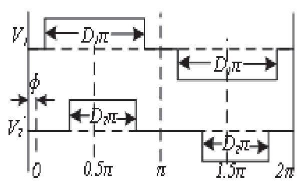
(b) Case2: $0 < \phi - 0.5(1-D_2)\pi < 0.5(1-D_1)\pi < \phi + 0.5(1-D_2)\pi$



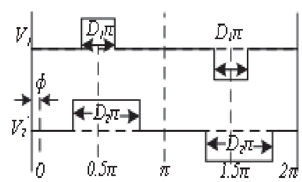
(c) Case3: $0 < \phi - 0.5(1-D_2)\pi < \phi + 0.5(1-D_2)\pi < 0.5(1-D_1)\pi$



(d) Case4: $0 < 0.5(1-D_1)\pi < \phi + 0.5(1-D_2)\pi < 0.5(1+D_1)\pi < \phi + 0.5(1+D_2)\pi$



(e) Case5: $0 < 0.5(1-D_1)\pi < \phi + 0.5(1-D_2)\pi < \phi + 0.5(1+D_2)\pi < 0.5(1+D_1)\pi$



(f) Case6: $0 < \phi + 0.5(1-D_2)\pi < 0.5(1-D_1)\pi < 0.5(1+D_1)\pi < \phi + 0.5(1+D_2)\pi$

Fig. 11: Different Cases for Combined Phase Shift & Duty Cycle Modulation

In the combined phase shift and duty cycle method, the three variables under considerations are winding voltage duty cycles D_1, D_2 and phase shift angle ϕ. In this method, for any change in the values of D_1, D_2, ϕ, the intermediate phase angle ϕ_k is evaluated such that the dc transient from winding current is removed. The phase angle ϕ_k is evaluated in such a manner that for a change of operating point from old set of ${D_1}^{old}, {D_2}^{old}, \phi_{old}$ to a new set of operating point of ${D_1}^{new}, {D_2}^{new}, \phi_{new}$ is obtained in half a switching cycle. In each switching cycle the new set of values are updated at $\omega t = \frac{3\pi}{2}$ instant. The duty ratios ${D_1}^{new}, {D_2}^{new}$ are same for both the positive half cycle and negative half cycle, whereas the angle ϕ_k is applied for positive half cycle and the angle ϕ_{new} is applied for negative half cycle. The winding current expressions at $\omega t = \frac{3\pi}{2}$ for current cycle with old sets of values of ${D_1}^{old}, {D_2}^{old}, \phi_{old}$ are given in equation (6). The winding current expressions at $\omega t = \frac{\pi}{2}$ for next cycle with new sets of values of ${D_1}^{new}, {D_2}^{new}, \phi_{new}$ are given in equation (7). The intermediate phase angle ϕ_k is derived from the equation (8), where m' is the slope for each intermediate sub-intervals and $\Delta\theta$ denotes each sub-interval duration. The intermediate phase angle ϕ_k is derived for each of the possible cases defined above and the expression for ϕ_k comes out to be same in all the three cases, as given in equation (9), same to that in equation (4). The negative half cycle phase angle is given by ϕ_{new}.

$$i_1(\frac{3\pi}{2}) = -\frac{{V_2}'}{\omega L}\phi_{old} \quad (6) \qquad i_1(\frac{\pi}{2}) = \frac{{V_2}'}{\omega L}\phi_{new} \quad (7)$$

$$i\{\frac{\pi}{2}\} = i(\frac{3\pi}{2}) + \sum m(V_1, V_2', \omega L, \phi_k, {D_1}^{new}, {D_2}^{new}) * \Delta\theta \quad (8)$$

$$\phi_k = \frac{V_{dc1}\phi_{new} + {V_{dc2}}'\phi_{old}}{V_{dc1} + {V_{dc2}}'} \quad (9)$$

The experimental waveforms for two phase shift method combined with phase shift and duty cycle change are shown in figures 12 & 13. In the figures, it can be observed that the current settles by one switching cycle. Ihe control action is implemented in such a way that when the external command comes(represented by the signal CS changes state), the controller takes one cycle to calculate the transition phase shift angle and it updates the phase angles at $\omega t = \frac{3\pi}{2}$.

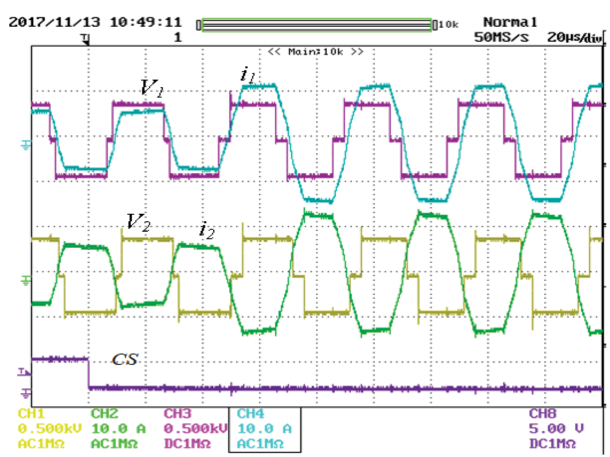


Fig. 12: Transients for combined Phase Shift & Duty Cycle Change

C. Two Phase Shift Method for Power Reversals of DAB Converter

The two-phase shift method is also applied for power direction reversal of Dual Active Bridge(DAB) converter. The two phase shift method, given by equations (4) and (5) when applied to a phase shift direction reversal, creates a dc shift in transformer winding currents as shown in figure 14.

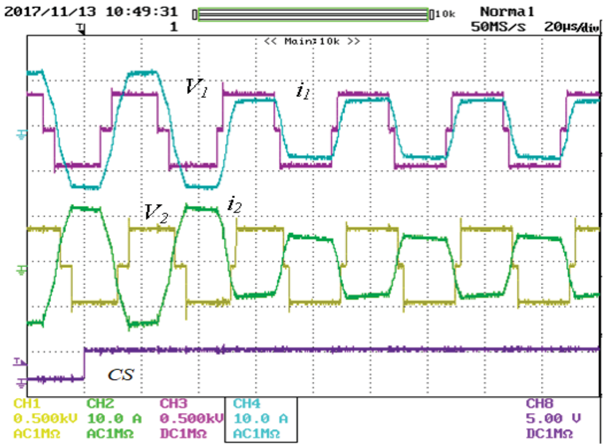


Fig. 13: Transients for combined Phase Shift & Duty Cycle Change

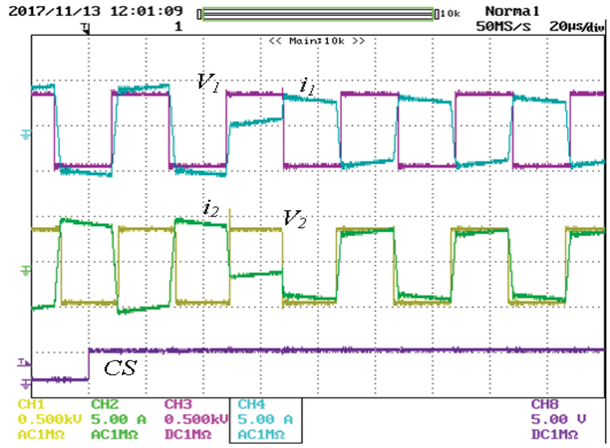


Fig. 15: Transients During Modified Power Reversal Method

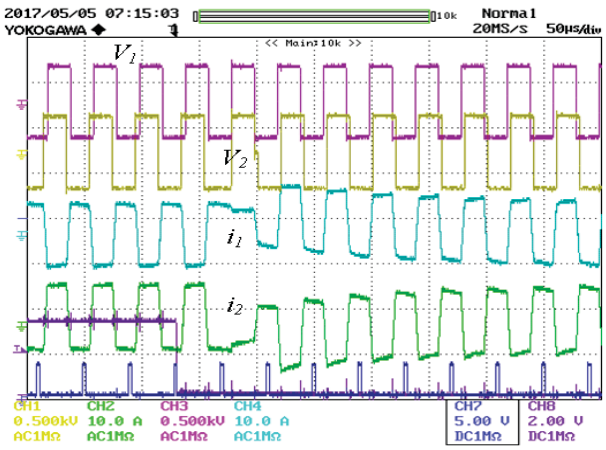


Fig. 14: Transients During Power Reversal

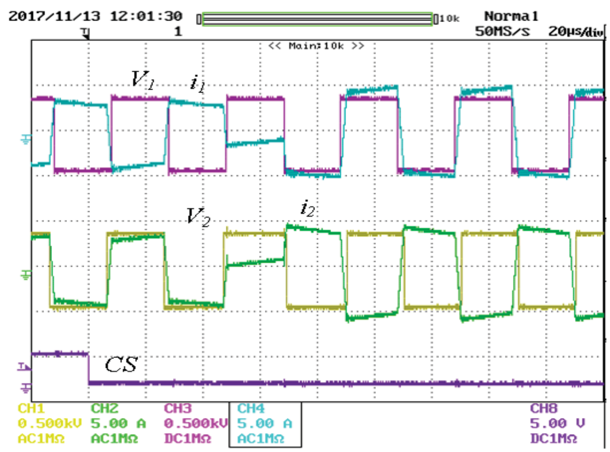


Fig. 16: Transients During Modified Power Reversal Method

In order to avoid the transients during power reversals, an intermediate half switching cycle of zero power is created. When the phase shift angle changes from ϕ_{old} to $-\phi_{new}$ by making the positive half cycle phase shift as $\phi_k = 0.5\phi_{old}$ and by making the negative half cycle phase shift as $-\phi_{new}$. Figures 15 and 16 show the two cases of power reversal, where power flow is changing from 1-2 to 2-1 and vice versa. In figures 15 and 16, a small current flows in the transformer windings during the zero half cycle power, which is due to the magnetizing inductance of the windings.

III. Two Phase Shift Method for Triple Active Bridge(TAB) Converter

A. *Two Phase Shift Method with Square Wave Voltages*

The two phase shift method has been extended to three port Triple Active Bridge(TAB) converter in this section. The approach for two phase shift method is similar to that implemented in previous section. The two phase shift method for three port TAB converter is explained in figure 17.

The square wave winding voltage V_3 is taken as reference and the other two voltages V_1 and V_2 are phase shifted by ϕ_1 and ϕ_2 w.r.t V_3. The two phase shift method for eliminating dc transient is explained in figure 17. The winding voltages V_1 and V_2 have phase angles ϕ_1 and ϕ_2 respectively w.r.t V_3. A typical winding voltage position for Triple Active Bridge(TAB) converter is shown in figure 17. The update

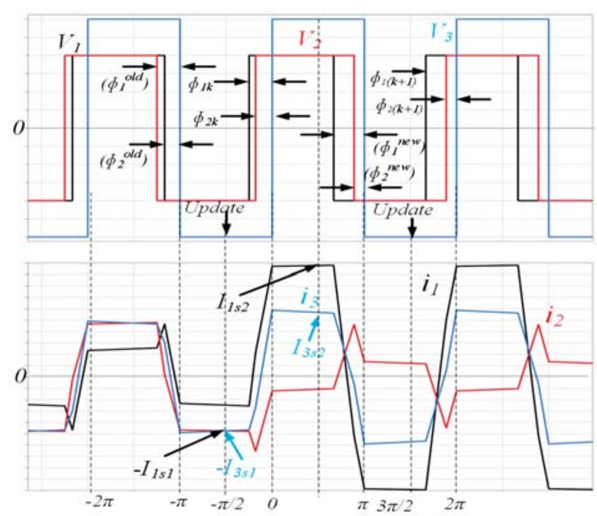


Fig. 17: Two Phase Shift Method for TAB Converter

of intermediate phase angle ϕ_k is done at $\omega t = \frac{3\pi}{2}$, i.e. at midpoint of V_3 during negative half cycle. The currents $-I_{1s1}$ and $-I_{3s1}$ are the steady state current values at instant $\omega t = \frac{3\pi}{2}$ for phase angles ${\phi_1}^{old}$ and ${\phi_2}^{old}$. The currents I_{1s2} and I_{3s2} are the steady state current values at instant $\omega t = \frac{\pi}{2}$ for phase angles ${\phi_1}^{new}$ and ${\phi_2}^{new}$. The currents $-I_{1s1}$, $-I_{3s1}$, I_{1s2}, I_{3s2} are related to each others as functions of slopes, as given in equations (10)-(11), where ${m_1}^1$, ${m_2}^1$, ${m_3}^1$ and ${m_1}^3$, ${m_2}^3$, ${m_3}^3$ are the slopes of winding currents during different intervals. The current expressions $-I_{1s1}$, $-I_{3s1}$, I_{1s2}, I_{3s2} are expressed in terms of ${\phi_1}^{old}$, ${\phi_2}^{old}$, ${\phi_1}^{new}$, ${\phi_2}^{new}$ in equations (12)-(15).

$$I_{1s2} = -I_{1s1} + {m_1}^1(\pi - \phi_{1k}) + {m_2}^1(\phi_{2k} - \phi_{1k}) + {m_3}^1(\phi_{2k}) \tag{10}$$

$$I_{3s2} = -I_{3s1} + {m_1}^3(\pi - \phi_{1k}) + {m_2}^3(\phi_{2k} - \phi_{1k}) + {m_3}^3(\phi_{2k}) \tag{11}$$

$$-I_{1s1} = 0.5\{-{m_1}^1(\pi - {\phi_1}^{old}) - {m_2}^1({\phi_2}^{old} - {\phi_1}^{old}) - {m_3}^1({\phi_2}^{old})\} \tag{12}$$

$$-I_{3s1} = 0.5\{-{m_1}^3(\pi - {\phi_1}^{old}) - {m_2}^3({\phi_2}^{old} - {\phi_1}^{old}) - {m_3}^3({\phi_2}^{old})\} \tag{13}$$

$$I_{1s2} = 0.5\{{m_1}^1(\pi - {\phi_1}^{new}) + {m_2}^1({\phi_2}^{new} - {\phi_1}^{new}) + {m_3}^1({\phi_2}^{new})\} \tag{14}$$

$$I_{3s2} = 0.5\{{m_1}^3(\pi - {\phi_1}^{new}) + {m_2}^3({\phi_2}^{new} - {\phi_1}^{new}) + {m_3}^3({\phi_2}^{new})\} \tag{15}$$

Using expressions (12)-(15) in equations (10),(11) and solving for ϕ_{1k} & ϕ_{2k}, the derived expressions are given in (16),(17). The phase shift angles used for negative half cycle are ${\phi_1}^{new}$ and ${\phi_2}^{new}$ respectively.

$$\phi_{1k} = 0.5({\phi_1}^{old} + {\phi_1}^{new}) \tag{16}$$

$$\phi_{2k} = 0.5({\phi_2}^{old} + {\phi_2}^{new}) \tag{17}$$

The experimental study on the three port phase shifted converter control is performed using a 400V/400V/600V three port TAB converter. In this experimental study, the phase angles are changed from ${\phi_1}^{old}$, ${\phi_2}^{old}$ to ${\phi_1}^{new}$, ${\phi_2}^{new}$. The angle values are chosen such that the power flowing into port 3 remains constant whereas the power flowing out of port 1 and 2 changes. Figures 18 and 19 show the TAB converter waveforms using two phase shift method control.

It can be observed in figures 18 and 19 that the shape of current i_3 remains same before and after change of operating point, which is initiated by CS command. This indicates that the power flowing out of port 1 and 2 changes only in these cases. In figure 18, as current i_1 increases, current i_2 changes direction to absorb extra power required to maintain constant power flowing into port 3. Similarly in figure 19, as current i_1 decreases, current i_2 changes direction to deliver extra power required for port 3.

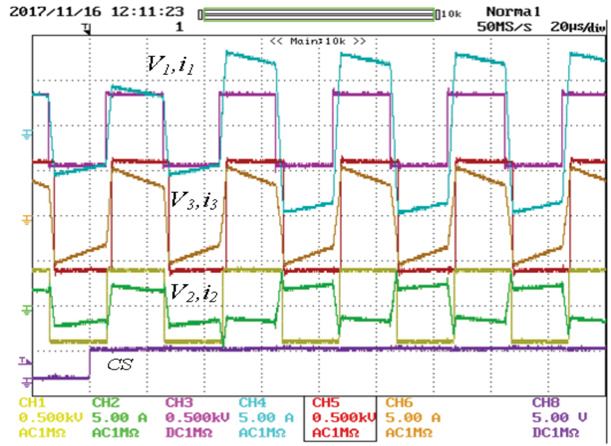


Fig. 18: Two Phase Shift Method in TAB Converter

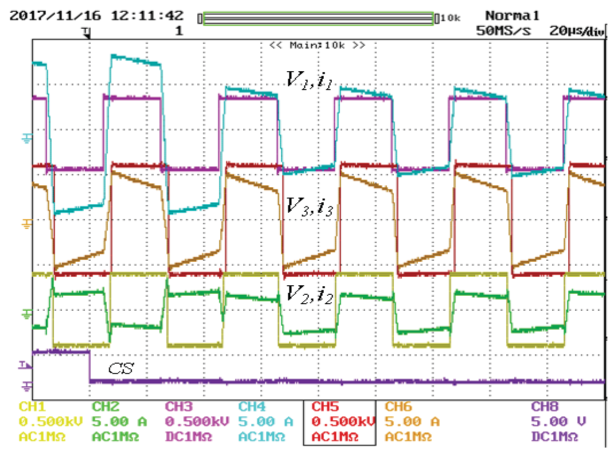


Fig. 19: Two Phase Shift Method in TAB Converter

B. Two Phase Shift Method with Quasi-Square Wave Voltages

The two phase shift method is implemented for quasi square wave voltages as well for three port phase shifted TAB converter. The implementation method is similar to that for DAB converter discussed before. In this case, there are five control parameters, $D_1, D_2, D_3, \phi_1, \phi_2$. For ease of implementation, only ϕ_1 and ϕ_2 are considered as control parameters. The values for duty cycles D_1, D_2, D_3 are updated with new values instantly. As an external command comes for changing from an old operating point of ${\phi_1}^{old}, {\phi_2}^{old}, {D_1}^{old}, {D_2}^{old}, {D_3}^{old}$ to a new set of values ${\phi_1}^{new}, {\phi_2}^{new}, {D_1}^{new}, {D_2}^{new}, {D_3}^{new}$, the controller takes one cycle to calculate the new values of ϕ_{1k}, ϕ_{2k} for the positive half cycle and ${\phi_1}^{new}, {\phi_2}^{new}$ for negative half cycle phase angles and updates the new values at $\omega t = \frac{3\pi}{2}$. The expressions for ϕ_{1k}, ϕ_{2k} are same given in equations (16),(17). Figures 20 and 21 show the experimental cases for two phase shift control implemented in TAB converter for quasi-square wave voltage waveforms, where controller coomands a change from an old operating point of ${\phi_1}^{old}, {\phi_2}^{old}, {D_1}^{old}, {D_2}^{old}, {D_3}^{old}$ to a new set of values ${\phi_1}^{new}, {\phi_2}^{new}, {D_1}^{new}, {D_2}^{new}, {D_3}^{new}$. It can be observed that the winding currents change within one half cycle to their new steady state operating points to maintain the required power flow in both the cases.

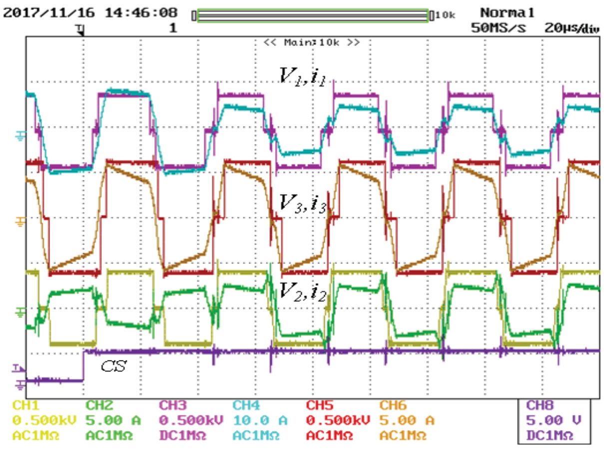


Fig. 20: Two Phase Shift Method with Duty Cycle Change in TAB Converter

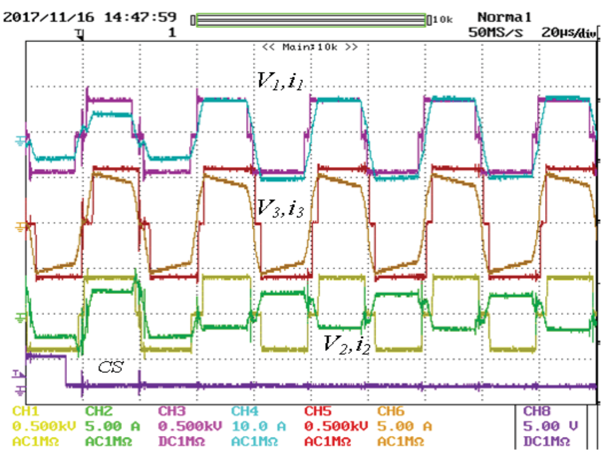


Fig. 21: Two Phase Shift Method with Duty Cycle Change in TAB Converter

C. Operating Mode Change for Three Port TAB Converter

One of the most important aspects of three port converter is to operate the converter while one port being idle. Smooth transition from three port operating mode to two port operating mode and vice versa, is an important feature for three port converter. In this section, the transition between two modes is achieved by using the concept of two phase shift method. In this paper, only port 1 is considered to switch ON & OFF depending on external commands. During two mode operation, port 2 is considered to supply the whole power requirement for port 3, therefore the required phase angle ϕ_{new} is the steady state phase angle for port 2. During three port active operation when the external signal CS for mode change comes, the gate pulses for port 1 are turned off at $\omega t = \frac{3\pi}{2}$ and for the next switching cycle, ϕ_{2k} for positive half cycle is made equal to $0.5\phi_2{}^{new}$ and for negative half cycle phase angle $\phi_2{}^{new}$ is used. In figure 22, it can be observed that when signal CS goes high, port 1 gate pulses are turned off by the PWM generator, current i_1 decays to zero, and phase shift angle ϕ_2 is updated to new values for positive half cycle and negative half cycle. A small duration of voltage bump is seen in V_1 during current decaying of i_1. Current i_2 changes to new steady state operating value within one half switching cycle and port 3 power is kept unchanged. Similarly, for transition from two port to three port operation, when the external signal CS goes low, for the next switching cycle 'k', ϕ_{2k} is made equal to $0.5\phi_{2ss}$(where ϕ_{2ss} is the steady state value of two port operating mode), and during negative half cycle all phase shift angles are made zero. In the next $(k+1)^{th}$ cycle, the steady state values for ϕ_1, ϕ_2 are updated according to equations (16),(17) where $\phi_1{}^{old}, \phi_2{}^{old}$ are equal to zeros and $\phi_1{}^{new}, \phi_2{}^{new}$ are equal to the new steady state values.

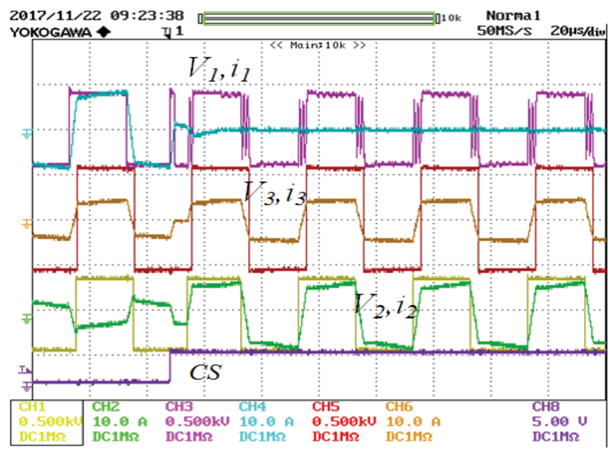


Fig. 22: Three Port to Two Port Mode Change

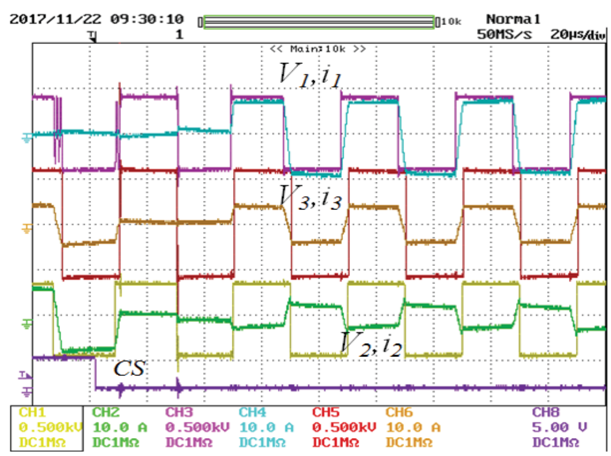


Fig. 23: Two Port to Three Port Mode Change

IV. Conclusion

The two phase shift method proposed here in the paper for phase shifted dc-dc converters, has controlled the transformer currents within one switching cycle during any change in operating phase angle of the transformer. The proposed technique has provided considerably satisfactory results for two port Dual Active Bridge(DAB) converter and three port Triple Active Bridge(TAB) Converter. The two phase shift technique also successfully operates for power flow direction reversal cases and three port to two port mode change cases. The two phase shift method also has the advantage of being independent of transformer leakage inductances and does not required any current sensor. Only requirements are dc voltage sensing for dc buses and knowledge of transformer turns ratio. The proposed two phase shift method provides satisfactory, stable and robust performance for phase shifted dc-dc converters.

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