A novel predictive phase shift controller for bidirectional isolated dc to dc converter for high power applications

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***Abstract*—in this paper a novel predictive algorithm has been proposed for bi-directional dc-dc converters with high frequency transformer isolation. The converter is a dual active bridge converter. The proposed algorithm is a faster alternative to the classical PI based phase shift controller. This mode of control can remove dc bias in the isolation transformer within several switching cycles hence preventing transformer saturation. Aspects of the proposed algorithm have been implemented on a hardware test bed and verified.**

I. INTRODUCTION

Predictive controller is an attractive mode of controlling power converters as it provides a faster mode of control during load transients [1]. Ideally the predictive controller should be able to latch on to the desired reference within one cycle [1]. However the accuracy of the controller heavily depends on the accuracy of sensors and the values of the passive elements in the circuit. In this paper the desired controller was implemented on a bidirectional dc to dc converter. It is a Dual Active Bridge (DAB) converter isolated by a high frequency transformer [2], [4], and [5]. The leakage inductance of the transformer is the main passive element which transfers power from input H-bridge to the output H-bridge. The input and output H-bridges are gated at 50% duty cycle. The power transfer takes place through the inductor by phase shifting the primary and the secondary pulses. The amount of power transferred depends directly on the phase shift applied as a quadratic function. The maximum power transfer take place at phase angle equal to π/2. In the predictive mode, this phase shift is calculated based on the sampled current from the beginning of the switching cycle to achieve a desired peak current. The corrective action can take place in the same switching cycle or the next switching cycle. In this paper further analysis of the predictive controller was done and a duty cycle based controller was proposed. Transient load changes, and short circuit behavior was studied as well with the predictive controller in operation. Advantages and disadvantages of the controller has been shown and discussed.

II. THE PROPOSED ALGORITHM

A. *Predictive phase shift mode*

The predictive controller usually predicts the duty cycle or in our case the phase shift angle of the converter. The sampling of the n^{th} cycle happens at the beginning of the cycle at $\theta = 0$ as I_n^o. The current to be regulated is $I(\theta = \phi)$. The required reference I_{ref} will produce the required phase shift angle for the n^{th} cycle. The following equation shows the relationship of the phase shift angle φ based on the sampled current I_n^o, the reference current I_{ref} and the input and output voltages (1a):

$$I_{ref} = I_n^o + \frac{\Delta V}{\omega L}\phi_n, \phi_n = \frac{\left(I_{ref} - I_n^o\right)F_{sw}L}{2\pi\left(V_{in} + V_{out}\right)} \tag{1a}$$

$$P = \frac{V_{in}V_{out}}{\omega L}\phi\left(1 - \frac{\phi}{\pi}\right) \tag{1b}$$

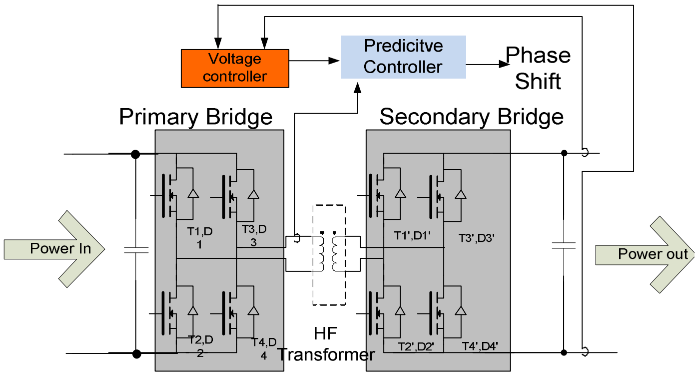

Figure 1. The DAB with the predictive controller.

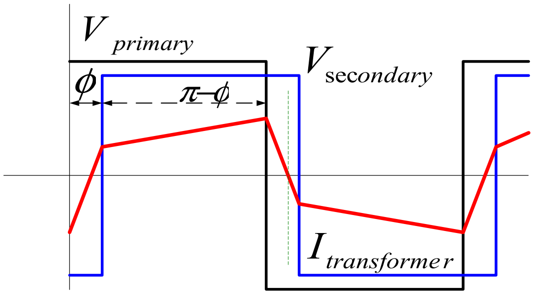

Figure 2. Current and voltage through the HF transformer of the DAB

Here F_{sw} is the switching frequency and L is the leakage inductance of the HF transformer. Since the power flow (P) through the DAB is given as in (1b), is a direct function of the phase shift angle, it becomes a controllable state. Another alternate algorithm can be to sample the current $I(\theta=0)$ and try to regulate the current at (figure 2) $I(\theta=\pi)$. The two current values are related by the following equation:

$$I_\pi = I_o + \frac{V_{in}+V_{out}}{\omega L}\phi + \frac{V_{in}-V_{out}}{\omega L}(\pi-\phi) \qquad \text{Or}$$

$$\phi_n = \frac{\pi}{2} + \frac{\omega L}{2V_o}(I_\pi - I_o) - \frac{\pi V_{in}}{2V_o} \qquad (2)$$

B. Predictive Duty Cycle mode (Sample and calculate mode)

In the previous section the output of the controller was the phase shift between the primary and the secondary bridges of the DAB. And both the bridges were switched at 50% duty cycle. In this case a different approach of switching the secondary bridge has been proposed. The primary bridge is the master bridge which remains switched at 50% duty cycle. The turn on and turn off period of the switches of the secondary bridge are pre-calculated in a predictive fashion in order to meet a particular reference current. Figure 4 shows the current waveforms of the DAB and the switching on times of the secondary side of the DAB (green). In this control mode the current is sampled twice. Once at θ = 0 and once at $\theta=\pi$. By doing this we regulate both the positive and the negative peak current. Sampling the current at θ = 0 we regulate the current at $\theta=\pi$ and again sampling the current at we regulate the current at $\theta=\pi+\varphi$. Hence in this method there is a requirement of sampling the current twice in one switching cycle. The advantage is that complete control over the current can be achieved in one cycle. Equation 3a and 3b calculates the required duty cycles for the switches on the secondary side of the DAB. From equation 3a, $d_{2'3'}$ is the required duty cycle for switches $T_2^{'}$ and $T_3^{'}$ on the secondary side and $d_{1'4'}$ is the duty for $T_1^{'}$ and $T_4^{'}$.

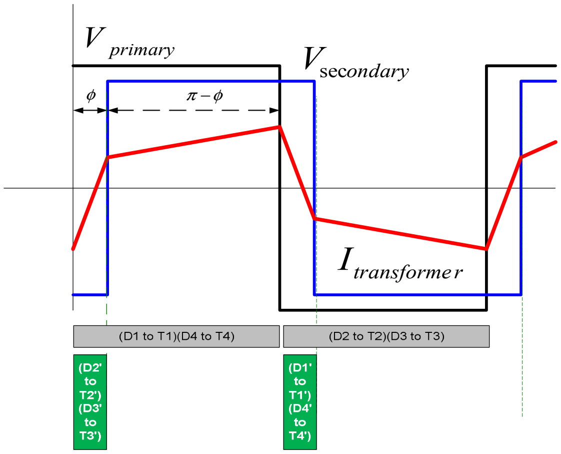

Figure 3. Current through the transformer with the modes showing when the switches and the diodes conduct.

$$i_\phi = i_0 + \frac{V_{in}+V_{out}}{LF_{sw}} d_{2'3'} \qquad (3a)$$

$$i_{\pi+\phi} = i_\pi + \frac{V_{in}+V_{out}}{LF_{sw}} d_{1'4'} \qquad (3b)$$

The gate pulses for the secondary switches are generated by comparing with a saw-toothed waveform.

C. Predictive Equal Area mode

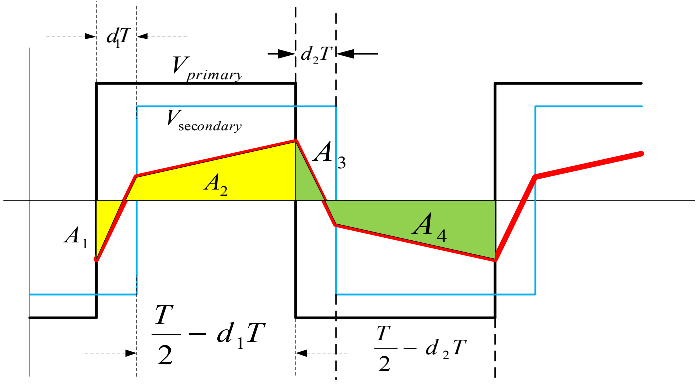

Figure 4. Figure showing the equal area criterion for romoving dc bias in the transformer current. $(A_1+A_2=A_3+A_4)$

The equal area mode of operation is an extension of the duty cycle mode of control. The idea is to sample the current at the start of the switching cycle and make it to follow a reference current that comes from the voltage PI controller. Considering the n'th switching cycle with the (n+1)'th cycle, we can get the following equation for the current:

$$i_{n+1} = i_n + \frac{V_{in} + V_{out}}{L} d_1 T + \frac{V_{in} - V_{out}}{L}\left(\frac{T}{2} - d_1 T\right)$$

$$- \frac{V_{in} + V_{out}}{L} d_2 T - \frac{V_{in} - V_{out}}{L}\left(\frac{T}{2} - d_2 T\right) \qquad (4)$$

Assuming that in one cycle the corrective action is achieved and $I_{n+1} = I_{ref}$ the above equation simplifies as:

$$\left(I_{ref} - I_n\right)\frac{L}{2V_{out}T} = d_1 - d_2 \qquad (5)$$

Now this is not enough to calculate the value of the duty cycles. We have two degrees of freedom here and we can independently change the values of d1 and d2 as long as they follow (5). Hence we can use this to make the current through the transformer a perfect AC i.e. remove any DC offset in it. We can do that by equating the area under the curve of current in the positive half cycle as in figure 4 $\left(A_1 + A_2\right)$ to that of the negative half cycle $\left(A_3 + A_4\right)$ i.e.

$$A_1 + A_2 = A_3 + A_4 \qquad (6)$$

Here $\left(A_1 + A_2\right)$ is a function of d1 and $\left(A_3 + A_4\right)$ is a function of d2. So from equations 5 & 6 we get the solutions for d1 and d2. The expressions of d1 and d2 are complicated and have been solved using Mathematica.

$$d_1 = \frac{\left(-I_n^2 L^2 + 2I_n I_{ref} L^2 - I_{ref}^2 L^2 - 2I_n L T_s V_{out}\right)}{4TV_{out}\left(I_n L - I_{ref} L + T_s V_{out}\right)}$$

$$\frac{-\left(2I_{ref} L T_s V_{out} - T_s^2 V_{in} V_{out} + T_s^2 V_{out}^2\right)}{4TV_{out}\left(I_n L - I_{ref} L + T_s V_{out}\right)}$$

$$d_2 = \frac{\left(I_n^2 L^2 - 2I_n I_{ref} L^2 + I_{ref}^2 L^2 - 4I_{ref} L T_s V_{out}\right)}{4TV_{out}\left(I_n L - I_{ref} L + T_s V_{out}\right)}$$

$$- \frac{\left(-T_s^2 V_{in} V_{out} + T_s^2 V_{out}^2\right)}{4TV_{out}\left(I_n L - I_{ref} L + T_s V_{out}\right)} \qquad (7)$$

Substituting this expression for the duty period in the controller we can get a precise control in one cycle.

III. ADVANTAGES OF IMPLEMETING DUTY CYCLE MODE PREDICTIVE CONTROL

The most important advantage of using the duty cycle based control is, as mentioned before the removal of any DC bias in the transformer current to prevent transformer saturation. This is possible since the two duty cycles can be decoupled as long as it satisfies equation 5. As long as $d_1 = d_2$ there will be no dc offset in the transformer current. However if $d_1 \neq d_2$ there will be dc offset. Hence by adjusting the values of d_1 and d_2 it is possible to remove dc offset in the transformer.

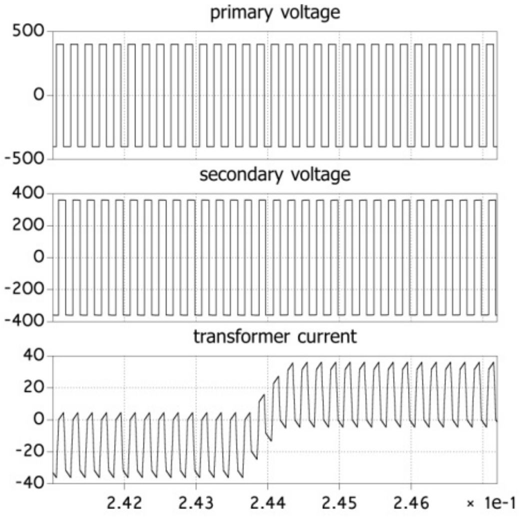

Figure 5. Example of current through the transformer with different duty $\left(d_1 \neq d_2\right)$

However since the values of d_1 and d_2 are calculated predictively the dc offset can be removed in several cycles compared to a normal phase shift control. This is the principal advantage of using the duty mode of control, be it the equal area mode or the sample and calculate mode. In the sample and calculate mode, since the sampling takes place twice every cycle, at $\phi = 0, \phi = \pi$ hence the duty is calculated separately as per equations 3a and 3b.

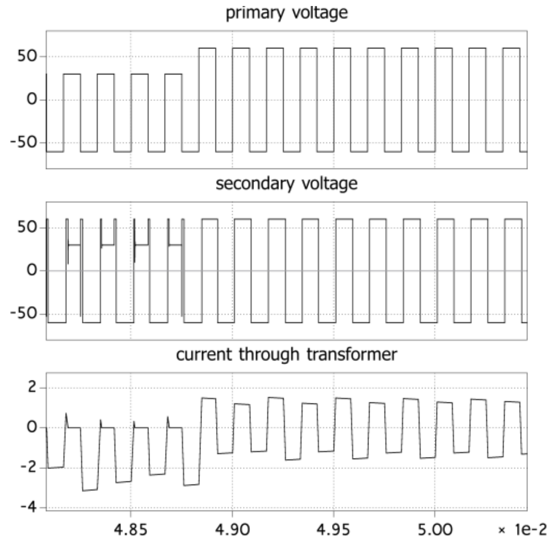

Figure 6. Example of dc bias removal in current through the transformer by varying the duty cycles.

Figure 6 shows the case where the transformer was carrying a dc bias in the current. Between 0.485 and 0.49 second the predictive controller was switched on and the bias is removed within one cycle. Figure 7 shows the response of the normal phase shift controller when there is a dc bias in the transformer current. At t=0 the controller is switched on and it takes many cycles before the dc bias is completely removed from the transformer current. The transformer is designed usually with significant margin in the saturation curve to account of small amount of saturation. However if the dc bias is too high, the predictive controller's fast response might be a better solution than the classical phase shift controller.

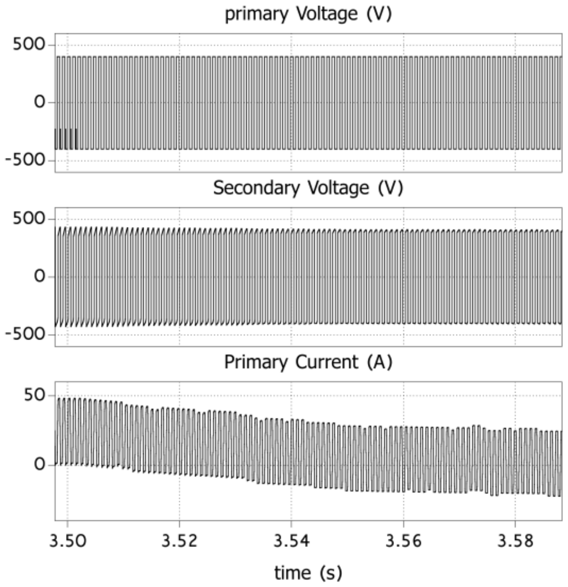

Figure 7. Example of dc bias removal in current through the transformer by simple phase shift controller..

Another advantage of the duty mode controller is the limitation of fault current for a primary fault. Hence if there is a short circuit on a primary leg, under normal phase shift operating condition the fault current would flow both from the primary capacitor and the secondary capacitor through the transformer. Hence the entire converter is susceptible to damage. It is also to be noted that the fault current is limited by the dead-band on the secondary side as well. The more the dead-band less will be the fault current. In the proposed duty mode of switching the fault current for a short in the primary limits the current only between the primary cap and the faulted leg. Hence the rest of the converter is protected.

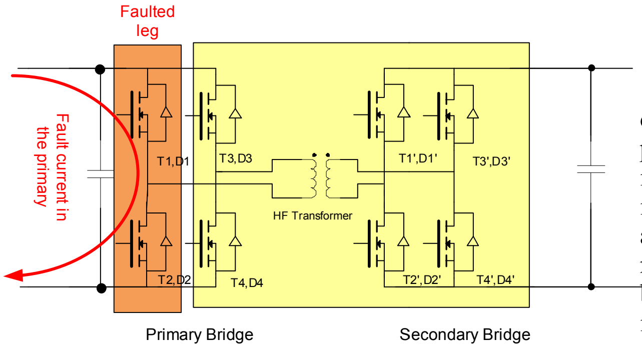

Figure 8. Fault in the primary leg of the DAB and the fault current is limited only in the primary faulted leg.

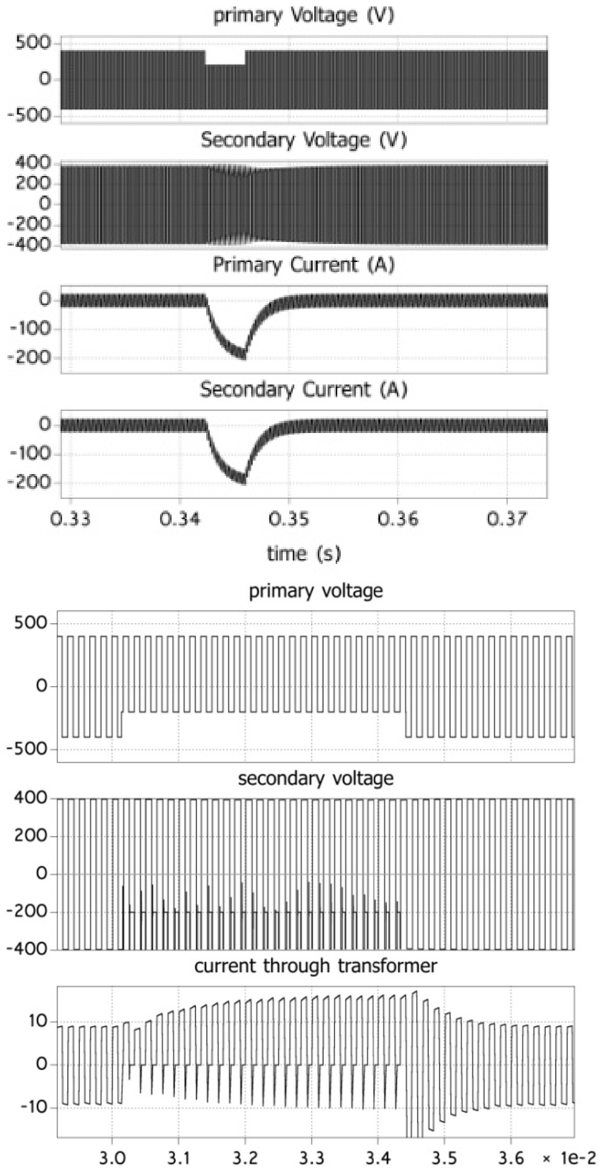

Figure 9. Fault currents in the transformer for (a) normal phase shift control (b) duty mode of control.

IV. INDUCTANCE MEASUREMENT ISSUES WITH THE PREDICTIVE CONTROLLER

For the predictive controller to calculate the next cycle duty ratio or phase shift one of the most important parameters is to have the accurate value of the circuit inductance. In the case for the DAB it's the leakage inductance of the transformer. Although the leakage is accurately measurable at a particular frequency, improper measurements can lead to steady state error. However in a buck or a boost converter the predictive controller is actually insensitive of the accurate value of the inductor used. Such is not the case here. An incorrect value of inductance will lead to a difference in the measured current and the reference current. But if the controller is supported by an external closed loop PI controller regulating the output capacitor voltage, the controller again becomes insensitive of the accuracy of the inductance value in the controller. However in the area mode predictive controller this leads to a potential problem. Mismatch in the inductance value will lead to $d_1 \neq d_2$ which will lead to a net dc offset in the transformer current.

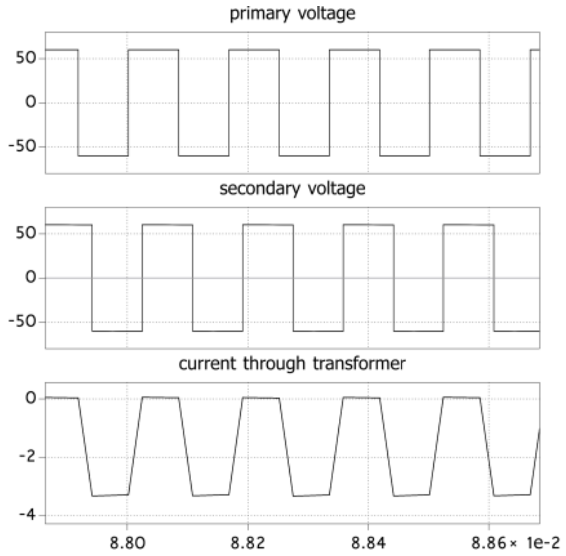

Figure 10. Plot showing the dc bias in the current through the transformer with the area mode of control, with measured inductance equals half the actual inductance.

V. EXPERIMENTAL RESULTS

A small scale prototype was built at the lab to test out the algorithm.

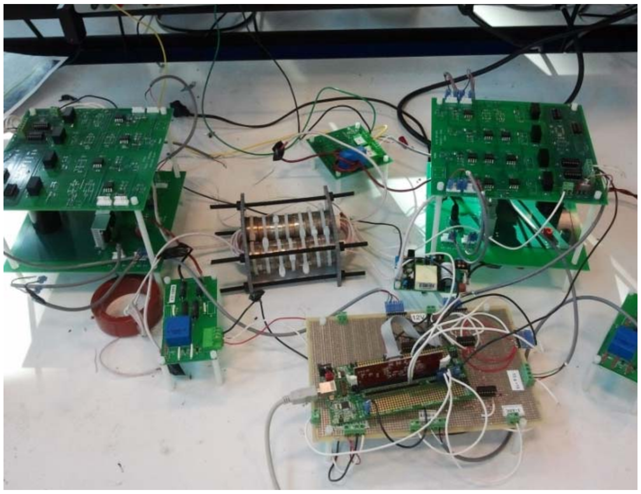

Figure 11. Picture of the lab prototype DAB where the controller was tested.

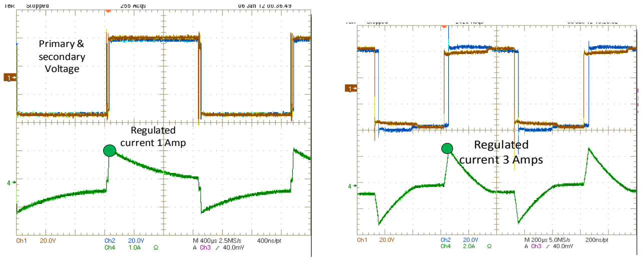

Figure 12. Hardware results showing the acurate current regulating property of the predictive controller.

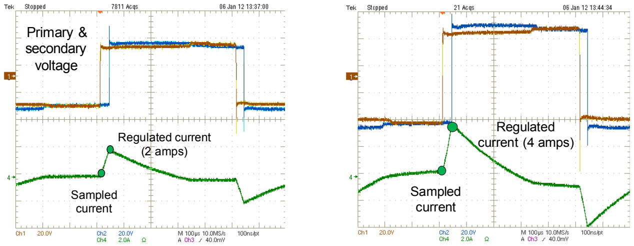

Figure 13. More hardware results showing current regulation.

The hardware results (figure 12 & figure 13) show the controller regulating the current as the reference given to it. The sampled current shown in the results are sampled at the beginning of each cycle and fed to the controller. Based on the measurement of the leakage inductance the predictive controller generated the required phase shift to get the required current peak.

VI. CONCLUSIONS

The paper proposes a novel predictive control algorithm for the Dual Active Bridge controller. There are three versions of the controller: the predictive phase shift control where the phase shift between the primary and the secondary, the duty cycle mode of control where the duty cycle for the secondary switches are controlled in a predictive fashion the third one is the equal area criterion of the duty mode controller. All three versions have been described and the advantages and disadvantages have been shown. The value of the transformer leakage inductance is an important parameter for the equal area mode of control as incorrect value introduces dc bias in the current. However in the other versions of the controller, the PI loop makes it insensitive of the inductance value.

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