DC Voltage Control of Inverter Interfaced Dual Active Bridge Converter for V2L applications

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Abstract—This paper proposed a dc voltage control for inverter interfaced dual active bridge converter. This converter is used in SiC based on-board charger for electric vehicle. The inverter interfaced dual active bridge converter has a dc link as a middle stage of AC/DC conversion. This dc-link voltage is unstable without control. Especially in applications like vehicle-to-load (V2L) applications, the converter is required to operate under both 120-volt ac load and 480-volt ac load so the vehicle can export power to external loads. The large variation of dc link voltage requires a robust general dc voltage control to guarantee a safe operation of load change. This paper analytically derives the small-signal model of the inverter interfaced dual active bridge converter at wide range of operating point. Based on the small-signal model, a robust dc voltage control is proposed to adapt to the wide range of dc link voltage. The proposed dc voltage control is verified by a 25-kW SiC based inverter interfaced dual active bridge converter prototype.

Keywords—inverter interfaced Dual Active Bridge (DAB), dc voltage control, small-signal model, vehicle to load (V2L)

I. INTRODUCTION

The inverter interfaced dual active bridge (DAB) converter has been widely used in electric vehicle on-board charger applications[1]. The inverter interfaced DAB converter consists of a three-phase front-end and two H-bridges as shown in Fig.1. The front-end three-phase inverter interacts with ac grid. The feature of this topology is that it has a wide range of operation and has a chance to adapt to multi-functions. This inverter interfaced DAB converter has been proposed with multi-functions in [2]. The converter discussed in [2] performed various functionalities such as battery charging (G2V), vehicle to grid (V2G) regenerative capability, and vehicle-to-load (V2L) feature. With the V2L function, the converter can output different types of voltage, such as 120-volt single-phase and 480-volt three-phase.

However, the multi-function concept increases the complexity of DAB control. In order to enhance the DAB with multi-function, we need to consider control algorithms for many operating points. To switch control algorithms from different operating points may consume valuable computation time of DSP. This becomes severe for wide-bandgap (WBG) based converters since normally the control algorithms are required to complete in one switching cycle. The switching frequency of WBG based converters normally falls in the range of 100 kHz to 500 kHz, which is 10 times faster than Si based converters. The fast switching requires the general control for multiple operating points, and even multiple functions. A faster and simpler controller is needed for WBG based inverter interfaced DAB system so that the converter can benefit most from the fast switching of WBG devices.

In scenarios like V2L applications, the converter is required to operate under both 120-volt ac load and 480-volt ac load. The wide range of dc-link voltage ($V_{CL}$) challenges the control system to adapt to wide range of operating points. However, few literatures discussed the dc voltage control especially in V2L applications. Many existing literatures discussed the small-signal model of DAB converters[3]–[5]. A few other papers discussed the small-signal model of inverter-interfaced DAB converters[6], [7]. The focus of existing literatures is to develop a general model of DAB to understand the dynamics of DAB. Some control algorithms are established on the small-signal model for DAB[8]–[11]. The control objectives are normally transformer current or output voltage. The dc bus voltage control...
for inverter interfaced DAB has been discussed in [12], [13]. The voltage control in these papers is too complicated to adapt to multi-function converters.

This paper proposed a general dc voltage control for inverter interfaced DAB converter that is suitable for a wide range of operating points. This paper is organized as follows. The small-signal model of inverter interfaced DAB converter that considers the primary side bus voltage as an independent state variable is derived in Section II. Based on the small-signal model of the converter, the wide range operating point for multi-functions are assessed in Section III. A robust dc voltage control is proposed in Section IV to cover all the operating points for the converter. Some experiment results to verify the effectiveness of the proposed method are presented in Section V.

II. SMALL-SIGNAL MODEL OF INVERTER INTERFACED DAB DC VOLTAGE DYNAMICS

To simplify the small-signal modeling of the converter, the topology is reduced to single phase as shown in Fig.2. To further simplify the analysis, we assume that $L_{bat}$ is small and the $C_2$ voltage is the same as the battery voltage. Therefore, $V_{C_2}$ is no longer a state variable. The high-frequency transformer model is replaced by the power transfer function,

$$ P = \frac{n V_{C1} V_{C2}}{f_{s} L_{leak}} D(1 - D) $$

Where $n = 1$ is the turns ratio of the transformer for this paper. $f_s$ is the switching frequency, $V_{C1}$ and $V_{C2}$ are the capacitor voltages. $D$ is the phase shift between primary voltage and secondary side voltage. The single-phase shift control is adopted in this paper. The DAB is modeled with the power transfer function in this paper because the high frequency transformer is externally presenting a power transfer function in lower frequency domain. If considering the internal dynamics of the high frequency transformer, the conventional averaging model is not suitable since the averaging window (one switching cycle) will eliminate all the high frequency components. For example, the leakage inductance current becomes zero after averaging. This makes the averaging model unsuitable for internal dynamics of the DAB. $C_1$ voltage $v_{C_1}$ and $L_s$ current $i_s$ are selected as state variables in this paper. The state equations are,

$$ \begin{align*}
  p &= \frac{n V_{C1} V_{C2}}{f_{s} L_{leak}} D(1 - D) \\
  p &= p_0 + p_{C1} \\
  p_{C1} &= \frac{d v_{C1}}{d t} \\
  p_0 &= d v_{C1} \\
  L_s \frac{d i_s}{d t} &= q v_{C1} - v_s
\end{align*} $$(2)

Where $q$ is the equivalent duty cycle of H-bridge $Q_1$-$Q_4$. Eq.(2) can be simplified as

$$ \begin{align*}
  C_1 v_{C1} \frac{d v_{C1}}{d t} &= \frac{n V_{C1} V_{C2}}{2 f_{s} L_{leak}} D(1 - D) - i_s v_s \\
  L_s \frac{d i_s}{d t} &= q v_{C1} - v_s
\end{align*} $$(3)

Replace $x = \bar{x} + x_s$, where $x = D_i q, v_{C1}$ or $i_s$. $x_s$ is the state variable values at steady state.

$$ \begin{align*}
  C_1 (\bar{v}_{C1} + v_{C1}) \frac{d(\bar{v}_{C1} + v_{C1})}{d t} &= \frac{(\bar{v}_{C1} + v_{C1})}{2 f_{s} L_{leak}} (\bar{d} + D) (1 - (\bar{d} + D)) - (i_s + l_s) v_s \\
  L_s \frac{d i_s}{d t} &= q(\bar{v}_{C1} + v_{C1}) - v_s
\end{align*} $$

Eq. (4) can be simplified as

$$ \begin{align*}
  C_1 v_{C1} \frac{d(\bar{v}_{C1})}{d t} &= \frac{(\bar{v}_{C1} + v_{C1})}{2 f_{s} L_{leak}} (\bar{d} + D - D^2 - 2 D\bar{d}) - (i_s + l_s) v_s \\
  L_s \frac{d i_s}{d t} &= q\bar{v}_{C1} + \bar{q} v_{C1} + q v_{C1} - v_s
\end{align*} $$

Since the steady state has

$$ \begin{align*}
  0 &= \frac{n V_{C1} V_{C2}}{2 f_{s} L_{leak}} D(1 - D) - l_0 v_s \\
  0 &= v_s - q v_{C1}
\end{align*} $$

Therefore,

$$ \begin{align*}
  C_1 v_{C1} \frac{d\bar{v}_{C1}}{d t} &= \frac{V_{C1} V_{C2}(1-2D)}{2 f_{s} L_{leak}} \bar{d} + \frac{V_{C2} D(1-D)}{2 f_{s} L_{leak}} \bar{v}_{C1} - \bar{l}_s v_s \\
  L_s \frac{d i_s}{d t} &= q\bar{v}_{C1} + \bar{q} v_{C1}
\end{align*} $$

Take Laplace transform to (7),

$$ \begin{align*}
  \frac{s C_1 V_{C1} P_{C1}(s)}{2 f_{s} L_{leak}} = \frac{s C_1 V_{C1} (1-2D)}{2 f_{s} L_{leak}} B(s) + \frac{V_{C2} D(1-D)}{2 f_{s} L_{leak}} B(s) - \bar{l}_s(s) v_s \\
  s L_s I_s(s) = q\bar{v}_{C1}(s) + \bar{q} v_{C1}(s)
\end{align*} $$

Therefore,

$$ \begin{align*}
  \frac{s C_1 V_{C1} - V_{C2} D(1-D)}{2 f_{s} L_{leak}} + \frac{\bar{q}_s}{s l_s} \bar{v}_{C1}(s) &= \frac{V_{C1} V_{C2}(1-2D)}{2 f_{s} L_{leak}} \\
  \frac{s C_1 V_{C1} - V_{C2} D(1-D)}{2 f_{s} L_{leak}} + \frac{\bar{q}_s}{s l_s} \bar{v}_{C1}(s) &= \frac{V_{C1} v_s}{s l_s}
\end{align*} $$

The transfer functions are

$$ \begin{align*}
  H_1(s) &= \frac{\bar{v}_{C1}(s)}{B(s)} = \frac{s L_s V_{C1} V_{C2}(1-2D)}{2 s^2 L_{leak} C_1 V_{C1} + s l_s V_{C2}(1-D) + \frac{V_{C1} V_{C2}}{s f_{s} L_{leak}}} \\
  H_2(s) &= \frac{\bar{v}_{C1}(s)}{Q(s)} = \frac{2 f_{s} L_{leak} V_{C1} v_s}{2 s^2 L_{leak} C_1 V_{C1} + s l_s V_{C2}(1-D) + \frac{V_{C1} V_{C2}}{s f_{s} L_{leak}}}
\end{align*} $$
III. OPERATING POINT ASSESSMENT

We can see from (11) that the transfer function $H_1(s)$ is a function of $V_{C1}$ and $D$. $D$ may vary from 0 to 0.5. In V2L applications, $V_{C1}$ may vary from 170 V to 700 V to adapt to 120-V load and 480-V load. The key parameters of the converter that under analysis in this paper is summarized in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>KEY PARAMETERS</th>
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<tbody>
<tr>
<td>Filtering</td>
<td>inductor, 10</td>
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<td></td>
<td>$L_1$, μH</td>
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<td>voltage, 350</td>
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The bode plot of 120-V load transfer function $H_1(s)$ and 480-V load transfer function $H_1(s)$ are shown in Fig.3. The bode plot of 120-V load transfer function $H_2(s)$ and 480-V load transfer function $H_2(s)$ are shown in Fig.4. The phase shift $D$ is discretized in every 15 degree. We can see from the figures that the transfer function does not deviate from each other too much at two operating points. Therefore, we could rely on a controller with identical parameters to regulate the state variables.

IV. ROBUST DC VOLTAGE CONTROL FOR WIDE RANGE OPERATION

As seen in (8), the state variable $\tilde{V}_{C1}(s)$ is coupled with $I_s(s)$. In order to decompose the state variables, the controller is designed to assign a fast loop to control $\tilde{I}_c(s)$ and a slow loop to control $\tilde{V}_{C1}(s)$. The control objective of the fast loop is ac voltage is real system since the output of converter should be controlled as a voltage source. The control objective remains to $\tilde{I}_c(s)$ in this paper since the test is conducted under resistive load. The output ac voltage is proportional to output current in this specific scenario. $\tilde{I}_c(s)$ term in (8) could be deemed as zero since $I_s$ has reached to steady state in the fast control loop. Also, $q\tilde{V}_{C1}(s)$ term in (8) could be deemed as zero since $V_{C1}$ changes very slow in the fast loop. Therefore, $\tilde{V}_{C1}(s)$ can be controlled by $\tilde{D}(s)$ independently and $\tilde{I}_c(s)$ can be controlled by $\tilde{Q}(s)$ independently. Eq. (8) can be simplified as

$$\begin{align*}
&\left\{ \begin{array}{l}
sC_1V_{C1}\tilde{V}_{C1}(s) = \frac{V_{C1}V_{C2}(1-2D)}{2fs_{leak}} \tilde{D}(s) + \frac{V_{C2}D(1-D)}{2fs_{leak}} \tilde{Q}_{C1}(s) \\
sl_{1s}\tilde{I}_c(s) = \tilde{Q}(s)V_{C1}
\end{array} \right.
\end{align*}$$

(13)

The transfer functions are

$$\begin{align*}
&H(s) = \frac{\tilde{P}_{C1}(s)}{\tilde{D}(s)} = \frac{V_{C1}V_{C2}(1-2D)}{2fs_{leak}C_1} - \frac{V_{C2}D(1-D)}{2fs_{leak}}C_2 \frac{1}{1-2D} \\
&G(s) = \frac{\tilde{I}_c(s)}{\tilde{Q}(s)} = \frac{V_{C1}}{sL_{1s}}
\end{align*}$$

(14)
(15)

The $H_1$ bridge $Q_1-Q_2$ are used to control $I_s$. The dual active bridge is used to control $V_{C1}$. The bode plot of 120-V load transfer function $H(s)$ and 480-V load transfer function $H(s)$ are shown in Fig.5. The bode plot of 120-V load transfer function $G(s)$ and 480-V load transfer function $G(s)$ are shown in Fig.6.

A PI controller is designed for the $V_{C1}$ regulation and another PI controller is designed for $I_s$ regulation. The control strategy is shown in Fig.7. The parameters of PI controller are summarized in Table II. The open-loop bode plots after implementing the PI controls are shown in Fig. 8-9. We can see from the bode plot that the phase of zero cross point is less than 180 degree for all operating points. This guarantees that the general PI controller is suitable for both 120-V load and 480-V load.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>PARAMETERS FOR PI CONTROLLERS</th>
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<tr>
<td>$K_{P_1}$</td>
<td>$K_{I_1}$</td>
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<tr>
<td>$K_{P_2}$</td>
<td>$K_{I_2}$</td>
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V. EXPERIMENT

To verify the effectiveness of the proposed dc voltage control, the scale-down experiments are conducted. The experiment circuit is similar to Fig.1. The ac terminals are
12 Ω each phase. The battery voltage is 130 V. The load voltage is set to 80 and 140 V. The PI controller parameters for these two operating points are the same. In order to demonstrate that the PI controller parameters are the same, the experiment sets a hot dc link voltage change from 80 V to 140 V and backward. The key parameters of the experiment setup are summarized in Table III. The control is implemented in TI-DSP TMS320F28379D. The CPU clock is 200 MHz. The sampling frequency is 100 kHz. The equivalent PI controller parameters in continuous time domain is defined by,

\[ K_p^{DSP} = K_p^{Cont.} \]  \hspace{1cm} (16)

\[ K_i^{DSP} = K_i^{Cont.} f_{sam} \]  \hspace{1cm} (17)

The PI controller equivalent parameters are the same as Table II.
The corresponding experiment results are shown in Fig. 10-13. $V_{\text{Prim}}$ is the primary side voltage of the transformer which is close to $C_1$ bus. $V_{\text{Sec}}$ is the secondary side voltage of the transformer which is close to $C_2$ bus. $I_{\text{leak}}$ is the transformer current which is measured on the primary side. Fig. 10 shows the dc voltage jumps from 140-volt to 80-volt under the proposed controller. Fig. 11 is the zoom-in details of the jump-down dynamics with the leakage inductance current waveform. Fig. 12 shows the dc voltage jumps from 80-volt to 140-volt. Fig. 13 is the zoom-in details of the jump-up dynamics with the leakage inductance current waveform. The experiments indicate that the controller parameter is validated to both operating points of the dc-link voltage.

VI. CONCLUSION

This paper proposed a robust dc voltage control for inverter interleaved DAB converter. The small-signal model of the inverter interfaced DAB converter is derived at a wide range of operating point. Based on the small-signal model, a robust dc voltage control is proposed to adapt to the wide range of dc-link voltage. The proposed dc voltage control is verified by a SiC based inverter interfaced dual active bridge converter prototype. The experiment results showed that the proposed control could cover a wide range of dc-link voltage.

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