Impedance Modeling and Stability-Oriented Parameter Optimization of Isolated Dual Active Bridge-Based Two-Stage AC-DC-DC Converter

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The isolated dual active bridge (DAB)-based two-stage AC-DC-DC converters have been widely applied in grid-connected power electronics systems. However, the impedance interactions between the DAB converter and the AC-DC rectifier can cause instability problems to the two-stage converter systems. The accurate terminal impedance characteristics of the DAB converters are still not clear due to the high frequency ac conversion stage. This makes it difficult to assess the impacts of the DAB circuit parameters on the stability of the two-stage converters. To address these issues, the impedance models of the DAB converters are originally derived in this paper. Based on the developed impedance models, the stability of the DAB-based two-stage AC-DC-DC converters is analyzed. The impacts of the DAB converter circuit parameters on the stability of the two-stage AC-DC-DC converters are comprehensively revealed by the Bode and Nyquist plots. The analysis results offer instructive implications to finetune the design rules of the DAB converters. The conclusions are validated by comprehensive simulation and experimental results.

Keywords: dual active bridge, impedance modeling, stability analysis, two-stage converter, parameter optimization

1 INTRODUCTION

In order to connect various DC energy storage sources, such as the batteries and supercapacitors, to the AC utility grids, one of the most common topologies is the two-stage AC-DC-DC converter which consists of an isolated DC-DC conversion stage and an AC-DC stage (Blaabjerg et al., 2004; Wu et al., 2015; Feng et al., 2020). Among the bidirectional DC-DC converter topologies, the dual active bridge (DAB) converter is becoming more and more popular because of its advantages on the high-power density, galvanic isolation, and soft switching (Krismer and Kolar 2009; Roggia et al., 2013; Ye et al., 2017). Figure 1 shows the DAB-based two-stage AC-DC-DC converter. Literature (Wu et al., 2018) proposed the cooperative triple phase shift (CTPS) control is proposed to eliminate the dual-side flow back currents and reduce the current stress of the DAB converter. The CTPS-based DAB converter has a great potential for being used as the interface converter for the energy storage. Therefore, it is also applied in the two-stage AC-DC-DC converter in this paper.

However, it is found that this two-stage converter has instability issues. Although the DAB converter and the AC-DC rectifier are stable individually, the instable problem may occur when they are cascaded
together. Similar problems have also been reported in other two-
stage systems (Radwan and Mohamed 2012; Wu et al., 2012; Liu 
et al., 2014; Wen et al., 2015). Driven by this issue, a lot of efforts have 
been made to investigate the stability criterion of the two-stage 
systems. The concept of the impedance-based stability criterion is 
first proposed in Literature Middlebrook and Cuk (1976), and later 
becomes the base for the stability analysis of cascaded systems (Sun 
2011; Zhang et al., 2015). A general representation of a two-stage 
cascaded converter configuration is shown in Figure 2. The stability 
of the two-stage converter depends on the minor loop gain $T_m$, 
expressed as the ratio of the source converter output impedance $Z_{out,S}$ to the load converter input impedance $Z_{in,L}$. If the impedance 
ratio $T_m$ satisfies the Nyquist criterion, the two-stage converter will 
be stable.

Hence, to analyze the stability of the two-stage converter, it is 
necessary to derive the impedance models of the AC-DC rectifier 
and the DAB converter. The impedance model of AC-DC rectifier 
has been well established. However, the high frequency ac 
conversion stage brings difficulties to the model generation of the 
DAB converter. The reduced-order impedance models are derived in 
Literature (Tian et al., 2016; Tian et al., 2016), based on the “small-
ripple” assumption. Since the dc average of the transformer current 
over a switching period is 0, the dynamics of the transformer current 
are neglected, thus leading to the sacrifice of accuracy. A full-order 
discrete-time model, which can obtain higher accuracy compared to 
the reduced-order model, is developed in Literature Zhao et al. 
(2010). However, for control design, the continuous model is more 
desirable. Based on the generalized averaging method, a full-order 
continuous-time model of the single-phase shift (SPS) modulated 
DAB converter is proposed and verified to be more accurate than the 
reduced order models at dc and low frequency (Qin and Kimball 
2012). But the model is not extended to the derivation of the DAB 
converter input or output impedances. In Literature (Mueller and 
Kimball 2017), the closed-loop impedance of the SPS-DAB 
converter is calculated based on the Extra Element Theorem with 
a dummy controller. However, the derivation process is cumbersome and time-consuming for practical use. So far, the 
existing impedance models are derived from SPS-DAB converters 
and are not suitable for CTPS-DAB converters. Since the CTPS 
modulation is drawing increasing attention among the DAB 
converter applications, the impedance model of the CTPS-based 
DAB converters should be developed. Moreover, in previous 
applications, the design of the DAB converter circuit parameters 
is focused on the steady and dynamic performance (Tan et al., 2012). 
The influences of the circuit parameters on the stability of the two-
stage converter have not been studied yet.

To fill up the gap, the full-order small signal impedance model of 
the CTPS-based DAB converter is originally derived in this paper. 
The developed impedance model is used to analyze the stability of the 
two-stage converter and the influences of the circuit parameters on 
the stability. Furthermore, the design of the DAB converter circuit parameters 
is revisited. The optimization guideline of the DAB circuit parameters is 
proposed to improve the stability of the two-stage converter.

The rest of this paper is organized as follows. The operation 
mechanism of the CTPS based DAB converter is analyzed in Section 
2. And the small signal impedance models of the two-stage converter 
are derived in Section 3. The stability of the system and the effects of 
the filter capacitances are analyzed in Section 4. The simulation and 
hardware-in-the-loop (HIL) experimental results are presented in 
Section 5 to verify the theoretical analysis. And Section 6 gives the 
conclusions of this work.

2 PRELIMINARY: OPERATION PRINCIPLE 
AND STABILITY ASSESSMENT OF 
TWO-STAGE CONVERTERS 

2.1 Operation Principle of CTPS-DAB 
Converters 
The phase-shift modulation methods are the most widely used to 
regulate the power transferred in the DAB converters. It has been 
verified in Literature Wu et al. (2018) that the CTPS modulation
can eliminate the dual side flow back currents in the DAB converter and achieve better current characteristics, including the inductor current stress and RMS value. The CTPS-DAB converter is more efficient and reliable compared to other traditional phase-shift control methods. Therefore, the CTPS modulation is applied to the DAB-based two-stage converter in this paper. For the purpose of impedance modeling derivation, the relationship of the three control degrees, i.e., the phase-shift modulation is applied to the DAB-based two-stage converter. The CTPS operation principle is omitted due to space limit but can be found in Literature Wu et al. (2018).

Figure 3 depicts the typical operation waveforms of CTPS-DAB converter. $S_1$–$S_4$ are the driving signals for the switches of the DAB converter. $i_L$ is the inductor current. $I_1$ and $I_2$ are the input and output current of the DAB converter, respectively. $v_{h1}$ and $v_{h2}$ are the output voltages of the two H-bridges on the primary and secondary side of the transformer, respectively. $T_s$ is the switching cycle of the DAB converter. $d_\phi$ is the phase-shift ratio between $v_{h1}$ and $v_{h2}$. $d_1$ and $d_2$ are the phase-shift ratios of both primary and secondary H-bridges. All the time points $t_1$–$t_6$ can be found in Table 1. The driving signals $S_1$ or $S_2$ is reversed only when the $I_1$ or $I_2$ is zero. Thus, the polarities of $v_{h1}$ and $v_{h2}$ can be consistent with that of $i_L$. To meet this requirement, the total increment of $i_L$ should be zero during half of a switching cycle, which can be expressed as in Eq. 1. And this constraint can be further simplified as in Eq. 2.

**2.2 Stability Analysis of Two-Stage Converters**

According to Literature Zhang et al. (2015), the stability of the two-stage converter relies on the minor loop gain $T_m$, which is organized as the ratio of the voltage-controlled converter’s output impedance to the current-controlled converter’s input impedance.

Figure 4 shows the schematic and the control system block diagram of the two-stage AC-DC-DC converter, which is used to connect a battery to the utility grid. Between the DAB converter and the AC-DC rectifier, a DC-bus capacitor $C_{dc}$ is used to smooth the DC-bus voltage ripple. The control of the two-stage AC-DC-DC converter is split into two parts: the DC-DC conversion stage and the AC-DC conversion stage. The AC-DC rectifier is responsible for maintaining the DC bus voltage $V_{dc}$ constant and realizing the grid current closed-loop control. The DAB converter closes the control loop regulating the battery charging current $I_b$. It should be noted that the control strategy of the two-stage converter keeps the same in bidirectional operation. From Figure 4, $T_m$ can be calculated as:

$$T_m = \frac{Z_{\text{out}}}{Z_{\text{in,DAB}}}(4)$$

where $Z_{\text{out}}$ is the output impedance of the DC-AC rectifier and $Z_{\text{in,DAB}}$ is the input impedance of the DAB converter.

The stability analysis of the two-stage converter therefore relies on the model-based determinations of the required impedances in Eq. 4. According to Literature (Tian et al., 2016), two-stage converters have unstable problems only when the power is transferred from the voltage-controlled sub-

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**TABLE 1 | Mathematical expression of each time point.**

| Time point | Value | Time point | Value |
|------------|-------|------------|-------|
| $t_0$      | 0     | $t_1$      | 0     |
| $t_2$      | $(d_1 + d_2)$ | $t_3$      | $(1 + d_1)$ |
| $t_4$      | $(1 + d_1)$ | $t_5$      | $(1 + d_1 + d_2)$ |
| $t_6$      | $T_s$  |            |       |

$$\left[1 - d_2 - \left(1 - d_1 - d_\phi\right)\right] \frac{T_s}{2} \frac{v_{dc}}{L_s} = d_\phi \frac{T_s}{2} \frac{v_{dc} - n v_c}{nL_s}$$

$$+ \left(1 - d_1 - d_\phi\right) \frac{T_s}{2} \frac{v_{dc} - n v_c}{nL_s}$$

$$d_\phi = d_2$$

**FIGURE 3 | Operating waveforms of the CTPS based DAB converter.**
converter to current-controlled sub-converter. Considering the control arrangement in Figure 4, the stability of the two-stage converter in battery charging mode, i.e., the power is transferred from the rectifier to the DAB converter, should be analyzed. Hence, the input impedance of the DAB converter in the battery charging mode are derived in the following section.

2.3 Output Impedance of the AC-DC Rectifiers

The performance and control of the three-phase AC-DC rectifier have been well studied in the existing literature. The derivation process of the small signal model of the rectifier which can be found in Literature Twining and Holmes (2003) is omitted here for conciseness. The output impedance $Z_{o, rec}$ of the rectifier can be expressed as:

$$Z_{o, rec} = \frac{-2(sL_g - V_{dc}G_{ci})}{2s^2C_{dc}L_g - 2sC_{dc}V_{dc}G_{ci} + 3(D_d^2 + D_q^2) - 3G_{ci}D_d I_{ld}}$$

(5)

where $C_{dc}$ is the dc-link capacitance; $L_g$ is the input filter inductance of the rectifier; $G_{ci}$ is the controller of the rectifier; $I_{ld}$ is the d-axis component of the inductor current; $D_d$ and $D_q$ denote the d- and q-axes components of the duty ratio of the rectifier, respectively.

3 IMPEDANCE MODELING OF CTPS-DAB CONVERTERS

3.1 Small Signal Impedance Modeling

The impedance model of the CTPS-DAB converter is derived first based on the simplified circuit shown in Figure 5. The voltage-controlled AC-DC rectifier can be regarded as a DC voltage source. $R_b$ is the equivalent load of the battery in the charging operation mode. $R_t$ is the winding resistance of the transformer. The capacitor voltage $V_c$ and the inductor current $i_L$ are taken as the state variables. The state equations of the CTPS-DAB converter can be expressed as:

$$L_d \frac{di_L}{dt} = \frac{v_{h1}}{n} - v_{h2} - R_t i_L = \frac{g_1 v_{dc}}{n} - g_2 v_c - R_t i_L$$

(6)

$$C_p \frac{dv_c}{dt} = i_L - i_b = g_2 i_L - \frac{v_c}{R_b}$$

(7)

where $g_1$ and $g_2$ are the switching functions of the two H-bridges at the primary and secondary sides of the transformer. They can be expressed as follows according to Figure 3.

$$g_1(t) = \begin{cases} 1, & [t_3, t_5] \\ 0, & [t_0, t_3) \cup [t_4, t_5] \\ -1, & [t_3, t_4) \end{cases}$$

(8)

$$g_2(t) = \begin{cases} 1, & [t_2, t_4] \\ 0, & [t_1, t_2) \cup [t_4, t_5] \\ -1, & [t_0, t_1) \cup [t_5, t_6) \\ \end{cases}$$

(9)

Due to the high-frequency ac link in the DAB converter, the generalized state-space averaging (GSSA) method is applied (Caliskan et al., 1999; Qin and Kimball 2012). The averages of the state variables and the switching functions are approximated.
by the sum of the index-0 and index-1 coefficient of their Fourier series. This leads to the following state-variable vector,

\[
\mathbf{x} = \begin{bmatrix} \langle v_c \rangle_0 & \langle v_c \rangle_1 & \langle v_d \rangle_1 & \langle i_d \rangle_0 & \langle i_d \rangle_1 & \langle i_d \rangle_1 \end{bmatrix}^T
\]

(10)

where the subscripts denote the number of the coefficients of the Fourier series; the superscripts “R” and “I” mean the real and imaginary parts of the first coefficients, respectively. These rules apply in the whole paper.

In Literature Qin and Kimball (2012), the authors show that the dynamics of \(\langle v_c \rangle_0, \langle v_c \rangle_1\) and \(\langle i_d \rangle_0\) are decoupled from the rest of the system. Hence, the state-variable vector is reduced to \(\mathbf{x} = [\langle v_c \rangle_0 \langle i_d \rangle_1 \langle i_d \rangle_1]^T\).

Taking the Fourier series of the switching functions, the zeroth coefficients \(g_1(t)_0 = g_2(t)_0 = 0\) due to the symmetry of the operation waveforms. The complex number index-1 coefficients of \(g_1(t)\) and \(g_2(t)\) are given by,

\[
\begin{align*}
\langle g_1 \rangle_1 &= \frac{-\sin(d_1 \pi)}{\pi} \\
\langle g_1 \rangle_1^I &= \frac{-1 + \cos(d_1 \pi)}{\pi} \\
\langle g_2 \rangle_1 &= \frac{-\sin(d_1 \pi) + \sin(d_1 + d_2) \pi}{\pi} \\
\langle g_2 \rangle_1^I &= \frac{\cos(d_1 \pi) + \cos(d_1 + d_2) \pi}{\pi}
\end{align*}
\]

(11-14)

The resulting GSSA state equations can be obtained as Eq. 15. The output vector \(\mathbf{y} = [i_t \ i_v]^T\) can be expressed as Eq. 16.

\[
\begin{bmatrix}
-\frac{1}{C_b R_b} & \frac{2 \langle g_2 \rangle_1}{C_b} & \frac{2 \langle g_2 \rangle_1^I}{C_b} \\
\langle g_1 \rangle_1 & \frac{R_t}{L_t} & \omega_s \\
\langle g_1 \rangle_1^I & -\omega_s & \frac{R_t}{L_t}
\end{bmatrix} \mathbf{x} + \frac{\langle v_d \rangle_0}{n L_t} \mathbf{x} + \frac{\langle v_d \rangle_0}{n L_t} \mathbf{x} + \frac{\langle v_d \rangle_0}{n L_t} \mathbf{x}
\]

(15)

where \(\dot{x}\) is the derivative of the state vector.

\[
\begin{bmatrix}
0 & 2n \langle g_2 \rangle_1 & 2n \langle g_2 \rangle_1^I \\
1 & 0 & 0
\end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\
0
\end{bmatrix} \mathbf{v}_d
\]

(16)

The equilibrium point can be derived by solving \(\dot{x} = 0\). The small signal model can be obtained by perturbing the input variables around the equilibrium point. Note that in this paper, for the variable \(x\), its small signal notation is \(\dot{x}\) and its steady state value is denoted by the uppercase letter \(X\). \(d_2\) is calculated from Eq. 2. Substituting Eq. 2 into Eqs 15, 16, \(d_2\) is replaced by \(d_1, v_c\) and \(v_{dc}\). The input vector is thus given by,

\[
\mathbf{u} = \begin{bmatrix}
\dot{v}_{dc} \\
\dot{d}_1
\end{bmatrix}
\]

(17)

The open-loop small signal model of the CTPS-DAB converter is expressed in Eq. 18.

\[
\dot{x} = A \mathbf{x} + B \mathbf{u} \\
\dot{y} = C \mathbf{x} + D \mathbf{u}
\]

(18)

where \(A, B, C, D\) are system matrix:

\[
A = \begin{bmatrix}
A_{11} & 2 \langle g_2 \rangle_1 & 2 \langle g_2 \rangle_1^I \\
A_{21} & -\frac{R_t}{L_t} & \omega_s \\
A_{31} & -\omega_s & \frac{R_t}{L_t}
\end{bmatrix}
\]

(18a)

\[
B = \begin{bmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22} \\
B_{31} & B_{32}
\end{bmatrix}
\]

(18b)

\[
C = \begin{bmatrix}
0 & 2n \langle g_2 \rangle_1 & 2n \langle g_2 \rangle_1^I \\
1 & 0 & 0
\end{bmatrix}
\]

(18c)

\[
D = \begin{bmatrix}
0 & 2 \left( I_1 \frac{\partial (g_2)_1}{\partial d_1} + I_1 \frac{\partial (g_2)_1^I}{\partial d_1} \right) \\
0 & 0
\end{bmatrix}
\]

(18d)

\[
A_{11} = \frac{1}{C_b R_b} + \frac{2 \langle g_2 \rangle_1}{C_b} \left( I_1 \frac{\partial (g_2)_1}{\partial v_{dc}} + I_1 \frac{\partial (g_2)_1^I}{\partial v_{dc}} \right)
\]

(18e)

\[
A_{21} = -\frac{\langle g_2 \rangle_1}{L_t} - \frac{V_c}{L_t} \frac{\partial (g_2)_1}{\partial v_c}
\]

(18f)

\[
A_{31} = -\frac{\langle g_2 \rangle_1^I}{L_t} - \frac{V_c}{L_t} \frac{\partial (g_2)_1^I}{\partial v_c}
\]

(18g)

\[
B_{11} = \frac{2 \langle g_2 \rangle_1}{C_b} \left( I_1 \frac{\partial (g_2)_1}{\partial v_{dc}} + I_1 \frac{\partial (g_2)_1^I}{\partial v_{dc}} \right)
\]

(18h)

\[
B_{21} = \frac{\langle g_2 \rangle_1}{L_t} - \frac{V_c}{L_t} \frac{\partial (g_2)_1}{\partial v_{dc}}
\]

(18i)

\[
B_{31} = \frac{\langle g_2 \rangle_1^I}{L_t} + \frac{V_c}{L_t} \frac{\partial (g_2)_1^I}{\partial v_{dc}}
\]

(18j)

\[
B_{22} = -\frac{V_c}{L_t} \frac{\partial (g_2)_1}{\partial d_1} + \frac{n L_t}{\partial d_1}
\]

(18k)

\[
B_{32} = \frac{V_c}{L_t} \frac{\partial (g_2)_1^I}{\partial d_1} + \frac{n L_t}{\partial d_1}
\]

(18l)

The partial derivatives are given by,

\[
\frac{\partial (g_2)_1}{\partial d_1} = -\cos(D_1 \pi)
\]

(19a)

\[
\frac{\partial (g_2)_1^I}{\partial d_1} = \sin(D_1 \pi)
\]

(19b)

\[
\frac{\partial (g_2)_1}{\partial d_1} = -\cos(D_1 \pi) - (1 + k) \cos((D_1 + D_2) \pi)
\]

(19c)

\[
\frac{\partial (g_2)_1^I}{\partial d_1} = \sin(D_1 \pi) + (1 + k) \cos((D_1 + D_2) \pi)
\]

(19d)

\[
\frac{\partial (g_2)_1}{\partial v_c} = \frac{D_1 - 1}{n V_c} \cos((D_1 + D_2) \pi)
\]

(19e)
The open-loop transfer functions can be obtained as Eqs 20a–d by solving the open-loop small signal model Eq. 18 using MATLAB.

\[
\begin{align*}
Z_{\text{in,DAB}}^2 &= \frac{(s - A_0) (s + B_0) + \omega_0^2 (A_0 + B_0 w)}{s^2 + (A_0 + B_0 w) s + A_0 B_0 w^2}
\end{align*}
\]

\[
G_{\text{in}} = \frac{\left[ (s + B_0) (s + A_0) + \omega_0^2 (A_0 + B_0 w) \right] \left[ (s + B_0) (s + A_0) + \omega_0^2 (A_0 + B_0 w) \right]}{(s - A_0) (s + B_0) + \omega_0^2 (A_0 + B_0 w)}
\]

\[
G_{\text{in}} = \frac{C_0 \left[ (s + B_0) + \omega_0^2 (A_0 + B_0 w) \right] \left[ (s + B_0) + \omega_0^2 (A_0 + B_0 w) \right]}{R \left[ (s - A_0) (s + B_0) + \omega_0^2 (A_0 + B_0 w) \right]}
\]

The battery current is measured in the control loop of the DAB converter. The control block diagram is shown in Figure 6. \( G_c \) is the controller of the DAB converter based on PI structure. From Figure 6, the closed-loop input impedance \( Z_{\text{in,DAB}} \) can be obtained in Eq. 21 based on Mason’s gain formula (Nise 2007).

\[
\frac{1}{Z_{\text{in,DAB}}} = G_{\text{in}} = \frac{1}{Z_{\text{OL,DAB}}} - \frac{G_{\text{OL}} G_{\text{id}}}{1 + T}
\]

where \( T \) is the loop gain of the DAB converter and \( T = G_t G_{\text{id}} \). And \( Z_{\text{in,DAB}} \) can be further simplified as Eq. 22.

\[
Z_{\text{in,DAB}} = \frac{(1 + T) Z_{\text{OL,DAB}}}{(1 + T) G_{\text{OL}} G_{\text{id}} Z_{\text{OL,DAB}}}
\]

Eq. 22 can be used to determine the closed-loop input impedance of DAB converters around a certain operating point when the battery voltage changes \( V_c \) due to the state-of-charge variations.

It should be mentioned that the battery voltage varies between 270 and 300 V due to the SOC change. Therefore, it is meaningful to investigate the influences of the battery voltage on the DAB input impedance models. Figure 7 shows the bode plots of a set of linearized input impedance models around four different operating points, when \( V_c \) is incrementally changed from 270 to 300 V. The magnitude of \( Z_{\text{in,DAB}} \) is slightly decreased with the increase of \( V_c \), although the phase angles of \( Z_{\text{in,DAB}} \) are almost the same. According to the Middlebrook criterion, the stability of the two-stage converter requires \( Z_{\text{in,DAB}} \) larger than \( Z_{\text{o,rec}} \). The unstable problem of the two-stage converter most likely happens when the input impedance of the DAB converter presents the lowest magnitude. Therefore, to ensure the stability within the whole operation range, the stability of the
two-stage converter should be assessed when the battery voltage is 300 V.

3.2 Validation of Input Impedance Models
The validity of the developed input impedance model is verified using fully detailed simulation in MATLAB/Simulink environment. The measurement of $Z_{in,DAB}$ is shown in Figure 8. Similar impedance measurement methods have been successfully applied in (Huang et al., 2009; Rygg and Molinas 2017). The parameters of the two-stage converter are shown in Table 2. The deadtime of the switches and the sampling period are set as 0.2 and 250 μs, respectively. The simulation time step is fixed to 0.1 μs. The AC-DC rectifier is replaced by a controllable ripple voltage source connected in series with a 660 V DC voltage source. A sinusoidal perturbation is generated at the DC bus, which is superimposed on steady-state DC voltage as the ripple voltage, $v_{dc,r}$. The magnitude of $v_{dc,r}$ is set to 1 and the frequency of $v_{dc,r}$ varies logarithmically from 2 Hz to 10 kHz. The corresponding DC bus currents are also measured. The magnitude and phase of the current ripple, $i_{dc,r}$, are extracted by FFT analysis at each frequency. The impedance of the DAB converter at different frequencies can be calculated by Eq. 23.

$$Z_{in,DAB} = \frac{v_{dc,r}}{i_{dc,r}}$$

The bode plots of $Z_{in,DAB}$ with measured values and model predictive values are shown in Figure 9. The impedance model predicted results match well with the measured results from the low frequencies up to the half of the switching frequency $f_s$. Therefore, the developed impedance model can provide fairly accurate prediction for the input impedance of the CTPS-DAB converter. Furthermore, $Z_{in,DAB}$ shows negative resistance characteristics at the low frequencies. Moreover, the magnitude of $Z_{in,DAB}$ is reduced at about 200 Hz. This is the potential threat for stability consideration of the two-stage converter. If the magnitude of $Z_{in,DAB}$ is lower than that of $Z_{o,rec}$ within the low frequency range, the two-stage converter will be unstable. Hence, it is necessary to increase the minimum magnitude value of $Z_{in,DAB}$. Since the DAB converter circuit parameters are included in the impedance model, the most straightforward method to modify the DAB input impedance is to optimize the DAB circuit parameters. Thus, the effects of the DAB converter circuit parameters on the stability of the two-stage converter should be analyzed.

### 4 Stability-Oriented Optimization of Circuit Parameters

4.1 Stability Improvement by Optimization of $L_s$

To analyze the effects of $L_s$ on the minimum of $Z_{in,DAB}$, Figure 10A shows the bode plots of $Z_{in,DAB}$ with different values of $L_s$. The rest of the circuit parameters are listed in Table 2. The minimum of $Z_{in,DAB}$ increases with the reduction of $L_s$. When $L_s$ is 200 μH or 100 μH, $Z_{in,DAB}$ intersects with $Z_{o,rec}$ indicating that the two-stage converter

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| Equivalent load resistance $R_b$ | 25 Ω | DC bus voltage $V_{dc}$ | 660 V |
| The turns ratio of the transformer $n$ | 2 | DC bus filter capacitance $C_{dc}$ | 2,000 μF |
| DC side output voltage $V_c$ | 300 V | Proportional coefficient of the DC voltage controller for the AC-DC rectifier $K_{pv}$ | 150 |
| The DC side output filter capacitance $C_p$ | 1,000 μF | Integral coefficient of the DC voltage controller for the AC-DC rectifier $K_{pv}$ | 4 |
| Capacitance equivalent series resistance $R_c$ | 0.8 μF | Proportional coefficient of the current controller for the AC-DC rectifier $K_{er}$ | 100 |
| DC inductor $L_s$ | 100 μH | Filter inductor of the AC-DC rectifier $L_g$ | 0.002 H |
| Winding resistance $R_t$ | 0.4 μΩ | Parasitic resistance of the filter inductor $R_p$ | 0.16 |
| Proportional coefficient of the current controller for the DAB converter $K_f$ | 1.2 | | |
| Integral coefficient of the current controller for the DAB converter $K_i$ | 160 | Switching frequency of the DAB converter $f_s$ | 20 kHz |
is unstable. However, for $L_s$ smaller than 50 $\mu$H, the minimum value of $Z_{in, DAB}$ is larger than the magnitude of $Z_{o, rec}$ within all operation frequencies. According to the Middlebrook criterion, the two-stage converter is stable under such conditions.

The influences of $L_s$ on the stability of two-stage converter can be further illustrated by the Nyquist plots of $T_m$ shown in Figure 10B. The trajectory of $T_m$ encircles the critical point ($-1, 0$) when $L_s$ is 200 $\mu$H or 100 $\mu$H, suggesting that there is a right-hand plane pole in the s-plane. The two-stage converter is hence unstable with these two inductors. And the stability of the two-stage converter can be improved by reducing the value of $L_s$. As seen from Figure 10B, with the reduction of $L_s$, the gain margin and phase margin are both

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FIGURE 10 | (A) Bode plots and (B) Nyquist plots of $T_m$ with decreased $L_s$.  

FIGURE 11 | (A) Bode plots and (B) Nyquist plots of $T_m$ with decreased $C_r$.  

FIGURE 12 | (A) Waveforms of the two-stage converter with original parameters; (B) FFT analysis of $V_{dc}$ with original parameters.
FIGURE 13 | (A) Waveforms of the two-stage converter with reduced $L_s$; (B) FFT analysis of $V_{dc}$ with reduced $L_s$.

FIGURE 14 | (A) Waveforms of the two-stage converter with reduced $C_b$; (B) FFT analysis of $V_{dc}$ with reduced $C_b$.

FIGURE 15 | (A) Dynamic performance of the two-stage converter with reduced $L_s$; (B) dynamic performance of the two-stage converter with reduced $C_b$. 
increased. When \( L_s \) is smaller than 50 \( \mu \)H, the trajectory of \( T_m \) no longer encircles \((-1, 0)\) anymore. This can also be deduced from Figure 10A, where the minimum value of \( Z_{in,DAB} \) is gradually increased with the reduction of \( L_s \). Therefore, for improving the stability of the two-stage converter, a relatively small value of \( L_s \) is preferred, although the other factors such as power transfer ability should also be considered.

4.2 Stability Improvement by Optimization of \( C_b \)

Similarly, to analyze the influences of \( C_b \) on the stability of the two-stage converter, a set of \( C_b \) are selected. The relationship between the value of \( C_b \) and the minimum magnitude of \( Z_{in,DAB} \) is shown in Figure 11A. The minimum magnitude of \( Z_{in,DAB} \) keeps decreasing with the reduction of \( C_b \). From Figure 11A, when \( C_b \) is larger than 200 \( \mu \)F, \( Z_{in,DAB} \) and \( Z_{o,rec} \) intersect with each other, which can cause the unstable problem to the two-stage converter.

The effects of \( C_b \) on system stability are further illustrated by the Nyquist plots shown in Figure 11B. From Figure 11B, When \( C_b \) is larger than 200 \( \mu \)F, the trajectory of \( T_m \) encircles the point \((-1, 0)\). This indicates that the two-stage converter cannot maintain its stability. However, with \( C_b \) decreasing from 1,000 \( \mu \)F to 50 \( \mu \)F, the gain margin and the phase margin of the two-stage converter increase gradually. And the two-stage converter is stable when \( C_b \) is smaller than 100 \( \mu \)F. The conclusion that can be drawn from the Nyquist plot together with the bode plots is that a relatively small value of \( C_b \) is good for the stability consideration.

5 EXPERIMENTAL RESULTS AND DISCUSSION

The hardware-in-the-loop (HIL) experimental system has been proven to be an effective method for stability analysis of power electronic converters (Zhang et al., 2018). To verify the theoretical analysis, the stability of the two-stage converter is tested based on the OPAL-RT based HIL experimental system. The parameters of the experimental system are shown in Table 2. It should be noted that the waveform of \( V_{dc} \) in Figures 12–15 are only its AC components to show the stability.

Figure 12A shows the waveforms of the two-stage converter with original circuit parameters \((L_s = 200 \mu \text{H}, C_b = 1,000 \mu \text{F})\). As seen, the oscillation at \( V_{dc} \) can be found. Moreover, the oscillating frequency is around 180 Hz, which is consistent with the prediction of the bode plot in Figure 10A. The unstable problem of the two-stage converter can be more visualized from the FFT spectra of \( V_{dc} \) shown in Figure 12B. The amplitude of the 180 Hz harmonic component is significant. This is the root cause of the waveform oscillation.

Considering the effects of \( L_s \) on the minimum magnitude of \( Z_{in,DAB} \), \( L_s \) should be reduced to improve the stability. Figure 13A shows the waveforms of the two-stage converter with reduced \( L_s = 50 \mu \text{H} \) and other parameters being unchanged. The oscillation at \( V_{dc} \) is mitigated as expected. This is because the minimum magnitude of \( Z_{in,DAB} \) is increased and there is no intersection between \( Z_{in,DAB} \) and \( Z_{o,rec} \) as shown in Figure 10A. It can be also observed from the FFT spectra of \( V_{dc} \) in Figure 13B that the quantities of the 180 Hz harmonic response are suppressed.

Similarly, according to the above-mentioned analysis, \( C_b \) should be reduced to for stability consideration. Figure 14A shows the waveforms of the two-stage converter with \( C_b = 100 \mu \text{F} \) and other parameters being constant. The waveforms show that the two-stage converter is stable with reduced \( C_b \). According to FFT spectra of \( V_{dc} \) in Figure 14B, the 180 Hz harmonic response is also greatly suppressed.

The dynamic performances of the two-stage converter with reduced \( L_s \) and \( C_b \) are also tested and shown in Figure 15. When \( I_b \) steps up from 6 to 12 A, \( V_{dc} \) can be stabilized with reduced \( L_s \) or \( C_b \) after a short transient period. However, when reduced \( L_s \) is applied, the overshoot of \( V_{dc} \) is about 14 V. When reduced \( C_b \) is applied, the overshoot of \( V_{dc} \) is only about 5 V.

Hence, the stability of the two-stage converter can be improved by optimizing \( L_s \) or \( C_b \). Furthermore, the dynamic performance of the two-stage converter with reduced \( C_b \) is better than that of the two-stage converter with reduced \( L_s \) according to the experimental waveforms.

6 CONCLUSION

The full-order impedance model of the CTPS based DAB converter has been derived in this paper. The developed impedance model can fully represent the dynamics of the ac conversion stage of the DAB converters. Based on the developed impedance model, the stability of two-stage converter has been analyzed. Furthermore, the effects of the DAB circuit parameters on the stability of the two-stage converter have been presented and analyzed. The design of the DAB circuit parameters is revisited. The stability-oriented optimization guideline of circuit parameters is provided for the DAB converter. The stability of the two-stage converter can be improved by reducing the leakage inductance or the DC side output filter capacitance of the DAB converter.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

FF contributed to the conception of the study and wrote the manuscript; JF performed the data analyses; HG contributed to analysis and manuscript preparation. UM and LW performed the experiment.

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REFERENCES

Blaabjerg, F., Chen, Z., and Kjaer, S. B. (2004). Power Electronics as Efficient Interface in Dispersed Power Generation Systems. IEEE Trans. Power Electron. 19 (5), 1184–1194. doi:10.1109/tpel.2004.833453

Caliskan, V. A., Verghese, O. C., and Stankovic, A. M. (1999). Multifrequency Averaging of DC/DC Converters. IEEE Trans. Power Electron. 14 (1), 124–133. doi:10.1109/63.737600

Erika Twinning, E., and Holmes, D. G. (2003). Grid Current Regulation of a Three-phase Voltage Source Inverter with an LCL Input Filter. IEEE Trans. Power Electron. 18 (3), 888–895. doi:10.1109/tpe.2003.810838

Feng, F., Zhang, X., Zhang, J., and Gooi, H. B. (2020). Stability Enhancement via Controller Optimization and Impedance Shaping for Dual Active Bridge-Based Energy Storage Systems. IEEE Trans. Industrial Electron. 68 (7), 5863–5874.

Hengsi Qin, H., and Kimball, J. W. (2012). Generalized Average Modeling of Dual Active Bridge DC-DC Converter. IEEE Trans. Power Electron. 27 (4), 2078–2084. doi:10.1109/tpe.2011.2165734

Huang, J., Corzine, K. A., and Belkhayat, M. (2009). Small-signal Impedance Modeling and Stability Improvement of a Three-Phase Zero-Voltage-Switching Phase-Shift Bidirectional DC-DC Converter. IEEE Trans. Power Electron. 24 (2), 445–455. doi:10.1109/tpel.2008.2007212

Krismer, F., and Kolar, J. W. (2009). Accurate Small-Signal Model for the Digital Control of an Automotive Bidirectional Dual Active Bridge. IEEE Trans. Power Electron. 24 (12), 2756–2768. doi:10.1109/tpe.2009.2027904

Liu, F., Liu, J., Zhang, H., and Xue, D. (2014). Stability Issues of S+Z Type Cascade System in Hybrid Energy Storage System (HESS). IEEE Trans. Power Electron. 29 (11), 5846–5859. doi:10.1109/tpe.2013.2295259

Middlebrook, R., and Cuk, S. (1976). A General Unified Approach to Modelling Switching-Converter Power Stages. In Power Electronics Specialists Conference. IEEE. doi:10.1109/pesc.1976.7072895

Mueller, J. A., and Kimball, J. W. (2017). “Model-based Determination of Closed-Loop Input Impedance for Dual Active Bridge Converters,” in Applied Power Electronics Conference and Exposition (APEC), 2017 IEEE (IEEE). doi:10.1109/ apec.2017.7930824

Nise, N. S. (2007). Control Systems Engineering. (With CD). John Wiley & Sons.

Radwan, A. A. A., and Mohamed, Y. A.-R. I. (2012). Assessment and Mitigation of Interaction Dynamics in Hybrid AC/DC Distribution Generation Systems. IEEE Trans. Smart Grid 3 (3), 1382–1393. doi:10.1109/tsg.2012.2201965

Roggia, L., Schuch, L., Baggio, J. E., Rech, C., and Pinheiro, J. R. (2013). Integrated Full-Bridge-Forward DC-DC Converter for a Residential Microgrid Application. IEEE Trans. Power Electron. 28 (4), 1728–1740. doi:10.1109/tpel.2012.2214061

Rygg, A., and Molinas, M. (2017). Apparent Impedance Analysis: A Small-Signal Method for Stability Analysis of Power Electronic-Based Systems. IEEE J. Emerg. Sel. Top. Power Electron. 5 (4), 1474–1486. doi:10.1109/jeste.2017.2729596

Sun, J. (2011). Impedance-based Stability Criterion for Grid-Connected Inverters. IEEE Trans. Power Electron. 26 (11), 3075–3078. doi:10.1109/tpel.2011.2136439

Tan, N. M. L., Abe, T., and Akagi, H. (2012). Design and Performance of a Bidirectional Isolated DC-DC Converter for a Battery Energy Storage System. IEEE Trans. Power Electron. 27 (3), 1237–1248. doi:10.1109/tpel.2011.2108317

Tian, Y., Loh, P. C., Chen, Z., Deng, F., and Hu, Y. (2016). Impedance Interactions in Bidirectional Cascaded Converter. IET Power Electron. 9 (13), 2482–2491. doi:10.1049/iet-pel.2015.0559

Tian, Y., Loh, P. C., Deng, F., Chen, Z., Sun, X., and Hu, Y. (2016). Impedance Coordinative Control for Cascaded Converter in Bidirectional Application. IEEE Trans. Ind. Appl. 52 (5), 4084–4095. doi:10.1109/tia.2016.2564359

Ye, Q., Mo, R., and Li, H. (2017). Low-frequency Resonance Suppression of a Dual Active Bridge (DAB) DC/DC Converter Enabled DC Microgrid with Constant Power Loads (CPLs) Based on Reduced-Order Impedance Models. IEEE J. Emerg. Sel. Top. Power Electron. 7 (4), 916–925. doi:10.1109/tset.2014.2373673

Ye, Q., Zhong, Q.-C., Kadirkamanathan, V., He, J., and Huang, J. (2018). Source-side Series-Virtual-Impedance Control to Improve the Cascaded System Stability and the Dynamic Performance of its Source Converter. IEEE Trans. Power Electron.

Zhao, C., Round, S. D., and Kolar, J. W. (2010). Full-order Averaging Modelling of Line-Source-Series-Virtual-Impedance Control to Improve the Cascaded System Stability. IEEE Trans. Power Electron. 25 (4), 925–936. doi:10.1109/tpe.2009.2032557

Zhong, X., Zeng, X., and Tse, C. K. (2015). Impedance-based Local Stability Criterion for DC Distributed Power Systems. IEEE Trans. Circuits Syst. I 62 (3), 916–925. doi:10.1109/tcis.2014.2373673

Zhang, X., Zhong, Q.-C., Kadirkamanathan, V., He, J., and Huang, J. (2018). Source-side Series-Virtual-Impedance Control to Improve the Cascaded System Stability and the Dynamic Performance of its Source Converter. IEEE Trans. Power Electron.

Zhang, X., Ruan, X., and Tse, C. K. (2015). Impedance-based Local Stability Criterion for DC Distributed Power Systems. IEEE Trans. Circuits Syst. I 62 (3), 916–925. doi:10.1109/tcis.2014.2373673

Tian, Y., Loh, P. C., Chen, Z., Deng, F., and Hu, Y. (2016). Impedance Interactions in Bidirectional Cascaded Converter. IET Power Electron. 9 (13), 2482–2491. doi:10.1049/iet-pel.2015.0559

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