Impedance-Based Stability Analysis of DAB Converters With Single-, Double-, or Cooperative Triple-Phase-Shift Modulations and Input LC Filter

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The impedance-based criterion has turned out to be a very effective tool for the stability analysis of the dual active bridge (DAB) converter with its input LC filter. While the input impedance of the DAB converter is highly dependent on the modulation methods, the influences of the modulation methods on the input impedances of the DAB converters are still not clear. To close this gap, three typical modulation methods of DAB converters, traditional single-phase-shift (SPS), dual-phase-shift (DPS) and the emerging cooperative triple-phase-shift (CTPS) modulation, are studied in this paper. First, the full-order input impedance models of the DAB converter with these modulation methods are derived for the first time. Second, based on the developed models, the impacts of these modulation schemes on the DAB input impedances are revealed. An interesting phenomenon is found that the open-loop impedances of SPS-DAB and DPS-DAB converters present the characteristics of the parallel-connected inductor and capacitor, while the open-loop impedance of CTPS-DAB converter presents the resistor characteristics. Third, the optimal modulation scheme for system stability is investigated. Finally, the theoretical analysis has been validated by the experimental results.

Keywords: dual active bridge, input impedance, phase-shift modulation, stability analysis, comparison

INTRODUCTION

The dual active bridge (DAB) converter is drawing more and more attention in both academics and industry because of its advantages of galvanic isolation, high power density and efficiency (Zhao et al., 2014; Alonso et al., 2010; Hengsi Qin and Kimball, 2012). The state-of-the-art researches focus on the modulation methods (Kheraluwala and De Doncker, 1993; Inoue and Akagi, 2007; Hua Bai and Mi, 2008; Zhao et al., 2012; Wu et al., 2018), soft-switching solution (Oggier et al., 2010; Huang et al., 2016), control strategy (Song et al., 2018; Takagi and Fujita, 2016; Shan et al., 2018; Oggier et al., 2014) and optimization of hardware design (Fan and Li, 2011; Wang et al., 2009). The typical configuration of a DAB converter-based DC microgrid is shown in Figure 1. The switching converters are necessary for the power transfer between the source and dc/ac loads. However, they also introduce strong electromagnetic interference (EMI) due to the high-frequency switching. These high-frequency components can cause improper operation of other EMI sensitive loads/equipment in this microgrid. Compliance with electromagnetic interference (EMI) standards, the insertion of an LC filter between the DAB converter and the DC bus is required (Weichel et al., 2010;
However, although the DAB converter is designed properly for stand-alone operation (Shi et al., 2017), the stability can be a problem when the DAB converter is cascaded with its LC filter. This instability issue is actually caused by the coupling of the DAB converter and the LC filter. Similar instability issues have also been found in other cascaded systems (Middlebrook and Cuk, 1976; Kelkar and Lee, 1983). Existing approaches (Sun, 2011; Zhang et al., 2015) to analyzing the stability necessitate the input impedance of the DAB converter with three typical modulation methods: SPS, DPS, and CTPS are developed for the DAB converter with the LC filter could be different due to the different modulation methods applied.

The determination of the required DAB input impedance model is highly dependent on the modulation methods of the DAB converters. Up to now, the most widely used method is the single-phase-shift (SPS) modulation (Kheraluwala and De Doncker, 1993; Inoue and Akagi, 2007). Through adjusting the outer-phase-shift between the output voltages of the two H-bridges, the transferred power can be easily regulated. However, the large circulating current is generated in the SPS-DAB converter, which can lower the efficiency of the whole system (Harr ye et al., 2014; Wen et al., 2014; Karthikeyan and Gupta, 2016). To reduce the circulating current, the concept of the dual-phase-shift (DPS) modulation is first proposed in (Hua Bai et al., 2008). Compared to SPS, an additional inner phase-shift ratio is applied to the H-bridges, reducing the circulating current and current stress. Furthermore, in Literature Wu, et al. (Wu et al., 2018), the cooperative triple-phase-shift (CTPS) modulation is proposed to eliminate the dual side circulating currents. With the CTPS method, better current characteristics, including the current stress, average absolute, and RMS values of the inductor current, can be achieved. Therefore, the CTPS method has gained increasing attention in many applications: Solid State Transformers (Shi et al., 2019), energy storage systems (Feng et al., 2020), and the DAB variants (Fang et al., 2020; Cao et al., 2021). Apart from affecting the circulating current, different modulation methods also lead to different performances of the DAB converter. The differences of the steady-state operation and dynamic responses of DAB converters with SPS and DPS modulation methods have been compared in (Hua Bai et al., 2010; Hou and Li, 2019). However, to the best of the authors’ knowledge, the influences of these modulation methods on the DAB input impedance characteristics and stability performance have been rarely studied. In the existing literature (Tian et al., 2016; Ye et al., 2016; Mueller and Kimball, 2017), the stability of the DAB based cascaded configuration is analyzed only considering SPS modulation. The differences of the input impedances of the DAB converters with SPS, DPS and CTPS modulation are not clear. Since the stability criterion directly depends on the input impedance, the stability performance of the DAB converter with its LC filter could be different due to the different modulation methods applied.

The purpose of this paper is to present the comparative study on the influences of different modulation schemes on the stability of the DAB-based cascaded topologies. Three typical modulation schemes, SPS, DPS and CTPS, are selected and the input impedances of the DAB converter with these three modulation schemes are derived and analyzed. This paper presents the following contributions:

- The full-order input impedance models of the DAB converter with three typical modulation methods: SPS, DPS and CTPS are developed for the first time.
- The effects of SPS, DPS and CTPS modulation methods on the input impedance characteristics of the DAB converters are disclosed.
- The stability performance of SPS-, DPS- and CTPS-DAB converter with the LC filter are analyzed and compared. The optimal modulation method from stability point of view has been pointed out, which is further verified by experimental results.

The rest of this paper is organized as follows. The operation mechanisms of the SPS, DPS and CTPS modulation methods are analyzed in Operation Principles and Stability Analysis of DAB Converters With Input LC Filter. The input impedance models of the SPS-, DPS-, and CTPS-DAB converters are derived in Input Impedance Modeling of DAB Converters with SPS, DPS and CTPS Modulations. The SPS, DPS and CTPS modulation methods are compared in terms of stability performance of DAB converters with the LC filter in Stability Comparison of Cascaded System with SPS, DPS and CTPS Modulations. Experimental Results presents the experimental results to verify the theoretical analysis. The conclusion is given in Conclusion.
**OPERATION PRINCIPLES AND STABILITY ANALYSIS OF DAB CONVERTERS WITH INPUT LC FILTER**

Operation principles of DAB converter with SPS, DPS and CTPS modulation methods.

**Figure 2** shows the circuit topology of the DAB converter, which consists of two H-bridge and one high-frequency transformer. $i_L$ is the leakage inductor current. $v_{h1}$ and $v_{h2}$ are the output voltages of the input and output H-bridges, which can be calculated as:

$$v_{h1} = s_1v_{dc}, \quad v_{h2} = s_2v_o$$

where $s_1$ and $s_2$ are the switching functions at the input and output H-bridges, respectively; $v_{dc}$ is the voltage across the capacitance $C_f$ and $v_o$ is the output voltage of the DAB converter.

The operation principles of the DAB converter with different modulation methods are shown in **Figure 3**.

**Figure 3A** depicts the operation mechanism of the SPS modulation method. In this method, two H-bridges both generate square voltage waveforms at the primary and secondary sides of the transformer. Through adjusting the outer phase shift ratio $d_p$ between these two output voltages of the H-bridges, the direction and magnitude of the transferred power can easily be regulated. The switching functions $s_{1_{-SPS}}$ and $s_{2_{-SPS}}$ can be expressed as in (2).

$$s_{1_{-SPS}} = \begin{cases} 1, & [0, \pi] \\ -1, & [\pi, 2\pi] \end{cases}$$

$$s_{2_{-SPS}} = \begin{cases} 1, & \left[d_p\pi, (1+d_p)\pi\right] \\ -1, & \left[0, d_p\pi\right] \cup \left[(1+d_p)\pi, 2\pi\right] \end{cases}$$

For DPS modulation (**Figure 3B**), besides the phase shift $d_p$ used in SPS, an additional duty ratio $d_1$ is applied to the two H-bridges. The output voltages of the H-bridges are modulated as three-level waveforms. During the time intervals of the zero voltage of the three-level wave, the circulating power is zero. Therefore, compared to SPS method, DPS method reduces the current stress of the switches and increases the overall efficiency for the given transmission power. According to **Figure 3B**, the switching functions $s_{1_{-DPS}}$ and $s_{2_{-DPS}}$ in DPS are changed to (3).

$$s_{1_{-DPS}} = \begin{cases} 1, & [d_1\pi, \pi] \\ 0, & \left[0, d_1\pi\right] \cup \left[(1+d_1)\pi, 2\pi\right] \end{cases}$$

$$s_{2_{-DPS}} = \begin{cases} 1, & \left[(d_1 + d_p)\pi, (1+d_1+d_p)\pi\right] \\ 0, & \left[d_p\pi, (d_1 + d_p)\pi\right] \cup \left[(1+d_p)\pi, (1+d_1+d_p)\pi\right] \\ -1, & \left[0, d_p\pi\right] \cup \left[(1+d_1+d_p)\pi, 2\pi\right] \end{cases}$$

In order to address the circulating current problem, three control variables, describing the duty ratio of $v_{h1}$ ($d_1$), $v_{h2}$ ($d_2$) and the phase shift between them ($d_p$) are used in CTPS modulation (**Figure 3C**). It has been shown in Literature Wu et al. (2018), in order to eliminate the circulating current, these three control variables should satisfy the constraint in (4).

$$d_2 = 1 + k(d_1 - 1)$$

$$d_p = d_{2_{-min}}$$

where $k = nV_{dc}/V_o$; and $n$ is the turns ratio of the transformer.

The switching functions of CTPS can be derived from **Figure 3C**.
\[ s_{1,\text{CTPS}} = \begin{cases} 1, & \left[ (d_1 + d_2)\pi, \pi \right) \\ 0, & \left[ 0, (d_1 + d_2)\pi \right) \cup \left( \pi, (1 + d_1)\pi \right) \\ -1, & \left[ (1 + d_1)\pi, 2\pi \right) \end{cases} \]  
\[ s_{2,\text{CTPS}} = \begin{cases} 1, & \left( d_1 + d_2\right)\pi, (1 + d_1)\pi) \\ 0, & \left[ 0, (d_1 + d_2)\pi \right) \cup \left( (1 + d_1)\pi, (1 + d_1 + d_2)\pi \right) \\ -1, & \left[ (1 + d_1 + d_2)\pi, 2\pi \right) \end{cases} \] (5a) (5b)

**Stability Analysis of DAB Converters With Its LC Filter**

For the cascaded system consisting of the DAB converter and the input LC filter, according to (Huang et al., 2016), the stability of the cascaded system depends on the minor loop gain \( T_m \), which is expressed as follows:

\[ T_m = \frac{Z_{\text{out,LC}}}{Z_{\text{in,DAB}}} \] (6)

where \( Z_{\text{out,LC}} \) is the output impedance of the LC filter and \( Z_{\text{in,DAB}} \) is the input impedance of the DAB converter. If and only if \( T_m \) satisfies Nyquist criterion, the stability of the cascaded system will be stable.

While the output impedance of the LC filter is given in (7), the input impedance model of the DAB converter should be determined for the stability analysis.

\[ Z_{\text{out,LC}} = \frac{sL_f + R_f}{s^2L_f C_f + sR_f C_f + 1} \] (7)

where \( L_f \) and \( C_f \) are the inductor and capacitor of the input filter, respectively; \( R_f \) is the leakage resistance of \( L_f \).

**INPUT IMPEDANCE MODELING OF DAB CONVERTERS WITH SPS, DPS AND CTPS MODULATIONS**

**Generalized Averaging of DAB Converters**

For the modeling of DAB converters, all the switches are considered as the ideal switches. So the voltage drop across the transistor diode and switching transients are negligible. Since the input filter capacitor is relatively large, the dynamics of the input filter capacitor are much slower than those of the DAB converter and therefore are neglected. \( i_L \) and \( v_o \) are taken as the state variables. The state equations are derived as:

\[ L_s i_L = \frac{v_{dc}}{n} - v_{in2} = s_1 v_{dc} - s_2 v_o \] (8)
\[ C_o v_o = i_L - i_o = s_2 i_L - \frac{v_o}{R_L} \] (9)

where dot notation is used to indicate derivatives with respect to time; \( L_s \) is the leakage inductor of DAB converters; \( C_o \) is the output filter capacitor; and \( R_L \) is the equivalent load resistor.

Due to the ac characteristics of the DAB inductor current, the generalized state space averaging (GSSA) is applied. The idea of GSSA is based on the representation of the signal \( x(t) \) on the interval \( r \in [t-T, t] \) by its Fourier series

\[ x(t) = \sum_{k=-\infty}^{\infty} \langle x \rangle_k (t) e^{jk\omega_r t} \] (10)

where \( \omega_r = \frac{2\pi}{T} \) and \( \langle x \rangle_k (t) \) is the \( k \)-th complex coefficients of the Fourier series, which is given by

\[ \langle x \rangle_k = \frac{1}{T} \int_{t-T}^{t} x(t) e^{-jk\omega_r t} dt \]

\[ = \frac{1}{T} \int_{t-T}^{t} x(t) \cos(k\omega_r t) dt - j \frac{1}{T} \int_{t-T}^{t} x(t) \sin(k\omega_r t) dt \] (11)

For the DAB converter, to represent the dc and ac components of the state variables and the switching functions, they are extended to index-0 and index-1 terms of their Fourier series, which can be derived from (9). Note that the index-1 coefficients of these variables have both real and imaginary parts. This leads to the following state variable vector,

\[ x = \begin{bmatrix} \langle v_o \rangle_0 & \langle v_o \rangle_1^R & \langle v_o \rangle_1^I & \langle i_L \rangle_0 & \langle i_L \rangle_1^R & \langle i_L \rangle_1^I \end{bmatrix}^T \] (12)

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

Since \( i_L \) is purely ac, and \( i_L \) varies faster than \( v_{dc} \) and \( v_o \), it is assumed that,

\[ \langle i_L \rangle_0 = \langle v_{dc} \rangle_1^R = \langle v_{dc} \rangle_1^I = \langle v_o \rangle_1^R = \langle v_o \rangle_1^I = 0 \] (13)

State variables are now reduced to the following vector,

\[ x = \begin{bmatrix} \langle v_o \rangle_0 & \langle i_L \rangle_1^R & \langle i_L \rangle_1^I \end{bmatrix}^T \] (14)

Applying the Fourier series properties to (8) and (9) yields the GSSA state equations of the DAB converter:

\[ \dot{x} = \begin{bmatrix} 1 & 2\langle s_2 \rangle_1^R & 2\langle s_2 \rangle_1^I \\ -\frac{\langle s_2 \rangle_1^R}{L_s} & 0 & \omega_s \\ -\frac{\langle s_1 \rangle_1^I}{L_s} & -\omega_s & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \langle s_1 \rangle_0^R \\ \langle s_1 \rangle_0^I \end{bmatrix} \] (15)

where \( \omega_s = 2\pi f_s f_s \) is the switching frequency.

The output vector \( y = [i_L \ i_o]^T \) can be expressed as (16).

\[ y = \begin{bmatrix} 0 & 2n\langle s_1 \rangle_0^R & 2n\langle s_1 \rangle_0^I \\ 1 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \] (16)

Input impedance modeling of DAB with SPS, DPS and CTPS modulations.

The small-signal model of the SPS-, DPS- and CTPS-DAB converters can be obtained by applying perturbation to the input
variables \(v_{dc}\) and \(d\) in the average model (15) and (16). The control signal \(d\) refers to \(d_{s}\) for SPS, and \(d_{t}\) for DPS and CTPS. Note that in this paper, for the variable \(x\), its small-signal notation is \(\hat{x}\) and its steady-state value is denoted by the uppercase letter \(X\). The input vector is thus given by

\[
\mathbf{u} = \begin{bmatrix} \hat{v}_{dc} & \hat{d} \end{bmatrix}^T
\]

The open-loop small-signal model of the DAB converter is expressed in

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

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

where \(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}\) are system matrices, which are given as:

\[
\mathbf{A} = \begin{bmatrix}
A_{11} & \frac{2\langle s_2 \rangle}{L_{s}} & \frac{2\langle s_2 \rangle}{L_{s}} \\
A_{21} & 0 & \omega_x \\
A_{31} & -\omega_y & 0
\end{bmatrix}
\]

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

\[
\mathbf{C} = \begin{bmatrix}
0 & 2n\langle s_1 \rangle & 2n\langle s_1 \rangle \\
1 & 0 & 0
\end{bmatrix}
\]

\[
\mathbf{D} = \begin{bmatrix}
0 & \frac{1}{L_{s}} \frac{d\langle s_1 \rangle}{d\hat{d}} + \frac{1}{L_{s}} \frac{d\langle s_1 \rangle}{d\hat{d}} \\
0 & 0
\end{bmatrix}
\]

\[
A_{11} = -\frac{1}{C_{o}R_{L}} + \frac{2}{C_{o}} \left( \frac{\partial\langle s_2 \rangle}{\partial\hat{v}_{dc}} + \frac{\partial\langle s_2 \rangle}{\partial\hat{d}} \right)
\]

\[
A_{21} = \frac{\langle s_2 \rangle}{L_{s}} - \frac{V_{o}}{L_{s}} \frac{\partial\langle s_2 \rangle}{\partial\hat{v}_{dc}}
\]

\[
A_{31} = -\frac{\langle s_2 \rangle}{L_{s}} - \frac{V_{o}}{L_{s}} \frac{\partial\langle s_2 \rangle}{\partial\hat{d}}
\]

\[
B_{11} = \frac{1}{C_{o}} \left( \frac{\partial\langle s_2 \rangle}{\partial\hat{v}_{dc}} + \frac{\partial\langle s_2 \rangle}{\partial\hat{d}} \right)
\]

\[
B_{12} = \frac{1}{C_{o}} \left( \frac{\partial\langle s_2 \rangle}{\partial\hat{v}_{dc}} + \frac{\partial\langle s_2 \rangle}{\partial\hat{d}} \right)
\]

\[
B_{21} = \frac{\langle s_1 \rangle}{L_{s}} - \frac{V_{o}}{L_{s}} \frac{\partial\langle s_1 \rangle}{\partial\hat{d}}
\]

\[
B_{22} = \frac{\langle s_1 \rangle}{L_{s}} - \frac{V_{o}}{L_{s}} \frac{\partial\langle s_1 \rangle}{\partial\hat{d}}
\]
Note that the above model is valid for any modulation method of the DAB converter. The specific formulation of the small-signal model of the SPS-, DPS- and CTPS-DAB converters can be derived by substituting the corresponding switching functions.

Due to the symmetry of the operation waveforms shown in Figure 2, the index-0 coefficients of these switching functions are all equal to 0. Substituting (2), (3) and (5) into (11), the complex index-1 coefficients of the switching functions for SPS, DPS and CTPS modulation can be obtained. The real and imaginary parts of these coefficients are calculated in (19) (20) and (21).

\[
\langle s_{2_{PS}} \rangle^R_1 = 0 \quad (19.a) \\
\langle s_{2_{PS}} \rangle^I_1 = -2 (2/\pi) \quad (19.b) \\
\langle s_{2_{CTPS}} \rangle^R_1 = -2 \sin(d_2 \pi)/\pi \quad (19.c)
\]

\[
\langle s_{2_{PS}} \rangle^R_1 = -\sin(d_1 \pi)/\pi \quad (20.a) \\
\langle s_{2_{DPS}} \rangle^R_1 = -2 \sin(d_1 \pi + d_3 \pi + d_4 \pi)/\pi \quad (20.b) \\
\langle s_{2_{DPS}} \rangle^R_1 = -\sin(d_3 \pi + d_4 \pi)/\pi \quad (20.c) \\
\langle s_{2_{DPS}} \rangle^R_1 = -\sin(d_4 \pi)/\pi \quad (20.d)
\]

\[
\langle s_{2_{CTPS}} \rangle^R_1 = -\sin(d_1 \pi)/\pi \quad (21.a)
\]
\[
\begin{align*}
\langle s_1 \rangle &= -[1 + \cos(d_1 \pi)]/\pi \quad (21.b) \\
\langle s_2 \rangle &= -[\sin(d_1 \pi) + \sin(d_1 + d_2 \pi)]/\pi \quad (21.c) \\
\langle s_3 \rangle &= -[\cos(d_1 \pi) + \cos(d_1 + d_2 \pi)]/\pi \quad (21.d)
\end{align*}
\]

Substituting (19)–(21) into (18) produce the small-signal models for the DAB converter with SPS, DPS and CTPS modulation methods, respectively.

The transfer functions defined in Table 1 are obtained in (22) by solving the small-signal models of DAB converters using MATLAB. The analytical solutions of the open-loop transfer functions \(Z_{\text{OL}}^{\text{DAB}_1} \), \(G_{\text{OL}^\text{d}1} \), \(G_{\text{OL}^\text{vd}1} \) and \(G_{\text{OL}^\text{io}1} \) are given in the Appendix (A1)–(A4). It should be noted that although they share the same form, the actual analytical expressions of these transfer functions for SPS, DPS and CTPS are different since they are generated from different GSSA models.

\[
\begin{bmatrix} i_1 \\ i_o \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_{\text{OL}}^{\text{DAB}_1}} & G_{\text{OL}^\text{d}1} \\ G_{\text{OL}^\text{vd}1} & G_{\text{OL}^\text{io}1} \end{bmatrix} \begin{bmatrix} v_{dc} \\ d \end{bmatrix}
\]

(22)

The determination of the closed-loop impedances depends on the feedback control loops. Figure 4 shows the feedback control block diagram of the DAB converter. It should be mentioned that the same feedback control loop is applied to SPS-, DPS- and CTPS-DAB converters. \(G_c \) denotes the DAB controller and \( G_c = k_p + k_i/s \). \( k_p \) and \( k_i \) are the proportional and integral coefficients, respectively.

Substituting all the open-loop transfer functions into Figure 4, the closed-loop input impedances of DAB converters with SPS, DPS and CTPS are calculated using MATLAB, respectively. The unified expression of \( Z_{\text{in, DAB}} \) is given as in:

\[
Z_{\text{in, DAB}} = \frac{(1 + T)Z_{\text{OL}}^{\text{DAB}}} {(1 + T) - G_{\text{OL}^\text{vd}1} \hat{G}_c G_{\text{OL}^\text{id}} Z_{\text{OL}}^{\text{DAB}}}
\]

(23)

where \( T \) is the loop gain of DAB converters and. \( T = G_c G_{\text{OL}^\text{id}} \).

### STABILITY COMPARISON OF CASCADED SYSTEM WITH SPS, DPS AND CTPS MODULATIONS

#### Input Impedance and Stability Comparison of Cascaded System With Different Modulations

To compare the influences of the modulation methods on the stability of the cascaded system, the input impedance of the DAB converter should be compared with the output impedance of the LC...
The circuit parameters are shown in Table 2. The equilibrium point can be derived by solving (15) making $x = 0$. So the steady-state value of the control signal for SPS DPS and CTPS modulations can be determined. For the DPS modulation, $D_\phi$ is set as 0.5. For the CTPS modulation, $D_2$ and $D_\phi$ are calculated according to (4).

The PI parameters for the DAB converters are selected to guarantee the same cut-off frequency for SPS, DPS and CTPS. According to Literature Erickson and Maksimovic (Erickson and Maksimovic, 2007), if the cut-off frequency of the closed-loop DAB converter is close to or greater than the resonant frequency of the input LC filter, the cascaded system tends to be unstable. Therefore, the cut-off frequencies of the closed-loop DAB converter with SPS, DPS and CTPS are all selected as 200 Hz, which is smaller than the LC filter resonant frequency 1,340 Hz.

For the stand-alone operation of the DAB converter, the poles of the closed-loop current control transfer function are shown in Figure 5. The eigenvalues of the current control transfer functions all appear in the left half-plane, indicating that the DAB converter under SPS/DPS/CTPS are all stable for standalone operation with the selected PI parameters.

To assess the stability of the cascaded system, the Bode plots of the open-loop input impedances, the closed-loop input impedances of DAB converters and the output impedance of the LC filter are shown in Figure 6. The circuit and controller parameters are also shown in Table 2.

By Figure 6A, the characteristics of the open-loop DAB input impedances are highly affected by the modulation schemes. $Z_{in, DAB}$
(CTPS) shows the positive resistor characteristics, while \( Z_{in,DAB}^{OL} \) (SPS) and \( Z_{in,DAB}^{OL} \) (DPS) both intersect with \( Z_{out,LC} \) around 1,030 Hz.

As seen from Figure 6B, the comparisons between the closed-loop impedances and stabilities of SPS-, DPS-, and CTPS-DAB converters are summarized as:

- At low frequencies, the input impedances of DAB converters with SPS, DPS, and CTPS modulation methods show negative resistor characteristics.
- At high frequencies (beyond 600 Hz), \( Z_{in,DAB}^{SPS} \) and \( Z_{in,DAB}^{DPS} \) show a capacitive behavior, while \( Z_{in,DAB}^{CTPS} \) presents a positive resistance behavior.
- The closed-loop impedance of DAB converters intersects with \( Z_{out,LC} \) around 1,030 Hz, which is the same with the open-loop impedance intersection frequency. According to the Middlebrook criterion, the same impedance intersection condition indicates that the system stability performance of open-loop and closed-loop operation should also be the same.
- At this intersection frequency, the negative impedance of \( Z_{in,DAB}^{SPS}/Z_{in,DAB}^{DPS} \) will lead to instability as the phase difference is larger than 180°. The resistive characteristics of \( Z_{in,DAB}^{CTPS} \) ensure that the CTPS-DAB converter has high stability robustness at the intersection frequency.
- Hence, for stability consideration, the CTPS modulation is preferred for the cascaded system.

**Case.** Studies for the Stability Comparison

![FIGURE 14](image14.png) Waveforms of DAB converters in closed-loop operation (A) SPS; (B) DPS; (C) CTPS.

![FIGURE 15](image15.png) Dynamic waveforms of the CTPS-DAB converter with its LC filter: (A) when the load steps between half load and full load; (B) when the input voltage steps between 80% and 120% rated voltage.
To verify the influence of the modulation methods on the stability, the Nyquist plots of the minor loop gain $T_m$ are drawn using MATLAB. The circuit parameters are shown in Table 2.

The Nyquist plots of $T_m$, which is the ratio of $Z_{in,DAB}$ to $Z_{out,LC}$, are shown in Figure 7. When SPS or DPS is applied, the cascaded system is not stable as the trajectory of $T_m$ encircles the critical point (-1, 0). However, the trajectory of $T_m$ no longer encircles (-1, 0) anymore when CTPS is applied. Therefore, CTPS is the optimal modulation methods for the cascaded system for stability consideration.

**EXPERIMENTAL RESULTS**

To verify the theoretical analysis, the stability of the cascaded system with the SPS, DPS and CTPS modulation methods are tested through based on the OPAL-RT based hardware-in-the-loop (HIL) experimental system.

Figure 8 illustrates the overall structure of the HIL system. The real-time simulator OP5600 functions as the main circuit. To ensure the real-time behavior of the power switches, the sampling frequency is set as 2 MHz, 100 times faster than the switching frequency. The hardware controller is realized by dSPACE 1,202 (Microlab Box) with a sampling rate of 20 kHz. The analog signals of $I_{in}$, $V_c$ and $V_{dc}$ are generated by OP5600 and sent to the dSPACE controller. After calculation, the duty cycle information for the DAB converters will be sent from the dSPACE controller back to OP5600. The oscilloscope YOKOGAWA DL850E captured all the waveforms of the HIL system.

The steady-state waveforms of the single DAB converter with SPS, DPS and CTPS modulation methods are shown in Figure 9. The waveforms are all stable, which indicates that the DAB converters with SPS/DPS/CTPS are well designed for stand-alone operation. Additionally, Figure 10 further illustrates the effectiveness of the CTPS method on eliminating the dual side flow back currents. As seen, $v_{h1}$ and $v_{h2}$ always change their polarities when $i_L$ is equal to zero. Both dc side currents $i_1$ and $i_2$ (indicated in Figure 2) are always not less than zero.

Figures 11–13 show the dynamic performances of the DAB converter with SPS, DPS and CTPS, respectively. When the load steps between half load and full load conditions, it can be found that the dynamic performances of the DAB converter with SPS, DPS and CTPS are all good. The waveforms become stable after a short transient period, which is less than 3 ms. Similarly, when the input voltage steps between the 80% and 120% rated voltage (100 V) at full load condition, the dynamic waveforms of the DAB converter with SPS, DPS and CTPS are also good.

In summary, the experimental results given in Figures 9–13 show that the single DAB converter can operate properly with SPS, DPS and CTPS modulation methods.

Figure 14 shows the closed-loop operation waveforms of the DAB converter with SPS, DPS and CTPS modulations. The oscillation can be found when SPS or DPS modulation methods are applied, as shown in Figures 14A,B. This is because the input impedance of SPS- or DPS-DAB converter intersect with the output impedance of the input LC filter at 1,030 Hz, as shown in Figure 6. And the input impedance of SPS- or DPS-DAB converter shows capacitive impedance characteristics at this intersection frequency range. So, the resonance path is formed between the DAB converter with input LC filter. From Figures 14A,B, the oscillating frequency of the waveforms is around 1,030 Hz, which coincides the analysis of the Bode plots.

The dynamic performance of the CTPS-DAB converter with its LC filter is also tested and the results are shown in Figure 15. As shown, the dynamic waveforms of the CTPS-DAB converter with its LC filter are also stable under the load step change and the input voltage step change. Therefore, the experimental results prove that the CTPS modulation method presents better stability performance for the cascaded system compared to those of the SPS and DPS methods.

**CONCLUSION**

The stability of the DAB-based cascaded systems with SPS, DPS and CTPS modulation methods have been assessed and compared in this paper. The open-loop and close-loop input impedances of DAB converters have been derived with respect to these modulation methods. The influences of different modulation schemes on the input impedance characteristics have been revealed. The resonant path which has been found between the SPS- or DPS-DAB converter and its LC filter can degrade the stability. Furthermore, the presented analysis has shown that the resistive input impedance of the CTPS-DAB converter ensures higher stability robustness. Experimental results verify the CTPS modulation is the optimal method for DAB-based cascaded systems as it provides the best stability performance compared to those of SPS and DPS modulation methods.

**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 PX performed the experiment.

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APPENDIX A1

The analytical solutions of $Z_{\text{m},\text{DAB}}^{\text{OL}}, G_{\text{v},\text{d}}^{\text{OL}}, G_{\text{v},\text{d}}^{\text{OL}}$, and $G_{\text{v},\text{d}}^{\text{OL}}$ are expressed as (A1)—(A4).

$$
Z_{\text{m},\text{DAB}}^{\text{OL}} = \frac{(s - A_{1})[s^2 + \omega^2] - \frac{2n}{C_{2}} [2(\omega s^2)_{\text{R},\text{d}} + 2n(\omega s)_{\text{R},\text{d}}] [A_{1}(s - A_{1})]}{[2n(\omega s)_{\text{R},\text{d}} + 2n(\omega s)_{\text{R},\text{d}}] [A_{1}(s - A_{1})] + 2n(s)_{\text{R},\text{d}} (s - A_{1})}B_{11}
$$

(A1)

$$
G_{\text{v},\text{d}}^{\text{OL}} = \frac{C_{2}[s^2 + \omega^2]B_{11} + 2(s_{\text{R},\text{d}})^2 B_{12} - 2(s_{\text{R},\text{d}})^2 w_{\text{R},\text{d}} B_{13} + 2(s_{\text{R},\text{d}})^2 w_{\text{R},\text{d}} B_{13} + 2(s_{\text{R},\text{d}})^2 B_{13}}{R_{\text{c},\text{d}} (s - A_{1}) [s^2 + \omega^2] - 2R_{\text{c},\text{d}} [A_{1} + A_{1} w_{\text{d}}] - 2R_{\text{c},\text{d}} [A_{1} + A_{1} w_{\text{d}}]}
$$

(A2)

$$
G_{\text{v},\text{d}}^{\text{OL}} = \frac{C_{2}[s^2 + \omega^2]B_{12} + 2(s_{\text{R},\text{d}})^2 B_{12} - 2(s_{\text{R},\text{d}})^2 w_{\text{R},\text{d}} B_{13} + 2(s_{\text{R},\text{d}})^2 w_{\text{R},\text{d}} B_{13} + 2(s_{\text{R},\text{d}})^2 B_{13}}{R_{\text{c},\text{d}} (s - A_{1}) [s^2 + \omega^2] - 2R_{\text{c},\text{d}} [A_{1} + A_{1} w_{\text{d}}] - 2R_{\text{c},\text{d}} [A_{1} + A_{1} w_{\text{d}}]}
$$

(A3)

$$
G_{\text{v},\text{d}}^{\text{OL}} = \frac{C_{2}[s^2 + \omega^2]B_{12} + 2(s_{\text{R},\text{d}})^2 B_{12} - 2(s_{\text{R},\text{d}})^2 w_{\text{R},\text{d}} B_{13} + 2(s_{\text{R},\text{d}})^2 w_{\text{R},\text{d}} B_{13} + 2(s_{\text{R},\text{d}})^2 B_{13}}{R_{\text{c},\text{d}} (s - A_{1}) [s^2 + \omega^2] - 2R_{\text{c},\text{d}} [A_{1} + A_{1} w_{\text{d}}] - 2R_{\text{c},\text{d}} [A_{1} + A_{1} w_{\text{d}}]}
$$

(A4)