ORIGINAL RESEARCH PAPER

DC-side current compensation control in the rectifier terminal for power variations in back-to-back converters

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Abstract
Back-to-back (BTB) converters, which consist of an AC/DC rectifier cascaded with a DC/AC inverter, have been widely adopted in the interconnection of power systems. The DC link, being the interface between the rectifier and inverter terminals, is susceptible to disturbances, particularly from power fluctuations. Regardless of the magnitude of power or changes in the power flow direction, stability degradation will occur. To lessen the influence of power, a DC-link current compensation control scheme is proposed and applied to the rectifier terminal. The proposed scheme reduces the DC link impedance gain of the rectifier terminal to balance the impedance at both ends, and thus enhance stability and controllability. The scheme is applied to a BTB converter to improve the system's resistance to disturbance, regardless of variations in power magnitude or power flow direction. The accuracy of the theoretical analysis and the effectiveness of the proposed scheme are verified using simulations and a scaled-down experimental setup.

1 | INTRODUCTION

Large disparities between electrical supply and demand in a region cause several inconsistencies and limit the development of the region [1–3]. Balanced power supply and demand represent an optimum condition and allow for more regional developments. Power grid interconnection is a significant tool for integrating energy resources [4–5] and back-to-back (BTB) converters are a vital part of power network interconnection systems. The BTB converter is also widely applied to flexible high voltage direct current power transmission, variable speed wind turbines in wind power generation systems, variable speed pumped storage plants and other applications. This is due to the advantages of small output harmonics and high controllability. Bidirectional power flow is needed in many situations, e.g. in the interconnection of power systems, or in grid-connected systems of large-scale renewable energy, such as wind-solar power, and in pumped-storage power stations. Therefore, it is important to analyze the stability of the system when power reverses. The uncontrollability of renewable energy causes high power fluctuations in the grid-connected system. Thus the influence of stepped power changes on the stability of the system is also a matter of concern.

A BTB converter can be treated as two voltage source converters cascaded through a DC capacitor. Professor R.D. Middlebrook first proposed the impedance criterion to analyze the stability of a cascaded system [6]. Many scholars have continuously supplemented and improved on this theory since then [7–9]. In addition, the modified impedance criterion is applied to the analysis of the stability of grid-connected inverter systems [10–11]. The impedance analysis method has become the most significant method applied to the analysis of cascaded systems. Furthermore, researchers have divided a cascaded system into a source converter and a load converter based on the power flow direction. The output impedance is defined in the source converter [12–13], and the input impedance is defined in the load converter [14]. According to the impedance criterion, if the output and input impedances satisfy the Nyquist criterion [15–16], the cascaded system will be stable. Thus, several studies were devoted to changing either the output or input impedance. The application of the impedance analysis method must establish the impedance model first. In [17], the small-signal impedance model of a grid-connected inverter in d and q-axis was established under different control strategies. The reason for grid-connected inverter instability is apparent when considering impedance, but the impedance model
that was established only contains an AC terminal without considering the DC terminal impedance.

In [18], a self-regulated virtual impedance, equivalent to locate in parallel with the load converter's input, was designed to change the input impedance of the load converter. The variable input impedance was matched with the fixed output impedance to stabilize the entire system. In addition, the input impedance of the load converter could also be changed due to the equivalent series virtual impedance [19]. But the implementation of the method in [18–19] is complicated. In [20], the DC impedance characteristics of the dual active bridge (DAB) Inverter cascaded system were analyzed, and the impedance interaction between DAB and the inverter, caused by different power flow directions, may result in instability in the cascaded system. Similarly, in [21], a DC–AC cascaded system was used as a topology to study the effects of bidirectional power flow on DC impedance characteristics. The DC–AC cascaded system consisted of the DAB and the single-phase H-bridge. The aforementioned studies only analyzed the impact of bidirectional power flow on the stability of the cascaded system without providing any possible improvements or solutions. In [22], several passive dampers such as the RC parallel damper, RL parallel damper and RL series damper were proposed to solve the instability problem of constant-power load (CPL). Although the method stabilized the cascaded system caused by CPL, the system loss was increased due to the addition of extra dampers, which is not a long-term consideration. In [23], an adaptive active capacitor converter was parallel between the source converter and the load converter. This was equivalent to a capacitor between the two parallel converters to reduce the output impedance of the source converter. Although the method effectively improved the stability of the cascaded system, the addition of extra links in the DC terminal, including the change of main circuit topology and the addition of extra control, raises the economic cost.

Power fluctuations often cause unstable operational states in a power system [24–25]. The effect of power disturbances on the power quality and stability of a BTB system is yet to be studied further. Many researchers have studied the BTB converter from various perspectives, but in-depth analysis of the stability of the BTB converter from the perspective of power is still relatively limited.

This study analyzes the influence of power disturbances on a BTB converter system from the perspective of impedance. The DC impedance model of the BTB converter has been developed, and an equivalent sensorless DC-link current control scheme is proposed to enhance the stability of the BTB converter when subjected to power disturbances. The DC current disturbance is derived directly from the formula without sensors. The proposed scheme reduces the impedance gain without changing the regulator parameters. In addition, it can enhance the stability and dynamic characteristics of the converter if the power increases or reverses. Simulations and experimental results verified the feasibility of the proposed scheme. The rest of this paper consists of four sections. Section 2 introduces the modelling process and analyzes the stability problems caused by power variations. Section 3 proposes the improved scheme and verifies it using simulation. Section 4 presents the

![Figure 1: BTB converter structure diagram](image1)

![Figure 2: Rectifier terminal structure diagram](image2)

experimental verification of the proposed scheme. Finally, conclusions are drawn in Section 5.

2 | BTB CONVERTER MODEL

A schematic diagram of the simplified BTB converter, used in this study, is shown in Figure 1. The operating state of the subconverter changes when its power reverses. However, when one works as a rectifier, the other works as an inverter.

The BTB converter consists of two cascaded converters. The impedance method is employed to analyze the BTB converter stability. Therefore, the impedance ratio \( \frac{R}{X} \), which is the ratio of output impedance to input impedance, is used as the stability criterion [26–27].

2.1 | Rectifier terminal model

To keep the DC bus voltage stable, the rectifier terminal adopts a voltage and current double-loop proportional-integral (PI) control mode. The DC bus voltage \( V_{dc} \) and grid-connected current \( i_{g} \) are used as the outer and inner loops, respectively. Figure 2 presents a schematic diagram of the rectifier terminal structure.

In Figure 2, \( V_{dc} \) is the set value of DC terminal voltage. \( i_{g} \) and \( i_{g}^{*} \) are the grid-connected currents in the d–q axes of the rectifier, respectively. Further, the modulation signal is achieved through control.

Based on the main topology of the rectifier shown in Figure 1 and the schematic diagram of the control structure of the rectifier shown in Figure 2, a block diagram of the relationship between the DC bus voltage and D-axis current in the rectifier can be constructed, as shown in Figure 3. Due to the power flow reversal, the circuit relationship in the main topology is changed; however, the structure diagram of the control loop is
not changed. Consequently, the block diagram of the control structure is identical despite the variation in the direction of power flow. The solid and dotted lines denote the block diagram associated with the forward and reverse power flow directions, respectively. The solid and dotted lines in Figures 5 and 12 also represent that.

According to Figure 3, the transfer function for the DC voltage to the $D$-axis current can be acquired as follows:

$$G_1 V_{dc Id FD} = \frac{\hat{i}_{1 d}}{\hat{u}_{dc}/2} = \frac{2G_1 \dot{i}_{1 d} + D_1 \dot{i}_{1 q}}{sL_1 + r_1 + G_1}$$

$$G_1 V_{dc Id RD} = \frac{\hat{i}_{1 d}}{\hat{u}_{dc}/2} = \frac{-2G_1 \dot{i}_{1 d} + D_1 \dot{i}_{1 q}}{sL_1 + r_1 + G_1}$$

(1)

where $G_1 V_{dc Id FD}$ is the transfer function associated with the forward power flow direction, and $G_1 V_{dc Id RD}$ is the transfer function associated with the reverse power flow direction. Additionally, $G_1$ represents the transfer function of the PI controller used in the outer loop, $G_2$ is the transfer function of the PI controller used in the inner loop, $r_1$ is the duty ratio at the static operating point, $L_1$ represents the filter inductance, and $r_1$ is the parasitic resistance of the inductance $L_1$.

The small-signal disturbance of the rectifier terminal duty cycle is expressed as follows:

$$\dot{\hat{\theta}}_{1 d} (t) = \frac{2}{V_{dc}} \left( G_{1 d} \dot{\hat{\theta}}_{1 d} (t) + G_{2 d} \dot{\hat{\theta}}_{2 d} \right)$$

(2)

Combining the relationship between the currents at the capacitor $C$ terminals and applying the power conservation principle, the relationships between the $D$-axis current $i_{1 d}$, DC voltage $u_{dc}$, and DC-link current $i_{dc}$ can be expressed as

$$\frac{3}{4} \left( D_1 \ddot{i}_{1 d} + I_1 \dot{i}_{1 d} \right) - G_2 \dot{u}_{dc} = \dot{\hat{\theta}}_{dc}$$

(3)

Substituting (2) and (1) into (3) individually, the expression of the DC terminal impedance is presented in (4). $Z_{dc_{out}}$ and $Z_{dc_{in}}$ are the output and input impedances, respectively:

$$Z_{dc_{out}} = \frac{\hat{u}_{dc}}{i_{dc}} \quad Z_{dc_{in}} = \frac{\hat{u}_{dc}}{i_{dc}}$$

(4)

2.2 Inverter terminal model

The inverter impedance modelling process is similar to that of a rectifier. Figure 4 shows the inverter structure diagram. The inverter controls the direction of power flow.

In Figure 4, $i_{2_d}$ and $i_{2_q}$ represent the grid-connected current on the $d$ and $q$-axes of the inverter, respectively.

Figure 5 shows a block diagram of the relationship between the DC voltage and $D$-axis current in the inverter terminal.

The transfer functions of the $D$-axis current $i_{2_d}$ and DC bus voltage $u_{dc}$ can be acquired as follows:

$$G^2 V_{dc Id FD} = \frac{\dot{\hat{\theta}}_{2 d}}{\dot{\hat{u}}_{dc}/2} = \frac{2V_{2 d}}{sL_2 + r_2 + G_2}$$

$$G^2 V_{dc Id RD} = \frac{\dot{\hat{\theta}}_{2 d}}{\dot{\hat{u}}_{dc}/2} = -\frac{2V_{2 d}}{sL_2 + r_2 + G_2}$$

(5)

where $G_2$ is the transfer function of the PI controller used in the power loop, $D_2$ is the duty ratio at the static operating point, $L_2$ is the filter inductance, and $r_2$ represents the parasitic resistance of the inductance $L_2$. 

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**FIGURE 3** Block diagram showing the relationship between the DC voltage and $D$-axis current in the rectifier terminal

**FIGURE 4** Inverter terminal structure diagram

**FIGURE 5** Block diagram of the relationship between the DC voltage and $D$-axis current in the inverter terminal
The small-signal disturbance of the duty cycle of the inverter terminal is expressed as

\[ \hat{d}_{2,d} = \frac{2}{V_{dc}} G_{2,d}\hat{i}_{2,d} \]  

(6)

The principle of power conservation is applied the same as a rectifier, enabling the relationship between the D-axis current \( i_{2,d} \) and DC-link current \( i_{dc} \) to be expressed as follows:

\[ 0.75 (\hat{d}_{2,d} i_{2,d} + D_{2,d}\hat{i}_{2,d}) = \hat{i}_{dc} \]  

(7)

By substituting (6) and (5) into (7) individually, the expression for the inverter’s DC terminal impedance can be readily derived.

### 2.3 Power influence

Analyzing the influence of power on the stability of a BTB converter using the impedance criterion requires a discussion about amplitude-frequency characteristics and phase-frequency characteristics of the DC terminal impedance.

Figure 6a shows the rectifier’s output impedance Bode plots for increasing power in the forward direction. Figure 6b shows the rectifier’s input impedance Bode plots for increasing power in the reverse direction. According to Figures 6a and b, increasing power does not significantly affect the rectifier terminal impedance. However, the power flow direction changes the phase-frequency characteristic of the impedance. In the forward direction, the output impedance appears to exhibit inductive characteristics in the low frequency range and capacitive characteristics in the high frequency range. However, the phase-frequency characteristics of the input impedance are reversed when the power flow direction is reversed.

Figure 7 shows Bode plots of the DC terminal impedance of the inverter when the power increases. Figure 7a shows the Bode plot of the input impedance for forward power flow, and Figure 7b presents the Bode plot of the output impedance for reverse power flow. In Figures 7a and b, the impedance gain in the low frequency range decreases as the power increases. Therefore, an increase in power reduces the amplitude margin of the impedance ratio. This phenomenon is not beneficial to the stability of a BTB converter. Moreover, the variation of power amplitude affects the phase-frequency characteristics of the impedance. The phase of the input impedance in Figure 7a decreases as the power increases. However, the phase of the output impedance in Figure 7b increases as the power increases. The increasing power strengthens the negative impedance characteristic, which is detrimental to a cascaded converter. However, the increasing power enhances the resistive impedance characteristics, which is beneficial to the stability of a BTB converter.

Bode plots are used to analyze the impedance characteristics because the stability of a BTB converter cannot be determined intuitively. Consequently, the Nyquist criterion was adopted to analyze the stability of the converter. Figure 8 shows the impedance ratio of Nyquist plots in the case of increasing power. Furthermore, Figures 8a and b demonstrate Nyquist plots of the impedance ratio for forward and reverse power flows, respectively.

According to Figures 8a and b, the stability of the BTB converter in the reverse direction is superior to that of the forward direction. The intersection point between the Nyquist plot of impedance ratio and the negative real axis in Figure 8b is smaller than the same point in Figure 8a. In Figure 8a, the intersection point moves closer to the point \((-1, 0)\) as the power increases. Additionally, the system gain margin decreases gradually as the power increases, which indicates a decrease in system stability. Additionally, the phase information shown in the Nyquist plot in Figure 8b reveals that the stability decreases when power increases.

Therefore, the analysis of impedance reveals that increasing power is not beneficial to the stability of a BTB converter, regardless of power flow direction. Additionally, the results
prove that the stability of a BTB converter is superior when the power flows in the reverse direction.

3 | OPTIMIZATION SCHEME ANALYSIS

3.1 | Impedance measurement in Matlab

To verify the impedance model, the amplitude and phase of impedance are measured in Matlab. The circuit of the BTB system is established on the Matlab/Simulation platform, based on the topology in Figure 1 and the control strategy in Figures 2 and 4. To measure the impedance of the simulated system, the voltage disturbance injection method is used. Figure 9 presents comparative graphs of the DC terminal impedance of the rectifier. Figure 9a shows the model’s impedance curve, and Figure 9b shows the measured data scatter plot. Correspondingly, Figure 10 shows comparative graphs of the DC terminal impedance of the inverter. The curves and measured data shown in Figures 9 and 10 are in decent agreement, which illustrates the accuracy of the impedance model.

3.2 | Proposed scheme

Power affects the stability of the BTB converter. The proposed scheme involves changing the rectifier impedance to reduce the negative influence on stability. The DC terminal impedance is described by the ratio of the DC voltage disturbance to the DC-link current disturbance. The small-signal disturbance characteristics of the DC terminal voltage are controlled by a voltage loop. Thus, when the small-signal disturbance characteristics of the DC-link current are controlled, the DC-terminal impedance of the rectifier will change accordingly. As a result, a DC-link current compensation control strategy is introduced. Figure 11 shows the optimized rectifier structure diagram.
This differs from the structure diagram shown in Figure 2 as a DC terminal current compensation scheme is added. The kernel of the proposed scheme is the proportional control of DC-link current without the use of direct sampling. The sampled DC-link current requires an extra sensor, and the current contains numerous harmonics. The messy signals are difficult to control and manipulate. The DC terminal current disturbance is directly equivalent instead of being the actual sampling current. The equivalent disturbance of the DC-link current shown in Figure 11 can be expressed as follows:

\[
\hat{i}_{dc} = \hat{p}_{dc} - \hat{i}_{d} \frac{I_{dc}}{V_{dc}}
\]

(8)

The instability is mainly caused by a mismatch between the output and input power. The DC terminal power is mainly reflected in the DC voltage and current. The DC voltage is controlled by the former rectifier. Therefore, the DC-link current becomes the variable that responds to power variations in the real-time system. Furthermore, the current responds faster than...
the voltage. However, in practice, the sampling current contains too many harmonics to be controlled as a variable because of the simple filter circuit used in the DC terminal. From the perspective of equivalent variable substitution, DC-link current is not directly sampled. The DC-link current can be obtained by dividing the DC terminal power by DC voltage. Further, small-signal disturbances are observed in the DC-link current, including power disturbances and DC voltage disturbances. The power and DC voltage have been sampled in the original system. In (8), the power disturbance of the rectifier grid-connected terminal is chosen to be the disturbance. The power in the DC-terminal is messy, and thus is unsuitable to be introduced into the control loop. The power loss between the AC and DC terminals is fixed when the BTB operates at the steady state. Thus, the small-signal disturbances of grid-connected power at the rectifier is equal to the small-signal disturbance of the DC terminal. The AC power was adopted in the study. In previous studies, converter instability was mainly studied from the perspective of using voltage and power as compensation or control variables [28–29] and did not analyze the influence of DC-link current in any great depth.

Figure 12 shows the block diagram of the relationship between the DC terminal voltage and $D$-axis current in the rectifier when the proposed scheme with different power flow directions is implemented. Introducing DC terminal current disturbance into the control structure is equal to changing the regulator parameters in the control structure. Therefore, the feedback coefficient of the current loop changes from a fixed value to an adaptive parameter. Subsequently, the parameter can vary along with the variable $V_{dc,ref}$. In addition, the transfer function of the voltage loop has been improved. The original proportionality coefficient of the PI controller is changed to become a variable parameter, and it is no longer fixed. The coefficient is determined by the power and DC terminal voltage at the static operating point. In Figure 12, $K_p$ is the proportionality coefficient of the proposed scheme.

From Figure 12, the transfer function representing the relationship between the DC terminal voltage and grid-connected current on the $D$-axis can be expressed as follows:

$$\begin{align*}
G_{V_{dc,ld,FD}}^{1_{\text{new}}} &= \frac{\hat{i}_{d,ld}}{2G_i + \frac{P_{\text{new}}}{V_{dc}^2} K_p} \left( G_r + \frac{\hat{p}_{\text{new}}}{V_{dc}^2} K_p \right) + D_{1,d} \\
G_{V_{dc,ld,RD}}^{1_{\text{new}}} &= \frac{\hat{i}_{d,ld}}{2G_i + \frac{P_{\text{new}}}{V_{dc}^2} K_p} \left( G_r + \frac{\hat{p}_{\text{new}}}{V_{dc}^2} K_p \right) + D_{1,d}
\end{align*}$$

(10)

where $G_{V_{dc,ld,FD}}^{1_{\text{new}}}$ denotes the transfer function for forward power flow, and $G_{V_{dc,ld,RD}}^{1_{\text{new}}}$ is the transfer function for reverse power flow.

Incorporating (7) into the main circuit allows a new impedance expression to be obtained for the proposed scheme.

### 3.3 Proposed scheme analysis

For comparison purposes, Figure 13 shows the Bode plot of the rectifier impedance before and after optimization. Figures 13a
and b show the impedance plots for forward and reverse power flows, respectively.

The most important contribution of the proposed scheme is reducing the rectifier’s low frequency range impedance gain compared with the system with a conventional control scheme. The distance between the minimum impedance gain of the inverter’s DC terminal and the maximum impedance gain of the rectifier’s DC terminal increases. If an intersection point between the rectifier and inverter impedance exists in the system with conventional control, the intersection point may not exist in the system with improved control. As an example, Figure 13a shows that the amplitude of impedance of the rectifier with the conventional control is $-6.37$ dB at the point where the angular frequency is $10$ rad/s. At the same angular frequency, the impedance amplitude of the rectifier with the proposed control scheme is $-12.7$ dB. The impedance gain is decreased by approximately 50%. In terms of the output impedance of the voltage source, a smaller amplitude represents a stronger voltage source. Because the input impedance represents the load characteristics with respect to the current source, a smaller amplitude makes the system easier to drive. Thus, the reduction in the amplitude of impedance is beneficial to the stability of the BTB converter.

Because the transmission power $P_{trf}$ and the given DC terminal voltage $V_{dc,ref}$ in the BTB converter system are fixed system parameters, the DC terminal impedance of the rectifier under the proposed control is primarily influenced by the coefficient $K_p$, which is the parameter of the newly added control loop. Figure 14 shows a Bode plot of the output impedance of the rectifier when the proposed control scheme was implemented with a varying $K_p$. With increasing $K_p$, the feedback coefficient of the current loop decreases gradually, as shown in Figure 12, and the proportionality coefficient of the PI regulator in the voltage loop increases. The DC-link current compensation control changes the structure diagram of the control loop. The relationship between the DC voltage and current along the $D$-axis is changed, and the DC-terminal impedance of the rectifier is also changed. The impedance amplitude decreases as the coefficient $K_p$ increases, which is beneficial to the system stability. However, the impedance phase increases as the coefficient $K_p$ increases and adversely affects the stability. Considering the stability of the BTB converter, $K_p$ is selected to be 0.9 in this study.

To discuss system stability, Figure 15a shows the Nyquist plot of the DC terminal impedance ratio both with and without using the proposed control for forward power flow, and Figure 15b shows the Nyquist plot of the impedance ratio for reverse power flow.

The partially enlarged view in Figure 15a clearly shows that the intersection point between the Nyquist plot of the improved impedance ratio and the negative real axis is far away from the point $(-1, 0)$ compared to the intersection point between the Nyquist plot of original impedance ratio and the negative real axis. The improved impedance ratio is composed of the impedance of the rectifier using the proposed control, whereas the original impedance ratio is composed of the impedance of the rectifier using conventional control. The position of the intersection point indicates the stability margin. Based on the
Nyquist criterion, if the position is closer to the point (−1, 0), the system is less stable [13]. Expressly, the reliability of the BTB converter using the proposed control is higher than that of the converter using conventional control. When the power flow is reversed, although the stability cannot be determined by the amplitude margin, the phase margin is shown in Figure 15b reveals that the stability of the BTB converter is improved.

To compare the dynamic characteristics of the BTB converter under the proposed scheme to those under the conventional scheme, the root locus of the open-loop transfer function between the DC voltage and the given DC voltage is obtained, as shown in Figure 16. The solid and dotted lines in Figure 16 represent the root locus of the open-loop transfer function of the rectifier under the conventional and proposed schemes, respectively. With the gradual increase in open-loop gain, the variation trend of the closed-loop poles is shown in Figure 16. It can be seen that, at the same frequency, the closed-loop poles of the rectifier under the proposed scheme are closer to the negative real axis and far away from the virtual axis than the closed-loop poles of the rectifier under the conventional scheme. Being further away from the virtual axis indicates that the rectifier under the proposed scheme has a faster response speed and a shorter adjustment time. Being closer to the negative real axis indicates that the overshoot of the system with the proposed scheme is smaller. An eigenvalue analysis reveals that the rectifier with the proposed scheme has a better dynamic response characteristic. This indicates that the proposed scheme has a certain optimization effect on the dynamic characteristics of the BTB converter.

4 SIMULATION AND EXPERIMENTAL VERIFICATION

To verify the theoretical analysis, both simulation and experimentation are performed.

4.1 Simulation verification

The BTB converter model was built using the Matlab/Simulink software. The main topology was established, as shown in Figure 1. The control structure of the rectifier was established, as shown in Figure 3, and the control structure of the inverter was established, as shown in Figure 5. The parameters of the simulation model are displayed in Table 1. The parameters of the simulation model are displayed in Table 1. The parameters of the simulation model are displayed in Table 1. The parameters of the simulation model are displayed in Table 1. The parameters of the simulation model are displayed in Table 1.

![Figure 16](image16.png) Open-loop root locus of DC voltage $V_{dc}$ to the given DC voltage $V_{dc_{ref}}$ of rectifier terminal

![Figure 17](image17.png) Power of the grid-connected rectifier terminal

![Figure 18](image18.png) DC voltage

![Figure 19](image19.png) Power of the grid-connected inverter terminal

![Figure 20](image20.png) DC voltage

![Figure 21](image21.png) Power of the grid-connected inverter terminal

![Figure 22](image22.png) DC voltage

**Table 1 Main circuit parameters**

| Parameter                        | Value       |
|----------------------------------|-------------|
| Set DC terminal voltage ($V_{dc}$) | 800 V       |
| Effective value of grid voltage ($e$) | 220 V       |
| Filter inductance of rectifier ($L_1$) | 2 mH        |
| Parasitic resistance of inductance ($r_1$) | 0.1 Ω       |
| Capacitance ($C$) | 2.35 mF |
| Filter inductance of inverter ($L_2$) | 2 mH        |
| Parasitic resistance of inductance ($r_2$) | 0.1 Ω       |
| Grid inductance ($L_g$) | 1 mH     |
| Grid resistance ($r_g$) | 0.1 Ω     |
| Switching frequency ($f_s$) | 10 kHz     |
FIGURE 19  Power of the grid-connected inverter terminal

FIGURE 20  Power of the grid-connected rectifier terminal with power variations

generated by the converter using the proposed scheme. To make the effect of regulation clearer, the proportional coefficient of the DC voltage loop is decreased deliberately to reduce the stability of the BTB converter, which caused the oscillations in Figures 17 and 18. The grid-connected power plot of the rectifier using the conventional control shown in Figure 17 differs when the power flows in different directions. The oscillation time of power plots differs when the power flow reverses. The grid-connected power oscillation attenuation is not evident for forward power flow over half a cycle (0.5–0.75 s). However, when the power flows in the reverse direction (0.75–1 s), the power oscillation is attenuated, and the grid-connected power will remain steady. This reveals that the stability is superior when the power flows from the inverter terminal to the rectifier terminal. The comparison before and after optimization shown in Figures 17–19 clearly illustrates the effectiveness of the proposed scheme. The power plots and DC voltage plot of the BTB converter using the proposed control method is smoother than the system using the conventional control. The peak-to-peak value of power plot is equal to 30 kW in the rectifier terminal with the conventional scheme, while the power waveform in the BTB converter under the proposed control method remains stable after a short oscillation period of 0.1 s with a peak-to-peak value of 10 kW. In Figure 18, DC voltage of the system with conventional control persistently oscillates when the power flows in the forward direction with a peak-to-peak value in excess of 200 V. The oscillation decays slowly upon the reversal of power and cannot stabilize within 0.3 s. However, the converter under the proposed scheme stabilizes at the given voltage of 800 V within 0.1 s. The oscillation time is evidently shortened, and waveforms immediately maintain stability after reaching a short peak. The power and voltage plots of the BTB converter with proposed scheme do not exhibit significant differences when power flows in different directions.

Figures 20 and 22 show the AC terminal power plots for the rectifier and inverter with stepped power, respectively. Figure 21 shows the DC terminal voltage plots with stepped power. The applied power is stepped from 6 to 18 kW and finally to 36 kW. An unavoidable power error exists in the rectifier terminal owing to the rated power is controlled by the inverter terminal. The blue and red plot lines in the figures indicate the curves of the original converter for varying power, whereas the yellow and purple plot lines represent the curves of the improved converter. Regardless of power flow direction, an increase in power is not conducive to maintain the BTB converter’s stability. The converter demonstrates an improved stability margin using the proposed scheme; however, it does not eliminate the influence of increasing power on the converter’s stability completely.

4.2  Experimental verification

To verify the feasibility of the theoretical simulation analysis, a laboratory-based 2 kW scaled-down prototype of a three-phase BTB converter was constructed. The parameters of the prototype are shown in Table 2. Since the rated power of the prototype is different in the simulation, several circuit parameters of the prototype are changed. Although there are several differences between an experiment and a simulation for some parameters, the main topology, control mode and theoretical analysis method adopted by an experiment and a simulation respectively are the same. Experimental parameters do not affect the verification of the optimal control.

Figure 23 shows the experimental setup, which was consistent with the main topology presented in Figure 2. The control
TABLE 2  Main circuit parameters used in the experiment

| Parameter                          | Value  |
|------------------------------------|--------|
| Set DC terminal voltage ($V_{dc}$) | 400 V  |
| Effective value of grid voltage ($e$) | 110 V  |
| Filter inductance of rectifier ($L_1$) | 5 mH  |
| Capacitance ($C$)                  | 800 µF |
| Filter inductance of inverter ($L_2$) | 5 mH  |
| Switching frequency ($f_s$)        | 10 kHz |

part was designed based on the proposed model. In the experimental setup, the voltage signal was sampled using a Hall element (LV-25), and the current signal was sampled using another Hall element (LA-25P). The converters were controlled using the dSPACE DS1202 platform to compute the signals and generate the drive signal. The experimental plots are output using a digital oscilloscope.

Figures 24–26 are extracted from experiments with different variables and varying applied power. Figure 24 shows DC-link voltage $V_{dc}$, rectifier terminal grid-connected power $P_{rec}$, DC-link power $P_{dc}$, and inverter terminal grid-connected power $P_{inv}$ for a stepped power changing periodically between -2 kW and 2 kW. Figure 24a shows the curves in the case of conventional control, where the DC-link power plot indicates that the stability of the BTB converter is not the same as the converter operating in the reverse direction. Therefore, the experimental results are consistent with the theoretical analysis results. The oscillation peak-to-peak value of the DC voltage is 70 V in the original system, it is reduced to approximately 30 V after the incorporation of the optimized control. This corresponds to a reduction of approximately 57.14 %. In addition, the power fluctuation amplitude of the rectifier terminal also decreased from 8 to 2.5 kW, which is a reduction of approximately 68.75 %. The waveform stabilizes at 100 ms, i.e. the time is reduced by an approximate factor of 80 %. DC-link voltage and power plots presented in Figure 24b clearly indicate the effectiveness of the proposed scheme. The grid-connected current $I_{A,a}$ in the rectifier terminal is shown in Figure 25. The oscillation suppression...
and rapid dynamic response of the improved BTB converter are also evident.

Figure 26 shows DC-link voltage and power plots when power is stepped from 0.5 to 2.5 kW by steps of 0.5 kW. As shown in Figure 26a, the converter stability is reduced when the power increases. The converter is predisposed to oscillation, and the oscillation stabilization time is prolonged as the power increases. Additionally, the response speed is reduced, and the required time is increased. This is consistent with the conclusion that increasing power is disadvantageous to the converter’s stability. Figure 26b shows the improved stability of the converter when the proposed control was used. The step response of the BTB converter is faster, and the peak value resulting from the stepped power changes is much lower than that of the converter using conventional control, which effectively proves the feasibility of the proposed scheme.

5 | CONCLUSION

This study proposed a sensorless DC-side current compensation control scheme in the rectifier terminal of the BTB converter, applied in the field of asynchronous interconnection. The DC impedance model was established to analyze the stability problems with the impedance match theory. The analysis indicated that the stability of the BTB converter was different when power reverses, however, the proposed compensation scheme suppressed the phenomenon successfully. The proposed scheme obtained the current by using a formula derivation without sensors, thereby decreasing the disturbance caused to the converter. The proposed scheme decreased the impedance gain of the rectifier terminal to some extent, and thus, improved the DC-link impedance match. Regardless of changes in the power flow direction or the presence of power surges, the stability of the BTB converter was significantly improved. A 2 kW laboratory-based scaled-down prototype was fabricated. Simulation and experimental results verified the accuracy of the theoretical analysis and the effectiveness of the proposed scheme.

Further work includes introducing a coordinated control strategy applied to the rectifier and inverter to change the two-terminal impedances, so that a better match for the DC terminal of the BTB system is achieved.

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