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A Nonlinear Control Strategy for DC-DC Converter with Unknown Constant Power Load Using Damping and Interconnection Injecting

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Abstract: DC-DC converters with constant power loads are mostly used in DC microgrids. Negative impedance and large disturbances of constant power loads may lead to the instability of DC-DC converters. To address this issue, a nonlinear control strategy consisting of an improved passivity-based controller and nonlinear power observer is proposed in this paper. First, an improved passivity-based controller is designed based on the port-controlled Hamiltonian with dissipation model. By proper damping and interconnection injecting, the fast dynamic response of output voltage and stability of the DC-DC converter is achieved. Second, the constant power load is observed by a nonlinear power observer, which is adopted to estimate the power variation of the constant power load within a small settling time and improve the adaptability of the DC-DC converter under power disturbance. Finally, the simulation and experimental results are presented, which illustrate the proposed control strategy not only ensures the stability of the DC-DC converter under large disturbances, but also can track the desired operating point with low voltage overshoot in no more than 10 milliseconds.

Keywords: DC-DC converter; constant power load; nonlinear control strategy; improved passivity-based controller; damping and interconnection injecting; nonlinear power observer

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1. Introduction

With the development of the DC Microgrid (DM), the DM is becoming an effective way of distributing power supplies [1–3]. Meanwhile, the DC-DC converters (DDCs) are becoming increasingly common and play an important role in the DM due to their advantages in efficiency, flexibility, isolation, controllability, etc. [4].

The typical diagram of DM is shown in Figure 1; the DC sources and loads are commonly connected to DC BUS through the DDCs. The DDC is acting as a load from the input side and exhibits the constant power load (CPL) behavior. The negative impedance characteristic of CPL behavior [5,6] will lead to the instability of the DDC [7,8]. Therefore, it is necessary to develop some advanced control methods which can eliminate the influence of negative impedance on the DDC, achieve the fast dynamic response, and guarantee the DDC stability.

To solve the instability problem of the CPL, linear control methods have been introduced in the literature. In [9–11], the small signal model is established in order to analyze the influence of CPL on the stability of the DDC, and the virtual impedance method is proposed to realize the stability of the DDC with CPL. However, as the small signal model is only applicable to linear systems or linearized systems near the desired equilibrium point, the accuracy of the model will decrease in the case of large disturbances [12]. Furthermore, the traditional linear control strategy only provides an accurate control performance in

close proximity to the desired equilibrium point and has a slow dynamic response when the CPL changes significantly [13,14]. In summary, research on the stability and control of the DDC using the small signal model has some limitations. Therefore, the numerous nonlinear control strategies are introduced based on large signal.

Figure 1. Typical diagram of DM.

Based on the affine nonlinear model and feedback linearization control theory [15], the state feedback controller and input/output feedback linearization controller of the DDC with CPL are designed in [16,17], which improve the dynamic response of the converter and enhance the stability of DC voltage. However, they need full state measurement, and have complex controllers and a large dependence on parameters. In order to improve the disturbance rejection ability of the DDC, the active disturbance rejection controller (ADRC) [18] with CPL is designed in [19]; this improves the performance of the converter and has the robustness to face various disturbances and uncertain factors. Although satisfactory disturbance rejection performance of the DDC can be obtained by ADRC, there are many parameters of the controller which need to be determined, and the optimization of these parameters is difficult. The sliding-mode duty-ratio controller is proposed in [20], which can maintain the stability of the DDC in the operating domain under the significant changes in load power and input voltage, and it improves the dynamic response and steady performance of the DDC. However, the controller is very complex, and the output voltage fluctuation of the DDC is large. Moreover, the switching frequency of a sliding-mode controller is not fixed, and the filter design is difficult. In [21], the backstepping controller is designed in order to achieve better dynamic performance and robustness of the DDC. However, the virtual controller needs to be differentiated repeatedly, and becomes complex with the increase in system order.

The passivity-based controller (PBC) [22] has been widely employed in many physical systems [23,24] based on the energy function, and is an effective practical nonlinear control technique due to its simplicity, efficiency, and ease of implementation in comparison to the other nonlinear control techniques. The various types of PBC are designed in [25–27] based on the Euler-Lagrange (EL) model and the port-controlled Hamiltonian with dissipation (PCHD) model, which can ensure the large-range stability and reliability of the DDC. However, the output voltage has the steady-state error, and the transient stability of the DDC will be reduced under the variations and uncertainties of system parameters and operating conditions. In [28], the interconnection and damping assignment passivity-based controller (IDA-PBC) is designed based on the PCHD model with PI controller. It can guarantee the stability of the DDC under disturbance. However, the global stability of the DDC cannot be guaranteed, and its dynamic response is slow. In [29], the stability of the cascaded LC filter DDC is realized by the modified IDA-PBC based on the port-controlled Hamiltonian (PCH). However, the control law of this strategy is complex, and does not allow for the principle of parameters design.

To obtain excellent dynamic and steady characteristics of the DDC with CPL, this paper will utilize the DC-DC boost converter (DDBC) to study the stability and control based on

the passivity. An improved passivity-based controller (IPBC) is proposed to realize the dynamic response and stability of DDBC based on the PCHD model, and the damping and interconnection injecting in IPBC is determined according to the dynamic energy storage function. Meanwhile, the nonlinear power observer (NPO) is used with IPBC, which can improve the adaptability of DDBC, and ensure the desired operating point tracking when CPL and input voltage change. In summary, the nonlinear control strategy which consists of the IPBC and NPO is proposed in this paper. Finally, the comparative study of the proposed control strategy with IDA-PBC and PBC is verified by detailed simulation and experimental results in this paper, suggesting that the DDBC has a better dynamic response characteristic while ensuring stability by using the proposed control strategy.

This paper is organized as follows. The stability analysis of DDBC with CPL based on passivity is analyzed in Section 2. The IPBC based on PCHD model is proposed in Section 3. The NPO of unknown CPL is designed and the selection principle of IPBC parameters is analyzed in Section 4. Subsequently, some realistic simulation and experimental results are given in Section 5. The conclusion of this paper appears in Section 6.

2. Stability Analysis of DDBC Converter with CPL

2.1. Constant Power Load Characteristic

The U - I characteristic of a CPL is illustrated in Figure 2.

Figure 2. The U - I Characteristic Curve of CPL.

The voltage-current characteristic of a CPL is given by:

$$i = \frac{P_{\text{CPL}}}{u} \quad (1)$$

where P_{CPL} is the power of CPL, i and u are the instantaneous values of input current and voltage of the CPL. For a given operating point $M(U, I)$, the rate of change in current can be obtained from (1) as follows:

$$\frac{\partial i}{\partial u} = -\frac{P_{\text{CPL}}}{U^2} \quad (2)$$

Therefore, the curve representing the current versus voltage for a CPL can be approximated by a straight line tangent to the curve at the operating point. The equation for this line is as follows:

$$i = 2\frac{P_{\text{CPL}}}{U} - \frac{P_{\text{CPL}}}{U^2}u \quad (3)$$

According to (3), at a given operating point, a CPL can be equivalent to a controlled current source I_{CPL} in parallel with a negative resistance. I_{CPL} and R_{CPL} are given by the following:

$$\begin{cases} I_{\text{CPL}} = \frac{2P_{\text{CPL}}}{U} \\ R_{\text{CPL}} = -\frac{U^2}{P_{\text{CPL}}} \end{cases} \quad (4)$$

From (4), the CPL has a negative impedance characteristic and this will pose negative impact on system performance [30].

2.2. Stability Analysis of DDBC with CPL Based on Passivity

2.2.1. Effect of CPL on Stability of DDBC

The power circuit of DDBC with CPL is shown in Figure 3, where u_S is the input voltage; L and C are the inductance and capacitance in DDBC, respectively; i_L and i_C are the inductor and capacitor current, respectively; u_C is the output voltage; i_{CPL} is the current of CPL; T is insulated gate bipolar transistor; s_g is the gate drive signal of T ; and D is the diode. To facilitate the analysis, the components are considered as ideal devices.

Figure 3. Power Circuit of Boost Converter with CPL.

According to the principle of volt-second balancing, the average switch model of DDBC [31] can be given as follows:

$$\begin{cases} L \frac{di_L}{dt} = (\sigma - 1)u_C + u_S \\ C \frac{du_C}{dt} = (1 - \sigma)i_L - \frac{P_{CPL}}{u_C} \end{cases} \quad (5)$$

where σ is the duty ratio of s_g .

According to (5), the phase portrait and simulation results of DDBC can be concluded when the desired average output voltage $U_{CD} = 60$ V, desired average inductor current $I_{LD} = 2$ A, switching frequency $f = 10$ kHz, $P_{CPL} = 60$ W, $\sigma = 0.5$, $L = 2$ mH, $C = 940$ μ F, and $u_S = 30$ V.

As shown in Figure 4, the phase portrait displays clearly the characteristics of DDBC with a CPL. The blue line is the trajectory of the state variable (i_L, u_C) ; the blue arrow indicates the evolving direction of the trajectory. The state plane is divided into two regions by the separatrix: S . The region above the separatrix is a stable region, and the region below is an unstable region; the DDBC is unstable when the state variable is in the unstable region. Moreover, the trajectory will converge to a limit cycle when the state variable is in the stable region. Due to the existence of the limit cycle, the DDBC cannot operate stably at the desired voltage and current. As can be seen in Figure 5, the state variables oscillate in a periodic steady state. When the oscillation is significant, it is easy to damage the switching devices and capacitors, and result in the damage of the DDBC.

Figure 4. Phase portrait of DDBC.

Figure 5. Voltage and current of DDBC under open control. (a) output voltage and desired output voltage; (b) inductor current, CPL current, desired inductor current, and CPL current.

2.2.2. Passivity Analysis of DDBC with CPL

Consider the system with input u and output y as follows:

$$\begin{cases} \dot{x} = f(x, u) \\ y = h(x) \end{cases} \quad (6)$$

The system depicted in (6) exists a nonnegative storage function $H(x)$ and a positive definite function $Q(x)$ such that:

$$H(x(t)) - H(x(0)) \leq \int_0^t u^T y d\tau - \int_0^t Q(x) d\tau, \quad t > 0 \quad (7)$$

or

$$\dot{H}(x) \leq u^T y - Q(x) \quad (8)$$

If $\dot{H}(x) < 0$ when $Q(x) > 0$, the system is said to be strictly passive; it must be internally stable [32].

From (5), it is further changed to:

$$\begin{cases} Li_L \frac{di_L}{dt} = (\sigma - 1)u_C i_L + u_S i_L \\ Cu_C \frac{du_C}{dt} = (1 - \sigma)u_C i_L - P_{CPL} \end{cases} \quad (9)$$

According to the characteristic of CPL, the $P_{CPL} = i_{CPL}^2 R_{CPL}$ and $R_{CPL} = -u_C^2 / P_{CPL}$ in DDBC with CPL, the following equation can be obtained by combining the two equations in (9).

$$Li_L \frac{di_L}{dt} + Cu_C \frac{du_C}{dt} = u_S i_L - i_{CPL}^2 R_{CPL} \quad (10)$$

The energy storage function can be expressed as:

$$\begin{aligned} H_O(t) &= H_L(t) + H_C(t) \\ H_L(t) &= \frac{1}{2} Li_L^2(t) \\ H_C(t) &= \frac{1}{2} Cu_C^2(t) \end{aligned} \quad (11)$$

From (10) and (11), $\dot{H}_O(t)$ can be written as:

$$\dot{H}_O(t) = u_S i_L - i_{CPL}^2 R_{CPL} \quad (12)$$

Let the $u_S = u$, $i_L = y$, according to (8) and (12), $Q(x) < 0$, the DDBC with CPL is non-passive and is the reason why the DDBC cannot work at a constant stable state. Therefore, in order to eliminate the limit cycle in Figure 4 and realize the stable work of the DDBC, the DDBC needs to be passivated.

3. IPBC of DDBC Based on PCHD Model

3.1. PCHD Model of DDBC

In order to establish the PCHD model of DDBC, let inductive magnetic flux $x_{1P} = \varphi_L = Li_L$, capacitive charge $x_{2P} = q_C = Cu_C$, then take the vector as $x_P = [x_{1P} \ x_{2P}]^T = [Li_L \ Cu_C]^T$, the desired state vector is $x_{DP} = [x_{1DP} \ x_{2DP}]^T = [Li_{LD} \ Cu_{CD}]^T$, thus the error state vector $x_E = x_P - x_{DP}$, $x_E = [x_{1E} \ x_{2E}]^T = [Li_l \ Cu_c]^T$, i_l and u_c are the error of the inductor current and output voltage, respectively. Therefore, (5) can be changed to:

$$\begin{cases} \dot{x}_{1P} = \dot{x}_{1E} = -\frac{x_{2P}}{C} + \sigma \frac{x_{2P}}{C} + u_S \\ \dot{x}_{2P} = \dot{x}_{2E} = \frac{x_{1P}}{L} - \sigma \frac{x_{1P}}{L} - \frac{CP_{CPL}}{x_{2P}} \end{cases} \quad (13)$$

According to (13), the PCHD model of DDBC is:

$$\begin{cases} \dot{x}_E = (J - R) \frac{\partial H(x_P)}{\partial x_P} + J_\sigma x_P + u \\ y = \frac{\partial H(x_P)}{\partial x_P} \end{cases} \quad (14)$$

where J is a skew symmetric matrix and satisfies $J = -J^T$, and $J = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$, $x_P^T J x_P = 0$,

$$R = \begin{pmatrix} 0 & 0 \\ 0 & \frac{C^2 P_{CPL}}{x_{2P}^2} \end{pmatrix}; H(x_P) = \frac{1}{2L} x_{1P}^2 + \frac{1}{2C} x_{2P}^2, \frac{\partial H(x_P)}{\partial x_P} = \begin{pmatrix} x_{1P} & x_{2P} \end{pmatrix}^T; u = \begin{pmatrix} u_S \\ 0 \end{pmatrix}; J_\sigma = \begin{pmatrix} 0 & \frac{\sigma}{C} \\ -\frac{\sigma}{L} & 0 \end{pmatrix}.$$

3.2. IPBC Design of DDBC

In order to overcome the non-passivity and realize the stable work of the DDBC, interconnection and damping injecting are added in (16). If there is a dynamic energy storage function $H_P(x_P)$ and a skew symmetric matrix $J_P = J + J_a$, where $J_a = \begin{pmatrix} 0 & -j_a \\ j_a & 0 \end{pmatrix}$, $j_a > 0$, and a positive definite matrix $R_P = R + R_a$, where $R_a = \begin{pmatrix} r_a & 0 \\ 0 & g_a \end{pmatrix}$, $r_a > 0$, $g_a > 0$, r_a, g_a are positive damping injecting and conductance injecting, the controller of DDBC is taken as

$$\begin{cases} u = (J_P - R_P) \frac{\partial H_P(x_P)}{\partial x_P} - (J - R) \frac{\partial H(x_P)}{\partial x_P} - J_\sigma x_P \\ \dot{x}_E = (J_P - R_P) \frac{\partial H_P(x_P)}{\partial x_P} \end{cases} \quad (15)$$

From (15), the dynamic energy storage function $H_P(x_P)$ can be written as

$$H_P(x_P) = H_P(x_E) = \frac{1}{2} x_E^T M_P x_E = \frac{1}{2L} x_{1E}^2 + \frac{1}{2C} x_{2E}^2 \quad (16)$$

where $\mathbf{M_P} = \text{diag}(1/L \ 1/C)$.

According (15) and (16), $\dot{H}_p(\mathbf{x_P})$ can be obtained

$$\begin{aligned}\dot{H}_p(\mathbf{x_P}) &= \dot{H}_p(\mathbf{x_E}) = \mathbf{x_E}^T \mathbf{M_P} \dot{\mathbf{x_E}} \\ &= \left(\frac{\partial H_p(\mathbf{x_E})}{\partial \mathbf{x_E}} \right)^T (\mathbf{J_P} - \mathbf{R_P}) \frac{\partial H_p(\mathbf{x_E})}{\partial \mathbf{x_E}} \\ &= - \left(r_a i_l^2 + (g_a + \frac{C^2 P_{CPL}}{x_{2P}^2}) u_c^2 \right) < 0\end{aligned}\quad (17)$$

According to (17), $\mathbf{M_P}$ is a positive-definite matrix and $\dot{H}_p(\mathbf{x_P}) < 0$, $\dot{H}_p(\mathbf{x_P})$ is qualified as a Lyapunov function [33], and the passivation of the DDBC with CPL is realized by (15). Therefore, (15) is the IPBC.

From (15), the duty cycle corresponding to the IPBC is represented by

$$\begin{cases} u_S = -(1+j_a)u_c - r_a i_l + (1-\sigma)u_C \\ 0 = (1+j_a)i_l - (g_a + \frac{P_{CPL}}{u_c^2})u_c + \frac{P_{CPL}}{u_c} - (1-\sigma)i_L \end{cases}\quad (18)$$

According to the direction of energy flow, the i_L should be established first, and the u_C should be established later. It can be obtained from the first equation of Equation (19):

$$\sigma = 1 - \frac{u_S + (1+j_a)u_c + r_a i_l}{u_C} = 1 - \frac{u_S + (1+j_a)(u_C - U_{CD}) + r_a(i_L - I_{LD})}{u_C}\quad (19)$$

where $I_{LD} = P_{CPL}/U_{SD}$.

From (19), duty ratio σ is associated with u_C and i_L , and a correlation degree is decided by j_a and r_a . Therefore, the good dynamic and steady state performance of DDBC is obtained by selecting proper j_a and r_a .

4. Unknown Nonlinear Power Observer and Preferences in IPBC

4.1. Nonlinear Power Observer of Unknown CPL

In practice, the power of CPL may be changed under the influences of various uncertain factors, and the operating point of DDBC may be changed. Therefore, the nonlinear power observer of CPL is introduced in the proposed control strategy to adjust the I_{LD} in real time to ensure the operating point tracking. Learning from [34,35], the NPO of CPL for DDBC can be expressed as

$$\begin{cases} \dot{\hat{P}}_{CPL} = -\frac{1}{2}\gamma C x_2^2 + \hat{P}_A \\ \dot{\hat{P}}_A = \gamma x_1 x_2 (1-\sigma) + \frac{1}{2}\gamma^2 C x_2^2 - \gamma \hat{P}_A \end{cases}\quad (20)$$

where $\hat{P}_{CPL}$ is the observed value of P_{CPL} , γ is a NPO gain.

Let power observed error be:

$$\tilde{P}_{CPL} = \hat{P}_{CPL} - P_{CPL}\quad (21)$$

According to (21) and (5), $\dot{\tilde{P}}_{CPL}$ is transformed as:

$$\begin{aligned}\dot{\tilde{P}}_{CPL} &= \dot{\hat{P}}_{CPL} - \dot{P}_{CPL} = \dot{\hat{P}}_{CPL} \\ &= -\gamma(\hat{P}_{CPL} - P_{CPL}) = -\gamma\tilde{P}_{CPL}\end{aligned}\quad (22)$$

Equation (22) can be written compactly as:

$$\begin{cases} \dot{\tilde{P}}_{CPL} + \gamma\tilde{P}_{CPL} = 0 \\ \tilde{P}_{CPL} = e^{-\gamma t}\tilde{P}_{CPL}(0) \end{cases}\quad (23)$$

Equation (23) shows that $\tilde{P}_{CPL}$ goes to zero exponentially. How fast $\tilde{P}_{CPL}$ goes to zero depends on the magnitude of γ . The larger γ is, the faster $\tilde{P}_{CPL}$ goes to zero, and $\hat{P}_{CPL} = P_{CPL}$. Furthermore, the dynamic response of the NPO needs to be fast enough to adjust the I_{LD} in real time, and ensure the CPL tracking, and the large NPO gain, is selected in general [36]. Therefore, an appropriate γ can be selected to realize effective real-time observation of $\hat{P}_{CPL}$ on unknown P_{CPL} , and can ensure the operating point tracking when CPL changes.

4.2. Design of Damping Injecting and Conductance Injecting for IPBC

The convergence rate of the output voltage and inductor current is affected by the values of damping injecting r_a and conductance injecting g_a . Therefore, the parameters are designed from the perspective of energy conservation.

Combining (16) and (17), $\dot{H}_p(x)$ can be expressed as:

$$\dot{H}_p(x_P) = \dot{H}_p(x_E) = \frac{1}{2}L\frac{di_L^2}{dt} + \frac{1}{2}C\frac{du_C^2}{dt} = -\left(r_a i_L^2 + \left(g_a + \frac{C^2 P_{CPL}}{x_{2P}^2}\right)u_C^2\right) \quad (24)$$

Equation (24) is further changed to:

$$\dot{H}_p(x_E) = -\beta H_p(x_E) = r_a i_L^2 + \left(g_a + \frac{C^2 P_{CPL}}{x_2^2}\right)u_C^2 \quad (25)$$

where $\beta > 0$.

Equation (25) can be transformed as:

$$\dot{H}_p(x_E) + \beta H_p(x_E) = 0 \quad (26)$$

and

$$H_p(x_E) = H_p(0)e^{-\beta t} \quad (27)$$

Equation (27) shows that $H_p(x)$ can approach zero exponentially, and the convergence rate of $H_p(x)$ depends on β . The larger β is, the faster $H_p(x)$ will approach zero. As the $H_p(x)$ goes to zero, desired output voltage and inductor current will be realized.

By substituting (16) into (25), it can be expressed as:

$$r_a i_L^2 + \left(g_a + \frac{C^2 P_{CPL}}{x_{2P}^2}\right)u_C^2 = -\beta\left(\frac{1}{2}Li_L^2 + \frac{1}{2}Cu_C^2\right) \quad (28)$$

Originating from (28), r_a and g_a satisfy:

$$\begin{cases} \frac{1}{2}L\beta = -r_a \\ \frac{1}{2}C\beta = -\left(g_a + \frac{P_{CPL}}{u_C^2}\right) \end{cases} \quad (29)$$

Further, β and r_a are selected by:

$$\begin{cases} \beta = -\left(\frac{2}{C}\left(g_a + \frac{P_{CPL}}{u_C^2}\right)\right) \\ r_a = \frac{L}{C}\left(g_a + \frac{P_{CPL}}{u_C^2}\right) \end{cases} \quad (30)$$

According to (30), α and r_a depend on g_a , P_{CPL} and u_C . In order to improve the robustness to the load and let $H_p(x_E)$ rapidly approach zero, a large g_a can be selected. g_a is determined by:

$$g_a \gg \frac{P_{CPL}}{u_C^2} \approx \frac{P_{CPL}}{U_{CD}^2} \quad (31)$$

Therefore, r_a is mainly determined by g_a as $g_a > P_{CPL}/(u_C^2)$ according to (30) and (31). This means the tuning of r_a is not significantly affected by operating points to ensure the robustness to the load.

4.3. Design of Interconnection Injecting for IPBC

In order to analyze the ability of interconnection injecting j_a to track U_{CD} and I_{LD} , substituting (19) into (5) results in a voltage equation of

$$L \frac{di_l}{dt} + r_a i_l = -(1 + j_a) u_c \quad (32)$$

It can be seen from (32) that j_a is mainly related to the voltage and current. According to (32), when $u_c > 0$ and $u_c > U_{CD}$, i_l will become a negative incremental trend, which makes the i_L and u_C decrease; when $u_c < 0$ and $u_c < U_{CD}$, i_l will become a positive incremental trend, which makes the i_L and u_C increase. From the dynamic perspective, the regulation speed depends on j_a . The larger j_a is, the faster the regulation is, which means smaller dynamic error and shorter regulation time. On the contrary, the smaller j_a will have the slower adjustment speed and lead to greater dynamic error. Thus, j_a can be selected according to the maximum change in CPL to obtain the desired transient response of DDBC.

In summary, the structure of the proposed control strategy is shown in Figure 6. The implementation procedures for the proposed control strategy are as follows:

- (1) First, the parameters γ , r_a , and j_a are designed according to (23), (30) and (31).
- (2) Second, the power of CPL is estimated according to (20), and I_{LD} is calculated with the measured input voltage.
- (3) Finally, the duty cycle is calculated according to (19) with determined parameters and measured inductor current, output voltage, and input voltage.

Figure 6. The structure of the proposed control strategy.

5. Simulation and Experimental Results

5.1. Simulation Results

The proposed control strategy in Figure 6 is simulated in MATLAB/Simulink to validate its effectiveness. The system parameters are listed in Table 1. First, the procedure for tuning design parameters is illustrated, then the simulation results under different operating conditions will be presented.

Table 1. Simulation parameters of DDBC.

Symbols	Parameter Names	Values
u_S	Input voltage	30 V
U_{CD}	Desired average output voltage	60 V
I_{LD}	Desired average inductor current	2 A
P_{CPL}	Rated power	60 W
C	Capacitance	940 μ F
L	Inductance	2 mH
f_S	Switching frequency	10 kHz
j_a	Interconnection injecting	7
r_a	Positive damping injecting	6.36
g_a	Conductance injecting	3
γ	Power observer gain	2000

5.1.1. Tuning of Design Parameters

1. NPO Gain

The proposed control strategy consists of NPO for the CPL estimation and IPBC for the output voltage regulation. The dynamic responses of the observed CPL variation and output voltage when the CPL steps from 60 W to 90 W and 90 W to 60 W at 0.5 s under different values of γ ($\gamma = 50, 200, 500, 1000$, and 2000) are shown in the following simulations.

It can be observed from Figures 7 and 8 that the NPO and u_C can track the CPL variation and U_{CD} with fast dynamic response, and the larger γ will result in a faster convergence rate for output voltage and operating point tracking when the CPL changes. As the CPL steps, the power of the CPL and U_{CD} need to be tracked quickly to maintain DDBC stability, and the large power observer gain is typically selected [37]. Therefore, γ can be selected as 2000 to ensure the faster dynamic response can be obtained. This set of the parameters will be used in the simulations and experiments below to verify the feasibility of the proposed control strategy, and show its advantage in terms of dynamic characteristics by comparing with other strategies.

Figure 7. Simulated CPL observation of the different γ when CPL steps up and down. (a) CPL: 60 W to 90 W; (b) CPL: 90 W to 60 W.

Figure 8. Simulated u_C responses of the different γ when CPL steps up and down. (a) CPL: 60 W to 90 W; (b) CPL: 90 W to 60 W.

2. Positive Damping Injecting and Conductance Injecting

From (25), (30) and (31), the convergence rate of $H_P(x_E)$ depends on g_a and r_a , and impacts on the dynamic response of the u_C . The dynamic responses of the u_C when the CPL steps from 60 W to 90 W and 90 W to 60 W at 0.5 s under different values of g_a and r_a ($g_a = 1, r_a = 2.12$; $g_a = 2, r_a = 4.24$; $g_a = 3, r_a = 6.36$; $g_a = 4, r_a = 8.48$; $g_a = 5, r_a = 10.6$) are shown in Figure 9.

Figure 9. Simulated u_C responses of the different g_a and r_a when CPL steps up and down. (a) CPL: 60 W to 90 W; (b) CPL: 90 W to 60 W.

It can be observed from Figure 9 that the larger g_a and r_a will lead to a faster convergence rate for $H_P(x_E)$, and the u_C can track the U_{CD} within a short transition while the voltage fluctuation peak is lower. Thus, the proper values of g_a and r_a should be selected to obtain a fast dynamic response of u_C while avoiding a large voltage overshoot.

3. Interconnection Injecting

Figure 10 shows the simulation results of the output voltage dynamic response when the CPL steps from 60 W to 90 W and 90 W to 60 W at 0.5 s with different values of j_a ($j_a = 3, 5, 7, 9$ and 11).

Figure 10. Simulated u_C responses of the different j_a when CPL steps up and down. (a) CPL: 60 W to 90 W; (b) CPL: 90 W to 60 W.

It is clearly observed in Figure 10 that a larger j_a will lead to a shorter settling time and a lower voltage fluctuation peak for the U_{CD} tracking. Thus, j_a can be selected at a larger value in order to obtain a better dynamic response of u_C .

In order to further verify the influence of control parameters on DDBC stability, and guide the selection of parameters, the phase portraits of DDBC using IPBC under different value of parameters are shown in Figures A1 and A2 (Appendix A). It can be observed that larger g_a , r_a , and j_a will lead to a larger unstable region. According to the influence of control parameters on dynamic response and stability, the g_a , r_a and j_a can each be made a compromise choice. Therefore, g_a and r_a can be selected as 3 and 6.36, respectively, and j_a can be selected as 7; these parameters will be used in the following simulations and experiments.

Based on the selection of the above parameters, the phase portrait of DDBC by using IPBC as shown in Figure 11 is compared with Figure 4; the output voltage and inductor current can converge to the desired equilibrium point P and realize the stable work of the DDBC.

Figure 11. Phase portrait of DDBC by using IPBC when feeding CPL.

5.1.2. Simulation Verification

Simulations are carried out based on MATLAB/Simulink to validate the proposed control strategy. The simulation parameters are shown in Table 1 of DDBC with CPL, and used in the simulations for comparative purpose. To verify the advantages of the proposed control strategy, the IDA-PBC [28] and PBC [22] are implemented for the DDBC with the same simulation parameters. The u_C is considered to operate into a steady state when it fluctuates at $U_{CD} \pm 0.2$ V.

1. Step Change in u_S

Figure 12 shows the simulation results of the output voltage when u_S steps from 30 V to 40 V at 0.5 s with different control strategies. The u_C has approximately 21 V deviation from the U_{CD} when the PBC is used, while the steady-state output voltage error is eliminated by using the proposed control strategy and IDA-PBC. Furthermore, the voltage overshoot of the proposed control strategy is less than 0.2 V, significantly smaller than the IDA-PBC under the u_S steps, and it has the faster convergence rate for U_{CD} .

Figure 12. The simulation results of the different control strategies under input voltage mutation.

2. Step Change in P_{CPL}

Figure 13 gives the comparison results of the output voltage when the CPL steps from 60 W to 90 W at 0.5 s and 90 W to 60 W at 1 s with different control strategies.

As shown in Figure 13, the output voltage performances of the proposed control strategy, IDA-PBC and PBC, can be obtained. Comparing the simulation results, the u_C has approximately 3.5 V deviation from the U_{CD} when the PBC is used, and the PBC cannot realize the operating point tracking when the CPL steps. Meanwhile, the steady-state output voltage error is eliminated by using the proposed control strategy and IDA-PBC, and the voltage overshoot of proposed control strategy is significantly smaller than the

IDA-PBC. Moreover, the u_C has the faster dynamic performance by using the proposed control strategy, and it can track the U_{CD} accurately within a very short transition, which is much better than the IDA-PBC. Therefore, the proposed control strategy can realize the faster convergence rate of operating point tracking when the CPL steps.

Figure 13. The simulation results of the different control strategies under CPL steps. (a) 60 W to 90 W at 0.5 s; (b) 90 W to 60 W at 1 s.

Based on the simulation results of Tables 2 and 3, the proposed control strategy can ensure the faster dynamic performance and stability of DDBC, and realize the accurate output voltage and operating point tracking.

Table 2. Simulation results for u_C of DDBC under different control strategies and input voltage disturbances.

Input Voltage Disturbance	Control Strategy	Fluctuation Peak Value of u_C (V)	Transient Time of u_C (ms)	Steady State Error (V)
30 V to 40 V	Proposed control strategy	≈ 0	≈ 0	≈ 0
	PBC [22]	21	-	21
	IDA-PBC [28]	3.1	33	≈ 0

Table 3. Simulation results for u_C of DDBC under different control strategies and CPL disturbances.

CPL Disturbance	Control Strategy	Fluctuation Peak Value of u_C (V)	Transient Time of u_C (ms)	Steady State Error (V)
60 W to 90 W	Proposed control strategy	0.5	2	≈ 0
	PBC [22]	3.9	-	3.5
	IDA-PBC [28]	0.8	16	≈ 0
90 W to 60 W	Proposed control strategy	0.5	2	≈ 0
	PBC [22]	3.5	-	3.5
	IDA-PBC [28]	0.8	16	≈ 0

5.2. Experimental Results

The experimental system setup is shown in Figure 14, and the experimental parameters are the same as Table 1. It consists of a boost converter, a DC source, an oscilloscope, and a DC electronic load which is used to emulate the CPL. The u_C of the DDBC is considered to enter a steady state when the output voltage fluctuates at $U_{CD} \pm 1$ V.

Figure 14. Experimental system setup.

1. Step Change in u_S

The impact of the u_S steps is shown in Figure 15. In Figure 15a, the u_C has little or no overshoot, and quickly tracks the U_{CD} when the u_S steps from 30 V to 40 V by using the proposed strategy. In Figure 15b,c, the output voltage overshoots are much larger than the proposed control strategy, and the u_C of PBC has approximately 23 V deviation from the U_{CD} when the PBC is used. Therefore, compared to other control strategies, the proposed control strategy can track the U_{CD} within a very short transition, and has better dynamic response when the u_S changes.

(a)

(b)

Figure 15. Cont.

(c)

Figure 15. u_C and i_L experiment results of the different control strategies when u_S steps from 30 V to 40 V. (a) The proposed control strategy; (b) PBC; (c) IDA-PBC.

2. Step Change in P_{CPL}

As shown in Figure 16a, when the CPL steps from 60 W to 90 W and 90 W back to 60 W, the output voltage has the overshoot below 1 V and then drops back to U_{CD} by using the proposed strategy. However, in Figure 16b, the PBC cannot track the desired value and has approximately 8 V deviation from the U_{CD} under the CPL steps. In Figure 16c, the overshoot of output voltage is much larger than the proposed control strategy, and the settling time is more than 350 milliseconds using IDA-PBC. Thus, the proposed control strategy can realize the faster convergence rate of u_C and ensure the operating point tracking when the CPL changes significantly.

(a)

Figure 16. Cont.

(b)

(c)

Figure 16. u_C and i_L experiment results of the different control strategies when CPL steps up and down (60 W to 90 W and 90 W to 60 W, respectively). (a) The proposed control strategy; (b) PBC; (c) IDA-PBC.

Based on the experiment results from Tables 4 and 5, the proposed control strategy can ensure DDBC stability with a fast dynamic performance, and realize the accurate output voltage and operating point tracking under various disturbances. The dynamic response and overshoot for experimental cases are slightly slower and larger than the corresponding simulation results. This is acceptable, as in the simulation studies the ideal CPL with the step change is used, whereas in the experimental tests, the u_S and CPL steps are restricted by their controller bandwidth. Moreover, the experimental results suffer from real-life system conditions such as Electro-Magnetic Interference (EMI), noise, delays, and various uncertainties disturbances which are not considered in the simulations.

Table 4. Experimental results for u_C of DDBC under different control strategies and input voltage disturbances.

Input Voltage Disturbance	Control Strategy	Fluctuation Peak Value of u_C (V)	Transient Time of u_C (ms)	Steady State Error (V)
30 V to 40 V	Proposed control strategy	≈ 0	≈ 0	≈ 0
	PBC [22]	23	-	23
	IDA-PBC [28]	5	500	≈ 0

Table 5. Experimental results for u_C of DDBC under different control strategies and CPL disturbances.

CPL Disturbance	Control Strategy	Fluctuation Peak Value of u_C (V)	Transient Time of u_C (ms)	Steady State Error (V)
60 W to 90 W	Proposed control strategy	< 1	≈ 0	≈ 0
	PBC [22]	8	-	8
	IDA-PBC [28]	7	380	≈ 0
90 W to 60 W	Proposed control strategy	< 1	≈ 0	≈ 0
	PBC [22]	8	-	8
	IDA-PBC [28]	6	360	≈ 0

6. Conclusions

The instability problem caused by the CPL for DDBC is addressed in this paper. To solve this problem, the stability of DDBC with CPL is studied based on passivity, and the nonlinear control strategy which consists of the IPBC and NPO is proposed. First, the IPBC is studied using damping and interconnection injecting based on the PCHD model and the parameters of IPBC are designed from the perspective of energy conservation. From the phase portraits of DDBC, the stability of DDBC is realized by IPBC. Second, the adaptability of the DDBC is improved as the CPL and input voltage change through the design of NPO. The NPO with large γ is employed to estimate load power with a fast dynamic response to ensure the accurate desired operating point tracking. Meanwhile, extensive numerical simulation and experimental results are given to verify the validity of the proposed control strategy. Under different large disturbances, both results indicate that the output voltage has the voltage overshoot below 1 V and can accurately track the U_{CD} within 10 milliseconds by using the proposed strategy, which are significantly better than PBC and IDA-PBC. Furthermore, the consistency of simulation and experimental results is validated. Finally, the proposed control algorithm is also applicable to other DDC topologies.

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Appendix A

Figure A1. Cont.

(c)

(d)

(e)

Figure A1. Phase portraits of DDBC with different g_a and r_a when feeding CPL. (a) $g_a = 1$ and $r_a = 2.12$; (b) $g_a = 2$ and $r_a = 4.24$; (c) $g_a = 3$ and $r_a = 6.36$; (d) $g_a = 4$ and $r_a = 8.48$; (e) $g_a = 5$ and $r_a = 10.6$.

(a)

(b)

(c)

Figure A2. Cont.

Figure A2. Phase portraits of DDBC with different j_a when feeding CPL. (a) $j_a = 3$; (b) $j_a = 5$; (c) $j_a = 7$; (d) $j_a = 9$; (e) $j_a = 11$.

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