Research on the Control Strategy of dual Boost bridgeless PFC based on Lyapunov stability

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Abstract: In order to prevent power electronic devices from causing harmonic pollution to the power grid, PFC technology is widely used between power electronic devices and the power grid. Therefore, the improvement of system power factor and robust performance has become a research focus today. This paper is aimed at dual Boost bridgeless PFC (power factor correction) converters, establishes a mathematical model in virtual dq mode, and a new nonlinear control strategy based on Lyapunov stability is proposed. The MATLAB simulation results show that the input current can better track the input voltage in the steady state, and when the load or output voltage changes, the system can quickly enter stability, and the system has strong anti-disturbance ability.

1. Introduction

With the widespread application of power electronics equipment, a large number of harmonics are injected into the power grid. In order to solve this problem, PFC technology has been proposed. Compared with the traditional bridge PFC converter, the dual Boost bridgeless PFC converter eliminates the rectifier bridge, reduces the system loss and improves the working efficiency, which is a hot research topic today [1-2].

In [3], a classic average current method is introduced. This method can get more accurate data, but the amount of calculation in a switching cycle is too large. The deadbeat control strategy proposed in [4] is to update the duty cycle once every high-frequency control cycle to reduce the calculation frequency of the controller, but it is very sensitive to system parameters. The control strategy of introducing virtual dq mode into the single-phase converter proposed in [5] and [6], greatly improves the power factor of the system and can achieve precise output voltage control. However, higher accuracy of component parameters is required this strategy. The robustness and performance of system is deteriorated when the load changes in a wide range. It will cause the system can’t be adjusted quickly. In [7], a nonlinear adaptive robust control is proposed, which can achieve stable tracking of output voltage under uncertain parameters, but it is currently only used in DC-DC converters.

In this paper, the virtual dq transformation and Lyapunov stability control is combined to design a nonlinear controller based on the Lyapunov stability in the virtual dq mode. It effectively improves the power factor of the system, reduces the input current THD, and improves the robustness and stability of the system. On the basis of the theoretical model, results of MATLAB simulation show the effectiveness of the proposed control method.
2. System modeling in virtual dq mode

The circuit topology of the dual Boost bridgeless PFC converter is shown in Fig.1. The topology is composed of two Boost converters with positive and negative half-cycle symmetrical to each other.

![Fig.1 Dual Boost bridgeless PFC converter](image)

If $V_{ac}>0$, the Boost converter will be constituted of $S_1$, $D_1$, $D_3$, $L_1$ and $C_f$; If $V_{ac}<0$, the Boost converter will be constituted of $S_2$, $D_2$, $D_4$, $L_2$ and $C_f$. The function of the diodes $D_3$ and $D_4$ is to make the positive and negative half cycles form independent loops, reduce common mode noise interference, and simplify control [2]. The working mode of this topology is shown in Table 1.

| Mode | $V_{ac}$ | Switch status | Inductor working state | Working circuit |
|------|---------|---------------|------------------------|-----------------|
| 1    | $>0$    | 1 0           | Magnetizing            | $V_{ac}$, $L_1$, $S_1$, $D_3$ |
| 2    | $0$     | 0 0           | Demagnetizing          | $V_{ac}$, $L_1$, $D_1$, $C_f$, $D_3$ |
| 3    | $<0$    | 0 1           | Magnetizing            | $V_{ac}$, $L_2$, $S_2$, $D_4$ |
| 4    | $0$     | 0 0           | Demagnetizing          | $V_{ac}$, $L_2$, $D_2$, $C_f$, $D_4$ |

In CCM mode, the continuous time model of Boost converter as follows:

$$
\begin{align*}
L \frac{di_L}{dt} &= V_{ac} - (1-d) \cdot V_o \\
C_f \frac{dV_o}{dt} &= - \frac{V_o}{R} \\
d &= \begin{cases} 
1, & S=1 \\
0, & S=0
\end{cases}
\end{align*}
$$

(1)

Where $i_L$ is the inductor current, $V_o$ is the output voltage, and $d$ is the duty cycle of the continuous state. Record $u=1-d$, then when $S=1$, $u=0$; when $S=0$, $u=1$.

By introducing coordinate transformation, the AC component $V_{ac}$ in Fig.1 can be transformed into a DC voltage in a rotating dq coordinate system, which can simplify the design of the controller. Delay the phase of the input voltage $V_{ac}$ by 90° to create an orthogonal voltage component $V_{acm}$, and perform dq transformation between $V_{ac}$ and $V_{acm}$. The orthogonal virtual circuit is shown in Fig.2.
The mathematical model in the virtual dq mode established according to the state space averaging method as follows:

\[
\begin{align*}
L \frac{di_d}{dt} &= v_d - u_d V_o + \omega L i_q \\
L \frac{di_q}{dt} &= -u_q V_o - \omega L i_d \\
C \frac{dv_o}{dt} &= \frac{u_d i_d}{2} + \frac{u_q i_q}{2} - \frac{V_o}{R}
\end{align*}
\]  

(2)

Where \(v_d, v_q, i_d, \) and \(i_q\) are the input voltage and input current component in the dq coordinate system, \(u_d, u_q\) is component duty ratio in the dq coordinate system, \(\omega\) is the angular frequency of the AC.

Defining the state variables as \(x_1 = i_d, x_2 = i_q, x_3 = V_o, \alpha_1 = 1/L, \alpha_2 = v_d/L, \beta_1 = 1/C, \beta_2 = 1/RC\). For the dual Boost bridgeless PFC converter, the uncertainty of the output parameters will affect the power factor and stability of the system. In order to ensure the stability of the system, the mathematical model shown below is established according to (2):

\[
\begin{align*}
\dot{x}_1 &= -u_d \alpha_c x_3 + \alpha_2 + \omega x_2 \\
\dot{x}_2 &= -u_q \alpha_c x_3 - \omega x_1 \\
\dot{x}_3 &= 0.5u_d (\beta_1 + \Delta \beta_1) x_1 + 0.5u_q (\beta_1 + \Delta \beta_1) x_2 - (\beta_2 + \Delta \beta_2) x_3
\end{align*}
\]  

(3)

Where \(\Delta \beta_1\) and \(\Delta \beta_2\) are the error value corresponding to \(\beta_1\) and \(\beta_2\).

3. Nonlinear controller design based on Lyapunov stability

3.1. Design of Lyapunov function

According to the mathematical model established by (3), the observed state equation in the virtual dq mode designed in this paper can be written as [7]:

\[
\begin{align*}
\dot{\hat{x}}_1 &= -u_d \alpha_c \hat{x}_3 + \alpha_2 + \omega \hat{x}_2 + k_1 (x_1 - \hat{x}_1) \\
\dot{\hat{x}}_2 &= -u_q \alpha_c \hat{x}_3 - \omega \hat{x}_1 + k_2 (x_2 - \hat{x}_2) \\
\dot{\hat{x}}_3 &= 0.5u_d (\beta_1 \hat{x}_1 + \Delta \hat{\beta}_1 x_1) + 0.5u_q (\beta_1 \hat{x}_2 + \Delta \hat{\beta}_1 x_2) - (\beta_2 + \Delta \beta_2) x_3 + k_3 (x_3 - \hat{x}_3)
\end{align*}
\]  

(4)

Where \(\hat{x}_1\), \(\hat{x}_2\) and \(\hat{x}_3\) respectively denotes the estimated value of \(x_1, x_2\) and \(x_3\), \(k_1, k_2\) and \(k_3\) are coefficients greater than 0.

According to (3) and (4), the error state equation of the system as follows:
\[ \begin{aligned}
\dot{x}_1 &= -u_d \alpha_1 \ddot{x}_3 + \omega \ddot{x}_2 - k_1 \ddot{x}_1 \\
\dot{x}_2 &= -u_d \alpha_1 \ddot{x}_3 - \omega \ddot{x}_1 - k_2 \ddot{x}_2 \\
\dot{x}_3 &= 0.5 u_d \left( \beta_1 \ddot{x}_1 + \Delta \dddot{x}_3 \right) + 0.5 u_d \left( \beta_1 \ddot{x}_2 + \Delta \dddot{x}_2 \right) - \left( \beta_2 \ddot{x}_3 + \Delta \dddot{x}_3 \right) - k_3 \ddot{x}_3 
\end{aligned} \]  
(5)

Where \( \ddot{x}_1, \ddot{x}_2 \) and \( \ddot{x}_3 \) is the difference between \( x_1, x_2, x_3 \) and \( \ddot{x}_1, \ddot{x}_2 \) and \( \ddot{x}_3 \). The Lyapunov function designed based on (5) as follows:

\[ V(x) = \frac{1}{2 \alpha_1} \dddot{x}_1^2 + \frac{1}{2 \alpha_1} \dddot{x}_2^2 + \frac{1}{\beta_1} \dddot{x}_3^2 \]

\[ + \frac{1}{2 \beta_1 \xi_1} \Delta \dddot{x}_1^2 + \frac{1}{2 \beta_1 \xi_2} \Delta \dddot{x}_2^2 \]

(6)

Where \( \xi_1 \) and \( \xi_2 \) are greater than 0. Take the derivative of \( V(x) \) to get:

\[ \dot{V}(x) = \frac{1}{\alpha_1} \dot{x}_1 \dddot{x}_1 + \frac{1}{\alpha_1} \dot{x}_2 \dddot{x}_2 + \frac{2}{\beta_1} \dddot{x}_3 \dddot{x}_1 + \frac{1}{\beta_1 \xi_1} \Delta \dddot{x}_1 \dot{\Delta} \dddot{x}_1 + \frac{1}{\beta_1 \xi_2} \Delta \dddot{x}_2 \dot{\Delta} \dddot{x}_2 \]

(7)

According to the Lyapunov direct method, when \( V(x) \) satisfies the following properties, the system is globally asymptotically stable at the equilibrium point [12]:

1) \( V(\ddot{x})=0 \); 2) If \( \ddot{x} \neq 0 \), \( V(\ddot{x})>0 \); 3) If \( ||\dddot{x}|| \to \infty \), \( V(\dddot{x}) \to \infty \); 4) If \( \dddot{x} \neq 0 \), \( \dot{V}(\dddot{x})<0 \).

In order to ensure the stability of the system, the following error equations are obtained by combining (5) and (7):

\[ \begin{aligned}
\dot{\Delta} \dddot{x}_1 &= \xi_1 \left( u_d \dddot{x}_1 + u_d \dddot{x}_2 \right) \dddot{x}_3 \\
\dot{\Delta} \dddot{x}_2 &= -2 \xi_2 \dddot{x}_1 \dddot{x}_3 
\end{aligned} \]  
(8)

3.2. Nonlinear controller design

The error tracking equation in the virtual dq mode used in this article as follows:

\[ \begin{aligned}
S_d &= \hat{x}_1 + \lambda_1 \int \left( \hat{x}_3 - V_{ref} \right) dt \\
S_q &= \hat{x}_2 + \lambda_2 \int \left( \hat{x}_3 - V_{ref} \right) dt 
\end{aligned} \]  
(9)

Where \( S_d \) and \( S_q \) are respectively a tracking error of the d-axis and q-axis, \( \lambda_1 \) and \( \lambda_2 \) is positive tracking coefficient value, \( V_{ref} \) is the reference value of the output voltage. When the system reaches a steady state, \( \dot{S}_d=0, \dot{S}_q=0 \). Combining (4) and (9), the controller equation can be obtained as:

\[ \begin{aligned}
u_d &= \frac{\alpha_2 + \alpha_1 \dddot{x}_2 + k_1 \dddot{x}_1 + \lambda_1 \left( \hat{x}_3 - V_{ref} \right)}{\alpha_1 \dddot{x}_3} \\
u_q &= \frac{-\alpha_1 \dddot{x}_2 + k_2 \dddot{x}_2 + \lambda_2 \left( \hat{x}_3 - V_{ref} \right)}{\alpha_1 \dddot{x}_3} 
\end{aligned} \]  
(10)

A term \( k_4 \left( \hat{x}_3 - V_{ref} \right) \) is added to the calculation formula of \( u_d \) to increase the dynamic performance of the controller and reduce the system observation error. Therefore, the Lyapunov stability controller based on dq transformation is designed as:
4. Control Strategy

In this paper, a nonlinear control strategy based on Lyapunov stability in dq mode is used to achieve the power factor correction and improve system stability of the dual Boost bridgeless PFC. According to the designed controller equation, the control block diagram designed in this paper is shown in Fig.3.

\[
\begin{align*}
    u_d &= \frac{\alpha_1 + \alpha_2 \hat{x}_1 + k_1 \hat{x}_1 + \lambda (\hat{x}_3 - V_{ref})}{\alpha_3 \hat{x}_3} + k_3 (\hat{x}_3 - V_{ref}) \\
    u_q &= -\frac{\alpha_4 \hat{x}_1 + k_4 \hat{x}_1 + \lambda (\hat{x}_3 - V_{ref})}{\alpha_4 \hat{x}_3}
\end{align*}
\]

(11)

5. Simulation

In this paper, a dual Boost bridgeless PFC converter circuit is built through the MATLAB simulation platform to model the uncertainty of the output capacitance and load, assuming \( C=1500\mu F, R=300\Omega, \) coefficients \( k_1=12000, k_2=10000, k_3=7000, k_4=0.0003, \lambda_1=0.7, \lambda_2=0, \xi_1=45, \xi_2=0.8. \) Table 2 shows the circuit simulation parameters.

| Type                        | Parameter value |
|-----------------------------|-----------------|
| Effective value of input voltage \( V_{ac}/V \) | 220 |
| Rated output voltage \( V_o/V \)             | 380 |
| Rated power \( P_o/W \)                | 1000 |
| Switching frequency \( f_s/Hz \)          | 50k |
| Energy storage inductor \( L_1, L_2/mH \)   | 5 |
| Output filter capacitor \( C/f\mu F \)       | 1000 |

The expected performance index of the controller designed in this paper is: output voltage ripple<3%, power factor PF>0.99, and input current THD<3% under full load.

5.1 Full load simulation

Fig.4 shows the simulation result of full load output in steady state. Among them, Fig.4 (b) is the input current Fourier analysis (FFT). The power factor is 0.996, the input current THD is 2.63%, and the output voltage ripple is 2.24%. The simulation results meet the design requirements.
5.2. Load jump simulation
Fig.5 is the simulation result of the output load jump. Among them, the load is switched from full load to half load state at 0.5s, the dynamic response time is about 100ms, and the amplitude of Vo during the response is about 3.68% overshoot. It can be seen from the waveform that when the load has a large disturbance, both is and Vo can reach a new stable state, and the response speed is faster and the adjustment range is small.

5.3. Output voltage jump simulation
Fig.6 shows the simulation result of the output load voltage jump. Among them, Vo drops from 380V to 360V at 0.5s, and the dynamic response time is about 100ms. During the response, the amplitude of Vo is about 2.2% overshoot. It can be seen from the waveform that when Vo undergoes a jump, both is and Vo can reach a new stable state, with a faster response speed and a smaller adjustment range.

6. Conclusion
In this paper, a control strategy combining single-phase virtual dq mode and Lyapunov stability is adopted to establish a mathematical model of a dual Boost bridgeless PFC converter and design a nonlinear controller. The simulation results show that under different output load powers, the power factor of the system is close to 1, the input inductor current THD is small, the system stability is good, the response speed is fast, and the robustness is strong. The simulation verified that the designed nonlinear controller can effectively improve the system power factor, reduce the inductor current THD, and improve the current quality of the input current.
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