Boost PFC Constant Voltage Control with Constant Power Load

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ABSTRACT

The power factor correction (PFC) can be realized by the input-output linearization method for boost converter. The advantage is that the duty cycle of MOS transistor can be calculated directly without control parameter setting, but when the converter is connected to constant power load (CPL), because the duty cycle formula includes the ratio of output voltage to current, the load of Buck CPL has no current flow during the $t_{\text{off}}$ period, so the normal calculation results cannot be given. In order to solve the problem that the output duty cycle cannot be calculated, this paper starts from the relationship of equal input and output power, and merges resistance into the output terminal. At the same time, in order to reduce the power loss, the capacitor is connected to the original circuit to provide continuous current to correct the current discontinuity, and then the output voltage is precisely adjusted to realize the fast constant voltage control of Boost PFC converter under CPL.

KEYWORDS

Input and Output Linearization, Power Factor Correction, Current Discontinuity, Input and Output power, Capacitance, Constant Voltage Control.

INTRODUCTION

Power factor correction technology is one of the main means to reduce harmonic pollution in power grid\cite{1}. Boost circuit topology and control strategy are the key research objects in this field\cite{2-4}. Some nonlinear control algorithms are also used in power factor correction, such as differential flattening algorithm\cite{5}, deadbeat control\cite{6}, sliding mode variable control structure\cite{7}. These control strategies have been widely used in various fields\cite{8-10}.

In recent years, constant power load (CPL) has attracted much attention in the field of power electronic load research. The stability analysis\cite{11-13}, control strategy and application\cite{14-15} Based on the former voltage source conversion circuit are the key research contents. In reference\cite{16}, a basic model and an equivalent circuit model of constant power load are proposed. Due to the influence of its own switching characteristics, the current flowing through the former PFC circuit shows discontinuous characteristics. Therefore, when this kind of constant power load is connected to the nonlinear control algorithm as the control strategy and the pre-stage circuit with power factor correction, the normal operation of the whole control strategy will be affected by the output current variables sampled by the traditional detection points.

In this paper, aiming at the current discontinuity of Boost PFC converter
under constant power load (CPL), the duty cycle control law of boost converter under the condition of constant power load is derived by using the input-output linearization method. According to the working characteristics of the switch, the discontinuity of its output current is analyzed. The appropriate resistance and capacitance are connected to the output terminal, so that the control law of the circuit can be calculated normally. The PSIM simulation software is used to model it and the algorithm is used to simulate it under the condition of constant power load. The results show that the input current of the algorithm can accurately track the sinusoidal voltage signal under constant power load, and the circuit has the characteristics of constant voltage output. The control system has good static and dynamic performance and good robustness to the disturbance of input voltage and load.

**STATES SPACE MODEL OF BOOST PFC CONVERTER**

When the boost converter is connected to a buck load, when the buck adopts closed-loop control, it can be equivalent to a constant power load relative to the previous boost PFC converter[19]. Figure 1 shows the topology of boost circuit under CPL.

![Figure 1. Structure diagram of Boost PFC constant power load.](image)

In the Figure, let the input current be \(i_{in}\); take the instantaneous value of the input voltage after the AC rectification, and the current passing through the inductor be \(i_{in}\); take the output voltage as \(v_{o}\), and take the average value in the single cycle of the switch, \(u\) is the duty cycle of the MOSFET switch \(Q_{1}\), and \(i_{out}\) is the output current. The state space representation method is used to build the mathematical model, and the results are as follows:

\[
\begin{align*}
L \frac{di_{in}}{dt} &= (u - 1)v_{o} + v_{in} \\
C \frac{dv_{o}}{dt} &= (1 - u)i_{in} - i_{out}
\end{align*}
\]

Based on the mathematical model of (1) which is established by the boost topological structure through the state space average method, the state variable of the system is defined as \(x = [x_{1}, x_{2}] = [i_{in}, v_{o}]\), and the output variable is \(y = h(x)\), thus the specific mathematical model of the system with single input and single output can be obtained:
DESIGN OF CONTROL STRATEGY OF BOOST CONVERTER WITH CONSTANT POWER LOAD

If there is \( \forall x \in \Omega \) for the single input single output nonlinear system of formula (2), the following conditions are satisfied:

\[
\begin{align*}
L_g L_f^k h(x) &\equiv 0, 0 \leq k \leq r - 2 \\
L_g L_f^r h(x) &\neq 0, k = r - 1
\end{align*}
\]

(3)

The corresponding order of the system on \( \Omega \) is called \( r \), and the system whose output function \( y = h(x) \) corresponds to (2) has the corresponding order of \( r \).

\[
y^{(r)} = L_f^r h(x) + L_g L_f^{r-1} h(x) u
\]

(4)

It can be seen from the formulas (3) and (4) that if the control input variable function of the system is connected with its output function, then the corresponding order of the system on \( \Omega \) is \( r \), then its output function \( h(x) \) also needs differential \( r \) times.

Set the reference output voltage and current as \( V_{ref} \) and \( i_{inref} \), the corrected input voltage peak value as \( V_m \) and current peak value as \( I_m \), and the output power \( P \) of the system can be expressed as: \( P = 0.5V_m I_m \). When the above system is described by the expected input current and voltage, the state equation of the system is shown in formula (5):

\[
\begin{align*}
\dot{x} &= \left[ \begin{array}{c}
-\frac{1}{L} x_2 + \frac{1}{L} V_m \\
\frac{1}{C} x_1 - \frac{i_{out}}{C}
\end{array} \right] + \left[ \begin{array}{c}
\frac{1}{L} x_2 \\
-\frac{1}{C} x_1
\end{array} \right] u \\
y &= h(x) = x_1 - i_{inref}(t) = x_1 - \frac{V_{ref} \cdot i_{inref}}{\frac{1}{2} V_m^2}, v_m
\end{align*}
\]

(5)

Combined with the above, for the nonlinear system described in formula (2), the original system can be completely and accurately linearized only when the constraints of formula (3) and (4) are met. Therefore, according to the single input single output nonlinear system model of formula (2), further detailed calculation and analysis are carried out in combination with formula (3) and (4):

\[
\begin{align*}
L_f h(x) &= \frac{\partial h(x)}{\partial x} \cdot f(x) = -\frac{1}{L} x_2 + \frac{1}{L} V_m \\
L_g L_f^r h(x) &= \frac{1}{L} x_2 \neq 0
\end{align*}
\]

(6)
\[ \dot{y} = L_j h(x) + L_x L_j^0 h(x) \cdot u \]
\[ = -\frac{1}{L} x_2 + \frac{1}{L} v_m + \frac{1}{L} x_1 \cdot u \]  \hspace{1cm} (7)

Let the \( \text{Span}\{g(x)\} \) be a distribution composed of \( g(x) \) in formula (5). Because it is involutive, there is a scalar function \( \psi(x) \) in the system, which makes the following formula hold:

\[ L_j \psi(x) = \frac{\partial \psi(x)}{\partial x_i} \cdot g(x) = \frac{\partial \psi(x)}{\partial x_i} \cdot \frac{x_i}{C} = 0 \]  \hspace{1cm} (8)

From the above analysis, the following non-linear coordinate transformation can be selected:

\[ z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} y \\ \psi(x) \end{bmatrix} = \begin{bmatrix} h(x) \\ \psi(x) \end{bmatrix} = \Phi(x) \]  \hspace{1cm} (9)

From the coordinate transformation described in equation (9), it can be seen that the nonlinear system described in equation (5) can be partially precisely linearized as follows:

\[ \dot{z} = \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} \dot{y} \\ \dot{\psi}(x) \end{bmatrix} \begin{bmatrix} L_j h(x) + L_x L_j^0 h(x) \cdot u \\ L_j \psi(x) + L_x L_j^0 \psi(x) \end{bmatrix} \]  \hspace{1cm} (10)

Set:

\[ L_j h(x) + L_x L_j^0 h(x) \cdot u = a(x) + b(x)u = v \]  \hspace{1cm} (11)
\[ L_j \psi(x) = L_j \psi\left(\Phi^{-1}(z)\right) = q(z) \]  \hspace{1cm} (12)

Therefore, equation (10) can be transformed into a quasi linear system described in equation (13):

\[ \begin{cases} 
[\dot{z}_1] = \begin{bmatrix} 0 & 1 \end{bmatrix} [z_1] + [1] v \\
[\dot{z}_2] = [q(z)] \\
y = z_1 
\end{cases} \]  \hspace{1cm} (13)

Where \( v = -k z_1 \) (k is the normal number)

In conclusion, the control law of Boost PFC converter under CPL can be obtained:

\[ u = 1 - \frac{k L i_L - \frac{1}{2} V_m^2}{V_m} \]  \hspace{1cm} (14)
IMPROVEMENT OF LOAD CONTROL STRATEGY WITH CONSTANT POWER FOR BOOST PFC CONVERTER

Equation (14) shows the control law of Boost PFC converter connected to CPL. Figure 2 shows that the peak value of the input AC current is 150V, the output voltage is 230V, and the reference power is 112.5W under the condition of W, the output current waveform of formula (14) is measured directly. Obviously, when the switch of CPL is turned off, there is no output current passing through the circuit, and the current is discontinuous as a whole. Therefore, the above control strategy cannot give the correct calculation results when there is no output current passing through. Figure 3 is the output current waveform. The purpose of the control algorithm in this paper is to make the system achieve the effect of stable output in the steady state, and then make the whole circuit stable. It can be seen from the figure that under the power condition of reference load 120W, after a short period of overshoot, the output voltage tends to 230V precise regulation process, but the whole output voltage cannot achieve the expected effect as a whole. When the voltage regulation tends to 230V, there is obvious fluctuation, especially when it is close to the expected output voltage for precise regulation. At the same time, when this kind of ripple fluctuates, the trend of its voltage cannot be clearly judged. Therefore, according to the above analysis, when the CPL load is connected, the boost output voltage cannot be precisely controlled by the control strategy derived above, and the voltage fluctuates greatly when the voltage is regulated, which may cause the whole system out of control if the voltage fluctuates for a long time.

![Figure 2. Waveform of output current.](image)

![Figure 3. The waveform of output voltage in steady state.](image)

In view of the above situation, the traditional method is to connect an appropriate resistance at the output end of the boost circuit, but in this way, the power consumption of the additional system can be increased, so on this basis, the output end of the boost circuit can be incorporated into a capacitor, which provides continuous current, so that the control algorithm can be calculated normally. As shown in Figure 4.
SYSTEM SIMULATION

This simulation uses PSIM as the simulation platform and the simulation parameters are as follows:

| Parameter            | Symbol | Value  |
|----------------------|--------|--------|
| Input voltage        | $V_{ac}$/V | 150    |
| Output voltage       | $V_{ref}$/V | 230    |
| Switching frequency  | $f_s$/kHz | 80     |
| Capacitance size     | $C_1$/$ \mu $F | 800    |
| Capacitance size     | $C_2$/$ \mu $F | 800    |
| Constant coefficient | $k$    | 20000  |
| Inductance size      | $L$/mH  | 2      |
| Initial load power   | $P$/W   | 112.5  |
| Initial load         | $R$/Ω   | 200    |

Figure 5 shows the output voltage waveform when the reference power is 112.5 W after the output terminal of the circuit is connected to the capacitance C2 in parallel. Compared with Figure 3, the continuous output current provided by C2 solves the problem of intermittent current, and the control law of the system can be calculated normally. At the same time, compared with the method of directly incorporating resistance at the output end of the circuit, the power loss of the circuit is reduced. It can be seen from the figure that the output voltage can be maintained at 230 V, so as to achieve the effect of constant voltage output.

CONCLUSION

To solve the problem of output current discontinuity of Boost PFC converter under constant power load. Based on the linearization control strategy of single
input and single output under CPL load, this problem can be solved by analyzing the incorporation resistance according to the equal input and output power. On this basis, in order to reduce the power loss of the system, the resistance is replaced by the capacitance, and the continuous current provided by the capacitance enables the control algorithm to calculate normally. Simulation results show that the method can make the circuit output constant voltage, and its input current can accurately track its input voltage, showing the characteristics of power factor correction.

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