The Zero-Crossing Distortion and One Cycle Control in Single-phase PFC

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Abstract—Input current distortion in the vicinity of input voltage zero crossing of Boost single-phase active power factor corrected rectifier in high line frequency is studied based on one cycle control method in this paper. The current loop model and input admittance model of active power correction based on one cycle control is particularly analyzed. The results point out that its equivalent power stage of current loop is a 1st order system, and that its input admittance is the pure resistive around low frequency domain and the capacitive characteristics above 1 kHz. From about the frequency 1 kHz, then, the input line current phase leads input voltage. However, it does not matter in aero ac power system with 400Hz or 360~800Hz line frequency in the future, and it is suitable for applications as front converter in aero power supply system.

Index Terms—power factor corrected, zero-crossing distortion, one cycle control, input admittance

I. INTRODUCTION

Active Power factor correction (APFC) technology, which is being instead of uncontrolled diode rectification, is widely being used in power electronics in order to resolve input current harmonics. But in aero AC power system whose frequency is constant 400Hz or variable frequency 360-800Hz in the future, APFC based on conventional control has more serious zero-crossing distortion in single-phase APFC [1], which causes large input current harmonics. So the bulky passive multi-pulse rectifiers, which have higher reliability and acceptable power factor, are widely used in aero power system. In order to improve aero power performance and meet aero power criterion, APFC will be continuous to be researched for single-phase voltage source to solve zero-crossing distortion in stead of bulky passive multi-pulse rectifier [2].

By analyzing zero-crossing distortion problem from the topology of single-phase APFC based on average current control method, two types of factors causing zero-crossing distortion will be got. The first factor is that the current of boost inductor can not availably follow the input voltage because the voltage value on boost inductor is too small, when the input voltage crosses zero domains. It means that the smaller is the value of boost inductor, the smaller effect has the zero-crossing distortion. The second factor is that the power stage model changes to a first order system from formerly second order system when the input voltage crosses zero domains. So it causes to drop the gain of current loop and greatly reduces the response speed of the current loop. It means that the larger is the value of boost inductor, the smaller effect has the zero-crossing distortion. So multi-level technology was introduced to alleviate zero-crossing distortion by improving change rate of inductor current under using smaller inductance [3]. From above analysis, the boost inductor plays an important role in the average current control method and designing the boost inductor must be synthetically taken into account.

But in recent years, the dynamic interactions of zero-crossing distortion from the input impedance of single-phase APFC was firstly researched, and the key factors that causes zero-crossing distortion was pointed out that the inductor current phase leads the input voltage phase and that the characteristics of current loop is underdamping[4]. Later, the compensation technology of the current phase leading by voltage phase was analyzed and was widely used in single-phase APFC converter with achieving a good performance reducing zero-crossing distortion [5] [6]. At the same time, the feedforward current control method [7] and the novel nonlinear average current control method [8] were studied on to resolve the zero-crossing distortion.

In fact, from analyzing the novel control method above, it can be achieved that the nonlinear average current control method is very like as one cycle control method (OCC) [9], and that its designing process is also similar to OCC. OCC technology is widely used in power conversion, such as ac/dc, dc/dc, dc/ac and power amplifier etc and even used in controlling power quality in electrical power system [10]. At the same time, IR Company has already successfully popularized OCC control IC such as IR1150 [11] in Boost APFC applications. So researching OCC to resolve zero-crossing distortion is feasible.

In this paper, single-phase Boost APFC zero-crossing
distortion in aero ac power system is researched by OCC method. It is found that APFC based on OCC method has a good capacity of reducing the zero-crossing distortion through analysis of its equivalent power stage of current loop and input admittance.

II. THEORY ANALYSIS

A. Zero-Crossing Distortion

In aero AC power system, AC source frequency is 400Hz or variable frequency 360-800Hz in the future, which is more higher the frequency 50/60Hz. Then in conventional Boost APFC boost converter designing under frequency 50/60Hz, the zero-crossing distortion usually hardly be observed, but the phenomena of the zero-crossing distortion is more serious and even can not meet harmonic current limits in the aero AC power system.

From the aim of Boost APFC, AC line input current can well follow the AC line input voltage with unity PFC. This means that input impedance of Boost APFC shows pure resistive from the input terminal. In fact, switching frequency may be above 100 kHz under using average current loop control in Boost APFC. The bandwidth of the conventional average current loop controller should be high enough to pass all significant harmonics of the rectified sine wave. The bandwidth usually is in 1/10~1/5 of switching frequency to enforce input impedance around low frequency 50/60 Hz to be pure resistive according to classical linear control theory. While the input impedance shows the capacitive characteristics around frequency 400Hz, so the input current phase leads the line input voltage. Considering the effect of the high frequency filter capacitors at input terminal and output terminal of rectified diodes bridge, the input current phase will more leads the input voltage.

Because of the characteristics of unilateral conduction of a diode, the diode that will be needed to be turned on still continues to turn off due to the input voltage polarity also keeping the above state, when the line input current crosses zero in diode rectified bridge. So the line input current is clamped at zero, and it causes the occurring of serious zero-crossing distortion. Further, the line input current instantly follows the current reference after the input voltage crosses zero via the current loop control. So the current loop compensation net designed according to classical linearly control theory will be underdamping around middle frequency domain. So it will cause extra zero-crossing distortion in Boost APFC. In order to achieve the pure resistive characteristics around middle frequency domain, the feedforward technology based on the current reference and the nonlinear average current control method were introduced in Boost APFC, and these control methods will be good for reducing zero-crossing distortion.

Because OCC method is similar to the nonlinear average current control method, OCC control method may have the same capacity of reducing zero-crossing distortion. Through researching the input admittance of the current loop equivalent power stage based on Boost APFC average model under OCC method, the capacity of OCC reducing zero-crossing distortion will be quantitatively analyzed in detail in the next sections.

B. Boost APFC Average Model Based on OCC

The Boost APFC diagram based on OCC control method is shown in Fig.1. In Boost APFC, the relationship of line input voltage \( v_{in} \) and output voltage \( V_o \) is

\[
|v_{in}| = (1 - d(f_{in}))V_o
\]  

(1)

where \( f_{in} \) is the frequency of input voltage \( v_{in} \), \((1-d(f_{in}))\) is duty ration and varies around the fundamental frequency of line input voltage. Under not considering high-frequency harmonics of input current \( i_s \), the output of voltage outer loop in the period of fundamental frequency is

\[
v_m = g_1V_0
\]  

(2)

where \( g_1 \) is constant. Achieving OCC method, the current inner loop reference is

\[
i_{ref} = \frac{v_m(1-d(f_{in}))}{R_s}
\]  

(3)

From equation (1), equation (2) and equation (3), the inner loop current reference \( i_{ref} \) is further described by

\[
i_{ref} = g_1v_{in}/R_s = g_1v_{in}
\]  

(4)

where \( g \) is equal to \( g_1/R_s \) and is constants. Because the modulating speed of OCC method is quick enough, the current reference \( i_{ref} \) has the same frequency and phase with line input voltage. That is \( g \) is pure resistive. So the outer voltage-regulating control loop providing reference to inner current loop, which is necessary in traditional average current control method, is not needed in OCC method.

Because the average value \( \bar{i}_L \) of boost inductor current

\[
\bar{i}_L
\]  

Figure 1. Circuit diagram of APFC boost converter with OCC

From equation (1), equation (2) and equation (3), the inner loop current reference \( i_{ref} \) is further described by

\[
i_{ref} = g_1v_{in}/R_s = g_1v_{in}
\]  

(4)
is equal to the average value of the transient inductor current \( i_L(t) \) in a switching period \( T_s \), or to the average value of the current following through a switch in the switch conduction time \( dT_s \), where \( d \) is duty ratio, and \( T_s \) is period. From Figure 1, the average value of the inductor current \( \bar{i}_L \) in the time \( dT \) can be expressed as

\[
\bar{i}_L = \frac{1}{T_s} \int_{0}^{T_s} i_L(\tau) d\tau = \frac{1}{dT_s} \int_{0}^{dT_s} i_L(\tau) d\tau
\]  

(5)

And under OCC method, the average inductor current is described as

\[
\bar{i}_L = i_{ref} = \frac{V_m}{R_s} (1 - d) 
\]  

(6)

From equation (1) and equation (2), it can be obtained

\[
di_{ref} = \frac{1}{T_s} \int_{0}^{dT_s} i_L(\tau) d\tau
\]  

(7)

Because OCC method can guard its controller output average value equal to reference in a period \( T_s \), then (3) can also be rearranged

\[
d\bar{i}_L = d_{\text{n}} i_{ref}
\]  

(8)

where \( d_{\text{n}} \) is duty ratio in the former switching period \( T_s \), and \( d \) is a new duty ratio. Especially \( d_{\text{n}} \) is equal to \((1 - |v_{in}/V_o|)\), when boost inductor current operates in continuous conduction mode. So in next switching period \( T_s \), a new duty ratio \( d \) can be precisely obtained

\[
d = \frac{i_{\text{ref}}}{i_L} (1 - \frac{|v_{in}|}{V_o})
\]  

(9)

Because the average model of power stage of Boost converter is

\[
L \frac{d\bar{i}_L}{dt} = |v_{in}| - (1 - d)V_o
\]  

(10)

From (9) and (10), the equation (11) can be got

\[
\frac{d\bar{i}_L}{dt} = \frac{V_o - |v_{in}|}{L} \frac{i_{\text{ref}} - i_L}{i_L}
\]  

(11)

When the input voltage and the output voltage are constant, the equation (11) by using a small signal model is rearranged

\[
\frac{d(i_L + \hat{i}_L)}{dt} = \frac{V_o - v_{in}}{L} \left( \frac{d(i_{\text{ref}})}{d(i_L)} - 1 \right)
\]  

(12)

From equation (12), a small signal model of equation (11) is shown below

\[
\frac{d\hat{i}_L}{dt} = \frac{V_o - v_{in}}{L} (i_{\text{ref}} - \hat{i}_L)
\]  

(13)

Considering \( i_L = i_{\text{ref}} \) when Boost APFC operates in stable stage, the equation (13) can be further expressed as

\[
\frac{d\hat{i}_L}{dt} = \frac{V_o - v_{in}}{L} (\hat{i}_L - \hat{i}_L)
\]  

(14)

From (14), we can get

\[
\frac{I_L(S)}{I_{ref}(S)} = \frac{1}{1 + S/\omega_p}
\]  

(15)

where \( \omega_p \) is equal to \((V_o - v_{in})/(L \cdot i_L)\).

From (15), we can conclude that the equivalent model of power stage of the current loop is first-order system and \( \omega_p \) is around high frequency domain. So the power stage of the current loop may be regard as an ideal follower that is shown in Fig. 2, where \( T_i \) is equal to \( \omega_p / S \), and \( G_{iv} \) is equal to \((1/(LS))\). Then the boost inductor current can well follow the current reference right now, and the zero-crossing distortion dose not exist, which is caused by the underdamping of current loop.

![OCC Boost PFC control loop diagram](image1)

![Bode of power stage of current loop](image2)

**Figure 2.** OCC boost APFC control model
under the average current control method.

C. Boost APFC Input Admittance Based on OCC

For Boost converter, \(i_L\) is equal to \(i_{in}\), the input admittance \(Y_{in}(S)\) can be obtained from Fig.2.

\[
Y_{in}(S) = \frac{i_{in}(S)}{v_{in}(S)} = \frac{G_{in}(S)}{1 + T_{in}(S)} + \frac{T_{in}(S)}{1 + T_{in}(S)} g
\]

(16)

Defining

\[
Y_{in1}(S) = G_{in}(S) \quad Y_{in2}(S) = \frac{T_{in}(S)}{1 + T_{in}(S)} g
\]

where \(Y_{in1}(S)\) is in high-frequency domain and \(Y_{in2}(S)\) is in low-frequency domain. By simplifying \(Y_{in1}(S)\) and \(Y_{in2}(S)\), we can obtain

\[
Y_{in1}(S) = \frac{1}{LS + \frac{V_o - V_{in}}{I_L}} \quad Y_{in2}(S) \approx g
\]

(17)

(18)

Considering the AC input terminal and DC input terminal high-frequency filter capacitors \(C_{ac}\) and \(C_{dc}\), the below equation can be got

\[
Y_{in3}(S) = C_{in} S
\]

(19)

where \(C_{in} = C_{ac} + C_{dc}\). From above analysis, boost APFC input admittance based on OCC method can be written as

\[
Y_{in}(S) = Y_{in1}(S) + Y_{in2}(S) + Y_{in3}(S)
\]

\[
\approx g + \frac{1}{LS + \frac{V_o - V_{in}}{I_L}} + C_{in} S
\]

(20)

The inner relationships of the equation (20) can be shown in Fig.3, and Fig.4 illustrates its Bode plots. From Fig.4, it can be got that the Boost APFC input admittance is pure resistive characteristics around low-frequency domain and is the capacitive characteristics around 1 kHz. Obviously for AC aero power system with constant 400Hz or variable frequency 360-800Hz in the future, the zero-crossing distortion will not be obviously represented. That is to say that APFC based on OCC may be used in AC aero power system.

III. EXPERIMENTAL RESULTS

A single-phase boost APFC converter based on the IR1150 OCC power factor IC is used to verify the above analysis. A laboratory prototype is built and the parameters important for the design of the APFC are listed in table1.

<table>
<thead>
<tr>
<th>TABLE I. CIRCUITS PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ac input voltage (V_p)</td>
</tr>
<tr>
<td>Output voltage (V_o)</td>
</tr>
<tr>
<td>Input voltage frequency</td>
</tr>
<tr>
<td>Switching frequency</td>
</tr>
<tr>
<td>Input capacitor</td>
</tr>
<tr>
<td>Boost inductor</td>
</tr>
<tr>
<td>Output capacitor</td>
</tr>
<tr>
<td>Current sampling factor</td>
</tr>
</tbody>
</table>

The waveforms depicted in Fig.5 show the input line voltage \(v_{in}\) and the input line current \(i_{in}\) under different input line-voltage frequency when virtual value of input line voltage is 115V, output power is 2000kW and output voltage \(V_o\) is controlled at 250V. The experimental results in Fig.5 indicates that the input currents phase can well follow the input voltage phase with input line voltage frequency 360Hz, 400Hz and 800Hz based on OCC method. And it is necessary pointed out that the input current has a little zero-crossing distortion when the input voltage frequency is 800Hz from Fig.5(c). This is caused by the input voltage frequency close to 1 kHz. But it also
meets the demands in AC aero power system from Fig. 6. Furthermore, Fig.6 compares the input current spectrum of the experimental results with the demands of RTCA DO-160D [12] based on OCC method under different input voltage frequency. The results clearly illustrates that the single-phase Boost APFC based on OCC method can availably reduce the effect of the zero-crossing distortion and be well used as a first stage converter for other aero power converters in AC aero power system.

The experimental results illustrate that high power factor will be got by using the OCC method under different input voltage frequency and that the zero-crossing distortion can not impact the application of APFC technology in aero power system. So APFC technology may be instead of the conventional bulky multi-pulse rectifier.

VI. CONCLUSIONS

In this paper, it is pointed out that the key factors that cause the zero-crossing distortion are input admittance
shows the capacitive and the underdamping of the current loop in single-phase Boost APFC when the traditional average current control method is adopted. The average model of single-phase Boost APFC based on OCC method is presented, and the small signal model of single-phase APFC under the OCC method indicates that the zero-crossing distortion is very small when the input voltage frequency is in 360-800Hz, because the input admittance shows the pure resistive around low frequency domain and the capacitive only above about 1kHz. The experimental results verify that single-phase Boost APFC based on OCC method can well reduce the zero-crossing distortion and meet the harmonics demands of aero power system.

REFERENCES

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