Design of Boost-Type Power Factor Correction with Stepped Air-Gap Ferrite Inductor for Peak-Power-Load Condition

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ABSTRACT This paper presents the designed method and the implementation of stepped air-gap ferrite inductor applied in power factor correction (PFC). Conventionally, the input inductor of the PFC has a designed consideration on the maximum output power; thus, designing the PFC for peak-power-load conditions results in a very large inductor. The proposed designed method improves the load-carrying capability without increasing the volume of the inductor when the PFC is operating in peak-power-load conditions. The stepped air-gap ferrite inductor maintains the inductance in the rated-full-load and sustains the peak-power-load conditions with the lower inductance. Compared with the conventional ferrite inductor, the proposed method can maintain the size and the efficiency of the power supply, and promote the power-carrying ability. The detailed analysis and the design of the proposed method are described. Experimental results are recorded and evaluated by a prototype PFC with an AC input voltage of 110–264 VAC and a DC output voltage of 384 VDC. Finally, the volume of input inductor is kept with 40950 mm3, the efficiency is also same compared with the conventional inductor, and the load-carrying capability of the converter is promoted from the normal rated power of 1 kW to the peak power load of 2 kW.

INDEX TERMS Power Factor Correction; stepped air-gap inductor; peak power

I. INTRODUCTION

In the century of green energy, the power industry is striving for high efficiency and power density of converters. Fig. 1 shows that power factor correction (PFC) has the benefits ranging from reducing the demand charges on the power system to increasing the effectiveness of power usage. It shapes the input current of the power supply to synchronize with the input voltages and avoid large harmonic current. The input current of PFC should also comply with the standard regulation [1]. Besides, the PFC converter has been applied in disk drives, motor derives, fans, and pump derivers. These applications require a large output power at the duration of start-up and are usually higher than the rated-full-load conditions. Therefore, the inductor of the PFC converter is designed for peak-power-load conditions, but the volume and the cost of the inductor are evidently increased and wasted.

In reference [2]-[5], the active technique is proposed to injected the magnetic flux to input inductor and solved the saturation of the inductor in peak-load conditions. However, this method might result in the redundant circuit and complicating the control strategy. In reference [6,7], the configurable inductor is proposed to control the inductance and applied in wide load range converter. However, this method will additionally complex the control of the switches on inductor which might increase the switching loss and EMI problems. In reference [8,9], the coupled inductor is introduced and used in interleaved CCM boost PFC converter. Although, the DC magnetic flux can be canceled in the coupled inductor. The interleaved architecture is only suited for high power levels. In reference [10], a small piece of permanent magnet is added in to the air gap. The permanent DC magnetic field will double the saturation current with the same size of inductor. However, this method will shape the permanent magnet into flaky shape. The reliability of the permanent magnet will be questioned. In this paper, the passive method is proposed and adopted in single phase CCM boost PFC converter. The stepped air-gap ferrite inductor can ensure high inductor current with smaller volume and used in so many applications [11]. However, the non-linear characteristic of the stepped air-gap inductor is hard to analysis. In [12,13], the characteristic curve of inductor is depicted with asymptote. This method is precise, but hard to quantitative analysis. In [14,15], the B-H curve of the ferrite is decomposition into linear subproblem. This helps the mathematic module to approximate the real characteristic of...
the stepped air-gap inductor, easily. Even so, [14,15] still lack of an intuitive method to find out the boundary inductor current. In this paper, the stepped air-gap ferrite inductor is analyzed according to the magnetoresistance to help realize the composition of the equation and applied in the boost-type PFC converter. The proposed geometry shape of ferrite inductor is utilized to reduce the volume and sustain more current through the duration of peak-power-load conditions. The boost input inductor is not saturated. Thus, input current total harmonic distortion (iTHD) can be maintained for the standard regulation [16,17]. Compared with the conventional geometry shape of the ferrite inductor, the proposed inductor can also maintain the same conversion efficiency of the converter at normal-rated-power conditions with smaller volume. According to the above, the calculated modules of the stepped air-gap inductor are introduced in section II, and the simulated results are also verified. Besides, the designed progress of the stepped air-gap ferrite inductor is presented in section III. Finally, theoretical discussions are validated with the experimental results on a prototype PFC circuit that delivers an AC input of 110–264 VAC and a DC output of 385 VDC with conventional inductor and stepped air-gap inductor, respectively.

The boost type PFC converter is shown Fig. 2. From the average current method, the greater output power enhances the inductor current and pushes the magnetic flux of the conventional inductor to the limit. Thus, the input inductor might become fully saturated and cause a large short-circuit current in peak-power operation. To solve this problem, a stepped air-gap inductor is proposed, as shown in Fig. 3. The equivalent inductance under different load currents is designed, as shown in Fig. 4. When the PFC converter is operated in normal conditions, the inductance is a constant value $L_1$, which is designed to achieve the requirement of current ripple. When the PFC converter is operated in peak-power conditions, inductance drops to $L_2$ and enters the second state to provide a higher load-carrying ability. Equation (1) depicts the phase angle $\theta$ of the input current when inductance drops.

$$\theta = \sin^{-1}\left(\frac{1}{\sqrt{2}}\frac{I_{\text{rms}}}{I_{\text{surge}}}\right)$$

To calculate the inductance varying with the operating current, the following assumptions are introduced. First, core loss is neglected. The magnetization of the material, especially soft ferrite, makes the magnetic component shift the domain boundaries (Bloch wall) [18] over imperfections in the crystallite. Hence, the irreversible movement causes hysteresis loss [19,20] and varies initial permeability, as shown in Fig. 5. Under this assumption, the B-H curve can be modeled into three sections, namely, fixed initial permeability, nonlinear, and saturated linear.
The inductor current between $I_{\text{surge}}$ and $I_{\text{max}}$ can be predicted as a model in Fig. 9. The inductance rolls off rapidly until $\mathcal{R}_{\text{core1}}$ is saturated deeply as Ansys Maxwell simulation shows in Fig. 8. Hence, the equivalent magnetic circuit can be predicted as a model in Fig. 9. The inductance $L_2$ and the magnetic flux density of $\mathcal{R}_{\text{core2}}$ can be expressed in Equations (7) and (8), respectively. $I_{\text{surge}}$ can be also expressed in Equation (9).

\[
L_2 = \frac{N^2}{\mathcal{R}_{\text{outside}} + \mathcal{R}_{\text{core2}} + \mathcal{R}_B} \approx \frac{N^2}{\mathcal{R}_{g1} + \mathcal{R}_{g2}}
\]  
(7)

\[
B_2(I) = \frac{L_2}{A_e} \cdot \frac{I}{N} - \frac{\mathcal{R}_{g2}}{\mathcal{R}_{g1} + \mathcal{R}_{g2}}
\]  
(8)

\[
I_{\text{surge}} = \frac{N \mathcal{B}_{\text{max}} A_e}{L_1} \cdot \frac{\mathcal{R}_{g1} + \mathcal{R}_{g2}}{\mathcal{R}_{g2}}
\]  
(9)

Where

\[
\mathcal{R}_{g1} = \frac{I_{g1}}{\mu_0 A_{e,\text{min}}}
\]  
(10)

\[
\mathcal{R}_{g2} = \frac{I_{g2}}{\mu_0 (A_e - A_{e,\text{min}})}
\]  
(11)

When the operating current of the inductor is over $I_{\text{max}}$, $\mathcal{R}_{\text{core2}}$ and $\mathcal{R}_{\text{outside}}$ are deeply saturated, and the inductance falls rapidly to $L_3$ region. Therefore, this condition causes a large short-circuit current through the power switch of the PFC converter, and the design of the stepped air-gapped inductor should avoid this situation region. $I_{\text{max}}$ can be expressed as Equation (11).

The stepped air-gap inductor flow chart is shown in Fig. 10. When winding area is enough for the choke, define the proportion of $\mathcal{R}_{\text{core1}}$ and $\mathcal{R}_{\text{outside}}$. If yes, define the geometric shape of the choke. If yes, finish.
III. DESIGNED PROGRESS OF PEAK POWER APPLICATION

In the peak-power-load application places, the conventional design the air-gap inductor uses a bulky inductor for peak-power load because the large input current causes the inductor to become deeply saturated [21]-[23]. In this section, the design method of the stepped air-gap inductor is presented to solve the above problems. Fig. 10 shows the designed flow of the stepped air-gap inductor. First, the specification of the PFC circuit including the inductance of the inductor in regular-load conditions, the volume, and the material of the inductor should be confirmed. Table I shows the comparison between soft and hard magnetic material of the inductor. Soft ferrites, such as 3C96 and PC47 of TDK corporation [24], are recommended for the application of the stepped air-gap inductor. Compared with the powder core [25], the soft ferrite has not only lower core loss and copper loss but also cheaper. In addition, ferrite core has a drastic variation on permeability according to DC magnetizing force. These advantages help in designing the stepped air-gap inductor. The environment temperature in the worst case should also be considered. Fig. 11 shows the influence of environment temperature on PC47. The saturated magnetic flux density has a 100 m Tesla difference between 25 °C and 120 °C.

TABLE I

| Parameter                      | Ferrite core (Soft) | Powder core (Hard) |
|--------------------------------|---------------------|--------------------|
| Space utilization              | high                | low                |
| Saturation Flux Density (Bsat) | low                 | high               |
| Core loss                      | low                 | high               |
| Copper loss                    | low                 | high               |
| Price                          | low                 | high               |

FIGURE 11. B-H curve of soft material of PC47

Second, to achieve the volume requirement of the peak-load operation, (11) can help designers optimize L2 wisely. Moreover, inductance L1 can be optimized by the concern of current ripple and efficiency in normal operation (L1 below Isurge). Finally, the designers can determine the proper proportion of \( \Re_{core1} \) and \( \Re_{core2} \) by using (9).

In the application of PFC converter, the maximum inductor current \( I_{L\text{max}} \) varies with input inductance and output power. With average current method, the relationship can be easily found out and expressed as Equation (12). Additionally, the designers can overlay (12) with Fig. 4 as Fig.12 shown. Thus, the designed inductor can be sure to operate in \( L_1 \) region in full load conditions and operate in \( L_2 \) region in peak load conditions.

\[
L\left(I_{L\text{MAX}},P_0\right) = \sqrt{\frac{\sqrt{V_{in\text{rms}}}}{V_o}} \left(1 - \sqrt{\frac{V_{in\text{rms}}}{V_o}}\right) \frac{1}{2f_s L_{(L_{\text{MAX}}-1/V_{in\text{rms}})}}
\]

(12)

FIGURE 12. Stepped air-gap inductor curve and \( I_{L\text{MAX}} \) curve at full-load and peak-load conditions

IV. EXPERIMENTAL RESULTS

To confirm the validity of the proposed method, the normal power 1 kW prototype of the PFC converter is implemented and promoted to 2 kW with stepped air-gap inductor. The bridge rectifier GBJ50006 is used to rectify the input current. STW70N65M2 is used for main switches, and CVFD20065A is used for the diode in the boost structure. The specification of the prototype is shown in TABLE II. Inductance, 110 and 55 μH, are selected as \( L_1 \) and \( L_2 \) of stepped air-gap inductor in full-load and peak-load conditions, respectively. Finally, the inductor is presented in Fig. 13. The proposed inductor can handle peak power operation. TABLE III shows that the volume of the inductor is also limited as the conventional one. However, the turns are increased to 36 turns to widen the load range of operation further.

TABLE II

| Parameter                     | Value |
|-------------------------------|-------|
| Input voltage                 | 110–264 VAC |
| Output voltage                | 384 V |
| Normal rated maximum power    | 1 kW |
| Peak power                    | 2 kW |
| Operating frequency           | 65 kHz |

TABLE III

| Parameter             | Conventional inductor | Stepped air-gap inductor |
|-----------------------|------------------------|--------------------------|
| Inductance, \( L_1 \) | 110 μH                 | 110 μH                   |
| Inductance, \( L_2 \) | 55 μH                  | 55 μH                    |
| Isurge                | 25 A                   | 25 A                     |
| Iloss                 | 55 A                   | 55 A                     |
| Volume                | 40950 mm²              | 40950 mm²                |
| A0                    | 266 mm²                | 266 mm²                  |
| Bmax                  | 320 mT                 | 320 mT                   |
| Turns                 | 30                     | 36                       |
The stepped air-gap inductor is compared with the conventional air-gap inductor in the case of same turns and volume. Based on finite element simulation software, fringing loss, core loss, and copper loss are included. Moreover, the same DC triangle current excites both inductors, as shown in Fig. 14. The loss simulation results are shown in Table IV. The benefits of the proposed inductor can raise not only the performance of the magnetic component but also the load-carrying capability. In TABLE IV, the proposed inductor has smaller fringing-flux effect on winding and improves the total copper loss of the inductor. The core loss is also reduced because of the difference of the geometry between two inductors.

In the AC analysis, since the behavior of the average quantities has great effect in converters. The influence of the stepped change on inductor can be verified by the three-terminal PWM switch model proposed in [26]. According to three-terminal PWM switch model in Fig. 15(a), the equivalent dc and small-signal model of PWM switch is shown as Fig. 15(b). The voltage source and the current source depend on the terminal voltage and current in Equation (13) and (14). Where $D$ represents the duty-ratio, and $d$ represents the small signal of the duty-ratio. In this model, the value of stepped air-gap inductor is based on the inductor current. Thus, the average quality of the inductor, $L_{avg}$, can be modeled as Equation (15) and shown in Fig. 15(c). Where $k$ is the time proportion constant of inductor current depicted in Fig. 16.

![FIGURE 13. Inductance measurement results](image)

![FIGURE 14. The magnetic flux density of the two inductors.](image)

![FIGURE 15. Small signal model of PWM switch.](image)

![FIGURE 16. The time proportion of inductor current](image)

![FIGURE 17. The dual loop control of the converter](image)

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![FIGURE 15. Small signal model of PWM switch.](image)

![FIGURE 16. The time proportion of inductor current](image)

![FIGURE 17. The dual loop control of the converter](image)
Fig. 17 shows the dual loop control of converter. Where $F_{in}$ is the modulator gain of PWM generator, $R_I$ is the current sensed resistor, $K_M$ is the divided voltage sensed from input line voltage. They all list in TABLE VI. Besides, $G_{CA}$ and $G_{EA}$ are the compensator of current loop and voltage loop, respectively. They are both 2p-2z filter in the Equation (16) and list in TABLE VII, finally. The expected duty-to-input transfer function can be thus model as Equation (17). The inductor characteristic will be changed according to different inductor current conditions and time proportion constant, $k$. Therefore, Fig. 18 shows the bode plot of $G_{id}$ when the input inductor current is equal to 10A, 25A and 40A, respectively. The simulation results verified the mathematic model. Besides, the variation of the inductor doesn’t affect dynamic behavior badly. The crossover frequency is just double, compared 40A with 10A. Thus, the bandwidth of the current loop can be still controlled to one-sixth of the switching frequency as Fig. 19 shown. Finally, with the compensator, $G_{CA}$, the bandwidth of current loop is 10 kHz, the gain margin is -90 dB, and the phase margin is 60 degree. The high-frequency current ripple of the inductor will be filtered out, successfully.

$$H(z) = \frac{B_0 + B_1 z^{-1} + B_2 z^{-2}}{A_0 + A_1 z^{-1} + A_2 z^{-2}}$$  \hspace{1cm} (16)  

$$G_{id}(s) = \frac{E_{L}}{E_{d}} = K_{id} \frac{1 + s/\omega_{nc}}{1 + s/\omega_{nc} + s^2/\omega_e^2}$$  \hspace{1cm} (17)  

Where  

$$K_{id} = \frac{2V_o}{R_i (1-D)^2}, \omega_{nc} = \frac{2}{R_i C_o}, \omega_e = \frac{1-D}{\sqrt{L_{avg} C_o}}, Q = \frac{R_L (1-D)}{\sqrt{C_o L_{avg}}}$$  \hspace{1cm} (18)

For the voltage loop, to achieve stable output voltage, the bandwidth will be set to one-sixth of line-voltage frequency. The tracked input voltage will be thus view as a DC source, $V_{in, rms}$. In Fig. 20(a), according to the three-terminal method proposed in [27]. The ac model shown in Fig. 20(b) can be construct to illustrate the relationship between the small signals. The current source and the resistance are based on the power conversation of the input and output terminals and depicted in Equation (19). Finally, the equivalent model can be further simplified to Fig. 20(c) to discuss the influence from the command, $V_{con}$, to the output voltage, $V_o$. The expected control-to-output transfer function can be thus model as Equation (20). It can be seen that the stepped air-gap inductor has no influence on voltage loop because of low-bandwidth. At last, with the compensator, $G_{EA}$, the bode plot of the voltage loop on 1 kW and 2 kW are shown in Fig. 21. The bandwidth is 19Hz, the gain margin is -180 dB, and the phase margin is 65 degree. The output voltage will be regulated at fixed voltage.

![FIGURE 18. Bode plot of $G_{id}$](image)

![FIGURE 19. Bode plot of current loop after compensation](image)

![FIGURE 20. Equivalent small-signal model of $G_{EA}$](image)

![FIGURE 20. Equivalent small-signal model of three-terminal method](image)
\[ M = \frac{V_o}{V_{in rms}} \cdot r_i = \frac{r_i}{M^2} \cdot \frac{V_{in rms}}{K_M} \cdot r_i = R_L \]
\[ G(s) = \frac{V_o}{V_{in}} = \frac{r_i}{1 + sC_i (r_i/R_L)} \]

(19)

(20)

\[ \text{Bandwidth} = 19 \text{ Hz} \]
\[ \text{Gain margin} = -180 \text{ dB} \]
\[ \text{Phase margin} = 65^\circ \]

**FIGURE 21.** Bode plot of voltage loop after compensation

The experiment waveforms of conventional and stepped air-gap inductor are shown in Fig. 22 and 23, respectively. In the full-load conditions, both inductors are not saturated, and the current \( i_L \) of the stepped air-gap inductor and conventional inductor are all the same waveforms. Therefore, the efficiency and power factor (PF) values are similar, as shown in Fig. 24. In normal operation, the proposed inductor has the slightly lower inductance when the input voltage is 110 Vac. Thus, the RMS value of input current will be increased and slightly aggravate the conduction loss. Finally, TABLE V concludes the advantages of the proposed inductor.

**FIGURE 22.** Key waveform of conventional inductor with 110 VAC input and 1 kW output conditions [ch1 = \( v_{in} \), ch2 = \( i_L \), ch3 = \( v_{gs} \), and ch4 = \( V_o \) (Time: 2.2 ms/div)]

**FIGURE 23.** Key waveform of conventional inductor with 230 VAC input and 1 kW output conditions [ch1 = \( v_{in} \), ch2 = \( i_L \), ch3 = \( v_{gs} \), and ch4 = \( V_o \) (Time: 2.2 ms/div)]

**FIGURE 24.** Comparison between conventional and stepped air-gap inductor

Fig. 25 and 26 show the key waveform of stepped air-gap inductor operated in peak-load conditions and low input voltage. The stepped air-gap inductor is reduced after 25 A, and according to (1), it occurs at the \( \theta \) about 77°. Thus, the ripple of the inductor increases. Fig. 27 and 28 show the key waveform of stepped air-gap inductor operated in peak-load conditions and high input voltage. The input inductor is kept with 110 μH because the inductor current is below 25 A. Fig. 29 and 30 show the step transient responses from 1 kW to 2 kW.

**FIGURE 25.** Key waveform of conventional inductor with 110 VAC input and 1 kW output conditions [ch1 = \( v_{in} \), ch2 = \( i_L \), ch3 = \( v_{gs} \), and ch4 = \( V_o \) (Time: 2.2 ms/div)]

**FIGURE 26.** Key waveform of stepped air-gap inductor
VI. CONCLUSION

This paper presents a modified input inductor for the peak power application of the PFC converter. The geometry of the inductor is analyzed, and the design is presented. The stepped air-gap inductor can increase the power-carrying capability by the partial saturation of the magnetic core. Compared with the conventional inductor, the volume of the magnetic component can be effectively reduced. Moreover, the conversion efficiency and the PF value are identical with those of the conventional inductor under normal-load conditions. The validity of this paper is confirmed by the experimental results. Finally, the proposed design is fulfilled with input of 110/264 V\textsubscript{AC} and output of 384 V\textsubscript{DC}. The power-carrying capability of the PFC input inductor is promoted from 1 kW to 2 kW for peak-power-load conditions and the prototype is shown in Fig. 31.
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