Study and Implementation of the Passive Snubber with Coupled-Inductor in a Single-Stage Full-bridge Boost PFC

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Abstract

In this paper, an improved passive snubber is investigated in a single-phase single-stage full-bridge boost power factor correction (PFC) converter, by which the voltage spike across primary side of the power transformer can be suppressed and the absorbed energy can be transferred to the output side. Compared with the basic passive snubber proposed earlier, the two single-inductors are replaced by a coupled-inductor in the improved snubber. As a result, the synchronous resonances in the snubber can be achieved, which can avoid the unbalance of the voltage and current in the snubber. The operational principle of the improved passive snubber is analyzed in detail based on a single-phase PFC converter, and the design considerations of both the snubber and the coupled-inductor are given. Finally, a laboratory-made prototype is built, and the experimental results verify the feasibility of proposed method and the validity of the theoretical analysis and design method.

Key words: Coupled-inductor, Full-bridge, Passive snubber, Power factor correction (PFC), Single-stage

I. INTRODUCTION

In the research field of power factor correction (PFC), single-stage PFC integrates the functions of PFC and isolated DC/DC conversion in a single power converter, and it has the advantages such as high efficiency, simplicity and low cost when compared with two-stage PFC [1], [2]. In recent years, many low power single-stage PFC converters have been investigated, however, fewer high power scheme [3].

The isolated full-bridge boost topology is attractive in applications of medium or high power single-stage PFC. The reasons why these type of PFC has not been widely used can be attributed to: 1) an additional starting-up circuit is required to establish an initial output voltage, and 2) there is a voltage spike across the bridge leg caused by the transformer leakage inductor [4], [5]. For the normal single-stage full-bridge boost PFC, starting-up has been realized through many efficient methods. For example, the flyback starting schemes are proposed in [4]-[6], and a direct starting mode of the converter in the state of no load is presented in [7].

To suppress the voltage spike, a number of techniques have been proposed. A method based on the basic active clamping technique is introduced in [8]-[10], and it has been the most widely investigated [11]. Two new active clamping techniques are proposed in [12], [13] respectively. A two-switch clamping circuit is presented in [14]. Some active auxiliary circuits with single-switch are adopted in [11], [15] and [16] respectively. The voltage spike is efficiently suppressed after adoption of each of the active methods above, however, the active methods above have a common drawbacks, that is: one (or two) additional switch is introduced, which increases the complexity of control circuit and reduces the reliability of the whole system, moreover, the switching frequency of the additional switch is two times as high as that of the main switches, so it is difficulty to choose the switch. Besides the active methods, some passive methods have also been proposed. For example, a LC resonance scheme is studied in [17]-[19], which can also
achieve the soft switching of the main switches, however, its resonance energy can not be transferred to the load, but add to the conduction losses of the converter. A RCD snubber is used in [20], but the energy of the snubber circuit is released by the resistor. A passive clamping technique is proposed in [21], while, the problem of magnetic bias of the power transformer appears after adoption of the passive clamping circuit. A passive snubber is investigated in [22], however, after adoption the passive snubber, a diode is connected in series with the bridge leg switches, which will reduce the efficiency of the converter. In [23], another passive snubber is investigated in a three-phase single-stage PFC which overcomes the disadvantage of the snubber in [22], but there will appear unbalance of the voltage and current between the two resonant circuits.

In this paper, based on the passive snubber in [23], an improved passive snubber is investigated in a single-phase single-stage full-bridge boost PFC converter. In the improved snubber, the two single-inductors are replaced by a coupled-inductor. Theoretical analysis and experimental results show that the voltage spike can be suppressed efficiently after adoption of the improved snubber which can also overcome the drawback of the passive snubber in [23].

II. THE PFC CONVERTER AND ITS PRINCIPLE

A. The PFC Converter

The single-phase single-stage full-bridge boost PFC converter is shown in Fig.1, where the improved passive snubber is composed of $C_1$, $C_2$ ($C_1=C_2$), $D_{C1}$, $D_{C2}$, $D_C$ and the coupled-inductor ($L_1=L_2$ are the equivalent inductance). $D_{S1}$-$D_{S4}$ and $C_{S1}$-$C_{S4}$ are the parasitic components of switches $S_1$-$S_4$. $L_k$ and $n$ are the equivalent leakage inductance and the voltage ratio of transformer $T$, respectively. The switching mode of $S_1$-$S_4$ is the same as that in [23]. The converter in Fig.1 operates in continuous current mode (CCM). When the bridge leg switches are shorted ($S_1$ & $S_2$ or $S_3$ & $S_4$ are turning on), the boost inductor $L$ is charged by $u_i$, and the input current increases almost linearly. When the bridge-diagonal leg switches turn on ($S_2$ & $S_3$ or $S_1$ & $S_4$ are turning on), the output current is provided by $u_i$ and $L$, and the input current decreases. The process above is repeated periodically, the input current follows input voltage, and both PFC and AC/DC conversion can be achieved.

B. Analysis of the Operational Process

The working process of the snubber is closely related to the principle of the PFC converter, and the special control strategy has not been introduced for the snubber. The PFC converter in Fig.1 operates in CCM, which is different to the converter in [23], so its operational process is presented as followed for the further analysis and design.

To simplify the analysis, we assumed that: 1) all devices are ideal, 2) the capacitor $C$ is large enough, so the output voltage $U_o$ can be considered as a constant value, and 3) during one charging period of $L$, the change of $u_i$ is negligible because the charging period is much shorter than the line period. The following analysis is during one charging period of $L$ when $u_i>0$. The theoretical waveforms and the equivalent circuits of different stages are shown in Fig.2 and Fig.3, respectively.

Stage 1 (before $t_0$): $S_2$ and $S_3$ are turning on, while $S_1$ and $S_4$ are turning off. The voltage across the primary side of transformer $T$: $U_{CS1}=U_{CS2}=U_0$, $U_{CS3}=U_{CS4}=0$, and $U_{CS5}=U_{CS6}=0$. The current in $L$ ($i_L$) flows through $S_2$, $S_3$, $T$ to the load, and it decreases. On the secondary side of $T$, $D_{S1}$, $D_{S4}$ are turning on, and $D_{S2}$, $D_{S3}$ are turning off.

Stage 2 ($t_0$-$t_1$): At $t_0$, $S_1$ turns on, and $S_3$ turns off. $L$ is charged by $u_i$, and $i_L$ increases linearly. In the snubber, $C_1$ is resonant with $L_1$ through $D_{C1}$, $S_1$ and $S_2$, furthermore, $C_2$ is resonant with $L_2$ through $S_1$, $S_2$ and $D_{C2}$. The current of $L_k$ ($i_{Lk}$) can not be mutated, so $i_{Lk}$ flows through $S_2$, $D_{S4}$ and $T$ to the load and $i_{Lk}$ decreases immediately. At $t_1$, $i_{Lk}$ reduces to zero (the excitation current of $T$ isn’t considered here), and $D_{S1}$, $D_{S4}$ are turned off. The inductance of $L_k$ is very small, so the duration of this stage can be ignored.

Stage 3 ($t_1$-$t_2$): The resonances in stage 2 are continuous, and the voltage of $C_1$, $C_2$ and the current in $L_1$, $L_2$ are:

$$u_{C1/C2}(t)=\frac{nU_0}{2}\cos\left(\frac{1}{\sqrt{L_1C_1}}(t-t_1)\right)$$

$$i_{L1/L2}(t)=\frac{nU_0}{2}\sqrt{L_1}\sin\left(\frac{1}{\sqrt{L_1C_1}}(t-t_1)\right)$$

At $t_2$, $U_{C1}=U_{C2}=0$, the energy of $C_1$ and $C_2$ is transferred to $L_1$ and $L_2$ entirely. The duration of this stage is calculated as:

$$t_2=\frac{\pi}{2}\sqrt{\frac{1}{L_1C_1}}$$

Stage 4 ($t_2$-$t_3$): In this stage, $i_L$ still increases linearly and the output current is also provided by the capacitor $C$ alone. The voltage of $C_1$ or $C_2$ is zero, so diode $D_C$ is turned on, $L_1$ is connected in series with $L_2$, and their current flows through $D_{C1}$, $S_1$, $S_2$, $D_{C2}$ and $D_C$. During stage 1–4, $U_{CS3}$ is still zero, so $S_1$ turns off with zero voltage at $t_0$.

Stage 5 ($t_3$-$t_4$): At $t_3$, $S_2$ turns off, and $S_4$ turns on with zero voltage. $C_{S2}$, $C_{S3}$, $C_1$ and $C_2$ are charged by $L_1$, $L_2$ and $L$. The voltage across the bridge leg increases from zero, so
S₂ turns off with zero voltage. The capacitance of C₃₁~C₄₄ is much smaller than that of C₁ and C₂, so only the charging process of C₁ and C₂ is considered in the following calculation. In this stage, the following relationships can be obtained:

\[ C₁ \frac{du_{C₁/C₂}(t)}{dt} = iₐ(t₃) + iₐ₁/₂(t) \]  \hspace{1cm} (4)

\[ u_{C₁/C₂}(t) = -L₁ \frac{diₐ₁/₂(t)}{dt} \]  \hspace{1cm} (5)

From (4) and (5), the following differential equation is obtained:

\[ L₁C₁ \frac{d^2u_{C₁/C₂}(t)}{dt^2} + u_{C₁/C₂}(t) = 0 \]  \hspace{1cm} (6)

This equation (6) has the following initial data:

\[ u_{C₁/C₂}(t₅) = 0 \]  \hspace{1cm} (7)

\[ iₐ₁/₂(t₅) = \frac{nU₀}{2 \sqrt{L₁}} \]  \hspace{1cm} (8)

Therefore, the voltage expression of C₁ or C₂ and the current expression of L₁ or L₂ can be obtained:

\[ u_{C₁/C₂}(t) = \left[ \frac{L₁}{C₁} iₐ(t₃) + \frac{nU₀}{2} \right] \sin \left( \frac{t}{\sqrt{L₁C₁}} \right) \]  \hspace{1cm} (9)

\[ iₐ₁/₂(t) = \frac{nU₀}{2 \sqrt{L₁}} \left( \cos \left( \frac{t}{\sqrt{L₁C₁}} \right) - 1 \right) + \frac{nU₀}{2 \sqrt{L₁C₁}} \cos \left( \frac{t}{\sqrt{L₁C₁}} \right) \]  \hspace{1cm} (10)

At t₄, the charging process of C₁ and C₂ is over. Therefore, \( Uₖ = -nU₀ \), \( U_{C₁} = U_{C₂} = nU₀/2 \), \( U_{C₃₁} = U_{C₄₄} = 0 \), \( U_{C₃₂} = U_{C₄₃} = nU₀ \). In this stage, the output current is only provided by the capacitor C. The inductance of L is large enough, so that the change of \( iₚ \) can be ignored during this stage. During the whole line period, the value of \( iₚ(t₃) \) is varying, so the duration of this stage is different during the whole line period.

Stage 6 \((t₄-t₅)\): In this stage, the current of L₁, L₂ and L flows through S₁, S₄ and T to the load, and then it decreases. On the secondary side of T, D₀₂ and D₀₃ turn on. In this stage, the expression of \( iₐ₁,ₐ₂ \) is:

\[ iₐ₁/₂(t) = \frac{nU₀}{2L₄} (t - t₄) \]  \hspace{1cm} (11)

At t₅, \( iₐ₁ \) and \( iₐ₂ \) reduces to zero. The inductance of Lₖ is so small that the rising process of \( iₕₖ \) is ignored in this stage.

Stage 7 \((t₅-t₆)\): In this stage, \( iₕ \) flows through S₁, S₄ and T to the load, and it still decreases, which is similar to that in the stage 1.
After \(i_{s2}\), the converter operates in another charging period, and the switching state between \(S_1\) and \(S_3\), \(S_2\) and \(S_4\) are exchanged.

**C. Analysis of Parameters in the snubber**

According to the analysis in [23] and the analysis above, the voltage and current stress of switches \(S_1\sim S_4\) in Fig.1 can be calculated:

\[
U_S = nU_o + i_s(t) \sqrt{2L_1 \over C_1} \sin \sqrt{\frac{2t}{L_1C_1}}
\]  

(12)

\[
I_S = I_{L,\max} + 2i_{L1/L2}(t) = I_{L,\max} + nU_o \sqrt{C_1 \over L_1}
\]  

(13)

The duration of stage 2 is so small that \(i_{L,k}\) is ignored in calculation of the current stress of \(S_2\) or \(S_4\). It can be seen that \(U_S\) decreases as \(C_1\) increases, and \(I_S\) increases as \(C_1\) increases or \(L_1\) decreases.

According to the analysis in [23], the first limitation of \(L_1\) and \(C_1\) can be obtained:

\[
L_2C_1 \leq 2.87D_{\min}^2T^2
\]  

(14)

Where \(D=(t_2-t_1)/T\) is the duty cycle of the PFC converter, and \(T\) is the charging period of \(L\).

In [23], the three-phase PFC converter operates in discontinuous current mode (DCM), generally, its duty cycle is within 50%, so the current in \(L_1\) or \(L_2\) must reduce to zero during the phase when the bridge diagonal-leg switches are turning on. However, in this paper, the single-phase PFC converter operates in CCM, the maximum duty cycle will be much more than 50%, so another constraint condition of \(L_1\) and \(C_1\) must be analyzed to make sure the current in \(L_1\) and \(L_2\) can reduce to zero in order to avoid the magnetic saturation of \(L_1\) and \(L_2\) after several charging period.

The current in \(L_1\) and \(L_2\) begins to decrease during stage 5, and it can be seen from (10) that \(i_{L1/L2}(t)\) will decrease faster as \(i_{L1}(t)\) increases, and we should make sure that \(i_{L1/L2}(t)\) can reduce to zero when \(i_{L1}(t)=0\). In that case, the energy of \(L_1\) and \(L_2\) will be transferred to \(C_1\) and \(C_2\) entirely. So the following relationship can be obtained:

\[
\frac{\pi}{2}\sqrt{L_1C_1} \leq (1-D_{\max})T
\]  

(15)

From (15), we can get the second limitation of \(L_1\) and \(C_1\):

\[
L_2C_1 \leq \frac{4(1-D_{\max})^2T^2}{\pi^2}
\]  

(16)

From the analysis above, we can see that the voltage stress of \(D_{C1}\) or \(D_{C2}\) is equal to that of \(C_1\) or \(C_2\), which is \(U_S/2\), the voltage stress of \(D_{C}\) is \(U_s\), the current stress of \(D_{C1}\) or \(D_{C2}\) is equal to that of \(L_1\) or \(L_2\), which can be obtained from (8), and the current stress of \(D_{C}\) is equal to that of \(S_1\sim S_4\), which can obtained in (13).

**III. DESIGN CONSIDERATIONS OF THE COUPLED-INDUCTOR**

**A. Mechanism Analysis of the Coupled-Inductor**

In section II, we think that \(C_1=C_2\) and \(L_1=L_2\), so the resonances between \(C_1\) (or \(C_2\)) and \(L_1\) (or \(L_2\)) are synchronous. However, there are some differences between two capacitors with the same capacitance, which is due to their tolerance feature, and for the same reason, the inductance of two inductors with the same configuration are not exactly the same. Therefore, the resonances between \(C_1\) (or \(C_2\)) and \(L_1\) (or \(L_2\)) are asynchronous, which would result in unbalance of the voltage and current between \(C_1\) and \(C_2\), \(L_1\) and \(L_2\), \(D_{C1}\) and \(D_{C2}\). In actual fact, to avoid over voltage on the capacitors \((C_1\) or \(C_2\)) or the diodes \((D_{C1}, D_{C2} \) or \(D_{C}\)) and avoid saturation of the inductors \((L_1\) or \(L_2\)), the capacitors and diodes with higher voltage or current stress and the inductors with larger magnetic core volume must be considered.

To resolve this problem, the coupled-inductor is adopted. Here, the two inductors \((L_1\) and \(L_2\)) are made on a common magnetic core, and they have the common magnetic circuit and the same number of turns. Therefore, the difference of the inductance between the two inductors can be ignored. So the asynchronous resonances brought from the difference between the two inductors have not been considered.

The resonances between \(C_1\) (or \(C_2\)) and \(L_1\) (or \(L_2\)) appear in stage 2, 3 and 5. The following analysis is based on the circuit model in Fig.4 and Fig.5, which show the equivalent circuit of the passive snubber in stage 2, 3 and 5. The model of the coupled-inductor is made up of \(L_{k1}, L_{m1}, L_{k2}, L_{m2}\), and \(T_{ideal}\), where \(L_{k1}\) and \(L_{k2}\) are the leakage inductance, \(L_{m1}\) and \(L_{m2}\) are the excitation inductance \((L_{k1}+L_{m1}=L_1, L_{k2}+L_{m2}=L_2)\), and \(T_{ideal}\) is the ideal transformer. The two inductors have the common magnetic circuit and the same number of turns, so the difference of the inductance between them can be ignored, so we can get: \(L_{k1}=L_{k2}\) and \(L_{m1}=L_{m2}\). Here, we define that:

\[
L_{m1}=aL_1, \quad L_{k1}=(1-a)L_1
\]  

(17)

Where, \(0<a<1\).
For Fig. 4, we define the time $t_m$ ($t_0 \leq t_m \leq t_1$), before $t_m$, $U_{C_1}=U_{C_2}$ and $i_{L_1}=i_{L_2}$. We assume that there appears a difference between $U_{C_1}$ and $U_{C_2}$ after $t_m$.

$$U_{C_2} = U_{C_1}(t_m) + \Delta U$$  \hspace{1cm} (18)

Where $\Delta U > 0$.

After $t_m$, we can get the following relationships:

$$\begin{align*}
i_{L_1}(t) &= i_{L_1}(t_m) + \int_{t_m}^{t} \left[ \frac{i t}{L_{k_1}} - \frac{U_{C_1}(t) - U_{T_i}(t)}{L_{k_1}} \right] dt \\
i_{L_2}(t) &= i_{L_2}(t_m) + \int_{t_m}^{t} \left[ \frac{i t}{L_{k_2}} - \frac{U_{C_2}(t) - U_{T_i}(t)}{L_{k_2}} \right] dt \\
i_{L_1} + i_{L_2}(t) &= i_{L_1}(t_m) + i_{L_2}(t_m) + \int_{t_m}^{t} \left[ \frac{U_{C_1}(t)}{L_{m_1}} + \frac{U_{C_2}(t)}{L_{m_2}} \right] dt \\
\end{align*}$$  \hspace{1cm} (19)

From (19) and (20), we can get:

$$U_{T_i}(t) = \frac{a}{2} \left[ U_{C_1}(t) + U_{C_2}(t) \right]$$  \hspace{1cm} (21)

From (18), (19), (21), we can get the following expression:

$$\begin{align*}
i_{i_1}(t) &= i_{i_1}(t_m) + \int_{t_m}^{t} \left[ \frac{1}{2} a \Delta U \right] dt \\
i_{i_2}(t) &= i_{i_2}(t_m) + \int_{t_m}^{t} \left[ \frac{1}{2} a \Delta U \right] dt \\
\end{align*}$$  \hspace{1cm} (22)

From (22), we can see that: after $t_m$, $i_{i_1}<i_{i_2}$, which can help to accelerate the discharging of $C_2$. Furthermore, the following expression can be obtained:

$$\Delta I = i_{L_2}(t) - i_{L_1}(t) = \int_{t_m}^{t} \left[ \frac{1}{2} a \Delta U \right] dt$$  \hspace{1cm} (23)

From (23), we can see that $\Delta I$ will increase as the value of $a$ increases, and the synchronous changing of between $U_{C_1}$ and $U_{C_2}$ can be achieved more easily.

After $t_m$, the expression of $i_{L_1}+i_{L_2}$ can be obtained from (20) and (21):

$$i_{L_1}(t) + i_{L_2}(t) = i_{L_1}(t_m) + i_{L_2}(t_m) + \int_{t_m}^{t} \frac{U_{C_1}(t)}{L_1} + \frac{U_{C_2}(t)}{L_2} dt$$  \hspace{1cm} (24)

We can see from (24) that $i_{L_1}+i_{L_2}$ is independent with $\Delta U$. Therefore, the magnetic core excitation of the coupled-inductor can not be affected by the value $\Delta U$.

The same analysis process can also be suitable in Fig. 5, which hasn’t to be repeated.

### B. Design of the Coupled-Inductor

According to the analysis above, the design scheme of the coupled-inductor is as shown in Fig. 6, where the two inductors are made on the common magnetic core, and they have the same number of turns.

From the theory of coupled-inductor, the basic mathematical model of the coupled-inductor is:

$$\begin{align*}
u_{L_1} &= L_1 \frac{di_{L_1}}{dt} + M \frac{di_{L_2}}{dt} \\
u_{L_2} &= L_2 \frac{di_{L_2}}{dt} + M \frac{di_{L_1}}{dt} \\
\end{align*}$$  \hspace{1cm} (25)

Where $L_{11}=L_{22}$ are the self inductance, and $M$ is the mutual inductance.

The two inductors have the common magnetic circuit, so the following relationship can be obtained approximately:

$$M = L_{11} = L_{22}$$  \hspace{1cm} (26)

If the asynchronous resonances in the snubber could be ignored, we can get that: $u_{L_1}=u_{L_2}$ and $i_{L_1}=i_{L_2}$. Therefore, the following relationship can be obtained approximately:

$$\begin{align*}
u_{L_1} &= L_1 \frac{di_{L_1}}{dt} + 2L_1 \frac{di_{L_1}}{dt} \\
u_{L_2} &= L_2 \frac{di_{L_2}}{dt} + 2L_2 \frac{di_{L_2}}{dt} \\
\end{align*}$$  \hspace{1cm} (27)

From (27), the relationship between the equivalent inductance and the self inductance of the coupled-inductor can be obtained approximately:

$$L_1 = L_2 = 2L_{11} = 2L_{22}$$  \hspace{1cm} (28)

From (27), the following expression can also be calculated:

$$u_{L_1} = L_{11} \frac{di_{L_1} + i_{L_2}}{dt}$$  \hspace{1cm} (29)

From (29), we can see that the coupled-inductor can be equivalent to that of a single-inductor, of which the inductance is $L_{11}$ and the current is $i_{L_1}+i_{L_2}$.

Generally, the following expression can be used when the magnetic core of a single-inductor being designed.

$$AP = A_w A_e = \frac{L_{11} i_{max}^2}{B J K}$$  \hspace{1cm} (30)

Where, $A_w, A_e$ are window area and cross sectional area of the magnetic core, $B$ is the maximum magnetic induction intensity, $J$ is current density and $K$ is the utilization of window area.

Therefore, for the coupled-inductor, $AP$ can be calculated:

$$AP = \frac{L_{11} i_{max}^2}{B J K}$$  \hspace{1cm} (31)
If two single-inductors ($L_1$ and $L_2$) are used in the snubber, the value $AP$ of them can be calculated:

$$
\begin{align*}
AP_{L1} &= \frac{L_1 L_{1\max}^2}{BJK} \\
AP_{L2} &= \frac{L_2 L_{2\max}^2}{BJK}
\end{align*}
$$

(32)

Under ideal conditions, the resonances in the snubber with two single-inductors are synchronous, and we can get: $I_{L1\max} = I_{L2\max} = \frac{I_{C\max}}{2}$, so the expression (33) can be obtained:

$$
AP = AP_{L1} + AP_{L2}
$$

(33)

Under real conditions, the resonances in the snubber with two single-inductors are asynchronous, so the maximum current of $L_1$ or $L_2$ is increasing. However, the maximum current of coupled-inductor has not been changed. Therefore, under real conditions, the volume of the snubber with a coupled-inductor is smaller than that of the snubber with two single-inductors.

IV. EXPERIMENTAL VERIFICATIONS

To verify the theoretical analysis and evaluations mentioned above, a laboratory-made prototype of the converter was built, in which the average current mode control strategy is adopted. The basic circuit parameters and the main utilized components’ type are: $u_i=110V\text{rms} \pm 10\%$, $U_o=100V\text{dc}$, $P_{\text{omax}}=500W$, $L=0.58mH$, $C=1000\mu F$, $L_2=6\mu H$, $n=2$, $S_1$-$S_4$: 24N60C3 (Infineon, $R_{\text{DS max}}=0.16\Omega$, switching frequency is about 37kHz). In the snubber, $C_1=C_2=44nF \pm 10\%$ (two capacitors CBB223K are connected in parallel), and $L_{11}=L_{22}=38\mu H$ (EI28, $L_1=L_2=76\mu H$, the value of $L_{k1}$ or $L_{k2}$ is within 2$\mu H$, and $a>0.97$).

Fig.7 shows the input waveforms of the PFC converter. Table I shows the experimental data of power factor (PF), the efficiency ($\eta_c$) and the efficiency when the two single-inductors are adopted ($\eta_s$) according to the output power ($P_o$) variation. When two single-inductors are adopted, the asynchronous resonances occur in the snubber, so the experiment is only within 300W to protect circuit. We can see that a good PFC effect has been achieved, and the prototype shows good performance in conversion efficiency. Fig.8 shows the experimental waveforms of the switches $S_1$ and $S_2$. It can be seen that $S_1$ turns off with zero voltage, and $S_2$ turns on and off with zero voltage. The switching states of $S_3$ and $S_4$ are the same as those of $S_1$ and $S_2$, so the related experimental results are not presented here.

![Fig.7 Input voltage and current](image)

**TABLE I**

<table>
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<th>$P_o/W$</th>
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<th>400</th>
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</tbody>
</table>

To verify the above analysis, two single-inductors with the same structure have been made (EI25, inductance $L_1=L_2=76\mu H$). Fig.9 and 10 are the experimental results (the efficiency data is shown in Table I). To protect the circuit, the results of Fig.9 and 10 are obtained under a relative low bus voltage.

Fig.9 shows the voltage waveforms of $C_1$ and $C_2$, when the two single-inductors are adopted. We can see that regardless of $C_1=C_2$ or $C_1 \neq C_2$, the voltage between $C_1$ and $C_2$ is unbalance, which is equal to say that the resonances between $C_1$ (or $C_2$) and $L_1$ (or $L_2$) are asynchronous. Furthermore, the conclusion can be obtained from Fig.9: the asynchronous resonances in the snubber become more serious.
as the difference of between $C_1$ and $C_2$ increases.

Fig. 10 shows the voltage waveforms of $C_1$ and $C_2$, when the coupled-inductor is adopted. We can see that regardless of $C_1=C_2$ or $C_1\neq C_2$, the voltage between $C_1$ and $C_2$ is balance, which is equal to say that the resonances between $C_1$ (or $C_2$) and $L_1$ (or $L_2$) are synchronous after the coupled-inductor being adopted. Fig.9 and 10 prove the analysis in section III A. Furthermore, comparing the experimental results in Fig.9 (c) with that in Fig.10 (c), we can see that the charging and discharging time of capacitors are approximately equal when two single-inductors and a coupled-inductor being adopted respectively, from which the analysis about the self inductance of the coupled-inductor in section III B is verified.

**Fig.9** Voltage waveforms of with two single-inductors

(a) Voltage of $C_1$ and $C_2$

(b) Voltage of $C_1$ and $C_2$ when $C_1$ is connected in parallel with an additional capacitor CBB472J (4.7nF±5%)

(c) The expanding waveforms of Fig.9 (b) at $t_{EX1}$

**Fig.10** Voltage waveforms with a coupled-inductor

(a) Voltage of $C_1$ and $C_2$

(b) Voltage of $C_1$ and $C_2$ when $C_1$ is connected in parallel with an additional capacitor CBB472J (4.7nF±5%)

(c) The expanding waveforms of Fig.10 (b) at $t_{EX2}$

**Fig.9** Voltage waveforms of with two single-inductors

**V. CONCLUSIONS**

In this paper, an improved passive snubber with a coupled-inductor is investigated based on a single-phase single-stage full-bridge boost PFC converter. The theoretical analysis and experimental results show: 1) The adoption of this snubber can realize both the suppression of the voltage spike across the primary side of the power transformer and the energy transfer from the snubber itself to the load, and 2) A coupled-inductor is used in the improved snubber to replace the two single-inductors, which can help to achieve the synchronous resonances in the snubber and avoid the unbalance of the voltage and current among each device of the snubber.

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