

# Starting strategies of three-phase single-stage PFC converter based on isolated full-bridge boost topology

**Abstract.** Starting strategies were investigated for a three-phase single-stage power factor correction (PFC) converter. Starting process and mechanism of input over current was analyzed in detail. A lossy method was proposed and designed in which a resistor was connected in series with the filter capacitor to increase effective value of output voltage. Based on them, the boost inductors were replaced by central-tapped inductors with flyback windings, and a lossless starting strategy was proposed. Experimental results prove the validity and feasibility of the proposed methods.

**Streszczenie.** Przeanalizowano strategię startu trójfazowego przekształtnika do korekcji współczynnika mocy PFC. Zaproponowano metodę w której rezystor połączony jest szeregowo z pojemnością filtru w celu zwiększenia napięcia wyjściowego. Cewka została zastąpiona cewką z zaczepami umożliwiającą zmianę uzwojeń. Zaproponowano bezstratną strategię startu. (Strategie startu trójfazowego przekształtnika PFC bazującego na pełnomostkowej topologii typu boost)

**Keywords:** power factor correction (PFC), single-stage, starting, three-phase.

**Słowa kluczowe:** korekcja współczynnika mocy, przekształtnik.

## Introduction

Single-stage power factor correction (PFC) and power conversion technique are important researching orientation in power electronics field [1-3]. The isolated full-bridge boost topology is attractive in applications such as isolated DC/DC converter, single-phase and three-phase single-stage PFC, because: (1) it can realize electrical isolation between input and output sides and output voltage regulation, (2) achieve soft-switching for all switches, and (3) avoid short-through problem of the bridge legs switches [4, 5]. While, the topology itself has the following drawbacks: (1) due to the existing of the transformer leakage inductance, there is a voltage spike across each bridge leg switch, (2) an additional starting-up circuit is required to establish an initial output voltage [6, 7].

To solve the problems above, a number of techniques have been proposed. In an effort to suppress the voltage spike across the bridge leg switches, a method based on active clamp technique is introduced in [8-11], and a passive snubber is proposed in [12, 13]. The voltage spike is suppressed efficiently after adopting either of the two methods. For the starting problem, a RCD circuit is connected in parallel with the bridge leg of DC/DC converter in [14]. However, the method itself can result in low efficiency and long starting time. In [7, 15, 16], a flyback winding is coupled with boost inductor to realize starting-up of the DC/DC converter. The method can also suitable for single-phase PFC circuit, while, there are three boost inductors in the input side of typical three-phase PFC circuit, and the current of them flows bi-directionally, which are different to that in single-phase PFC circuit, so the same method can not be used in the typical three-phase PFC circuit directly. A starting method based on flyback mode is presented for three-phase PFC in [17]. However, three low power RCD circuits must be adopted to absorb the leakage energy during starting process, which increases the complexity of the PFC converter.

In this paper, aiming at a three-phase single-stage PFC converter based on isolated full-bridge boost topology, two starting strategies are proposed and investigated, and the validity and feasibility of the proposed methods is proved in experiment.

## Working principle and starting process

The PFC converter with active clamping circuit is shown in Fig.1, where the active clamping circuit that made up of  $S_C$  and  $C_C$  is to suppress the voltage spike. The driving

signal of each switch is shown in Fig.2, where duty cycle of switches  $S_1$ - $S_4$  is fixed at 50%, the switching state of  $S_1$ ,  $S_2$  is contrary to that of  $S_3$ ,  $S_4$  respectively, and the switching phase between  $S_1$  or  $S_3$  and  $S_2$  or  $S_4$  can be controlled. The switch  $S_C$  opens when the bridge diagonal leg switches ( $S_1$ ,  $S_4$  or  $S_2$ ,  $S_3$ ) are turning on, and the dead time  $t_{d1}$ ,  $t_{d2}$  are used to avoid that  $S_C$  opens when the bridge leg switches are shorted ( $S_1$ ,  $S_2$  or  $S_3$ ,  $S_4$  are turning on).

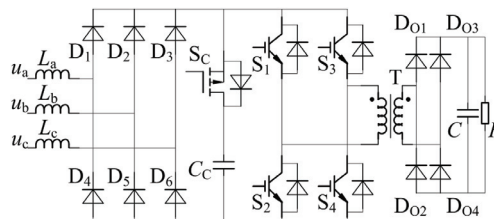


Fig.1 The PFC converter with active clamping circuit

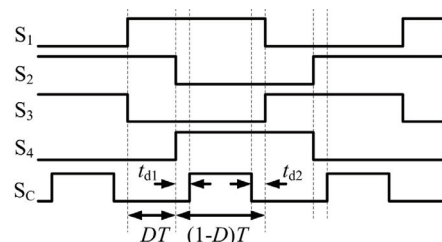


Fig.2 Driving signal of each switch

The converter operates in discontinuous current mode (DCM). When the bridge leg switches are shorted, the boost inductors  $L_a$ ,  $L_b$ ,  $L_c$  are charged by three-phase input source, and their current  $i_{La}$ ,  $i_{Lb}$ ,  $i_{Lc}$  increases from zero almost linearly. When the bridge diagonal leg switches turn on, the output current is provided by both three-phase input source and boost inductors, and  $i_{La}$ ,  $i_{Lb}$ ,  $i_{Lc}$  decreases. It can be seen that the process above is repeated periodically, the discontinuous current  $i_{La}$ ,  $i_{Lb}$ ,  $i_{Lc}$  follow envelopes which is proportional to the respective phase voltage.

When the converter starting, the voltage of output filter capacitor  $C$  (the output voltage) increases from zero, so the converter would operate in maximum duty cycle without any soft-starting method. So the following analysis of the converter's starting process is under the condition of constant duty cycle.

The converter starts from zero output. After several charging periods of boost inductors, the output voltage can be increased to the steady value  $U_o$ , and the starting process is over. So during the  $m$ -th period, when the bridge leg switches are shorted, the current increment of boost inductors can be calculated:

$$(1) \quad \begin{cases} I_{L_{am}1+} = u_{an}DT/L \\ I_{L_{bm}1+} = u_{bn}DT/L \\ I_{L_{cm}1+} = u_{cn}DT/L \end{cases}$$

where,  $L_a=L_b=L_c=L$ ,  $D$  and  $T$  are the duty cycle and the charging period of boost inductors respectively, as shown in Fig.2, and  $u_{an}$ ,  $u_{bn}$ ,  $u_{cn}$  are the phase voltage of three phase input source, which are defined as:

$$(2) \quad \begin{cases} u_{an} = U \sin \omega t \\ u_{bn} = U \sin(\omega t - 2\pi/3) \\ u_{cn} = U \sin(\omega t + 2\pi/3) \end{cases}$$

When the bridge diagonal leg switches are turning on, we will get:

$$(3) \quad \begin{cases} u_{an} - L \frac{di_{L_{am}}}{dt} - nU_{om} + L \frac{di_{L_{bm}}}{dt} = u_{bn} \\ u_{cn} - L \frac{di_{L_{cm}}}{dt} - nU_{om} + L \frac{di_{L_{bm}}}{dt} = u_{bn} \\ u_{an} + u_{bn} + u_{cn} = 0 \\ i_{L_{am}} + i_{L_{bm}} + i_{L_{cm}} = 0 \end{cases}$$

where  $U_{om}$  is the voltage of the output filter capacitor during the  $m$ -th charging period (The varying of  $U_{om}$  is negligible here), and  $n$  is the turn ratio of transformer T.

From Eq. (3), the current increment can be calculated when the bridge diagonal leg switches are turning on:

$$(4) \quad \begin{cases} i_{L_{am}}(t) = \frac{DT}{L}u_{an} - \frac{nU_{om} - 3u_{an}}{3L}(t - DT) \\ i_{L_{bm}}(t) = \frac{DT}{L}u_{bn} + \frac{2nU_{om} + 3u_{bn}}{3L}(t - DT) \\ i_{L_{cm}}(t) = \frac{DT}{L}u_{cn} - \frac{nU_{om} - 3u_{cn}}{3L}(t - DT) \end{cases}$$

In Eq. (4), the former is current increment of boost inductors when the bridge leg switches are shorted, the direction of which is the same as that of the phase voltage itself. The latter is the current expression of boost inductors when the bridge diagonal leg switches are turning on.

To simplify the analysis, the following analysis is during the time  $0 \leq \omega t \leq \pi/6$ . From Eq. (4), we can get the current increment of phase B (the maximum one) when the bridge diagonal leg switches are turning on:

$$(5) \quad I_{L_{bm}2+} = \frac{2nU_{om} + 3u_{bn}}{3L}(1-D)T$$

During the time  $0 \leq \omega t \leq \pi/6$ , we know  $u_{bn} \leq 0$ , while we can see that  $i_{L_{bm}1+} < 0$ . So according to  $i_{L_{bm}2+}$ , the starting process can be divided into three phases as the output voltage increases, as shown in Fig.3.

From Fig.3, we can see that: when the converter operating in the starting phase 1 or phase 2, the current of boost inductors increases in each charging period, and after several periods, there will be serious over current in boost

inductors. The maximum current appears at the intermediate time of phase 2 and phase 3, which time we assume is the  $k$ -th charging period. So the maximum current can be given by:

$$(6) \quad I_{L_{bk}+} = \frac{kDT}{L}u_{bn} + \sum_{n=1}^k \frac{2nU_{om} + 3u_{bn}}{3L}(1-D)T$$

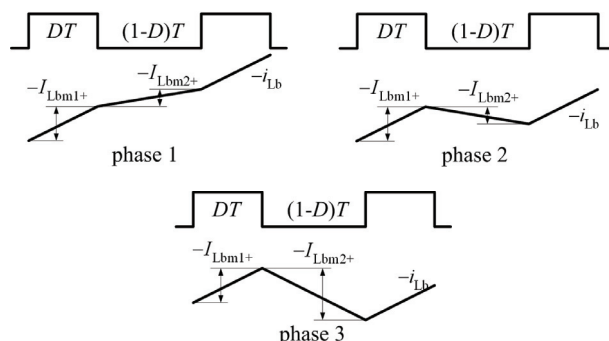


Fig.3 Current varying of each phase

### Lossy starting strategy

From the analysis above, we know that the over current of boost inductors when the converter starting must be suppressed efficiently. However, when the converter operates in the starting phase 1, the current of boost inductors increases not only in  $DT$  but also in  $(1-D)T$  during the whole period  $T$ . So the additional soft-starting method can not be used here.

According to the working principle of the converter, a lossy starting strategy is proposed. The circuit of output side is shown in Fig.4 (the circuit of another side is the same as that in Fig.1), A resistor  $R_r$  ( $R_r=R_1+R_2$ ) is connected in series with capacitor  $C$  to increase the effective output voltage when boost inductors discharging. When the output voltage increases to some a certain value,  $R_1$ ,  $R_2$  will be shorted respectively to realize the steady transition of the converter from starting state to normal state.

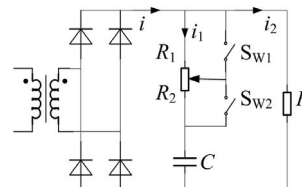


Fig.4 Lossy starting circuit

The  $m$ -th charging period is also considered here. When the bridge leg switches are shorted, the current increment expression of boost inductors is the same as that of Eq. (1), however when the bridge diagonal leg switches are turning on, the current increment of phase B is given by:

$$(7) \quad I_{L_{bm}2+} = \frac{2nU_{om} + 3u_{bn}}{3L}(1-D)T$$

where  $U_{om}$  is output voltage during the  $m$ -th period, and its expression can be given by:

$$(8) \quad U_{om} = Ri_2 = (R_1 + R_2)i_1 + U_{om}$$

$$(9) \quad i_1 + i_2 = i$$

Compare Eq. (7) with Eq. (5), we can see that  $U_{orm} > U_{om}$ . So if the value of  $R_r$  is suitable, the starting phase 1 of the converter could be eliminated, the starting phase 2 could be shorten, and the converter can start normally.

### Lossless starting strategy

Based on the lossy starting strategy, a lossless starting strategy based on flyback mode for the converter is proposed to increase efficiency of the converter when starting. The circuit is shown in Fig.5, the boost inductors in Fig.1 are replaced by the central-tapped inductors with flyback windings, where  $L_{a1}=L_{a2}=L_{b1}=L_{b2}=L_{c1}=L_{c2}=L$ ,  $n_f$  is the turn ratio of the boost inductors. The converter operates in boost mode when working in steady state, while it operates in flyback mode when starting. The driving signal of each switch in flyback mode is shown in Fig.6.

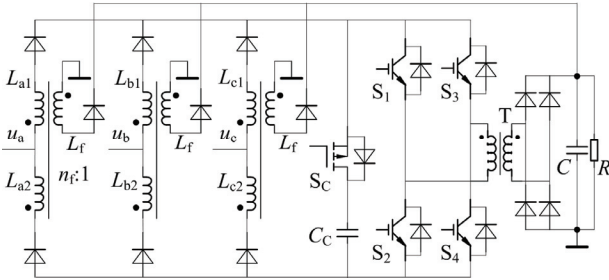


Fig.5 Lossless starting circuit

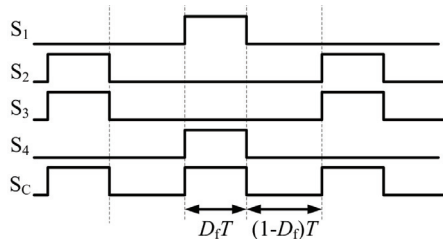


Fig.6 Driving signal of each switch in flyback mode

During one charging period, there are two stages when the converter starting. The current waveforms of boost inductors during one period are shown in Fig.7. The following analysis is during the time  $0 \leq \omega t \leq \pi/6$ .

Stage 1 ( $t_0-t_1$ ): The bridge diagonal-leg switches are turning on (assume that  $S_2$  and  $S_3$  are turning on), the equivalent circuit is shown in Fig.8. Capacitor C is charged by three-phase input source, and  $i_{La1}$ ,  $i_{Lb2}$ ,  $i_{Lc1}$  increases. The following relationships can be obtained:

$$(10) \begin{cases} u_{an} - L \frac{di_{La}}{dt} - nU_{ofm} + L \frac{di_{Lb}}{dt} = u_{bn} \\ u_{cn} - L \frac{di_{Lc}}{dt} - nU_{ofm} + L \frac{di_{Lb}}{dt} = u_{bn} \\ u_{an} + u_{bn} + u_{cn} = 0 \\ i_{La1} + i_{Lb2} + i_{Lc1} = 0 \end{cases}$$

where,  $U_{ofm}$  is output voltage of this period. From Eq. (10), the current expressions of boost inductors can be calculated as:

$$(11) \begin{cases} i_{La1}(t) = \frac{3u_{an} - nU_{ofm}}{3L} (t - t_{f0}) \\ i_{Lb2}(t) = \frac{3u_{bn} + 2nU_{ofm}}{3L} (t - t_{f0}) \\ i_{Lc1}(t) = \frac{3u_{cn} - nU_{ofm}}{3L} (t - t_{f0}) \end{cases}$$

The output voltage is increasing in starting process. From Eq. (11), we can see that: when  $nU_{ofm} > 3u_{an}$ , the current of phase A will be fixed at zero, and then the following relationships can be obtained:

$$(12) \begin{cases} u_{cn} - L \frac{di_{Lc}}{dt} - nU_{ofm} + L \frac{di_{Lb}}{dt} = u_{bn} \\ i_{Lb2} + i_{Lc1} = 0 \end{cases}$$

From Eq. (12), the current expressions of boost inductors can be calculated as:

$$(13) \begin{cases} i_{La1}(t) = 0 \\ i_{Lb2}(t) = -i_{Lc1}(t) = \frac{u_{bn} + nU_{ofm} - u_{cn}}{2L} (t - t_{f0}) \end{cases}$$

Stage 2 ( $t_1-T$ ): All the switches are turning off, the equivalent circuit is shown in Fig.8. The current of boost inductors became zero, and the energy of boost inductors is transferred to output side through flyback windings (the leakage energy of boost inductors can be absorbed by capacitor  $C_C$ ). The current expressions of flyback windings are given in Eq. (14) and Eq. (15) respectively, when  $U_{ofm} < 3u_{an}$  and  $U_{ofm} > 3u_{an}$ .

$$(14) \begin{cases} i_{af}(t) = \frac{3u_{an} - nU_{ofm}}{3L} n_f D_f T - \frac{U_{ofm}}{L_f} (t - t_{f1}) \\ i_{bf}(t) = -\frac{3u_{bn} + 2nU_{ofm}}{3L} n_f D_f T - \frac{U_{ofm}}{L_f} (t - t_{f1}) \\ i_{cf}(t) = \frac{3u_{cn} - nU_{ofm}}{3L} n_f D_f T - \frac{U_{ofm}}{L_f} (t - t_{f1}) \end{cases}$$

$$(15) \begin{cases} i_{af}(t) = 0 \\ i_{bf}(t) = i_{cf}(t) = \frac{u_{cn} - nU_{ofm} - u_{bn}}{2L} n_f D_f T - \frac{U_{ofm}}{L_f} (t - t_{f1}) \end{cases}$$

where,  $D_f = (t_1 - t_0)/T$  is the duty cycle of the converter in flyback mode.

From the analysis above, we can see that: when the converter is starting, energy can be transferred to the output side through flyback windings, and the output voltage can be established, so the converter can achieve starting-up normally.

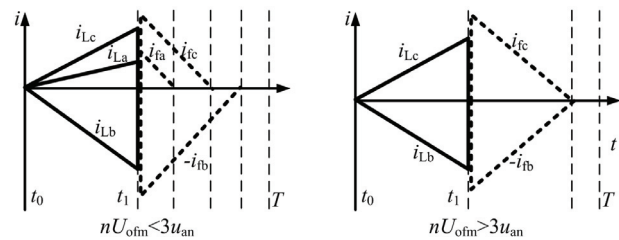


Fig.7 Current of boost inductors when the converter starting

From the analysis of operational principles, we know that the flyback windings coupled with boost inductors are used to achieve starting-up of the converter, and they can not be used in the steady state. In the steady state, the bridge voltage is  $nU_o$  when the bridge diagonal-leg switches turn on, while if the flyback windings are working, the bridge voltage would be  $2n_f U_o$ . So to make sure the flyback windings can not be working in the steady state, the following relationship is obtained:

$$(16) \quad nU_o \leq 2n_f U_o$$

It's equal to:

$$(17) \quad n \leq 2n_f$$

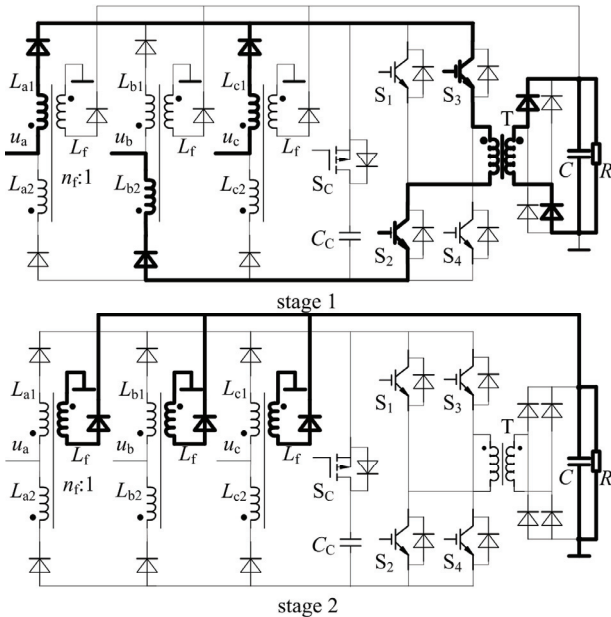


Fig. 8 Equivalent circuit of the converter when starting

Under the same output voltage, the bridge voltage of the converter operating in flyback mode is higher than that in boost mode, which will result in the over-voltage of each switch. If the over-voltage here is limited within  $20\%nU_o$ , the following relationship is obtained:

$$(18) \quad 2n_f \leq 1.2n$$

So, we can get the design principle of  $n_f$  from Eq. (17) and Eq. (18):

$$(19) \quad 0.5n \leq n_f \leq 0.6n$$

### Experiments

A 3kW prototype is fabricated to verify the analysis above, where  $L=76\mu\text{H}$ ,  $n_f=1.143$  (16:16:14),  $C_c=4\mu\text{F}$ ,  $C=1000\mu\text{F}$ ,  $R=30\Omega$  (full load),  $n=2$ , the switching frequency of  $S_1$ - $S_4$  is 20kHz. Fig.9-13 shows the experimental results.

Fig.9 shows the input waveforms of the converter in steady state. We can see that the peak of input current is sinusoidal which follows the input voltage.

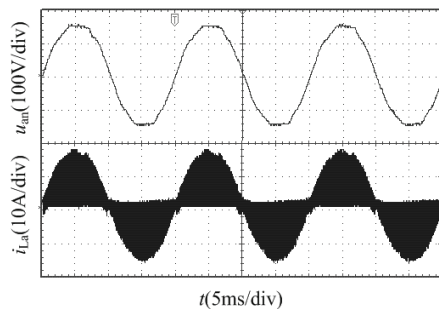


Fig.9 Input voltage and current in steady state

Fig.10 shows the input current waveform when the converter starts under the condition that  $D=40\%$ . To protect the circuit, this experiment is under the condition that  $u_{bn}$ ,  $u_{cn}$

$u_{bn}$ ,  $u_{cn}$  is decreased to 40Vrms and the capacitor  $C$  is decreased to  $470\mu\text{F}$ . We can see the serious over current when the converter is starting.

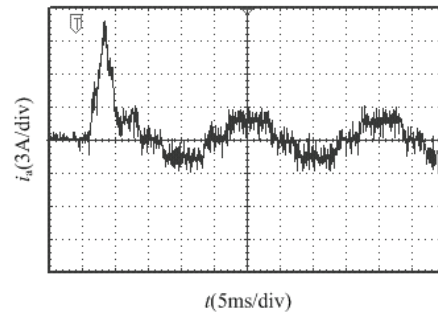


Fig.10 Input current when converter starting in  $D=40\%$

Fig.11 and Fig.12 show the experimental results of lossy starting, where  $t_{w1}$  and  $t_{w2}$  are the times that  $R_1$  and  $R_2$  are shorted respectively. We can see that after 1-2 line cycles (20-40ms), the converter begin to operate in steady state, the over current in starting state is suppressed efficiently, and it achieves starting-up normally and steady transition from starting state to normal state for the converter.

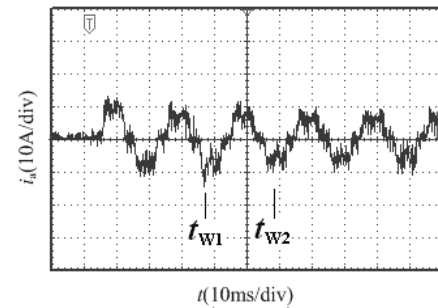


Fig.11 Input current when lossy starting strategy is adopted

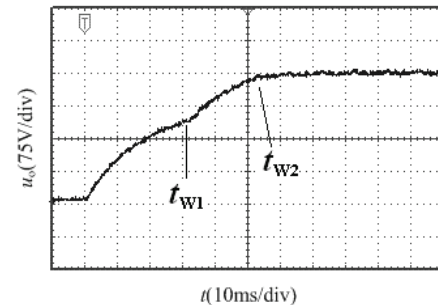


Fig.12 Output voltage when lossy starting strategy is adopted

Fig.13 shows the experimental results of lossless starting. We can see that: 1) the converter operates in flyback mode in the starting process, 2) after about three line cycles (60ms), the output voltage is established, and the converter is transferred into boost mode, 3) no over-current appears during the whole starting process.

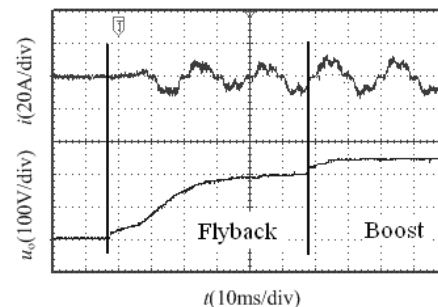


Fig.13 Experimental results of lossless starting

## Conclusions

Starting strategies of a three-phase single-stage PFC converter is investigated in this paper.

(1) Starting process under the condition of constant duty cycle is analyzed in detail, and the mechanism of over current during starting process is obtained.

(2) A lossy starting strategy is proposed in which a resistor is connected in series with the output filter capacitor to increase the effective value of output voltage. Experimental results show that it achieves starting-up without over current and steady transition from starting state to normal state for the converter.

(3) A lossless starting strategy is proposed in which the converter operates in flyback mode when starting, and the flyback windings are used to establish the output voltage. Experimental results show that the converter realize starting-up normally.

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