A Family of Single-Phase Hybrid Step-Down PFC Converters

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***Abstract*—The conventional Boost PFC usually suffers from high output voltage and low efficiency at low input condition. Recently, the Buck PFC has attracted a lot of research interests for its low output voltage and high efficiency at low input condition. However, the conventional Buck PFC converter usually has low power factor (PF) and poor harmonic performance due to the inherent dead angle of the input current, especially at low input condition. How to achieve high power factor, low output voltage and high efficiency at the same time is still a big challenge for the PFC converters. This paper proposes a family of hybrid PFC converter topologies combine the advantages of Boost PFC and Buck PFC converters, which feature low output voltage and continuous input current (high PF). The derivation methodology is presented. The experimental results verify the advantages of the proposed topologies.**

I. INTRODUCTION

The ever-present trend of size reduction of power supplies requires even higher efficiency and power density. For power supply above certain power rating, a front-end PFC converter is necessary to meet the harmonic current and power factor (PF) requirement, such as IEC61000-3-2 and Energy Star specifications [1]. At present, the boost converter is the most popular PFC topology due to its simplicity and good performance. And the output voltage should be higher than the maximum input peak voltage. It is preferred that the AC input voltage range of a power supply should be wide to cover the applications in different countries and area. For typical universal input, the AC input voltage ranges from 90Vrms to 264Vrms considering the voltage variation. However, the input voltage will be even wider for some applications like LED lighting. The input may connect to 277Vrms grid or 480Vrms grid. Therefore, the output voltage will be too high for Boost PFC converter. Furthermore, a boost PFC converter exhibits 1%-3% lower efficiency at 100Vac line compared to that at 230Vac line [2].

Recently, using the buck converter as a front end PFC converter has been introduced in [2-8]. The Buck PFC converter has higher low line efficiency and lower EMI noise compared with the conventional Boost PFC converter [2], [9]. Due to the inherent dead-time in the input current when the input is lower than the output, the Buck PFC usually has limited PF and high current distortion, which may not meet the current harmonic requirement, especially for lighting applications. A lot of researches have been conducted to analyze and improve the PF of the Buck PFC converter by compensating the current during the dead time [4-6]. But there is still not a systematical derivation methodology to give a thorough insight for these kinds of topologies.

In order to solve the issues mentioned above, this paper proposed a family of single phase step-down converter with high power factor. The objective is to combine the advantages of conventional Boost PFC and Buck PFC using hybrid method. And the derivation methodology is discussed. Finally, the experimental results from a proposed topology with universal AC input and 85V output are presented.

II. HYBRID STEP-DWON PFC CONVERTERS

The conventional Buck PFC converter and its steady state operation waveforms are shown in Fig. 1. Compared with the conventional Boost PFC, the Buck PFC has some attractive features, such as low output voltage, low common mode noise, small inductor size, inherent inrush current limitation and high efficiency at low input condition. However, the PF and THD performance are poor due to the discontinuous input current. If we can compensate the input current for a Buck PFC when its input voltage is below its output voltage, the PF and THD will be similar to a Boost PFC while keeping all the other desired features. In order to achieve this, a step-up converter should be integrated in a conventional Buck PFC to compensate the input current during the dead time, which is referred as a hybrid method in this paper. The step-up converter can be a Boost converter or a Buck-Boost converter (also Flyback as its isolated version).

Generally, there are two ways to integrate a step-down converter and a step-up converter, i.e. parallel connection and cascade connection.

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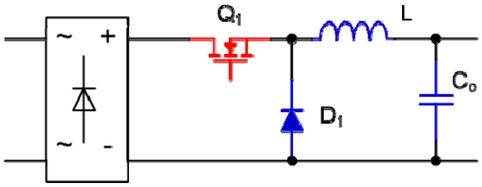
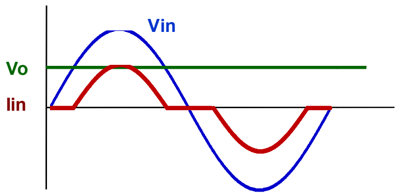


(a)



(b)

Fig. 1 Conventional Buck PFC and its steady state waveforms

A. Cascade Connection

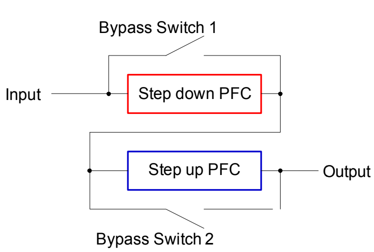
The circuit diagram of a hybrid PFC with cascade connection is shown in Fig. 2(a). And the circuit in Fig. 2(b) is an example of that, which is a kind of conventional four-switch Buck-Boost converter. When the input is lower than the output voltage, Q1 is always on and the circuit operates as a Boost converter. When the input is higher than the output voltage, Q2 is off and the circuit operates as a Buck Converter. However, the circuit has large device counts, high conduction loss and needs a high-side (HS) gate driver, which is not preferred in practical application.

B. Parallel Connection

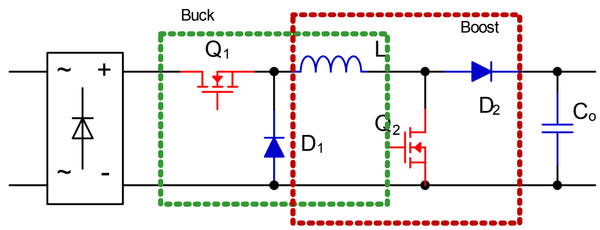
The circuit diagram of a hybrid PFC with parallel connection is shown in Fig. 3. Since the Boost converter does not have input to output disconnection capability, so it cannot be adopted for parallel connection. The Buck-Boost converter can be used as step-up converter since it only has one inductor. As shown in Fig. 4, the Buck converter and Buck-Boost converter has very similar input structure (shown in green dash box) and output structure (shown in red dash box), they can share part of the circuits during the integration. Based on the shared components, there are three ways to integrate these two converters to derive a hybrid PFC converter.

1) Share the input block

Fig. 5 shows the hybrid PFC converter based on Buck converter and Buck-Boost converter by sharing the input block (switch and input rectifier bridge).



(a) Circuit diagram



(b) Four-switch Buck-Boost converter

Fig. 2 Hybrid PFC with cascade connection

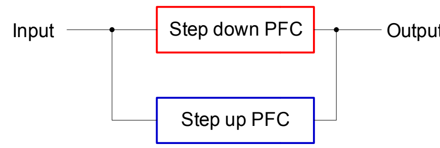
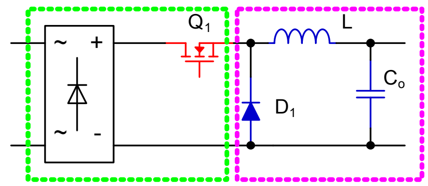
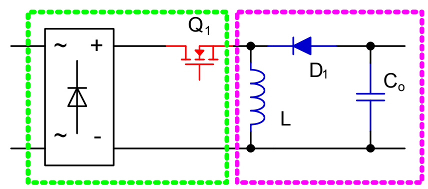


Fig. 3 Circuit diagram for hybrid PFC with parallel connection

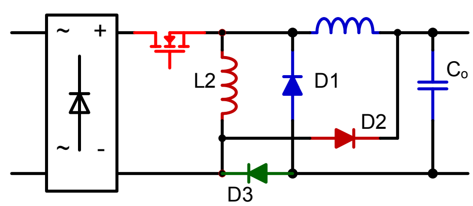


(a) Buck converter

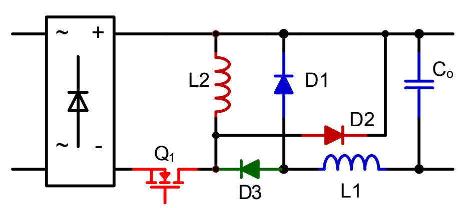


(b) Buck-Boost converter

Fig. 4 Similarity of between Buck and Buck-Boost converters



(a)



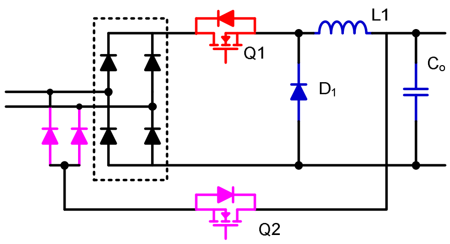
(b)

Fig. 5 Hybrid PFC with parallel connection – share the input block

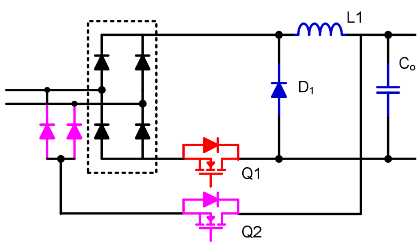
In these two topologies, only one active switch is required. But they need two inductors, and the Buck converter and Buck-Boost converter works simultaneously. So, the power loss is high and the circuit is bulky. Also, an extra diode D3 is required to block the output capacitor discharge when D2 is on. So, they are not preferred in applications need high power density.

2) Share the output block

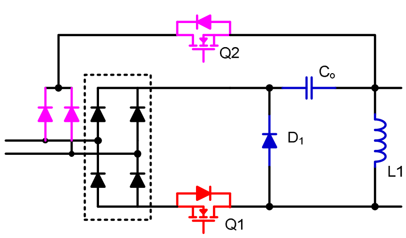
Fig. 6 shows the hybrid PFC converter by sharing the output block (inductor and diode). Topology 1 to topology 4 is derived based on Buck converter and Buck-Boost converter. Since the Flyback converter is an isolated version of the Buck-Boost converter, it can also be integrated with a Buck PFC using coupled-inductor method. Therefore, topology 5 to topology 8 is the hybrid PFC converter based on Buck converter and Flyback converter.



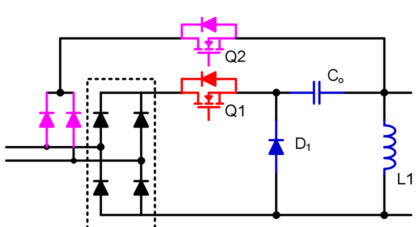
(a) Topology 1



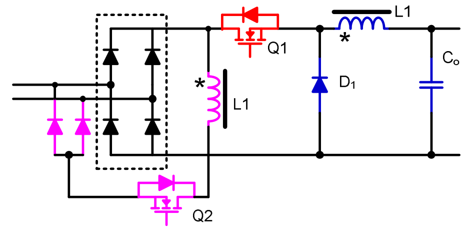
(b) Topology 2



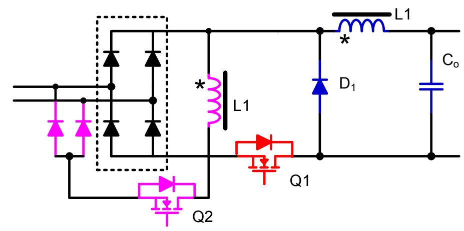
(c) Topology 3



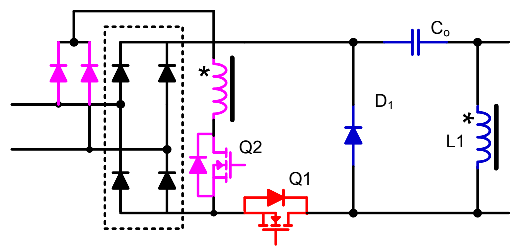
(d) Topology 4



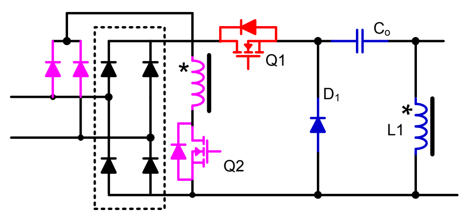
(e) Topology 5



(f) Topology 6



(g) Topology 7



(h) Topology 8

Fig. 6 Hybrid PFC with parallel connection – share the output block

Among these topologies, topology 2 and topology 7 were already proposed in [5] and [6]. All the topologies except topology 7 need high-side gate driver. And for topology 2, topology 4, topology 6, and topology 8, the output terminal is floating (not connected to any line input), which are not preferred for EMI noise.

These topologies need only one inductor, which is attractive for size reduction. However, the differential mode (DM) filter must be located in the AC side, which may increase the size of the EMI filter. Furthermore, the switching frequency current also flows through the input rectifier bridge, which may increase the conduction loss.

3) Share the input & output block

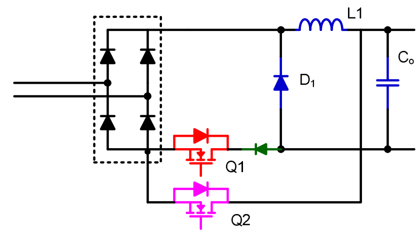
As a further improvement, the hybrid PFC converters by sharing the input block and output block are shown in Fig. 7. For proper operation, the switch Q1 should be a unidirectional switch, a Schottky diode in series with a MOSFET can be used. For topology 9 and topology 10, the DM filter can be located in the DC side, which can reduce the size a lot. Also, the conduction loss of the input bridge is also reduced.

A summary of the derived hybrid step-down PFC converter based on Buck converter and Buck-Boost converter is shown in Table 1. From Table 1, the topology 9 and 10 do not need HS gate driver, and the EMI filter can be located in the DC side, which is attractive for practical application.

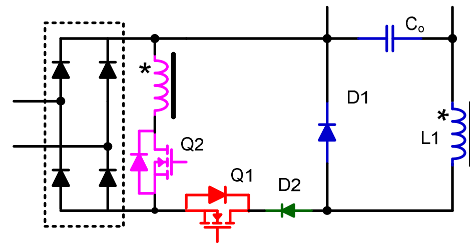
III. PROPOSED CONTROL SCHEME AND EXPERIMENTAL RESULTS

For the hybrid PFC converter, the converter operates as a Buck-Boost converter when the input is below the output voltage, and the converter operates in Buck mode when the input is above the output voltage. A smooth transition between these two modes is very important. In this paper, a new control scheme for the proposed hybrid PFC converter is shown in Fig. 8, topology 10 is used as an example for its better performance. Two current references are used to control peak current of the switches during Buck-Boost mode operation and Buck mode operation, and a smooth transition between two modes can be achieved with proper design, which is not affected by the variation of the input voltage. The theoretical current waveform is also shown in Fig. 9.

A 100W hybrid PFC prototype was built with universal input (90V~264Vrms) and 85Vdc output. The measured current waveform at AC 90Vrms input is shown in Fig. 10. The PF is around 0.99 and the THD is around 17%, which can be further improved with new control scheme. The measured harmonics are shown in Fig. 11. It can pass Class C or Class D requirement even at worst case.



(a) Topology 9



(b) Topology 10

Fig. 7 Hybrid PFC with parallel connection – share the input & output block

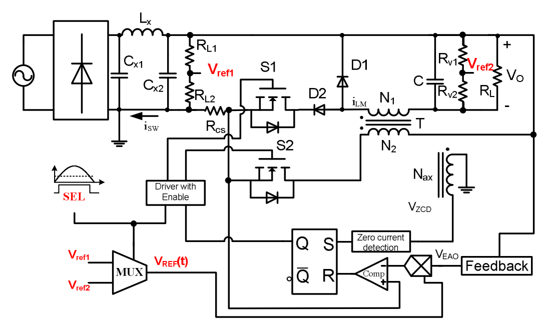


Fig. 8 Proposed control scheme

TABLE I. COMPARISON OF HYBRID PFC CONVERTER WITH PARALLEL CONNECTION BY SHARING THE OUTPUT BLOCK

	HS Driver	Step-up operation	EMI filter	Extra Components	Output Floating?
Topology 1	YES	Q1:On; Q2: PWM	AC side	2 diodes, 1 switch	NO
Topology 2	YES	Q1: Off, Q2: PWM	AC side	2 diodes, 1 switch	YES
Topology 3	YES	Q1: Off, Q2: PWM	AC side	2 diodes, 1 switch	NO
Topology 4	YES	Q1: On, Q2: PWM	AC side	2 diodes, 1 switch	YES
Topology 5	YES	Q1: Off, Q2: PWM	AC side	2 diodes, 1 switch	NO
Topology 6	YES	Q1: Off, Q2: PWM	AC side	2 diodes, 1 switch	YES
Topology 7	**NO**	Q1: Off, Q2: PWM	AC side	2 diodes, 1 switch	NO
Topology 8	YES	Q1: Off, Q2: PWM	AC side	2 diodes, 1 switch	YES
Topology 9	**NO**	Q1: Off, Q2: PWM	**DC side**	1 diodes, 1 switch	YES
Topology 10	**NO**	Q1: Off, Q2: PWM	**DC side**	1 diodes, 1 switch	NO

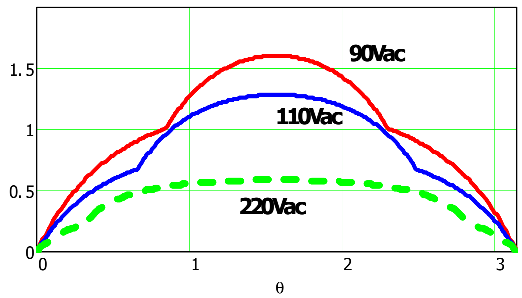


Fig. 9 Theoretical current waveform with proposed control scheme

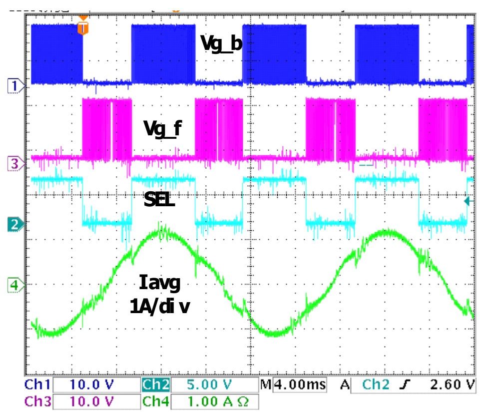


Fig. 10 Waveforms @Vin=90V (Vg_b (Vgs for Q1), Vg_f (Vgs for S2), SEL (mode selection), Iavg (average input current))

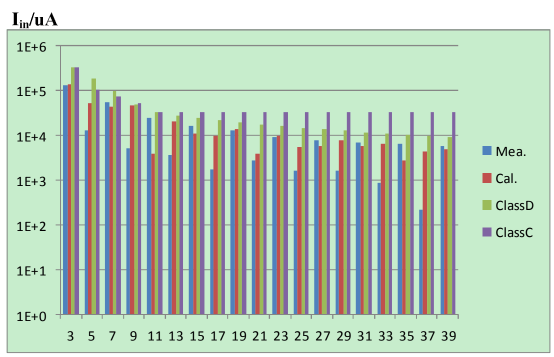


Fig. 11 Current harmonics @Vin=90V

IV. CONCLUSIONS

As a summary, this paper presents a family of hybrid PFC converter based on Buck converter and Buck-Boost (or Flyback) converter. The proposed topologies features low output voltage, high power factor and high efficiency, which is quite attractive for application with wide AC input range or high AC input. Detailed topology derivation method and design considerations are presented in the paper. Finally, a 100W prototype with universal AC input was built to verify the advantages of the proposed method.

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