6개의 2차측 스위치를 갖는 3상 1단 AC-DC 컨버터

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Three-phase Single-stage AC-DC Converter with 6-switch secondary

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ABSTRACT

This paper introduces a three-phase single-stage AC-DC converter with three half-bridge legs on the secondary side. It combines the current-fed interleaved totem pole and three half-bridge legs. The proposed topology effectively reduces the number of switches on the secondary side by half, reduces the secondary board volume by 70% and the total switch cost by 35%. This topology suits EV chargers, Energy Storage Systems, and PV Solar applications. Furthermore, the proposed topology can almost achieve ZVS turn-on over a wide voltage range from 460V to 800V. An 11kW prototype is built to verify the proposed topology.

1. Introduction

The EV chargers, ESS, and PV Solar's converter configuration traditionally involve a power factor correction (PFC) AC-DC converter and an isolated DC-DC converter, connected through an electrolytic capacitor bank [1-2]. However, this arrangement presents challenges, especially for compact applications, as the bulky capacitors can impact the lifespan, efficiency, and overall size of the converter. To address these challenges, researchers have turned their focus toward single-stage converters. These converters combine the functions of both the PFC AC-DC and DC-DC converters into a single-stage, with the overarching goal of enhancing efficiency, reducing product cost, and improving the converter's reliability [3-4].

This paper presents a three-phase single-stage AC-DC converter, which integrates interleaved Totem-pole Power Factor Correction (TTP-PFC) with a Half Bridge secondary employing a configuration of six switches on the secondary side for three-phase operation. This topology is based on Dual Active Half-Bridge operation.

The proposed AC-DC converter offers several features:
1. Reduces the number of secondary switches by half compared to conventional three-phase single-stage [3].
2. Reduces the secondary side's volume by 70%.
3. Reduces the total cost of secondary side switches by 35%.
4. Reduces the number and cost of output capacitors by 66%.
5. Achieves nearly full zero voltage switching (ZVS) with a wide range of battery voltages (460V-800V) and loads.

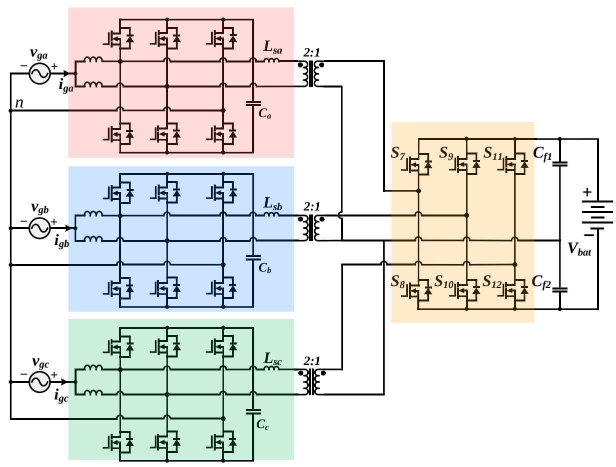


Fig.1 Proposed three-phase single-stage AC-DC converter

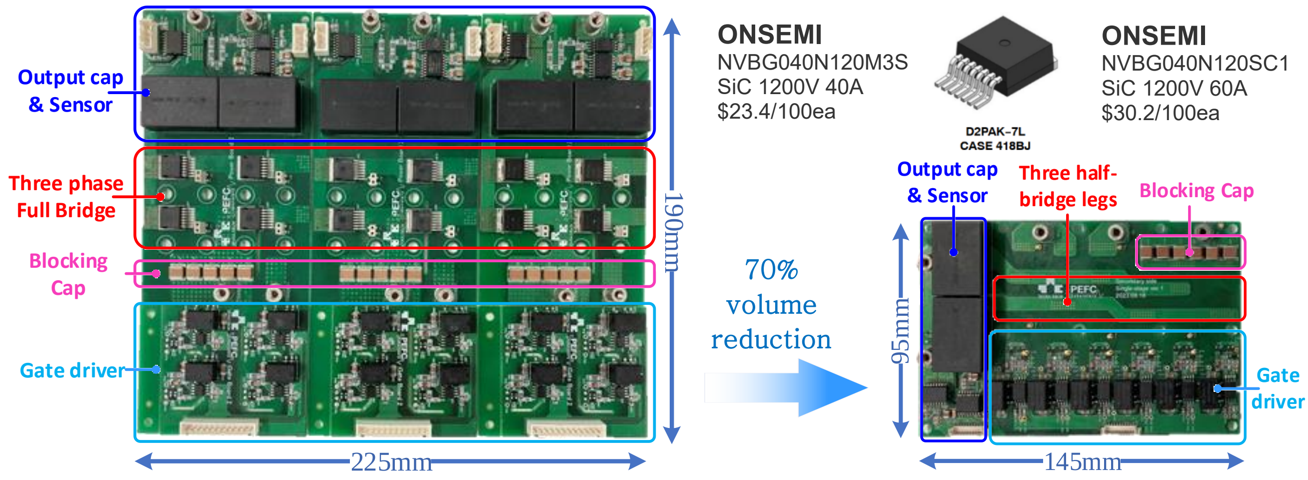
2. Proposed three-phase single-stage AC-DC converter with 6-switch secondary

The proposed three-phase single-stage AC-DC converter is depicted in Figure 1. In this configuration, each phase combines an interleaved 2-modules Totem-pole AC-DC converter with an isolated half-bridge DC-DC converter on the secondary side. Fig 2 shows an 11kW module featuring three half-bridge legs and two series capacitors employed, replacing the three full-bridge 3.7kW modules. The three negative points of the output transformers are connected to

Table 1. Comparison between the **secondary side** of conventional [3] and proposed AC-DC converter

Items	Conventional	Proposed
Total number of sec's switch	12ea	**6ea**
Cost of sec's switch	1 pu	**0.65 pu**
Current rating of sec's switch	1 pu	**1.6 pu**
Cost of gate driver components	1 pu	**0.33pu**
Number of output capacitors	6ea	**2ea**
Cost of output capacitors	1pu	**0.33 pu**
Cost of Blocking capacitors	1 pu	**0.67 pu**
Volume of the sec's board	1 pu	**0.30 pu**
Peak efficiency	**97.01%**	96.2%

*Price is based on Mouser (Quantity 100ea)



a) b)

Fig 2. Secondary board volume comparison: a) Conventional vs. b) Proposed

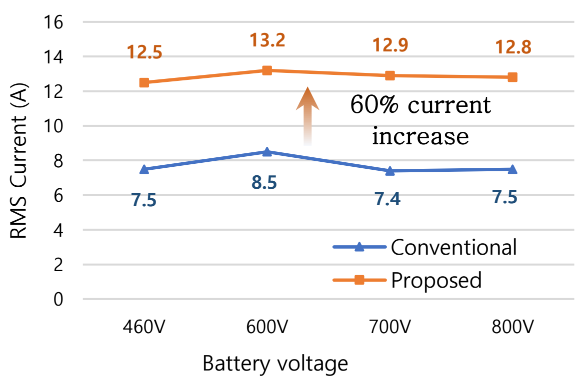


Fig 3 Comparison of secondary switches' current ratings

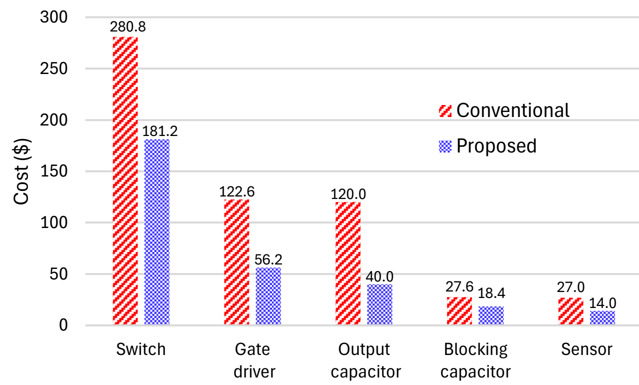


Fig 4. Comparison of main components costs on sec's board

the midpoint of the series output capacitor on the secondary side. The three negative points of the output transformers are connected to the midpoint of the series output capacitor.

In this way, the volume of the secondary side's board can be reduced by 70%. Moreover, by using three half-bridge legs, the price of secondary side switches is reduced by 35%, even though the current rating of the secondary switches is increased by 1.6 times. Additionally, the number and cost of output capacitors have been reduced by three times. A comparison between the conventional [3] and the proposed single-stage AC-DC converter is shown in Table 1.

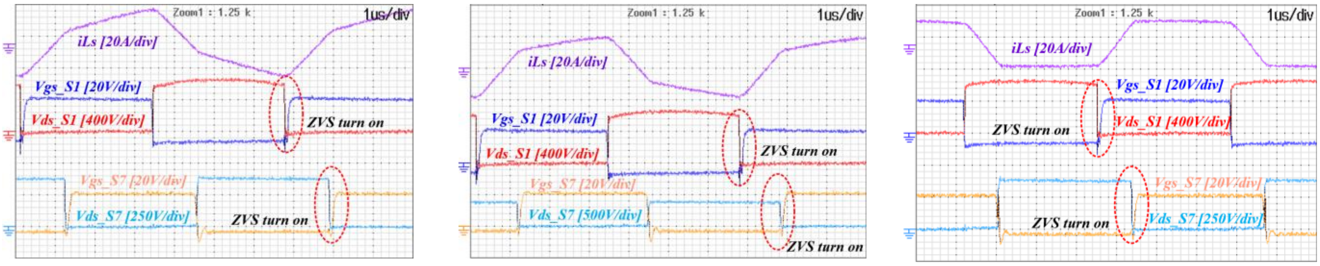
To maintain voltage balance across the output capacitors (C_{f1}, C_{f2}), symmetrical modulation for the secondary switches is recommended over asymmetrical modulation. Both high-side and low-side switches are switched to identical duty cycle values, represented as 'ds'. But the low-side switch is delayed a half switching cycle than the high-side switch. The phase of each modulation signal is determined by the phase of grid phase voltage respectively. With this modulation, ensuring conductive times between two switches in one leg helps prevent uneven heat distribution among the switches. This simplifies the implementation of heatsink design and switch selection.

3. Experiment results

To validate the performance and theory of the proposed 3-phase single-stage AC-DC converter, an 11kW prototype (consisting of 3 modules x 3.7 kW on the primary side and an 11kW secondary side) was constructed. The prototype specifications and parameters are outlined in Table 2. Fig 5 & Fig 6 present the experimental waveforms and ZVS waveforms of switches captured from the proposed single-stage AC-DC converter with a wide battery voltage range. Both primary and secondary switches can achieve ZVS with a full battery voltage range. Fig 7 shows the proposed topology's efficiency under a wide load condition range.

Table 2 Prototype specifications and parameters of the proposed three-phase single-stage AC-DC

Items	Symbol	Value
Rated power	P	**11 kW**
Grid voltage	V_{ga}, V_{gb}, V_{gc}	220V
Battery voltage	V_{bat}	460V~800V
Switching frequency	f_s	150 kHz
Secondary switch	S_7~S_{12}	NVBG040N120SC1
Output capacitor	C_{f1}, C_{f2}	10 μF
Series inductor	L_{sa}, L_{sb}, L_{sc}	35 μH



a) 460V b) 600V c) 800V

Fig 5. Experimental ZVS waveforms with wide battery voltage range at full power load (11kW) a) 460V, b) 600V, c) 800V

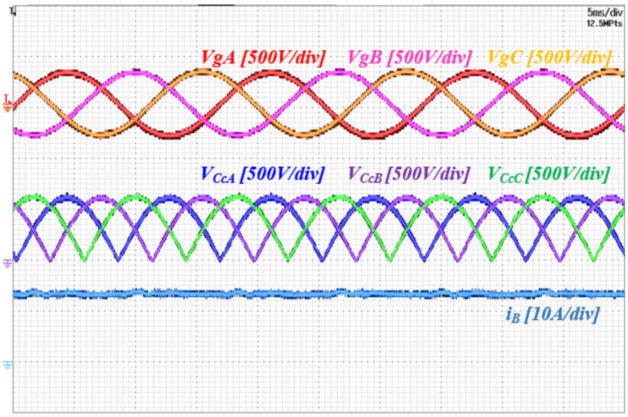


Fig. 6. Three-phase experimental waveform at 600 Vdc

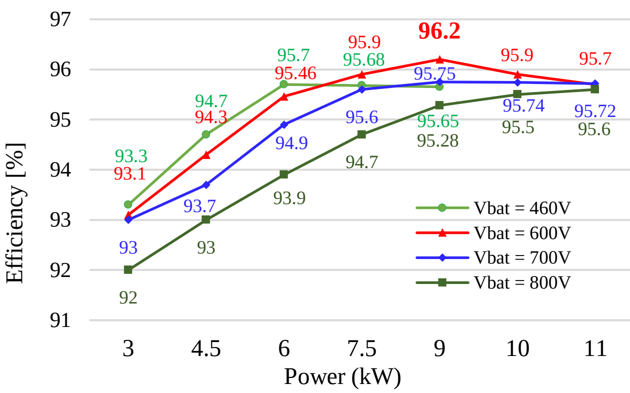


Fig. 7. Efficiency of the proposed AC-DC converter (measured by Yokogawa WT5000)

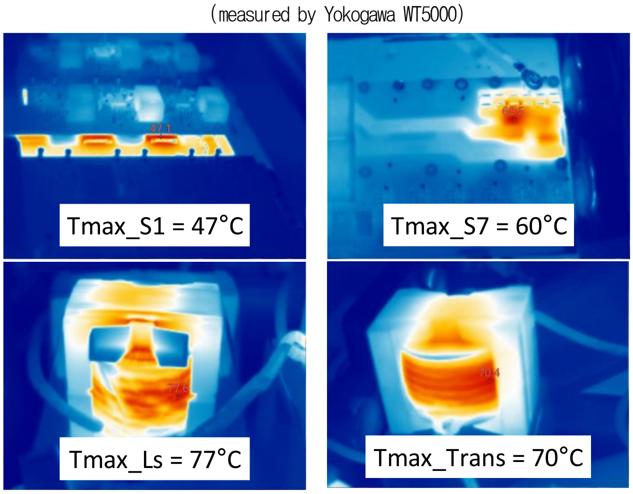


Fig. 8. Temperature of switches and magnetic components under 30 minutes operation (ambient temperature = 20℃)

The peak efficiency of 96.2% can be achieved at a battery voltage of 600V and can be improved by optimizing component design in the future. The temperature of the main components is shown in Fig 8 under 30 minutes of operation with an ambient temperature of 20°C and fan cooling at a battery voltage of 600V and full power.

4. Conclusion

This paper proposed a 3-phase single-stage AC-DC converter with numerous advantages. It reduced the number of semiconductors by using three half-bridge legs on the secondary side, and based on that, board volume and production cost can be decreased significantly. Furthermore, the proposed 11kW prototype can achieve ZVS turn-on for all switches at full battery voltage range at full load. This topology can be used for EV chargers, Energy Storage Systems, and PV Solar applications as well.

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