10kW급 HVAC 시스템을 위한 Enhanced Interleaved PFC Boost 컨버터 형태의 650V IPM 개발

이기현, 홍승현, 김태현, 정진용, 권태성
온세미컨덕터, 파워 솔루션 그룹, Industrial IPM

Development of Enhanced Interleaved PFC Boost Converter typed 650V Intelligent Power Module for up to 10kW HVAC Systems

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ABSTRACT

This paper introduces an enhanced interleaved (IL) PFC (Power Factor Correction) boost converter typed 650V Intelligent Power Module (IPM), which is fully optimized hybrid IGBT converter modules; Silicon (Si) IGBT and Silicon Carbide (SiC) diode, for up to 10kW HVAC (Heating, Ventilation, and Air Conditioning) systems. It utilizes newly developed 4th Generation Field Stop (FS) trench IGBTs, EXTREMEFAST^{TM} anti-paralleled diodes, SiC Junction Barrier Schottky (JBS) diodes, Bridge rectifiers, Multi-function LVIC, and Built-in thermistor provide good reliable characteristics for the entire system. This module also takes technical advantage of DBC (Direct Bonded Copper) substrate for the better thermal performance. It is shown that the Si IGBT/SiC diode hybrid IL PFC module can achieve excellent EMI performance and greatly enhance the power handling capability or switching frequency of various applications compared to the Si IGBT/Diode.

This paper provides an overall description of the newly developed 650V/50A Hybrid SiC IL PFC IPM product.

Keywords- *Interleaved, Power Factor Correction, PFC, Boost, Converter, Hybrid, IPM, Module, IGBT, SiC, Field Stop, Schottky, HVAC*

1. INTRODUCTION

Three phase motor drive systems are used in wide variety of applications operating from as single phase AC supply. However the inductive nature of motors, use of an AC rectifier and capacitors caused the drawn current to be distorted due to the nonlinearity of the rectification stage, hence the power factor is compromised. PFC stage is used in the rectifier design in these applications to comply with regulations, such as IEC61000-3-2, which limit the input current harmonics. Thus PFC stage is becoming an integral part of most rectifier designs.

A typical HVAC systems operating from a single phase supply with PFC, Fig. 1, consists of three major power stages:

- AC Rectifier to rectify the input AC voltage;
- Boost PFC power stage;
- Motor inverter stage(s).

Also, by employing interleaved PFC boost converter, offers various distinctive attributes including input current ripple reduction, low current stress, reduced inductor volume, reduced current rating of semi-conductor devices, increased power handling capability, modularity and lesser electromagnetic interference (EMI). Especially, one of the most important requirements in the system is more compactness and easier mass production process with high reliability resulting in more cost effectiveness comparing to discrete motor solutions [1].

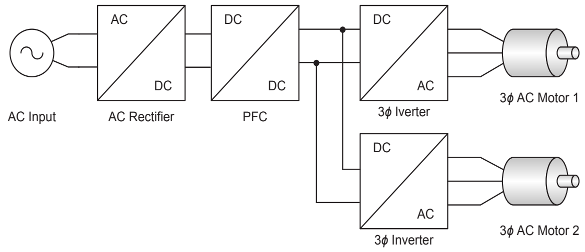


Fig. 1. Three phase motor drive systems from single phase supply for HVACs

In order to meet these needs, ON Semiconductor has developed and successfully improved a series of IPM devices with new enhanced interleaved PFC package for a highly efficient integrated solution. A new 650V Hybrid SiC IL PFCM is quite specialized for motor drives. This module has been fully developed as an answer to the strong demands particularly in industrial HVACs up to 10kW. Especially, the adopted FS4 trench IGBT turn-on / turn-off performance is optimized by its own characteristic. In addition, adapted SiC diode also has better low reverse recovery characteristics than existing Si IL PFC module device. This paper describes performance of FS4 IGBT and SiC boost diode and other important considerations for designing systems about the new improved 650V/50A Hybrid SiC IL PFC module.

2. FEATURES OF DESIGN AND FUNCTIONS

2.1 External View and Circuit Structure

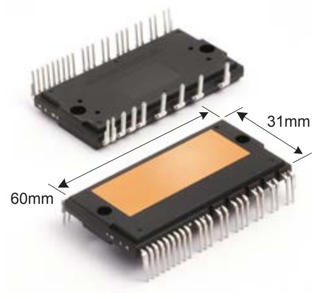


Fig. 2. Photograph of Hybrid SiC IL PFC module

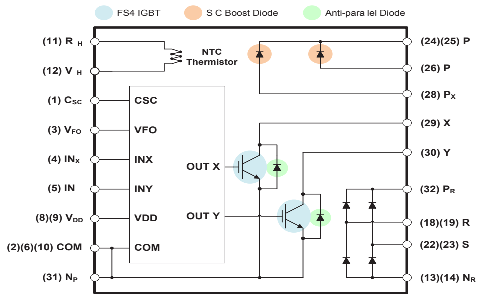
The 650V/50A Hybrid SiC IL PFC module product offers the size of 60 x 31 mm2 as shown in Fig. 2. This product is composed of two 4th Generation field stop trench technology (FS4) IGBTs, anti-paralleled EXTREMEFAST^{TM} diodes, SiC boost diodes and four bridge diode for interleaved PFC boost converter with bridge rectifier together with one low voltage gate drive IC (LVIC) and thermistor as shown Fig.3 (a). In Figure 3, IGBT and Boost diode are used as FS4 IGBT and SiC diode in order to enhance switching and EMI characteristics compared with existing IL PFCM products.

2.2 Internal Devices

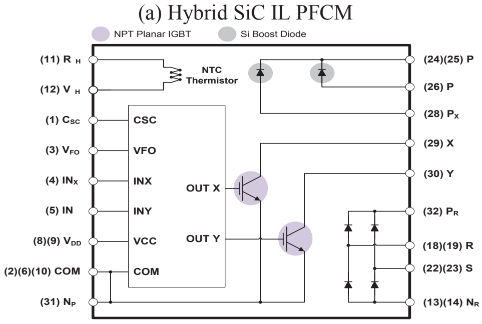
(1) IGBTs and Anti-paralleled Diodes

Hybrid SiC IL PFCM product includes a 2-phase PFC boost converter stages with a 650V FS4 IGBT and 800V EXTREMEFAST^{TM} anti-parallel diode. These are optimized for HVAC systems over all driving conditions.

Typical collector to emitter voltage of 650V/50A FS4 IGBT is 1.50V at the condition of I_C=50A and T_J=25°C, and 1.72V at the condition of I_C=50A and T_J=150°C than 600V/50A NPT Planar IGBT is 1.65V at the condition of I_C=50A and T_J=25°C, and 1.90V at the condition of I_C=50A and T_J=150°C. Table 1 and Fig. 4-5 show the comparison results about the electrical characteristics and the turn-on/off waveform between Hybrid SiC IL PFC module and existing Si based IL PFC module.



(a) Hybrid SiC IL PFCM



(b) Existing IL PFCM

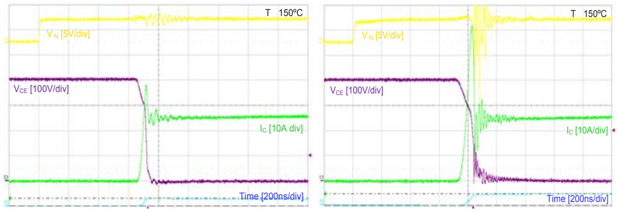
Fig. 3. Internal equivalent circuit diagram

Table. 1. Comparison of IGBT/Anti-parallel Diode characteristics

DUT	$V_{CE(SAT)}$ @ IC=50A, V_{DD}=15V		E_{SW} @ I_C=50A, V_{DD}=15V, V_{DC}=400V	
T_j	25 C	150 C	25 C	150 C
Hybrid SiC IL PFCM	1.50	1.72	1600uJ	2040uJ
Existing Si IL PFCM	1.65	1.901	2900uJ	3950uJ

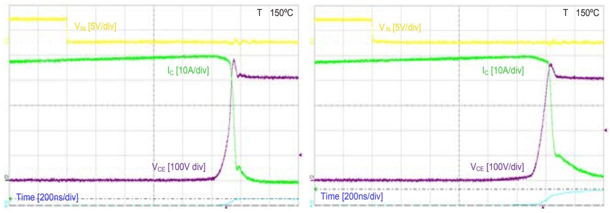
The proposed FS4 IGBT is fabricated using high density trench IGBT cells for the purpose of the proper breakdown voltage level and lower conduction loss as well. And N+ emitter area is optimized to adjust the maximum current level of IGBTs for their short circuit ruggedness enhancement. In this experiment stripe patterned trench cells are designed with dummy gates and floating P-base region without emitter contact for the low conduction loss by accumulating the hole carrier nearby cathode area [2]. Also, it is designed with multiple buffer layers to optimize process variation and device performance [3]. The FS4 IGBT allows for a significant reduction in conduction losses $V_{CE(SAT)}$ in Table 2 and turn-off switching losses (E_{OFF}) in Fig.7 (b). In addition, an increased breakdown voltage of 650V is offered for a higher margin and reliability than old 600V Si based IL PFC module.

Additionally, Hybrid SiC IL PFC module newly involves the anti-parallel diode of 800V EXTREMEFAST^{TM} diode. If anti-parallel diode is not used with IGBT, unexpected large negative Vce can be generated at low input voltage condition. This phenomenon can cause the IGBTs damage by thermal runaway due to increase the power loss in IGBTs [2].



(a) Hybrid SiC IL PFCM (b) Existing Si IL PFCM

Fig. 4. Switching turn-on waveforms of the Hyrbid SiC and existing Si IL PFCM with current ratings of 50A



(a) Hybrid SiC IL PFCM (b) Existing Si IL PFCM

Fig. 5. Switching turn-off waveforms of the Hybrid SiC and existing Si IL PFCM with current ratings of 50A

(2) Boost Diodes

Boost diodes for Hybrid SiC IL PFCM use the 650V SiC Junction Barrier Schottky (JBS) diode. SiC diode contributes to the proper placement of anti-parallel diodes, and other peripheral components. It is also improved reverse recovery characteristics, which is for high-frequency switching (up to 40kHz), where EMI emissions are critical design parameters. Turn-on waveform of figure 4 shows low reverse recovery current (Irr) and EMI than existing Si based IL PFCM.

(3) Bridge Rectifiers

This module has 900V/50A build-in bridge type rectifiers. It is to rectify the AC input voltage to DC. So, The use of this module can significantly reduce the size of the applications compared to using individual rectifier power semiconductor devices.

(4) LVIC

The gate drive LVIC is designed with fully dedicated and minimum necessary functions. It helps optimized IGBT switching and provides under voltage lock out (UVLO) of drive supply and over current protections functions. Also, it is designed to have noise immunity which comes from input signals with optimized filtering function.

(5) Thermistor

This package includes a Negative Temperature Coefficient (NTC) thermistor for module case temperature (T_C) sensing.

2.3 Simulation for Interleaved PFC Boost Circuit

Figure 6 shows IL PFC boost converter with rectifiers through PSIM simulation. The simulation is performed based on the parameters of interleaved PFC boost converter as specified in Table 2.

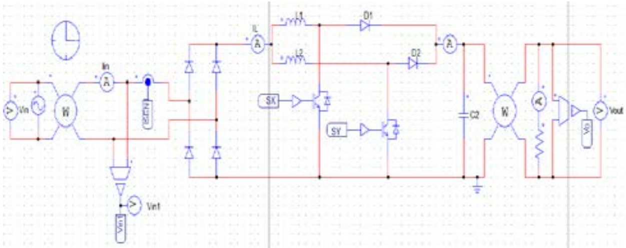


Fig. 6. PSIM simulation circuit for interleaved PFC boost converter

Table. 2. Simulation parameters of interleaved PFC boost converter

Interleaved PFC Boost Converter			
Parameters	Symbol	Value	Unit
Output power	P_{out}	7.24	kW
Frequency	f_{in}	50	Hz
Input Voltage	V_{in}	220	V
Inductor	L	350	uH
DC-link voltage	$V_{DC\text{-}link}$	380	V
Switching frequency	f_{sw}	40	kH
Control Method	Continuous Conduction Mode (CCM)		

Fig. 7 shows the PSIM simulation results of an interleaved PFC boost converter. The input current is in phase with input voltage, and it has close to unity power factor. Also the output voltage is regulated at around 380V, with a 100Hz low frequency ripple. The converter is operating at 40kHz switching frequency, 220V input voltage and 7.24kW output power.

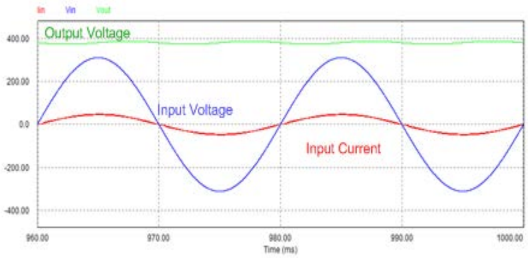


Fig. 7. Simulation waveforms for interleaved PFC boost converter including output voltage, input voltage, and input current

2.4 Comparison of Power losses

The power-carrying potential of a device is dependent on the heat transfer capability of the device. The proposed module provides not only good thermal performance by taking the advantage of DBC substrate, but also operating frequency options in accordance with the application. The single IGBT power loss is composed of conduction and switching losses caused in the IGBTs and anti-parallel diodes. The conduction loss depends on the DC electrical characteristics of the device i.e. saturation voltage. Therefore, it is a function of the conduction current and the device's junction temperature. Conversely, the switching loss is determined by the dynamic characteristics like turn-on/off time and over-voltage/current. Hence, in order to obtain the accurate switching loss, we should consider the DC-link voltage, the applied switching frequency and the power circuit layout in addition to the current and temperature [5]. Fig. 7-9 show the total loss distribution results about the module power loss characteristics between the Hybrid SiC IL PFCM and existing Si IL PFCM. These values are obtained based on typical experimental data. It should be noted that the $V_{AC\ input}$=230Vrms, PF=1.0 V_{DC}=380V, V_{DD}=15V, T_J=150°C, f_{SW}=40kHz per chip, T_C=90°C, and CCM PFC including rectifier are used as common simulated parameters in all the calculations. In this result, it is shown that new Hybrid SiC IL PFCM with FS4 IGBT shows significantly less switching losses than the existing IL PFCM. Also, Hybrid SiC IL PFCM can reduce power loss by about 30% compared to conventional products at 35A AC input rms current level.

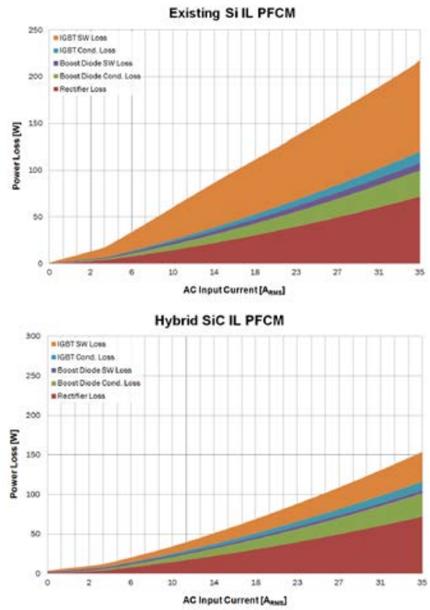


Fig. 8. Total loss distribution regarding conduction, switching for each current between Hybrid SiC IL PFCM and existing Si IL PFCM.

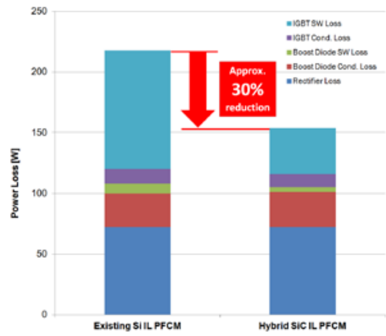


Fig. 9. Total loss distribution regarding conduction, switching between Hybrid SiC IL PFCM and existing Si IL PFCM.

3. CONCLUSION

In this paper, an overall description to the enhanced 650V/50A Hybrid SiC IL PFCM is presented. This IPM module offers tremendous advantages such as high efficiency, increased reliability, simple construction, and cost-effectiveness. The Hybrid SiC IL PFCM product provides a solution for up to 10kW HVAC systems by excellent performance of FS4 IGBTs and SiC diodes integrated inside.

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