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Considerations on the use of a Boost PFC Regulator Used in Household Air-conditioning Systems (over 3kW)

Ki-Young Jang, Bum-Seok Suh, and Tae-Hoon Kim

System Engineering Group, Discrete Team, Fairchild Semiconductor

ABSTRACT

The CCM (Continuous Conduction Mode) boost topology is generally used in the PFC (Power Factor Correction) regulator of household air-conditioning systems. There are three kinds of power devices - bridge rectifier diodes, FRDs (Fast Recovery Diodes), and IGBTs (or MOSFETs) - used in a boost PFC regulator. Selecting the appropriate device is very cumbersome work, specially, in the case of FRDs and IGBTs, because there are several considerations as described below:

1) High frequency leakage current regulation (conducted and radiated EMI regulation)
2) Power losses and thermal design
3) Device cost.

It should be noted that there are trade-offs between the power loss characteristic of 2) and the other characteristics of 1) and 3). This paper presents a detailed evaluation by using several types of power devices, which can be unintentionally used, to show that optimal selection can be achieved. Based on the given thermal resistances, thermal analysis and design procedures are also described from a practical viewpoint.

1. Introduction

Recently, international regulations governing the amount of harmonic currents (e.g. IEC 1000-3-2) became mandatory. Hence active power factor correction regulator circuits became inevitable for the AC/DC converters[1]. In order to minimize the penalty of using an additional PFC circuit, such as an increase in the overall system size and cost, most high power home appliances such as inverter air-conditioners use a boost regulator as the PFC circuit with a front-end single-phase bridge-diode rectifier. The reasons for using boost converter are simplicity in circuit and system design, reduced voltage stress on devices, and high conversion efficiency compared to other topologies. Further, the step-up voltage conversion makes it suitable for universal input voltage applications (90~264[V]) and is beneficial for the inverter motor based air-conditioning system.

Due to the remarkable progress in power electronics and power device module technology, an inverter-based motor operation is more efficient and quiet. It is being widely adopted in air-conditioning systems. However, there are problems as the power goes up:

1) Power devices' power dissipation.
2) Switching noise level increases.

The following three factors should be carefully considered when designing a PFC circuit.

1) Conducted or radiated EMI caused by the rapid variation of voltage and current of switching devices
2) Power losses and thermal design considerations
3) Cost consideration

Based on the above criteria, this paper presents the detailed analysis of power devices used for the PFC regulator by showing comparative evaluation results. In the thermal analysis portion, a practical system design guide is also given with consideration to operation rating.

2. Power Devices

Fig. 1 shows a boost PFC regulator. A boost regulator is comprised of semi-conductors such as a single-phase bridge diode, FRD and an IGBT.
A MOSFET can take the place of an IGBT. But the IGBT is more suitable in a high power application, and is also lower in price.

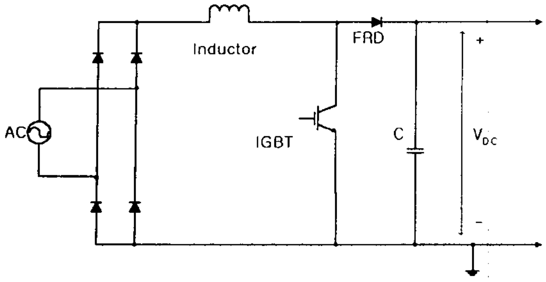


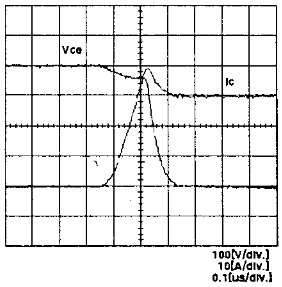
Fig. 1 Boost power factor correction pre-regulator

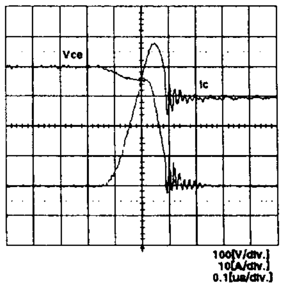
It should be noted that a PFC regulator may cause more severe dv/dt and di/dt noise problems due to larger current switching with higher switching frequency than a PWM inverter, which results in the need for larger LC filters. A High frequency leakage current may be generated by high dv/dt at switching, which flows to the ground wire though the stray capacitor

The switching noises are in the form of conducted or radiated emissions. In the case of conducted emissions, the high frequency signals generated by one equipment may interfere with other equipment that are connected at the point of common coupling, and cause malfunctioning in them. Also the radiated emission may disturb the operation of wireless installations or add high frequency conducted noise to the victim coupled with the conduction loops in the system.

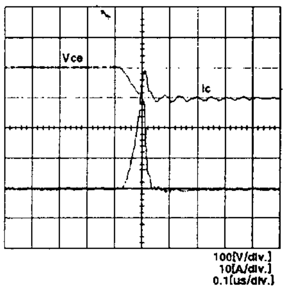
2.1 IGBT turn on switching

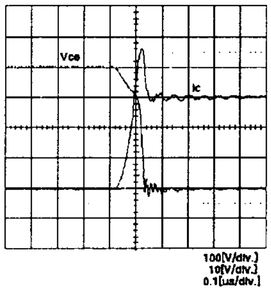
Fig. 2 shows the IGBT's switching on waveforms. Each figure is composed of different types of FRDs. Type A has good soft reverse recovery characteristics on ambient temperature (Fig.2 (a)). But under high temperature conditions (125 ° C), it loses soft reverse recovery characteristics (Fig. 2 (b)). Type B has the best characteristics for the reverse recovery time (trr) and reverse recovery current (Irr). But it does not show good soft reverse recovery characteristics under high temperature condition (Fig. 2 (d)). Therefore in Fig. 2 (d) the VCE of IGBT is ringing. And it can cause abnormal switching operation of an IGBT. It also increases the EMI noise level. The ringing voltage of the IGBT has a high dv/dt slope. It means that there is a high leakage current which increases the EMI noise level [2,3]. Type C does not show the best characteristics on reverse recovery time and reverse recovery current. But it shows the best soft reverse recovery characteristics under high temperature conditions (Fig. 2 (f)).



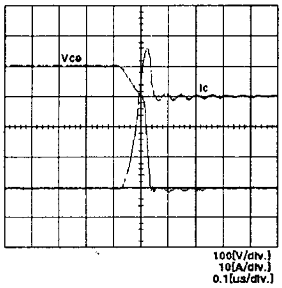


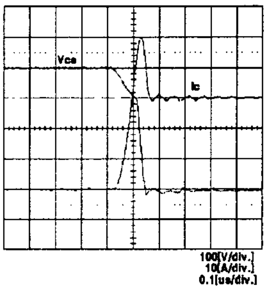
(a) A type FRD - 25[° C] (b) A type FRD - 125[° C]





(c) B type FRD - 25[° C] (d) B type FRD - 125[° C]





(e) C type FRD - 25[° C] (f) C type FRD - 125[° C]

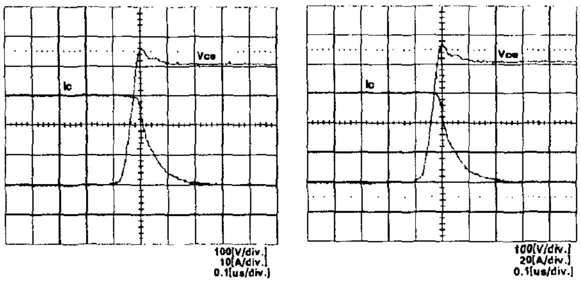
Fig. 2 IGBT switching on waveforms with different types of FRDs

2.2 IGBT turn off switching

The above experimental results show that the different types of FRDs have the same turn-off waveforms. Each of the waveforms in Fig. 3 show the IGBT's switching off waveform with two different FRDs, which are of the same type(C type). The FRD has no effect on the IGBT's switching off.

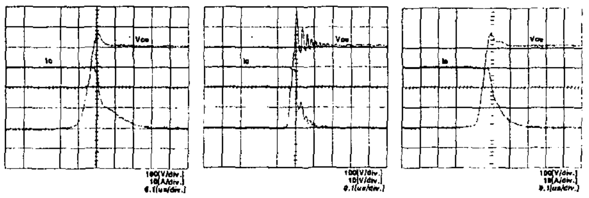
Fig. 4 shows the IGBT's turn-off switching waveforms with three different IGBTs that are of the same type (C type). Fig. 4 (b) shows that the B type has the lowest power loss. But it has serious ringing noises.

A and C type IGBTs have good characteristics related to switching noises. The C type has less switching loss than the B type.



(a) A type FRD - 25[° C] (b) B type FRD - 125[° C]

Fig.3 IGBT turn-off switching waveforms with two different types of FRDs



(a) A type (b) B type (c) C type

Fig. 4 IGBT turn-off switching waveforms with three different types of IGBTs

3. Thermal analysis and design

As the power rating goes up, the power loss also increases. The IGBT can reduce conduction loss when compared with a MOSFET. But the switching frequency must be decreased for a reduction in switching loss.

Table 1 shows each device's power consumption. The test conditions are:

V_{IN} = 176~264[V_{AC}]
V_{DC} = 400[V_{DC}]
Fs = 25[kHz]
PIN = 3[kW]
IGBT = C type
FRD = C type

The IGBT's power loss reduction is a dominant factor in designing a high power PFC. The thermal design is important in high power home appliance air-conditioning systems. In the worst case, the ambient temperature of the control board goes up to 80[° C]. The heat-sink temperature can be restricted to 100[° C]. Therefore the thermal resistance between the power semiconductor (IGBT, FRD) and the heat sink must be lower. The insulator (silicon rubber) inserted between the heat sink and the power semiconductor also increases the thermal resistance. Therefore the achievable thermal resistance between the semiconductor and the heat sink may be 1[° C/W]. For semiconductor reliability, the junction temperature of the semiconductor must not rise over 125[° C].

$$[P_{LOSS}]_{MAX} = (125-100)/1 = 25[W] \quad (1)$$

Eq. 1 shows the allowable maximum power loss of a single semiconductor with the above assumption. But the IGBT power loss in table 1 is 38.2[W]. Lower switching frequency can decrease the power loss. Fig. 5 shows the IGBT power loss at various switching frequencies. At 10[kHz] the loss is about 25[W]. But a lower switching frequency increases the system size. Another solution for reducing power loss may be using a device with a higher rated current. In this case, the conduction loss may be decreased. But, the switching loss (large amount of IGBT power loss) cannot be decreased. Hence, it is necessary to lower the switching frequency.

Interleaving two boost PFCs may be a good solution in this case[5-6]. But it is complex and increases the total cost. Although the rating of each component may be half of the original components', each component's cost is not half. The power semiconductor cost can be half of the original. But the inductor cost may be higher than half of the original. The assembly cost may also increase. The control design is more complex than that of the original.

The alternate switching method is the other good solution in this case. Fig. 7 shows the alternate switching method boost PFC circuit. It has a little increase in power loss compared to the original one. It is simple. The difference in the single boost PFC is that there are two IGBTs, and they switch alternately. Each IGBT is working with half the frequency of a single boost PFC, like an interleaving boost PFC. Hence, it drastically reduces the single IGBT's power loss. But, using two half current rated IGBTs can enlarge the conduction loss. Table 2 shows the alternate switching PFC power device's loss with a 25[kHz] switching frequency.

Fig. 6 shows one IGBT's power loss with various switching frequencies in an alternate switching boost PFC. The switching frequency can be higher than 30[kHz].

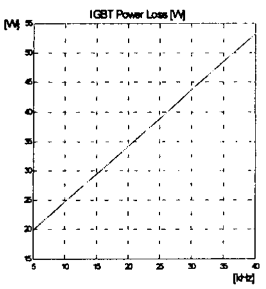


Fig. 5 IGBT's power loss (Single boost)

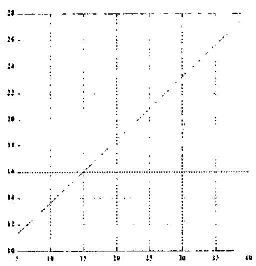


Fig. 6 IGBT's power loss (Alternate switching)

Table 1 Power devices' power loss (Single PFC boost)

Power Device		Power Loss [W]
Bridge Diode		7.6 x 4
FRD		12.8
IGBT	Cond.	13.4
	Sw.	24.8

Table 2 Power devices' power loss (Alternate switching)

Power Device		Power Loss [W]
Bridge Diode		7.6 x 4
FRD		12.8
IGBT	Cond.	8.5 x 2
	Sw.	12.4 x 2

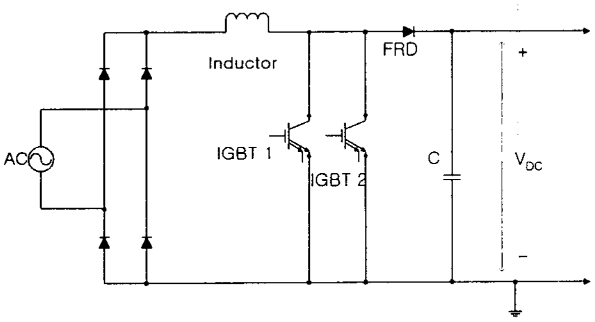


Fig. 7 Alternate switching boost PFC circuit

4. Conclusion

There are many factors in designing PFC boost regulators for 3[kW] household air-conditioners. Minimizing the switching noise is very important. High frequency switching noise can cause not only EMI noise but also the malfunctioning of the PFC controller. It may burn the IGB. The Inter-leaving method or alternate switching method is useful for a high current boost PFC regulator. The proposed alternate switching method is cost effective and has good heat spreading effects on the IGBT.

High power household air-conditioning systems require cost effective and low thermal resistances of power devices. The alternate switching boost PFC regulator best meets these two requirements.

참 고 문 헌

[1] Electromagnetic Compatibility. Part3: Limits-Sect. 2: Limits for Harmonic Current Emission, IEC 100-3-2, 1995

[2] Yo-chan Son and Seung-Ki Sul, "Conducted EMI in PWM Inverter for Household Electric Appliance," in Conf. Rec. of IEEE IAS, 2001, pp. 2441~2448.

[3] I. Takahashi, A. Ogata, H. Kanazawa, "Active EMI Filter for Switching Noise of High Frequency Inverters," in Conf. Rec. of IEEE PCC-Nagaoka '97, 1997, pp. 331-334.

[4] Zhou, C., and Jovanovic, M. M. (1992), "Design trade offs in continuous current-mode controlled boost power-factor-correction circuits," in Proceedings of 1992 VPEC Power Electronics Seminar, (1992) 57-68.

[5] B.A. Miwa, D.M. Otten and M.F. Schlecht, "High efficiency power factor correction using interleaving techniques," in Proceedings of APEC'92, pp. 557-568, 1992

[6] L.Balogh and R.Redl, "Power-factor correction with interleaved boost converters in Continuous-Inductor-Current Mode," Proceedings of APEC'93, pp. 168-174, 1993.