# 전철용 IGBT 모듈 설계연구

# Traction IGBT Modules Design Issues and Precautions

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## ABSTRACT

IGBT modules are designed for low loss, rugged for all environments and user friendly. Low on state saturation voltage with high switching speed is the primary concerns. In this paper selection of IGBT, module ratings and characteristics are discussed. The IGBT design topic of protection against over voltage and over current are covered. Emphasis on turn off switching, short circuit switching and necessary precautions are dealt. Selection of IGBT device, gate drive power, and its lay out considerations are covered in detail.

## 1. Introduction

In railway traction systems, thereis a choice to choose AC or DC power transmission system. In general, worldwide acceptance is AC for long distance and DCfor short distance. It is easier to boost AC voltage with more power and hence for heavy loads. AC is easier to transmit over a long distance with minimum loss. DC on the other hand is preferred for shorter lines mostly for urban railways.

The end useral ways wants low cost, small size and high performance for high power inverter system traction applications [1]. Therefore high blocking voltage IGBT modules are being used in place of conventional GTOs. With technological development higher blocking voltage IGBTs are available with high current ratings and better electrical characteristics [2]. Therefore, IGBT devices of high blocking voltages (6KV) have been applied for inverter in traction motor devices. These IGBTs have high speed as well as high current which increase the power. In order to make the inverter equipment compact the power devices must be small with desired electrical characteristic and reliability [3].

## 2. IGBT Design Module

The major problems to over come while designing the IGBT modules are (i) obtaining a high voltage junction termination of high reliability (ii) getting a soft and fast recovery high voltage diode for the free wheel circuit in the module (iii) receiving a parallel assembly of many IGBTs with proper current sharingand (iv) achieving reliable assembly technology for large size power modules which can withstand thermal stress caused by variation in temperature during operation.

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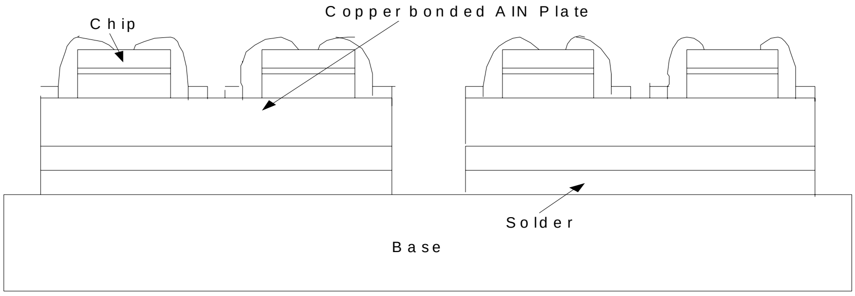
Considering all the above factors a high power IGBT module is to be designed. The module under development should be small in size, minimum electrical noise and should have high reliability.Fig.1 shows a typical cross-sectional sketch of power chip mounted on the base plate. Power chips are mounted on copper bonded AIN ceramic plates. This plate is mounted on a specially developed base which is made up of low thermal expansion material. Power chips and ceramic plates are arranged in mirror symmetry, in order to make sure that the electric current distribution is even.




Cross-section sketch of Power chip on plate

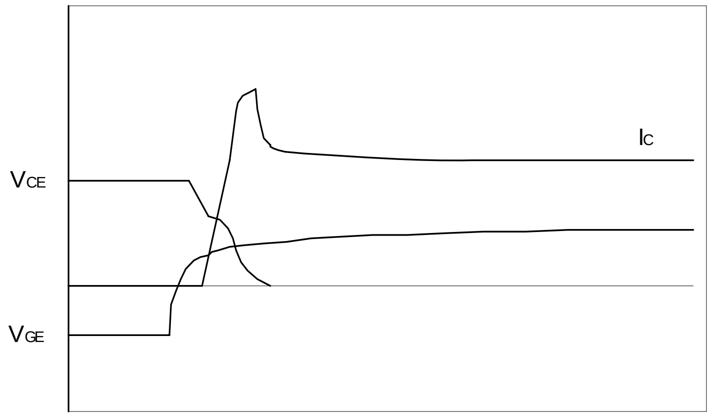
Fig.1

In order to avoid high fluctuation of voltage it is advisable to go for two level inverter designs. This will reduce the effective inductance of the inverter circuit and current slew rate, di/dt as switching speed is increased. Low noise and high breakdown voltage IGBT and diode chips are desired for this purpose.Module capacity is a function of module size. Larger module size means higher stresses on the module components. For higher output capacity, the number of IGBT and diode chips increases and hence the size of the module. It is important to see that the modules keep good mechanical and electrical reliabilities with maximum possible larger size. For this purpose, the power chips on the copper bonded AlN ceramic plates are connected in parallel in each module. The base plate is made of low thermal expansion material. In order to improve the reliability of humidity an inter-locking seal structure is recommended.

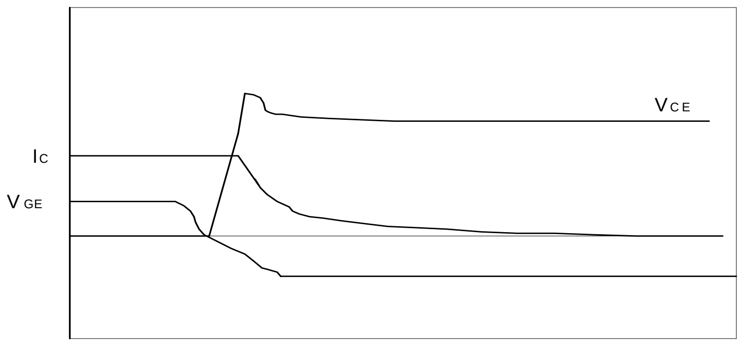
Emitter and collector terminals are closely set in the design and they have a short length inside the modules in order to reduce the internal inductance of the terminals. Diode chips are arranged near an emitter terminal in order to decrease fluctuation of the potential of the control terminals during high current switching. The gate terminal position is kept away from the emitter and collector terminals to reduce electrical noise.

**3. Electrical Characteristics**

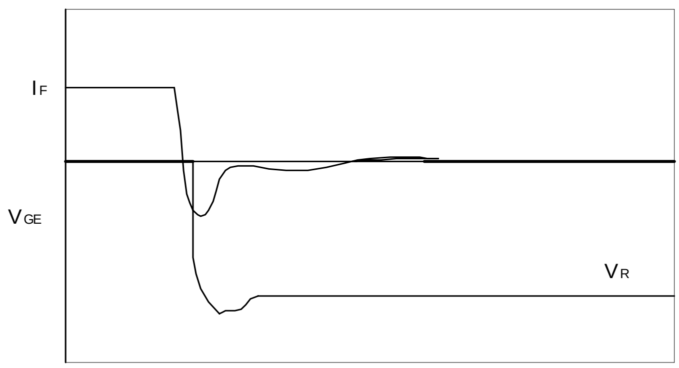
Low noise of traction motor drive applications is realized by the high current switching of IGBTs. With IGBT and diode it is possible to possible to use carrier distribution control technology. The high blocking voltage of the IGBT has a uniform and stable electric field due to the original field limiting ring and field plate structure. All new IGBTs have a wider reverse bias safe operating area than GTOs. Fig.2. shows a typical turn-on, turn-off and reverse recovery waveforms of the SFD (Soft and Fast recovery Diodes). Because of the soft and fast recovery characteristics of the diode, the electrical noise at the recovery is effectively arrested. There are no fluctuations from low current to high current recovery and also no surge voltage.




(a) Turn-on wave-form




(b) Turn-off wave-form




(c) Reverse recovery wave-form

Fig. 2.

**4. Reliability**

4.1 Humidity

It is important to avoid humidity effect as this being a high power and high voltage module (Refer Fig.3)Generally silicon gel is used to fill up the module package completely. Silicon gel protects the terminals and chip from moisture.

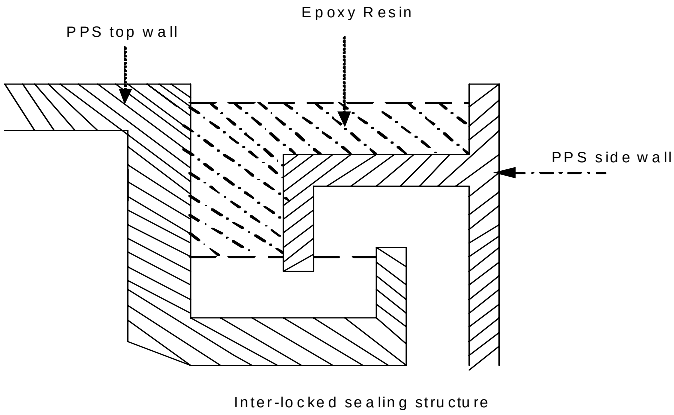



Fig.3

The module should have sufficient space for the gelto allow its contraction and expansion. Connection between the module case and terminal holder has to be interlocked and sealed. Polyphenylene pulfide (PPS) is applied to the module case and terminal holder. PPS side wall and PPS top wall are joined with epoxy resin. Surface of the internal terminals in the module are coated with PPS resin to avoid corrosion.

4.2 Life Time

To extend the lifetime, it is necessary to take care the following:

Well balanced of thermal expansion between module components.

Reduce the number of solder layers.

4.2.1 Thermal considerations

IGBT power module will have conduction loss and switching loss. The heat generated by the device as resultof these must be conducted away from the power chips using heat sink while designing. It is important to provide an appropriate thermal system to protect the power devices from failure at high temperature generated by the various devices within the module. This is important, in order to get high reliability of the system.

4.2.2 Estimation of Power Losses

The first step in thermal design is estimation of power losses in IGBT power module.

(a) Conduction loss

It is the loss while IGBT is ‘on’ state and conducts current. The total power dissipation during conduction is computed by ‘on’ state saturation voltage, current and duty cycle (for PWM is used).

$$\text{conduction loss} = V_{CE(Sat)} \,.\, I_C \,.\text{Duty Cycle}$$

When switching inductive loads, the conduction losses for free wheel diode must be included. Free wheel diode Free wheel diode loss is multiplying the diode forward voltage $V_{FM}$ and average diode current $I_{Dav}$.

$$\text{free wheel diode loss} = V_{FM} \;\; I_{Dav}$$

(b) Switching Loss

Switching loss is the power dissipated during the ‘turn-on’ and ‘turn-off’ switching transitions. In high frequency PWM switching losses is considerably high and must be included in thermal designthough ‘turn-on’ and ‘turn-off’ time is of short duration. Here the sum of the power losses is significant as it occurs repeatedly. Assuming the operating current and DC bus voltage are constant and therefore, $E_{SW(on)}$ and $E_{SW(off)}$ are the same for every 'turn-on' and 'turn-off' event. The average switching power loss ($P_{SW}$) can be computed as

$$P_{SW} = f_{SW}(E_{SW(on)} + E_{SW(off)})$$

where, $f_{SW}$ = switching frequency

$E_{SW(on)}$ = Turn-on switching energy

$E_{SW(off)}$ = Turn-off switching energy

The main use of power loss estimation is to provide a starting point for preliminary device selection.

(c) VVVF Inverter Loss

Power module common application is Variable Voltage Variable Frequency (VVVF) inverter PWM modulation is used for this purpose. Here IGBT current and duty cycle are constantly changing and hence the loss estimation becomes difficult. The following equations are used for initial loss estimation and the actual losses depend on temperature, output frequency, output, current etc. These equations are

(i) Steady state loss per switching

$$P_{SS} = I_{CP} + V_{CE(Sat)}\left(\frac{1}{8} + \frac{D}{3}\cos\vartheta\right)$$

(ii) Switching Loss per switching

$$P_{SW} = (E_{SW(on)} + E_{SW(off)}) \cdot f_{SW} \cdot \frac{1}{2}\oint \sin x.dx$$

(iii) Total Loss per IGBT

$$P_0 = P_{SS} + P_{SW}$$

Diode Loss

(i) Steady state Loss per diode

$$P_{DC} = I_{EP}.V_{EC}.\left(\frac{1}{8}\frac{D}{3}\cos\vartheta\right)$$

(ii) Recovery Loss per Diode

$$P_{rf} = 0.125\, I_{rr} I.t_{rr} V_{CE}(pk) f_{SW}$$

Loss per arm

$$P_A = P_{SS} + P_{SW} + P_{Dc} + P_{rf}$$

where, $E_{SW(on)}$ = IGBT switching energy /pulse at peak current I$_{CP}$ and T=125 C

$I_{SW(off)}$ = IGBT turn off switching energy / pulse at peak current I$_{CP}$ and T=125 C.

$f_{SW}$ = Switching frequency of PWM

I$_{CP}$ = Peak current (I$_{CP}$ = $I_{EP}$)

$V_{CE(sat)}$ = IGBT saturation voltage drop at peak current I$_{CP}$ and T=125 C.

$V_{EC}$ = FWD forward voltage drop @ $I_{EP}$

D = Duty Cycle of PWM

$\vartheta$ =Phase angle between output voltage & current.

$I_{rr}$ = Diode peak recovery current

$t_{rr}$ = diode reverse recovery time.

$V_{CE}(pk)$ = Peak voltage across the diode at recovery.

(d) Average Junction Temperature

The IGBT chips in the power Module have a maximum rated junction temperature of 150 C. This rating should not be exceeded under any operating condition. Good design practice limit, the worst design to a maximum temperature of 125 C.

Junction temperature is estimated using the equation

$$T_j = T_C + P_T . R_{th(j-c)}$$

where, $T_C$ = Module base plate temperature

$P_T$ = Total average power dissipated in device ( $P_{SW} + P_{cond}$)

$T_j$ = Semiconductor junction temperature

$R_{th(j-c)}$ = Junction to case thermal resistance

Initial design of heat sink is specified in the contact thermal resistance of the power module data sheet. The module base plate temperature is estimated using equation

$$T_C = T_a + P_T R_{th(c-f)} + R_{th(f-a)}$$

where, $T_a$ = ambient temperature

$P_T$ = Total power dissipated in an IGBT FWD pair

$R_{th(c-f)}$ = Interface thermal resistance

$R_{th(f-a)}$ = heat sink to ambient thermal resistance specified by the heat sink manufacturer.

The arrangement of power chips in the module is very important. It is necessary to arrange the power chips in such a way that they do not interfere with each other's heat dissipation. In order to extend the fatigue lifetime of IGBT modules, a low thermal expansion base plate (AIN) is recommended. The copper bonded AIN ceramic plate receives larger stresses under thermal load and possible cracks which is prevalent in conventional copper bonded is reduced considerably. Further to reduce the thermal stress concentration it is advisable to keep away the electrical contact terminals from the edge of the copper layer.

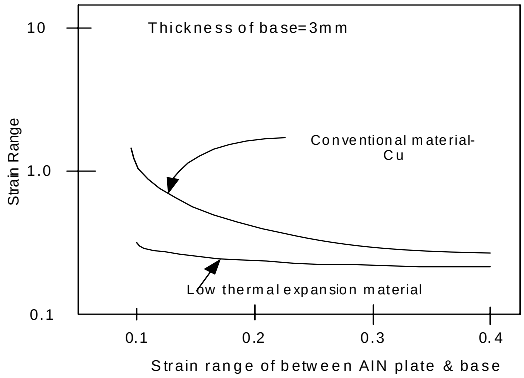



Fig. 4

## 5. Conclusion

The design parameters and precaution cited here serves as a guideline for designing high power IGBT modules. The module may have a simple in structure, low thermal expansion with interlock sealing body. The module size must be small, compact with high reliability**.**

## References


**1.** Steffen Bernet, Recent developments of high power converters for industry and traction applications, IEEE Trans. on power electronics, Vol. 15, Nov.2000.

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