

# Chapter 5

## DESIGN

## AND IMPLEMENTATION

## OF POWER CIRCUIT

### 5.1 Introduction

The overall performance and the cost of the Melter will be one of the important issues to be considered during the design process for the next generation of Induction Melting applications. The power circuit of Melter applications must achieve high efficiency and high reliability.

The quasi resonant converter presented in Chapter 4 has been used as the power circuit. The power circuit includes 3ph transformer, 3ph rectifier, filter choke, Igbt, snubber circuit, resonant tank capacitor & resonant tank coil.

### 5.2 Steps of Design of Tank Circuit

As heat energy is generated in the process of energy exchange between the inductor and the capacitor in the resonant circuit, the level of inductance and capacitance is a very important factor. The following is a description of some factors determining the value of this level.

#### Power Consumption:

As the most common design of Melter is 5 to 8kg, the overall power supply is designed based on this capacity, which is at maximum of 10kw. In order to get proper stirring effect the resonant frequency is set as 12khz for following calculations.

#### Current:

The Input current is the average of the resonant current. Hence for 10kw maximum power the Input current can be calculated as follows:

$$I = \frac{2\pi P}{V} = \frac{2\pi \times 10000}{140 \times \sqrt{2}} = 317.3A$$

#### C (Capacitance):

The Capacitance of the resonant circuit is determined as follows:

$$C = \frac{I}{2\pi fV} = \frac{317.3}{2 \times \pi \times 12000 \times 140 \sqrt{2}} = 21.25 \mu F$$

Thus a capacitor bank is formed using 10 pieces of  $2.0\ \mu\text{F}$  capacitors in parallel, which totals to  $20.0\ \mu\text{F}$ . Firstly the capacitor bank was made as shown in figure 5-1.



**Figure 5-1 Tank Capacitor Bank**

To reduce the overall space & to do proper connections with inductance and to take care of cooling of inductor the new capacitor bank is formed as shown in figure 5-2. In this bank the first terminal of each capacitor is touching the front plate and the second terminal is touching the back plate, thus connecting them in parallel.



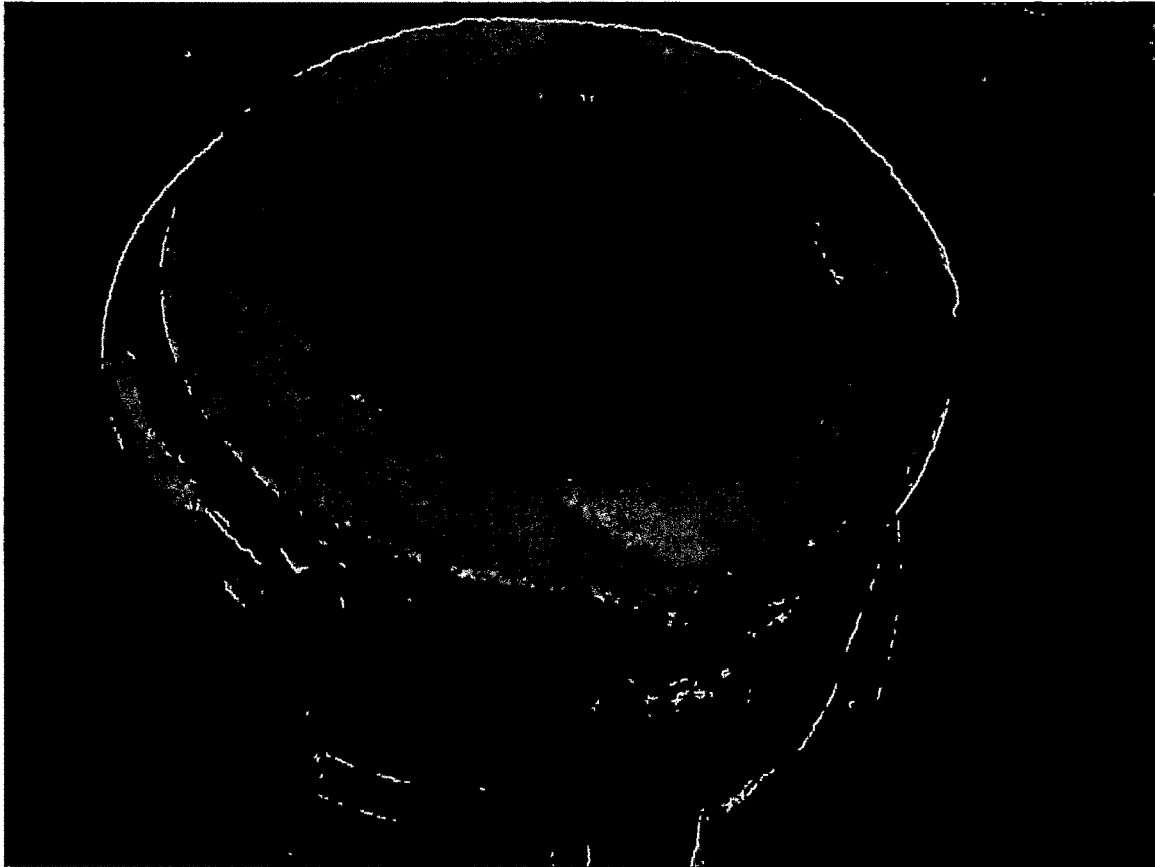
**Figure 5-2 Modified Tank Capacitor Bank**

**L (Inductance):**

The Inductance of the resonant inductor is computed with the above value of Capacitance.

$$L = \frac{1}{(2\pi f)^2 C} = \frac{1}{(2\pi \times 12000)^2 \times 20.0 \times 10^{-6}} = 8.79 \mu H$$

The inductor is made with a hollow pipe wound with 10 turns to get the required inductance. Water is passed through the hollow pipe for cooling purpose. The high temperature refractory cement is applied on the outer surface of coil to protect it from heat produced in the crucible.



**Figure 5-3 Tank Inductor**

Finally the L-C tank resonant circuit is formed as shown in figure 5-4 in such a way that no wires are required to complete the circuit. The tails of coil are themselves acting as interconnecting wires.

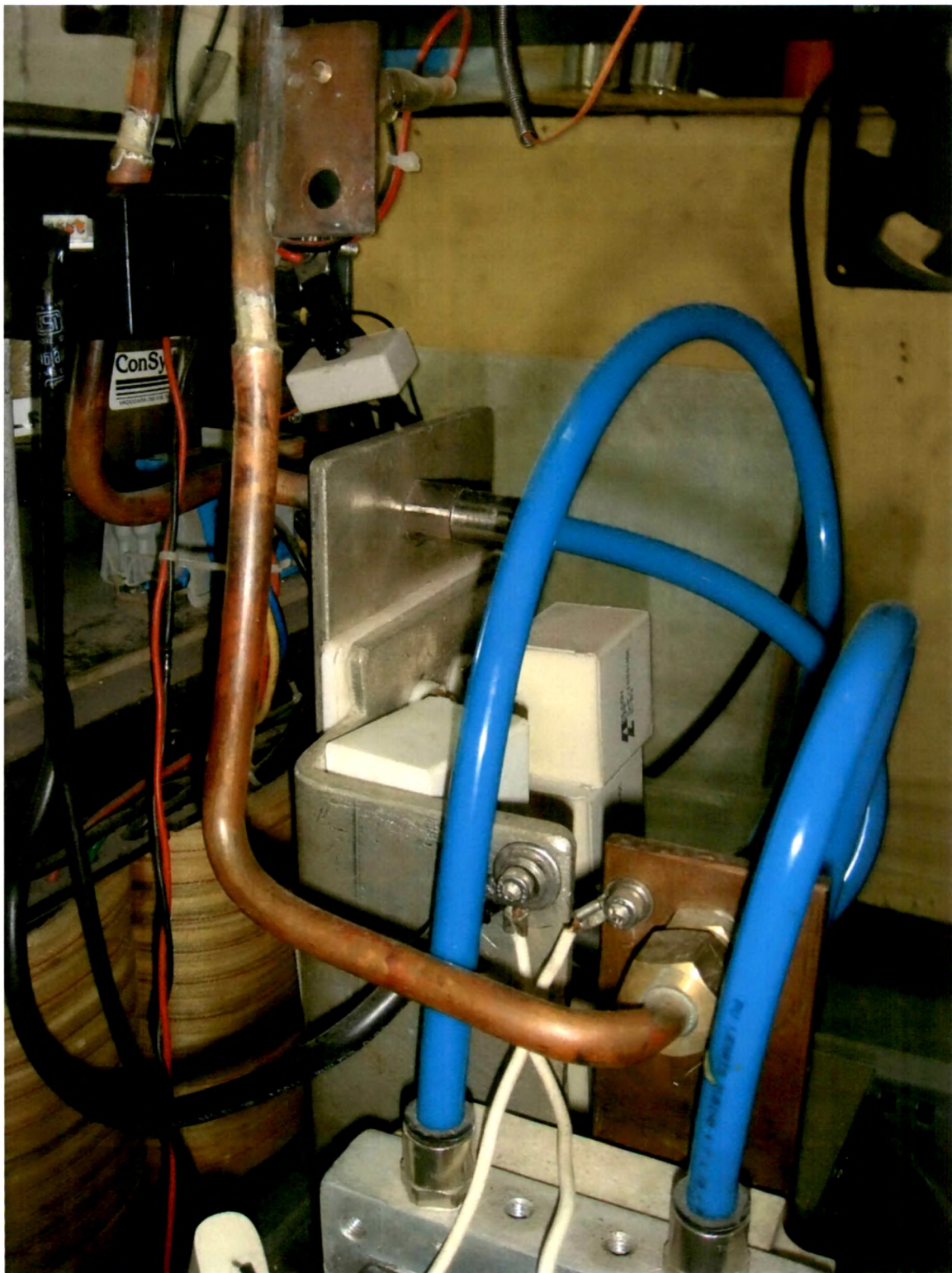


Figure 5-4 L-C Tank Circuit

### 3 Phase Transformer:

As the Melter is designed for 10kw the rating for 3ph transformer is chosen slightly higher than the maximum rating. Thus a 13kva transformer is used which steps down the 415v Line voltage to 140v Line voltage. The purpose is to operate the power circuit at low voltage and also to get isolation. Figure 5-5 shows the 3phase transformer in 3 limb construction with primary & secondary wound in star-star connection.

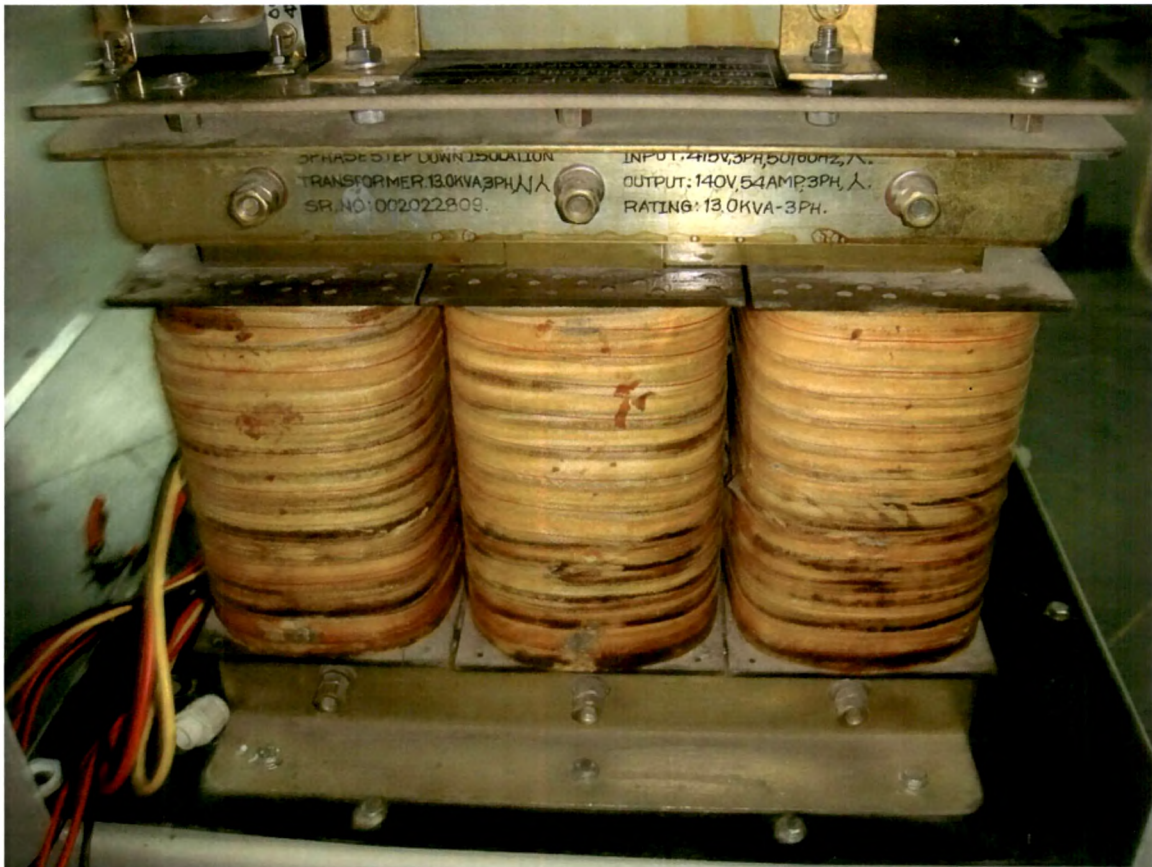


Figure 5-5 Three phase transformer

Three Phase Rectifier:

A three phase bridge rectifier of 160A & maximum repetitive peak reverse voltage of 1600V is used to rectify the output of transformer. Figure 5-6 depicts the features of the bridge rectifier.



FEATURES


- Package fully compatible with the industry standard INT-A-PAK power modules series
- High thermal conductivity package, electrically insulated case
- Excellent power volume ratio
- 4000 V<sub>RMS</sub> isolating voltage
- UL E78996 approved 
- Totally lead (Pb)-free
- Designed and qualified for industrial level

Figure 5-6 Three Phase Bridge Rectifier

Filter Choke:

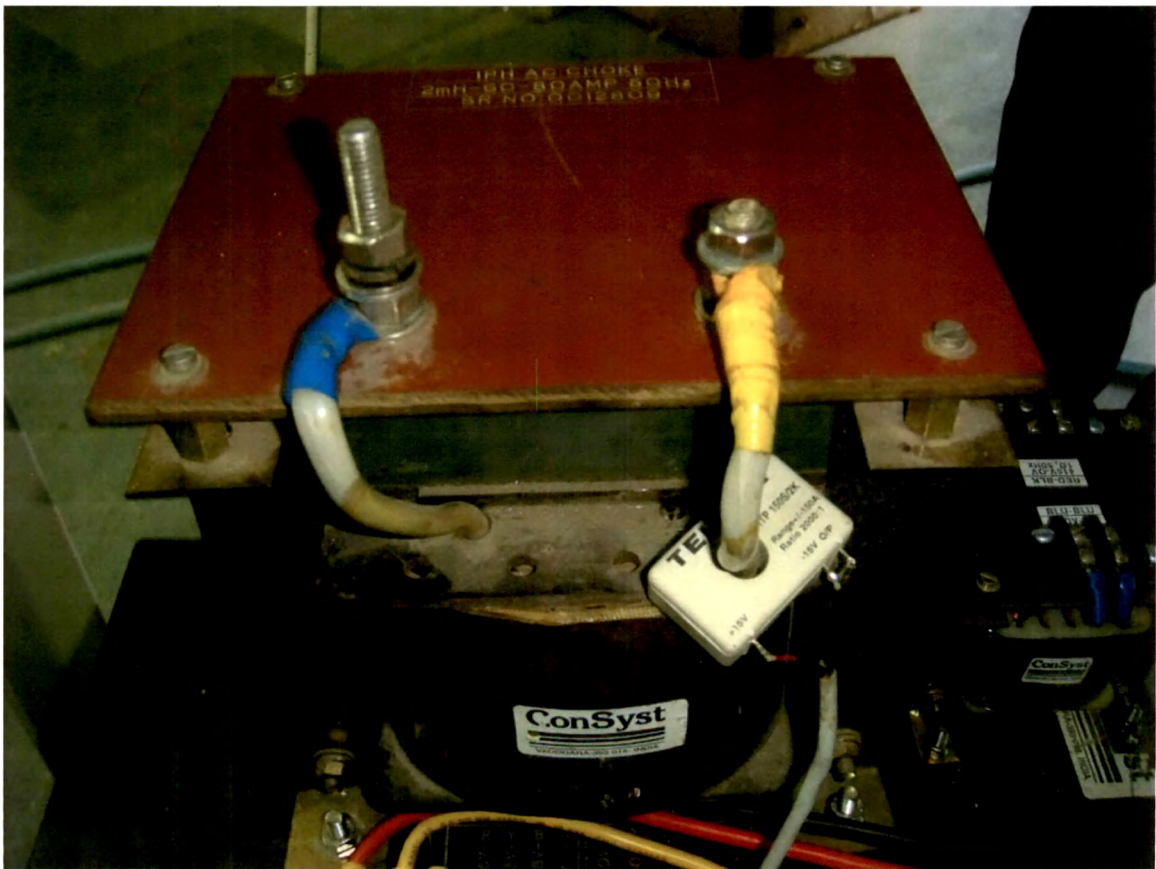


Figure 5-7 Filter Choke

**Switching Device (IGBT):**

The insulated-gate bipolar transistor (IGBT) has accrued success as a high-power solid-state switching device due to its combination of fast switching, low conduction loss, and high-impedance gate control. Manufacturers are therefore motivated to develop switches with extended voltage ratings and current carrying capability. Currently, commercial off-the-shelf (COTS) high-voltage IGBTs are rated up to 6.5 kV from multiple manufacturers. High voltage ( $> 1200$  V) IGBTs are commonly sold as modules with ratings from 200 to over 2000 A.

The IGBTs implemented in the IGBT stack are non punch through (NPT)-type devices. The NPT IGBT is a common type of IGBT due to excellent thermal properties such as negative temperature coefficient of resistivity and high-thermal reliability, which are favorable qualities for the synchronized switching of devices in series and parallel arrangement [12].

Today state off the art IGBTs are trench / field-stop devices.

**Trench IGBT**

The MOS channel of a Trench IGBT compared with a planar IGBT is rotated by  $90^\circ$ . Thus, a higher channel density can be realized at the chip top side which leads to a higher inundation of the top/emitter side with charge carriers. A maximum channel density would not only worsen the short circuit robustness but also increase the turn off losses dramatically. A good combination of a suitable trench density, a low backside emitter efficiency (collector doping) and a high charge carrier life time leads to a clear reduction of the saturation voltage without increase of turnoff losses [14].

**Field-stop IGBT**

In a field-stop IGBT, an additional  $n^+$  layer is introduced close to the collector. This layer, named field-stop, brings down the electric field within a very short spatial dimension. Therefore, it is possible to make the chips thinner and in such a way to reduce the static and dynamic losses. However, during switching events the silicon volume not affected by carrier extraction through the electric field is determining the amount of carriers contributing to the tail current.

This tail carrier/charge is crucial for the softness of an IGBT. In case of high transient over voltages the space charge region reaches far into the field stop and the residual/tail charge is very small. For a critical voltage the tail current disappears and the current flow snaps off. Such a snap-off results in high and hardly controllable over voltages. This, so far, was a big challenge for the design-in of trench field stop modules in high power applications.

Thus a 62mm C-Series module with Trench/Fieldstop IGBT4 (FZ600R12KE4) is selected with 600A DC-collector current & 1200V collector-emitter voltage. To achieve a 1200A current two of them are connected in parallel.

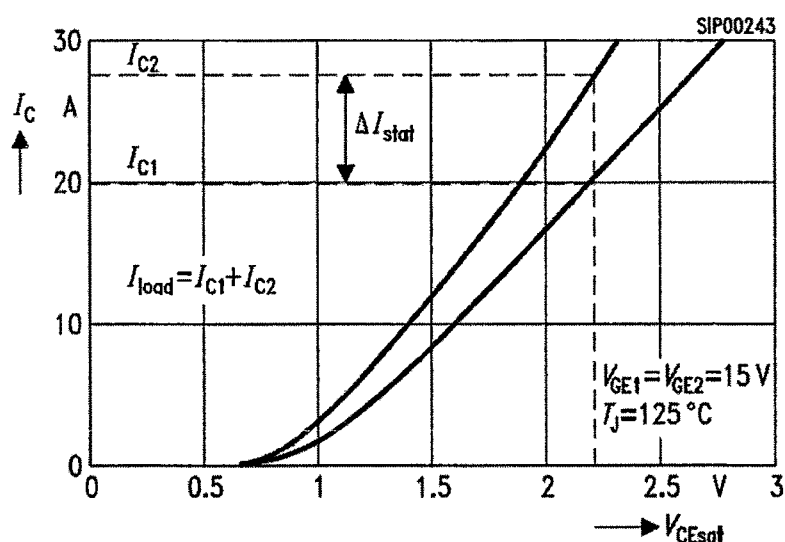
**IGBT'S in parallel:**

Apart from looking for an IGBT which is designed for a particular power range there is also the possibility, particularly at high currents, of connecting two or more smaller IGBTs in parallel. Noteworthy advantages of this are a more flexible and individual organization of the layout, the heat sources can be distributed so that higher levels of power loss can be dissipated, and possibly also cost advantages by comparison with module attachments, depending on the device type and power.

The disadvantage is the unequal split in losses. The main reason for this lies in the uneven current split between devices which results from differences in  $V_{CEsat}$ ,  $g_{fs}$  and  $V_{th}$  (variability in parameter values), which are manufacturer-dependent. Differences can arise in addition due to asymmetrical power and drive circuits, which are exhibited chiefly in the dynamic switching behavior.

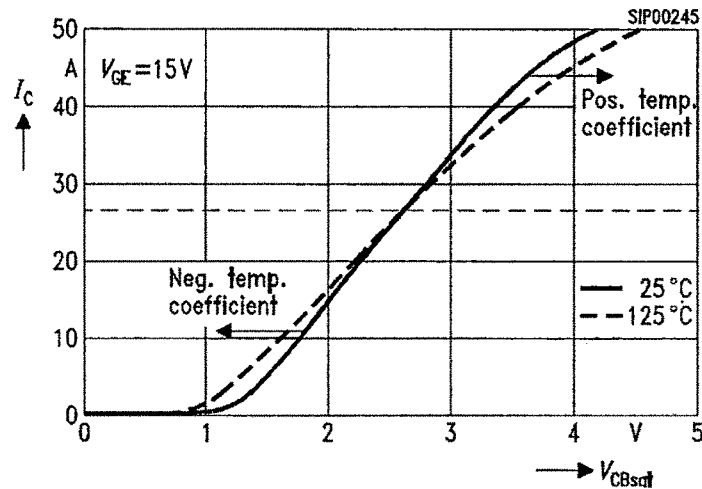
The blocking characteristics of parallel-connected IGBTs can be ignored, because in relation to the conducting state behavior many small sources of power loss have very little effect. For the behavior in the conducting state, then when the gate-emitter voltage is constant the static current split is determined by the conducting state voltage. Figure 5-8 shows the output characteristics for two PT IGBTs with different collector-emitter saturation voltages. The conducting state voltage across the parallel-connected IGBTs is the same. The static current ( $I_{load} = I_{C2} + I_{C1}$ ) splits as determined by the set of output characteristics.

The different split of the current between the devices results in different heating, and different power losses, for the IGBTs. When connected in parallel, the IGBT with the smaller saturation voltage must carry the greater partial current, has higher conducting-state losses and gets warmer.



**Figure 5-8 Set of Output Characteristics for two IGBT's with different Saturation Voltages**

Another point affecting the current split is the temperature coefficient (TC) of the set of output characteristics Figure 5-9.



**Figure 5-9 The TC of the Set of Output Characteristic Curves**

The IGBTs should have a symmetrical layout with respect to IGBT current paths & gate driver. The most sensitive parameter is the emitter stray inductance in the gate circuit. For the same drive voltage ( $V_{drive}$ ), unequal emitter stray inductances produce different gate-emitter voltages ( $V_{GE}$ ) during switching. This results in an asymmetrical dynamic split of the current or different switching losses. In addition, the switching behavior can be balanced by using separate gate dropping resistors. There should be symmetrical cooling conditions (identical heat-sink temperature and flow rate below the paralleled devices).

To achieve above requirements & to get equal distribution of current the two IGBT's are fitted on same heatsink & are connected using busbar as shown in Figure 5-10

### Snubber Circuit:

Power semiconductors are the heart of power electronics equipment. Snubber is a circuit which is placed across semiconductor devices for protection and to improve performance. Snubber can do many things:

- Reduce or eliminate voltage or current spikes
- Limit  $dI/dt$  or  $dV/dt$
- Shape the load line to keep it within the safe operating area (SOA)
- Transfer power dissipation from the switch to a resistor or a useful load
- Reduce total losses due to switching
- Reduce EMI by damping voltage and current ringing

There are many different kinds of snubber but the two most common ones are the resistor-capacitor (RC) damping network and the resistor-capacitor-diode (RCD) turn-off snubber.

An RC snubber, placed across the switch, can be used to reduce the peak voltage at turn-off and to damp the ringing. In most cases a very simple design technique can be used to determine suitable values for the snubber components ( $R_s$  and  $C_s$ ).

RC snubbers are very useful for low and medium power applications but when the power level is more than a few hundred watts the loss in the snubber can be excessive and other types of snubbers need to be considered.

The RCD snubber has several advantages over the RC snubber:

- In addition to peak voltage limiting, the circuit can reduce the total circuit loss, including both switching and snubber losses.
- Much better load lines can be achieved, allowing the load line to pass well within the SOA.
- For a given value of  $C_s$ , the total losses will be less

The key feature of this RCD snubber is that the switch voltage rises slowly as the switch current falls. This means that the high peak power associated with simultaneous maximum voltage and current is eliminated. The net result is much lower peak stress and switching loss.

Looking at all above advantages an RCD snubber is used which is connected across IGBT as shown in Figure 5-11.

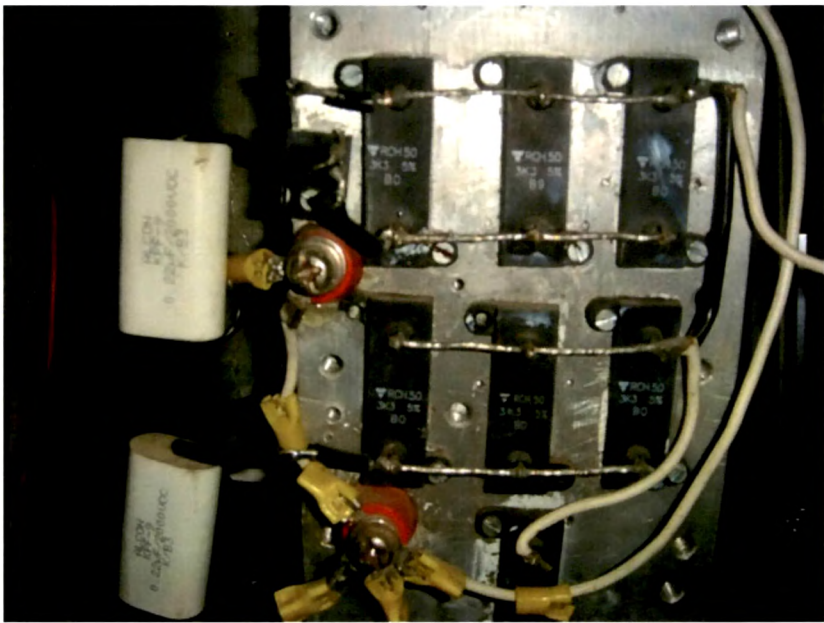


Figure 5-11 RCD Snubber

### 5.3 Summary

In this chapter the design & implementation of power circuit is presented. The calculations are shown & how to prepare inductor & capacitor are explained. The IGBT's are introduced & their types are explained. The new generation Trench/Fieldstop IGBT4 is selected and it is described how to connect two IGBT's in parallel. The need and details of RCD snubber is explained.