**Introduction**

As part of the control for the 400-GeV nuclear accelerator at Fermi National Accelerator Laboratory, we needed a power transistor with a safe operating area (SOA) of 1800A at 50V, dc current gain of 100,000 and 20 kHz bandwidth. Since the commercially available discrete devices and power hybrid packages did not meet these requirements, we developed a power transistor module, hereafter referred to as PTM, that enabled us to meet these requirements.

By connecting 13 power transistors in parallel, with due consideration for paralleling and the heat dissipation problems, and driving these 13 with another power transistor, what is realized, in essence, is a super power transistor having an equivalent current, power and safe operating area capability of 13 transistors. For higher capabilities, additional modules can be conveniently added.

**Definition of the Problem**

With the above requirements in mind, the development problem was to synthesize a physical package using commercially available components to satisfy the following objectives:

1. It should be relatively small in size and its physical configuration should be oriented toward flexibility of use and ease of maintainability.
2. Current output of 100A should be possible using commonly available op amp drivers.
3. The power dissipation of at least 1500W using 1 GPM 30°C water.
4. All transistors should share the current equally.
5. The failure of a single transistor should not affect the operation of other transistors.
6. It should accommodate the generally available power transistors.
7. It should be relatively simple and economical to produce.

The problem of developing such a package is an old one and it began with the production of the first power transistor. The solutions are many and range from a checker board arrangement on a 4 x 4' water-cooled copper sheet to an elaborate liquid nitrogen cooled assembly. This design follows "Value Engineering" approach and hopefully it will make the job of some people easier while stimulating others to develop better designs.

**Physical Characteristics of the PTM**

The Power Transistor Module is a sandwich-type structure, 3" square and 24" long as shown in Fig. 1. A water-cooled collector bus accommodates 15 TO-3 type power transistors and also serves as the power input terminal. The base bus with isolation diodes and the base input terminal is also mounted on the collector bar by means of insulated standoff terminals. A similarly constructed water-cooled emitter bus accommodates 15 current equilizing resistors, 15 indicating-type fuses and it also serves as the output terminal. The cooling water connections are by means of quick-disconnect type fittings. All copper surfaces are tin-plated, and the entire assembly weighs approximately 5 lbs. The total cost per module depends on the type of transistor used; in quantities of 10, the cost may range between $100 and $400.

**Thermal Characteristics**

The power transistor module was designed to be water cooled using 1 GPM 30°C water. The heat sink (collector bus bar) consists of a 3/16 x 1-3/4 x 24" copper stock with 1/4 OD x 0.030" wall copper tubing soft soldered all around. Quick-disconnect fittings are hard soldered to each end of the tube and the entire assembly is tin-plated .0005". The emitter bus bar is of similar construction, but its heat transfer requirements are less demanding.

Results of thermal tests on one module are shown in Fig. 3. The thermal resistance from heat sink to water is 0.24°C/watt at 1 GPM flow of 30°C water when dissipating 100W per transistor (1500W per module). Some improvement is obtained up to 2.0 GPM; however, beyond 2 GPM a point of diminishing returns is reached.

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DC Transfer Characteristics

The dc transfer characteristics, $I_C$ versus $I_B$ and $V_{BE}$ are shown in Fig. 4. The base-emitter voltage, $V_{BE}$ includes the diode drop in the base circuit plus the emitter resistor and the fuse drop. These curves were taken on a module having $13/2N5886$ transistors driven by another $2N5886$. Since the full output of 100A can be obtained with a current drive of 5mA and 4V, a commonly available operational amplifier is suitable for the purpose. The overall value of dc current gain, $h_{fe}$ per transistor is 100 @ 2A.

Frequency Response Characteristics (F/R)

Since in most of our applications power transistors are used in the linear mode within a feedback loop, the knowledge of the frequency response characteristics is essential. This information, however, is not generally available from the device manufacturers and furthermore may be quite involved to obtain by direct measurements. Our measurements indicate that the F/R of the PTM closely approximates the F/R of individual transistors. Result of one such measurement is shown in Fig. 5, where the frequency response of the emitter current to the base-emitter voltage is plotted. It should be noted that this measurement represents the response of a Darlington configuration, not a single transistor. These measurements indicate that the PTM using $13/2N5886$ power transistors driven by a single $2N5886$ is usable beyond 30 kHz (3 db down, 45 deg. lag.). Obviously, the specific F/R is function of the type of transistors, and the circuit configuration used.

Protection of the Power Transistors

Compared to a power vacuum tube, power transistor is a fragile device which requires protection against abnormal operating conditions and component failures. The abnormal operating conditions include:

1. High collector voltage.
2. High collector current.
3. Insufficient cooling.

The component failures include:

1. Power transistor short from collector to emitter.
2. Power transistor short from collector to base.
3. Change in current gain.

The protection against the above mentioned failures can be located on the power transistor module, on the assembly using PTM's or divided between the 2 locations.
On the PTM, provisions have been made for the following protection:

1. High Collector Voltage. A 50W zener diode designed to limit the collector to emitter voltage, can be located in one of the 15 TO-3 stations.

2. Secondary Breakdown. Additional components can be added to the PTM, which in conjunction with the 50W zener diode will minimize the negative resistance collector effects associated with reverse biasing of the base-emitter junction.

3. Indicating type isolation fuse in each emitter, to isolate transistors having collector-to-emitter shorts.

4. Isolation diode in the base of each transistor to guard against effects of collector-to-base shorts.

5. Emitter equalizing resistors in each transistor.

6. Test loop to accommodate a clamp-on current probe for current measurement in each transistor.

7. Temperature sensing bimetallic switch to sense abnormal temperature conditions.

On the assembly using PTM's, the following protective features are normally provided:


2. Overcurrent protection.

As part of the protection system, the PTM's are located in an accessible location where the condition of the individual transistors can be easily checked and the faulty components can be readily replaced.

Applications

The power transistor module was developed for use in the active filter of Fermilab RF Ferrite Bias Supply. This unit supplies 0-3000A dc in response to 0-10V at a 15 Hz rate into a 200pH, 4mΩ load. The additional essential requirements were low current ripple (1A or less p-p at 500A), small dynamic error (less than 1%)

and high slewing rate (200,000A/sec). To provide the required filtering and to serve as a source of high-frequency currents, 12 PTM's in parallel are connected as an active current shunt across the load. The entire active filter assembly, consisting of 12 PTM's a driver stage, cooling manifolds, collector and emitter bus bars and the emitter current sensor, is shown in Fig. 6. The driver stage consists of 4 power transistors in parallel driven by a monolithic Darlington stage. The entire assembly provides the safe operating area of 1800A at 50V for 16ms with current gain of 100,000 and 20 kHz bandwidth.

Fig. 6 Active Filter Assembly using Power Transistor Modules

In addition to the above application, the PTM has been used in a number of different applications at Fermilab. The largest one so far consists of 20 PTM's in parallel using 2N6259 power transistors.

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