EB108

Engineering Bulletin

Prepared by
Al Pshaenich
Power Products Applications

RELATIVE EFFICIENCIES OF MOTOROLA POWER SEMICONDUCTORS IN A PWM DC MOTOR CONTROLLER

RELATIVE EFFICIENCIES OF MOTOROLA POWER SEMICONDUCTORS IN A PWM DC MOTOR CONTROLLER

INTRODUCTION

The prime requisite of a power switch, semiconductor or otherwise, is to transfer the maximum power to the load and therefore contribute little system loss or dissipation. Additionally, the total system loss from an efficiency point of view should also include the input drive power, both forward for turning the device on and reverse for turning it off. How the relative efficiencies of the various power semiconductor switches compare will be demonstrated in a Pulse Width Modulation (PWM) application.

The semiconductors can be one of several types, be it a bipolar, Darlington, power MOSFET, or a GTO (Gate Turn Off) SCR. (A standard SCR can also be used with commutating circuitry however it is not included in this evaluation due to the additional circuit requirements and associated costs.) Motorola, with its extensive line of power semiconductors, manufactures all of these devices of which the 2N6487 bipolar, TIP100 Darlington, MTP12N06 TMOS (power MOSFET) and MCR5050 GTO were so tested. All devices are of comparable die size, package (TO-220) and current ratings, except for the GTO which has about twice the die area and current capability. All Devices Under Test (DUTs) were driven with the same test circuit; however, the forward input current (I_{B1}, I_G or I_{GT}) and input resistance were scaled for the particular DUT. Reverse current or turn-off current was derived from the same input clamp transistor switch and the magnitude of this current (I_{B2} or I_{GR}) was dictated by the DUT stored charge.

PWM DC MOTOR CONTROLLER TEST PARAMETERS

GENERAL

The load used in this test is a dc motor whose speed is controlled by PWM. Consequently, when narrow pulse widths are applied — low speed — the back emf is low and the load current (collector, drain or anode current) is high, about 11 A. To ensure device saturation under this worst case condition, adequate input current must be applied. For the devices tested, the forward input current for the bipolar, Darlington, TMOS and GTO were about 700 mA, 100 mA, 1.0 mA, and 120 mA, respectively.

Due to the motor time constant, the switching frequency was set for about 100 Hz and the min/max duty

© MOTOROLA INC., 1984

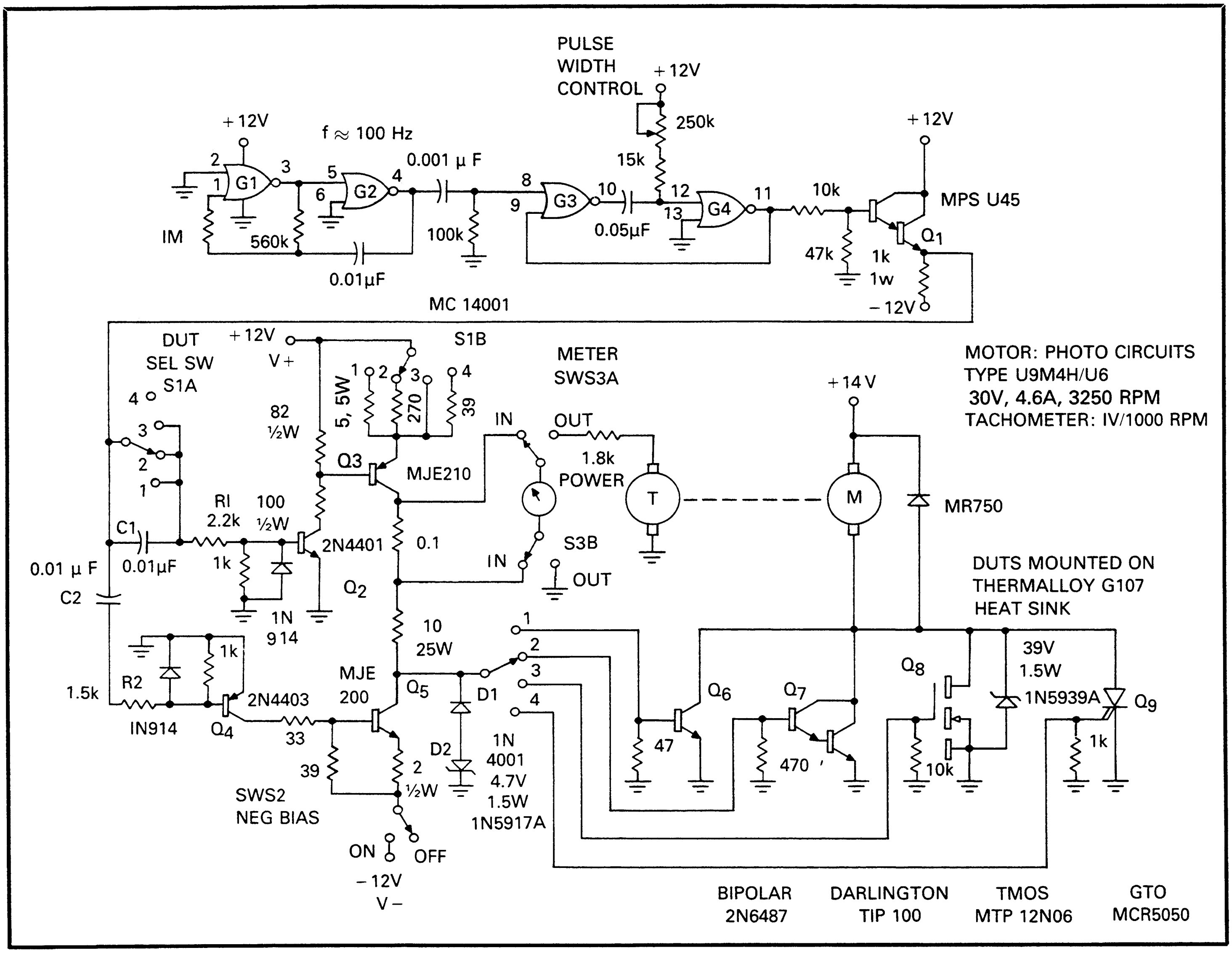

FIGURE 1 — Test Circuit for Measuring Relative Efficiency of DUT

cycles were about 8% and 70% respectively. At this low frequency, the use of off-bias for the bipolar, Darlington and TMOS produces negligible improvement in efficiency as the decrease in turn-off time is extremely small for the time frame involved. However, the GTO does require off-bias which for this test circuit and DUT was as much as 2.2 A lasting for about 10 µs. This turn-off power should be considered in the efficiency calculations. At low frequencies, it is relatively small, but as frequency increases, it can become substantial (refer to Figure 2 for drive circuits and input power equations).

The bipolar, Darlington, and TMOS are turned on by the input pulse whose width is a function of the required motor speed, whereas the GTO is turned on by a relatively narrow, positive gate current pulse and turned off by a narrow, negative gate current pulse. As the frequency is increased, it is apparent that the GTO input power increases and will reach a point where its input power is greater than that of the bipolar or Darlington. This crossover frequency is a function of the power supplies used and the particular duty cycle chosen. As an example, for a 50% duty cycle with the illustrated power supplies, this crossover point between the Darlington and GTO would be about 2.0 kHz.

TEST CIRCUIT ANALYSIS

The test circuit, shown in Figure 1, consists of a two gate CMOS, astable multivibrator (MV) clocking a CMOS configured monostable multivibrator (MV) to produce the approximate 100 Hz, variable pulse width output. Darlington transistor Q1 furnishes the buffered output to drive the two channels of the power amplifier, with transistors Q2 and Q3 supplying the positive input current to the DUT and Q4 and Q5 the negative current. When the DUT Selector Switch S1 is in positions 1, 2, or 3, the full pulse width will be applied to the DUTs as differentiating capacitor C1 is shorted out. Thus, positive input current is generated by the direct coupled pulse turning on the NPN transistor Q2 and the following PNP transistor Q3 connected, in positions 1, 2, and 4, as a constant current source. The respective emitter resistors set the current I_{B1} or I_{GT} for the DUTs. Negative current is derived by differentiating the input pulse with C2, R2 and using the negative going, trailing edge pulse for turning on the following PNP transistors Q4 and NPN clamp transistor Q5. Thus, an off-bias voltage (clamped by diodes D1 and D2) is supplied to the selected DUT. If required, the off-bias can be removed by the Negative Bias Switch S2.

The GTO requires only a relatively narrow positive gate current pulse to turn it on. This pulse is derived from the differentiating network C1, R1 (switch S1A open), with the positive going, leading edge pulse turning on Q2 and Q3. For the component values shown, a turn-on, positive drive current pulse I_{GT} of about 120 mA in amplitude and 40 μs wide is generated, followed by an approximate -6.0 V, 35 μs wide turn-off voltage pulse that is coincident with the trailing edge of the input pulse. This voltage pulse produces a reverse current I_{GR} of about 2.2 A for 10 μs (anode current of about 11 A) when the stored charge is depleted. Obviously, if no reverse bias is applied (Switch S2 open), the GTO will lose control, always being on, and the motor will run at its maximum speed.

RELATIVE EFFICIENCY MEASUREMENTS OF DUTs

In order to measure the relative efficiencies of the DUTs, both input power and output power are recorded. This is simply done by switching in a current meter to measure the average input current, or a voltmeter to measure output RPM by means of a tachometer coupled to the motor. The output voltmeter, in effect, measures the relative saturation loss of the DUT since this voltage is substracted from the applied motor voltage and, consequently, the motor speed will be indicative of this loss. Only the relative positive input current is measured as the reverse currents at this low frequency contribute very little additional drive power. However, as the power equations note in Figure 2, with increased operating frequency, this off-bias power can be substantial.

The relative efficiency measurements for the four DUTs are listed in Table 1. Of interest, in regards to efficiency, are the measured input currents (both pulsed and relative average), and tachometer outputs, on voltages and case temperatures. Within measurement repeatability, the DUTs with the highest On voltage had the lowest relative output power due to reduced motor voltage and the case temperature rise correlated with the total power dissipation (input plus output). These readings generally confirmed what was expected:

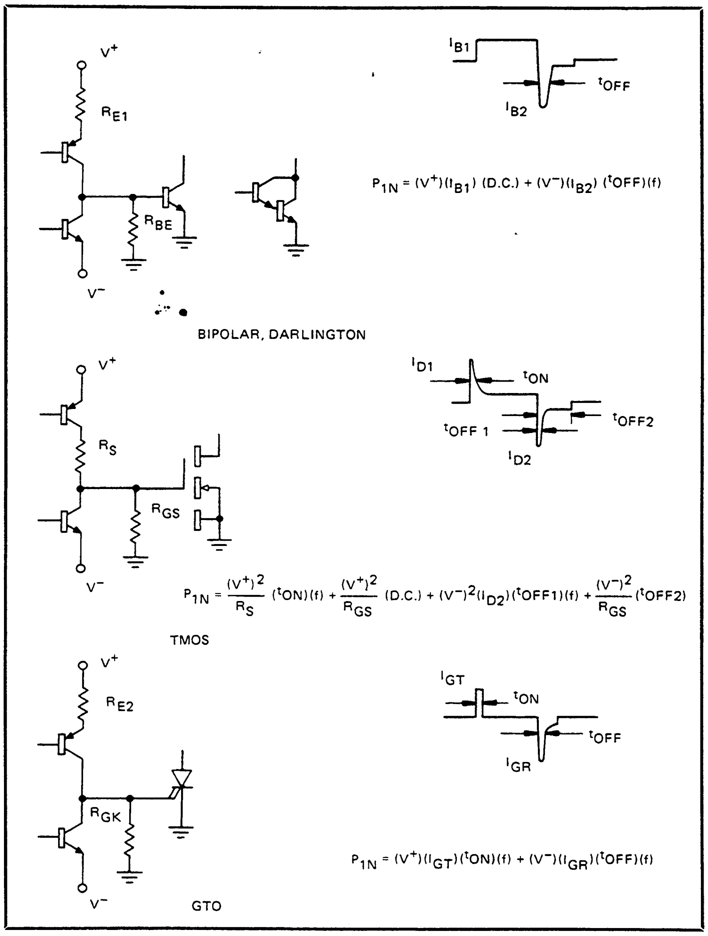

FIGURE 2 — DUT Drive and Input Power Calculation

DUT	BIPOLAR 2N6487			DARLINGTON TIP 100			TMOS MTP12N06			GTO MCR5050		
DIE SIZE (MIL)	110 x 130			120^2			120^2			180^2		
VOLTAGE RATING	60V			60V			60V			300V		
CURRENT RATING	15A			8A			12A			10A		
SWITCHING SPEEDS (RELATIVE)	MEDIUM			MEDIUM			FAST			SLOW		
INPUT CURRENT, FORWARD/(P.W.)	700mA			100mA			1.0mA			120mA (40µS)		
INPUT CURRENT, REVERSE/(P.W.)	1.0A@ I_{MAX} (0.2µS)			0.4A@ I_{MAX} (0.1µS)			0.2A@ I_{MAX} (0.1µS)			2.2A@ I_{MAX} (10µS)		
DUTY CYCLE	8%	12%	56%*	8%	12%	81%*	8%	12%	74%*	8%	12%	68%*
LOAD CURRENT, PEAK	11A	5A	0.9A	11A	5A	0.9A	11A	5A	0.9A	11A	5A	0.9A
POWER IN, (RELATIVE)	5	13	75	3	4	11	1	2	2	1	2	2
POWER OUT (RELATIVE)	20	59	85	16	57	84	17	59	87	17	55	84
$V_{(ON)IN}$	1.9V	1.3V	1.0V	2.8V	2.0V	1.6V	12V	12V	12V	1.4V	1.2V	0.85V
$V_{(ON)OUT}$	1.2V	0.4V	0.12V	2.1V	1.3V	0.78V	1.7V	0.9V	0.15V	2.0V	1.5V	1.0V
CASE TEMP	36.6°C	32.9°C	38.3°C	43.6°C	41.3°C	40.4°C	42.3°C	36.0°C	29.5°C	39.5°C	41.1°C	38.2°C

* CLOCK VARIED WITH TEMPERATURE

TABLE 1 — Relative Efficiency Measurement of DUTs

TMOS MTP12N06

At low frequency and low motor current, the TMOS is the most efficient device. Its input drive power is extremely low and its On voltage, due to the zero offset, relatively linear r_{DS} (On), is low.

BIPOLAR 2N6487

The bipolar, with its low V_{CE}(sat), has low output dissipation but its input power is the highest to satisfy high collector current — forced β conditions.

At medium and high load currents, the bipolar has the lowest On voltage followed by the TMOS with the Darlington and GTO being about equal in third place.

DARLINGTON TIP100

Total device dissipation and thus case temperature rise is due to input and output dissipation. The Darlington, with its high V_{CE}, can still have lower case temperature than the bipolar at some peak collector currents, due to its low drive power.

GTO MCR5050

The GTO is extremely efficient at low frequencies from a drive point of view since it requires only narrow turn-on and turn-off current pulses, but becomes less efficient as the frequency increases due to the higher duty cycles involved.

EFFICIENCY AS A FUNCTION OF FREQUENCY TESTS

The PWM Motor Control Circuit was tested at a constant, low frequency, so the relative efficiencies measured were primarily due to static (saturation) losses. To determine the effect of the dynamic (switching) losses, which increase with increasing frequencies, the four different devices were tested with a resistive load, using a variable frequency, constant duty cycle (50%) input signal. The load current was set for about 4.0 A (V_{CC} = 28 V, R1≈7Ω) and the same basic test circuit shown in Figure 1 was used. Most of the modifications were in the reverse bias circuit, with the off-bias voltage being either 0 V or −5 V for the bipolar, Darlington and TMOS tests and −12 V for the GTO.

Transistor Q4 emitter resistor (2Ω) was shorted out to form an off-bias voltage source; Q3 emitter was tied to the +12 V bus to furnish drive to Q4 when $V_{BE(off)}$ was 0 V; and differentiating capacitor C2 was increased to 0.02 μF to allow greater turn-off time for the GTO. Also, the bipolar forward base current was set for 600mA, resulting in a β_F of about 7.

TEST RESULTS

The results of this efficiency versus frequency test, as measured by the case temperature rise using a small heatsink, are shown in Figure 3.

TMOS MTP12N06

As expected, the TMOS device ran the coolest at higher frequencies, being very constant in temperature up to about 10 kHz and then rising slightly thereafter. At low frequencies, where static losses predominate, the TMOS MTP12N06 case temperature was only about 2°C warmer than the bipolar 2N6487, due to the respective saturation voltages of about 0.6 V ($r_{DS(on)}$ Typ = 0.15Ω) and 0.4 V. Although not shown, increasing the off bias voltage ($V_{GS(off)}$ from 0 V to −5 V showed only about a 2°C improvement at 33 kHz, due to slightly faster turn-off time; otherwise, at lower frequencies, the difference in turn-off time had little effect in case temperature.

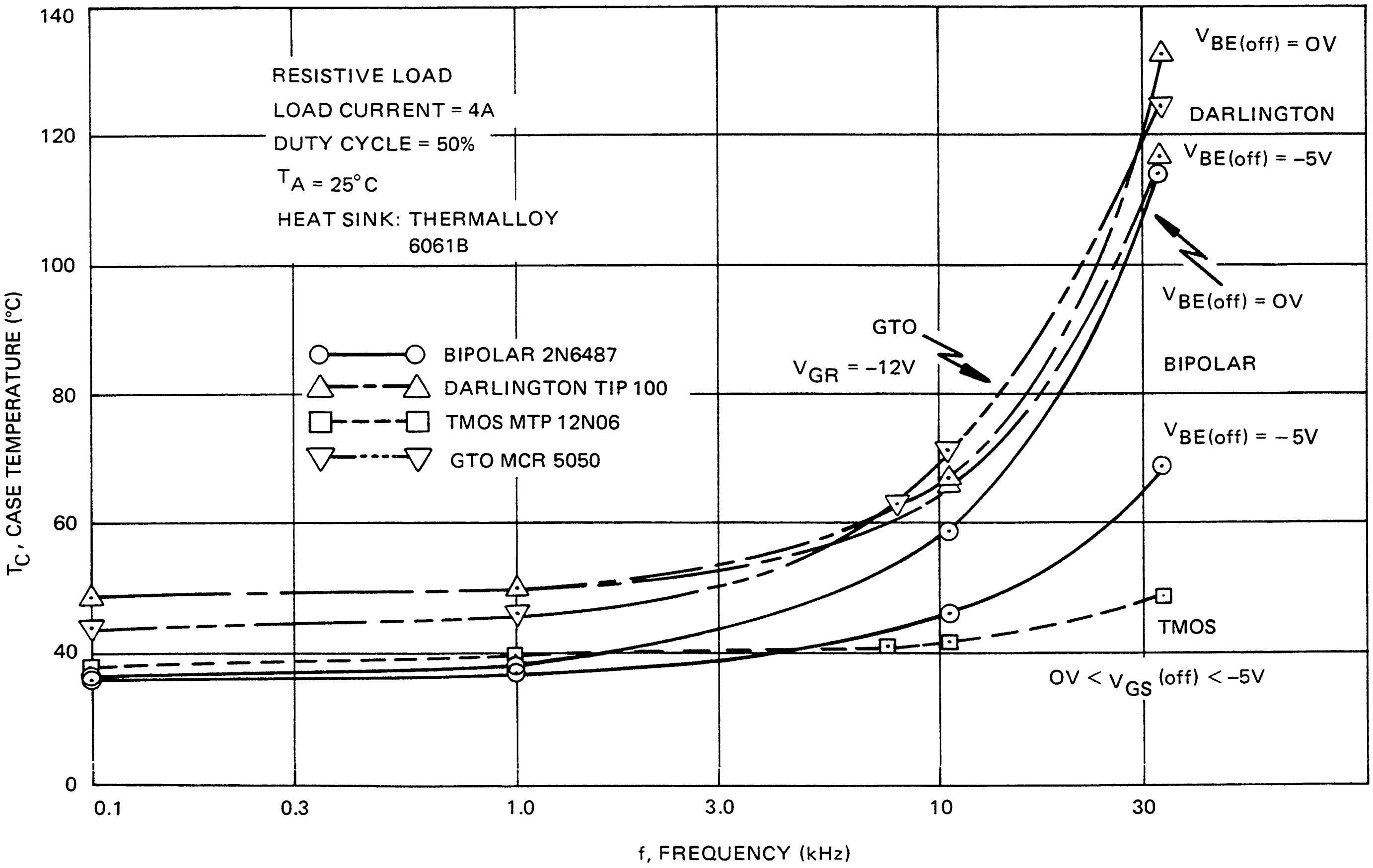

FIGURE 3 — Temperature Rise of Power Semiconductor as a Function of Frequency

BIPOLAR 2N6487

The bipolar transistor 2N6487 showed marked improvements in efficiency at the higher frequencies when the $V_{BE(off)}$ was increased from 0 V (base-emitter clamp) to −5 V. Without off-bias, the case temperature approached 115°C at 33 kHz, whereas, with −5 V, it was only about 70°C.

DARLINGTON TIP100

The low voltage TIP100 Darlington does not have a speed-up diode across its input emitter-base resistor and thus the stored charge of the output transistor cannot be efficiently removed. Consequently, there is no improvement in case temperature at low or nominal frequencies and only some moderate improvement at 33 kHz (117°C relative to 133°C) when the off-bias was increased to −5 V.

The Darlington, with the highest saturation voltage of the four devices, not surprisingly, had the highest case temperature at low frequencies and, beyond 5 kHz, was about as inefficient as the GTO.

GTO MCR5050

The GTO MCR5050 exhibited static losses somewhere between the bipolar and the Darlington due to its on-voltage of about 1.2 V at 4.0 A. The device did perform at 33 kHz, however, its case temperature rose to about 125°C. This was due to its relatively slower switching times, as shown by the oscillagrams in Figure 4. Figure 4 (A), (B) and (C) show the 33 kHz waveforms of anode current, anode-cathode voltage and gate current, respectively, relative to the TMOS drain current (Figure 4D) and drain-source voltage (Figure 4E). Note that the load current rise time is limited by the inductance of the wire-wound load resistor and that the TMOS switches much faster. Second, to ensure turn-off of the GTO at elevated temperatures, the peak reverse gate current with V_{GR} of −12 V was about 6.0 A with a pulse width of about 1 μs at the 50% point.

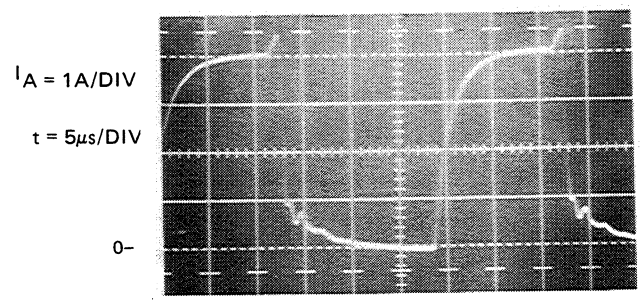

FIGURE 4A, GTO ANODE CURRENT

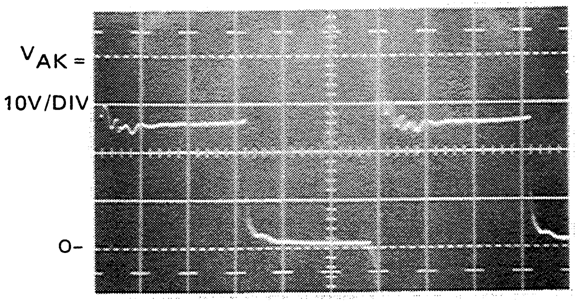

FIGURE 4B, GTO ANODE-CATHODE VOLTAGE

MCR 5050

$R_L \approx 7\Omega$

WIREWOUND
RESISTOR

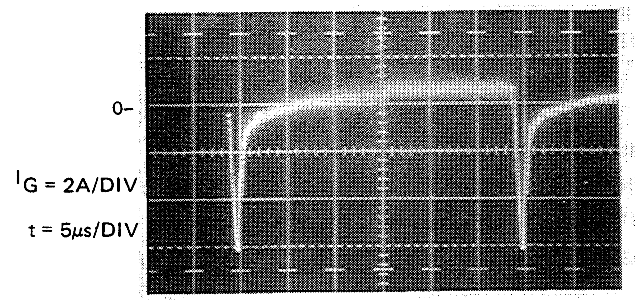

FIGURE 4C, GTO GATE CURRENT

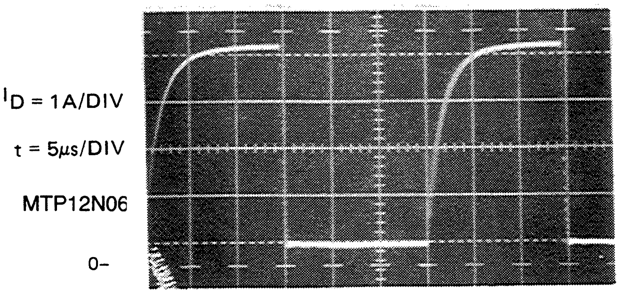

FIGURE 4D, TMOS DRAIN CURRENT

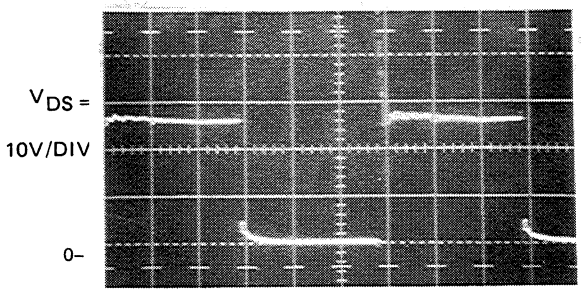

FIGURE 4E, TMOS DRAIN-SOURCE VOLTAGE

FIGURE 4 — Comparative Switching of a GTO and TMOS at 33 kHz

This page intentionally left blank.

This page intentionally left blank.

Motorola reserves the right to make changes without further notice to any products herein. Motorola makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does Motorola assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation consequential or incidental damages. "Typical" parameters can and do vary in different applications. All operating parameters, including "Typicals" must be validated for each customer application by customer's technical experts. Motorola does not convey any license under its patent rights nor the rights of others. Motorola products are not designed, intended, or authorized for use as components in systems intended for surgical implant into the body, or other applications intended to support or sustain life, or for any other application in which the failure of the Motorola product could create a situation where personal injury or death may occur. Should Buyer purchase or use Motorola products for any such unintended or unauthorized application, Buyer shall indemnify and hold Motorola and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that Motorola was negligent regarding the design or manufacture of the part. Motorola and Ⓜ are registered trademarks of Motorola, Inc. Motorola, Inc. is an Equal Opportunity/Affirmative Action Employer.

Literature Distribution Centers:
USA: Motorola Literature Distribution; P.O. Box 20912; Phoenix, Arizona 85036.
EUROPE: Motorola Ltd.; European Literature Centre; 88 Tanners Drive, Blakelands, Milton Keynes, MK14 5BP, England.
JAPAN: Nippon Motorola Ltd.; 4-32-1, Nishi-Gotanda, Shinagawa-ku, Tokyo 141, Japan.
ASIA PACIFIC: Motorola Semiconductors H.K. Ltd.; Silicon Harbour Center, No. 2 Dai King Street, Tai Po Industrial Estate,
Tai Po, N.T., Hong Kong.

MOTOROLA

16991 PRINTED IN USA (9/93) MPS/POD