A Dual High-Current High-Voltage Driver

Robin Shields and Robert A. Pease

Abstract— **A high-current driver which can control two independent 1.6-A, 20-V loads is described. Inductively-induced flyback voltage transients are clamped internally to safe voltages, for inductance values up to 80 mH. Short-circuit load conditions are tolerated and controlled.**

I. Introduction

THE design of circuits utilizing high-current n-p-n transistors to switch high-current resistive loads to ground is easy. However, if the load has an inductive component in addition to an ohmic value, when the load-switching transistor is switched OFF, the load voltage may rise to very high voltages, causing breakdown and likely damage to the transistor [1]. If a MOSFET is substituted for a bipolar transistor, some problems are avoided, but other failure mechanisms are still applicable [2].

In order to prevent this over-voltage situation from occurring, the load must be voltage-clamped to a safe, tolerable value for the output transistor. Frequently, an external clamp diode connected between the output and the power supply is a simple solution utilized to protect the output transistor. However, for high-performance applications where the stored energy of the load needs to be dissipated quickly, a high-voltage clamp is required so that a large V can cause a large di/dt.

A new circuit is described which is able to switch a load current of 1.6 A from a 20-V supply. At turn-off, the stored energy of the inductive load is dissipated internally, clamping the flyback voltage to 72 V. During this repetitive turn-off transient, the peak dissipation in the clamping circuit can be as high as 116 W for 2.4 ms typically. This monolithic circuit includes protection features for added robustness and comprehensive system interface capabilities.

II. Design Methodology

Fig. 1 shows the block diagram of one channel of the device. The control input provides the stimulus to drive the output transistor via the control amplifier and the linear current amplifier. The output transistor is surrounded by protection circuitry. In case the load is shorted from output to supply, a current-limiter circuit promptly decreases the current flowing in the output transistor to 2.1 A typical by way of a current regulation loop. After an internally-set time delay of 200 μs typical, the short-circuit detector sets the short circuit flag, indicating to the monitoring media that an overload condition exists. Additionally, the output transistor and associated drive circuitry are switched OFF for the remainder of the control input ON cycle. At the next rising edge of the control input, all internal monitoring circuitry is reset and the output is switched ON.

If the output transistor is switched ON and no significant load current is flowing after 200 μs, an open-circuit flag is set, indicating to the external monitoring medium that an open-circuit load condition exists.

An over-voltage detector circuit senses when the output voltage exceeds 28 V nominal. If this situation occurs, the output transistor and associated control circuitry are switched OFF promptly and remain so until the over-voltage condition is removed.

There are some additional situations which arise in the operation of an integrated circuit of this type in practical systems. An example is the situation when the load short circuit involves a long length of wire, perhaps in an automotive wireloom. A wire as long as 2–3 m can represent an inductance of 50–150 μH in series with less than 0.5 Ω. If such a load is connected to the output of this circuit, the power transistor can turn ON and pull the load to ground momentarily. When the small inductance causes the output current to build up to its maximum value, typically 3 A, the output transistor comes out of saturation and the output voltage rises up towards the 20-V supply. However, when the current-limiter circuit causes the output current to decrease from 3.0 to 2.1 A, or if any other transient causes a momentary decrease in the output current, the $\Delta V = L \times di/dt$ can cause the output to rise past the overvoltage detector threshold, at about 27 V. If this occurs, the output transistor is turned OFF promptly and the output voltage rises rapidly to the clamp level of 72 V. Momentarily, the dv/dt of the output voltage causes the output transistor to conduct, even although its base drive has been actively removed. Within a few microseconds, the output voltage falls back through the overvoltage detector threshold towards 20 V, allowing the output transistor to switch ON again. The repetitive cycling of this effect causes severe overheating of the output transistor, and destruction in less than 100 μs.

To prevent this mode of failure, improved protection circuits have been designed. These circuits sense the normally illogical condition of an over-voltage being detected at the output while the control input is high, instructing the output to be ON. (The logical conditions are: The output voltage is LOW when the control input is HIGH; also, the output is clamped HIGH momentarily on each cycle, after the control input returns to LOW.) If output HIGH and control input HIGH occur simultaneously, a gate (shown in Fig. 2) detects this condition, and the output transistor is switched off promptly and latched

Manuscript received January 31, 1994; revised July 25, 1994.

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IEEE Log Number 9404808.

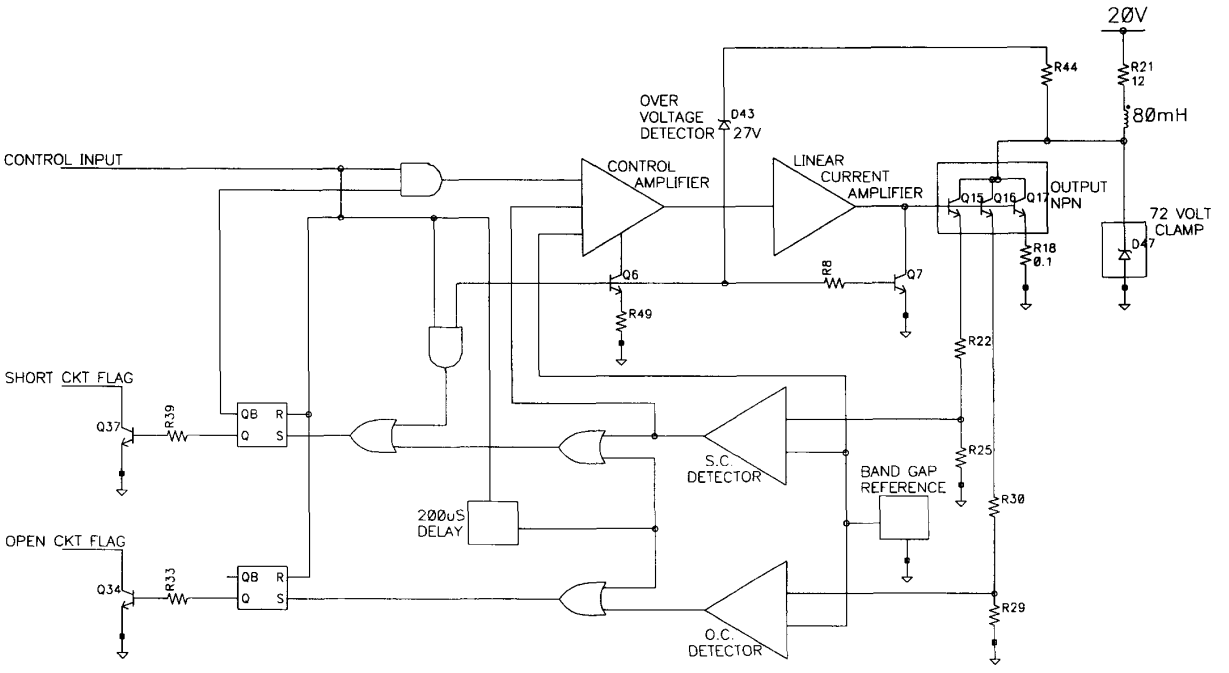

Fig. 1. Block diagram for high-voltage, high-current driver.

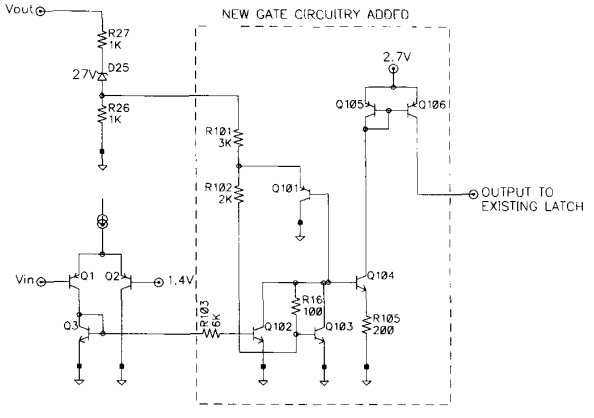

Fig. 2. Schematic diagram of gate circuit for over-voltage/over-current protection.

OFF until the next cycle of the control input signal. In this way, the severe overheating condition is considerably reduced, and no damage to the output transistor occurs.

When the V_{in} terminal is HIGH, $Q1$, $Q3$, and $Q102$ are OFF. Then if a transient higher than 30 V occurs at the V_{out} terminal, current will be fed through $R101$ and $R102$, turning on $Q103$, $Q104$, $Q105$, and $Q106$; $Q106$'s collector current will be fed to the Latch circuit, which turns OFF the $\text{n} - \text{p} - \text{n}$ output transistor. Transistor $Q101$ is added as a clamp to minimize the effect of very large signal currents through $R101$, and $R16$ and $R105$ also help to increase the current gain of this circuit for small signals, while decreasing the gain for large signals [3]. When V_{in} is LOW, $Q1$, $Q3$, and $Q102$ turn ON very quickly, and prevent any current pulse through $R101$ (which is a normal condition that occurs every cycle) from turning ON $Q103$, $Q104$, $Q105$, or $Q106$. When V_{in} goes LOW, this circuit must be able to rapidly gate OFF any current through $R101$; when V_{in} is going HIGH, the speed of gating is not at all critical. This gate appears to use a large amount of circuitry; however, one may observe that $Q102$, $Q103$, and $Q101$ can all be built in one epi tub, and $Q104$, $Q105$, and $Q106$ can all be constructed in one other tub, so this is actually a rather compact solution. (U.S. patent pending).

As previously discussed, the inductive flyback energy of the load (or long cable) is clamped internally. Due to inherent processing restrictions, the output n-p-n transistor itself cannot dissipate these large energy surges. Instead, high-power, deep-base vertical p-n-p structures have been designed in a high-voltage clamp circuit. Fig. 3 shows the schematic diagram of such a clamp circuit. The clamp voltage is derived as:

$$\text{VCLAMP} = (Vz1 + i1R5 + i1R4 + Vbe(Q4)) \times (R1 + R2 + R3)/R3.$$

Here, $i1$ is kept relatively constant by the use of $Q5$ and $Q6$ which dump excess current to ground, hence:

$$\text{VCLAMP} = (Vz1 + 1.5Vbe(Q5 + Q6) + Vbe(Q4))(R1 + R2 + R3)/R3.$$

A degree of thermal coefficient cancellation is employed to maintain the clamp voltage within 2 or 3 V over a 150° temperature range. The positive tempco of $Vz1$ is addressed by the negative tempco of the VBE's of ($Q4$), ($Q5$), and ($Q6$).

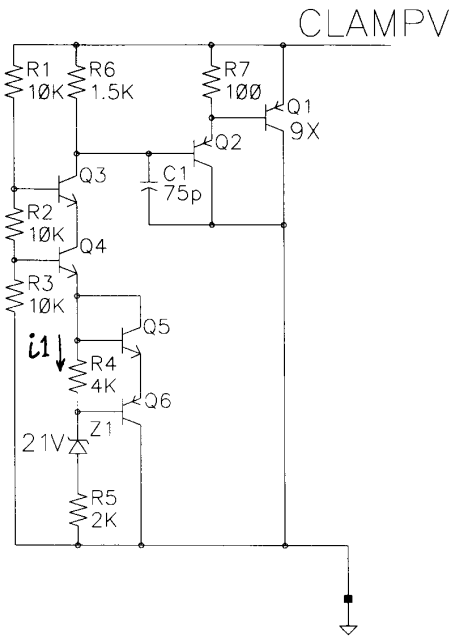

Fig. 3. Schematic diagram of 72-V high-current clamp circuit.

The resulting current flowing in $Q3$ provides drive to the $Q1$, $Q2$ power Darlington resulting in clamp voltages of 72 V at 1.6 A for milliseconds, or 75 V at 3 A for several μs.

Other device features include reverse supply protection and voltage transient protection on the supply rails for both integrated circuit power supply and load voltage supply rails. A thermal limit circuit detects excessive die temperature and can shut down the whole circuit.

III. Circuit Performance

Fig. 4 shows the Input/Output (I/O) response of one channel with a normal load of 18 mH and 15 Ω. The output transistor has a saturation resistance of 400 mΩ typical. The output clamp level at turn-off is 73 V for approximately 120 μs.

If this load is shunted by a low value resistance, the short-circuit current threshold is exceeded at around 1.8 A typical. Fig. 5 shows I/O waveforms where the short circuit threshold current has been exceeded. The output remains ON for the duration of the time delay of 200 μs, at which time the output is switched OFF and the short circuit flag is switched active LOW.

Fig. 6 shows a partial short circuit load condition of 36 μH in series with 4 Ω. Initially, the output transistor is allowed to saturate; however as the current builds in the load, the output transistor starts to come out of saturation. As the current regulation loop pulls the current down to the "short circuit current" value, the output voltage pops upwards in response. In this situation, the output voltage does not exceed the overvoltage detector threshold voltage, hence the output remains ON for the duration of the time delay period.

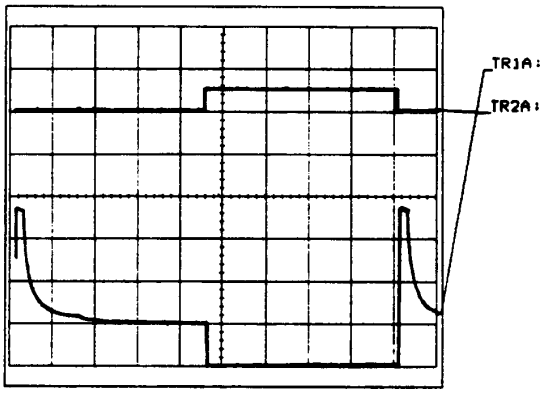

Fig. 4. Input/Output response of driver, with a 15-Ω, 18-mH load. $TR2A = V_{\text{input}}$, 10 V/div. $TR1A = V_{\text{out}}$, 20 V/div. Horizontal = 500 μs/div.

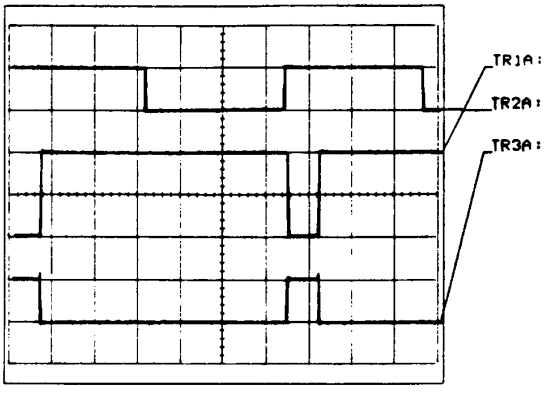

Fig. 5. Input/Output response of driver, with a 10-Ω load. $TR2A = V_{\text{input}}$, 5 V/div. $TR1A = V_{\text{out}}$, 10 V/div. $TR3A$ = short-circuit flag, 5 V/div. Horizontal = 200 μs/div.

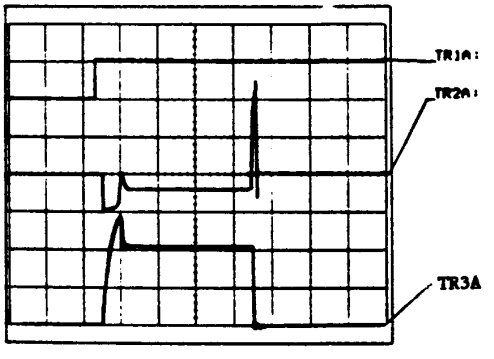

Fig. 6. Input/Output response of driver, with short inductive load, 4 Ω in series with 36 μH. $TR1A = V_{\text{input}}$, 5 V/div. $TR2A = V_{\text{out}}$, 20 V/div. $TR3A$ = output current, 1A/div. Horizontal = 50 μs/div.

Fig. 7 shows a partial short circuit load condition of 120 μH in series with 0.5 Ω, in a circuit where the gated latch is not connected. In this situation, the over-voltage detector

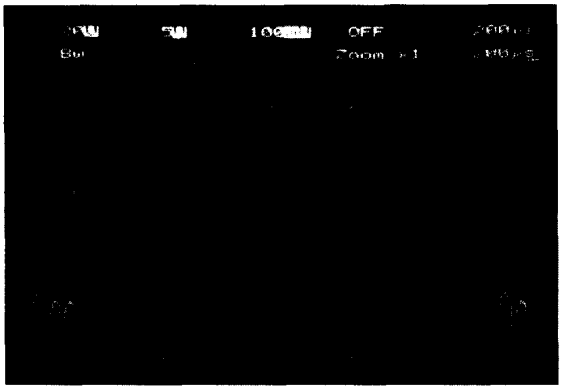

Fig. 7. Input/Output response of driver, with short inductive load, 0.5 Ω in series with 120 μH; gated latch is disabled. Upper trace = V_{input}, 5 V/div. Middle trace = V_{out}, 20 V/div. Lower trace = I_{out}, 2 A/div. Horizontal = 200 μs/div.

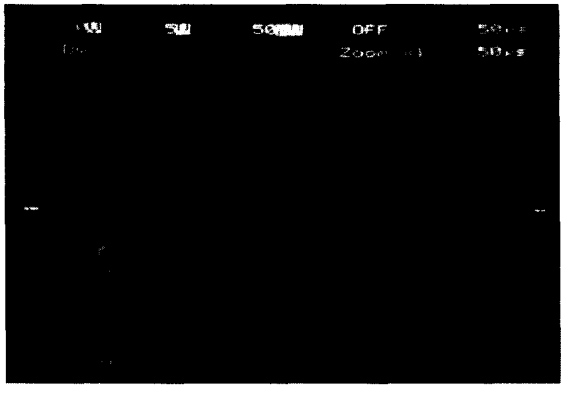

Fig. 8. Input/Output response of driver, with short inductive load, 0.5 Ω in series with 120 μH; gated latch is operative. Upper trace = V_{input}, 5 V/div. Middle trace = V_{out}, 20 V/div. Lower trace = I_{out}, 1 A/div. Horizontal = 50 μs/div.

threshold voltage is exceeded, and oscillation occurs at very high power levels. The power transistor is perilously close to destruction, and in fact if the power supply voltage or the load inductance were to be increased slightly, failure of the circuit would definitely result.

Fig. 8 shows the same partial short circuit load condition, with the gated latch connected. In this situation, when the overvoltage detector threshold voltage is exceeded, and the control input signal is also HIGH, the internal protection circuits promptly latch the output transistor OFF until the next rising edge of the control input.

This circuit was fabricated with conventional monolithic processes, on a silicon die of 201 × 157 milli-inches. The epi is 15 μ thick, at 5 Ω cm. The resistors are implanted at 2 kΩ per square, the base is 170 Ω per square, and there is a deep base at 30 Ω per square. The die-photo in Fig. 9 shows the large n-p-n power transistors at upper left and upper right. The deep-base p-n-p transistors are the H-shaped devices in the upper-center region.

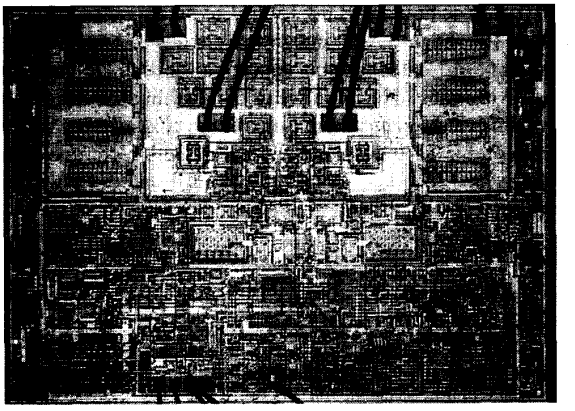

Fig. 9. Photomicrograph of dual high-voltage, high-current driver.

Some typical device characteristics are shown below:

CHARACTERISTICS

Supply voltage range	— 7–20 V
Supply current (quiescent)	— 4 mA typical
Supply current (both channels ON)	— 140 mA typical
Clamp energy rating (repetitive)	— 138 mJ at 80 mH and 72 V

CONTROL INPUTS

Input Impedance	— 80 KΩ typical
Input switch threshold	— standard CMOS/TTL

OUTPUT CURRENT DIAGNOSTIC THRESHOLDS

Open circuit threshold	—120 mA typical
Short circuit threshold	— 1.8 A typical
Diagnostic flags sinking current	— 5 mA typical

IV. Conclusion

This dual driver circuit with comprehensive protection circuitry is ideal for driving inductive loads such as electromechanical fluid valves where the time lag between electrical control signal and mechanical actuation is important to system accuracy. Its tolerance of inductive load transients, short circuits, and partial short circuits, coupled with internal diagnostics, gives it advantages over other solutions currently available.

Discrete bipolar transistors even as large as a 2N3055 still have only a finite tolerance for unclamped inductive-load energy, depending on how they are constructed. The obsolete single-diffused construction was more rugged than the epitaxial-base devices, which in turn are more rugged than modern high-speed planar devices [4]. Large discrete power MOSFET's such as the 60-V SMP60N06-18, which is rated to conduct 60 A, with an ON-resistance of 0.018 Ω, is only characterized with a Repetitive Avalanche Energy of 90 mJ (Absolute Maximum Rating) [5]. Similarly, the 60-V IRF151R, which is rated to carry 40 A with an ON-resistance

of 0.055 Ω, is only rated for 150 mJ of single-pulse avalanche energy [6]. High-power integrated circuits [7] are typically rated at 65 mJ, although this appears to be a single-pulse (not repetitive) rating. The circuitry of the dual high-voltage, high-current driver presented here is more rugged than these discrete or monolithic IC transistors, and can handle repetitive pulses as large as 138 mJ, with an 80 mH load and a 72-V clamp voltage.

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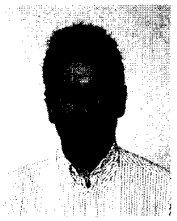

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