SGS-THOMSON MICROELECTRONICS

APPLICATION NOTE

TRANSISTORIZED POWER SWITCHES WITH IMPROVED EFFICENCY

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ABSTRACT.
An important objective for power electronic design is the reduction of power losses. This paper analyses the output characteristics of bipolar and MOS power stages and indicates limits for further on state loss reduction. A fast high voltage driver/switch combination with very low on state and switching losses is described. The switch is designed with cellular bipolar junction transistors driven by a smart power switch mode regulator. The driver handles duty cycles from 0...100 % and requires only one unregulated auxiliary supply. The static and dynamic behaviour of the switch and its new driver stage are shown and discussed. The switch exhibits low losses and is able to operate at inaudible switching frequencies on the rectified mains.

Keywords. Mains supplied operation, on state loss reduction, simplified base drive, smart power, high switching frequencies, Darlington, POWER MOSFET, cellular bipolar transistor.

INTRODUCTION

Loss reduction is a major objective in all power electronic equipment. The switching losses of all kinds of switching power semiconductors have been significantly reduced by means of structures with increased interdigitation, cellular structures and improved carrier lifetime control. Today performances are often close to those that physical laws allow. The switching losses have been reduced to such an extent, that lowering on state losses has become the key for further loss reduction. Further loss reduction can only be achieved through the reduction of on state losses which is the major topic discussed in this paper.

HOW TO REDUCE LOSSES?

Lowering on-state losses is of particular importance in inverter circuits operating with switching frequencies below 20kHz and in resonant converters where switching losses are already negligible.

For evaluation of on state losses, power semiconductor devices can be classified as:

a) devices with dominating resistive output behaviour

b) devices with dominating p-n junction behaviour of output characteristics (Fig.1).

The Power MOSFET (MOS), the Bipolar Modulated FET (BMFET)[5] and the Bipolar Junction Transistor (BJT) exhibit a resistive output behaviour (Fig.1a). Their on state voltage drop can be reduced through increasing die size, a question of technology and cost.

The Bipolar Darlington (DLT), the MOS Gated Bipolar Transistor (MOSBIP), the Insulated Gate Bipolar Transistor (IGBT) and Thyristors (GTO, FCTh...) exhibit a dominating p-n junction output behaviour (Fig 1b). The on state voltage drop of these devices is the sum of the threshold voltage of the p-n junction and the voltage drop across a resistance. The threshold voltage is determined by physical laws, only the resistive part of the on state voltage depends on the die size. The influence of die size on on-state losses is relatively limited and is not a feature that can be used to give significant loss reduction.

MOSFET AND BIPOLAR TRANSISTOR

The MOSFET, the BMFET and the BJT can have an on state voltage drop of less than 600mV and fast switching: A high power MOSFET e.g. a TSD4M450 ($R_{DS(on)} = 0.1\Omega$, V_{DS} =500V, I_D MAX = 45A) handles a current of 5 Amps with an on state voltage drop of only 500mV. The die area of such a device is about 170 mm^2. The MOSFET requires only short gate current pulses for its drive.

A very fast cellular BJT e. g. a BUF410 (450V/1000V, 15A) switches 5 Amps with about 500mV on state voltage drop. The die area of this device is about 36mm^2 and has therefore a very low silicon cost. The BJT requires base current:

— in excess of a fifth of the collector current
— and negative bias for fast turn off switching, immunity against reverse current and dv/dt.

Nevertheless, the power gain is very high, e.g. when switching 400V x 5A = 2kW, a drive power

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Fig.1: Symbols, equivalent circuits and output characteristics of power semiconductor devices;
a) devices with resistive output behavi0ur; b) devices with p-n junction behaviour

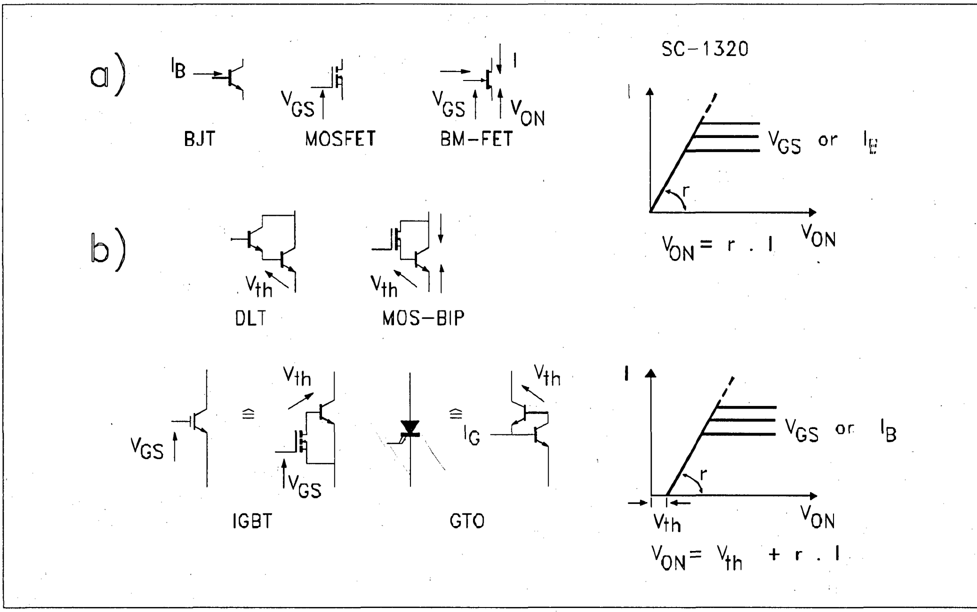


TABLE 1: On-state and driver losses of different device/driver configurations

Device + Driver	On-losses V_{CE} + I_C	Driver Consuptios V_S + I_B	Total Conductive Losses
BJT + (1)	0.5V x 20A = 10W	4A x 12V = 48W	58 W
DLT + (1)	1.5V x 20A = 30W	0.6A x 12V = 7W	37 W
BJT + (2)	0.5V x 20A = 10W	10W	20 W
DLT + (2)	1.4V x 20A = 28W	4W	32 W

of only 1A x 1V =1 W (base current multiplied by base emitter voltage) is needed.

The gap in die size between the POWER MOSFET and the cellular BJT, increasing with voltage and current, is so important, that it is worth thinking about low loss base drive for bipolar transistors.[1, 2, 3]

TRANSISTORS AND DARLINGTONS

The Darlington is the most popular switch in mains supplied, medium power applications. The major reason for this choice is its moderate base current consumption.

A typical fast switching 20A,450V Darlington requires a 0.6A base current. With a conventional driver circuit operating from an 8V to 12V auxilary supply, the worst case driver consumption would be 12V x 0.6A = 7W (Table 1).

The collector-emitter on state losses of the Darlington can be typically calculated to be about 30W. The total conduction losses amount to about 37W.

The bipolar junction transistor exhibits collector emitter on state losses of only 10W but requires a positive base current of 4A.

The total driver loss in the transistors is 4A x 1V = 4W (base current multiplied by base emitter voltage). With a conventional driver circuit operating

Fig. 2: Example of a switch-mode driver circuit for fast switching applications

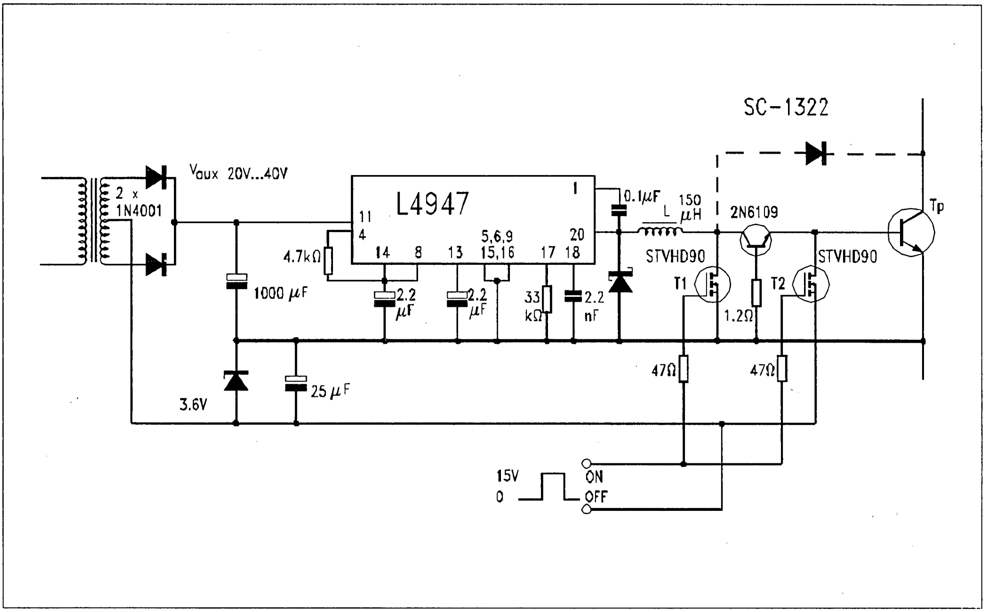
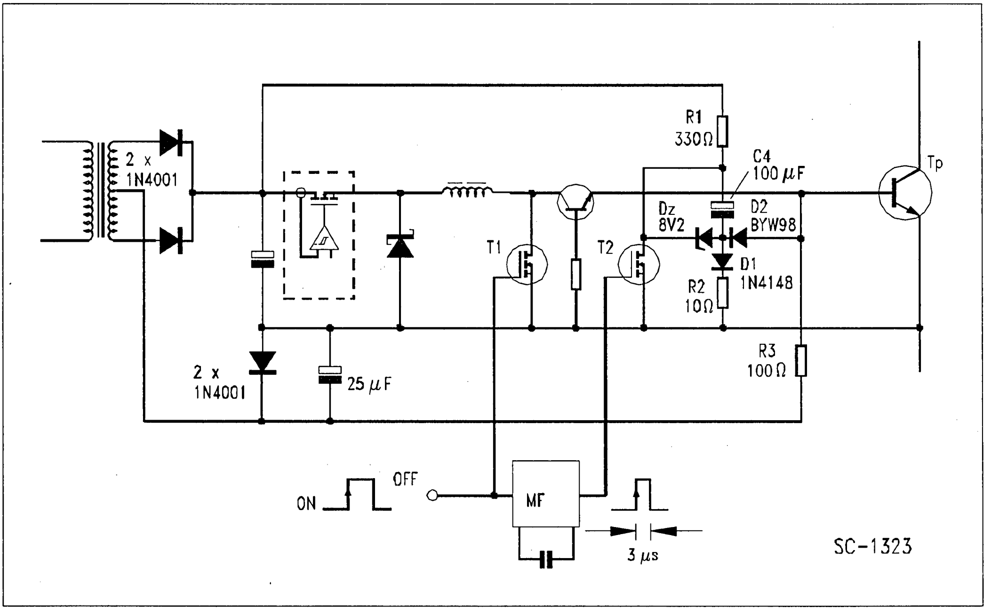


Fig.3: Self generation of negative bias from a positive supply voltage



from an 8V to 12V auxilary supply, the worst case driver consumption would be 48W - total conduction loss would be 58W. The poor efficiency of conventional driver stages is the reason that the transistor power switch exhibits higher conduction losses than the Darlington. Using driver stages with high efficiency allows BJT power stages to be used instead of Darlingtons which results in significant loss reduction.

DESCRIPTION OF THE SWITCH MODE BASE DRIVER

An L4974 smart power IC with a MOSFET output stage operates as a buck regulator in current mode. The IC is contained in a DIL package but is able to supply a 4 Amp base current. (Fig.2). The efficiency is so high that thermal conduction to the PCB provides sufficient cooling. During the off state of the power transistor, TP, a MOSFET T1 applies a short circuit to the output of the buck regulator. The IC operates with low duty cycle and maintains constant current in the choke L. For turn on of the power transistor TP, the MOSFET, T1, is turned off and the constant choke current flows into the power transistor's base. The rate of rise of base current is limited only by the MOSFET turn off speed. In order to obtain very fast switching, a high density MOSFET (STVHD90) which has a very reduced input and output capacitance, has been used.

If the power transistor base current is 4 Amps and the auxilary supply voltage 20V, the driver input current will be about 0.47 Amps. Increasing the auxilary supply voltage further reduces the input current.

NEGATIVE BIAS FOR FAST TURN OFF SWITCHING

The first version of the circuit generates negative bias with a Zener diode between auxilary supply and driver stage (Fig.2). The current return path to the auxiliary supply is through this diode. Losses in the Zener diode are small, due to the fact that input current of the driver circuit is small. For turn off, T1 and T2 are turned on, T2 applies the negative bias to the power transistor base, thus obtaining fast switching and immunity against reverse current and dv/dt.[4]

The second version of the circuit generates its negative bias directly from a positive auxilary supply:

a capacitor C1 (Fig.3) is permanently charged via a resistor R1 and a diode D1. At turn off switching, T2 is turned on for a time t1, slightly longer than the power transistor's storage

Fig. 4: Test circuits for switching losses

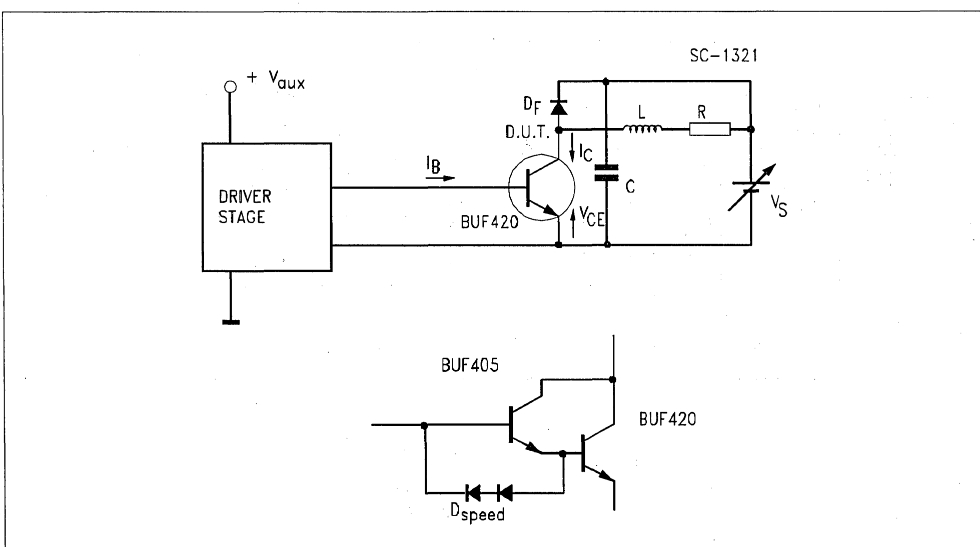
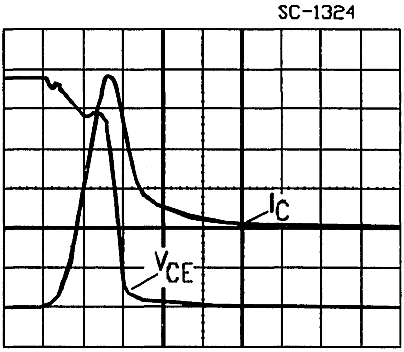
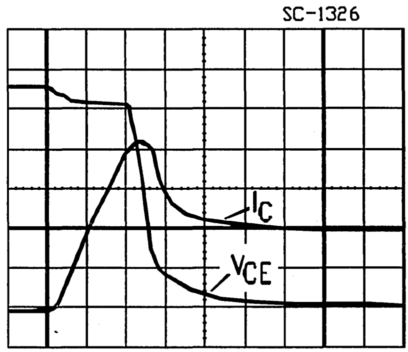


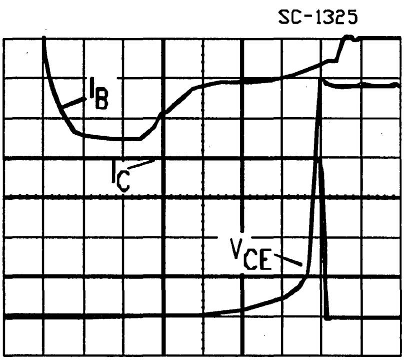
Fig. 5: Turn-on and off switching waveforms with transistors and Darlingtons



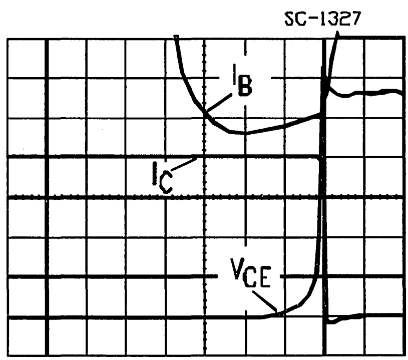
Darlington:
BUF405 + BUF420/BYT30-600
Turn-on: V_{CE} = 50V/div
I_C = 10A/div
t = 100ns/div
di_C/dt = 450A/μs



Bipolar Junction Transistor:
BUF420/BYT30-600
Turn-on: V_{CE} = 50V/div
I_C = 10A/div
t = 100ns/div
di_C/dt = 450A/μs



Darlington:
BUF405 + BUF420/BYT30-600
Turn-off: V_{CE} = 50V/div
I_C = 5A/div I_B = 2A/div
t = 500ns/div



Bipolar Junction Transistor:
BUF420/BYT30-600
Turn-off: V_{CE} = 50V/div
I_C = 5A/div I_B = 2A/div
t = 500ns/div

TABLE2: Switching energy losses of transistor and Darlington with BUF420 and BYT30-600

DEVICE UNDER TEST (DUT)	TURN-ON ENERGY	TURN-OFF ENERGY	TOTAL SWITCHING ENERGY
CELL. - BJT	1 mJ	0.5 mJ	1.5 mJ
CELL. - DLT	0.9 mJ	0.8 mJ	1.7 mJ

time, ts. T2 connects the positive electrode of C1 to ground, thus a negative voltage appears at the base of TP. T2 turns off after the turn off switching of TP and C1 continues charging. The state of charge of C1 is independant of duty cycle - sufficient negative bias is available with any duty cycle.

TEST RESULTS

Fast transistors and Darlingtons made using cellular technology (e.g.BUF420) have been tested in a buck converter with 280V supply voltage and 20A output current (Fig.4) Both types of switches have been driven from the same switch mode driver circuit. The turn on and turn off waveforms are shown in Fig. 5a and 5b. The devices were operated at Tj =85°C.

As expected, the turn on speed di_C/dt of the Darlington is twice as fast as that of the transistor switch. The reverse recovery current of the free wheel diode increases with di/dt. This makes the difference in turn-on loss between the fast switching transistor stage and the faster switching Darlington stage insignificant (Table 2). The storage time of a transistor stage is less than that of a Darlington stage. The test results confirm this well known fact.

With a given driver stage, the negative base current of a Darlington is reduced, due to the voltage drop of the speed up diodes. (Fig. 4) This explains the observed increased turn off losses with the Darlington.

CONDUCTION LOSSES

The conduction losses, including driver losses have been calculated and confirmed by measurement. With a duty cycle of 100% the total conduction losses of a 20A Darlington with conventional driver are O.6A x 12V + 1.5V x 20A = 37W. The same Darlington driven from the switch mode driver exhibits conduction losses of 32W. The conduction losses of the transistor with switch mode driver are 0.5A x 20V + 0,5V x 20A =20W.

This is about 60% of the switch mode driven Darlington.

CONCLUSION

Low loss driver circuits suffered from duty cycle limitations, or from excessive circuit complexity. New smart power devices reduce this complexity to an acceptable level, allowing the introduction of switch mode driver techniques in to transistorized power electronic equipment. The new configuration can be used to simplify and improve existing converter/inverter circuits (fewer auxiliary supplies, smaller heatsinks, higher efficiency).

The use of switch mode driver stages is not limited to BJTs, but offers improved efficiency in circuits with Darlingtons, BMFETs and GTOs.

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