# Arbitrary Waveform Power Controller for Thermal Measurements of Semiconductor Devices[1]

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Presented is a simple and easy-to-implement design for an arbitrary waveform power controller. The power dissipation in an active semiconductor device is controlled by virtue of its current and voltage for any waveform. By measuring the heating effect on an electronic product, an engineer can evaluate the effectiveness of its design. The controller is demonstrated practically with a MOSFET using an arbitrary waveform, and power dissipated in the device agrees well with intended dissipation.

*Introduction:* There is an increasing drive to reduce the size of electronic products. For high power products, the thermal ratings of components present a significant constraint on the design. An engineer must therefore ensure that components are adequately spaced and cooled to ensure that ratings are observed. Improvements in efficiency notwithstanding, reductions in volume can be achieved by more effective heat sinking, forced cooling and allowing components to operate closer to their ratings for longer [1-3]. In order to make these improvements, it is important to understand how the power dissipation in one device affects the temperature and characteristics of other components [3]. By applying an arbitrary power dissipation waveform to a device, mimicking operating conditions, it is possible to observe the transient and steady-state responses of its packaging, circuit board and heat sink arrangement. We can also observe how the collective power dissipation and ambient conditions around a group of devices brings them close to their individual ratings and affects their reliability. As a result, it is possible to evaluate the effectiveness of the thermal design during product development.

In order that a device accurately mimics its operating dissipation, a circuit is required to drive it such that its instantaneous power dissipation matches the desired operating waveform. Previous literature [4] has presented a method for this which involves pulse-width modulating a constant current and relying on the almost constant on-state resistance of a MOSFET, $r_{ds_{on}}$, to dissipate power corresponding to an arbitrary waveform. This set-up requires both complex switching logic and dummy loads, and feedback on the true value of $r_{ds_{on}}$ to account for differences between devices. It will not work with bipolar transistors, for example, whose on-state characteristics are not defined by a resistance. A more general purpose and easier to implement design is therefore presented here.

*Design Methodology:* For a bipolar junction transistor (BJT) or field-effect transistor (FET), such as those shown in Fig. 1, the instantaneous power dissipation ($p$) can be expressed as in (1) and (2) (see [5]). Power dissipation due to gate or base current can be neglected since gate current and the internal resistance of the gate terminal are negligible and $h_{FE}$, the BJT current gain, is large for most devices.

$$p_{FET} = v_{ds} i_{ds} \tag{1}$$

$$p_{BJT} = v_{ce} i_c + v_{be} i_b = \left( \frac{v_{ce}}{1+\frac{1}{h_{FE}}} + \frac{v_{be}}{h_{FE}+1} \right) i_e \approx v_{ce} i_e \tag{2}$$

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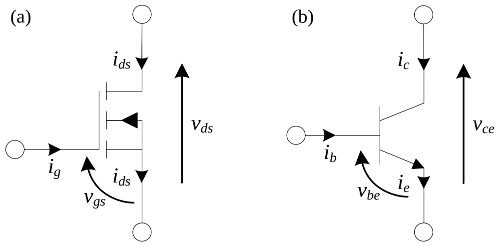


**Fig. 1** *Circuit diagrams of MOSFET (a) and BJT (b) with relevant voltages and currents indicated*

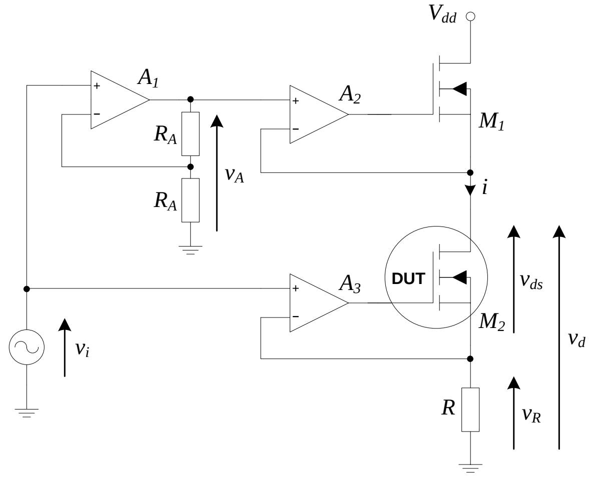


**Fig. 2** *Proposed design of arbitrary waveform power controller*

where $p_{FET}$ and $p_{BJT}$ are the instantaneous power dissipation in the FET and BJT respectively; $v_{ds}$ and $v_{ce}$ are the instantaneous drain-to-source (for a FET) and collector-to-emitter (for a BJT) voltage; $i_{ds}$ and $i_e$ are the instantaneous drain-to-source (for a FET) and emitter (for a BJT) current; $i_g$ and $i_b$ are instantaneous gate (for a FET) and base (for a BJT) current; and $i_c$ and $h_{FE}$ are the collector current and current gain of a BJT respectively.

Considering the case of a MOSFET, the power dissipated can be controlled by variation in $v_{ds}$, $i_{ds}$ or both. Possible approaches include varying $v_{ds}$ while keeping $i_{ds}$ constant, but this prevents $p$ dropping to zero because of the on-state resistance; and varying $i_{ds}$ while keeping $v_{ds}$ constant, but this requires complex circuitry to ensure stability since the gate signals for each transistor in the circuit are in anti-phase. In Fig. 2 we present a design which varies $v_{ds}$ and $i_{ds}$ in proportion to each other.

The combination of $A_3$, $M_2$ and $R$ form a constant current sink. The op-amp feedback controls the drain-source resistance of $M_2$ such that $v_R = v_i$ hence $i = \frac{v_i}{R}$. This is valid as long as the voltage $v_d$ is sufficiently greater than $v_R$ such that $v_{ds} \geq i \times r_{ds_{on}}$ (i.e. $R \geq r_{ds_{on}}$) or $v_{ce} \geq v_{ce(sat)}$ for a BJT, which is accounted for below.

The combination of $A_1$ and resistors $R_A$ provide an amplifier of gain 2. $A_2$ and $M_1$ are arranged in voltage-follower configuration and hence they keep $v_d$ at $2v_i$. The drain voltage ($v_d$) is therefore twice the source voltage ($v_R$) and it follows that $v_{ds} = v_R$. This means the voltages across $R$ and $M_2$ are identical and since the same current passes through both, they have identical instantaneous power dissipation as given in (3). $R$ can be adjusted to set the appropriate level of power dissipation and to ensure $v_{ds}$ and $i$ stay within device ratings for the required dissipation.

$$p(t) = \frac{v_i(t)^2}{R} \tag{3}$$

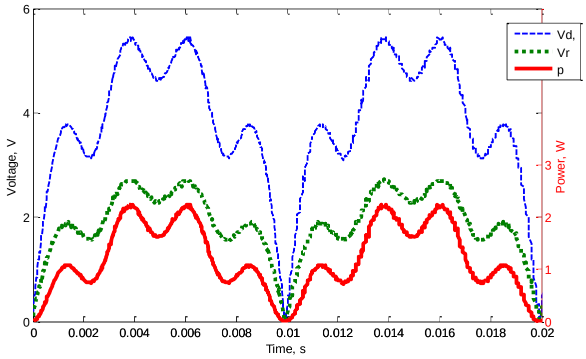


**Fig. 3** *Voltage and power waveforms observed on implemented system*

$R$ must be greater than $r_{ds_{on}}$ for MOSFETs otherwise the on-state voltage drop will be too large. For BJTs, $R$ must be large enough such that the peak input voltage, $\hat{v}_i$, is greater than $v_{ce(sat)}$ at $i = \frac{\hat{v}_i}{R}$ else the base of $M_2$ will saturate and the required voltage drop will not be possible.

The input waveform is set to the square root of the required arbitrary power waveform and scaled according to the required average power. The waveform would be supplied by an arbitrary function generator or from the output of a digital-to-analogue converter (DAC) from a microcontroller.

*Results:* Fig. 3 shows the measured voltage ($v_R$, $v_d$) and power ($p$) characteristics for the power controller circuit in Fig. 2, as constructed with op-amp LM324, MOSFET IRF510, $R_A = 1\,\text{k}\Omega$ and $R = 3.3\,\Omega$. $V_{dd}$ is regulated at 12 V. An arbitrary power dissipation function, $p(t)$, of $A(\sin\omega t + \sin^2 2\omega t + 1)$ is selected, where $A$ is a constant (fixed at 2.65 W), $t$ is time and $\omega$ is frequency. From (3), the input voltage waveform, $v_i(t)$, must be $\sqrt{AR(\sin\omega t + \sin^2 2\omega t + 1)}$. An 8-bit R-2R ladder DAC driven by a microcontroller is used to produce this waveform at 100 Hz.

The power output taken from $\frac{v_R v_{ds}}{R}$ shows good agreement with the intended function; they have a Pearson product-moment correlation coefficient of 0.998, an average power difference of 0.8% and the noise level is low. The direct control of both voltage and current ensures that power control is independent of semiconductor device nonlinearities.

The limit of accuracy comes from the gain and slew rate of the op-amps and the accuracy of $A_1$ which doubles the input voltage. At the low frequencies required for thermal experiments, op-amp proportional gain matches the output very well. The accuracy of the voltage doubler is dependent on the accuracies of resistors $R_A$; selecting low tolerance devices ensures correct voltage doubling. The resistance $R$ must also be accurately known as it directly affects power, as shown in (3).

*Conclusion:* A simple circuit to control the power dissipation in an active semiconductor device by controlling the device's voltage and current has been presented. By applying an arbitrary power waveform which mimics operating power dissipation, an engineer can evaluate the effect heating has on his design, and modify it accordingly. Practical implementation of the controller has shown a good match between actual and intended dissipation for an arbitrary waveform.

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