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Heat power source controller circuit

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Experimental works on thermal management of electronic systems, such as thermal resistance or thermal conductivity measurement, often require a controlled heat power source. This article proposes a circuit based on an integral automatic controller that sets a heat power dissipation level of a power metal-oxide-semiconductor field effect transistor used as a heating device. It can operate in dc mode, setting a steady power generation, and in pulsed mode, controlling a transient power wave form. The controller operation principle is established together with all details for its implementation and use. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1819451]

I. INTRODUCTION

Experimental works on thermal management[1] of electronic systems often require a controlled heat power source. The objective is to test package configurations and materials or the behavior under thermal stress of electronic components for developing new solutions.

There are several immediate solutions to implement heat sources from a standard voltage source, e.g., a resistance with an applied voltage or a power device, such as a metal-oxide-semiconductor field effect transistor (MOSFET) with a fixed gate voltage. Both solutions result in unstable heat generation due to the fact that resistance value and *I–V* characteristics of power MOSFETs change with temperature.[2] Moreover, heat power transient generation cannot be managed this way. When heat power must be steady, known and accurately adjustable, a more sophisticated feedback method is required. A heat power controller circuit has been designed and implemented aiming to obtain a versatile and useful experimental tool. Based on an integral automatic controller,[3] the proposed circuit is optimized to drive dynamically the gate of a power MOSFET device in saturation regime in order to dissipate a given amount of steady or transient heat power. A power MOSFET device is robust, versatile and can operate at relatively high temperatures (up to 175 °C the IXFH 76 N07-11 from IXYS), thus being suitable as a heat source. Nevertheless, other voltage controlled or gated devices may be driven by the proposed system with few adaptations.

An application example is described in Ref. 4 where the proposed circuit is used for an effective thermal conductivity measurement system.

II. OPERATION

The principle of the circuit operation is exposed in Fig. 1 and it consists, basically, of a feedback control circuit based on an integral regulator. Any fluctuation of the power generation level will be corrected immediately according to the reference signal. A Keithley 2420 high current source meter is used as the external voltage supply that provides a 60 W maximum power value. All needed implementation details are found in Fig. 2.

The ground of the controller circuit is chosen to be connected to the source of the MOSFET. This way the voltage V_G applied by the circuit is the gate-to-source voltage V_{GS} controlling the power device. The controller power supply is mounted in the same box and it is not shown in Fig. 2. It consists of two standard linear dc voltage sources set to supply +15 V and −15 V.

Drain current I_D is continuously measured by means of a shunt resistor R_{shunt}. V_{shunt} is a voltage signal proportional to the current. R_{shunt} must have a small and stable value even when high current causes a temperature rise. A RTO 20 from Vishay, was chosen with 1Ω of nominal value, 1% percent precision and packaged in TO220. The manufacturer ensures a stability of 150 ppm/°C. The drain-to-source voltage V_{DS} will vary depending on the current level due to the presence of R_{shunt}. This makes it essential again to implement a closed loop power controller that continuously compensates the V_{DS} drop increasing I_D up to the desired power dissipation level, instead of a current controller with a fixed V_{DS}.

The multiplier block of Fig. 1 produces a signal V_{pot} proportional to the heat power dissipated in the device P, that is used as the feedback signal for the automatic control:

$$V_{\mathrm{pot}} = KV_{\mathrm{DS}}V_{\mathrm{shunt}} = KR_{\mathrm{shunt}}P, \tag{1}$$

where K is a constant resulting from the proposed configuration of the AD633 analog integrate multiplier, its dimensions being V^{-1}. Its output signal V_{pot} is proportional to the product of two independent differential signals $X = X_1 - X_2$ and $Y = Y_1 - Y_2$, when Z is connected to the ground (0 V)[5]

$$V_{\mathrm{pot}} = \frac{(X_1 - X_2)(Y_1 - Y_2)}{10\ V} + Z. \tag{2}$$

The maximum voltage of the X and Y input signals is 18 V, but $V_{\mathrm{DS}}(Y)$ can reach the V_{CC} value (60 V in our case). A

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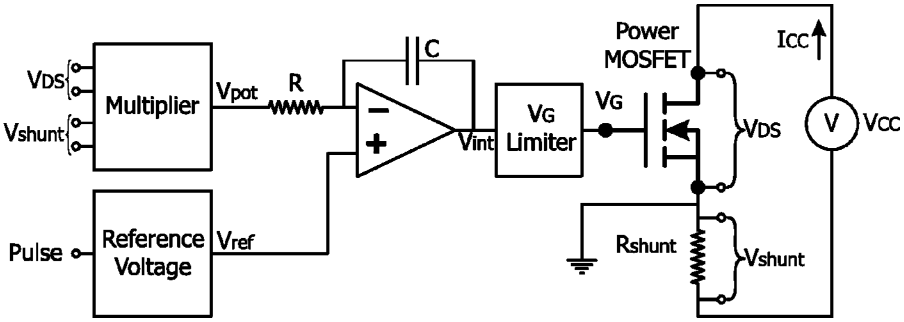

FIG. 1. Main parts of the power controller.

voltage divisor is implemented by resistances R_1 and R_2 in Fig. 2 getting approximately $Y = 0.2136 V_{DS}$ from its nominal values. The maximum Y signal value is maintained lower than 15 V, even with a V_{CC} of 70 V. If higher voltage is needed, the R_1 and R_2 pair should be modified. The final value of constant K is approximately 0.02136 V^{-1} in expression (1).

The V_{pot} signal is compared with the reference signal V_{ref} from the reference voltage block. Then, an integrator circuit made up of a LF411 general purpose operational amplifier and a RC pair generates a gate signal V_{out} such that

$$\frac{dV_{int}}{dt} = \frac{V_{ref} - V_{pot}}{RC}. \tag{3}$$

The V_{int} signal is connected to the MOSFET gate through a voltage limiter that will be explained further on. The power dissipated by the MOSFET in its saturation zone is determined by this gate voltage, closing the feedback loop. The controller response must be fast enough to seek a rapid V_{ref} transient evolution without endangering the system stability. $R = 1$ K and $C = 10$ nF have been chosen to obtain a stabilization time of V_{int} around 1 ms after a V_{ref} step.

If the heating device is dissipating an amount of power that produces a V_{pot} signal higher than V_{ref}, the gate signal is lowered, reducing the current I_D and V_{pot} towards the equilibrium state expressed by Eq. (4)

$$V_{pot} = V_{ref}. \tag{4}$$

Inverse reaction happens when the V_{pot} signal is lower than V_{ref}. The integral control eliminates the steady state error. From Eqs. (1) and (4) is deduced

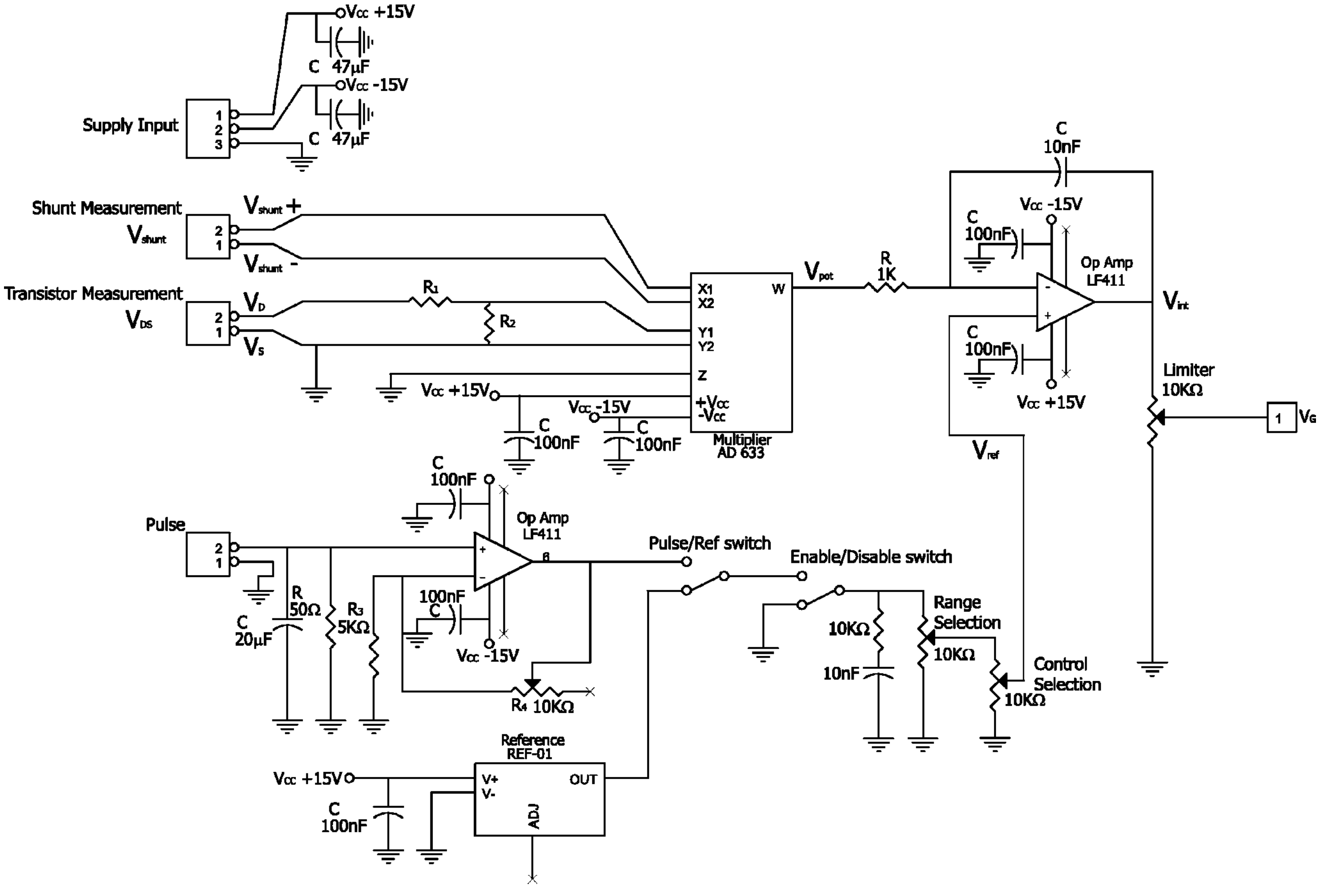

FIG. 2. Schematic of the implemented circuit.

$$P = \frac{V_{\mathrm{ref}}}{KR_{\mathrm{shunt}}}. \quad (5)$$

In the case of the chosen R_1, R_2 and R_{shunt} values an approximation of the controller gain is

$$P = 46823 \text{ mA } V_{\mathrm{ref}}. \quad (6)$$

If, due to reference demand, the compliance current of the power voltage source is achieved, the power source reduces the V_{CC} voltage near to 0 V keeping the current level. Consequently, the controller raises the gate voltage up to its limit (+15 V) attempting to increase the power dissipation according to the reference demand. Even fluctuations during normal operation at high current near the compliance value can produce this kind of failure. There is no way of leaving this trap state and once the control has failed this way, the power voltage supply V_{CC} must be turned off.

The described problem is solved with a potentiometer placed at the output of the integrator. This voltage divider prevents the gate voltage from exceeding a maximum V_{GS} voltage level selected by the user keeping the drain current below the compliance. The most suitable method is to set this limit as low as possible in accordance with the needed power level for the experimental work. The presence of the V_G limiter does not affect either the amount of controlled power or the quality of the control.

The reference voltage can be selected alternatively by the *Pulse/dc* switch. The dc part of the reference block is based on the voltage reference integrate circuit REF-01 from Analog Devices. It gives a stable 10 V dc voltage, and the final V_{ref} signal is chosen by the user via a voltage divider implemented with the *Range* and *Control* potentiometers. Both potentiometers must be multi-turn and very stable. The pulse part has been implemented in order to give the system the capability to dissipate arbitrary heat power wave forms (mainly pulses). An external signal input is adapted by an amplifier and connected to the integrator; R_4 resistor selects its gain. The input impedance can be adjusted with a *RC* pair, depending on the external signal source requirements.

The *Enable/Disable* switch connects V_{ref} to the selected voltage reference source (power enabled) or to the ground (power disabled). This stops power dissipation setting $V_{\mathrm{ref}} = 0$ V. A *RC* pair has been implemented in order to avoid switch bounce.

The controller user will proceed in the following way to set a particular power dissipation level using a fixed V_{CC} voltage value:

(1) set *Control* and *Range* potentiometers to their maximum value, then increase the *Limiter* potentiometer up to a value slightly above the maximum desired current level;
(2) adjust the *Range* potentiometer to obtain the maximum necessary current value; and
(3) choose the power level within the available power range with the *Control* potentiometer.

The circuit is mounted in a box and the shunt resistance and the MOSFET device are external to it and connected through the *shunt*+ and *shunt*−, *drain*, *source* and *gate* connections of Fig. 2. There is also a *Pulse In* coaxial connection for transient reference input.

The true generated heat power must be calculated as follows from the voltage and current applied by the power source, V_{CC} and I_{CC}, in steady state. The following expression consists of the product of the supplied voltage and current minus two minor terms, the lost power in the shunt resistor and the controller input

$$P = V_{\mathrm{DS}} I_D = V_{\mathrm{CC}} I_{\mathrm{CC}} - I_{\mathrm{CC}}^2 R_{\mathrm{shunt}} - \frac{(V_{\mathrm{CC}} - I_{\mathrm{CC}} R_{\mathrm{shunt}})^2}{R_Y}, \quad (7)$$

where R_Y is the input impedance of the V_{DS} measurement connection of the power controller circuit. This resistance is the sum of R_1 and R_2; nevertheless, for better reliability in power calculation its value should be directly measured, with the proposed configuration 10.21 ± 0.01 K.

As an example of the circuit operation the following parameters with $V_{\mathrm{CC}} = 60$ V and fixing $V_{\mathrm{ref}} = 0.61500$ V have been measured. The V_{pot} signal is 0.61594 V and produced current is $I_{\mathrm{CC}} = 502.8$ mA, therefore $V_{\mathrm{DS}} = 59.3196$ V and $V_{\mathrm{shunt}} = 0.5045$ V. Using Eq. (7) $P = 29.56$ W while the estimation of Eq. (6) gives a value of 28.79 W. The controller maintains these values fixed with a variation below 0.001% even after working 12 h.

ACKNOWLEDGMENT

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