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Analog Synthesized Fast-Variable Linear Load

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ANALOG SYNTHESIZED FAST-VARIABLE LINEAR LOAD

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ABSTRACT

A several kilowatt power level, fast-variable linear resistor has been synthesized by using analog components to control the conductance of power MOSFETs. Risetimes observed have been as short as 500 ns with respect to the control signal and 1 to 2 μ s with respect to the power source voltage. A variant configuration of this load that dissipates a constant power set by a control signal is indicated. Replacement of the MOSFETs by SITs to increase power handling, speed and radiation hardness is discussed.

INTRODUCTION

Fast-variable electronically synthesized electrical loads are thought to be desirable for control of certain quick responding space power generating systems that work best delivering a constant power, as for example the free-piston Stirling engine coupled to a linear alternator [1]. Such loads are also useful for testing the transient response, or stability, of various power generating and conditioning systems to sudden load variations.

This paper describes a several kilowatt power level linear resistor of variable value that has been synthesized electronically by using a fast analog multiplier and operational amplifier to control the conductance of one or more power MOSFETs. Unlike loads synthesized by digital switching of discrete resistors [2], here the control of resistance is very smooth. Because of feedback, this control follows a precise, device-independent rule. Moreover, the observed 500 ns risetime with respect to the control signal is considerably faster than the response of a known pulse-width modulator controlled load [3]. The potential for even higher speed and power based on the use of alternative transistors is pointed out. And this circuit may be reconfigured to dissipate a constant power, as set by a control signal, regardless of variations of the source voltage within some range.

PRINCIPLE OF OPERATION

Figure 1 shows the principle of operation to be that of a controlled current regulator, which, apart from the multiplier, is similar to the scheme used in a known current pulser [4]. The instantaneous load current (I) produces a voltage drop IR_S across the (fractional ohm) current sensing resistor (R_S). Within the range of normal operation, where the current control MOSFET shown is not saturated, the gate driving operational amplifier enforces the equality

$$IR_S = k V_C V, \quad (1)$$

where V_C is a control voltage and k is the product of the multiplier constant and any attenuation factor applied to the source voltage (V). Therefore this circuit appears to the power source as a resistor of value

$$R \equiv V/I = \frac{R_S}{k V_C}. \quad (2)$$

Note that in this simple dc analysis the value of the series load/current limiting resistor (R_L) does not enter, except as the dominant part of the least possible R , given by

$$R_{\min} = R_L + R_{DS,on} + R_S; \quad (3)$$

the on-state resistance ($R_{DS,on}$) of a high power MOSFET is usually fractional ohm. No higher order analysis is attempted here. Note too that V_C may readily be made composite, such as $V_C \rightarrow (V_C + V_0)$, since modern analog multipliers often have summing inputs to accept some additional voltage V_0 .

Power Ratings

The restrictions that heat sinking and dissipation ratings of R_L and the power transistor impose on the maximum permissible continuous source voltage (V_{\max}) are easily derived. Assuming controlled case temperatures, the dissipation limits $P_{T,\max}$ for the MOSFET and $P_{RL,\max}$ for R_L are then specified; the

absence of secondary breakdown in a MOSFET is clearly an advantage here. Neglecting R_S and $R_{DS, on}$, transistor operation will be within its Safe Operating Area, provided

$$\frac{1}{4} V_{max}^2 / R_L \leq P_{T, max} \quad (4)$$

and similarly heat damage to R_L will be avoided if

$$V_{max}^2 / R_L \leq P_{RL, max} \quad (5)$$

It follows that the minimum power rating of R_L must be 4 times that of the MOSFET to insure against heat damage at minimum R .

Increased Power

Paralleling resistors and transistors in order to increase load power is quite practicable with this circuit. One such arrangement that replaces the R_L -MOSFET combination of Figure 1 is illustrated in Figure 2. Although paralleling of resistors is easy, the paralleling of MOSFETs, which are hardly ever perfectly matched, requires care if performance is not to be compromised by unequal division of current. If the mismatch is not great, then the standard remedy shown of using low value source lead resistors suffices to enforce current sharing, but otherwise one may need more involved methods [5]. The small ferrite toroid shown in the gate leads chokes off any tendency of the transistors to oscillate in a circular mode. Two or more of the load units defined by Figure 2 may in turn be parallel connected to the same driver if the burden of driving the increased gate capacitance and the likely loss of speed are acceptable.

TEST CIRCUIT

The circuit outlined in Figure 1 was implemented using a Burr-Brown type MPY634BM wide bandwidth analog multiplier and a type 3554BM fast-settling operational amplifier for the driver. This multiplier has a 10 MHz bandwidth and a $\pm 0.5\%$ maximum 4-quadrant error, and the operational amplifier is rated to slew at 1000 V/ μ s and to settle to within $\pm 0.05\%$ in 150 ns. However, this multiplier has a 1% settling time of 1 or 2 μ s and this driver is limited to 0.1 A output current. Two 350 V load units, each as shown in Figure 2, were constructed on water cooled copper base plates and parallel connected to the same driver through 2 ft long coaxial cables. The type MTM15N40 is a 15 A, 400 V, 250 W, N-channel, enhancement mode power MOSFET - each load has two of these in parallel. Each of the 3 standard, aluminum housed, noninductive, 250 W rated resistors can dissipate at least 450 W to the water cooled plate, which is somewhat short in total power of the desired 4 times

the combined MOSFET power. Circuit details not shown include a provision to control the driver output to just below the MOSFET gate threshold voltage for the state of zero source voltage V . This obviates the need to move unwanted gate charge and thereby improves risetime in the case of a V -pulse rising from zero.

Performance

From the applications point of view, the aspects of most interest were taken to be risetimes with respect to both source voltage and control signal, linearity of the load current with respect to each of these voltages, and power dissipation capability. These interrelated properties are presented for the test circuit only to show what can be achieved with readily available components, but are otherwise very much dependent on circuit layout, component type, and power and current levels in complicated ways.

With source fixed at 350 V, the load current rose at about 16 A/ μ s maximum rate in response to a step in V_C . Output current limiting of the gate driver was found to be a large contribution to this limiting slew rate. The load current response to a 350 V source step rising in 1 μ s, with V_C fixed to give $R = 76 \Omega$, was a waveform of similar rise rate, but modulated by oscillatory transients. Thus the onset of these instabilities limited the usable source rise time to about 1 to 2 μ s. Load current traces produced by the above control and source step inputs are compared in Figure 3.

Several experiments were performed to test the bilinearity of the load current in V_C and V , as predicted by Eq. 1, since this property is important for use of the load in a control loop. These tests were based on large amplitude triangular waveforms ranging in frequency from 1 to 250 kHz for V_C and from 1 to 20 kHz for V ; V -source cutoff was responsible for the latter 20 kHz limit. Figures 4A and 4B show that good linearity of load current with V_C was obtained up to 250 kHz, a 0.4 μ s time delay and increased corner rounding being the only apparent infidelities at the high frequency. A 1 kHz triangular source waveform, with $R = 67 \Omega$, produced a load current trace that could be brought into indistinguishable overlap with the source waveform on the oscilloscope, as shown in Figure 5A. This experiment was repeated at 20 kHz and higher powers, with R set to 37 Ω and 67 Ω , and again practically congruent traces were obtained. The 20 kHz, 67 Ω traces are reproduced in Figure 5B.

Each load unit could consistently dissipate power up to the limits of its components, provided its base plate temperature was controlled and current sharing among its directly paralleled MOSFETs was enforced.

Deviation from equal current division among the load units was less critical because each unit remains individually protected. Should a MOSFET fail, experience has shown this circuit to be resistant to chain-reaction failure of the remaining MOSFETs. An overheated MOSFET usually short circuits and hence hogs the current, taking the load off the other MOSFETs and throwing the burden onto the resistors. This allows ample time for a safe shutdown or even a partial recovery through fused isolation of the failed unit. In my experience, the gate drive amplifier was never damaged by such a MOSFET failure.

SUMMARY AND DISCUSSION

A several kilowatt power level linear resistor of variable value has been synthesized electronically by using a fast analog multiplier and operational amplifier to control the conductance of one or more power MOSFETs. These transistors in series with low inductance power resistors are all mounted on a water cooled base plate and comprise a load unit. Two or more such load units can be operated in parallel from the same controller in order to increase the power dissipation capability. Experience has shown that this circuit is resistant to chain-reaction failure of the power MOSFETs. The electronic control of the resistance of this load is smooth and fast: load current risetimes of $0.5 \mu\text{s}$ have been observed with respect to the control signal. Usable risetime with respect to the power source voltage was a slower, but still respectable, 1 or $2 \mu\text{s}$.

This circuit may have the potential of even higher speed and specific power if the MOSFETs are replaced by a vertical channel power JFET called a static induction transistor, or SIT [6,7]. SITs have V-I control characteristics resembling those of a triode vacuum tube. In that sense a SIT is a closer approximation to a controllable resistor than is a MOSFET and hence may provide a faster response in the present circuit. Also, SITs are available in packages rated up to several kW and are highly resistant to fast neutron fluences up to at least 10^{13} n/cm^2 and to gamma irradiation up to at least 1.8 Mrads [8]. High power, speed and radiation hardness may make the SIT highly desirable in this load controller for use near space nuclear power reactors.

A potentially useful, although untested, variant of this load is the following. By reconfiguring the multiplier to form the quotient (V_C/V) of the control to the source voltage, this circuit can be made to dissipate a given power, as set by V_C , regardless of the variations of V within some bounded range. This mode of control may be useful in compensatory parasitic loading of constant power type generating systems.

ACKNOWLEDGMENTS

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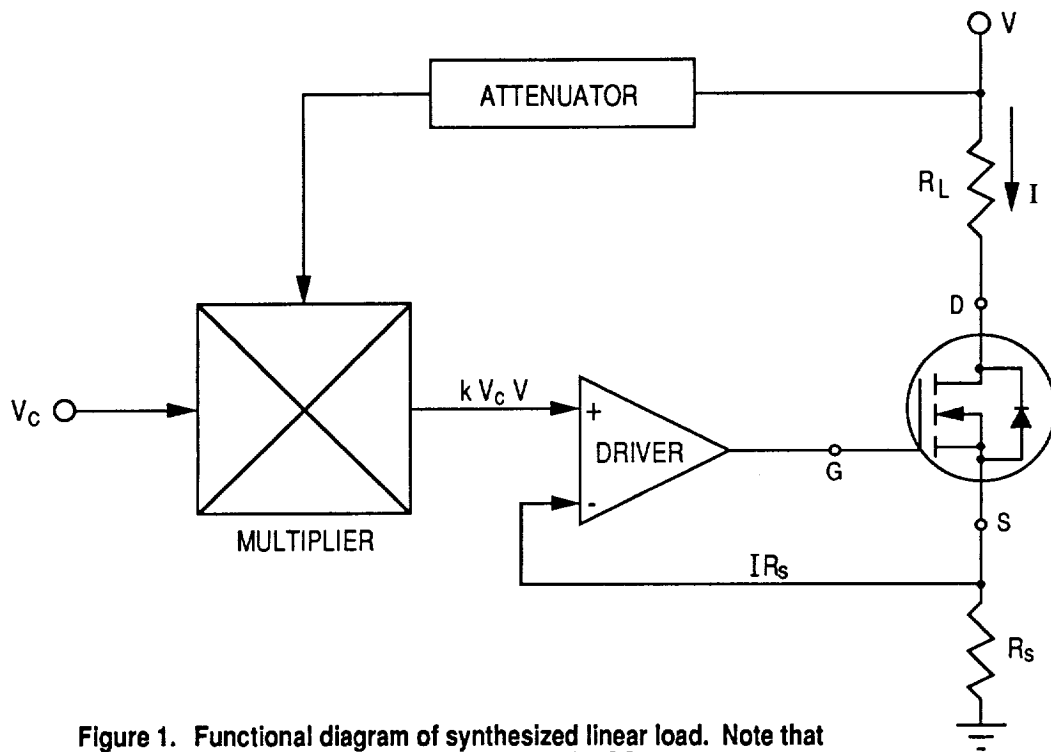


Figure 1. Functional diagram of synthesized linear load. Note that $V \geq 0$ is required by the N-channel MOSFET.

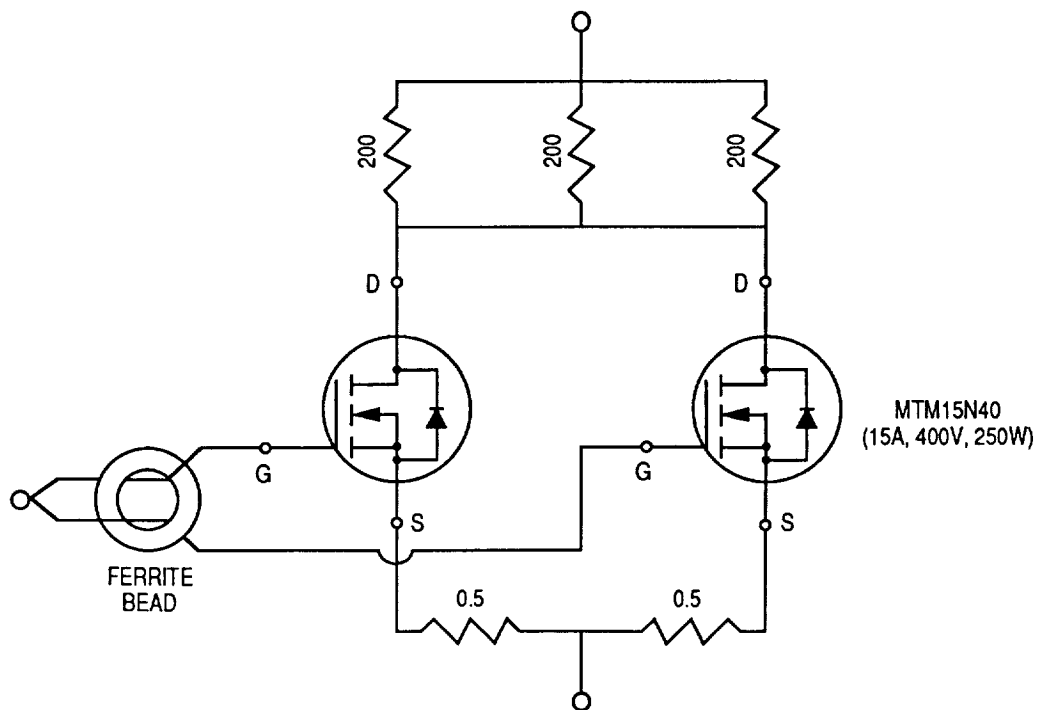
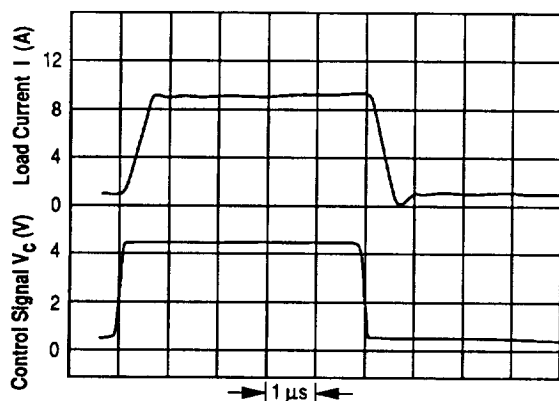
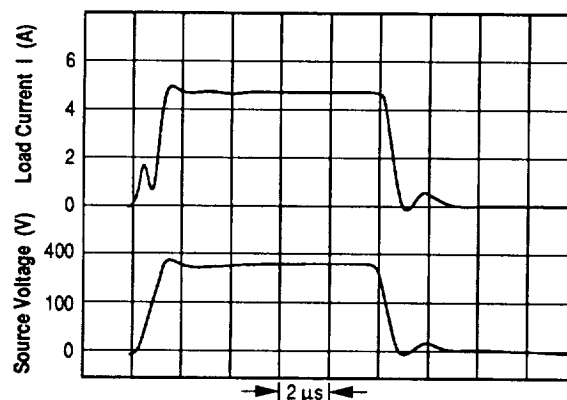


Figure 2. A 1500 W load unit using paralleled components. This unit replaces the R_L - MOSFET combination in Fig. 1.

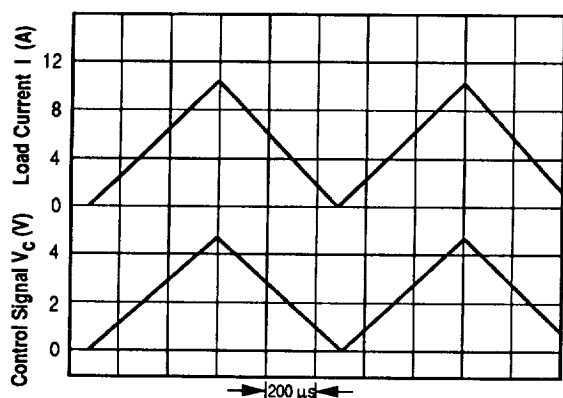


A. A load current step caused by a step in the control voltage V_c . Source: 350 V. The V_c shown varies the current between 10% and 90% of maximum.

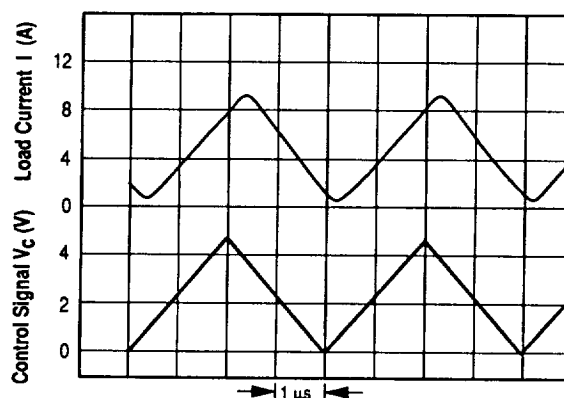


B. A load current step caused by a 350 V source step. V_c is fixed to give $R = 76 \Omega$.

Figure 3. Load current response to control signal and source voltage step inputs. Two paralleled load units were driven through 2 ft. long coaxial cables.

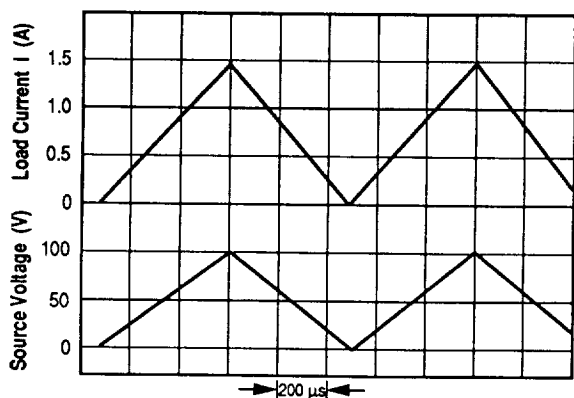


A. Control signal is a 1 kHz triangular wave.

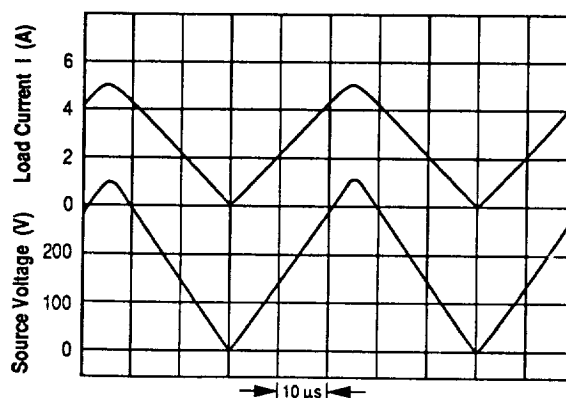


B. Control signal is a 250 kHz triangular wave.

Figure 4. Load current response to triangular wave control signals. Source: 350 V. Same load as in Figure 3.



A. Source voltage is a 1 kHz triangular wave.



B. Source voltage is a 20 kHz triangular wave.

Figure 5. Load current response to triangular wave source voltage variation. V_c is fixed to give $R = 67 \Omega$. Same load as in Figure 3.



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