of 1 hr, and hence lower in value for surface controlled, film forming reactions. These values are in agreement with that of Makrides[7] who reported that in $0{\cdot}52N$ H_2SO_4 iron corrodes at the rate of $5{\cdot}6 \times 10^{-4}$ amp/cm^2.

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Short Communications

A Linear Power Control Module

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A power control module with a linear transfer characteristic is described. Employing an inexpensive power transistor, 600 W of dc power is controlled. Effective control is possible from 0·2 to 100% of available power. The module is suitable for use with accurate temperature controllers of the programmed type.

POWER controllers with linear transfer characteristic are desirable where high accuracy in the controlled variable is the primary requirement. This is especially true where control is required over a large range of values of the variable, as in the programmed controllers. A switching mode power control module with a linear transfer characteristic developed for use in proportional temperature control systems is described in the present communication. The module is similar to the temperature controller[1] which uses vacuum tubes and relays. Solid state devices are used exclusively in the present system. The output power is directly proportional to the control signal with a linearity better than 2%. The control power is limited only by the maximum voltage and current ratings of the power transistor used as a series switch. The paper describes a circuit which controls up to 600 W with an input of ± 300 mV using a series-pass transistor well below its maximum ratings.

Principle of operation — Fig. 1 shows the block diagram of the complete unit. Square wave pulses are switched into the load from the power source. The frequency of the pulses is held constant, while the width is made proportional to the control signal. In the case of predominantly resistive loads, such as heaters, etc., the power is proportional to the duty ratio and hence the control signal.

As shown in Fig. 2, the outputs of the ramp generator and the control signal are added in the operational amplifier, the output of which drives a

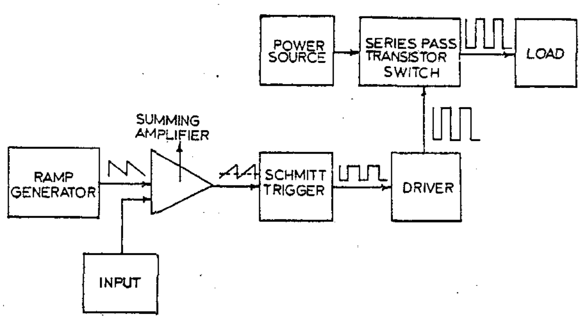


Fig. 1 — Block diagram of power control module

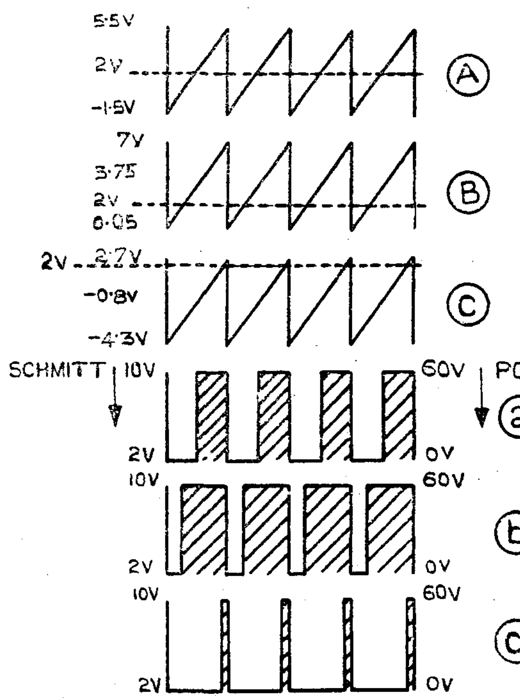


Fig. 2 — Duty ratio for various inputs [A, B, C, output of Q_6 for inputs 0, -150 and $+240$ mV respectively; a, b, c, output of Q_7 for the same inputs]

Schmitt trigger. Depending on the input amplitude, the reference 'pedestal' of the ramp is shifted up or down (Figs. 2B and 2C). Hence the Schmitt trigger is triggered at different points of the ramp, depending on the amplitude of the control signal. The Schmitt trigger always returns to the original state at the end of the ramp, the fall time of the waveform being very short compared to its period. As the period is constant, the pulse width is directly proportional to the control signal. The output of the Schmitt trigger goes to a driver, which supplies the necessary current to the series 'switch'. Power pulses with 'on' time proportional to the control signal are switched into the load.

Circuit description — Fig. 3 shows the complete circuit of the various blocks in Fig. 1. Transistors Q_1 and Q_2 form an emitter coupled multivibrator[2] with a constant current discharge path for the

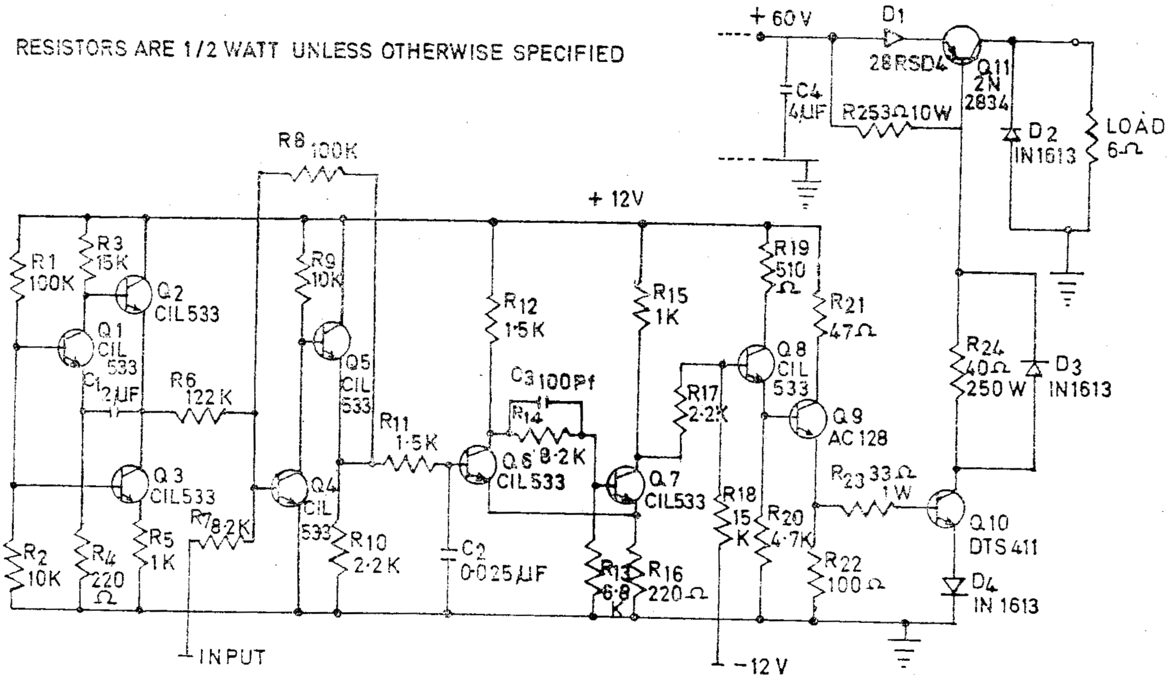
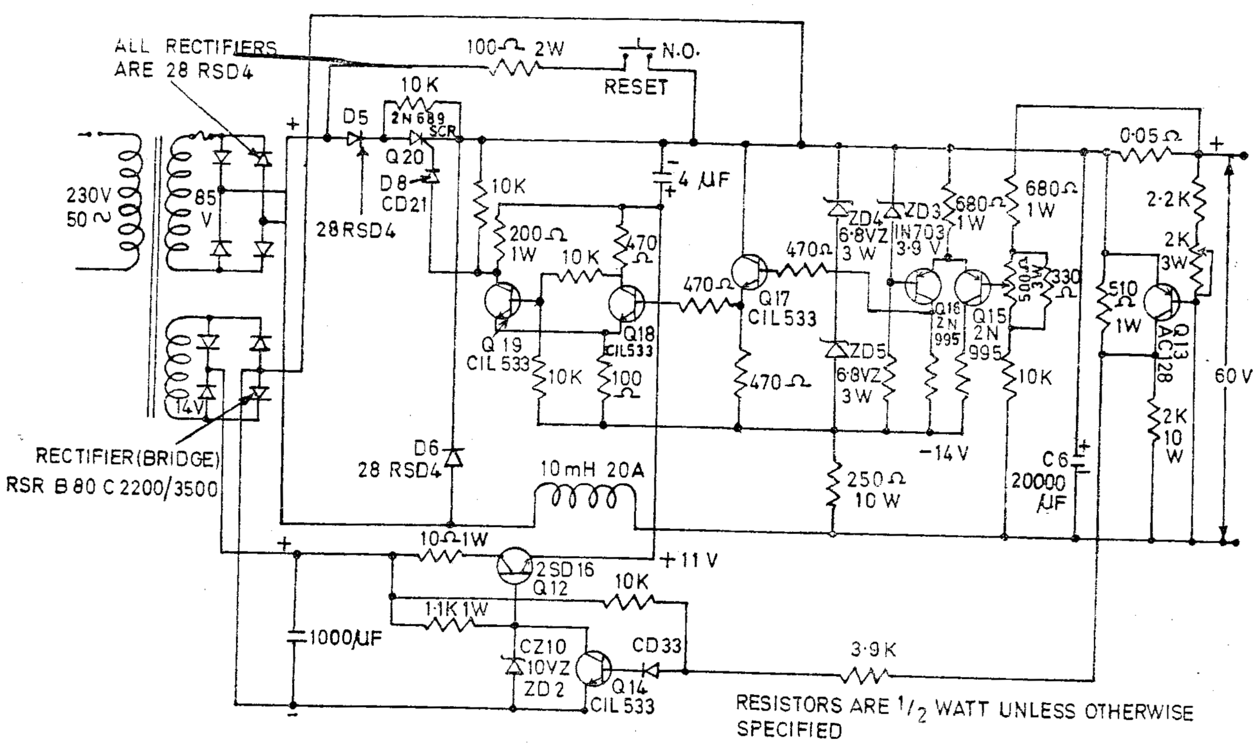


Fig. 3 — Circuit diagram of power control module



RESISTORS ARE 1/2 WATT UNLESS OTHERWISE SPECIFIED

Fig. 4 — Circuit diagram of power source

timing capacitor C_1. This configuration provides good linearity of the ramp and acceptable 'fly-back' characteristics. This circuit is chosen for its relative simplicity. Transistors Q_1 and Q_3 are mounted on a common header to reduce the dependence of frequency on ambient temperature.

A low frequency of 10 Hz is used to keep the dissipation in the power transistor at a minimum. The following three different operating modes of the transistor have to be considered in calculating the average power dissipation: (1) In the 'off' state the transistor has the full supply voltage across it, but the current flowing is very small, being equal to I_{CEX}. This component of the total power is relatively small; (2) in the 'on' state the transistor dissipates appreciable power equal to $V_{CE(sat)} \times I_C$; and (3) in the transient states (on-off and off-on), the peak power is high, being equal to $V_C I_C/4$. However, as the transient duration (10 μsec) is small compared to the period, the net contribution of this component to the average power is negligible at the frequency used. The transient component is proportional to the frequency[3] and becomes a significant part of the average power at frequencies above 1 kHz. The low frequency selected is, however, not a limitation for loads, such as heaters, etc., which have comparatively large time constants. It is easy to modify the circuit for frequencies up to 1 kHz with little change in performance.

The dc amplifier comprises transistors Q_4 and Q_5 and associated circuitry to include two inputs. Transistors Q_6 and Q_7 form a Schmitt trigger. The trigger has a differential between its upper and lower trigger points of about 0·5 V. The jitter in the circuit is extremely low even at small duty ratios, since the ramp generator and dc amplifier are stable.

The ramp generator, dc amplifier and Schmitt trigger are all wired on a printed card. This card is thermally insulated from the power transistor and other heat developing units.

Transistors Q_8, Q_9 and Q_{10} supply the necessary power required to switch the series transistor Q_{11}. The series transistor (2N2834) has a maximum current capability of 20 amp and a V_{CEX} of 140 V. The maximum power available from the device exceeds 1 kW. However, in the circuit shown, a power of only 600 W is switched into the load. The driver (DTS411) can supply more than 2 amp and can drive two power transistors in parallel with minor modifications. Diodes D_2 and D_3 'freewheel' to prevent sharp high voltage pulses (owing to stray inductances) appearing across the series transistors. All the power transistors are mounted on suitable heat sinks of conservative design.

Power source — The power source must have a reasonable regulation to enable operation in the vicinity of the maximum voltage and current ratings of the power transistor. This is also necessary to maintain a constant transfer gain for the controller when used in a closed loop system. Ordinary rectifier, L-C filter combinations are inadequate for this purpose. The requirement is a 60 V power source with a regulation of the order of 2% from zero to maximum load (15 amp). It would be uneconomical to design a linear power supply to meet these requirements. So a switching mode design using a thyristor is used (Fig. 4).

Transistors Q_{15} and Q_{16} (Fig. 4), connected as a differential amplifier, compare the output voltage with the reference and activate the Schmitt trigger through the emitter follower whenever the error exceeds a specific value. The thyristor Q_{20} is triggered by Q_{19}. Having turned on, the thyristor continues to conduct for one or more cycles until the Schmitt trigger is reset. The average output voltage of the supply thus oscillates between two close limits, depending on the trigger levels of the Schmitt trigger. The thyristor is mounted on a suitable heat sink, so that it can operate in an ambient of 40°C. The supply incorporates short-circuit protection through Q_{12}, Q_{13} and Q_{14}. The 0·05 ohm resistor in series with the load senses the load current. When it exceeds 15 amp, Q_{14} conducts shunting the Zener diode at the base of Q_{12}. Consequently, Q_{12} turns off removing power from the Schmitt trigger formed by Q_{18} and Q_{19}. SCR cannot turn on till the overload is removed.

Specifications of the power control module — The specifications of the module described are: Power available, 600 W; input required, ±300 mV; input resistance, 10 kohms (nominal); linearity, better than 2%; range of duty ratios, 0·2-100%; and temperature coefficient of duty ratio, approximately 1% per °C between 0·5 and 95% duty ratios (20-40°C).

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Analysis of the Effect of Variable Gravity & Free Convection on Boundary Layer Flows

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The problem of free convective heat transfer is analysed under conditions of uniform heat flux and uniform surface temperature with varying acceleration along the plate. The values of Nusselt number have been derived and compared with those for uniform gravitational field. On varying gravity, a zone of increasing heat transfer coefficients is obtained. The results obtained by this generalized approach compare favourably with those reported in literature, justifying the applicability of the method.

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