AN-509

Application Note

TRUE RMS VOLTAGE REGULATORS

Prepared by
Dave Perkins
Applications Engineering

This note describes ac voltage regulators that are ideal for use with electronic and electrical equipment such as lamps and heaters that are highly sensitive to supply voltage. These regulators maintain constant rms voltage levels for input or load changes.

MOTOROLA *Semiconductor Products Inc.*

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INTRODUCTION

Many types of electronic and electrical equipment are very sensitive to variations in their rms, or effective, supply voltage; examples are heating equipment, photographic enlarging, projection and spot lights, and certain types of motors.

For best results, this type of equipment should be supplied with a constant rms input, which can be provided by an ac regulator. For applications requiring only input voltage regulation, such as for loads that do not vary greatly, this regulation is relatively simple and straightforward. This is possible because the regulator can sense the sine-wave input. This type of open-loop or nonfeedback regulator is called a compensator in this note. However, when the load varies sufficiently that feedback is required to maintain a constant voltage, the problem becomes more difficult. The usual method of regulation requires controlling the conduction angle of a thyristor. This results in an output that is not a sine wave and its value is difficult to measure. No simple relation exists between the rms value and the peak or average value, which can be detected easily. Because of this, special circuitry must be used to sense the rms value in feedback circuits. Because of the feedback circuitry, this type of regulator is referred to as a closed-loop circuit, or simply as a regulator.

GENERAL DESCRIPTION

Operation of Phase-Control Circuitry

To understand the operation of the following regulator and compensator circuits, it is necessary to have a basic understanding of phase control. Figure 1 shows a simple phase-control circuit. The thyristor is inserted in series with the load and power source. At the beginning of each half cycle, the thyristor is in its blocking state, preventing power from reaching the load. At some point during the half cycle, the thyristor changes to its conducting state, permitting power to reach the load. The point at which this occurs is called the trigger or firing point. The periods of blocking and conduction are indicated in Figure 2. The portion of the half cycle from its beginning to the trigger point is known as the delay angle, while the remainder of the half cycle, while the thyristor is conducting, is known as the conduction angle.

The waveform and amount of the power reaching the load will depend entirely on the trigger scheme used by the control circuit. To hold a constant rms voltage across a load, it is necessary to delay the firing point of the thyristor as the input voltage increases. Sensing the input voltage is the technique used by the compensating circuits to be discussed, but obtaining increasing delay with increasing input voltage is just opposite of what normally happens in a typical simple open-loop phase-control circuit. Referring again to the simple phase-control circuit of Figure 1, as the voltage increases during each half cycle, capacitor C charges through resistor R; when the breakover voltage of the three-layer diode is reached, the voltage across that device drops, allowing the capacitor to discharge into the gate of the thyristor. The resulting current pulse turns the thyristor on and allows current to flow in the load. If the input voltage is increased, the capacitor

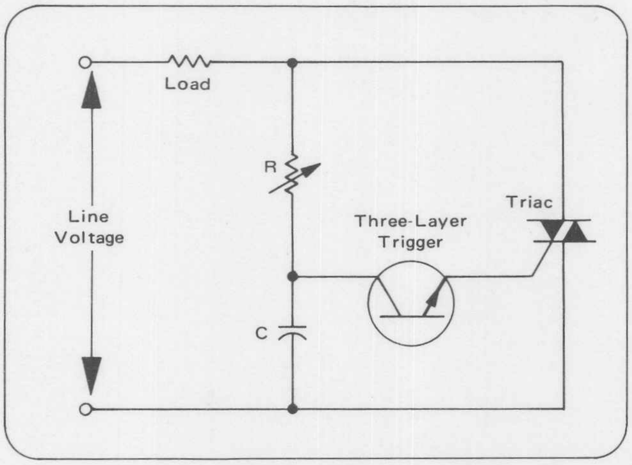

FIGURE 1 – Full-Wave Phase-Control Circuit

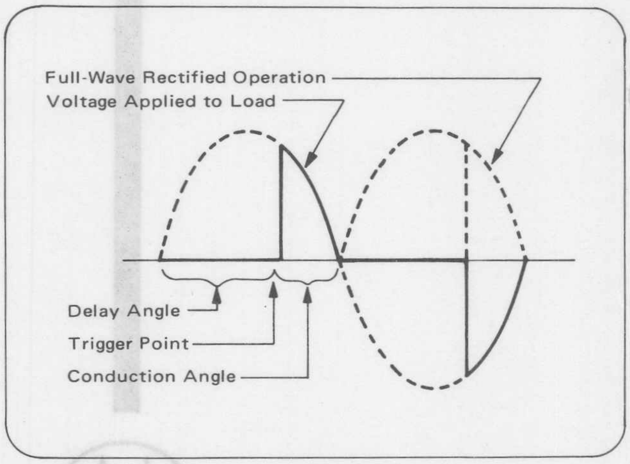

FIGURE 2 – Sine Wave Showing Principles of Phase Control

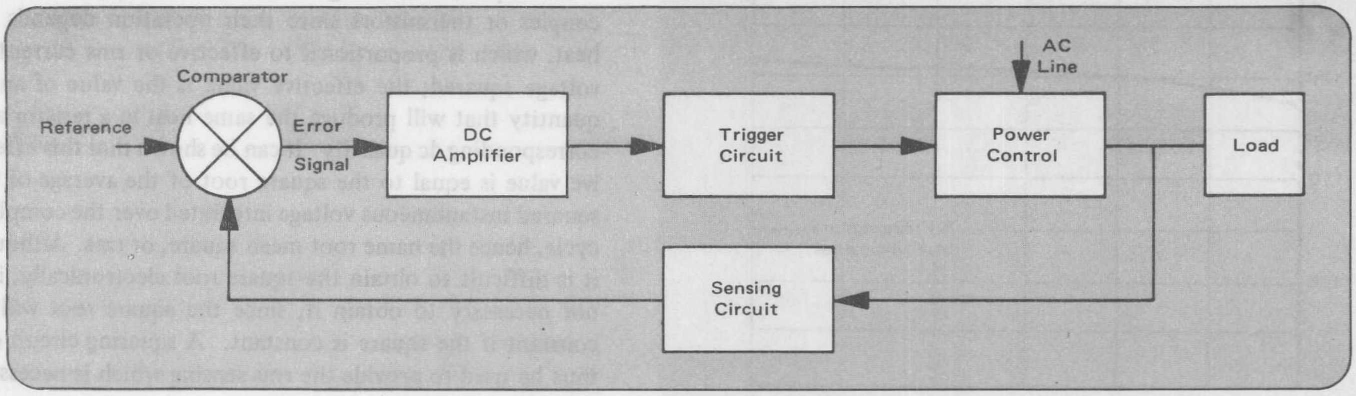

FIGURE 3 – Block Diagram of Closed-Loop Regulator

will charge faster, so the trigger point is actually reached sooner. In the light dimmer application, poor input regulation is acceptable since resistance R is usually manually controlled, allowing the user to set the light level desired for any input voltage level. However, for regulator applications adequate compensation circuitry must be provided to achieve the increased delay for increasing signal. Open-loop compensator circuits will generally be of a simpler form than the closed-loop feedback circuits, but they maintain good regulation over a more limited range.

Closed-Loop Regulating Systems

If the trigger delay is accomplished by sensing the load voltage, then the circuit is of the closed-loop type. The most important circuit section, since it determines the range of regulation, is the sense circuitry. It is also the most difficult part of the circuit to design in a closed-loop regulator since the actual voltage waveform across the load may vary from an almost pure sinusoid for full conduction to a series of short alternating positive and negative pulses for a very small conduction angle. True rms sensing must be used instead of the simpler peak or average sensing because at every conduction angle, the relationships between the rms, average, and peak quantities are different.*

Characteristic of a closed-loop circuit is the error signal, the difference between a reference signal and the sensing circuit output. These signals as well as the functions

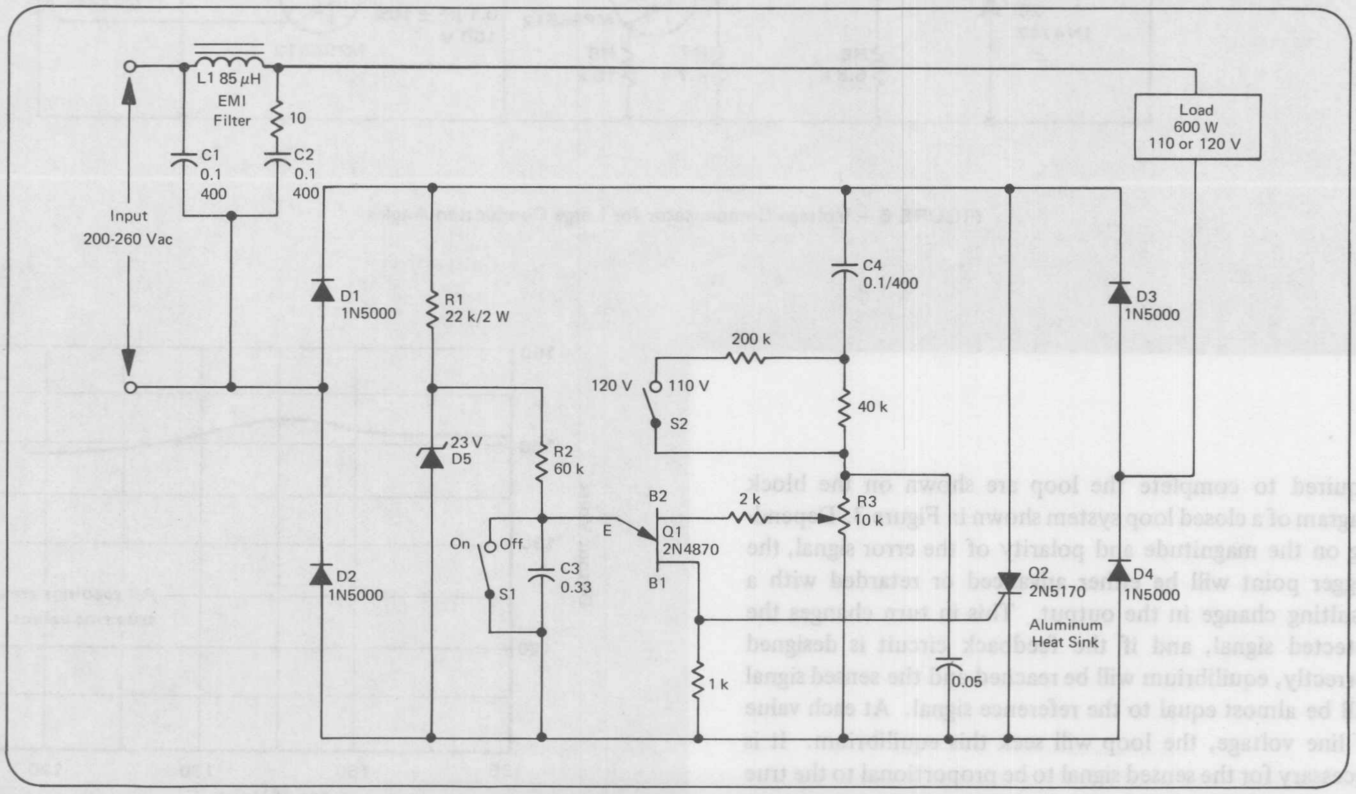

FIGURE 4 – Open-Loop Voltage Compensator for Small Conduction Angles

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*See Motorola Application Note AN-240, "SCR Power Control Fundamentals."

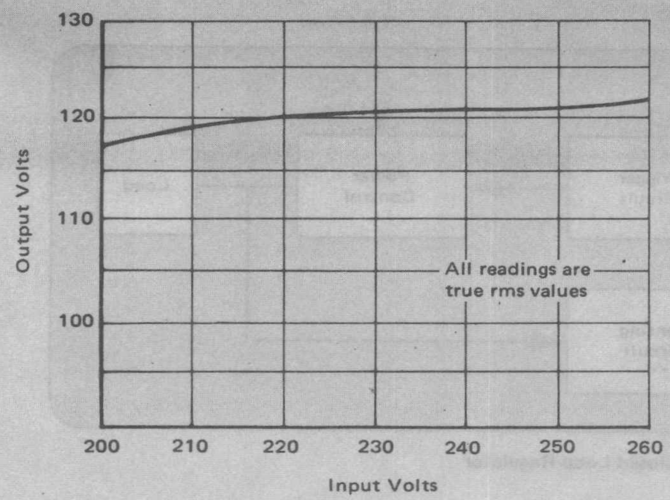

FIGURE 5 – Output versus Input for Voltage Compensator Shown in Figure 4

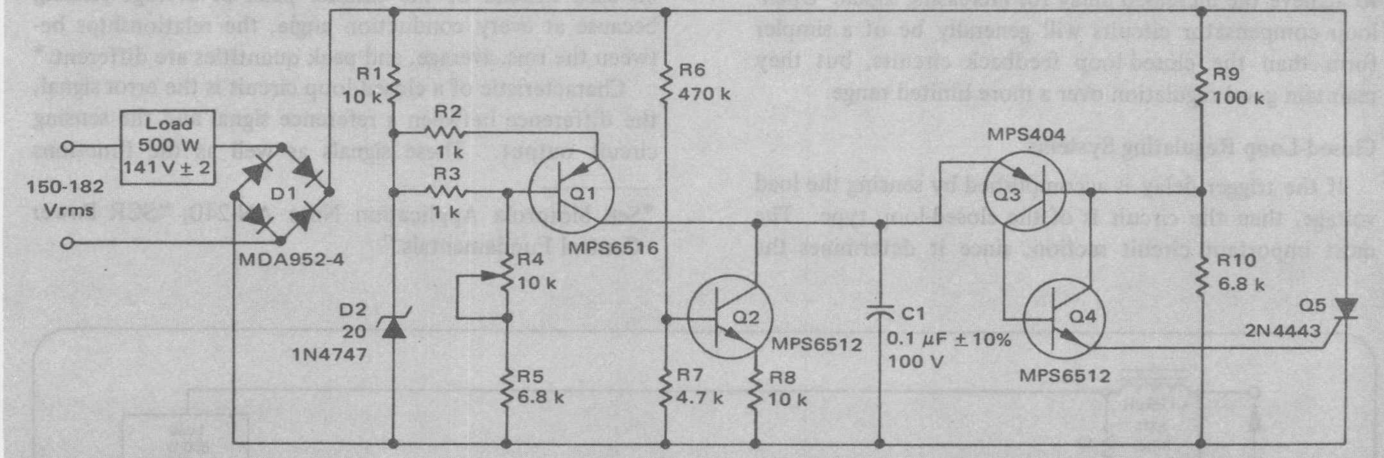

FIGURE 6 – Voltage Compensator for Large Conduction Angles

required to complete the loop are shown on the block diagram of a closed loop system shown in Figure 3. Depending on the magnitude and polarity of the error signal, the trigger point will be either advanced or retarded with a resulting change in the output. This in turn changes the detected signal, and if the feedback circuit is designed correctly, equilibrium will be reached and the sensed signal will be almost equal to the reference signal. At each value of line voltage, the loop will seek this equilibrium. It is necessary for the sensed signal to be proportional to the true rms value of the output voltage if rms regulation is desired.

In the past, rms sensing circuits have usually used thermocouples or thermistors since their operation depends on heat, which is proportional to effective or rms current or voltage squared; the effective value is the value of an ac quantity that will produce the same heat in a resistor as a corresponding dc quantity. It can be shown that this effective value is equal to the square root of the average of the squared instantaneous voltage integrated over the complete cycle, hence the name root mean square, or rms. Although it is difficult to obtain the square root electronically, it is not necessary to obtain it, since the square root will be constant if the square is constant. A squaring circuit can thus be used to provide the rms sensing which is necessary for a closed-loop rms regulator.

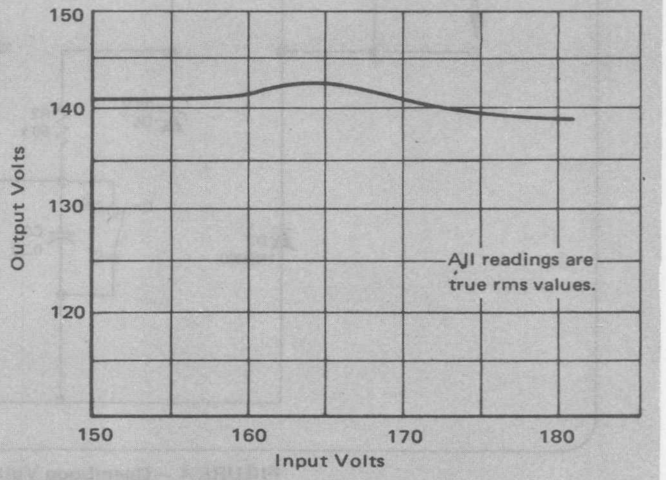

FIGURE 7 – Output versus Input for Voltage Compensator Shown in Figure 6

CIRCUIT EXAMPLES

Open-Loop Compensator for Small Conduction Angles

A relatively simple open-loop compensator is shown in Figure 4. It provides an output of 110 or 120 volts ±2.5 volts at 600 watts for an input voltage of 200 to 260 volts, as shown in Figure 5.

A full-wave bridge (D1 through D4) and a single SCR (Q2) are used to obtain full-wave control. A unijunction transistor (Q1) is the trigger device. Basic triggering frequency is determined by the charging and discharging of capacitor C3 through resistor R2. The supply for this circuit is regulated by zener diode D5.

RMS compensation is provided by capacitor C4 and the associated circuitry in the base-two B2 circuit of Q1. As the input voltage increases, raising the interbase voltage of Q1, the required trigger voltage also increases, retarding the firing point of the SCR since it takes longer for timing capacitor C3 to charge to this higher value. Potentiometer R3 allows some adjustment to compensate for differences in individual unijunction transistors so the output can be set to the desired level.

Switch S1 can be used to turn the circuit on or off. A small switch here can control a relatively large load.

Switch S2 permits a selection of 110 or 120 volts of output.

Choke L1 and capacitors C1 and C2 provide filtering to reduce electromagnetic interference (EMI).

This type of circuit is suitable primarily for applications requiring a conduction angle less than 90°, and consequently, output voltages of about one-half the input. At greater angles premature firing of the unijunction might occur. Since at the beginning of each half cycle, the unijunction interbase voltage is zero, a very low trigger voltage will latch the unijunction on at the beginning of the half cycle. To avoid this latch-up the charging rate of C3 must be sufficiently slow to allow buildup of the interbase voltage before triggering occurs. This requirement on the time constant of the charging circuit limits this type of circuit to small conduction angles. To operate over larger conduction angles, some type of delay on the charging would be required at the beginning of the half cycle while the trigger voltage was still low. A circuit which meets this requirement is discussed below.

Open-Loop Compensator for Large Conduction Angles

An open-loop compensator for large conduction angles is shown in Figure 6. It provides an output of 500 W at 141 volts rms ±2 volts with an input of 150 to 182 volts rms, as shown in Figure 7.

The circuit is basically similar to that of Figure 4, but incorporates an improved triggering system to permit reliable operation with large conduction angles.

Transistors Q3 and Q4, and resistors R9 and R10 are connected together forming a composite device with characteristics similar to a unijunction transistor. The trigger voltage is equal to the voltage drop across R10 plus the emitter-base voltage drop of Q3. As soon as Q3 turns on, Q4 also turns on, providing a discharge path between the capacitor and the gate of the SCR. The resulting discharge current pulse triggers the thyristor. This combination provides superior temperature stability compared to a standard unijunction trigger circuit.

Latch-up is prevented by delaying the turn-on of current-source transistor Q1 until the trigger voltage has reached a sufficiently high value. Prior to the conduction of zener diode D2, the emitter-base voltage of transistor Q1 is determined by the resistive divider comprised of R1, R3, R4 and R5. Since it takes approximately 0.6 volt across the base-emitter junction to turn a transistor on, the line voltage will be approximately 14 volts before Q1 begins conducting and charging C1. This delay provides sufficient time to raise the trigger voltage above a value which would cause latchup.

Two types of compensation provide correction for input voltage changes: First, the trigger point is delayed as the input voltage increases since the voltage reference, which is established by the divider composed of R9 and R10, will also increase. The composite UJT will trigger when the voltage on the timing capacitor charges to a value sufficient to turn Q3 on. Since the required capacitor voltage is offset from the reference voltage by one diode drop, the capacitor voltage will also increase with increasing input voltage; thus it will take the capacitor longer to reach this value.

The second means of compensation is provided by Q2 and its bias circuit (R6 and R7). As the input voltage increases, Q2 conducts more, diverting charging current from C1, and thereby delaying the firing of Q5.

The time required for the capacitor to reach a given voltage can be determined from the equation:

$$t = \frac{VC}{I},$$ where

t = time in milliseconds
V = voltage in volts
C = capacitance in microfarads
I = charging current in milliamperes.

If it is desired to operate this circuit over a different voltage range, all that is necessary is to change the charging current, which can be done by resetting potentiometer R4 or by changing R6.

Closed-Loop Regulator

A closed-loop rms regulator is shown in Figure 8. This circuit, which is more complex than those discussed previously, will hold the output voltage at 90 ± 2 volts rms with any input voltage between 105 volts and 260 volts.

The heart of the circuit is the sensing circuit. It uses a differential amplifier employing a dual transistor shown as Q1A and Q1B on the schematic. Q1A is biased to operate in the nonlinear cutoff region of the differential amplifier transfer function where the output current varies approximately as the square of the input voltage. The signal input magnitude is particularly important because it is necessary for the sensing circuit to operate about cutoff. R11 is provided to hold the base of Q1A approximately 300 mV below the base of Q1B, which is sufficient to insure that Q1A does operate about cutoff.

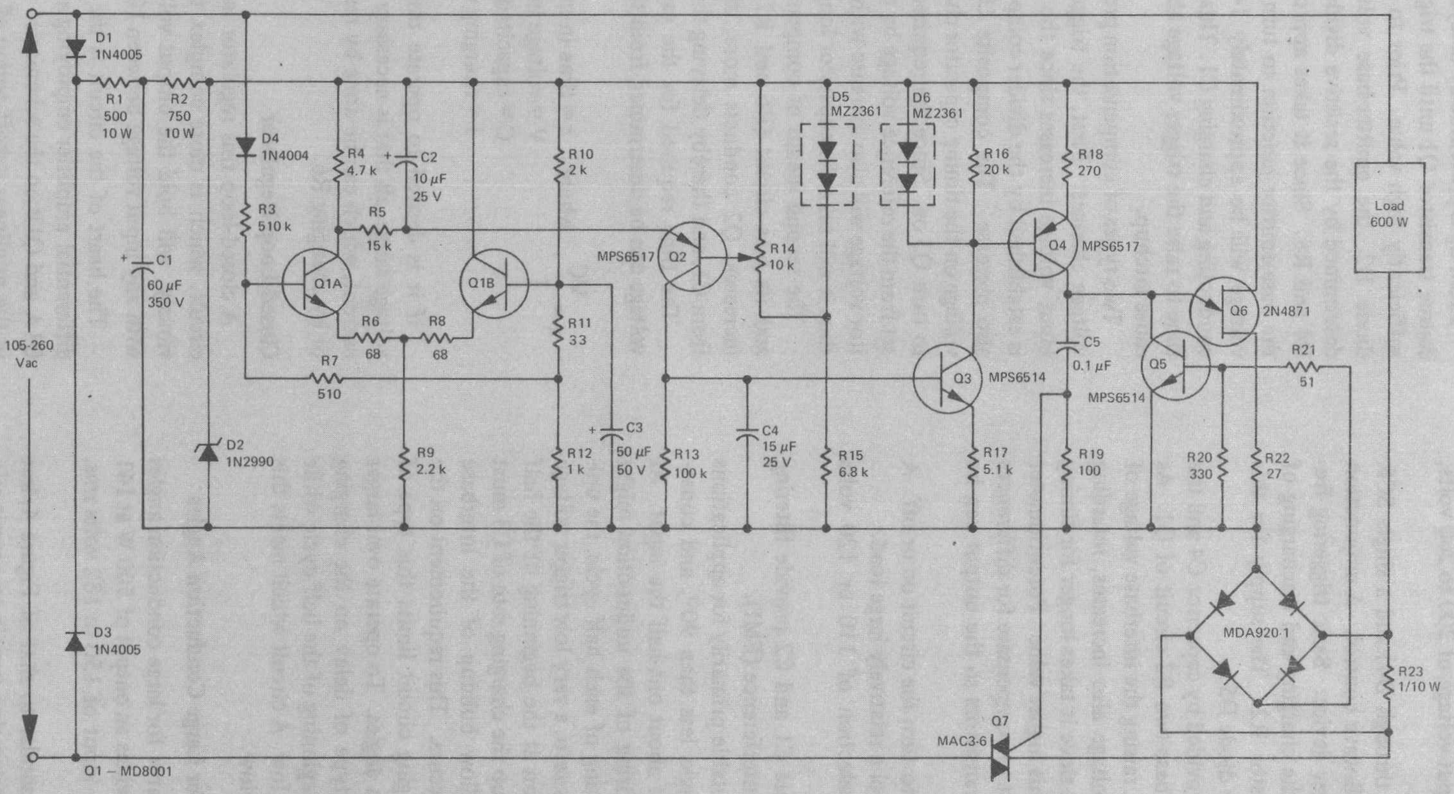

FIGURE 8 — Closed-Loop Voltage Regulator

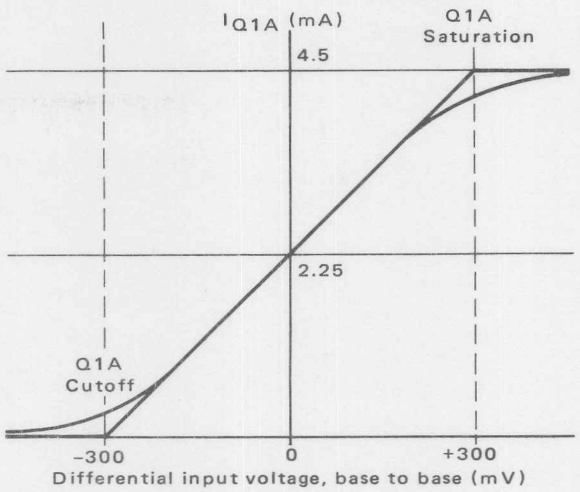

FIGURE 9 – Differential Amplifier Transfer Function

The transfer function of this circuit is shown in Figure 9. Since the rms sensing function is performed by the nonlinear base-emitter characteristic, V_{BE} must be stable with temperature changes since any change in V_{BE} would result in a change in the output. By using a dual transistor in a differential-amplifier configuration, changes in the sensing transistor can be offset by identical changes in the other transistor. These changes due to temperature cancel, leaving little effect on the output of the system. With the input adjusted to the proper level, the output will then be approximately the square of the input voltage. The output of Q1A is filtered by R4 and C2 to give a signal which is proportional to the mean square of the input voltage.

To complete the system, a triggering device, a power supply, a power control device (triac) and sufficient gain to give a loop gain of one are required. In addition, a circuit to synchronize the triggering to the line is also required.

The system works as follows: if the load voltage tries to increase, the input to the sensing circuit increases which results in a lower voltage at the output of the sensing circuit. This lower voltage, when seen by the emitter of Q2 and compared to the reference voltage at the base of Q2, results in a lower collector current through Q2 and consequently less base drive for Q3. The resulting decrease in current through Q3 results in a higher voltage at the output of Q3, which is coupled to Q4, resulting in less current through Q4. Q4 is a current source charging the timing capacitor C5. With less current charging C5, it takes longer to reach the trigger voltage necessary to fire the unijunction. With the firing angle retarded, the rms voltage will decrease. Thus, the circuit will provide a constant rms voltage across a load for a wide variation of input voltages.

The synchronizing circuit is made up of Q5, R20, R21, R23 and the diode bridge. When triac Q7 is not conducting, Q5 is off since its drive is zero. This allows C5 to charge to the firing voltage of unijunction transistor Q6. As soon as the triac fires, the voltage across R23, which is in series with the load, provides enough base drive to drive Q5 into saturation. This keeps C5 discharged until the load voltage goes through zero, turning Q5 off again and allowing C5 to start charging. One disadvantage of this type of circuit is that regulation is actually maintained across the combination of load and R23 instead of the load alone. This means that R23 must be selected for a given load and that the load must be relatively constant for proper regulation. To maintain proper regulation with a varying load, R23 can be replaced by a zener diode whose voltage is sufficient to drive Q5 into saturation when the triac is conducting.

Other trigger schemes employing either a power transformer or a pulse transformer could be used to provide synchronization independent of the load. However, size, weight and/or economy would have to be sacrificed.

The power supply consists of a capacitive filter and zener diode. The supply return is through the bridge and the triac or the load. When the triac conducts, D1 conducts, and when the triac is blocking, D3 conducts with the return through the load. The nominal voltage of the supply is 30 Vdc.

Adjustment of the output is by means of a potentiometer (R14) in parallel with reference diode (D5). If all other component values are optimized, then the output voltage can be set to the desired value by this potentiometer.

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