

# DESIGNING DIGITALLY-CONTROLLED POWER SUPPLIES

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This application note shows two design approaches; a basic low voltage supply using an inexpensive MC1723 voltage regulator and a high current, high voltage, supply using the MC1466 floating regulator with optoelectronic isolation. Various circuit options are shown to allow the designer maximum flexibility in any application.



**MOTOROLA Semiconductor Products Inc.**

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## INTRODUCTION

The current trend in electronic instruments is toward digital control. The advantages of this technique are many; convenience, accuracy and personal appeal are just a few of these. In the past, these advantages were obtained at a rather high cost that limited its use to expensive laboratory instruments. Recent advances in integrated-circuit technology have helped eliminate this disadvantage. This applications note shows two of Motorola's monolithic digital-to-analog converters (DAC's) teamed with Motorola integrated-circuit voltage regulators to provide two digitally-programmable power supplies. The digitally-controlled power supply can be used for a programmable laboratory power supply, as a computer-controlled power supply for automated test equipment, or in industrial control systems. There are several circuit options allowing the designer flexibility to meet his particular needs.

One of these power supplies uses an MC1408L\* 8-bit DAC coupled to an MC1723 regulator. It has a voltage range from 0 to 25.5 V in 0.1 V increments and it is capable of supplying currents in excess of 100 mA. This value can be extended with the addition of an external current-boost transistor.

The second power supply utilizes the MC1406L 6-bit DAC and the MC1466L floating voltage regulator to overcome the voltage and current limitations of the standard DAC's. The MC1406L DAC floats on the output voltage with the MC1466L regulator. The digital word is coupled into the DAC with Motorola 4N28 optoelectronic couplers, which allow the DAC to float as high as 500 V. The output voltage of the circuit, designed to supply up to 1 A and 63 V, may be incremented in 63 steps of 1 V each.

## DAC Operation

The MC1406 and MC1408 are digital-to-analog converters that have 6- and 8-bit digital inputs, respectively. The inputs are TTL compatible and are converted to an analog output by means of an R-2R ladder network, reference current, and current switches. An R-2R ladder network is shown in Figure 1. At each node of the R-2R ladder the reference current is split in half. Fifty percent of the current continues on through the ladder while the other half is shunted into the ladder termination circuits. The currents that flow into the ladder termination circuits

are summed together in the output or shunted to the positive supply, depending upon the digital inputs. The input is a digital word consisting of ones and zeros which turn the appropriate switches on or off. The output quantity is a unilateral current sink with the full scale current being set by an external resistor and reference voltage. Typically the reference current is set at about 2 mA, which means that the output will sink current from

0 to  $\frac{63}{64} \times 2$  mA with 64 discrete levels for the MC1406,

and from 0 to  $\frac{255}{256} \times 2$  mA with 256 discrete levels for the

MC1408. A single capacitor is used for compensation of the DAC.

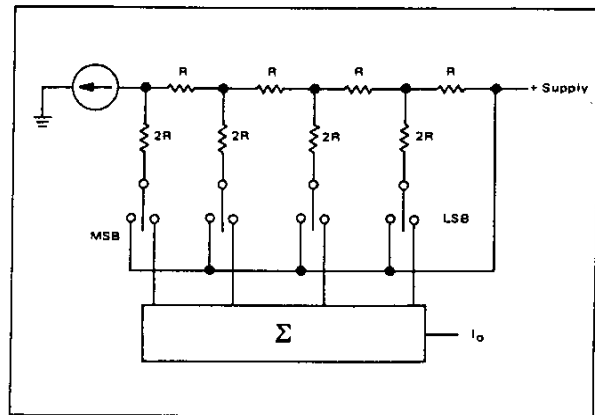


FIGURE 1 - R-2R Ladder Network

## LOW VOLTAGE SUPPLY

Since the output of the MC1408L is a current sink, an operational amplifier is needed to convert from current to voltage, for the low voltage supply. In this particular application, the MC1723 voltage regulator was chosen because it contains the needed operational amplifier with a current capability in excess of 100 mA. In addition, this package has an internal 7 V reference which can be used as the reference supply for the MC1408. The MC1723 regulator is also quite inexpensive. The MC1408 and MC1723 combination, shown in Figure 2, requires two negative power supply voltages. One is a -5 V supply which is used for the MC1723, while the other negative supply is for the MC1408. Minus 15 V is a typical supply value for the MC1408, although this can be less if convenient. However, it should be at least 3 V greater in magnitude than the negative supply for the regulator. The

(\*) This series of DAC's is available with devices specified for 6, 7, or 8-bit accuracy. A suffix after the "L" in the device number indicates the specified accuracy.

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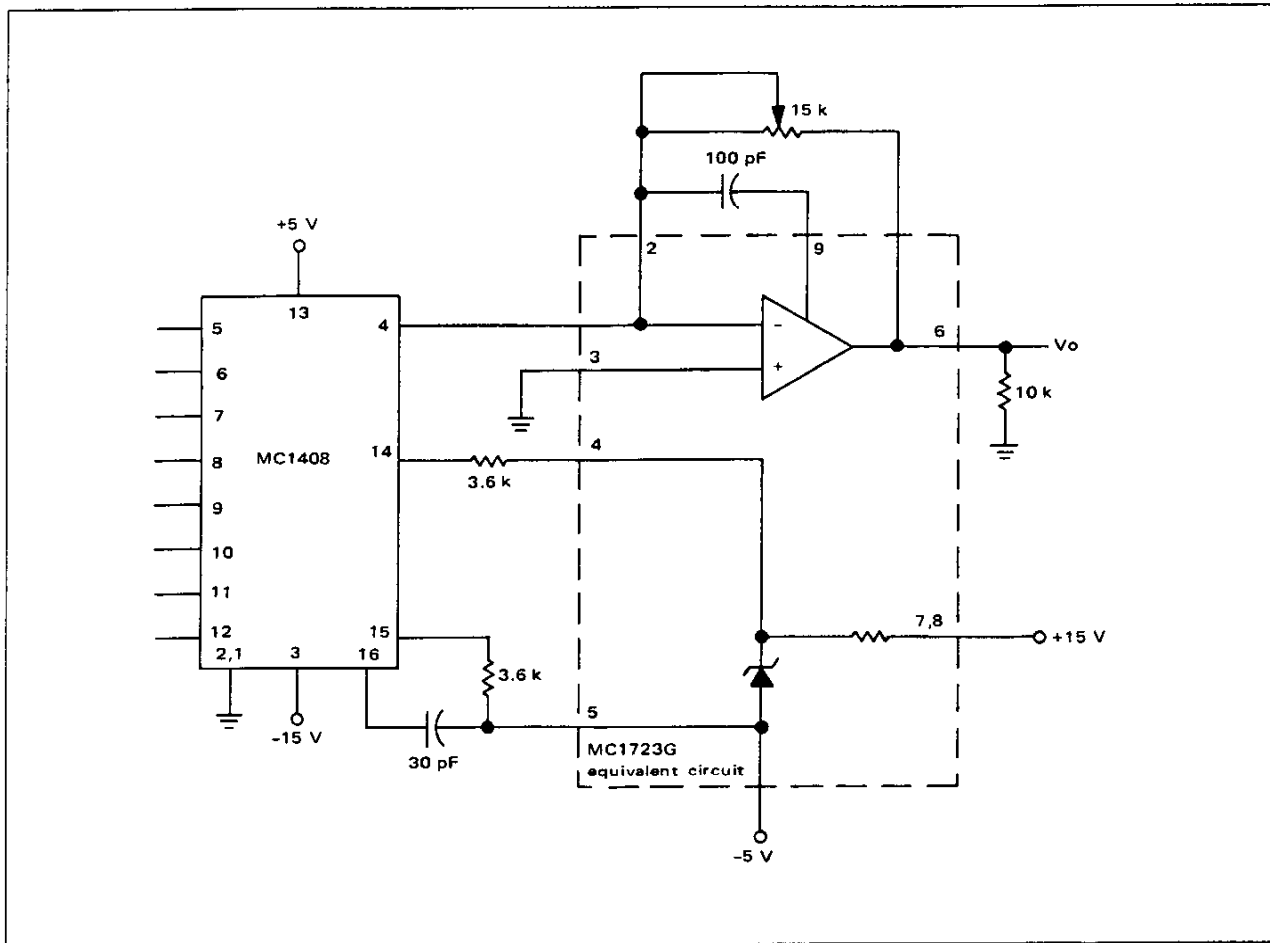


FIGURE 2 — 8-Bit DAC With Voltage Regulator

-5 V supply does not require a high degree of regulation, and it can be obtained from a resistor divider network off the -15 V supply. The 15 kohm trimpot is used for calibration of the output voltage. The calibration should be done for the maximum output voltage.

Two positive voltages are also required for operation. One is a 5 V supply needed for the MC1408, which is usually available from other TTL power supplies. The second is the voltage to be regulated by the MC1723, which should be at least 3 V above the maximum output voltage required. To take advantage of the entire range of the MC1408, to 25.5 V with 0.1 volt increments, 28.5 V would be required for this supply. One method for obtaining the required voltages for the supply is shown in Figure 3. This technique uses the MC1468  $\pm 15$  V regulator, for the  $\pm 15$  V, and an MLM109 5 V regulator for the logic and DAC supply.

At this point, we have a digitally-controlled power supply with binary inputs and an output current rating of 100 mA. The output of the MC1723 can be current-boostered to provide the desired output current range. Figure 4 shows a current-boost technique for a 2 A programmable power supply. Other current-boost configurations can be found on the Motorola MC1723 data sheet.

#### Accuracy, Regulation and Settling Time

The MC1408 is accurate to 1/2 of the least significant bit. The power supply is set up so that the least significant bit is 0.1 V which gives an accuracy of  $\pm 0.05$  V. The amplifier in the MC1723 is essentially being operated in the unity gain mode over the entire output range; this implies a constant output impedance over the entire voltage range. The output impedance is about 30 milliohm. Line regulation remains about the same as with the MC1723 in a normal configuration. Settling time for a 20 V swing for the MC1723, without current-boost, is less than 5  $\mu$ sec.

#### HIGH VOLTAGE SUPPLY

The second power supply uses the MC1466 as the regulator and the MC1406 for the DAC. The MC1408 can also be used if more resolution is needed. This supply provides a programmed high voltage output, in this case up to 63 V.

#### MC1466L Operation

The MC1466L regulator is unique in that it operates from a separate, 25 Vdc supply floating on the output voltage which may be as high as desired. The output

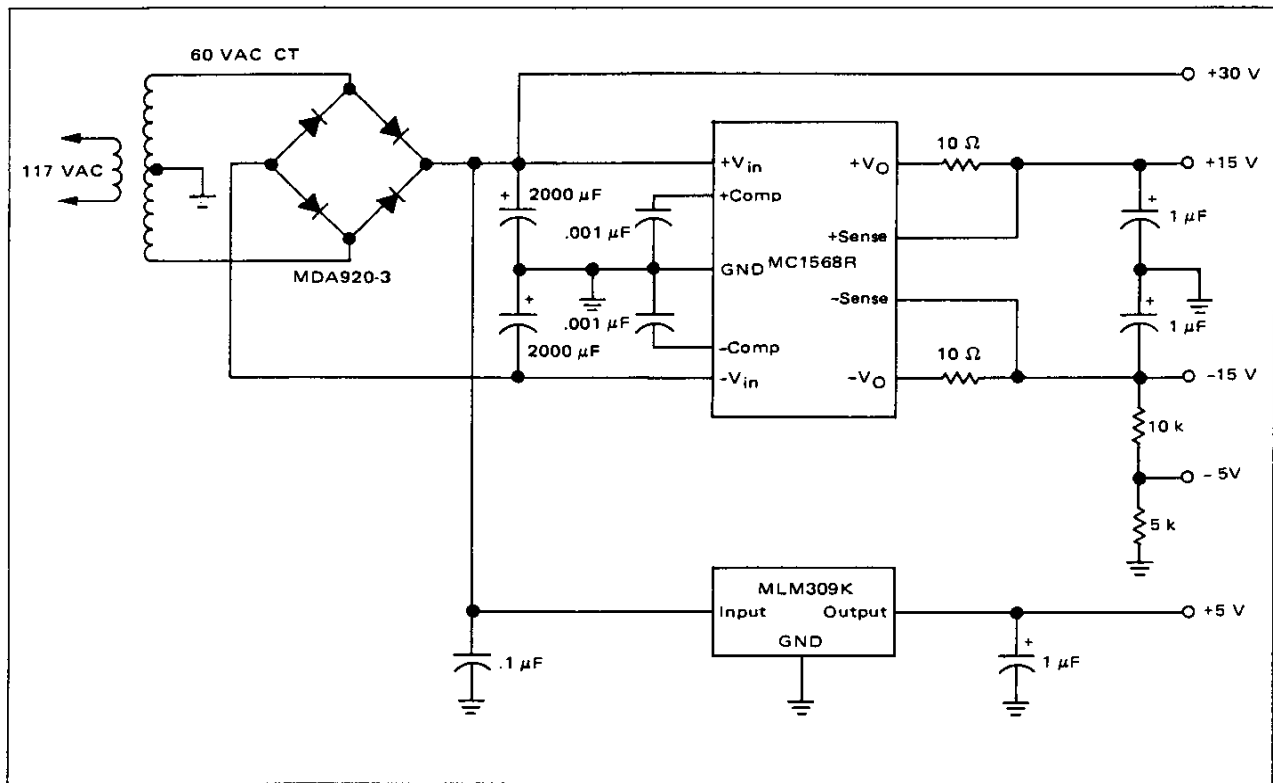


FIGURE 3 — Supply Voltage For Digitally-Controlled Low Voltage Power Supply

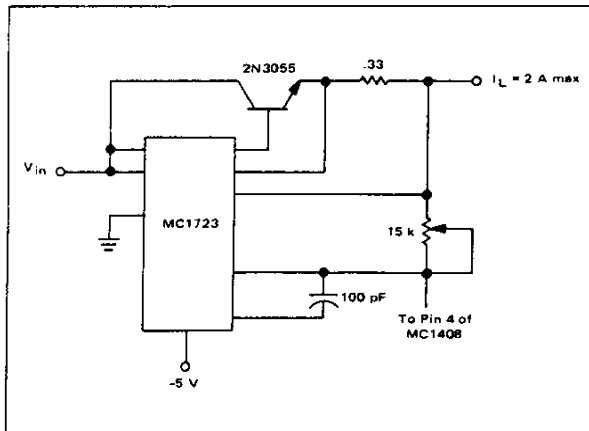


FIGURE 4 — Current-Boosted MC1723 Voltage Regulator

voltage range is limited only by the capability of the external pass transistors and, in this application, by the voltage rating of the optoelectronic couplers.

The regulated output voltage is established as shown in Figure 5. A reference current ( $I_1$ ), normally 1 mA, is passed to ground through a voltage setting resistor ( $R_{SET}$ ). This technique establishes a reference voltage which is applied to the non-inverting input of a differential amplifier. The inverting input of the amplifier is connected to the regulated output in a voltage follower configuration, thus assuring that the output voltage is equal to the reference voltage. If the reference voltage is varied by changing either  $I_1$  or  $R_{SET}$ , the output voltage changes accordingly.

### Optoelectronic Couplers

The 4N28 optoelectronic coupler is a NPN phototransistor and a gallium-arsenide infrared LED packaged so that they are optically coupled, but electrically isolated. Breakdown voltage between the phototransistor and the LED is 500 V, minimum. Current transfer ratio between the LED current and the transistor collector current is typically 30%, with a 10% minimum. The maximum current for the MC1406L digital input logic "0" level is 1.5 mA. Therefore, 15 mA of current through the LED assures a logic "0" at the MC1406L input, even at the minimum transfer ratio. The 15 mA diode current is also within the current-sink capability of standard TTL gates, which may be used to drive the diodes.

If higher breakdown voltages or current transfer ratios are needed in a particular application, other couplers are available. For example, the Motorola 4N25 exhibits a breakdown voltage rating of 2500 V and a 20% minimum transfer efficiency.

### Circuit Operation

Since the MC1466L output voltage is set by means of a current through a resistor and the MC1406L output sinks current in proportion to a digital word input, combining the two in a digitally-controlled voltage source should work quite well. However, in order to work together, the MC1406L must float with the MC1466L on the output voltage. The MC1406L is, therefore, powered from the 25 Vdc supply that powers the MC1466L.

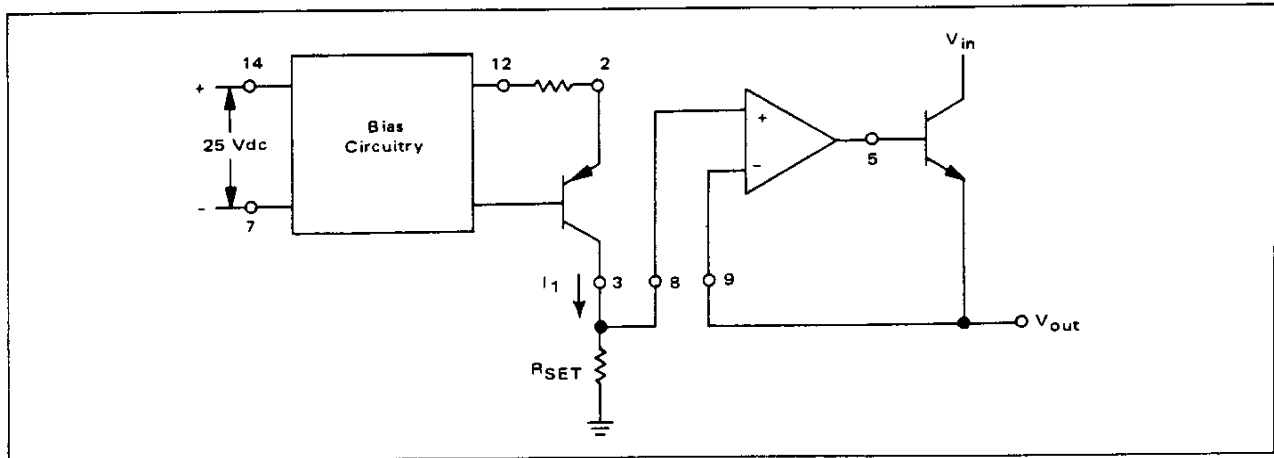


FIGURE 5 – Block Diagram of MC1466L Voltage Regulator

Circuit operation may be explained by referring to the block diagram in Figure 6.  $I_1$  is established at 1 mA by a current source in the MC1466L. The output of the MC1406L, current  $I_2$ , is programmed from 0 to 1 mA by the digital word coupled into the MC1406L through the 4N28 optical couplers. When  $I_2$  is 0,  $I_3$  is 1 mA and the voltage developed across  $R_{SET}$  is at a maximum. As  $I_2$  is increased, the current available for  $I_3$  decreases and consequently the voltage across  $R_{SET}$  decreases. When  $I_2$  equals 1 mA, the voltage across  $R_{SET}$  is zero. Since the MC1466L holds the output voltage,  $V_{out}$ , equal to the voltage developed across  $R_{SET}$ ,  $V_{out}$  is programmable by programming  $I_2$ .

The complete circuit schematic, which appears in Figure 7, illustrates how the zero voltage reference for the MC1406L is established by the 1N5235, a 6.8 V zener diode. This approach places the MC1406L zero reference at approximately the same voltage level as established at pins 3, 8 and 9 on the MC1466L by an internal zener. Since the output voltage, pin 4, of the MC1406L must stay within 1 diode drop of its zero reference, and since

pin 4 is connected to pins 3 and 8 of the MC1466L, the zener which establishes the MC1406L zero reference must match the MC1466L internal zener to within about  $\pm 0.5$  V. This internal zener is CR1 on the MC1466L data sheet, nominally 7.25 V, which may be measured between pins 7 and 9. The positive supply voltage for the MC1406L is provided by the 1N5231, a 5.1 V zener. Reference current is established by the 1N827, a temperature-compensated 6.2 V zener reference diode, and a 5.76 kohm resistor in series with a 1 kohm trimpot. For less critical applications, the reference current could be derived from the 5.1 V positive supply zener or from pin 12 of the MC1466L.

The output voltage is established by the current through the 57.6 kohm, 1% resistor in series with the 10 kohm potentiometer R1. This resistor and potentiometer should both be temperature-stable because of the wide changes in power dissipation in these components as the voltage is programmed over its range. Maximum output current is adjustable by means of resistor R3 and may be set from near zero to over 1 A.

The digital inputs of the MC1406L have internal pull-

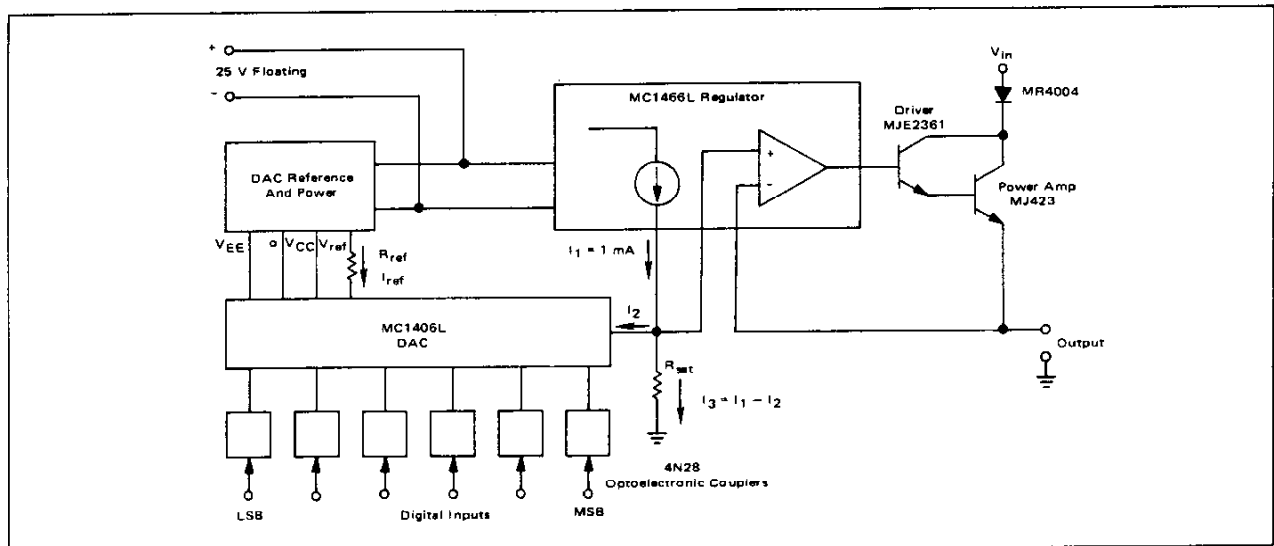


FIGURE 6 – High Voltage Supply Block Diagram

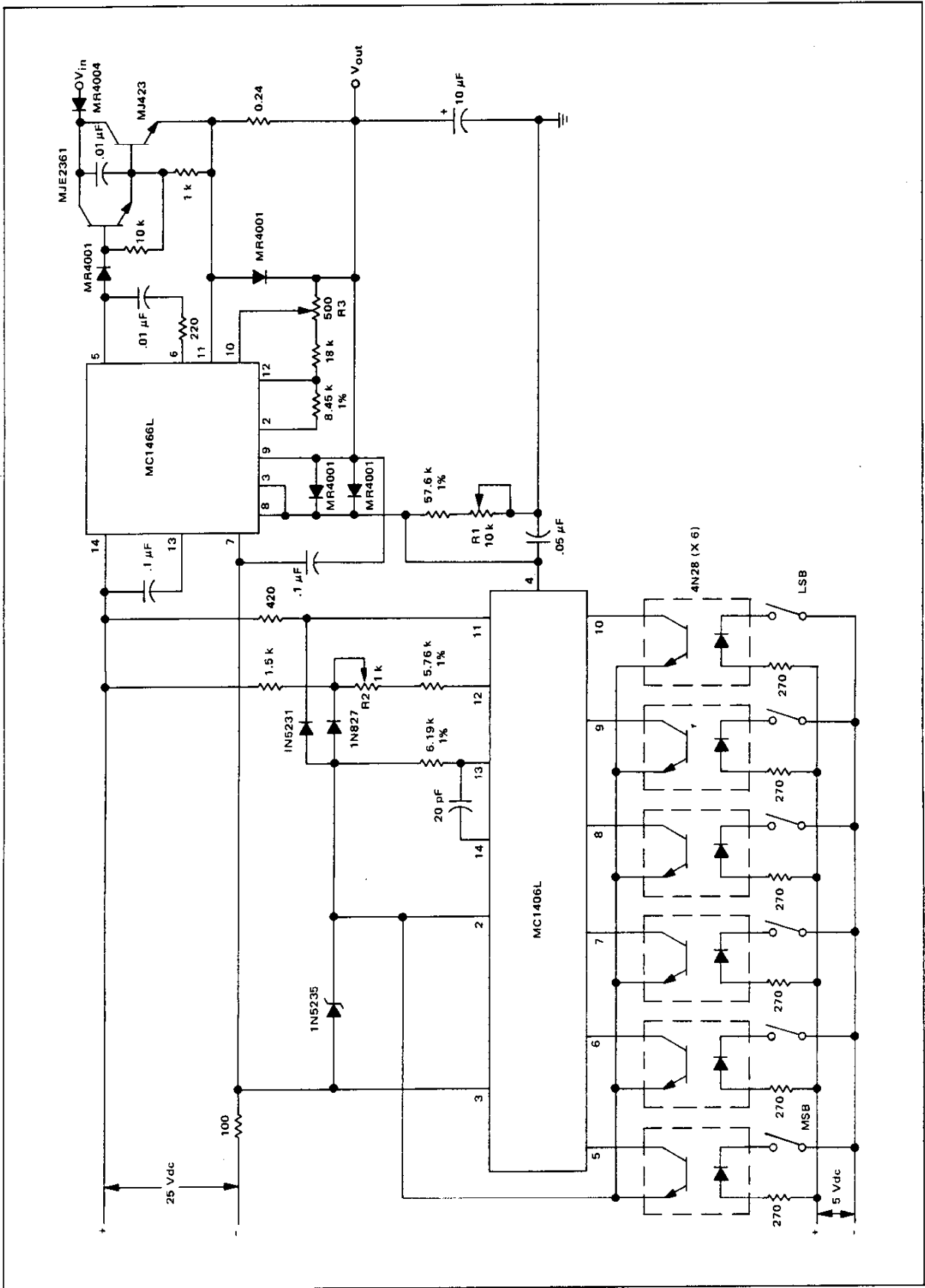


FIGURE 7 — High Voltage Power Supply Schematic

up resistors to the  $V_{CC}$  supply. This technique allows the collectors of the phototransistors in the 4N28 coupler to be connected directly to the digital inputs with no external pull-up resistors required. The emitters all are returned to the MC1406L zero reference at pin 2. The infrared LED current is about 15 mA when operated from a +5 V power supply, assuring that the phototransistor will be well saturated.

The current-amplifier output stage, consisting of the MJE2361 and the MJ423 in a Darlington connection, is designed to operate with a +70 V supply and deliver up to 1 A of load current over the full output voltage range of 0 to +63 V. The MJ423 must have a heat sink adequate to maintain the case temperature at +80°C while dissipating 70 W if operation at or near 0 V and 1 A output is expected, such as under short circuit conditions. Operation at higher output voltages is possible simply by increasing the size of resistor  $R_{ref}$  and increasing  $V_{in}$  accordingly. However, when this is done, care must be taken not to exceed the power dissipation ratings or the safe operating area curves of the MJE2361 and MJ423 transistors.

### Adjustment and Performance

The digitally-controlled output voltage is initially set to +63.00 V by setting the digital inputs to all "0s" (switches closed) and adjusting the 10 kohm trimpot R1. Set all the digital inputs to "1s" (switches open) and adjust the output to zero volts with resistor R2. This adjustment should be done with the output loaded rather than open or leakage currents may affect the accuracy of the zero setting. The output voltage should now remain within  $\pm 0.5$  V of its programmed value over the entire operating range of 0 to +63 V. Best overall accuracy may be obtained by checking each of the 6-bits to see which has the greatest error and trimming resistor R2 to split this error with the other bits.

An output filter capacitor is necessary for stability and good load transient response. Minimum value should not be less than 1  $\mu$ F. Large capacitors will begin to degrade the output voltage slew rate, as shown in Table I. Table I shows the output voltage rise and fall times when the most significant bit is switched with a 100 ohm load resistor and 3 different output filter capacitors.

The regulation of  $V_{in}$  has virtually no effect on output voltage. However, regulation of the floating 25 Vdc does have an effect, as shown in Table II for a  $\pm 10\%$  change in the 25 Vdc supply.

By simply changing one resistor,  $R_{SET}$ , the maximum

TABLE I  
Output Voltage Rise and Fall Times

|                         | OUTPUT CAPACITOR   |            |             |
|-------------------------|--------------------|------------|-------------|
|                         | $R_L = 100 \Omega$ |            |             |
|                         | 1 $\mu$ F          | 10 $\mu$ F | 100 $\mu$ F |
| $t_r$ (3.2 V to 28.8 V) | 7-ms               | 8-ms       | 10-ms       |
| $t_f$ (28.8 V to 3.2 V) | 8-ms               | 9-ms       | 30-ms       |

TABLE II

Output Voltages for Variations in Isolated Supply Voltage

| 22.5-V | 25.0-V | 27.5-V |
|--------|--------|--------|
| 63.00  | 63.00  | 63.00  |
| 31.10  | 31.00  | 30.93  |
| 3.37   | 3.17   | 3.02   |
| 1.41   | 1.20   | 1.05   |

output voltage may be set anywhere desired, up to the limits of the available power supply, series pass transistors and optical couplers used. Another possible variation is to set the reference current  $I_1$  from the MC1466L to twice the maximum  $I_2$  of the MC1406, either by doubling the current from the MC1466L or halving the MC1406L reference current into pin 12 of the MC1406L. This would allow twice the resolution over half the output voltage range, for example, from +31.5 V to +63 V in 0.5 V steps.

The MC1408L, an 8-bit monolithic DAC, offers 4 times the resolution of the 6-bit MC1406L. Using the MC1408L, the output voltage could be programmed to +255 V in 1 V steps. The MC1408L functions in the same manner as the MC1406L except that the input logic is inverted. With the MC1408L, maximum output voltage occurs with a logic "1" (switches open) applied to the 4N28 optoelectronic coupler.

Combining a monolithic DAC, a floating regulator, and optical couplers, provides a high-voltage/high-current 6-bit DAC which may be easily tailored by the user to suit specific requirements.

### CIRCUIT OPTIONS

#### BCD-To-Binary Conversion

To allow convenient operation of laboratory programmable power supplies by human operators, a decimal system is needed at the input. Since the MC1408L and MC1406L exhibit binary inputs, an interface stage is needed to convert from a decimal system to the binary required by the DACs. By incorporating an intermediate stage of BCD format, thumbwheel switches with a BCD output can be used. Thus an interface circuit to convert the BCD-to-Binary code is required. Figure 8 shows a BCD-to-Binary converter, which uses the CMOS MC14008 binary adders. The range of the converter is that of an 8-bit DAC which is from 0 to 255 V. Each BCD input code is converted to the corresponding binary number by means of binary adders. For example, the BCD input with a value of 40 is converted to a binary 40 which consists of 32 plus 8. Likewise the BCD number 80 is converted to 64 plus 16. The MC14008 is a 4-bit binary adder which has carry in and carry out terminals. A separate adder is needed for a third level of addition. The last adder in IC4 is used for this since there can be no carry out from the previous stage.

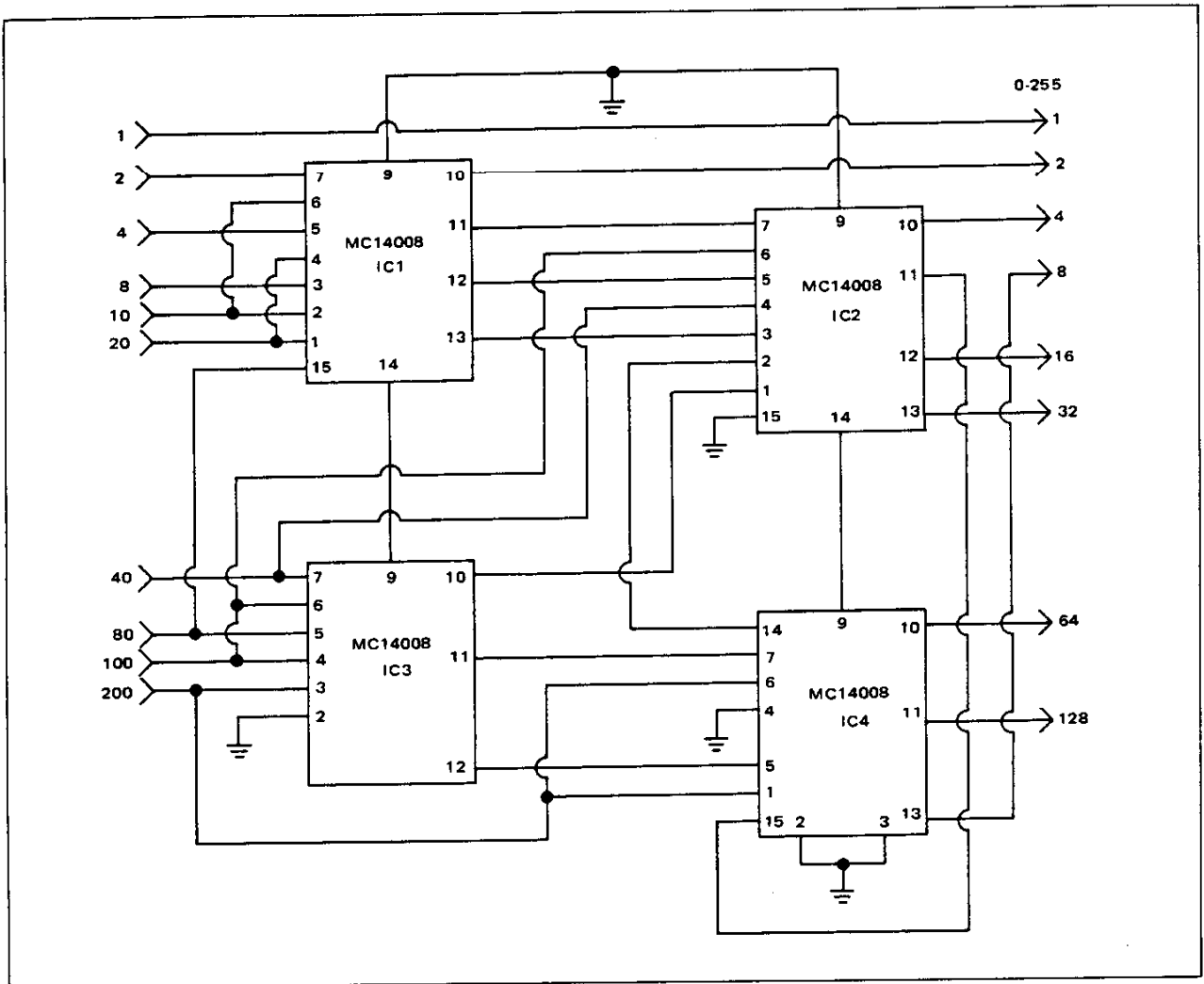


FIGURE 8 – CMOS BCD-To-Binary Converter

### Memory Option

For applications where the digital inputs to the power supply are only available momentarily, or the inputs are to be changed while the output is to remain constant, a memory can be used to store the controlling information. An attractive memory can be made from a single CMOS MC14508, dual 4-bit latches. The block diagram of the DAC with latches is shown in Figure 9. Each of the inputs to the D/A converter is connected to the input signal through the latches. The strobe line of the latch controls the flow of data to the D/A inputs. With a logic "1" on the strobe line, the output will follow the inputs. When the strobe goes to a logic "0" the output retains the state of the data inputs at the time of the transition.

This memory option can be used for both the computer-controlled power supply and the laboratory supply. For the laboratory supply, the advantages of this method are apparent when the voltage is set to 9.9 V and the operator wishes to go directly to 10.0 V. Without the series of latches the output voltage would have to be returned to zero and then changed to the desired 10.0 V, and then this final value transferred to the DAC.

### System Isolation

Another requirement for the computer-controlled or remotely-operated power supply is that of isolation between the systems. One of the newest methods to meet this requirement is with photon-coupled isolation to eliminate unwanted ground paths between the computer or controller and the system being controlled.

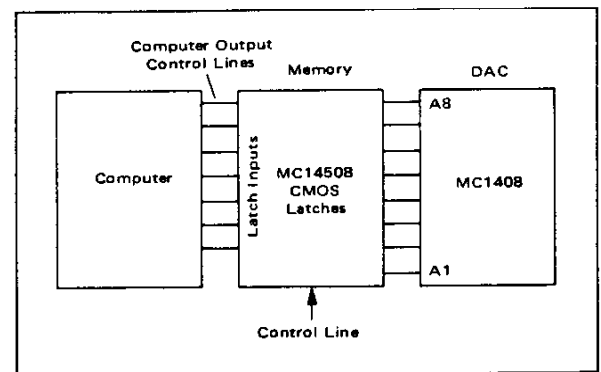


FIGURE 9 – CMOS Memory System For Programmable Power Supply



Motorola's 4N25-4N28 series of optoelectronic couplers may be used for this purpose to provide up to 2500 V of isolation between programmable supply and the remote driving equipment. The photon-coupled isolators must be used with the high voltage supply, since the inputs to the MC1406 are floating on the output voltage.

The MC1408 DAC is TTL/CMOS compatible. When CMOS IC's are used with the MC1406, or with the

MC1408 through photon-coupled isolation, a buffer must be used to supply or sink the required current. This buffer can be either a CMOS MC14009, an inverting buffer, or an MC14010 non-inverting buffer. There are 6 buffers per package, each of which is capable of sinking 8 mA at  $V_{OL} = 0.5$  V. An interface circuit for CMOS IC's through the 4N27 optoelectronic coupler provides 1500 V of isolation to a DAC is shown in Figure 10.

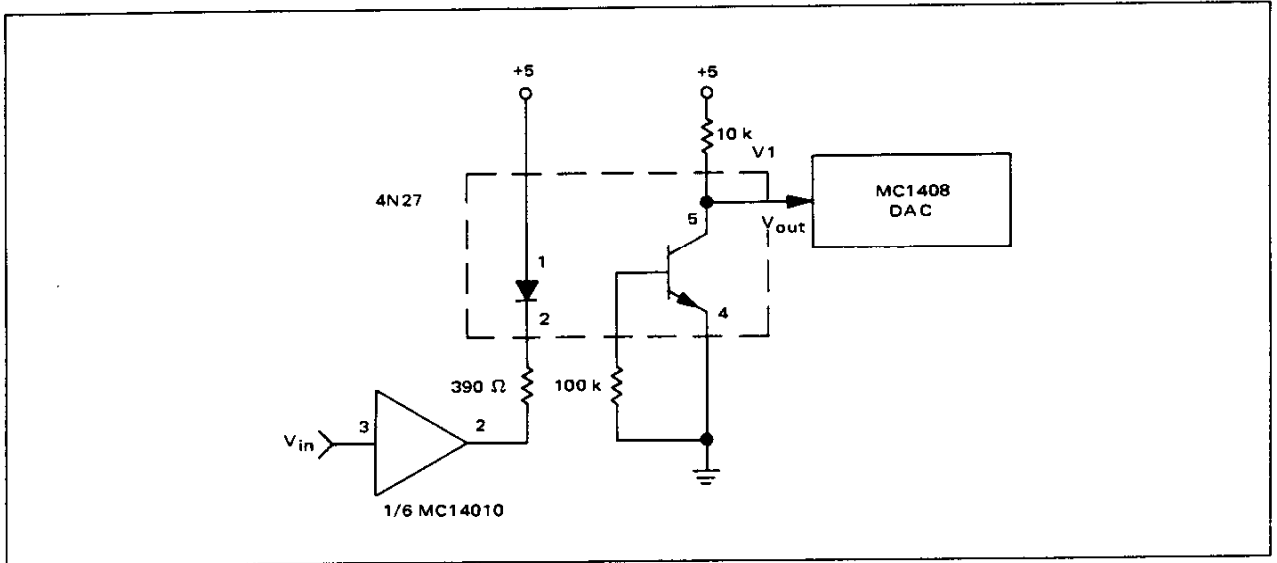


FIGURE 10 — Conversion of CMOS To-Opto-To-DAC

## CONCLUSION

The digitally-controlled power supply finds wide application in automated test equipment, computer-controlled systems, and laboratory power supplies. By making use of Motorola's low cost monolithic digital-to-analog converters and voltage regulators, the designer can now employ this useful building block in many applications where before it has not been economically feasible.

This application note has shown two design approaches; a basic low voltage supply using an inexpensive MC1723 voltage regulator and a high current, high voltage, supply using the MC1466 floating regulator with optoelectronic isolation. Various circuit options are shown to allow the designer maximum flexibility in any application.