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AECU-3222113-55-54A TRANSISTORIZED BINARY COUNTER FOR
EXTREME ENVIRONMENTS

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ABSTRACT

A transistorized binary counter circuit is described that operates over a temperature range of -65°F to $+165^{\circ}\text{F}$. The supply voltage is 28 ± 4 volts and the maximum trigger repetition rate is 5 kilocycles. The binary circuit is presettable and resettable by means of a switching arrangement that can be mechanized. Texas Instrument type 904 silicon transistors whose large signal current gain is 2.8 or greater at a -65°F can be used in this circuit.

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A TRANSISTORIZED BINARY COUNTER FOR EXTREME ENVIRONMENTS

A binary counter circuit that operates over a temperature range of -65°F to $+165^{\circ}\text{F}$ and uses type 904 Texas Instrument silicon transistors, whose large signal gain is 2.8 or greater at -65°F , has been developed. The circuit to be described should pass all Sandia environmental specifications when properly packaged.

The supply voltage is 28 ± 4 volts. However, the lower voltage limit that the counter operates at depends on the particular transistors used in the circuit and the temperature at which they are operating.

The trigger requirements for reliable operation over the temperature range from -65°F to $+165^{\circ}\text{F}$ are:

1. Amplitude - 15 volts
2. Length - 10 microseconds minimum
3. Repetition Rate - 5 kilocycles maximum

The circuit is presettable and resettable by means of a switching arrangement that can be easily mechanized. The circuit presets and resets within 10 microseconds after application of the reset voltage.

Principles of Operation

The transistors are operated in a grounded emitter connection. Consider the V_C - I_C characteristics shown in Figure 1 for a typical 904 transistor. Two stable d-c points are indicated at A and B. At point A the transistor is conducting. The ratio of the collector current at point A to the minimum base driving current required at this point is defined as the large signal current gain. Since the large signal current gain is different for each transistor, the base current drive is made large enough to insure that every transistor will be able to operate at point A over the required temperature range.

Point B is the transistor cut-off condition. The base to emitter bias is reversed so that a small current flows in the reverse direction (through the base to emitter circuit.) The collector current, I_{CO} , is small for silicon transistors. The value of I_{CO} is modified by the reverse bias current in the emitter base circuit.

Figure 2 shows the circuit connection used to hold one transistor "on" and the other transistor "off". The current through R_1 is $I_E = I_C + I_B$ where I_C is the "on" collector current and I_B is the base driving current for the "on" transistor. For either transistor "on", I_E is a constant and the voltage drop across R_1 is the emitter potential to ground which shall be treated as a voltage source, V_E . I_C is determined

by $\frac{E_{bb} - V_E}{R}$. I_B is determined approximately by

$$\frac{(E_{bb} - V_E)}{[R + R_c + (\text{base to emitter d-c resistance})]}$$

Resistors R_5 and R_6 provide a d-c path for the emitter to base current so that the base to emitter can be back-biased. R_5 and R_6 are made approximately 10 times the d-c resistance in the forward direction of the base to emitter diode.

For T_1 "on" and T_2 "off", the collector to emitter voltage of T_1 is less than +1 volt as shown in Figure 1, point A. The collector to emitter voltage of T_2 is determined by the amount of base driving current flowing through R to the base circuit of T_1 , and the emitter potential, V_E . The reverse biasing current through the emitter to base diode of T_2 is

$$\left[V_E - \frac{R_6}{R_6 + R_c} V_c \text{ "on"} \right] / \text{resistance of emitter to base diode.}$$

This reverse bias current insures that T_2 is in an inactive region of its characteristics for the "off" condition.

For the circuit to be stable over the temperature range of interest, I_c and I_B must be chosen so that the large signal current gain of the transistor, "B", times I_B is greater than the I_c chosen at all temperatures. It has been observed experimentally that "B" decreases quite rapidly with decreasing temperature for silicon transistors. Therefore, the type of silicon transistor chosen must have a large "B" at +72° F so that the base driving current required at -65° F is not excessively large.

The collector saturation current, I_c , was chosen to be 0.7 milliamperes at an E_{bb} of 30 volts. The base driving current, I_B , was chosen to be 300 microamperes. The voltage drop across R_1 was chosen to be 2 volts. Using the values chosen and Ohms Law, $R = 30K$, $R_c = 62K$, $R_1 = 2K$ and $R_5 = R_6 = 110K$.

Figure 3 shows the basic binary with a method of triggering plus capacitors needed for dynamic action in the circuit. Diodes D_1 and D_2 are "steering" diodes. Diode D_3 disconnects R_3 and R_4 during the negative phase of the trigger and limits the junction of C_1 and R_2 to the potential at the middle of the voltage divider, R_3 and R_4 , when positive going voltages are applied to C_1 . This action hastens the recovery time of the trigger circuit. Diodes D_4 and D_5 limit negative going voltages on the base of the transistors to ground potential. Capacitor C_1 is a coupling device. Capacitors C_c are "speed up" devices and C_2 is a by-pass for R_1 .

A negative trigger voltage applied to capacitor C_1 causes D_1 or D_2 to conduct which couples the trigger to the base of the "on" transistor through C_c . The time constant of the triggering circuit (essentially $C_1 R$) holds the base negative for a time which exceeds the "hole storage" time of the transistor. The "hole storage" time is related to how far the base is driven past the point required for collector current saturation. As the base comes out of saturation, the collector voltage starts to rise due to the decrease in I_c . This voltage increase is coupled to the base of the "off" transistor through C_c causing the base to turn "on". The collector voltage of the transistor that is going "on" starts to decrease and this voltage change is coupled to the base of the transistor that is being turned "off" thus holding the base off. This regenerative action continues until the d-c states for the two transistors have reversed.

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Figure 4 illustrates the typical collector to ground and base to emitter voltage waveforms for the circuit of Figure 3. The waveforms are shown for a binary stage that is triggered at a 5 kilocycle repetition rate. Note that the collector voltage rises slowly when the transistor is turned "off". This long time constant is due to capacitors C_1 and C_c "charging" through the collector circuit resistance, R . When the input trigger repetition rate is more than 25 kilocycles, the collector that is being turned "off" does not attain its steady state value before the next trigger pulse occurs. Consequently, this next negative transition may be too low in amplitude to trigger the succeeding stage.

At $+165^{\circ}\text{F}$ the maximum trigger repetition rate is 5 kilocycles for reliable operation with a supply voltage of 28 ± 4 volts.

Figure 5 shows the method used to reset and preset. Resistors R_5 and R_6 are returned to ground through switches S-1 and S-2. Switch S-1 is a preset arrangement which determines the "state" the binary will be in when S-2 is switched. When S-2 is operated, 30 volts is applied to the bottom of R_5 or R_6 depending on the position of S-1. Approximately 300 microamperes is driven through the base emitter circuit of the transistor that is being turned "on" forcing the binary into the desired state.

Laboratory Model

A seven stage binary counter has been constructed using the circuit of Figure 5. Figure 6 shows the circuit with the component values that were used.

The binary counter was temperature cycled from -65°F to $+165^{\circ}\text{F}$. The counter operated with a maximum trigger repetition rate of 5 kilocycles and trigger length of 10 microseconds minimum. The trigger for the first binary was supplied by Tektronix 161 and 162 waveform generator. Figures 7, 8, 9 and 10 show trigger voltage versus supply voltage areas for operation of the counter over the complete temperature range. The largest supply voltage that can be applied to the counter is 40 volts due to the manufacturer's specification of maximum collector to emitter voltage.

A total of 24 type 904 transistors were tried in the circuit. Of the 24 transistors used, only one would not stay turned "on" at -65°F . Investigation of the V_c-I_c static characteristic at -65°F showed that the amount of base driving current required for collector saturation was over 400 microamperes. The large signal gain had decreased to less than 1.7. The static characteristics of this transistor were not different from other transistors at temperatures greater than -45°F . Therefore, to obtain reliable operation of the counter at -65°F , all transistors used must have a large signal gain of at least 2.8 at -65°F .

All of the transistors work correctly in the binary counter at $+165^{\circ}\text{F}$. The main difficulty encountered at high temperatures was triggering. As mentioned previously, "hole storage" time increases when the base of the transistor is driven further into saturation. Since the large signal gain increases markedly with temperature, the base of the transistor is effectively further overdriven and "hole storage" time increases at high temperatures. Therefore, the negative trigger must be held on

the base of the "on" transistor for a longer time at $+165^{\circ}\text{F}$ than at 72°F . The method used to obtain reliable operation at high temperatures was to increase the time constant of the trigger input circuit. However, C_1 cannot be made too large because of its effect on the preceding stage. Therefore, the trigger input circuit was made more complex, thereby increasing the time constant by increasing the resistance in series with C_1 by adding diode D_3 .

Another method that could be used to reduce the length of time that the trigger need be applied to the base of the "on" transistor would be to reduce the "hole storage" time at high temperatures. This could be done by using a temperature sensitive element to divert current away from the base at high temperatures while at low temperatures no current would flow through this device. This suggests the use of diodes for D_4 and D_5 that have a high rectification ratio at temperatures below $+72^{\circ}\text{F}$ and a rectification ratio that degenerates rapidly with increasing temperature. Since the binary counter operated at $+165^{\circ}\text{F}$, no attempt was made to incorporate this change. However, if the "hole storage" times encountered in the 24 transistors used are not typical of type 904 transistors, then the method outlined above may be resorted to.

Power Requirements

Each binary stage dissipates approximately 40 milliwatts for a supply voltage of 28 volts. The "on" transistor dissipates 1 milliwatt. The "off" transistor has a negligible dissipation. The manufacturer's specification for type 904 transistors is 50 milliwatts maximum dissipation at 150°C .

Conclusions

A transistorized binary counter that operates over a temperature range of -65°F to $+165^{\circ}\text{F}$ has been developed. The binary stages are presettable and resettable. The counter will use all type 904 Texas Instrument silicon transistors that meet the manufacturer's specification and have a large signal current gain greater than 2.8 at -65°F . The supply voltage required is 28 ± 4 volts.

Sufficient detail has been included to indicate a method for designing binary circuits using other type transistors, such as germanium.

If all of a particular type of transistor are to be used in a particular binary circuit, the external circuit must "swamp" out the transistor characteristics. Selection of transistors is still necessary if the circuit is required to function over wide temperature limits (-65°F to $+165^{\circ}\text{F}$) because transistors are individuals. In particular, the gain of silicon transistors decreases with decreasing temperature.

Transistors must be selected on the basis of a minimum gain at the lowest operating temperature. Special attention must be paid to the increased trigger length required at the higher temperatures. Since the base driving current is larger than necessary for collector current saturation at $+72^{\circ}\text{F}$ and the current gain of transistors increases with increasing temperature, "hole storage" time increases.

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VC-IC CHARACTERISTIC FOR TYPICAL 904

FIGURE 1

FIGURE 2 A TRANSISTOR MULTIVIBRATOR CONNECTION

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FIGURE 3

6
S-899

COLLECTOR TO GROUND VOLTAGE

COLLECTOR WAVEFORM

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BASE TO EMITTER VOLTAGE WAVEFORM

FIGURE 4

668-9

FIGURE 5

FIGURE 6

COUNTER OPERATING AT -65°F

MINIMUM TRIGGER LENGTH = 10 MICROSECONDS

TRIGGER VOLTAGE

TRIGGER AREA →

NOTE:

SUPPLY VOLTAGE CAN VARY
TO A MAXIMUM OF 40 VOLTS
WITH CORRESPONDING IN-
CREASE IN TRIGGER VOLTAGE
AMPLITUDE.

66812

SUPPLY VOLTAGE - VOLTS

FIGURE 7

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COUNTER OPERATING AT 0°F
MINIMUM TRIGGER LENGTH = 10 MICROSECONDS

NOTE:

SUPPLY VOLTAGE CAN VARY
TO A MAXIMUM OF 40 VOLTS
WITH CORRESPONDING
INCREASE IN TRIGGER
VOLTAGE AMPLITUDE.

TRIGGER VOLTAGE

TRIGGER AREA →

FIGURE 8

.15

TRIGGER VOLTAGE

COUNTER OPERATING AT 72 F

MINIMUM TRIGGER LENGTH = 10 MICROSECONDS

NOTE:

SUPPLY VOLTAGE CAN VARY
TO A MAXIMUM OF 40 VOLTS
WITH A CORRESPONDING
INCREASE IN TRIGGER
VOLTAGE AMPLITUDE

TRIGGER AREA →

66-899

FIGURE 9

COUNTER OPERATING AT $\pm 165^{\circ}\text{F}$

MINIMUM TRIGGER LENGTH = 10 MICROSECONDS

NOTE:

SUPPLY VOLTAGE CAN VARY
TO A MAXIMUM OF 40 VOLTS
WITH CORRESPONDING
INCREASE IN TRIGGER
VOLTAGE AMPLITUDE

TRIGGER VOLTAGE

TRIGGER AREA →

FIGURE 10

SUPPLY VOLTAGE

51-899

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