

Microprocessor-based temperature indicator using thermocouple as the sensor

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Received on February 18, 1988; Revised on June 2, 1988.

Abstract

A microprocessor-based thermocouple temperature indicator has been developed and described. For a *k*-type thermocouple, this indicator provides a linear performance over a wide dynamic temperature range of 50 to 1000°C with an accuracy of better than $\pm 0.3^\circ\text{C}$. To carry out the linearization of thermocouple easily through software, the full-scale temperature range of the thermocouple is divided into ten sectors and each is approximated by a fourth-order polynomial equation. To extract millivolt signal of the thermocouple from a high common-mode voltage (0 to ± 300 v peak), a flying-capacitor multiplexer in conjunction with drift-free dc amplifier is used as a signal conditioner. Test results are given to support the theory.

Key words: Temperature measurement, thermocouple linearization, analog interface.

1. Introduction

Thermocouple sensors are popular devices for measurement of temperature in a multitude of industrial applications and preferred to other temperature transducers because of their ruggedness, moderate accuracy and wide temperature range of operation. The output from the thermocouples is very low, typically 7 to 60 microvolts per degree centigrade. Unfortunately, the voltage-temperature relationship of a thermocouple is not linear for a wide range of operations and varies with the type of thermocouple used. For accurate measurement of temperature, it is essential that the thermocouple characteristics are well conditioned and linearized. Although several hardware techniques of linearization and signal conditioning are available, their accuracy and stability against common-mode voltage are limited. With the advent of microprocessor and low-level solid-state relay it is now possible to get higher accuracy and better performance.

Analog Devices¹ presented a data sheet of a microprocessor-based thermocouple meter. For a *k*-type thermocouple the meter measures the temperature over a range from -50 to $+1250^\circ\text{C}$ with a resolution of 1°C . The accuracy of the temperature is $\pm 0.9^\circ\text{C}$.

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This is the only microprocessor-based thermocouple indicator available in published literature and the basic operation and linearization technique are not detailed.

Hence, a microprocessor-based temperature indicator making use of both hardware and software schemes, has been developed to cover a wide dynamic temperature range. This scheme offers good accuracy, resolution, sensitivity and reliability against fluctuations in ambient temperature and common-mode voltage. In this paper, a detailed study of the microprocessor-based temperature indicator so developed is presented. First, the theory of signal conditioning, linearization and cold-junction compensation are described. Then, the hardware and software implementation and also the performance study are described. The last section summarizes the work and gives the advantages of the proposed technique.

2. Theory of signal conditioning

Thermocouples cause problems unless proper signal conditioning is employed. The most popular and economical technique is a flying-capacitor multiplexer in conjunction with an ac amplifier². This technique helps to measure millivolt signals riding on ac and dc common-mode voltages ranging from a few to several hundred volts with near-infinite common-mode rejection at dc and also 100 to 120 db of rejection at 50 Hz. In addition, this allows the use of a single-ended amplifier in place of the high-cost instrumentation amplifier.

The technique is illustrated in fig. 1a, and comprises two pairs of analog switches, a large flying capacitor and a storage capacitor. One pair of switches is normally closed and the other is normally open. The multiplexer is shown in the unselected state. The flying capacitor is connected through a pair of switches to the analog input. The flying capacitor charges up to the differential input signal. When the input is selected, the first pair of switches opens disconnecting the flying capacitor from the input, and the second pair closes connecting the capacitor to the amplifier input. The input signal is stored on the storage capacitor and transferred to the amplifier input.

The equivalent circuit of a flying-capacitor multiplexer for duration t_1 (when the input is unselected) is illustrated in fig. 1b.

The application of Kirchhoff's current law to the network gives the relationship

$$\frac{(e_{mj} + e_{cm} - e_{o1})}{R_{on1}} = e_{o1} C_{D1}s + (e_{o1} - e_{o2}) C_f s, \quad (1)$$

$$\frac{(e_{cm} - e_{o2})}{R_{on2}} = e_{o2} C_{D2}s + (e_{o2} - e_{o1}) C_f s \quad (2)$$

where s is the complex frequency variable. By solving equations (1) and (2), the transfer function, neglecting the higher order terms, becomes

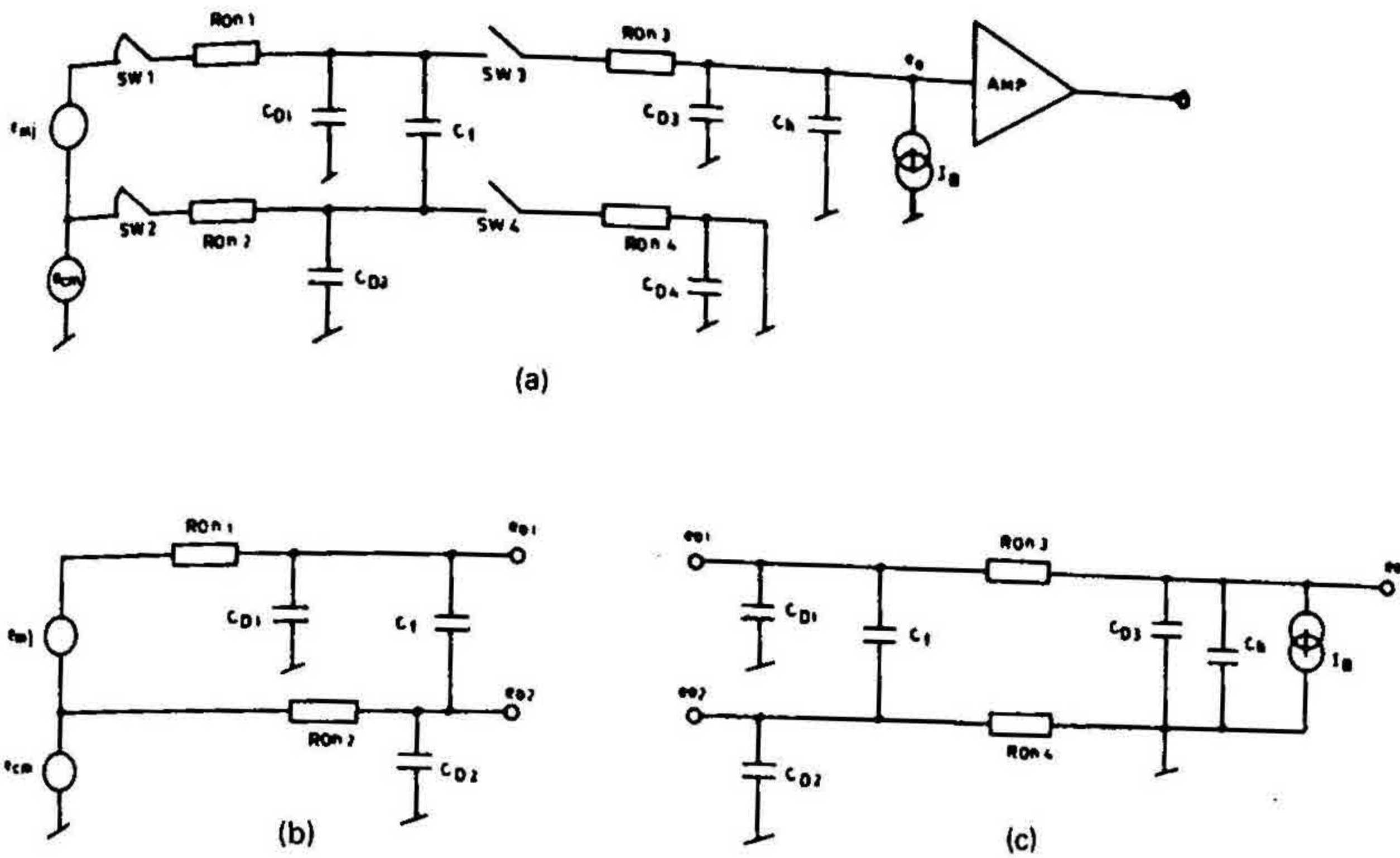


FIG. 1. Equivalent circuit of flying-capacitor multiplexer.

$$e_{o1} - e_{o2} = \frac{e_{mj}(1 + R_{on2} C_{D2} s) + e_{cm}(R_{on2} C_{D2} s - R_{on1} C_{D1} s)}{1 + s[R_{on2}(C_f + C_{D2}) + R_{on1}(C_f + C_{D1})]} \quad (3)$$

For step response, equation (3) becomes

$$(e_{o1} - e_{o2}) = e_{mj} \left[1 - \frac{R_{on1}(C_f + C_{D1}) + R_{on2} C_f}{R_{on1}(C_f + C_{D1}) + R_{on2}(C_f + C_{D2})} * \exp(-t_1/k_1) \right] + e_{cm} \left[\frac{R_{on2} C_{D2} - R_{on1} C_{D1}}{R_{on1}(C_f + C_{D1}) + R_{on2}(C_f + C_{D2})} * \exp(-t_1/k_1) \right] \quad (4)$$

where $k_1 = R_{on1}(C_f + C_{D1}) + R_{on2}(C_f + C_{D2})$,

C_{D1}, C_{D2} = stray capacitance plus output capacitance of the switches sw_1 and sw_2 ,

R_{on1}, R_{on2} = ON resistance of the switches sw_1 and sw_2 ,

e_{cm} = common-mode voltage,

e_{mj} = differential-input signal,

C_f = flying capacitor.

If $R_{on4} = R_{on3}$, then equation (10) becomes

$$de_o/dt = \frac{(e_s - I_B R_{on3}) C_{D3}}{4R_{on} C_f^2} \quad (11)$$

If $R_{on3} = 24$ ohms, $C_{D3} = 60$ pf, $C_f = 30$ μ f, $I_B = 50$ na and $e_s = 50$ mv, then the droop rate will be 0.3 μ v/s. These values are taken based on the present design. The droop rate is minimized by adding $C_h (= C_f)$ across the amplifier input.

3. Theory of linearization

Temperature vs voltage characteristic of a thermocouple may be approximated by using a power-series polynomial:

$$T = a_0 + a_1 e_{mj} + a_2 e_{mj}^2 + \dots + a_n e_{mj}^n \quad (12)$$

where T is the thermocouple-measuring junction temperature, e_{mj} the thermocouple-measuring junction voltage, a_n the polynomial coefficients and n the order of the polynomial. Thermocouple-output voltage is a function of the temperature difference between measuring and reference junctions. Therefore, equation (12) is based on a reference-junction temperature of 0°C . For other reference-junction temperature, equation (12) may be written as:

$$T = a_0 + a_1 e_T + a_2 e_T^2 + \dots + a_n e_T^n \quad (13)$$

where $e_T = (e_{mj} + e_r)$ and e_r the thermocouple reference-junction voltage. In equation (12), the accuracy of the temperature depends upon the order of the polynomial equation. Solving such higher-order polynomials through microprocessor is a time-consuming task. Hence, a limited number of break points (or sectors) plus a lower-order polynomial calculation is the most preferable and is incorporated. In the present design, the k -type thermocouple characteristic curve is divided into ten sectors and each is approximated by a fourth-order polynomial. Hence, equation (13) becomes

$$T = a_0 + a_1 e_T + a_2 e_T^2 + a_3 e_T^3 + a_4 e_T^4 \quad (14)$$

where a_0, a_1, a_2, a_3 and a_4 are the polynomial constants (Table I) for a k -type thermocouple. These constants are derived based on the numerical techniques viz., cubic spline and least-square approximations³. Equation (14) can now be solved more easily using a microprocessor. Hence, a linear relation between the computed value and the temperature of the thermocouple is obtained.

4. Theory of cold-junction compensation

Thermocouples are inaccurate if no correction is made for the variation in reference-junction temperature. Two techniques, hardware and software, exist to provide for this compensation.

In the hardware cold-junction-compensation technique, the temperature at the thermocouple cold or reference junction is converted to a voltage which is properly added to the measuring-junction voltage. The resultant voltage is proportional to the temperature referred to as 0°C . The disadvantage of this scheme is that the cold-junction-compensating circuitry requires high-quality components. In addition, this requires reed relays for selection of components for different thermocouples.

In the software-compensation technique, reference-junction temperature is monitored by the microprocessor and depending upon the type of the thermocouple being used, the reference-junction voltage is added properly to the measuring-junction voltage using software to give an absolute temperature value. The advantage of this technique is that this eliminates the need for selection of hardware components for different thermocouples. In the present design, the software-compensation technique has been selected and is incorporated. The voltage-temperature characteristic of a thermocouple for cold-junction compensation may be approximated using a fourth-order power series polynomial:

$$e_r = a_0 + a_1 T_r + a_2 T_r^2 + a_3 T_r^3 + a_4 T_r^4 \quad (15)$$

where e_r is the thermocouple reference-junction voltage, T_r the thermocouple reference-junction temperature, and a_0 , a_1 , a_2 , a_3 and a_4 are the polynomial constants and are tabulated in Table I for k -type thermocouple. By monitoring reference-junction temperature T_r , an equivalent reference-junction voltage e_r may be computed by solving equation (15) in the microprocessor.

Since thermistors are small in size, fast in response and do not require an ADC for interfacing⁴ they are the most suitable for monitoring the reference-junction temperature. The mathematical expression for the NTC thermistor is given by

$$T_r = \frac{N_3}{N_2 + N_1} - N_4 \quad (16)$$

where a_0 , a_1 , a_2 , a_3 and a_4 are the polynomial constants (Table I) for a k -type thermocouple. These constants are derived based on the numerical techniques *viz.*, cubics spline and least-square approximations³. Equation (14) can now be solved more easily using a microprocessor. Hence, a linear relation between the computed value and the temperature of the thermocouple is obtained.

where T_r is the temperature of the thermistor in degree centigrade, N_2 , N_3 and N_4 the constants for the given thermistor and

$$N_1 = N \ln(R_T/R_s) \quad (17)$$

where N is another constant, R_T the thermistor resistance, R_s a temperature range-selecting resistor. After obtaining N_1 for the thermistor through hardware, equation (16) can be solved easily using a microprocessor. Hence, a linear relation between the computed value and the temperature of the thermistor is obtained.

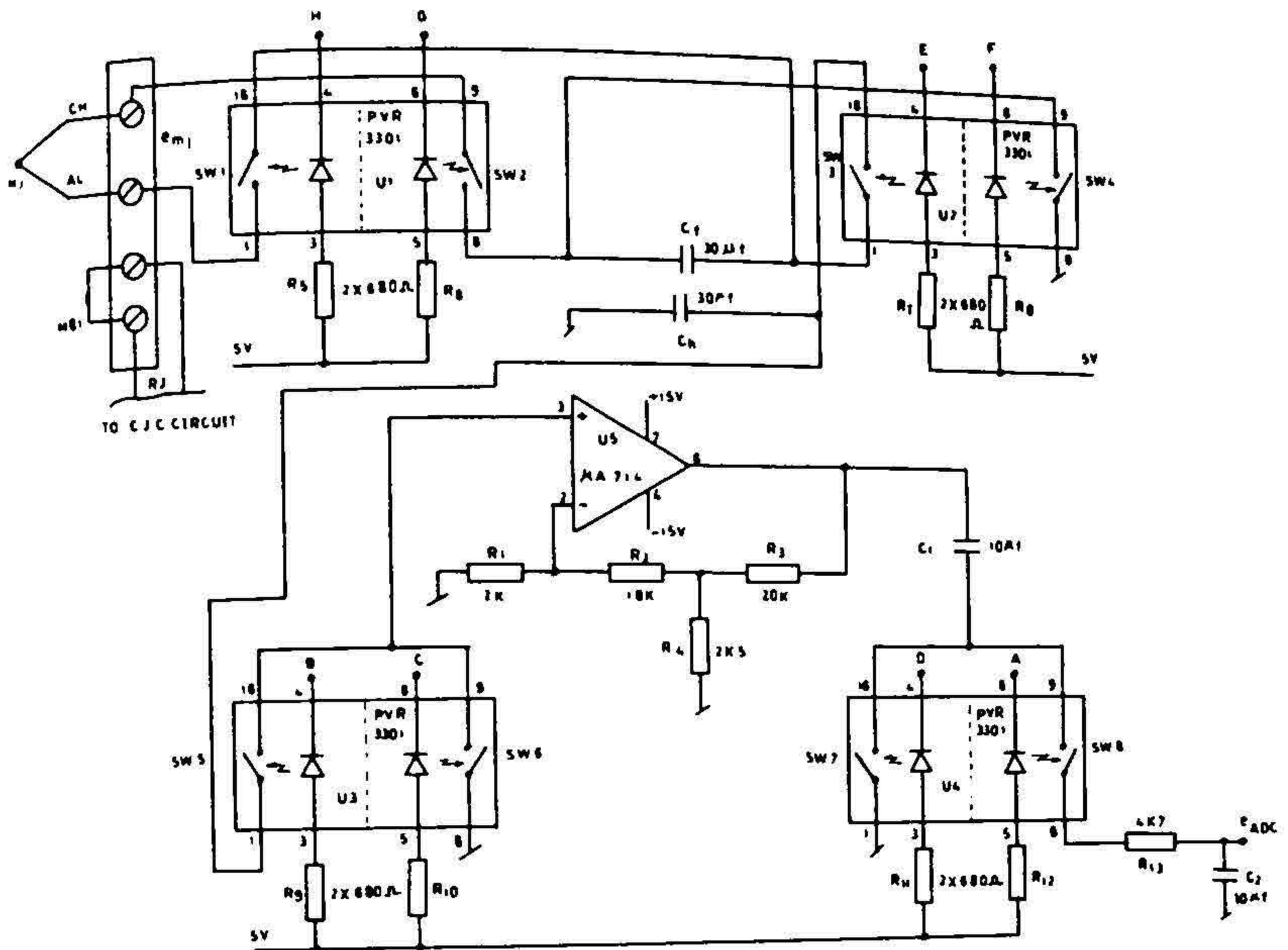


FIG. 2. Flying-capacitor multiplexer with a drift-free dc amplifier.

5. Hardware implementation

The hardware implementation of the individual blocks of the indicator is described below briefly.

5.1 Flying-capacitor multiplexer and drift-free dc amplifier

Switching millivolt signals of thermocouples riding on high common-mode voltages can be carried out with reed relays. However, these relays are slow-switching devices and generate thermal voltages. The main disadvantage of the switches is their contact bounce. For high-accuracy systems, the relays require more hardware for eliminating the contact bounce. Hence, recently developed, low-level solid-state or photo-voltaic relays are more economical devices. They switch low-level signals riding on a ± 300 v peak(max) ac or dc common-mode voltages. In addition, they have 200 nV thermally generated offset voltage and low ON resistance of 20 ohms, and are used in the flying-capacitor multiplexer (fig. 2). They comprise four switches each for the multiplexer (sw_1 to sw_4) and the amplifier U_5 (sw_5 to sw_8). The switches, sw_1 to sw_4 are connected to yield double-pole double-throw action (DPDT). The switches, sw_5 to sw_8 , with an amplifier U_5 form a drift-free dc amplifier. The flying capacitor C_f and storage capacitor C_h are

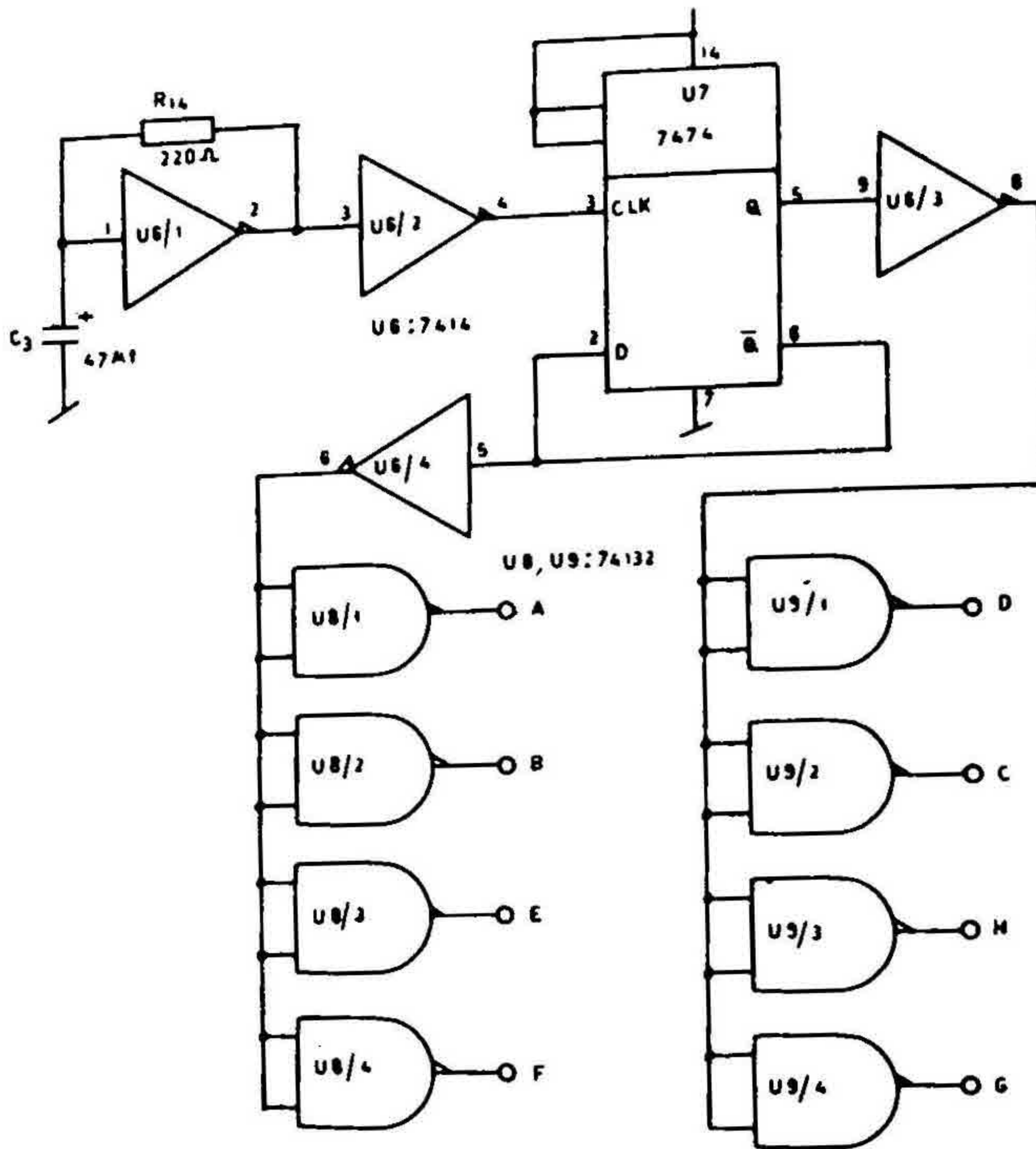


FIG. 3. Driving circuit for multiplexer.

connected as shown in the figure. The DPDT switch first connects the flying capacitor C_f across the thermocouple input e_{mj} for charging (during t_1) to its output voltage. The capacitor C_f is then disconnected (during t_2) from the thermocouple and connected to the amplifier input *via* switch sw_5 . The input e_{mj} is amplified by the amplifier U_5 . During t_1 , the capacitor C_1 charges to the offset voltage of the amplifier U_5 . Similarly, during t_2 , the capacitor C_1 charges to the input e_{mj} plus offset voltage of the amplifier. Hence, the capacitor blocks the dc offset and allows the square-wave signal which is filtered by the passive filter R_{13} and the capacitor C_2 . The dc-output signal e_{ADC} is directly proportional to the thermocouple input e_{mj} . Therefore, the output voltage e_{ADC} will be

$$e_{ADC} = e_{mj} \left[\left(\frac{R_1 + R_2}{R_1} \right) \left(\frac{R_3 + R_4}{R_4} \right) + \frac{R_3}{R_1} \right]. \quad (18)$$

The driving signals for the switches are derived from an RC-oscillator using Schmitt trigger $U_6/1$ (fig. 3). The D-FF U_7 is used to get 50% duty cycle. Gates U_8 and U_9 are used to drive the switches.

5.2 Cold-junction compensating circuit

The reference temperature-sensing circuit based on an operational-amplifier multi-vibrator is illustrated in fig. 4. A two-wire thermistor R_T is included as one of the elements in the feedback path of a differential amplifier U_{21} . The amplifier is excited by a reference voltage e_z and its output e_y is given by

$$e_y = e_z \frac{R_T - R_s}{R_T + R_s} \tag{19}$$

The temperature-dependent voltage e_y sets the positive and negative trigger levels of the multivibrator U_{22} . The ON-time period of the multivibrator will be

$$t_{On} = R_{27} C_7 \ln \frac{e_z + e_y}{e_z - e_y} \tag{20}$$

where $R_{27} C_7$ is the time constant of the multivibrator. From equations (19) and (20), the following relation is obtained.

$$t_{On} = R_{27} C_7 \ln(R_T/R_s) = t_{off} \tag{21}$$

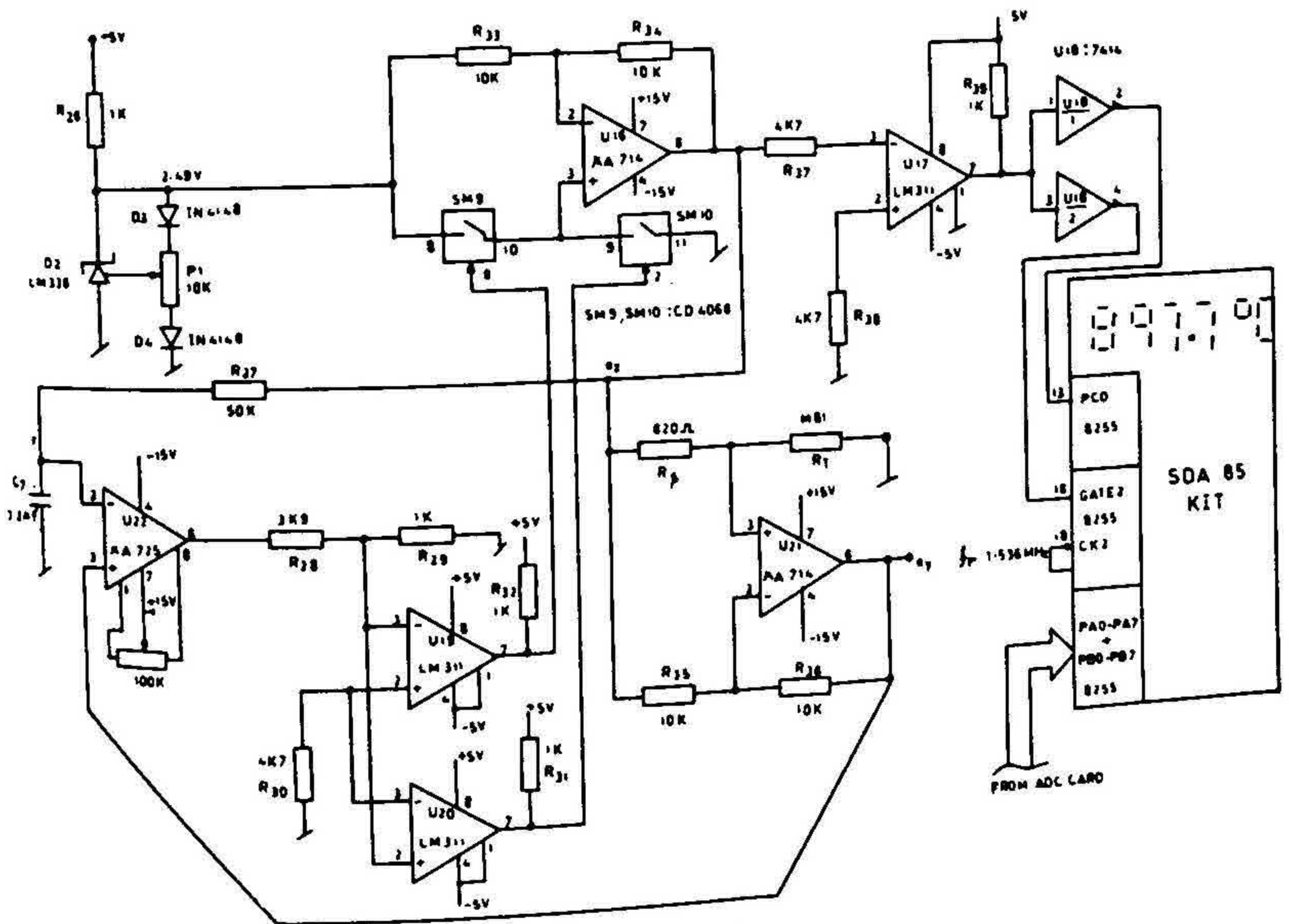


FIG. 4. Thermistor interface for cold-junction compensation.

Thus, the discharge and charge time of the multivibrator are directly proportional to the natural logarithm of the thermistor R_T . Gating a reference clock f_r over the time interval t_{On} yields a total number of counts N_1 and is given by

$$N_1 = R_{27} C_7 f_r \ln(R_T/R_s). \tag{22}$$

For the calibrated thermistor M81, the computed constants are $N_2 = 158137$, $N_3 = 66531037$, $N_4 = 312$ and $N_1 = 3336$ to 550816 if $f_r = 1.536$ MHz, $R_{27} = 50$ k ohms, $C_7 = 0.2$ uf and $R_s = 620$ ohms. To get an equal positive and negative peak-reference voltage, a bipolar converter is incorporated. An op amp U_{16} and the two analog switches sw_9 and sw_{10} convert the unipolar-reference voltage e_z , into a bipolar signal $\pm e_z$. The reference voltage e_z is derived from a reference diode D_2 . The control signals for switches are derived from comparators U_{19} and U_{20} . The comparator U_{17} gives out a TTL-compatible signal and is fed to the gate input of the counter 8253 and to an input port of PPI 8255 through an inverting Schmitt trigger U_{18} .

5.3 Dual-slope A/D converter interface

In an industrial environment, the line-frequency and other low-frequency noise components can cause serious problems in temperature measurement. A recently developed dual-slope ADC⁵ offers a high normal-mode line-frequency rejection, good resolution and linearity. This is available as an inexpensive 12-bit ADC [ICL 7109] chip and is employed (fig. 5) to achieve the above performances. In this ADC U_{13} , an input voltage

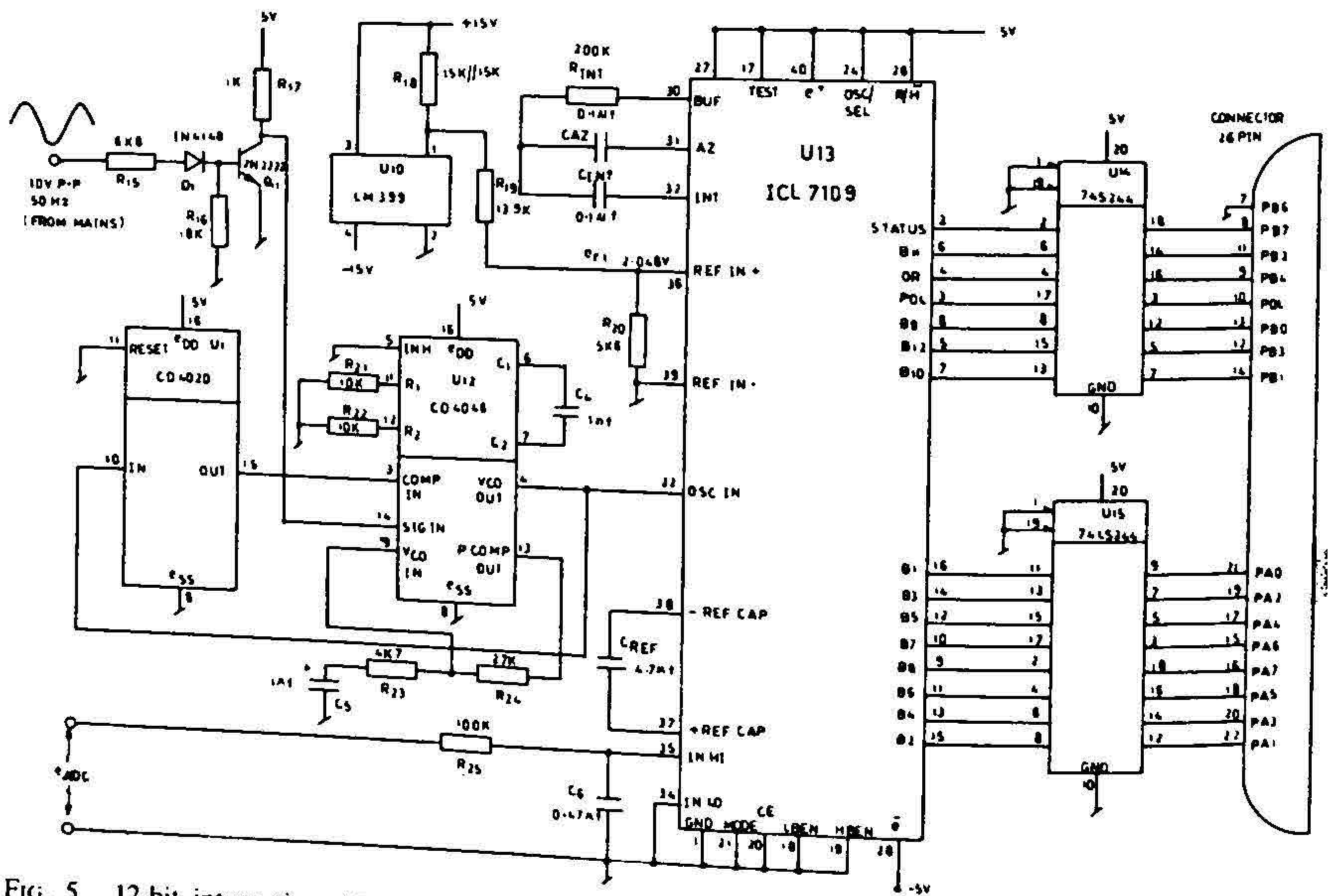


FIG. 5. 12-bit integrating ADC with a PLL for tracking mains frequency.

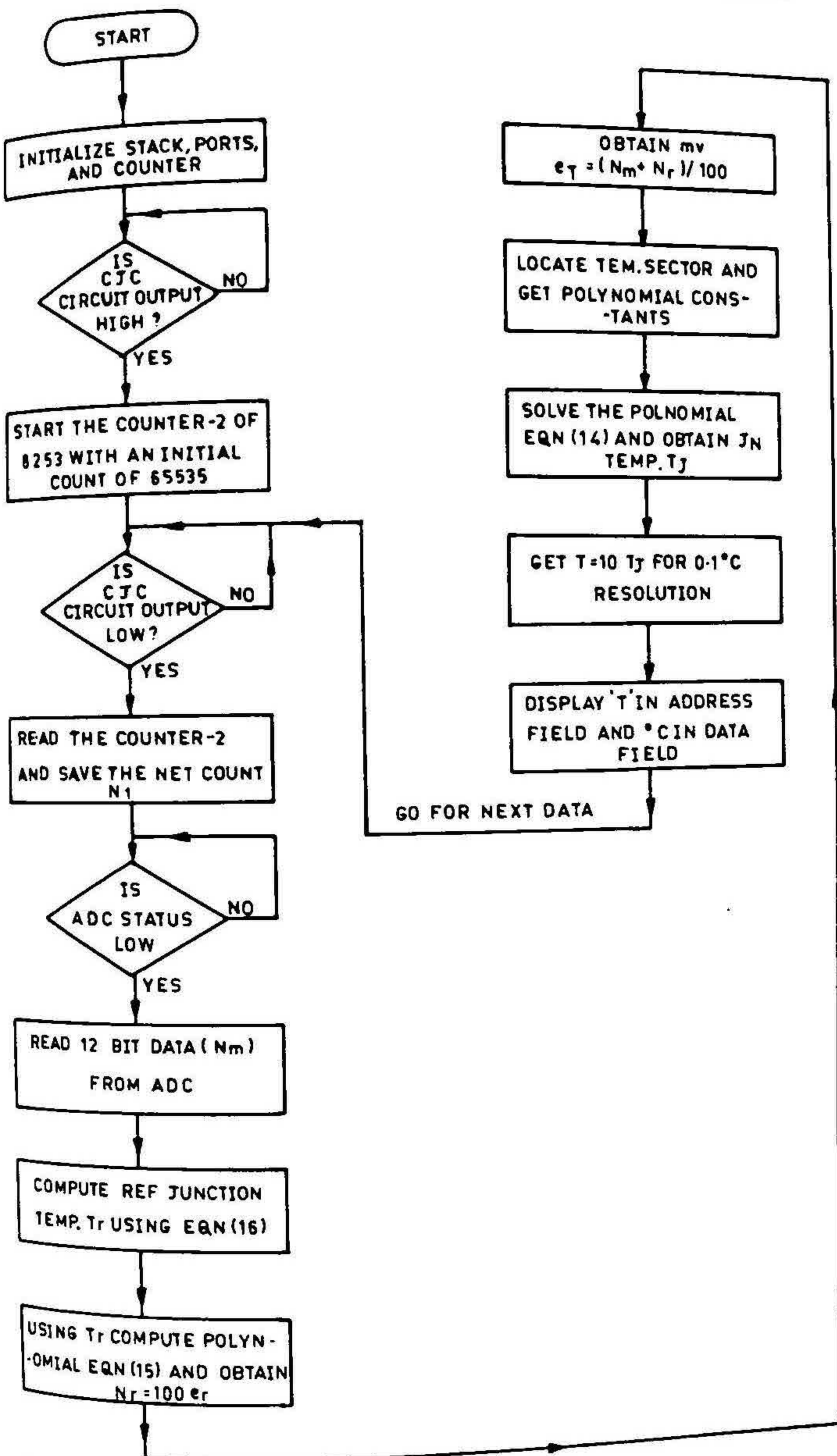


Fig. 6. Flow diagram of the software.

integration phase and an auto-zero phase are carried out in 8192 clock periods, serving to eliminate offset voltages and determine the magnitude and polarity of the sampled voltage.

The ADC integrates the input signal for only 2048-clock periods. To achieve high normal-mode line-frequency rejection, the integration period is made equal to the period of the mains supply by incorporating a phase-locked loop U_{12} and a divided-by-2048 counter U_{11} . Hence the clock frequency f_c for the ADC is $2048 f_s$, where f_s is the frequency of the mains supply.

The stability of the reference voltage is a major factor in the overall absolute accuracy of the ADC. For 1000°C full scale, the resolution of the ADC is 1 mv or 0.25°C. An external reference voltage e_{r1} is employed. This has a temperature coefficient of 2 ppm/°C. A change in temperature of 50°C in the environment introduces an error of 0.1°C. The roll-over errors of ADC are minimized by having REFIN and INLO at analog COMMON. The components are selected for 4.096 v full scale.

5.4 Microprocessor hardware

To carry out the computation of equations (14) and (15), a basic SDA-85 kit has been used. This kit provides the necessary facilities to develop and debug a program through the use of SDA-85 monitor and key/display board. In addition, this kit offers 2 k bytes each of RAM, monitor EPROM, and EPROM for user and two I/O ports of 8255. Here, the two I/O ports, one counter and 2 k EPROM have been utilised for interfacing ADC and linearization.

6. Software implementation

The flow diagram of the software for the indicator is shown in fig. 6. The software for the indicator illustrates port and counter initialization, read operation of counter and ADC, temperature break-point selection, computation of measuring junction and reference-junction temperature. In the first step, ports A, B and C are initialised as input ports and when the gate input of counter-2 of 8253 is high, the counter is initialised to operate in mode-2 with an initial count of 65535D. Similarly, when the gate input is low, the content of the counter is read and saved in memory after subtracting from the initial count. In the second step, when the status of the ADC goes low, the upper and lower bytes of ADC are read and stored in memory after masking the bits POL, OR and STATUS.

In the third step, using the net count N_1 , T_r , computed from equation (16), is substituted in the polynomial equation (15) and an equivalent voltage in millivolts is obtained for the thermocouple. This mv is added to the mvs from the measuring junction and selected temperature sector and its polynomial constants by comparison routine. Lastly, the measuring-junction temperature is computed by solving the fourth-order polynomial equation (14). The final result as a four-digit decimal number, is displayed in degree

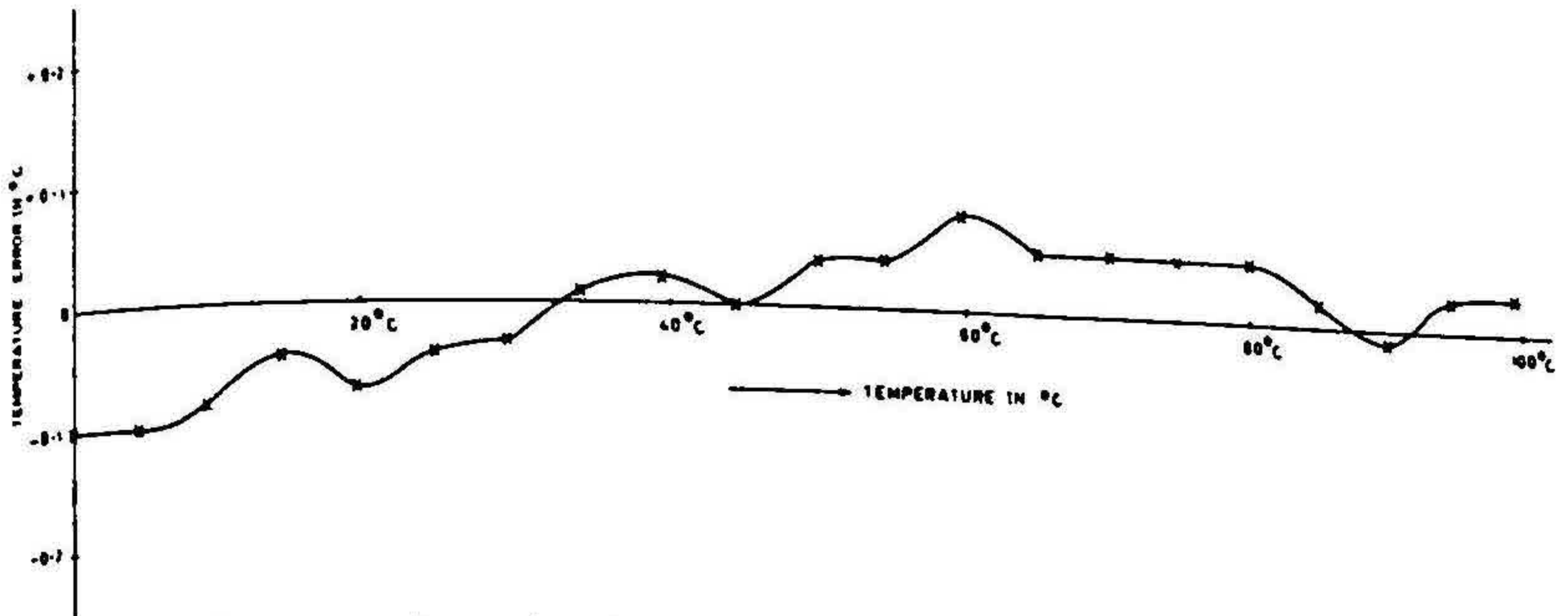


FIG. 7. Plot of error in reference-junction temperature vs temperature.

centigrade in the address and data fields of the display using the display sub-routines of the SDA-85 kit. The decimal point is placed in the second least significant digit of the address field. Hence, the display reads a maximum temperature of 999.9°C with a resolution of 0.1°C. The microprocessor 8085 with 3 Mz clock frequency takes the worst case time of 68 ms for computing a single data. The indicator requires 2 k bytes of EPROM including floating-point arithmetic routines and 100 bytes of RAM for linearization.

7. Performance study

This indicator has been constructed and tested for a *k*-type thermocouple. The whole circuit was fabricated on three printed circuit boards. Metal film resistors having 0.1%

Table I
Polynomial constants for *k*-type thermocouple

Temp. range (°C)	a_0	a_1	a_2	a_3	a_4
0-100	1.89307E-03	25.32997	-0.367113	3.0234E-02	1.24241E-03
100-200	-0.47236	26.24612	-0.84662	0.1299	-6.16375E-03
200-300	11.72426	17.34056	1.35796	-9.96092E-02	2.49615E-03
300-400	33.31219	14.78448	1.13713	-.05918	1.09961E-03
400-500	67.29846	10.39878	1.16968	-.04484	6.28149E-04
500-600	102.95118	7.04302	1.15866	-3.63061E-02	4.26018E-04
600-700	30.85405	20.83651	0.18782	-6.38059E-03	8.41052E-05
700-800	52.90970	18.38978	0.27471	-7.27153E-03	8.06424E-05
800-900	186.91467	6.09951	0.65078	-1.11125E-02	8.06965E-05
900-1000	103.98001	7.30849	0.87589	-1.94409E-02	1.61725E-04
1000-1100	-194.20831	39.56959	-0.46033	5.47897E-03	-1.37515E-05
1100-1200	1658.56179	-52.57361	0.38436	2.327E-02	-2.66851E-04
1200-1300	490.83771	-1.8964	0.40581	-1.34423E-03	-1.62955E-06
Cold-junction compensation 0-50	-1.77709E-04	3.95094E-02	2.05224E-05	3.92197E-09	-7.5639E-10

tolerance and polycarbonate capacitors were selected throughout. To reduce the ground-loop error, the digital and analog grounds were connected at power supply common. The circuit was operated using supply voltages of ± 15 v, ± 5 v and tested in the laboratory. The cold-junction compensating circuit was tested with M81 thermistor over the temperature range 0 to 100°C . The temperature error was measured at various temperatures using DIN-standard platinum-resistance thermometer (fig. 7). Similarly, in the place of a thermocouple, a standard dc-millivolt source was used to calibrate the measuring-junction temperature of the thermocouple. For different millivolts (as per OMEGA Tables)⁶, the temperature of the thermocouple was noted and the results are plotted in fig. 8. It may be noted that the deviations for both the thermistor and the thermocouple are approximately $\pm 0.1^{\circ}\text{C}$ and $\pm 0.3^{\circ}\text{C}$, respectively. This error may be attributed to the tolerance of the circuit components used, noise voltages, non-linearity of the amplifier, unrejected common-mode voltage of the multiplexer and any uncertainty involved in the calibration.

The common-mode rejection of the multiplexer was tested for both dc and ac voltages and it is better than 90 db.

To measure the long-term stability, the circuit was operated for a few hours continuously at constant input signal. No measurable change in the output-display reading was observed.

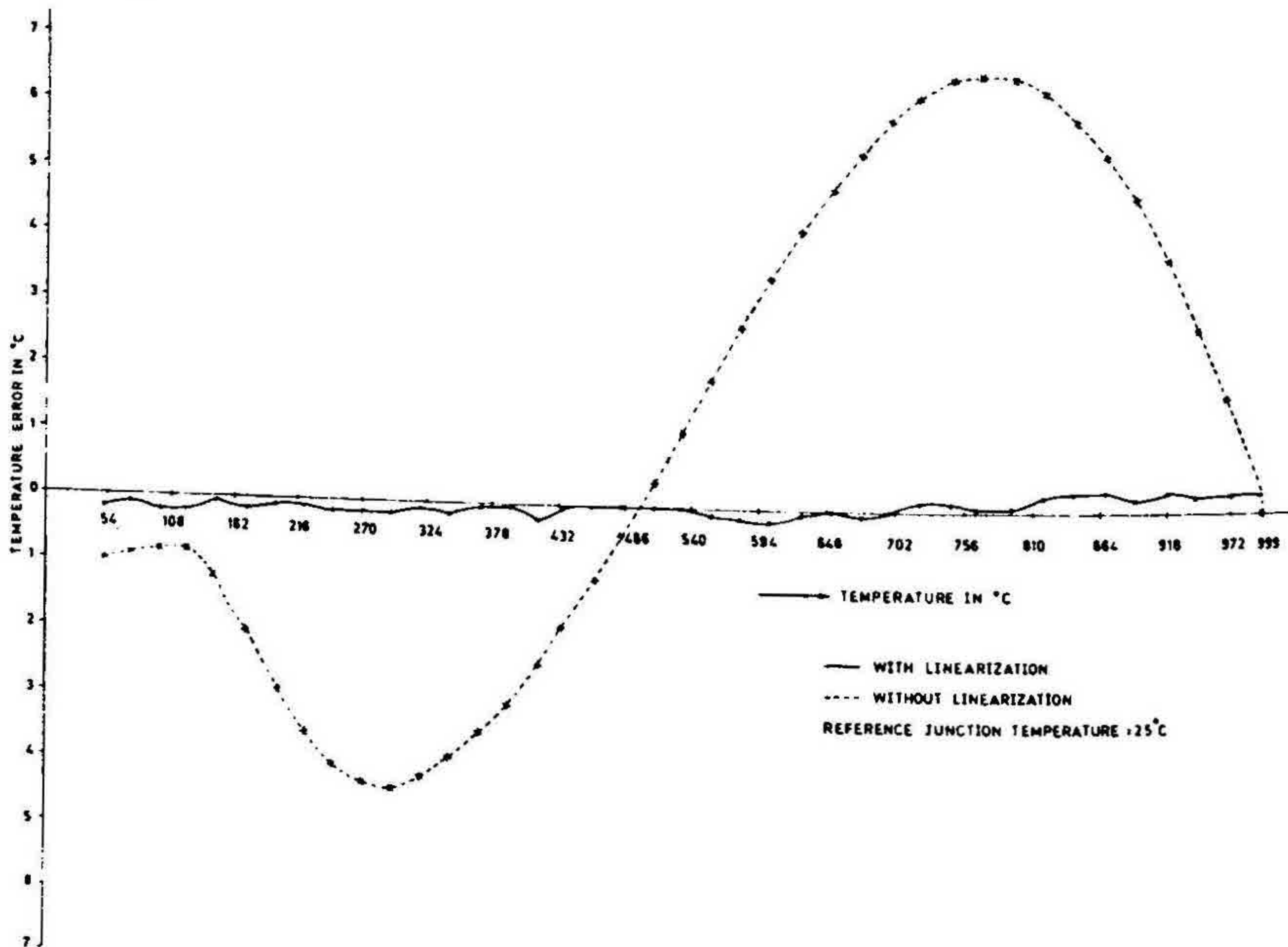


FIG. 8. Plot of error in thermocouple temperature vs temperature.

8. Conclusion

The microprocessor-based thermocouple temperature indicator described here offers a response linearity with a maximum error of about $\pm 0.3^{\circ}\text{C}$ in the range 50 to 1000°C as tested in the laboratory. This indicator takes a common-mode voltage of 0 to ± 300 v peak ac or dc voltages. Also, by changing the gain of the amplifier and by replacing the polynomial constants in the software, this indicator can be used for generally available thermocouple types T, J, E, R and S. In addition, this analog interface can be used for interfacing sensors like pressure transducers, load cells, etc.

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