# Chapter IV

# DESIGN OF THE SOLAR TRACKING SYSTEM

## 4.1 Introduction

The preliminary design of the solar tracking system has already been discussed in Chapter II. This chapter concerns with a practical design of the complete system. The design considerations starts with the detector and then the circuit components.

## 4.2 Detector

The following configuration of solar cells are considered for a position detector.

Solar Cell[10]

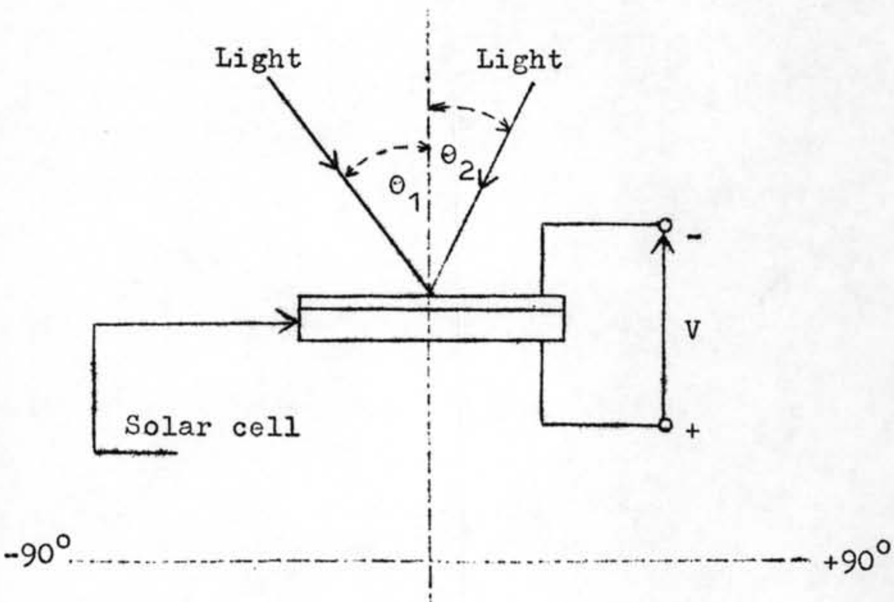


Figure 4.1. A Solar Cell as a Detector.

Assume that the illumination from the source is constant. The maximum incident flux occurs when $\theta_1$ or $\theta_2 = 0$.

Let $\Phi$ = incident flux on the cell,

$\Phi_m$ = maximum flux on the cell,

$B$ = flux density on the cell ($lumen/ft^2$),

and $A$ = area of solar cell ($ft^2$).

The following relationship can be written :

$$\Phi = BA\cos\theta \tag{4.1}$$

At $\theta = 0^\circ$, $\Phi = \Phi_m = BA$.

At $\theta = \pm 90^\circ$, $\Phi = 0$ .

Then, at any value of $\theta$ :

$$\Phi = \Phi_m \cos\theta \tag{4.2}$$

The solar cell acts as a constant current source (as described in Chapter III.), the generated current is proportional to the flux incident on it; therefore :

$$\Phi \propto I$$

From Ohm's law

$$V \propto I$$

So $V \propto \Phi$ ..........if there is no saturation in the solar cell.

Equation (4.2) can be written in another form :

$$V = V_m \cos\theta . \tag{4.3}$$

Figure(4.1) shows that, at any angle $\theta$, the voltage output is of the same polarity. Therefore, one cell cannot be usedas a detector to control the direction of rotation of a motor.

To use two solar cells as a detector, one must decide whether they should be connected in parallel or in series. Next, the two possibilities are considered.

Two solar cells in parallel

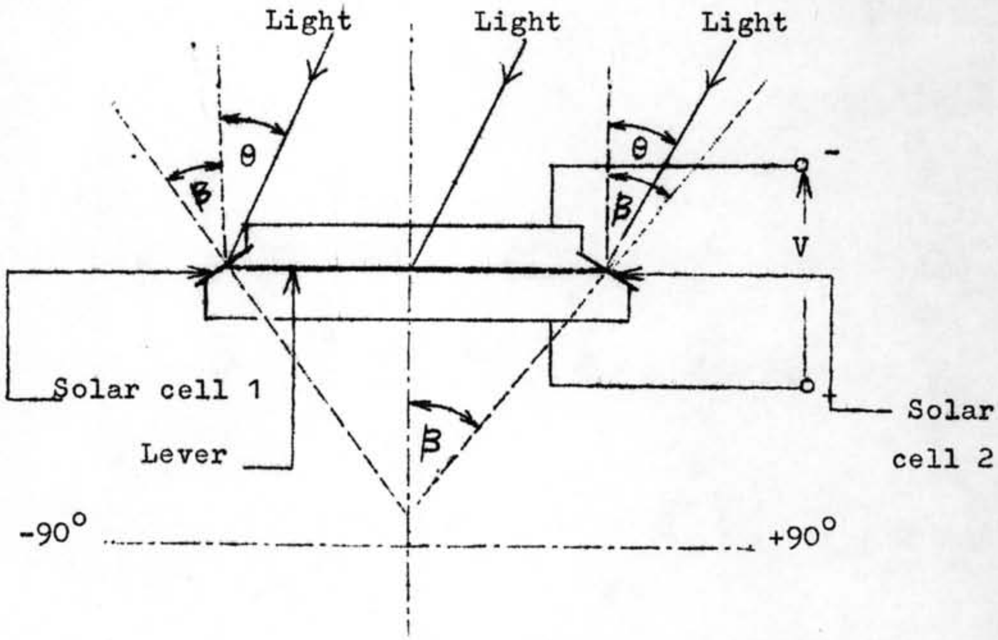


Figure 4.2. Two Solar Cells in a Parallel Connection as a Detector.

From Equation (4.3) the following equations can be written :

$$V_1 = V_{m1} \cos(\beta+\theta), \quad (4.4)$$

$$V_2 = V_{m2} \cos(\beta+\theta), \quad (4.5)$$

where

$V_1, V_2$ = voltage output of each cell(volts),

$V_m$ = maximum voltage at bright sunlight when the sun is vertical with respect to the plane of a cell ($\theta = 0$).

If the two cells have the same characteristic then $V_1 = V_2 = V_m$ at $\theta = 0^\circ$, no circulating current flows between the cells. The output voltage is $V_m$ which is the same as output voltage from one cell.

At $\theta = \pm 90^\circ$, or at any $\pm\theta$ one cell will act as a power source while the other acts as a load. The polarity of voltage is still the same but the magnitude varies. Therefore, two solar cells in parallel connection cannot be used to control direction of rotation of motor.

Two solar cells in series with opposite polarity

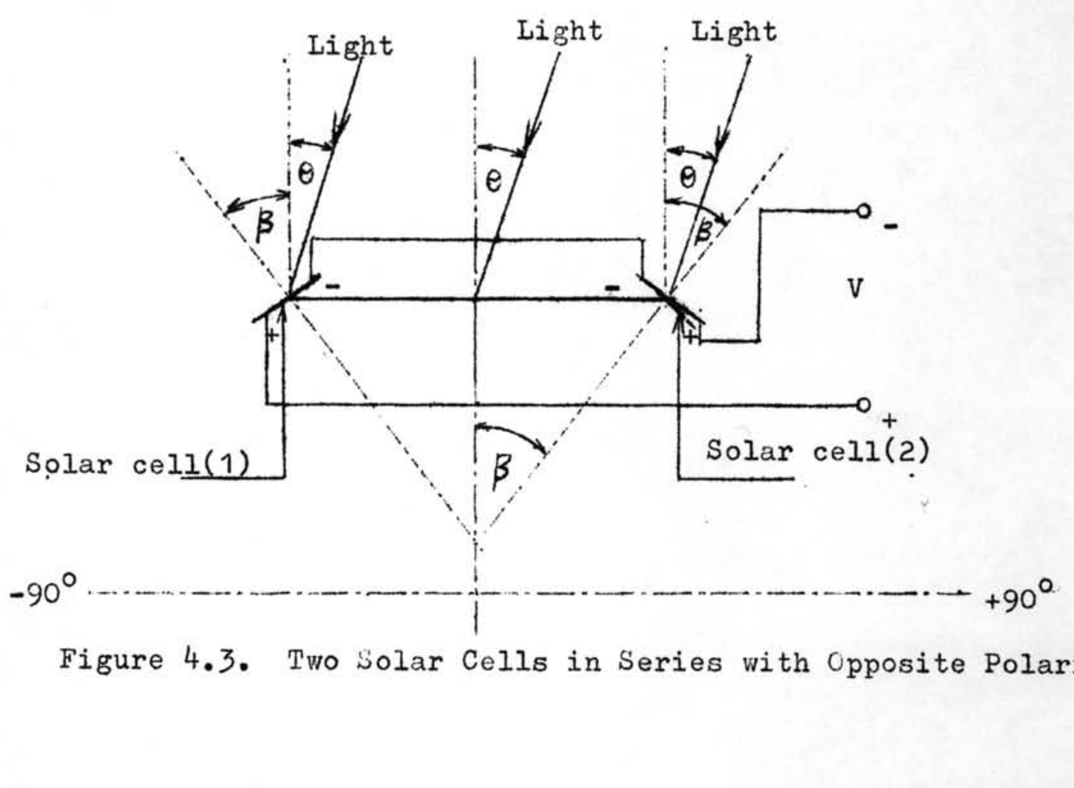


Figure 4.3. Two Solar Cells in Series with Opposite Polarity.

At $\theta = 0$, $V_1 = V_2 = V_m \cos\beta$ , therefore, $V = V_2 - V_1 = 0$

At any $\pm\theta$, one has :

$$V = V_2 - V_1, \qquad (V_2 > V_1)$$

$$V = V_m \cos(\beta - \theta) - V_m \cos(\beta + \theta),$$

$$= V_m \left[\cos\beta\cos\theta + \sin\beta\sin\theta - \cos\beta\cos\theta + \sin\beta\sin\theta\right],$$

$$= 2V_m \sin\beta\sin\theta, \qquad (4.6)$$

$$= 2K\sin\theta \quad (\beta = \text{constant}). \qquad (4.7)$$

As the polarity of the detector depends on $V_1$ and $V_2$, the detector output voltage can be used to control the direction of rotation of motor. If $V_1 > V_2$, the output voltage is negative. If $V_2 > V_1$, the output voltage is positive. Thus, the detector used should consist of two solar cells connected in series with opposite polarity. The maximum value of the position angle $\beta$ of detector may be determined as follows :

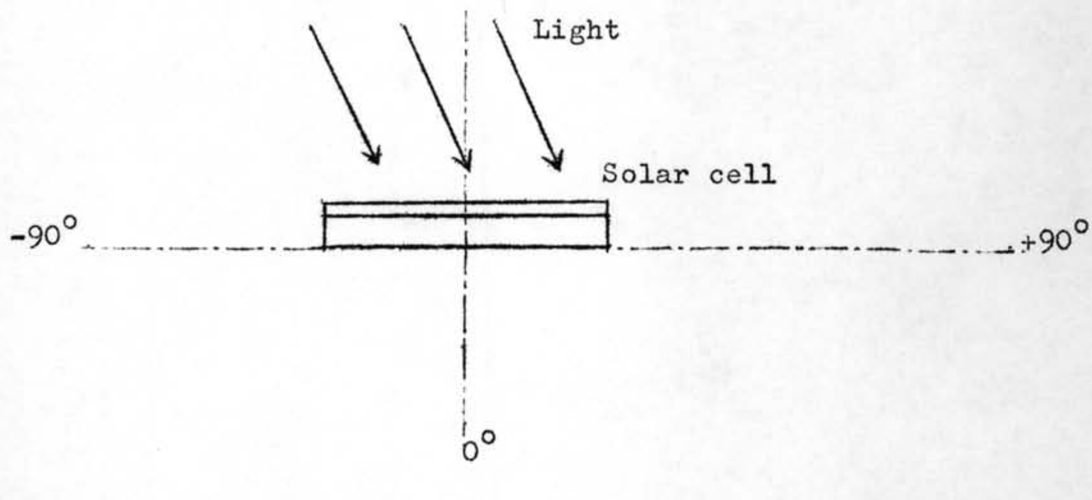


Figure 4.4. Capture Range Determination on a Cell = ±90°.

Consider a single cell in Figure 4.4. As the sun moves to an angle $\theta$, greater than $90^{\circ}$ or less than $-90^{\circ}$, the incident flux on the cell assumes a value of zero. Neglecting radiation and reflection from the surrounding, there is essentially no voltage output from the solar cell. The capture range of a cell istherefore $\pm 90^{\circ}$.

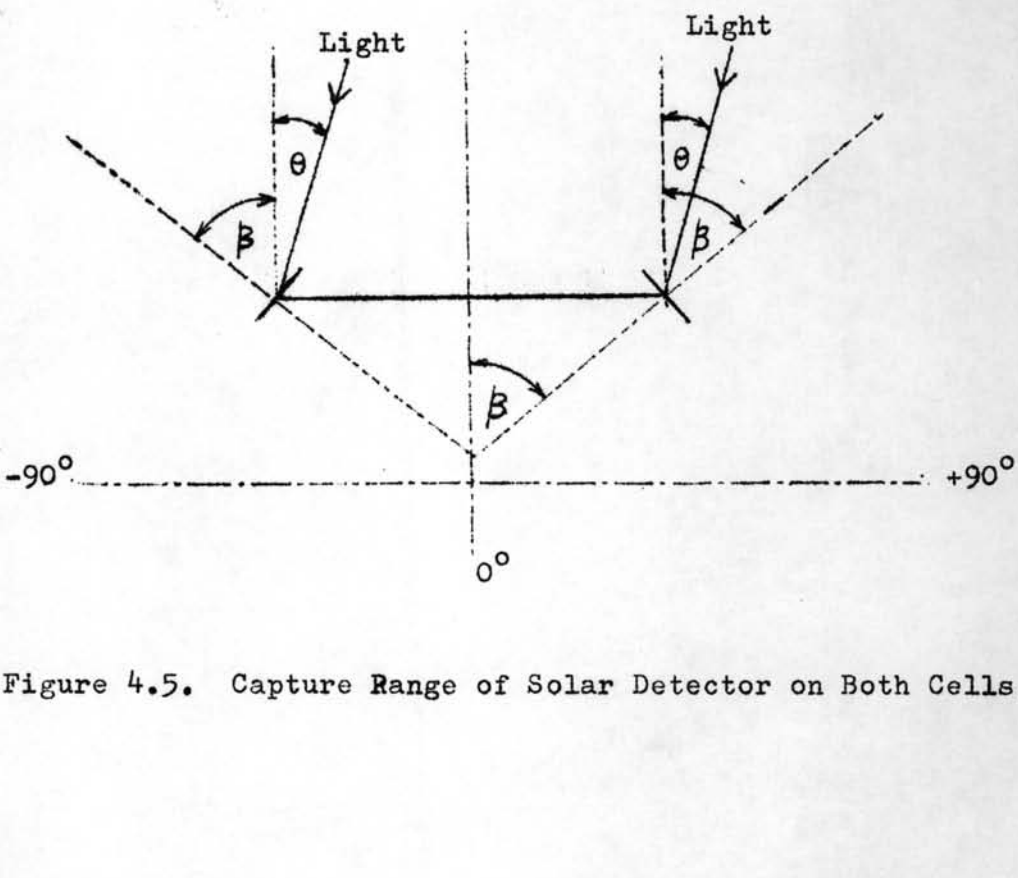


Figure 4.5. Capture Range of Solar Detector on Both Cells.

The capture range of solar detector using two solar cells is shown in Figure 4.5. When the light beam parallel to one cell; the voltage generated on that cell is zero. Therefore,

$$\beta + \theta = 90^{\circ} \quad \text{or} \quad \theta = 90^{\circ} - \beta \qquad (4.8)$$

Substituting $\theta$ into Equation (4.6),

$$V = 2V_m \sin\beta \sin(90^\circ - \beta),$$

$$= 2V_m \sin\beta \cos\beta,$$

$$= V_m \sin 2\beta. \quad (4.9)$$

The maximum output voltage V can be obtained by differentiating Equation (4.9) with respect to $\beta$ and equate the resulting expression to zero :

$$\frac{dV}{d\beta} = 2V_m \cos 2\beta = 0,$$

$$\cos 2\beta = 0 = \cos 90^\circ,$$

$$2\beta = 90^\circ,$$

$$\beta = 45^\circ.$$

Therefore, the maximum output voltage from the detector is delivered at $\beta = 45^\circ$, so the detector angle is set as shown in Figure 4.6.

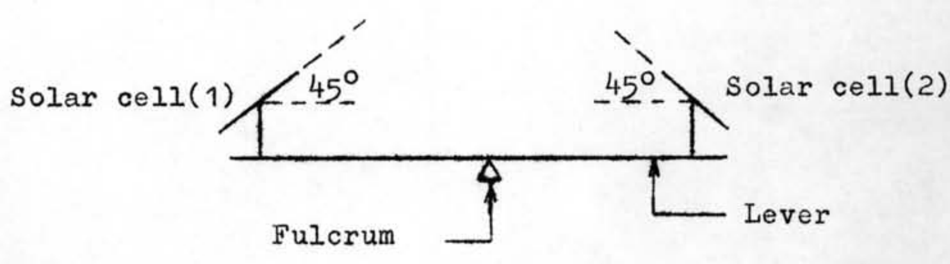


Figure 4.6. Detector Angles.

## 4.3 Design of Circuit Components

The material and components that are available can be listed as follows :-

1. Four operational Amplifiers $\mu$A741
2. Four Power transistors $Q_1$, $Q_2$, $Q_3$, $Q_4$

   $Q_1$, $Q_3$ - 2N 3055 (NPN)

   $Q_2$, $Q_4$ - 2N 2955 (PNP)
3. One D.C. permanent-magnet motor, 100 oz-in, 12 V, 1 rpm.
4. Two pieces of gear train

   $N_1 = 12$

   $N_2 = 24$
5. One metre of a hollow aluminum rod
6. One piece of 12" x 4" alumunum plate
7. Two solar cells, each is 1.5 V, 5-8 ma. at bright sunlight.
8. One 220/32 V, 96 VA power transformer with center tap on secondary side.

The circuit employs the parts listed above. In the design procedure, a load must be considered first. The load is an aluminum rod to which a flat plate and a solar detector are attached. To assess the performance of the load, the speed and voltage characteristic of motor has to be determined. Experiments reveal that the transfer function of the motor is nonlinear because of the dead zone effect. The measured dead zone is 4 volt. An electronic circuit will be designed to compensate for the nonlinearity of the motor. The characteristics of each block diagram of Figure 2.2 can be drawn as shown in Figure 4.7.

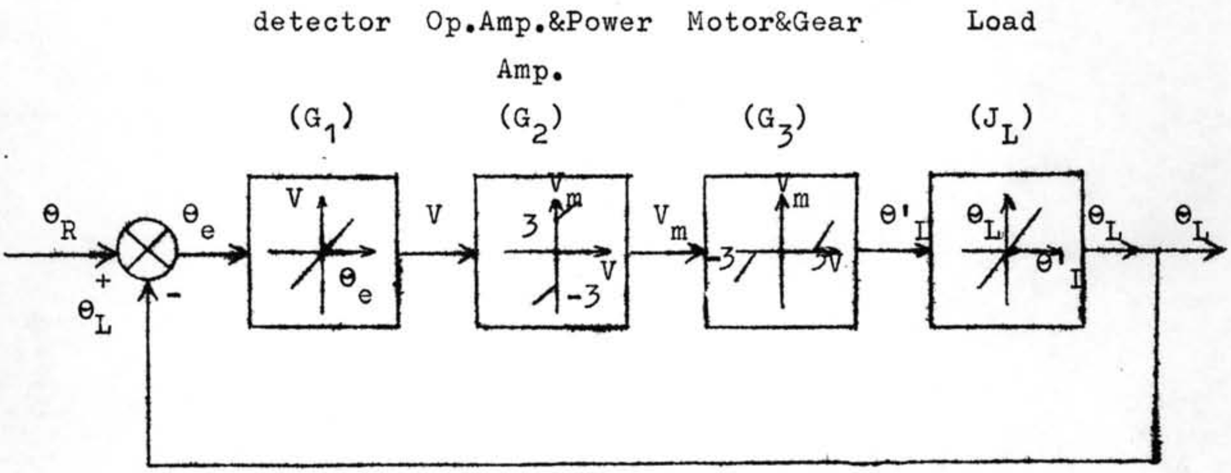


Figure4.7. The Block Diagram of Figure 2.2 Showing the Characteristic of each block.

To compensate the nonlinear characteristics of the motor, the component $G_2$ is specially selected.

## Inverting Amplifier[9]

The error signal from the detector is fed to an inverting amplifier with a gain of 1,000. The circuit and characteristic are shown in Figure 4.8.

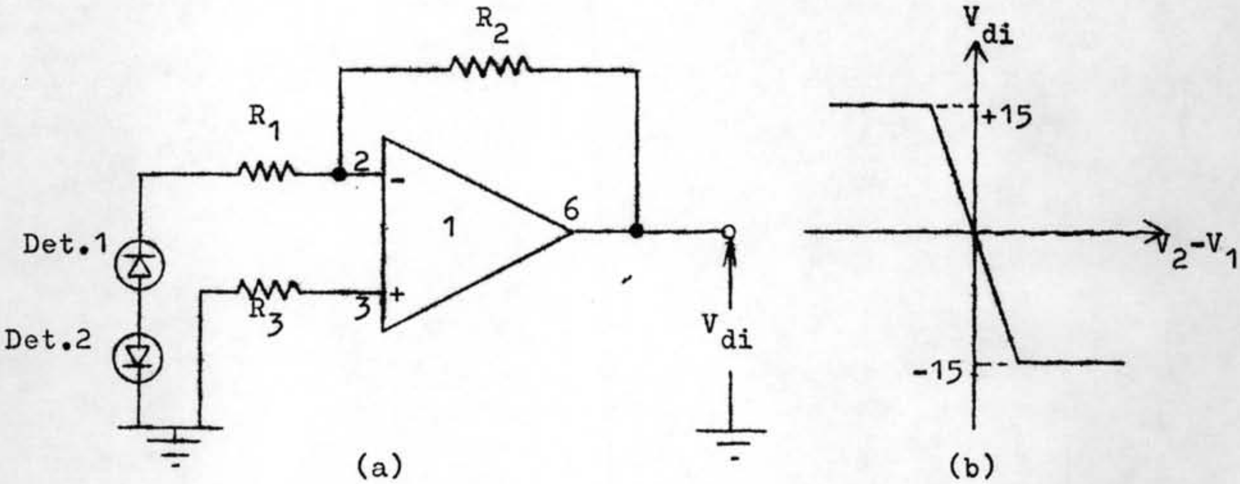


Figure4.8 (a) An Inverting Amplifier.

(b) Its Characteristic.

With gain = 1,000, $R_1 = 100\ \Omega$ ,

and $R_2 = 100\ K\Omega$ .

Then, $R_3 = \frac{R_1 R_2}{R_1 + R_2} = 100\ \Omega$ (approx).

The output voltage($Vd_i$) is limited within the range $\pm 15$ V. The advantage of a high gain is a accuracy of tracking. The slope $m_i$ of the graph is equal to 1,000.

To amplify without a change of sign, another inverting amplifier is connected in cascade with the preceeding amplifier.

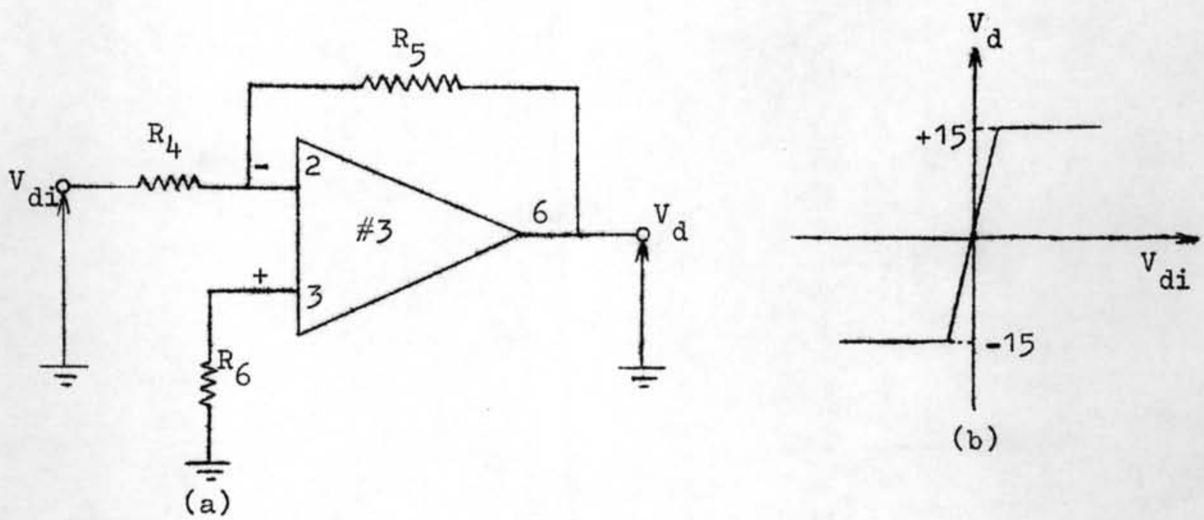


Figure 4.9. (a) An Inverting Amplifier.

(b) Its Characteristic.

With gain = 10, $R_4 = 1\ K\Omega$ ,

and $R_5 = 10\ K\Omega$ ,

Then, $R_6 = \dfrac{R_4 R_5}{R_4+R_5} = 1\ K\Omega$ (approx.).

The overall gain is 10,000 ( = 1,000 X 10) which is equal to the slope $m_1$. The output voltage $V_d$ is limited within the range $\pm 15$ V.

<u>Zero-crossing Detector</u> (ZCD) [9]

The nonlinear characteristics of the motor prevents the movement of the plate in a dead zone. Therefore, this dead zone is compensated by using a zero-crossing detector as shown in Figure 4.10.

The two Zener diodes of rating 7.2 volts and 50 ma. are selected. These diodes regulate the ZCD voltage output at $\pm 7.2$ volts. The resistor $R_7$(1K$\Omega$) is inserted to protect the OP AMP. from overloading.

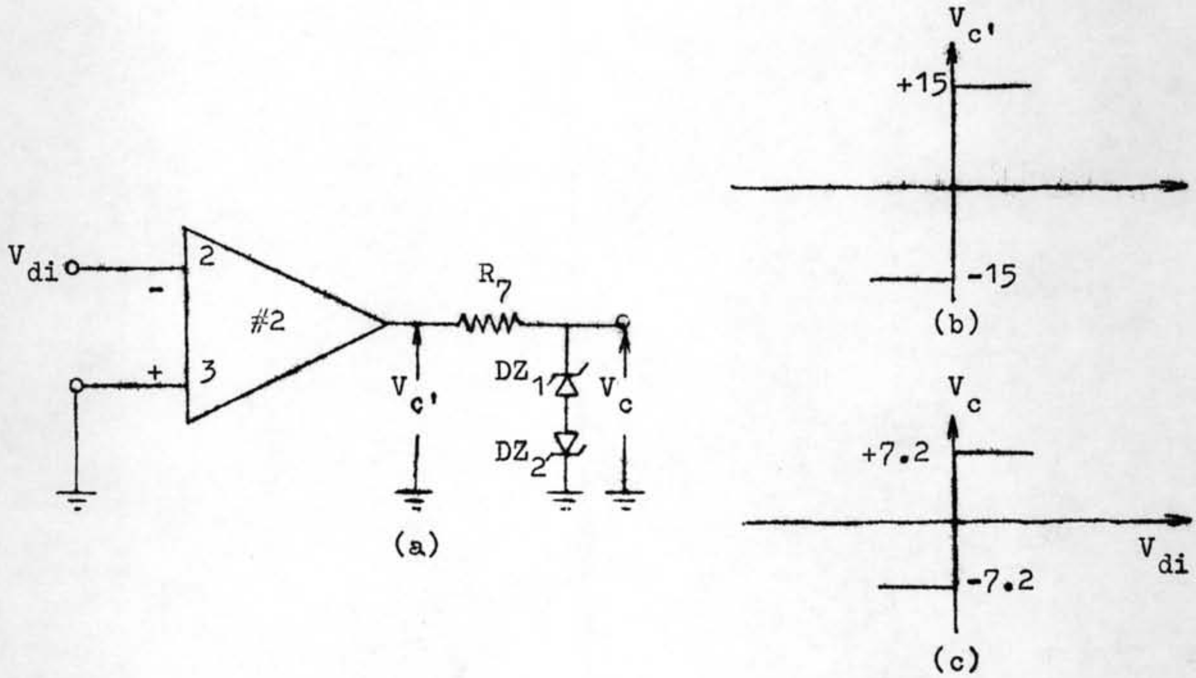


Figure4.10. (a) A Zero-crossing Detector.

(b) and (c) Its Characteristics.

Adjustable Voltage of Dead Zone Network (ADZ)

The voltage $V_c$ from Figure 4.10 is fixed at $\pm 7.2$ V by two zener diodes. These zener diodes, however, do not fit the voltages needed for the motor's dead zone. Therefore, a compensation network , called an ADZ network, is needed to alter these voltages to the correct values. Consider Figure 4.11, $P_1$ and $P_2$ are set to fit the motor's dead zone. They are set at $\pm 3$ V.

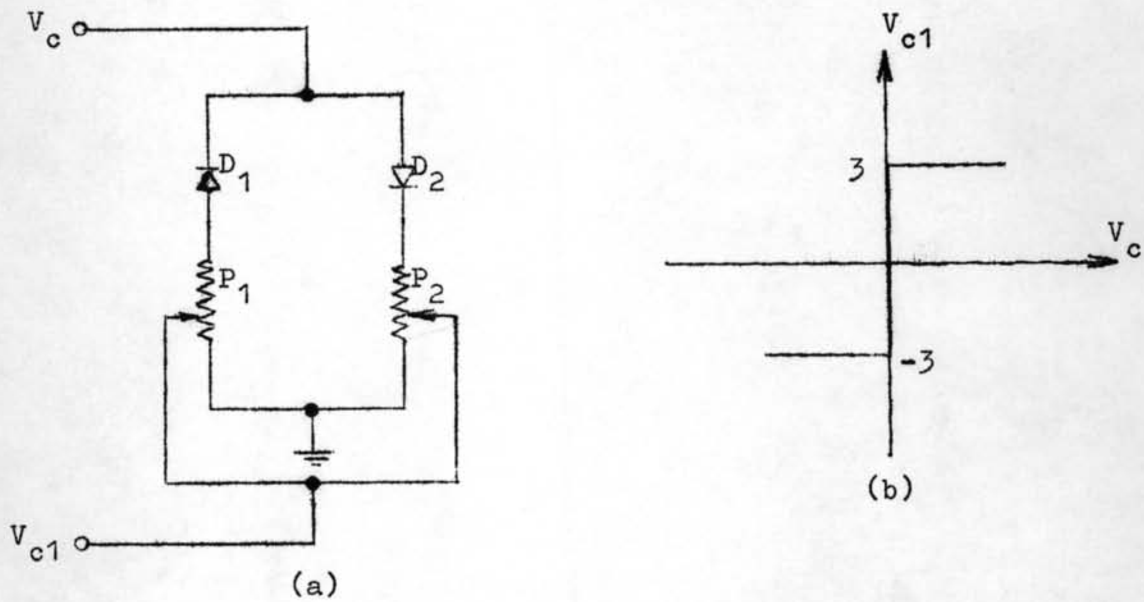


Figure 4.11. (a) An Adjustable Voltage of Dead Zone Network.
(b) Its characteristic.

The diodes $D_1$ and $D_2$ determine which potentiometer is used depending on the polarity of $V_c$.

<u>Adder or Summing Amplifier</u>[9]

To add the output voltage ($V_d$) from OP AMP # 2 and the constant output voltage ($V_{c1}$) from ADZ, an adder is used. The output of the adder is a linear combination of the two voltages, $V_d$ and $V_{c1}$.

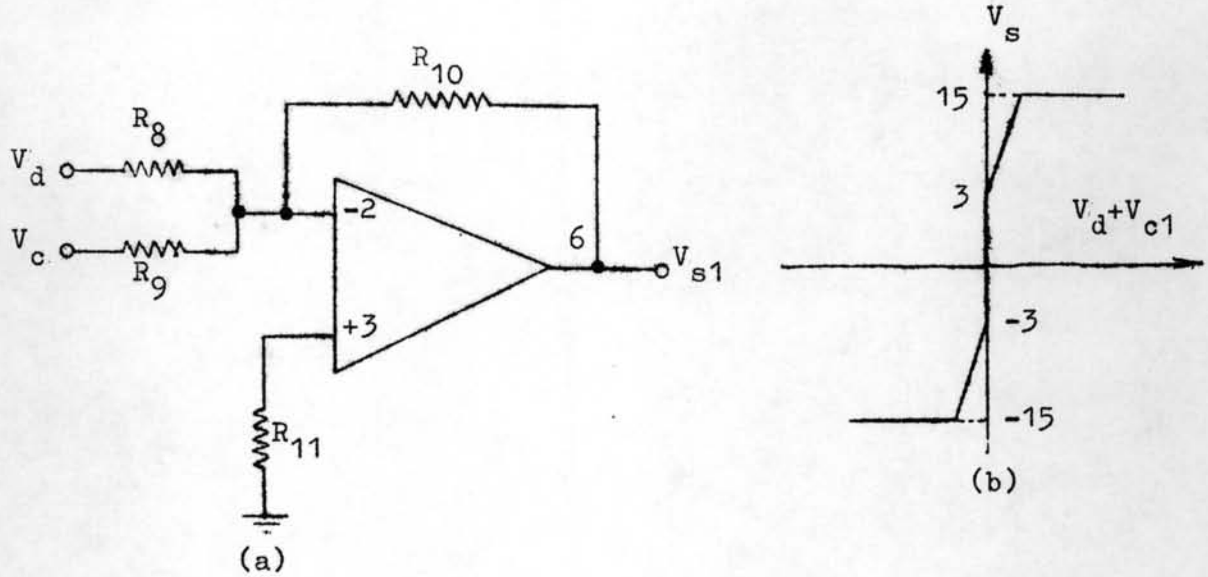


Figure4.12. (a) An Adder.

(b) Its Characteristic.

With gain = 1, $R_8 = R_9 = R_{10} = 10 \ K\Omega$

$$R_{11} = R_8//R_9//R_{10},$$

$$= 3.3 \ K\Omega.$$

The output voltage

$$V_{S1} = \pm(V_d+3.0) \qquad \text{Volt}$$

The slope of $V_S$ is equal to the slope of $V_d$ = 10,000 V/V.

Power Amplifier[11]

The output voltage $V_S$ cannot be directly fed to drive the motor because of its low power capability. Therefore, it is fed to a power amplifier and the output voltage from the power amplifier is used to drive the motor. The power amplifier used is a complementary type as shown in Figure 4.13.

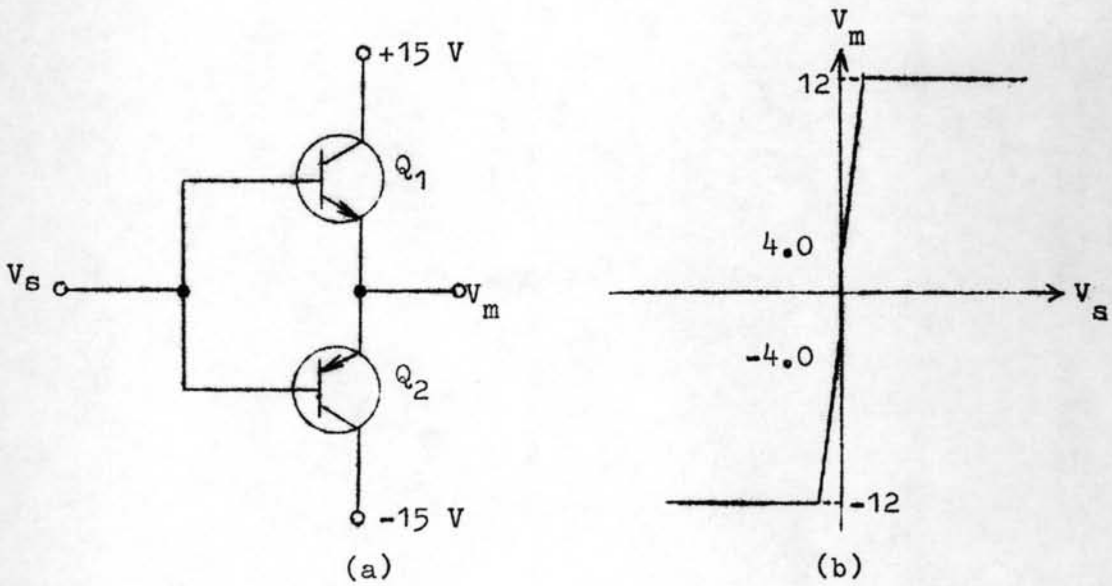


Figure 4.13. (a) Power Amplifier.
(b) Its Characteristic.

The measured voltage gain of the amplifier is 0.8. Therefore, the maximum output voltage is 15 X 0.8 = 12V. The compensated dead zone voltage will be decreased to 3 X 0.8 = 2.4 V, so the ADZ must be adjusted to 5 V in order to obtain the compensated dead zone voltage equal to 5 X 0.8 = 4 V. The slope of $V_m$ is then reduced to 0.8 X 10,000 = 8,000.

Regulated Power Supply [8,11]

A regulated power supply of $\pm 15$ V, 2.5 amp. is used to supply power to the circuitary of the system. It consists of a center tapped transformer $T_1$, a full bridge rectifier, a filter and a regulator. The rectifier provides $\sqrt{2}$ X 16 volts across each capacitor, $C_1$ and $C_2$ which filter the rectifier output. The The resistor $R_{12}$ and $Q_5$, $R_{13}$ and $Q_6$, provide bias voltages for $Q_3$ and $Q_4$. The rectified voltage is regulated by two zener diodes, $DZ_3$ and $DZ_4$.

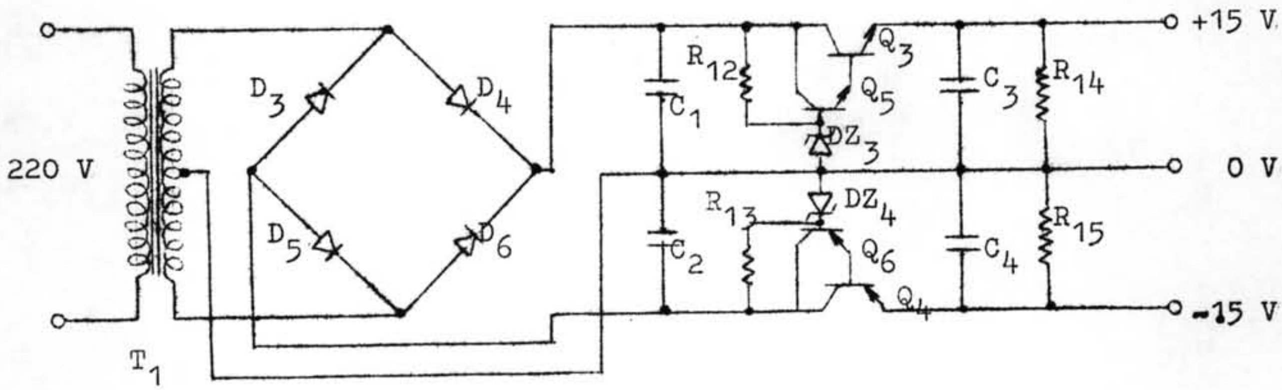


Figure 4.14. A Regulated Power Supply of $\pm 15$ V, 2.5 amp.

$R_{14}$ and $R_{15}$ is used to load the regulated voltage to a desired value ($\pm 15$ V). The parts for the regulated power supply in Figure 4.14 are listed as follows :

| | |
|---|---|
| $T_1$ | Power Transformer 220 V/32 V 3 amp. |

| | | |
|---|---|---|
| $D_3$, $D_4$, $D_5$, $D_6$ | Diodes | 3 amp. |
| $C_1$, $C_2$ | Capacitors | 9,000 $\mu$F. (by using three capacitors of 3,000 F. in parallel) |
| $R_{12}$, $R_{13}$ | Resistors | 500 $\Omega$, ½ watt |
| $Q_3$ | Power Transistor | 2N 3055, NPN |
| $Q_4$ | Power Transistor | 2N 2955, PNP |
| $Q_5$ | Transistor | BC 557, P627 (NPN) |
| $Q_6$ | Transistor | BC 337, P514 (PNP) |
| $DZ_3$, $DZ_4$ | Zener Diodes | 1N 4744, 15 V, 200 ma. |
| $C_3$, $C_4$ | Capacitor | 0.1 $\mu$F. |
| $R_{14}$, $R_{15}$ | Resistors | 1 k$\Omega$ , ½ watt |

4.4 The Complete Circuitary of the Tracking System

The complete circuitary of the system is shown in Figure 4.15. It requires the following additional parts :

| | | |
|---|---|---|
| $Q_7$ | Power Transistor | 2SC 1099, NPN |
| $Q_8$ | Power Transistor | 2SA 699, PNP |
| LD | Incandescent Lamp | 12 V, 3 W |
| $F_1$ | Fuse | 3 amp. |
| $F_2$, $F_3$ | Fuses | 2 amp. |
| $J_1$, $J_2$, $J_3$ | Jacks | |

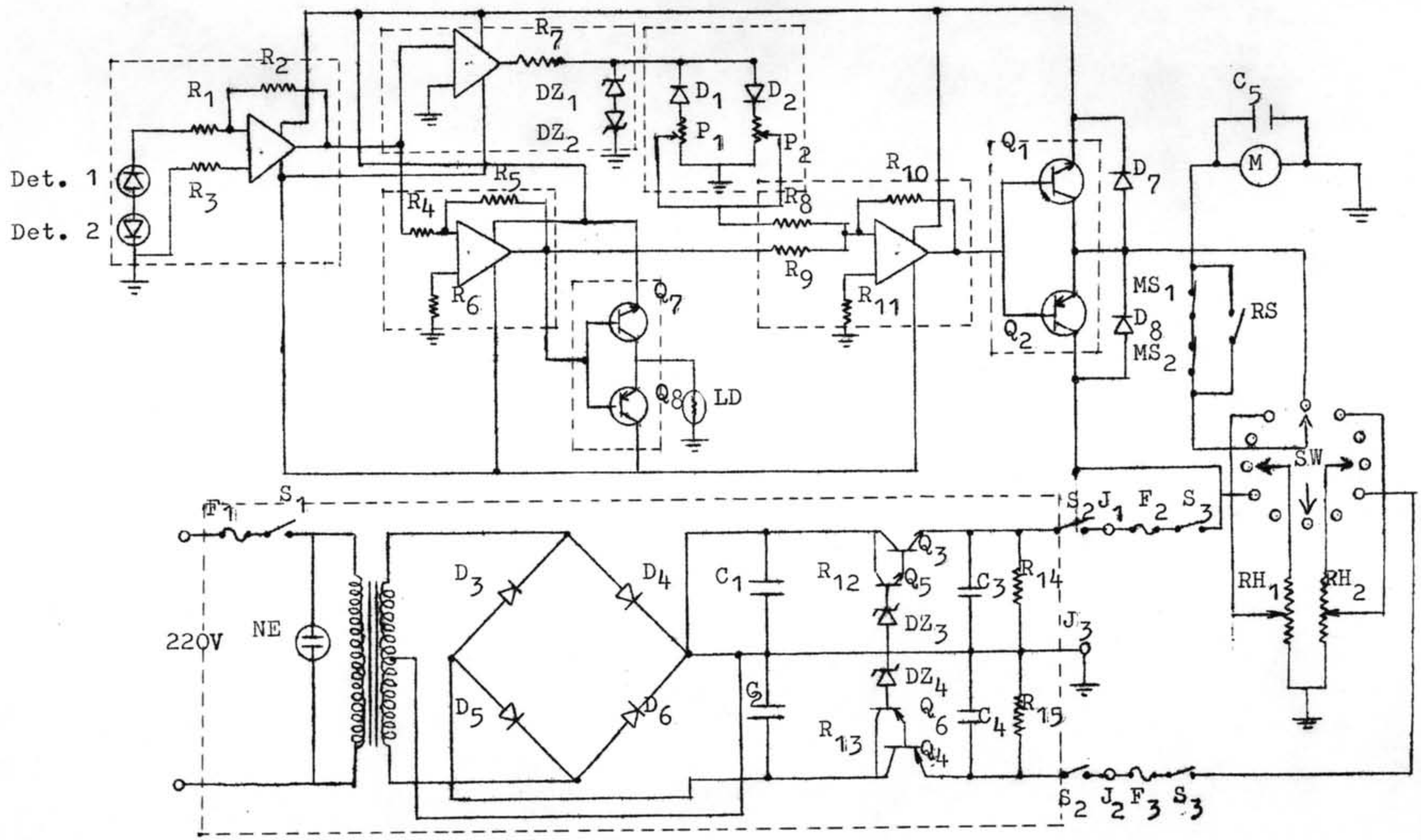


Figure 4.15 Circuit Diagram of an Automatic Solar Tracking System.

| | | |
|---|---|---|
| $S_2$, $S_3$ | On-off Switches | 6 poles |
| $RH_1$, $RH_2$ | Rheostats | 1 kΩ , 30 watt |
| $MS_1$, $MS_2$ | Microswitches | 250 V, 1 amp. |
| $S_1$, RS | On-off Switches | 2 poles |
| SW | Selector Switch | |
| $C_5$ | Capacitor | 0.1 μF., 50 V |
| $D_7$, $D_8$ | Diodes | 1 amp. |
| NE | Neon Lamp | 220 V |

The selector switch is designed for use with manual operation. The two microswitches prevent the lever from striking the stand in both East and West directions. Jacks are used for connecting an external d.c. power supply from battery. The photo graphs of the constructed model is shown in appendix C.

The operation of the circuit commences when the incident illumination falls on the solar detector. The illumination sets up a voltage $V_1$ on detector 1 and $V_2$ on detector 2. The output voltage (V) from the solar detector is $V_2$-$V_1$. Consider the detector connection in Figure 4.15; if $V_1 > V_2$, the output voltage (V) will be negative. This voltage is fed to the inverting amplifier; the amplified voltage will be positive and then it is fed to another inverting amplifier and the zero-crossing detector. The output from inverting amplifier is fed to the adder while the output from the zero-crossing detector is fed through the adjustable-voltage-of-dead-zone to the adder. These two signals are added and amplified. The output voltage from the power amplifier is positive and is fed to the armature of the d.c. motor. The motor will be run and the detector is moved until the output voltage (V) is zero. In other words, there is no difference in illumination of the two solar cells. (If $V_2 > V_1$, the output voltage (V) is positive , the voltage driving the motor is negative, and the motor runs in the oppositive direction). So the motor stops when the flat plate lies in a position that is perpendicular to the solar radiation.