STEADY-STATE PERFORMANCE OF DC MOTORS SUPPLIED FROM PHOTOVOLTAIC GENERATORS WITH STEP-UP CONVERTER

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Abstract - Photovoltaic (PV) generators exhibit nonlinear insolation-dependent I-V characteristics with poor voltage regulation. Because of their high cost, the user is interested in operating the generator close to its maximum power. However, maximum-power point varies with solar insolation (during the day and from season to season) which makes it difficult to achieve optimum utilization at all insolation levels. In this paper a dc motor is supplied from a PV generator with a step-up converter having a fixed duty ratio. There exists a unique duty ratio at which optimum utilization efficiency is achieved at all insolation levels. This remarkable property makes this technique attractive since it eliminates the need for continuous adjustments of the duty ratio.

Keywords: - Photovoltaic generators; solar cells; dc motors ; dc-dc converters; step-up converters; dc choppers.

INTRODUCTION

The simplest and least expensive method to convert solar energy into mechanical energy is to supply a dc motor directly from a photovoltaic generator (without storage batteries). It is typically used on noncritical loads such as water pumps, which need not operate continuously and water output can be stored easily. This arrangement is commonly used for water pumping in rural villages all over the world where no grid electricity exists. With the increased use of these systems, more attention is paid to their design and optimum utilization in order to achieve the most reliable and economical operation. Because of the relatively high cost of a PV generator, the system designer is interested in maximum power operation.

The system consists of three different devices; the PV generator, the dc motor, and the water pump. Each device is characterized by its own operating plane and there exists an optimal operating line for each device, which in turn defines the optimal operating line of the complete system. The dc motor drives the water pump whose torque requirements vary with the speed at which it is driven. The motor is supplied from the PV generator whose I-V characteristic depends non-linearly on the solar insolation variations. For most dc motors, and pumps, the equilibrium operating point of the system is very far from the maximum-power point of the PV generator at all insolation levels and utilization efficiency is very low.

In order to solve this problem, two options are generally available to the system designer. A) Carefully select the dc motor and the pump such that they match closely the maximum power line of the PV generator, or B) Use an electronic control device known as a peak-power tracker (PPT), which continuously matches the output characteristics of the PV generator to the input characteristics of the motor. Option (A) offers a compromise matching which is valid only for some solar insolation levels. Moreover, this option excludes some dc motors and pumps combinations which operate efficiently and economically from a constant-voltage source but operate poorly from a PV source. Reference [1] is a comprehensive study of the starting and steady-state characteristics of dc motors powered directly by a PV generator. It is concluded that a separately excited dc motor driving a centrifugal pump is the best candidate as far as better matching to the PV generator is concerned, while a shunt dc motor driving a volumetric pump is the worst candidate for such matching. In [2] matching of dc motors to PV generators for maximum daily gross mechanical energy is reported. Reference [3] deals with the operation of loads powered by separate sources or a common source of solar cells. In [4] the operation of permanent-magnet dc motors driving different types of water pumps and powered by a common PV generator is investigated.

Peak-power tracking (option B) is achieved either by discretely interchanging the series-parallel connections of solar cell modules within the PV array [5], or by using controlled dc-dc converters (choppers) in the normal mode [6, 7, 8], or in the step-up mode [9]. In [6], the output voltage of the converter is controlled in such a manner as to keep the PV generator output

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voltage constant. Microcomputers are normally used to control the dc converter for optimal operation which adds to the overall system cost considerably. In [9], the regenerative property of the step-up converter is utilized to maximize power output to the load.

In this paper a single step-up converter with a fixed duty ratio is used to supply a dc motor from a PV generator. There is a unique duty ratio which optimizes utilisation efficiency at all insolation levels This remarkable property makes this technique attractive for water pumping systems since it eliminates the costly insolation-dependent control equipment. A single power transistor is used as a switch in series with an inductor which stores energy when the transistor is on and release it to the motor when the transistor is off. Energy is thus transferred from the PV generator to the motor while the motor terminal voltage is higher than that of the PV generator. The same principle is used in mass transit systems which use dc motors, where the step-up converters force power flow from the slowing dc motors (with low back emf) to the dc supply which is at a higher voltage.

I-V CHARACTERISTICS OF THE PV GENERATOR

A PV generator consists of an array of PV cell modules connected in series-parallel combinations to provide the desired dc voltage and current. The terminal voltage, current, and internal resistance of the array depend on the number of cells in series and the number of parallel strings. The PV generator considered in this study consists of 18 parallel strings. Each string contains 324 cells in series. Resistance of each cell is $R_S = 0.05\ \Omega$. Reverse saturation current $I_o = 0.5 \times 10^{-3}$ A. An approximate equivalent circuit of a single cell is shown in Fig. 1 [10].

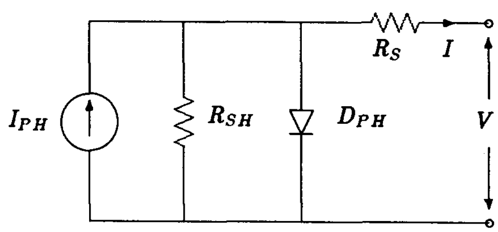

Fig. 1. Equivalent Circuit of a PV Cell.

The terminal voltage of each cell is given by

$$V = 0.0731\ \ln\left(\frac{I_{PH} - I + 0.0005}{0.0005}\right) - 0.05\,I \qquad (1)$$

where I is the current drawn from the cell, and I_{PH} is the photocurrent, which is proportional to insolation. For 100% insolation (1000 W/m^2), $I_{PH} = 0.8$ A., and the open-circuit voltage $V_{OC} = 0.54$ V. The overall volt-ampere characteristics is obtained by adding the voltages of all cells in series and adding currents of all strings in parallel. Therefore for the PV generator

$$V = 23.68\ \ln\left(\frac{I_{PH} - I + 0.009}{0.009}\right) - 0.9\,I \qquad (2)$$

The total reverse saturation current $I_o = 9.0 \times 10^{-3}$ A., and total resistance $R_S = 0.9\ \Omega$. For 100 % insolation the total photo-current $I_{PH} = 14.4$ A, and total open-circuit voltage $V_{OC} = 175$ V. The maximum power at 100 % insolation occurs at $I = 12$ A., and $V = 125$ V. A plot of equation (2) for various insolation levels (percent of 1000 W/m^2) is shown in Fig. 2.

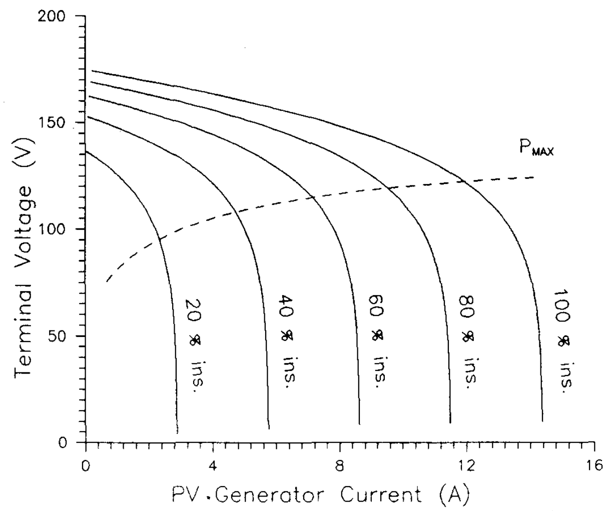

Fig. 2. I-V Characteristic of the PV Generator.

The voltage drops considerably as current increases, approaching zero as the current approaches I_{PH}. Maximum power at any insolation occur at some intermediate point (V_{MP}, I_{MP}). The loci of such points is indicated by the broken line in Fig. 2.

MOTOR AND PUMP CHARACTERISTICS

The motor and pump used in this study have the following parameters:

Motor type	Shunt.
Rated voltage	240 V.
Rated current	6.6 A.
Rated speed	$\omega = 157$ rad./sec.
Armature resistance	$R_A = 1.9\ \Omega$.
Shunt field resistance	$R_F = 200\ \Omega$.
Mutual Inductance	$M_{AF} = 1.2$ H.
Armature reaction	Neglected.
Iron losses	Neglected.
Motor rotational losses	$T_L = 0.2 + 0.0015\,\omega$ N-m.
Pump type	Centrifugal.
Rated torque	$T_P = 0.001\,\omega^{1.8}$ N-m.
Pump rotational losses	$T_L = 0.3 + 0.0025\,\omega$ N-m.

The steady-state motor voltage and torque are given by

$$V_A = M_{AF}\, I_F\, \omega + R_A\, I_A, \qquad (3)$$

$$\begin{aligned} T_M &= M_{AF}\, I_F\, I_A \\ &= 0.5 + 0.004\, \omega + 0.001\, \omega^{1.8} \end{aligned} \qquad (4)$$

Fig. 3 shows V_A and ω versus line current.

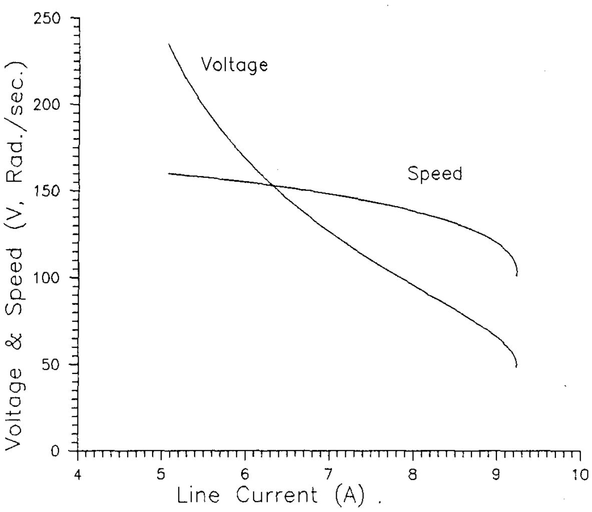

Fig. 3 Motor V-I and ω-I Characteristics

The common operating point if the motor is supplied directly from the PV generator is at the intersection of the I-V characteristics of both devices as shown in Fig. 4.

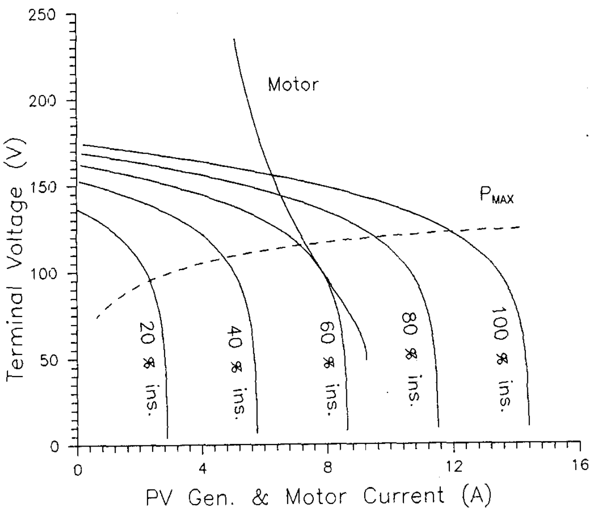

Fig. 4 Common V-I Characteristics

Fig. 4 indicates that if the motor is supplied directly from the PV generator, maximum power can only be achieved at about 62 % insolation. At higher insolation levels the power delivered to the motor is less than P_{MAX} by a wide margin.

STEP-UP CONVERTER AND MOTOR CIRCUIT

The main circuit components are the following: a power transistor Q, which is operated as a switch, a series coil L, a blocking diode D_1, and a free-wheeling diode D_2. The circuit is shown in Fig. 5.

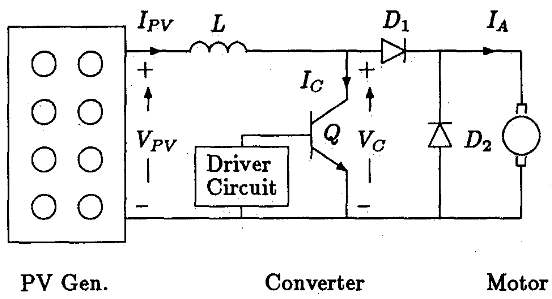

Fig. 5 Step-Up Converter and Motor Circuit

The power transistor Q is used as a switch which is turned on and off by an external driver circuit with a fixed duty ratio. When the transistor is turned on, the inductor L represents a short circuit across the terminals of the PV generator which supplies the energy stored in the inductor. In this case diode D_1 is reverse biased and diode D_2 is forward biased providing a path for the motor current. When the transistor is turned off, the stored energy in the inductor forces current to flow through the diode D_1 and the motor.

When the transistor is turned on, current from the PV generator increases until it reaches a maximum value I_{MAX}. At this instant the transistor is turned off, and current starts to decrease until it reaches some minimum value (I_{MIN}), where the transistor is turned on again, and so on. The average current and voltage are denoted by I_{AV} and V_{AV}. The average voltage across the inductor is zero, therefore the average voltage across the transistor V_C is equal to V_{AV}. The motor average voltage and current are given by

$$V_A = V_{AV}/(1-k) \qquad (5)$$

and

$$I_A = I_{AV}\ \ (1-k) \qquad (6)$$

where k is the duty ratio of the converter.

LOCATION OF MAXIMUM-POWER POINTS

At a maximum power point,

$$\frac{d}{dI}[VI]=0 \qquad (7)$$

Equations (7) and (2) are solved numerically for the maximum-power point (I_{MP}, V_{MP}). Figs. 6 and 7 show the resulting relationships.

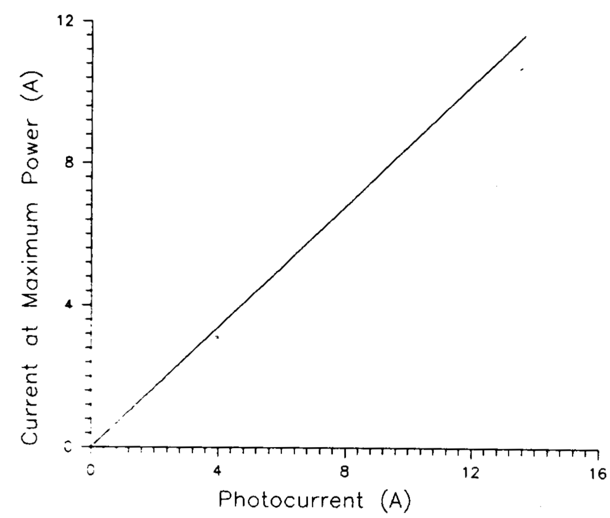

Fig. 6 Current at Maximum Power I_{MP}.

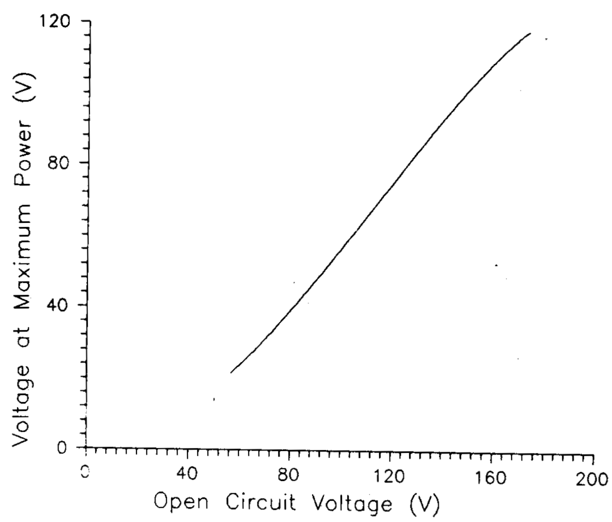

Fig. 7 Voltage at Maximum Power V_{MP}.

These relationships are approximately linear and, using curve-fitting, can be approximated as

$$I_{MP} = 0.849\ I_{PH} \qquad (8)$$

and

$$V_{MP} = 0.866\ V_{OC} - 29.35 \qquad (9)$$

Therefore, for maximum power I_{MP} is always approximately 84.9 % of I_{PH} at any insolation level.

OPTIMAL DUTY RATIO FOR MAXIMUM POWER

The duty ratio determines the frequency at which the transistor switch is operated on and off which determines I_{MAX} and I_{MIN}. For maximum-power operation, it is desired to fix the duty ratio such that

$$I_{AV} = 0.849\ I_{PH} \qquad (10)$$

This is achieved if $I_{MAX} = I_{PH}$ and $I_{MIN} = 0.7 I_{PH}$. It should be noted that the time required for current to increase from $0.7I_{PH}$ to I_{PH} in the series R_L circuit is independent of I_{PH}. Similarly the time required for current to decrease from I_{PH} to $0.7I_{PH}$ is independent of I_{PH}. Therefore the optimal duty ratio is independent of I_{PH} (insolation).

MOTOR OPERATION WITH STEP-UP CONVERTER

When the motor is supplied through the step-up converter, the average voltage applied to the motor and its line current are given by equations (5) and (6). Steady-state speed is given by

$$\omega = (V_A - R_A\ I_A)/\ M_{AF}\ I_F \qquad (11)$$

The motor voltage, speed, and torque when supplied through the step-up converter are shown in Figs. 8, 9, and 10 respectively.

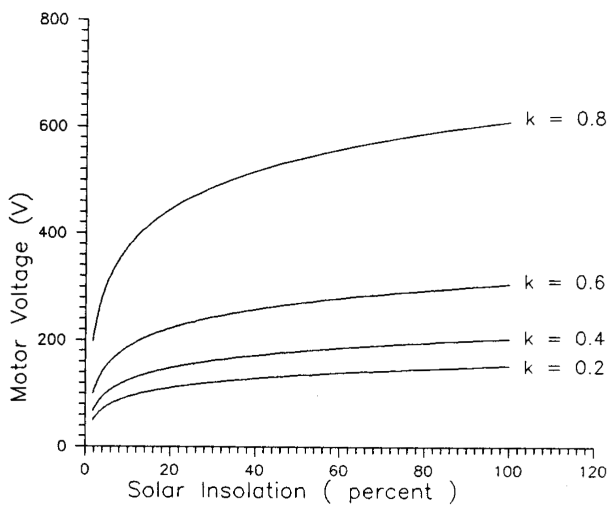

Fig. 8 Motor Voltage with Step-Up Converter

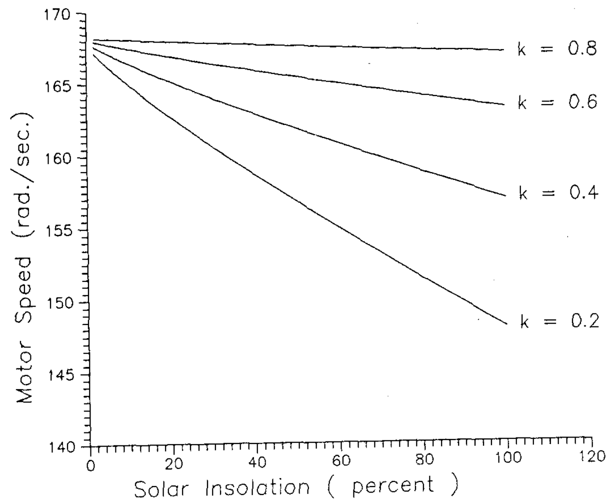

Fig. 9 Motor Speed with Step-Up Converter

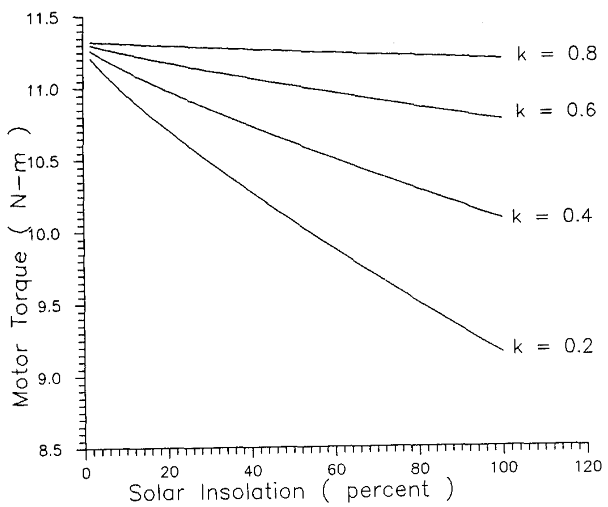

Fig. 10 Motor Torque with Step-Up Converter

The optimum duty ratio is set such that equation (10) is satisfied. Steady-state performance of the motor for this value of k is determined accordingly from Figs. 8, 9, and 10. The closer k to one, the higher the average voltage applied to the motor, and the higher speed and torque for the same insolation level. Moreover, speed and torque become less dependent on insolation.

CONCLUSIONS

A simple step-up converter circuit consisting of a single power transistor and an inductor is used as an interface between a PV generator and a shunt dc motor driving a centrifugal water pump. The step-up converter allows maximum power output from the PV generator to the motor at all insolation levels. Steady-state performance of the motor is vastly improved as its input voltage and current are stabilized by the regenerative action of the converter. The PV generator operates at maximum power regardless of insolation variations. The converter duty ratio can be set at a fixed optimal value which is valid for all insolation levels. This remarkable property makes this device economically attractive since it is easy to build and does not require any insolation-dependent control as compared to other peak-power tracking devices.

REFERENCES

[1] J. Appelbaum, "Starting and Steady-State Characteristics of DC Motors Powered by Solar Cell Generators", *IEEE Trans. on Energy Conversion*, vol. EC-1, no. 1, pp. 17-25, March 1986.

[2] M. M. Saied, "Matching of DC Motors to Photovoltaic Generators for Maximum Daily Gross Mechanical Energy", *IEEE Trans. on Energy Conversion*, vol. EC-3, no. 3, pp. 465-472, September 1988.

[3] J. Appelbaum, "The Operation of Loads Powered by Separate Sources or by a Common Source of Solar Cells", *IEEE Trans. on Energy Conversion*, vol. EC-4, no. 3, pp. 351-357, September 1989.

[4] J. Appelbaum and M. S. Sarma, "The Operation of Permanent Magnet DC Motors Powered by a Common Source of Solar Cells", *IEEE Trans. on Energy Conversion*, vol. EC-4, no. 4, pp. 635-642, December 1989.

[5] Z. Zinger, and A. Braunstein, "Dynamic Matching of a Solar-Electrical (Photovoltaic) System - An Estimation of the Minimum Requirements on the Matching System", *IEEE Trans. Power Apparatus and Systems*, vol. PAS-100, no. 3, pp. 1189-1192, March 1981.

[6] J. J. Schoeman and J. D. Van Wyk, "A simplified maximum power controller for terrestrial photovoltaic panel arrays", *IEEE Power Electronics Specialist Conference*, PESC-82, pp. 361-367, 1982.

[7] R. Hanitsch and R. Hauk, "Microcomputer Controlled DC Chopper for Optimal Operation of a Solar Generator-Motor System", Sixth *E. C. Photovoltaic Solar Energy Conference*, - Proceedings of the International Conference, London, England, Apr. 15-19, 1985.

[8] Robert A. Kichak, "Standard Power Regulator for the Multimission Modular Spacecraft", Proceedings of the 14th *Inter-society Energy Conversion Engineering Conference*, Aug. 1979.

[9] S. M. Alghuwainem, "Application of a DC Chopper to Maximize Utilization of Solar-Cell Generators", *IEEE/PES* 1991 Winter Meeting, New York, New York, Feb. 3-7, 1991, Paper 91 WM 145-3 EC.

[10] H.J Semi-Conductors and Semi-Metals, vol. 11, Academic Press, 1975.

[11] P. C. Sen, *Thyristor DC Drives*. John Wiley & Sons, Inc., New York 1981.

APPENDIX

The Driver Circuit:

The circuit shown in Fig. A-1 [11] is used as a driver to the converter (Fig. 5).

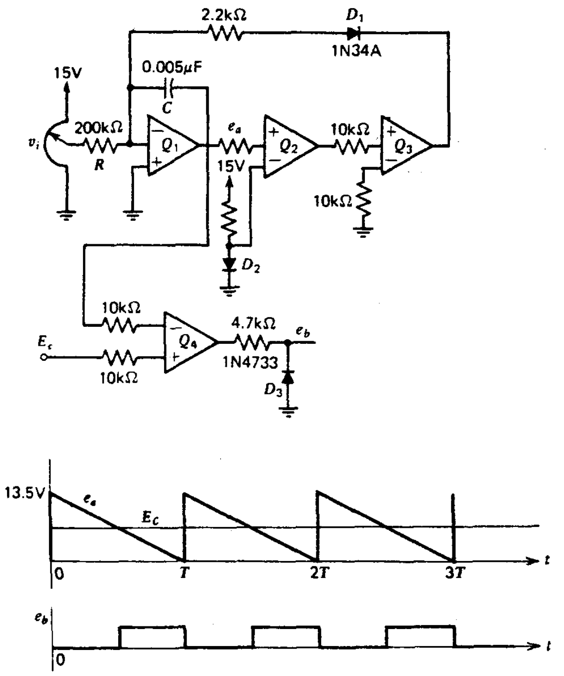

Fig. A-1. Pulse-Generating Circuit

The operational amplifiers Q_1, Q_2, and Q_3 form a triangular wave generator (e_a). As the voltage e_a decreases below the forward bias of diode D_2, the output of Q_2 changes from 13.5 V to -13.5 V, and it in turn causes the output of Q_3 to do likewise. Diode D_1 becomes forward biased and the 2.2 kΩ is the integrator resistance. The output of Q_1 rises quickly to 13.5 V, which triggers Q_2 and Q_3 to do likewise. Diode D_1 is now reverse biased, and the 200 kΩ is the integrator resistance which causes e_a to have a constant slope that depends on R, C and the input voltage v_i. The operational amplifier Q_4 is simply a voltage comparator. Whenever the control voltage E_c is less than e_a the output of Q_4 (e_b) changes state to produce the desired pulse. The pulse duty ratio is set at the desired value by adjusting the value of E_c.

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