MATCHING OF A DC MOTOR TO A PHOTOVOLTAIC GENERATOR USING A STEP-UP CONVERTER WITH A CURRENT-LOCKED LOOP

S. M. Alghuwainem
E.E. Department, King Saud University
Riyadh, Saudi Arabia 11421

ABSTRACT

A photovoltaic (PV) generator is a nonlinear device having insolation-dependent volt-ampere characteristics. Because of its relatively high cost, the system designer is interested in optimum matching of the motor and its mechanical load to the PV generator so that maximum power is obtained during the entire operating period. However, since the maximum-power point varies with solar insolation, it is difficult to achieve an optimum matching that is valid for all insolation levels. In this paper it is shown that for maximum power, the generator current must be directly proportional to insolation. This remarkable property is utilized to achieve insolation-independent optimum matching. A shunt dc motor driving a centrifugal water pump is supplied from a PV generator via a step-up converter whose duty ratio is controlled using a current-locked feedback loop.

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

INTRODUCTION

The simplest and least expensive method of converting photovoltaic (PV) power into mechanical power is to use a photovoltaic supplied dc motor to drive a mechanical load. To avoid additional costs, the motor is directly coupled to the PV generator without storage batteries. This arrangement is typically used on noncritical loads such as water pumps, which need not operate continuously and water can be used directly or stored easily. 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 mainly interested in its full utilization by optimum matching of the system components so that maximum utilization efficiency is achieved.

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The system consists of three different devices; the PV generator, the dc motor, and the mechanical load. Each device has its own operating characteristics which is the volt-ampere characteristics for the PV generator and dc motor, and the torque-speed characteristics for the mechanical load. The dc motor drives the mechanical load whose torque requirements vary with the speed at which it is driven. The dc motor is supplied from the PV generator whose volt-ampere characteristics depend non-linearly on the solar insolation variations and on the current drawn by the dc motor. There is a unique point on the volt-ampere curve at which power is maximum, and for optimum utilization the equilibrium operating point must coincide with this point. However, since the maximum power point varies with insolation it is difficult to maintain optimum matching at all insolation levels. For most dc motors, and water pumps, the equilibrium operating point of the system is very far from the maximum-power point of the PV generator at most insolation levels and thus full utilization is not achieved.

In order to correct this problem, two options are generally available to the system designer. A) Carefully select the dc motor and the pump so that they match as closely as possible 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 dc motor. Option (A) offers a compromise matching which is valid only for some solar insolation levels due to drifting of the maximum power point with insolation variations. Reference [1] is a comprehensive study of the starting and steady-state performance of different dc motors and water pumps directly coupled to 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 in the normal mode [6, 7, 8], or in the step-up mode [9, 11]. In [6], the output voltage of the converter is controlled in such a manner as to keep the PV generator output voltage constant. Microcomputers are normally used to control the dc converter for optimal operation which adds to the overall system cost considerably. In [10], the optimal design parameters of the system components are determined in relation to narrowest range of the dc transformer ratio variation which lead to maximum total gross annual mechanical energy delivered to the load. In [11] steady-state performance of a dc motor supplied form a PV generator with a step-up dc-dc converter is analyzed. It is shown that for optimal matching the current must be kept proportional to insolation level. The step-up converter is driven with a constant duty-ratio pulse. In [12] the motor starting to rated current and torque ratios are analyzed with and without peak-power tracker, for separately excited, series, and shunt dc motors.

In this paper a dc motor driving a centrifugal pump is matched to a PV generator using a step-up dc-dc converter with a controlled duty ratio. A current-locked loop is used to control the duty ratio in such a manner as to keep the PV generator current proportional to insolation by keeping the current "locked" to a reference value which is proportional to insolation (photocurrent).

The step-up converter consists of a single power transistor used as a switch in series with an inductor. The inductor 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 for many years in dynamic breaking of mass transit systems, 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.

CHARACTERISTICS OF THE PV GENERATOR

A PV generator consists of an array of photovoltaic cell modules connected in series-parallel combinations to provide the desired dc voltage and current. The overall volt-ampere characteristics of the array depend on the number of cells in series and the number of parallel strings. The PV generator used in this study consists of 18 parallel strings, 324 cells in series per string, such that the overall volt-ampere characteristic is given by

$$V_{PV} = 23.68 \ \ln\left(\frac{I_{PH} - I_{PV} + 0.009}{0.009}\right) - 0.9\, I_{PV} \tag{1}$$

where V_{PV} and I_{PV} are the generator terminal voltage and current. The photocurrent I_{PH} is directly proportional to insolation ($I_{PH} = 14.4$ A. at 100 % insolation). Total reverse current of the generator is 0.009 A., total series resistance is 0.9 Ω. Fig 1. is a plot of equation (1) for various insolation levels (percent of 1000 W/m^2).

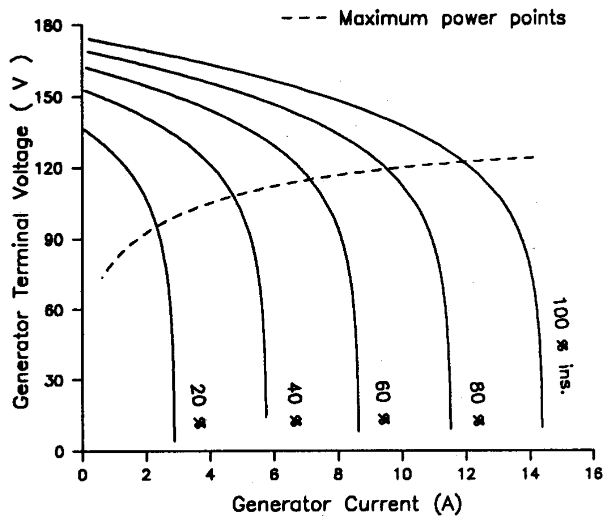

Fig. 1. V-I characteristic of the PV generator

The voltage drops considerably as the insolation decreases and as current increases, approaching zero as the current approaches I_{PH}. Current and voltage values at which power is maximum depend on the insolation level. The maximum power point for each insolation level lies on the dashed line in Fig. 1.

DETERMINATION OF MAXIMUM POWER POINTS

At a maximum power point,

$$\frac{d}{dI_{PV}} \left[\ V_{PV} \ I_{PV} \ \right] = 0 \tag{2}$$

Therefore

$$V_{PV} + I_{PV} \ \frac{dV_{PV}}{dI_{PV}} = 0 \tag{3}$$

Let I_{MP} be the value of current for which power is maximum, then

$$\ln\left(\frac{I_{PH} - I_{MP} + 0.009}{0.009}\right) - 0.076 I_{MP} - \frac{I_{MP}}{I_{PH} - I_{MP} + 0.009} = 0 \tag{4}$$

Equation (4) is solved for I_{MP} using iterative methods, taking I_{PH} as a constant each time. Fig. 2 is a plot of the derivative of power with respect to voltage for several values of I_{PH} corresponding to 40, 60, 80, and 100 percent insolation.

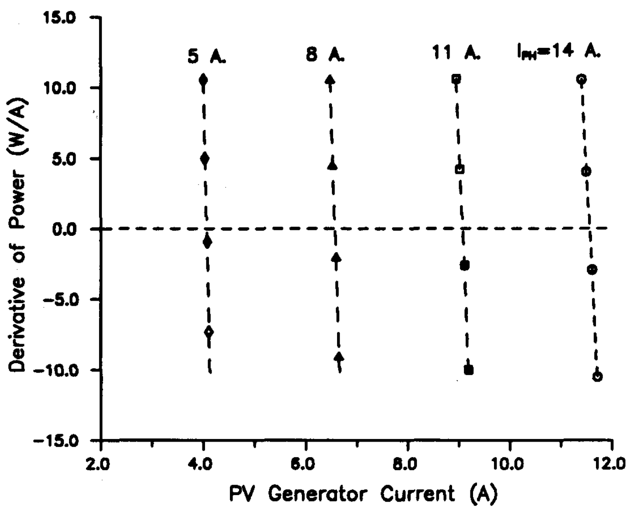

Fig. 2. Derivative of power versus current

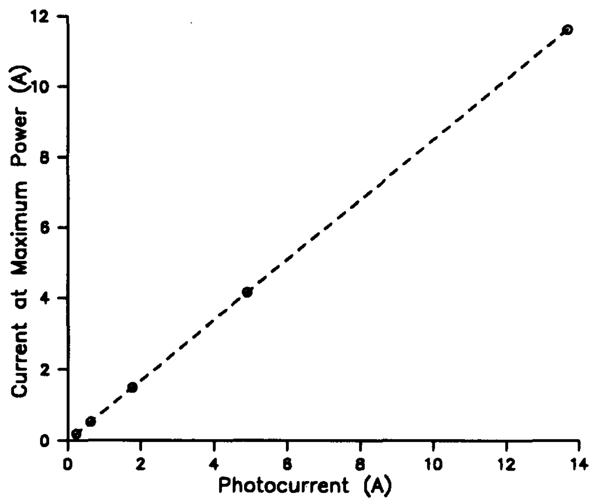

Fig. 3. Current at maximum power versus photocurrent

Fig. 3 is a plot of I_{MP} as a function of I_{PH}, showing a linear relationship which is approximated by

$$I_{MP} = 0.85 I_{PH} \tag{5}$$

Therefore, for maximum power the current drawn from the PV generator must be directly proportional to the photocurrent I_{PH} which is it self directly proportional to insolation level. This remarkable property of the PV generator is useful in achieving an adaptive matching of the dc motor and its mechanical load to the PV generator so that matching is optimum at any insolation level.

THE STEP-UP CONVERTER 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. 4.

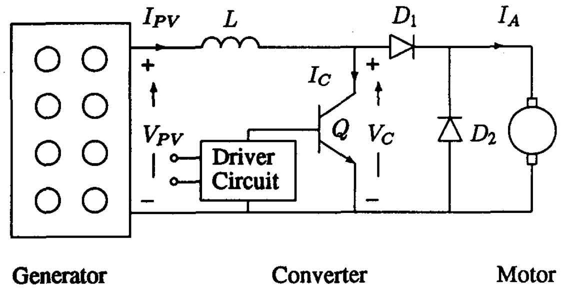

Fig. 4 Step-up converter circuit

The power transistor Q is used as a switch which is turned on and off periodically by an external driver circuit. The driver circuit is simply a voltage controlled oscillator (VCO) which generates a periodic rectangular pulse which turns the transistor on and off with a duty ratio which is directly proportional to the amplitude of the external voltage applied to its input. A typical driver circuit is given in the appendix (Fig. A-1). 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. If we let the average generator current and voltage be I_{PV} and V_{PV}, then the average motor current and voltage are given by

$$I_A = I_{PV} \ (1 - k) \tag{6}$$

$$V_A = V_{PV}/(1 - k) \tag{7}$$

where $k = t_{on}/(t_{on} + t_{off})$ is the duty ratio of the converter. The step-up converter acts like a dc-dc transformer with a transformation ratio $1/(1 - k)$.

For maximum power operation, it is desired to maintain the average generator current at

$$I_{PV} = 0.85 \ I_{PH} \tag{8}$$

for all values of I_{PH} (for all insolation levels). Therefore

$$I_A = 0.85 \ I_{PH} \ (1 - k) \tag{9}$$

THE CURRENT-LOCKED LOOP

The block diagram of the current-locked loop is shown in Fig. 5. The two voltage signals V_{ref} and V_{fb} are derived from I_{PH} and I_{PV} such that

$$V_{ref} = 0.85\ I_{PH} \tag{10}$$

and

$$V_{fb} = I_{PV} \tag{11}$$

V_{ref} is obtained from the short circuit current of a cell module which is exposed to the same insolation level. V_{fb} is taken across a 1 Ω resistance in series with the PV generator current.

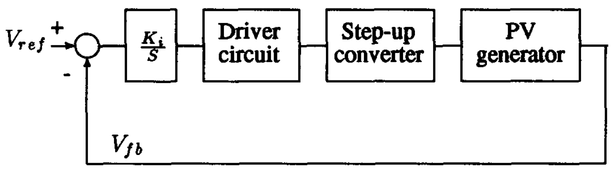

Fig. 5 Block diagram of the current-locked loop

An error voltage proportional to V_{ref} - V_{fb} is integrated and transmitted to the driver circuit. The driver circuit applies to the base of the transistor a periodic rectangular pulse whose duty ratio is directly proportional to its input voltage. When the error voltage is different from zero, the input to the driver circuit is continuously increasing or decreasing (depending on the sign of the error voltage), and hence the duty ratio will change in such a way as to reduce the error voltage to zero. If the insolation level changes V_{ref} will change, causing error voltage to exist which will cause I_{PV} to be "locked" to the new maximum power value.

APPLICATION TO A DC MOTOR LOAD

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	ω = 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, current, speed, and torque are given by

$$V_A = M_{AF}\ I_F\ \omega + R_A\ I_A \tag{12}$$

$$\begin{aligned} T_M &= M_{AF}\ I_F\ I_A \\ &= 0.5 + 0.004\ \omega + 0.001\ \omega^{1.8} \end{aligned} \tag{13}$$

Fig. 6 shows V_A and ω versus motor current.

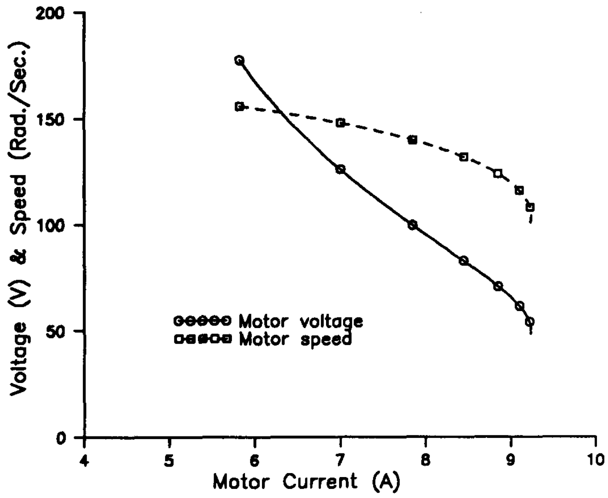

Fig. 6 V-I and ω-I motor characteristics

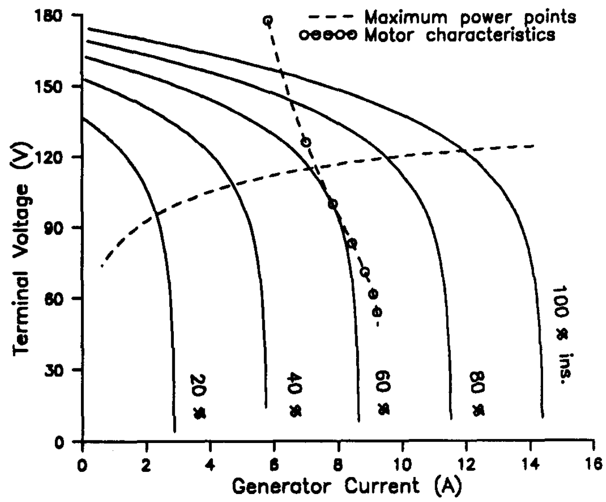

Fig. 7 Common V-I characteristics

Fig. 7 indicates that if the motor is supplied directly from the PV generator with no matching, maximum power can only be achieved at about 62 % insolation. It is clear from Fig. 7 that the motor characteristics is almost perpendicular to the maximum power line and matching in this is recommended.

MOTOR OPERATION WITH MATCHING

The motor is supplied through the step-up converter with the feedback loop, which controls the duty ratio so that $I_{PV} = 0.85 I_{PH}$, for all values of I_{PH}. Current I_A and voltage V_A on the motor side are determined from I_{PV} and V_{PV} using equations (6) and (7) respectively. Fig. 8 is a plot of the common PV and motor characteristics, all referred to the PV generator side.

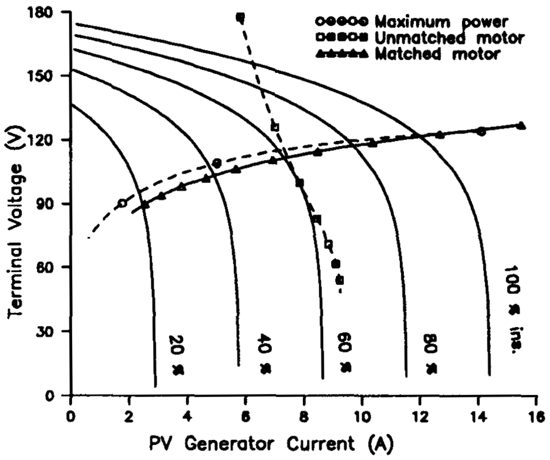

Fig. 8 Operation with and without matching

The advantage of matching is obvious from Fig. 8, as the motor operating points tend to coincide with the maximum power points of the PV generator.

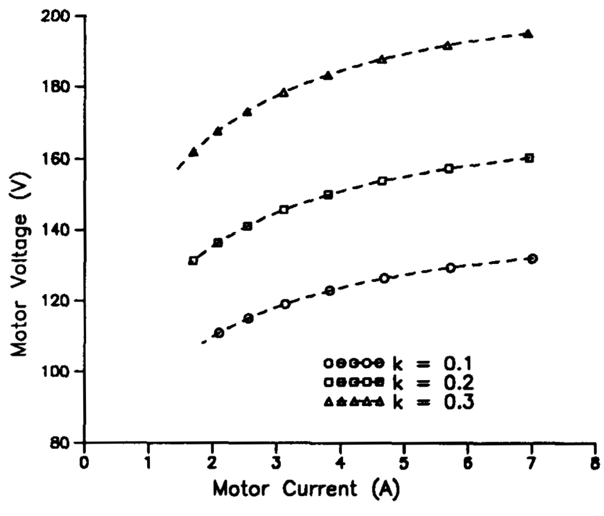

Fig. 9 Motor voltage with current-locked loop

Steady-state motor voltage and current depend on the insolation level and on the duty ratio k. However, the optimum value of k is adjusted by the feedback loop. Fig. 9 is a plot of motor voltage versus motor current, both referred to the motor side.

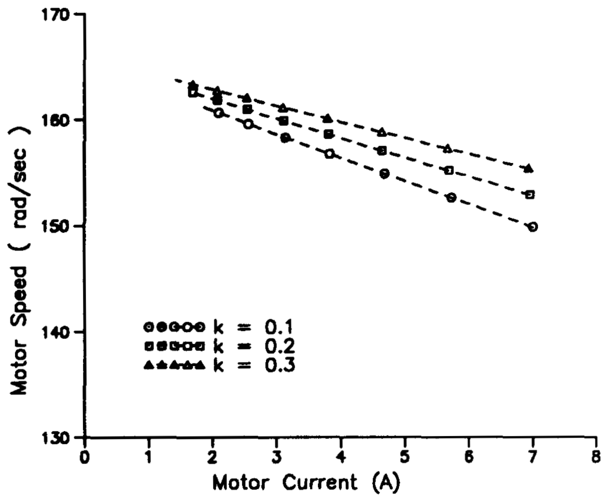

Fig. 10 Motor speed with current-locked loop

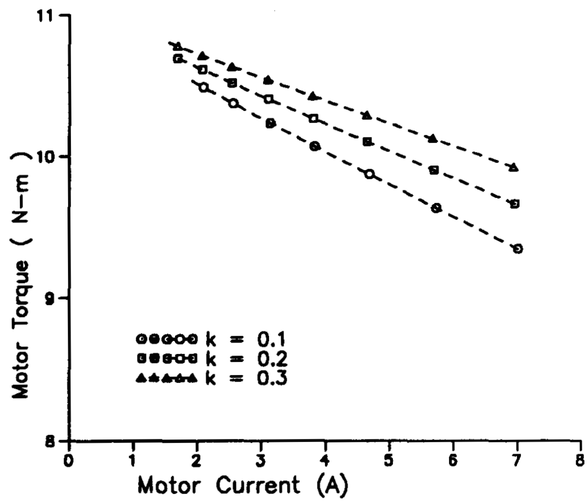

Fig. 11 Motor torque with current-locked loop

Figs. 10 and 11 are plots of steady-state speed and torque as functions of motor current referred to motor side.

CONCLUSIONS

The problem of poor utilization efficiency of a dc motor operating from a PV generator is solved by a feedback current-locked loop which controls the duty ratio of a step-up converter. It is shown that maximum power output from a PV generator is achieved at all insolation levels if the PV generator current is kept directly proportional to insolation level. This remarkable property is utilized to achieve optimum matching that is independent of insolation level. The output current of the PV generator is adjusted by the feedback loop whenever the insolation changes by changing the duty ratio of the step-up converter. The duty ratio is easily controlled since it is directly proportional to the input voltage of the driver circuit. Motor voltage and current are forced to be dependent on the PV characteristics only. The step-up converter used is a single power transistor (used as a switch) in series with an inductor. The driver circuit is a simple voltage-controlled oscillator. Motor performance is enhanced by the regenerative action of the step-up converter. The use of a centrifugal pump ensures minimal starting torque requirements at low insolation level.

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APPENDIX

The Driver Circuit:

A typical driver circuit [13], is shown in Fig. A-1.

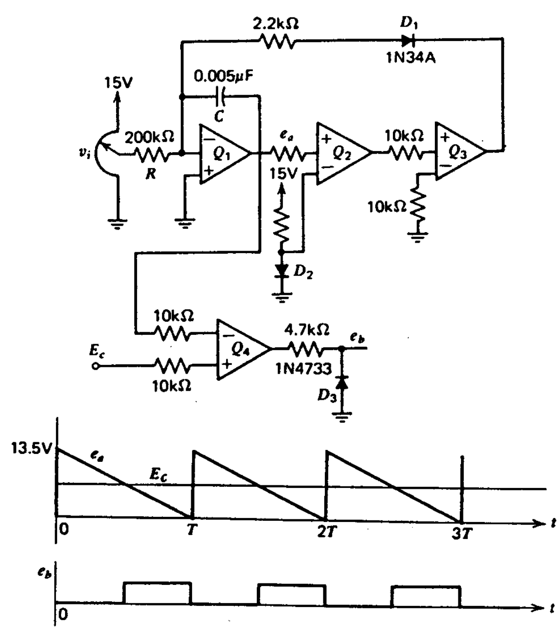

Fig. A-1. Driver Circuit

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 change from 13.5 V to -13.5 V. 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.

Saad M. Alghuwainem received B.Sc. in Electrical Engineering from University of Riyadh in 1974. From 1974 to 1976 he worked as a teaching assistant in the EE Department, Riyadh University. He received M.Sc. degree in Electrical Engineering (Power) from University of Colorado, Boulder in 1978. From 1979 to 1981 he worked in the EE Department, King Saud University as a research assistant. From 1982 to 1986 he attended The University of Michigan, Ann Arbor where he received Ph.D. in Electrical Engineering. Since 1986 he has been with the Department of Electrical Engineering, King Saud University, where he is currently an associate professor. His interests include renewable energy sources, energy conversion systems, power system relaying, and electromagnetic transients.