A Microprocessor Based Load Voltage Regulator for Photovoltaic Systems.

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A MICROPROCESSOR BASED LOAD VOLTAGE
REGULATOR FOR PHOTOVOLTAIC SYSTEMS

استخدام حاسب دقيق (ميكروبرسور) للتحكم فى تنظيم جهد الحمل لنظام فونوفلتى

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الخلاصــة

يتكون النظام الفوتوفلتى عادة من شبكة من الخلايا الفوتوفلتية متصلة ببطاريات تخزين ومنظم لتيار الشحن وحمل . وفى هذه الحالة يكون جهد الحمل مساويا لجهد البطاريات الذى يتغير طبقا لحالة الشحن من ٩٣،٥٪ الى ١٢٠٪ من الجهد المطلوب للحمل .

. ونظرا لان هذا التغير غير مقبول لبعض الاحمال الاليكترونية وخاصة لدوائر الاتصال ، فان الحل التقليدى يتلخص فى تشغيل شبكة الخلايا عند جهد أعلى من الجهد المطلوب وتوصيل مجموعة من وحدات التقويم الخافضة للجهد على التوالى مع الحمل بحيث يتم التحكم فى ادخال عدد منها فى الدائرة طبقا لحالة الشحن وشبكة الخلايا لضمان جهد حمل ثابت.

فى هذا البحث تم تصميم حل بديل باستخدام حاسب دقيق (ميكروبروسور) يتمل بدائرة تقطيع وتقويم وفلتر لحفظ جهد الحمل ثابتا بصرف النظر عن حالة شبكة الخلايا الفوتوفلتية.

وبناء على النتائج التى حصل عليها من برنامج محاكاة لحالة شبكة خلايا فوتوفلتية خاضعة للاحوال الجوية لمدينة القاهرة تبين أن النظام المقترح يوفر ٥٪ من الطاقة المستهلكة للحمل والتى كانت تفقد فى وحدات التقويم المتصلة على التوالى بالدائرة.

علاوة على أن النظام المقترح يودى الى استخدام شبكة فوتوفلتية أصغر ويضمن جهد ثابت للحمل ويوفر اشارات انذار تحدد حالة النظام

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BSTRACT

A conventional photovoltaic (PV) system driving a DC load consists of a PV array ,storage battery, a battery voltage regulator (BVR) and a load The voltage of typical lead acid batteries, widely used in PV systems, varies between 93 5 % and 120% of its nominal voltage according to its state of charge (SOC) Such voltage variations are not accepted for critical loads such as some communication systems

Conventional solution of this problem is to operate the PV system at higher voltage and to include a control circuit that introduces passive elements so that the load is operating within the allowed limits. Such a solution leads to power dissipation in the passive elements and this presents power loss.

In this work an alternative solution based on a microprocessor that keeps the load voltage at the predetermined level is discussed The system consists of an A/D converter, a microprocessor controller, a switching circuit and a filter The microprocessor reads the battery voltage variations via the A/D converter Corresponding duty cycle value is calculated and used to control the switching circuit to achieve the required regulation A detailed simulation program is used to study the performance of the PV system installed in Cairo city The proposed technique avoids the power loss and as a result the required PV array size becomes smaller. Hence the system economics is improved.

1. INTRODUCTION

Photovoltaic systems may be classified as follows.

1 PV grid connected system where a PV system is connected to an electric network. The block diagram of such a system is indicated in figure 1 [1]. The power conditioning unit (PCU) is composed of a DC/AC inverter and a synchronization control circuit to assure that the voltage generated by the PV system has the same voltage, frequency and phase of voltage of the electronic network [2] The battery is essential in this system since the inverter should be fed from a regulated DC voltage supply,
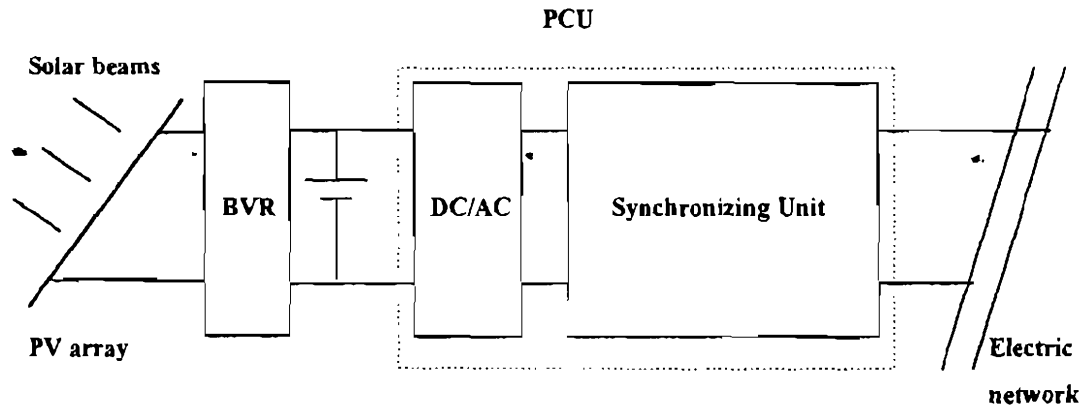
PCU

Figure 1   Block diagram of a PV grid connected system.

2. Stand alone systems driving DC loads. Two systems categories may be distinguished;

a. Directly coupled systems where the PV array is directly connected to DC load as indicated in Fig. 2 Directly coupled PV pumping systems are examples of this category. Directly coupled PV pumping systems are efficient, simple, reliable and cost effective [3,4]. Unfortunately directly coupled systems are recommended if and only if the product of the system may be stored. For pumping systems the product of the system is water which may be stored in a water tank.
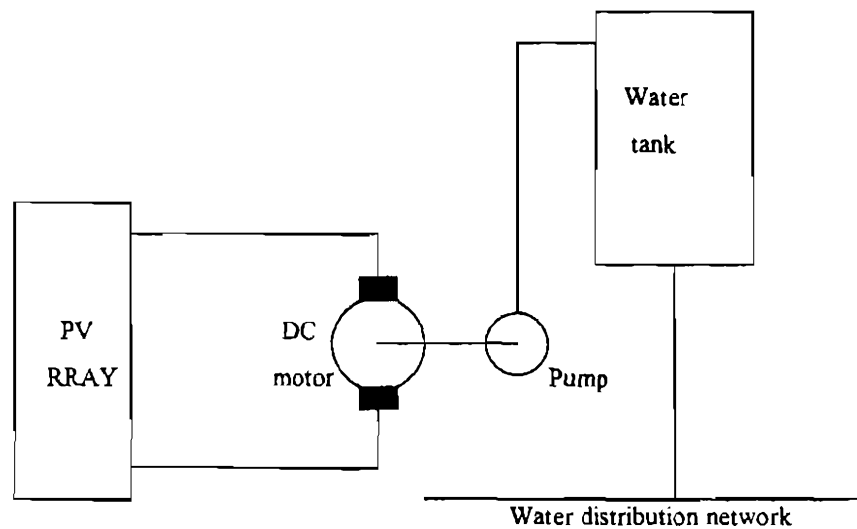

Figure 2   Schematic diagram of directly coupled PV pumping system

For other systems such as lighting or communications, one has to store the electrical energy so that the load may be supplied by energy during nights and cloudy days. Electrical energy may be stored in batteries

⟵   b PV battery buffered systems where a storage battery is connected across the PV array through a battery voltage regulator (BVR) as shown in figure 3. The load is connected across the storage battery The BVR's main function is to keep the battery voltage within the accepted limits so that the battery lifetime is maximized[5]. According to the arrangement shown in Fig. 3, the load voltage is equal to battery voltage. Thus the load voltage variation is equal to battery voltage fluctuations. The battery voltage varies according to the state of charge of the battery The voltage of conventional lead acid batteries varies from 93% of its nominal voltage (when its SOC is at the minimum allowed SOC) to 120% of the nominal voltage (when its SOC is at the maximum allowed SOC).
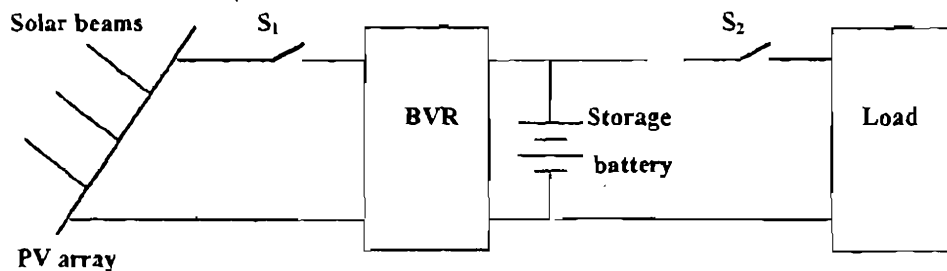
Figure 3   Block diagram of a battery buffered PV system.

3 PV stand alone system supplying an AC load Such systems require a DC/AC inverter to cover the DC energy stored in the battery to AC power supplied to the load [6]. Figure 4 shows the block diagram of his system. The storage battery is essential because the inverter should be fed from a regulated DC voltage supply.
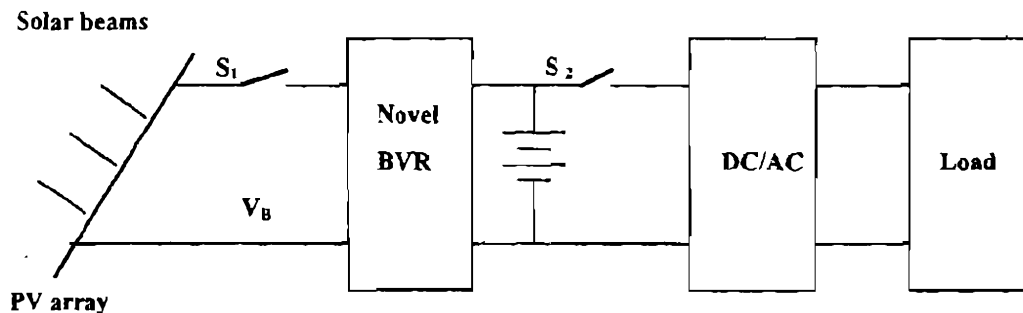
Figure 4   Block diagram of a PV system supplying an AC load.

2. CONVENTIONAL SYSTEM

Figure 5 shows a block diagram of a PV system using a conventional load voltage regulator to keep the load voltage within the allowed limits.
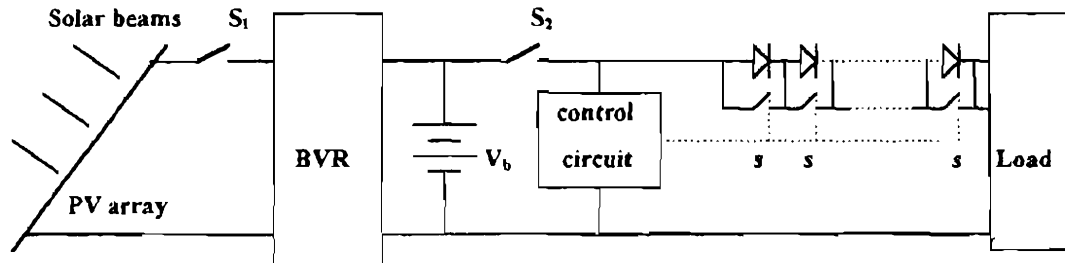

Figure 5   PV system using a conventional load voltage regulator.

The voltage regulator is composed of series connected diodes and a switch is connected across each diode The function of the control circuit shown in Fig. 5 is to close a number of switches according to the battery voltage. The load voltage is adjusted by inserting a number of diodes between the battery and the load in such a way that the load voltage is kept within the allowed limits. The control circuit senses the battery voltage and actuates the shunt switches across the diodes. The number of diodes inserted in series is proportional to battery voltage. The main disadvantage of the conventional system is the power loss in the diodes. Accordingly the PV array size required is larger. It is obvious that the power loss in series diodes Pd is given by

$$P_d = (V_b - V_L) * I_L \qquad (1)$$

where, V_L and I_L are the instantaneous load voltage and current respectively. P_d varies from instant to another depending on the instantaneous battery voltage. The integration of P_d over a complete day gives the daily energy loss. It is expected that the energy loss during summer is larger since the battery is fully charged and its voltage is large.

3. MICROPROCESSOR CONTROLLED SYSTEM

The same technique used in switch mode voltage regulation is applied by using a microprocessor controller instead of analog [7,8] or digital circuits [9]. Figure 6 shows a block diagram of a PV system using a microprocessor controlled load voltage regulator system. The PV array is charging the battery through a BVR. The switch S_1 is opened when battery voltage exceeds a specified level to avoid overcharging the battery S_2 is opened when battery voltage drops below a predetermined level to disconnect the load and prevent deep discharge of the battery. The switch S_3 is controlled by a microprocessor where it controls the duty cycle of the load voltage. The chopper circuit generates a square wave of controlled duty cycle and the load voltage V_L is determined by

$$V_L = V_b * D = V_b * [T_{on} / (T_{on} + T_{off})]$$ (2)

where D is the duty cycle of the square wave driving the switch S_3, as shown in Figure 7, T_{on} and T_{off} are the ON and OFF periods of the switch S_3.
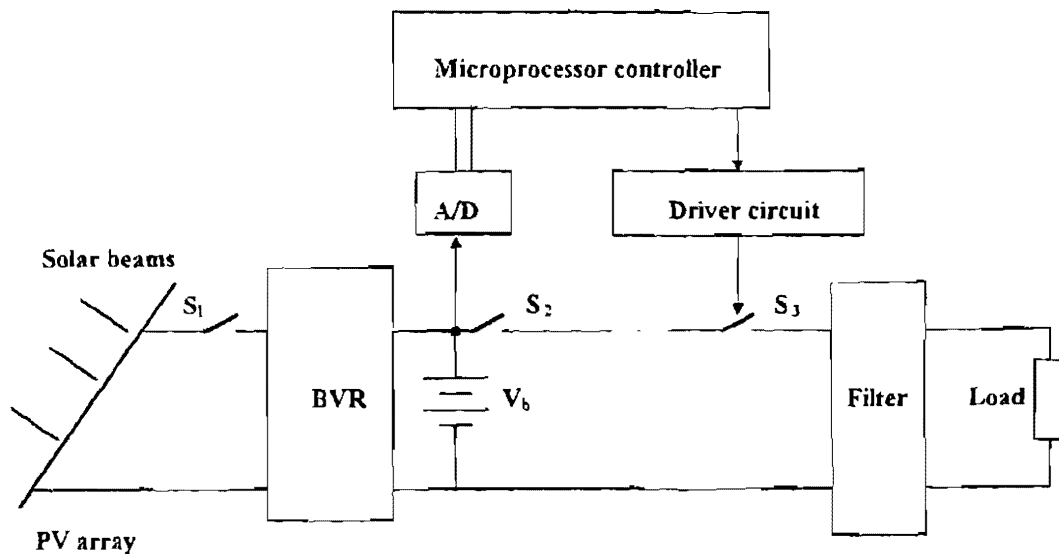

Figure 6 A PV system using a microprocessor controlled load
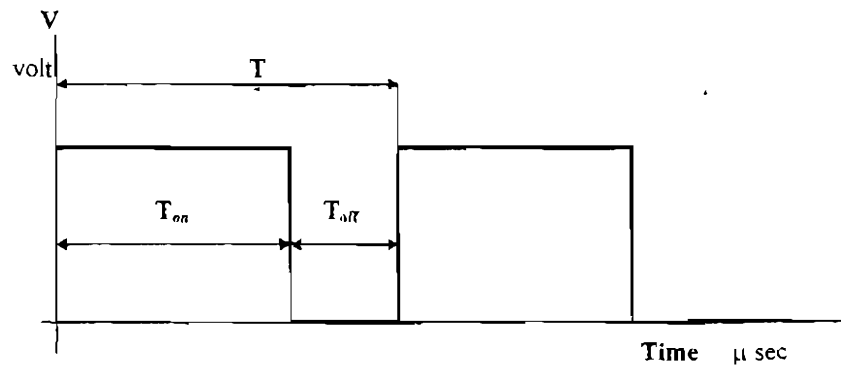voltage regulator applying a feedforward technique.

Figure 7   The wave form of the driving signal.

It is obvious that the output voltage of the chopper circuit is not DC voltage hence a filter circuit is needed.

The performance of the microprocessor system may be summarized as follows. The battery voltage is converted from analog to digital (A/D) and fed to an eight bit microprocessor such as Intel 8085 which produce a digital control signal inversely proportional to battery voltage so that the load voltage is kept almost constant. The digital control signal is converted from digital to analog (D/A) and fed to the driver circuit controlling ON and OFF periods of the switch S_3 and consequently the load voltage is kept within the allowed limits The major advantages of the proposed microprocessor based control system are (i) the switch S_3 is operated at a constant frequency which equals to the optimum operating frequency of the electronic switch S_3, (ii) reducing the PV array size since the power consumption is reduced. Two alternative control systems namely feedback and feedforward control systems may be used. Let us consider the two systems in the following paragraphs.

3.1 Feedback Control System

The configuration of this system is indicated in Figure 8 V is compared with a reference load voltage V_r The difference (error) is computed and used to adjust the timing of the control signal. The system dynamics and stability depends on the dynamics of all closed loop elements including filter dynamics A complete mathematical model of the closed loop system should be considered to design the program parameters as sampling time and controller gain. In fact, the main problem of the system is related to

steady state conditions and the slow variation of the output of the solar PV system. This fact of slow variations simplifies the system design if the steady state conditions are only considered.
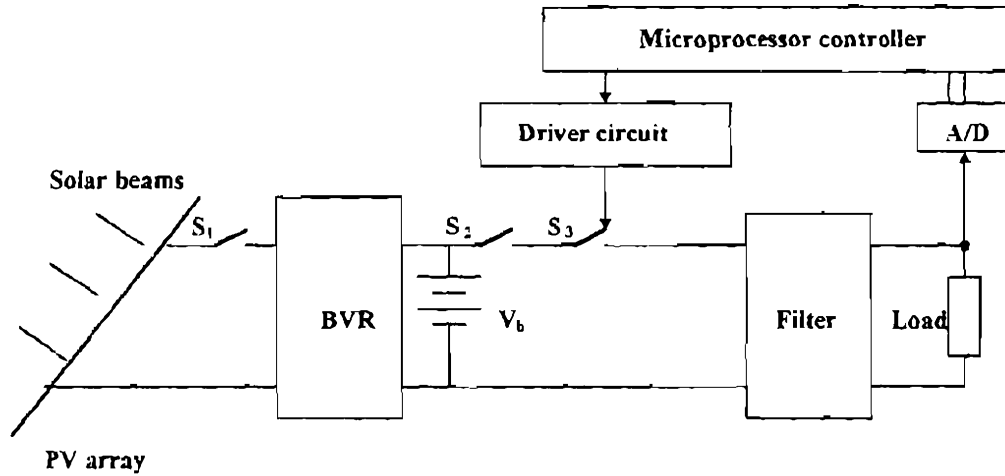

Figure 8   A PV system using a microprocessor controlled load
voltage regulator applying a feedback technique.

3.2 Feedforwared Control System

The block diagram of this system is indicated in Figure 6 In this system there is no feedback from the load voltage to the control system. The microprocessor computes the duty cycle according to battery voltage under steady state conditions which is accurate enough for a system with slow variations The microprocessor program explained hereafter is based on the feedforward control system

4. MICROPROCESSOR PROGRAM

The flowchart of the microprocessor program is shown in Figure 9. The program starts by system initialization. In this part input and output ports are programmed. The input port is connected to an 8 bit A/D converter to read the battery voltage and latch its value in a register. The microprocessor may read this register whenever it is required. The output port consists of three bit latches. The first bit B0 is connected to the electronic switch S3 driver The bits B1 and B2 of the output port are connected to system alarm circuit which indicates low and high battery voltages.

Notes

B controles the sampling time.

C controles no of decision cycles.

PCT = The path time compensation.

V_b is the battery voltage.

ADCT is Adjust Duty Cycle
  subroutine

B_0 of PPI port B is used to switch
  the load on and off.

START

System initialization

- Switch the load on
- DEC B

B = 0 ? —No

Yes

INPUT V_b

- 0 → PTC
- DEC B

- Store V_b in Decisiom array
- DEC C

No ← C = 0 ?

Yes

C = 0 ?

V_b in Range ? —No

- Store V_b in DecisiOn array
- 3 → C

No   Yes

Yes

CALL ADCT

Adjust PTC   Adjust PTC   Adjust PTC   Adjust PTC

S → B

- Delay of T_{on} → A & - A - PTC → A

CALL DELAY subroutine

- Switch the load off
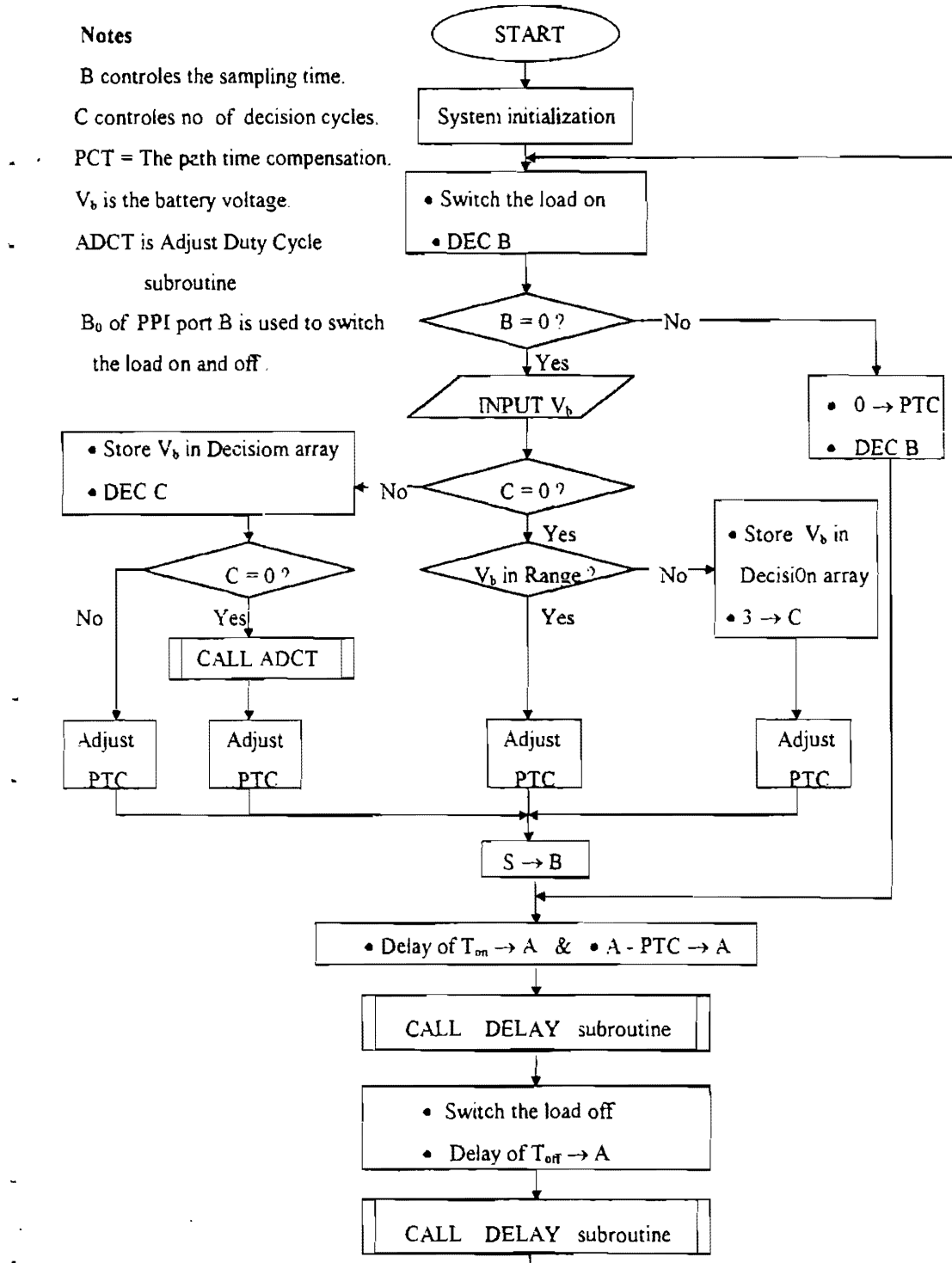- Delay of T_{off} → A

CALL DELAY subroutine

Figure 9   The flowchart of the microprocessor program to control the system load voltage.

A sample is taken every S duty cycles. After processing of each sample the S value is stored in register B It is decremented every duty cycle till it reaches zero and a new sample is taken. After each cycle adjustment. the battery voltage is stored as an acceptable voltage corresponding to the current duty cycle. A decision is already taken and the decision cycle control memory is cleared. The path of the program will go without any changing as long as the battery voltage is within the allowed limits. As soon as the battery voltage goes beyond the allowed limits, a new value is stored in the first location of the decision array. New adjustment and new decision based on the average of 4 samples is accomplished. The part of the program to read the required four samples is called the decision cycle Since one sample is already read and stored in the decision array. the decision control memory is set equal to 3 Register C is used for this function. When the four cycles are completed, the main program will call ADCT subroutine to calculate the duty cycle timing and set alarms. as shown in Figure 10

4.1 Duty cycle control

The periodic time of the driving signal produced by the microprocessor is adjusted to be 1.25 milliseconds corresponding to 800 HZ, the optimum operating frequency of the electronic switch S_i controling the operation of chopper circuit The nominal duty cycle is chosen to be 75% The allowed limits of the duty cycle range from 55% to 90% Whenever the voltage goes out of the allowed limits. the microprocessor reads four samples. calculates their average V_{ba} and accordingly calculates the ON time duration of the duty cycle If the nominal battery voltage is V_{bn} and the corresponding nominal ON time is T_{onn} then the new value of T_{on} will be

$$T_{on} = T_{onn} * (V_{bn} / V_{bav}) \tag{3}$$
and
$$T_{off} = T - T_{on} \tag{4}$$

where T is the periodic time of the driving signal. The number of delay cycles for both T_{on} and T_{off} are changed according to eqs (3) and (4) and stored in the assigned memories

Notes

ALARMS

- low voltage alarm

  $1 \rightarrow B_1$ of port B of PPI

- high voltage alarm

  $1 \rightarrow B_2$ of port B of PPI

- B_0 of port B of PPI = 1
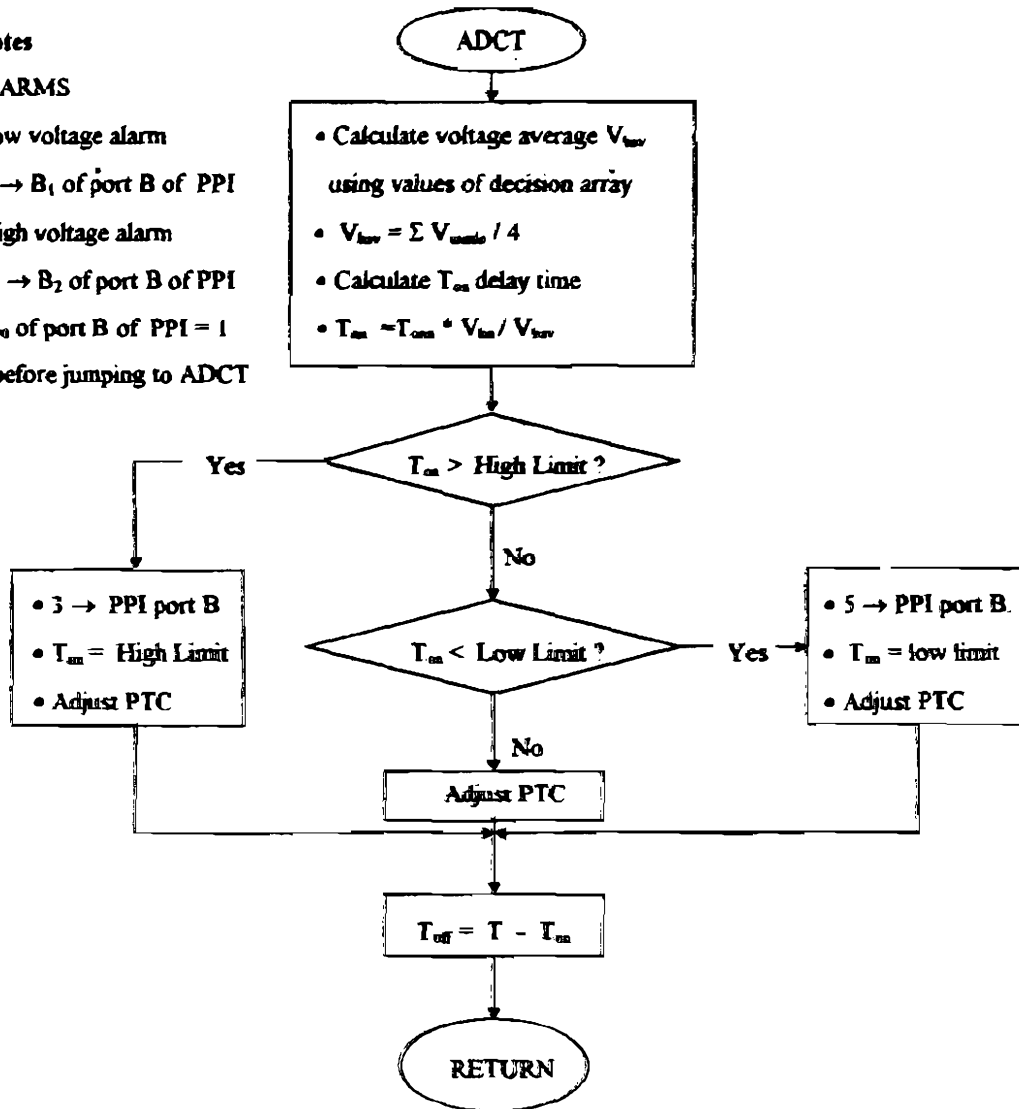
  before jumping to ADCT

Figure 10   The flowchart of the microprocessor subroutine ADCT To

Adjust the Duty Cycle on and off Times and set alarms

4.2 System Alarm

If the calculated ON time exceeds the maximum allowed limit of the duty cycle (90% in this case), the microprocessor sets $T_{on} = 0.9 * T$ and sets low voltage alarm. Contrarily if the calculated T_{on} is shorter

than the minimum allowed value (corresponding to 55% duty cycle in this case), the microprocessor sets $T_{on} = 0.55 * T$ and high voltage alarm is set. Both alarms are cleared as soon as the calculated value of T_{on} lies within the allowed limits.

5. LOSSES IN PV SYSTEM

A detailed simulation program for the performance of PV system installed in Cairo city (30°c) is conducted and results are summarized hereafter. The example considered is to design a PV system supplying a 1 kw constant load operating at 48 V with 2 V allowance, i.e. load voltage is allowed to be between 46 V and 50 V. The load requires energy day and night and during the cloudy days too. According to climatological conditions of Cairo city, the successive cloudy days considered are 2 days. The detailed simulation program gave the following results.

A 10 kw peak PV array titled at 45°c facing south and a 48 V,3360 AH storage battery size is the minimum PV system size to supply the load with the required energy day and night and during cloudy days throughout the year. This system allows the load voltage to range from 44.4 V during the winter cloudy days to 53.1 V during the summer sunny days The minimum load voltage(44.4 V) is below the allowed limit (46 V). To overcome the above mentioned difficulty, one has to increase the battery voltage to be 50 V while the array size is kept unchanged. Under these conditions the load operating voltage ranges from 46 2 V to 54.7 V Thus the minimum load operating voltage meets the load requirements However, the maximum allowed load voltage exceeds the maximum allowed limit The solution is to insert passive elements in series with the load to have the excess voltage across them The power dissipation in the passive elements is a power loss. The detailed simulation program showed that the energy loss due to the excess voltage is equivalent to 2% of the maximum array energy or 5% of the load energy. The previously mentioned solution by increasing the battery voltage from 48 V to 50 V means that the cost of the storage battery is increased by about 4%. Thus the conventional solution leads to some energy loss and increased system cost.

The proposed microprocessor controller system eliminates the above mentioned drawbacks The proposed system adds a control circuit, chopper and filter circuits to the conventional system which increases the system cost. However the slight increase in the system cost is justified by reducing the battery size and eliminating the energy dissipation in the passive elements. Moreover the operating voltage of the load can be easily adjusted within the allowed limits

6. CONCLUSIONS

Critical DC loads such as some communication systems require a regulated voltage. Since the battery voltage fluctuations are not accepted for such loads, a load voltage regulator must be used Conventional regulators have two major drawbacks namely energy losses(2% of array energy) and the requirement of somewhat enlarged storage battery size(4% enlargement). A load voltage regulator using a microprocessor for PV system applications is discussed. The proposed regulator avoids the drawbacks of the conventional load voltage regulator and allows an elaborate control of the load voltage at the expense of slight increase of system cost due to addition of chopper and filter circuits.

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