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E-2286

SUMMARY

The NASA Lewis Research Center is managing the Stand-Alone Application Project for the Department of Energy (DOE). Under this project, Lewis installed, in 1978, a photovoltaic power system in an Arizona Indian village. Under a DOE funded grant from Lewis, the Energy Research Center of the Cleveland State University performed an analysis of the control subsystem of this photovoltaic power system. The four major functions of the control subsystem are voltage regulation, load management, water pump control, and system protection. This report analyzes the control subsystem functions, presents flowcharts for the control subsystem operation, and presents a computer program that models the control subsystem.

INTRODUCTION

Many societies throughout the world have developed a large appetite for electrical energy. Of the many reasons for this appetite, the most important are the great variety of applications and the relative ease with which electricity is generated and distributed, and the desire of each society to upgrade its standard of living. Everyday we observe the tremendous impact on mankind's life style caused by advances in agriculture, transportation, medicine, telecommunications, computer technology, aerospace research, energy conversion and international trade. The key ingredient for the successful operation of all these complex processes is the availability of energy.

The sun is the source of nearly all earth's energy, either directly by heat and light or indirectly through fossil fuels. However, it is only through the photovoltaic (PV) effect that the sun's light energy is directly transformed into electricity (ref. 1). Many experts believe that this process will play a major role in meeting the future energy needs of the United States and, in particular, our goal for energy independence. In addition, this same process could be the most promising way for the developing countries to meet their energy needs.

PV technology is a relatively new and promising energy source and an alternative to fossil fuel and nuclear power. Energy systems based on this principle are quiet, nonpolluting, easy to operate and need not have any moving parts if stationary collectors are used (refs. 2 and 3). With proper design, these energy systems can be highly reliable. PV energy systems have proved capable of operating efficiently in a wide range of applications including small, low-power systems for remote communication equipment to midsize systems for schools and large systems for remote villages.

On December 16, 1978 (ref. 6), the Papago Indian village of Schuchuli, located about 120 miles west of Tucson, Arizona, became the first community in the world to rely entirely on PV energy for its basic human needs (refs. 3 and 4). Prior to the installation of the PV power system, kerosene was used for lamps, diesel fuel powered a water pump, and the villagers' diet consisted mostly of food not requiring refrigeration. Funded primarily by the Department of Energy (DOE), the Schuchuli village PV energy system has been designed, installed and managed by NASA Lewis Research Center as part of DOE's National PV Program (ref. 5). The Schuchuli system has a 3.5 kW (peak) solar array and is a stand-alone energy system (i.e., no backup power generating source). It provides power for the lights in the village buildings, village water pumping, refrigerators, a clothes washing machine, and a sewing machine. A solar collector is used to heat the water in the domestic service building.

NASA has reported (ref. 5) an on-line operation of 98.6 percent during the first two and one-half (2-1/2) yr operational period. This has shown the validity of the system design.

This report analyzes the control aspects of the Schuchuli village PV energy system.

COMPONENTS OF THE SCHUCHULI PV ENERGY SYSTEM

The Schuchuli stand-alone PV energy system consists of a PV array, batteries, loads, controls, power distribution system, instrumentation, data gathering devices, the Electrical Equipment Building (EEB) and the Domestic Services Building (DSB) (refs. 3 to 5). A detailed list of the various electrical components is given in table I while figure 1 shows an overall view of the system. The components are located throughout the village as shown in figures 2 and 3.

The PV array is composed of 24-4 ft by 8 ft (1.22 by 2.44 m) panels, each containing eight Solarex 9200J modules connected in series to form a 120 V nominal string. The panels are located within a locked fenced area and are designed to withstand 100 mph (160 km/hr) winds. To minimize land requirements and shadowing during low sun angles, the panels are arranged in three stepped rows. The tilt angle is adjusted four times per year to compensate for the seasonal variations in the sun's relative position.

The main battery consists of 52-2 V (nominal) cells, rated at a 2380 A-h capacity, connected in series with a parallel arrangement of four pilot cells, rated at capacities of 1055, 310, 310, and 310 A-h. These pilot cells are used by the control subsystem for load management (see Load Management section). The battery cells selected for this system are the 1.300 specific gravity lead-calcium grid lead acid cells designed specifically for deep discharge cycle operation. For safety considerations, the batteries are housed in a separate vented room in the EEB.

Also located in the EEB are the controls, which are housed in the Power Collection, Control and Instrumentation Assembly (PCCIA). The controls are discussed in the Control Aspects section. The refrigerators, washing machine and the sewing machine are installed in the Domestic Services Building (DSB). More information about the physical description of the Schuchuli system can be found in reference 5.

CONTROL ASPECTS

General

There are various objectives that must be met when designing a PV stand-alone energy system for a village. The needed power for the total expected load demand should be provided either from the array, the storage battery or both. In addition to cloudy day and nighttime operation, sufficient stored energy should be available to compensate for the seasonal loss of daylight. The batteries should be protected from excessive discharge which could cause permanent loss of capacity. Both the batteries and loads must be protected from under and over voltage situations. Certain loads may have a higher priority for service, than others.

In the design of the Schuchuli PV energy system, these objectives, along with others, were taken into consideration. There are several control functions, summarized in table II, associated with these objectives. For the most part, the controls are contained in the PCCIA in the EEB.

In this report, only the voltage regulation, load management, water pump, and watchdog control subsystems are addressed.

Voltage Regulation

The voltage regulation and load management (see next section) subsystems are implemented by a drum programmer (DP). The DP is a 24 position, 30 switch electromechanical device incorporating a stepping motor and timer circuit. Appropriate signals indicating the status of the system cause the DP to change position. The DP contact closure schedule is shown in figure 4 (ref. 5). Each of its 24 positions describe a possible state of the system and is summarized in table III with the conditions necessary to switch states.

Voltage regulation is accomplished by connecting or disconnecting array strings. For proper battery charging during sunlight periods, when power is obtained from the array, the system voltage should be maintained between 124 and 130 V. A meter-relay monitors the system voltage and signals the DP to connect additional strings if the voltage is below 124 V or disconnect strings if the voltage is above 130 V. The DP range for voltage regulation is from position 6 (all strings connected) through position 24 (all strings disconnected). There is a time delay (~2 to 5 sec) before the DP can change positions to allow the system to reach equilibrium and to avoid tracking fast transients. This control subsystem is illustrated in flowchart form in figure 9.

For a given insolation, temperature, and number of parallel strings connected to the DC bus, a unique operation curve describes the behavior of the array. The system operating point is determined by the intersection of the array I-V curve and the load line describing the effective load (including the battery) as seen by the array. When changes in the environment or load occur, the system operating point will change and the number of connected array strings may be adjusted accordingly.

As an example, consider the following (see fig. 5):

1. Present operating point = A

   a. 10 array strings connected

   b. system voltage = array voltage = 125 V

   c. load line, R_{L1}, battery and resistive load

   d. for a desired voltage range of 124 to 130 V, the system voltage is within range, so the system is stable.

2. A decrease in load occurs

   a. a parallel resistive load is turned off, the load line is now R_{L2}

   b. the operating point moves from A to B

   c. the voltage at B is 132 V, above the 130 V high limit, so two array strings are disconnected so the system voltage is below 130 V and the new operating point becomes C

   d. the new system voltage at C is 128 V, within range, so the system is stable with 8 array strings connected.

3. An increase in load occurs

   a. a parallel resistive load is turned on, the load line is now R_{L1} again

   b. the operating point moves from C to D

   c. the voltage at D is 122 V, below the 124 V low limit, so two array strings are reconnected so the system voltage is above 124 V and the new operating point becomes A

   d. the new system voltage at A is 125 V, within range, so the system is stable with 10 array strings connected.

Load Management

Load management is performed by utilizing the 53rd battery cell which is composed of 4 pilot cells in parallel. During discharge, the individual pilot cells are sequentially connected in series with the other 52 cells. Battery depth-of-discharge[1] (DOD) is determined by sequentially sensing the end-of-discharge voltage of each of the pilot cells. This then triggers sequential load shedding. As the batteries recharge, the loads and pilot cells are sequentially reconnected in the reverse order. The load management system protects the battery from excessive discharge, which would cause permanent loss of capacity, and maintains the operation of critical loads at the expense of less critical loads. This action is illustrated in flowchart form in figure 7.

The first pilot cell has a 1055 A-h capacity and the other three have 310 A-h capacities. In parallel, these four pilot cells represent ~80 percent of the 2380 A-h capacity of the main battery bank in increments of ~50, 10, 10, and 10 percent (44, 13, 13, 13 percent, actual) respectively. Since the actual battery capacity is dependent upon its net ampere-hours charging, its recent discharge/charge history, and the temperature environment, these approximations are assumed sufficient for indicating their respective nominal DOD levels.

When the system voltage is below the desired low limit (124 V) with all the array strings connected, and the battery is discharging, then the system can enter the load management mode. The DP will then be in position 5 with pilot cell 1 (1055 A-h) connected in series with the 52 cells. When the voltage of pilot cell 1 has dropped to a specified end of discharge voltage, this indicates that the main battery is at ~50 percent DOD. At this time, the DP changes from position 5 to position 4, which disconnects pilot cell 1, the washing machine and the sewing machine and reconnects pilot cell 2. If the battery continues to discharge to 60, 70, and 80 percent DOD, in a similar way, the village lights, the water pump, and finally the refrigerators are disconnected.

At any point in the discharge cycle that the battery begins to recharge, the connected pilot cell voltage will increase. As the pilot cell voltage attains the full charge voltage, the loads are reconnected and the next pilot cell is reconnected. As the last pilot cell recharges above its low voltage limit and the battery charging current is above the high set point (6 A), the drum programmer changes from position 1 to position 2, reconnecting the refrigerators. The other loads are sequentially reconnected as the pilot cells attain their full charge voltage. Table IV summarizes the load management control actions.

Water Pump

The pump is controlled automatically based on the water level in the storage tank with the control function divided into three cases. For the first case, the system is in the load management mode, DP positions 1 or 2. The pump load has been shed and will not start. The pump will stop if it had been running when the DP position changed to position 2 from 3. For the second case,

---

[1]Depth-of-charge is the percentage of capacity below the manufacturer's rated value or measured total capacity. State-of-charge (SOC) is the percentage of present storage to the rated value. Therefore, SOC + DOD = 100 percent. The capacities are normally given in ampere-hours and if the manufacturer's rating is conservative, DOD could be negative and SOC could be greater than 100 percent.

the system is in the load management mode, DP positions 3 to 5. The pump will start either when the water level has fallen to 18 inches below full and the array current is greater than 3 A or when the tank is less than half full. For the third case, the system is in voltage regulation mode, DP positions 6 to 24. The pump will start when the water level has fallen to 18 inches below full. The pump will continue operating until either the tank is full or until load management disconnects it. This control subsystem is illustrated in figure 8. The array current condition was included to limit the pump operation to daylight hours while in load management mode, except when the tank is less than one-half full.

Watch Dog System

The watch dog control subsystem is designed to protect the overall PV energy system from over and under voltage situations. If the system voltage falls below the minimum allowed value (99 V), the loads are disconnected from the battery and array. If the system voltage exceeds the maximum allowable limit (138 V), the array strings are disconnected from the battery and the loads. In this latter case, an audible alarm is triggered in the DSB and both situations activate alarm lights in the EEB. Figure 10 describes this operation in flowchart form.

Flowcharts

Five logic flowcharts, figures 6 to 10, were created to describe the operation of the various control subsystems for the Schuchuli stand-alone PV system. To simplify the logic, it is assumed that the number of array strings connected differentiates the voltage regulation mode from the load management mode even though this introduces some error compared with the actual system. Since the flowcharts were written as a basis for a computer simulation, timing paths are included to reflect the following:

(1) System voltage checked every second

(2) Array string switching possible every NDELAY second

(3) Check for water pump start/stop condition every minute

(4) Check for over/under voltage (watch dog) every 10 min

(5) update the battery SOC every one-half hour

(6) Update the insolation, temperature, and load profile every hour

The simulation timing intervals were arbitrarily chosen and do not necessarily reflect actual system operation at Schuchuli.

COMPUTER PROGRAM

This section contains a computer program, written in FORTRAN, which simulates the four major control subsystems utilized at Schuchuli. It follows directly from the flowcharts. A sample output based on generated data is at the end of this section. The various subroutines for the solar array, battery, loads, and for locating the operating point are still under development by Cleveland State University.

SUMMARY

This report examines the control aspects of a stand-alone photovoltaic power system for the first village (Schuchuli, Arizona) to have its energy needs supplied by a photovoltaic power system. The major components and control subsystems of the Schuchuli photovoltaic power system are discussed. Flowcharts describing the operation of its various control subsystems are developed and serve as a basis for a computer program.

In order to design and analyze future cost effective, efficient and reliable stand-alone photovoltaic energy systems, new methodologies, advanced controls concepts and advanced techniques need to be developed (ref. 7). We hope that the results of this report will form the basis for such future studies in improving further each subsystem of stand-alone photovoltaic energy systems.

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TABLE I. - MAJOR COMPONENTS OF THE SCHUCHULI PV SYSTEM

Name	Description/electrical characteristics
Solar array	3.5 kW (peak), 192 Solarex 9200 J modules Each module: 42 series connected solar cells 19.15 V at 28 °C maximum power point 16.46 V at 60 °C maximum power point 8 modules series connected for nominal 120 V string 24 strings total
Battery storage	130 V, 2380 A-h, nominal 52 - C and D Model LCPSA-19, 2380 A-h capacity at 77 °F (25 °C) 500 hr discharge rate. 1 - C and D Model KCPSA-15, 1055 A-h capacity at 77 °F (25 °C) 500 hr discharge rate, pilot cell 1. 3 - C and D Model DCPSA-15, 310 A-h capacity at 77 °F (25 °C) 500 hr discharge rate, pilot cells 2, 3, 4.
Battery storage (instrumentation)	rated 1055 A-h, nominal 12 V 6 - C and D Model KCPSA-15, connected in series
Loads[1]	(1) 1 - Jensen Jack water pump, rated 1100 gal/hr (4165 l/hr), 2 hp 120 V dc motor, normal load is ~6 A, used in conjunction with 11 000 gallon tank. (2) 53 - fluorescent lights, each rated 20 W with Bodine Co. "Tran-Bal" inverter-ballast, 120 V dc to 120 V ac/23 kHz, normal load is ~0.24 A/light. (3) 15 - refrigerators/freezers, custom manufactured by Magna Kold Inc. 5 - compressor motors (1 per 3 refrigerator units), 1/4 hp 120 V dc permanent magnet motors, normal load is ~1.45 A/motor, manufacturer estimates 25 percent on duty cycle at 110 °F ambient temperature. (4) 1 - Maytag wringer washer with Applied Motors 1/4 hp 120 V dc permanent magnet motor, full load current is 2.59 A. (5) 1 - stretch zigzag sewing machine, White Model 954, 1/8 hp 120 V dc universal motor, normal load is ~1.1 A. (6) 1 - hot water heater, Solahart Model 80 GE Hotwater System, contains 300 W resistance heating element to prevent water freeze-up in the solar collector during cold weather. (7) Instrumentation and controls, estimated current is 0.54 to 0.57 A.

[1]Loads cannot be arbitrarily added to this limited energy system.

TABLE II. - CONTROL SUBSYSTEMS

Name	Function and comments
1. Voltage regulation	Maintain system voltage between 124 and 130 V when power is available from array.
2. Load management	Sequentially shed loads beginning with lowest priority as battery reaches predetermined low state-of-charge (SOC) levels.
3. Water pump	Maintain sufficient amount of water in 11 000 gal storage tank.
4. Watch dog system	Protect system components from over voltage (138 V) and under voltage (99 V) conditions.
5. Cumulative daily timer for washing machine	Limit usage to 12 hr/day (disconnected in 1980 since it requires resetting after power outage and usage patterns dictated that it was not needed.)
6. DAT-3	Automatic data recorder, contains microprocessor that could be used for control purposes in the future.

TABLE III. - DRUM PROGRAMMER

Position	Number of array strings connected	Pilot cells connected #1 #2 #3 #4	Loads connected #4 #3 #2 #1	Down-count to next position	Up-count to next position
1	24	N N N Y	N N N N	(not allowed)	(V7 is not low) and (IB is hi)
2	24	N N N Y	N N N Y	(V7 is low)	(V7 is hi) and (IB is hi)
3	24	N N Y N	N N Y Y	(V6 is low)	(V6 is hi) and (IB is hi)
4	24	N Y N N	N Y Y Y	(V5 is low)	(V5 is hi) and (IB is hi)
5	24	Y N N N	Y Y Y Y	(V4 is low)	(V4 is hi) and (IB is hi)
6	24	Y Y Y Y	Y Y Y Y	(V1 < 124) and (IB is low)	(V1 > 130)
7	23			(V1 ≤ 124)	(V1 ≥ 130)
8	22				
9	21				
10	20				
11	19				
12	18				
13	17				
14	16				
15	15				
16	14				
17	13				
18	12				
19	10				
20	8				
21	6				
22	4				
23	2				
24	0	Y Y Y Y	Y Y Y Y	(V1 ≤ 124)	(Not allowed)

N = No
Y = Yes

V1 = system voltage
V4 = pilot cell No. 1
V5 = pilot cell No. 2
V6 = pilot cell No. 3
V7 = pilot cell No. 4

IB = battery current

TABLE IV. - THE LOAD MANAGEMENT CONTROL FUNCTION OF THE SCHUCHULI PV ENERGY SYSTEM

Battery depth-of-discharge	Loads disconnected	Pilot cell connected	Pilot cells disconnected	DP position
<50 percent	none	No. 1	No. 2, 3, 4	5
50 percent ≤ DOD <60 percent	washing and sewing machine	No. 2	No. 1, 3, 4	4
60 percent ≤ DOD <70 percent	above + 47 village lights	No. 3	No. 1, 2, 4	3
70 percent ≤ DOD <80 percent	above + water pump	No. 4	No. 1, 2, 3	2
≥80 percent	above + refrigerators	No. 4	No. 1, 2, 3	1

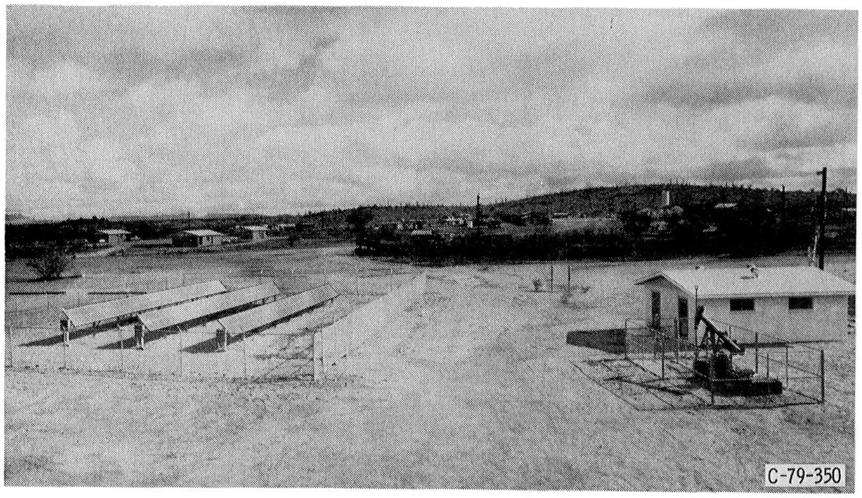

Figure 1. - Schuchuli photovoltaic village power project.

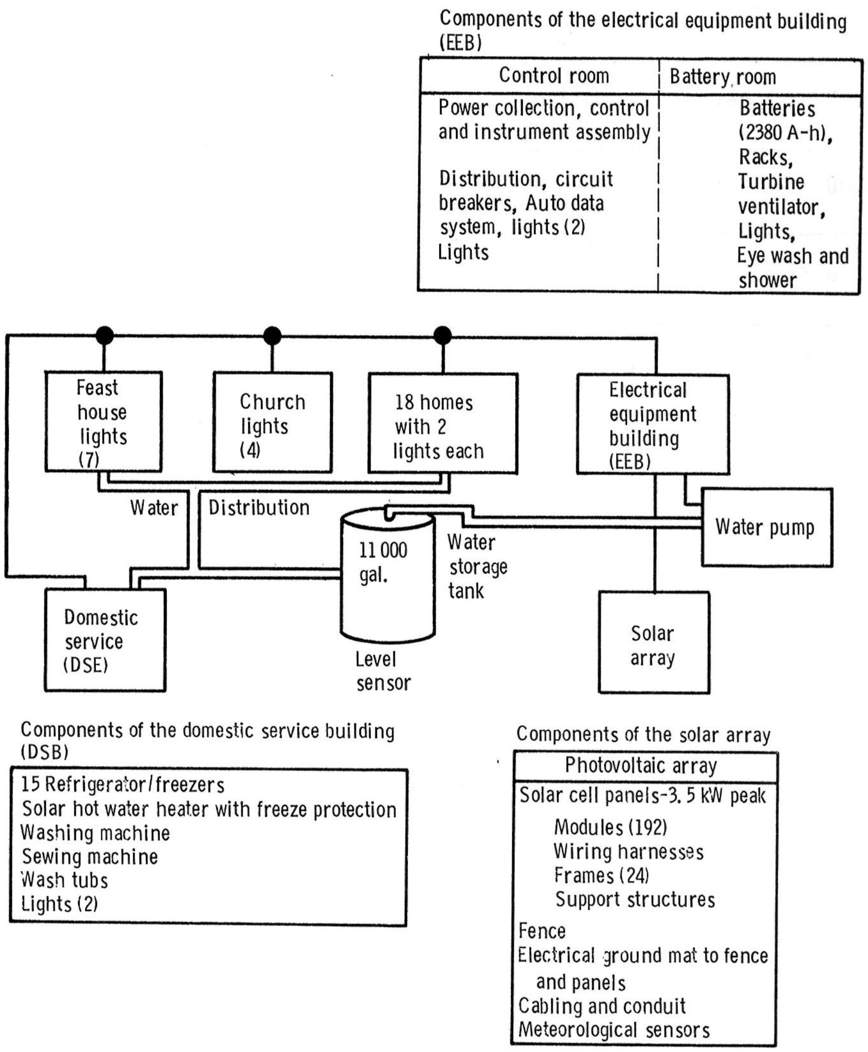

Figure 2. - A block diagram of the Schuchuli energy system.

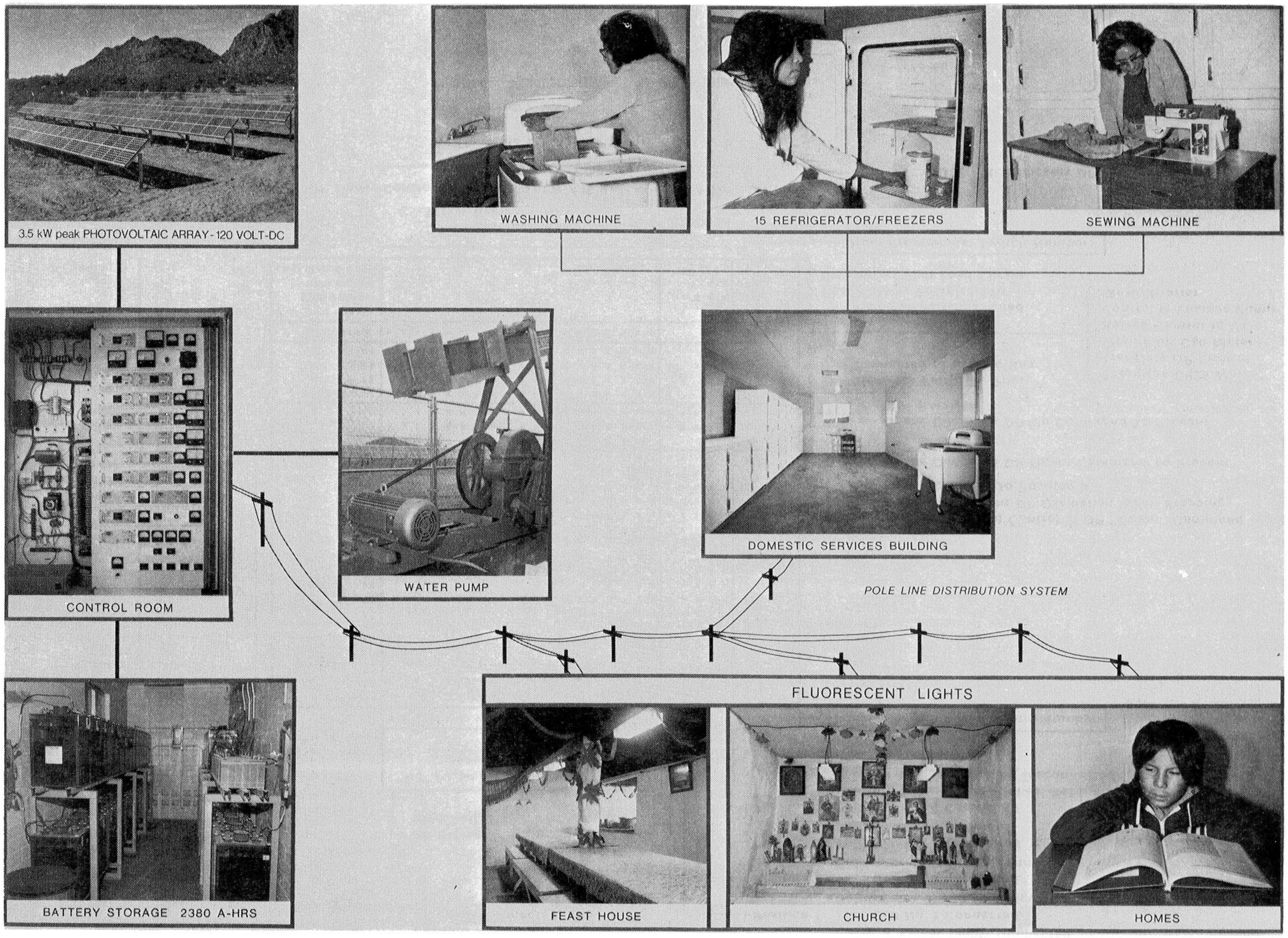

Figure 3. - World's first photovoltaic power system, Papago Indian village of Schuchuli, Arizona.

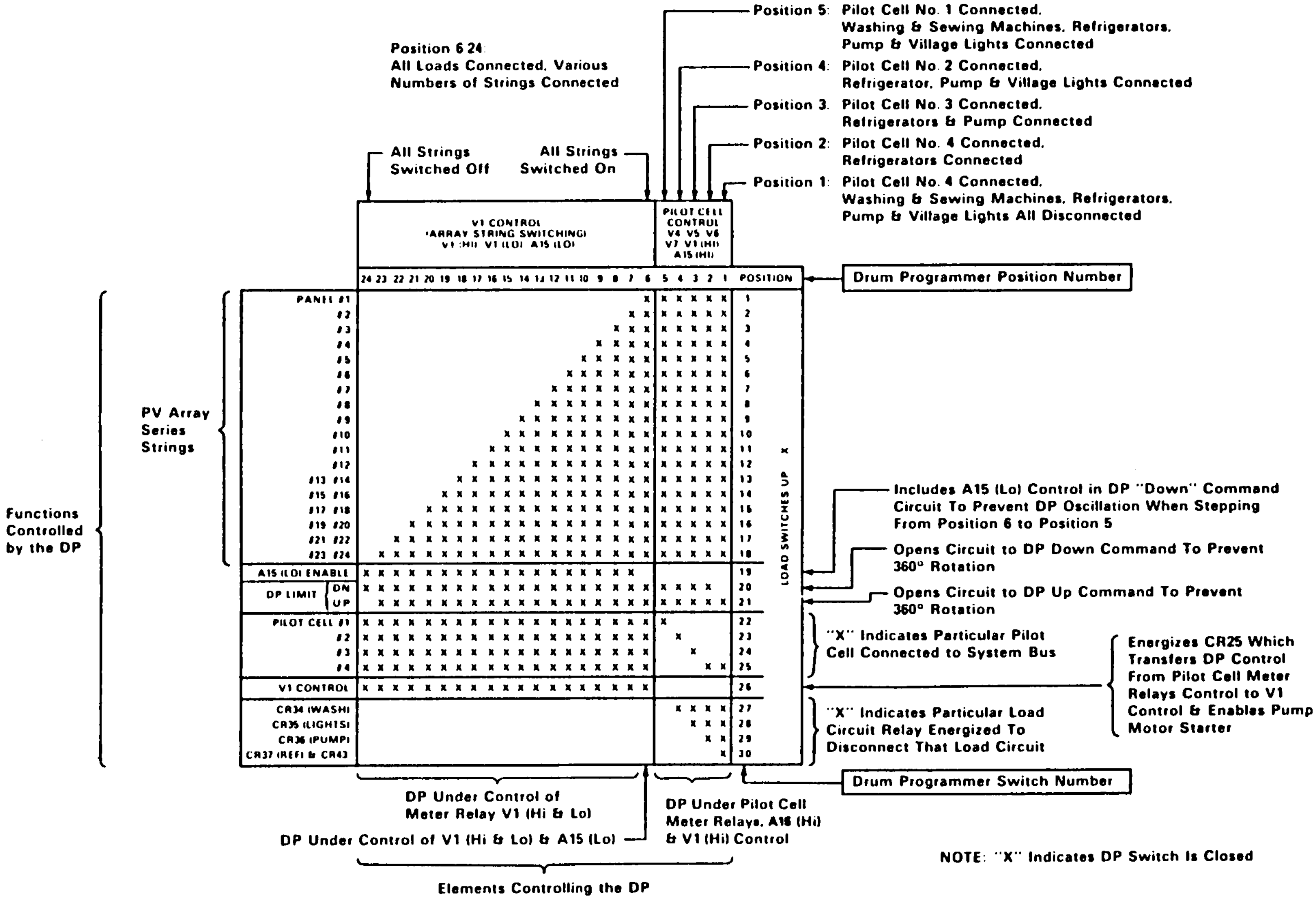

Figure 4. - Drum programmer contact closure schedule (5).

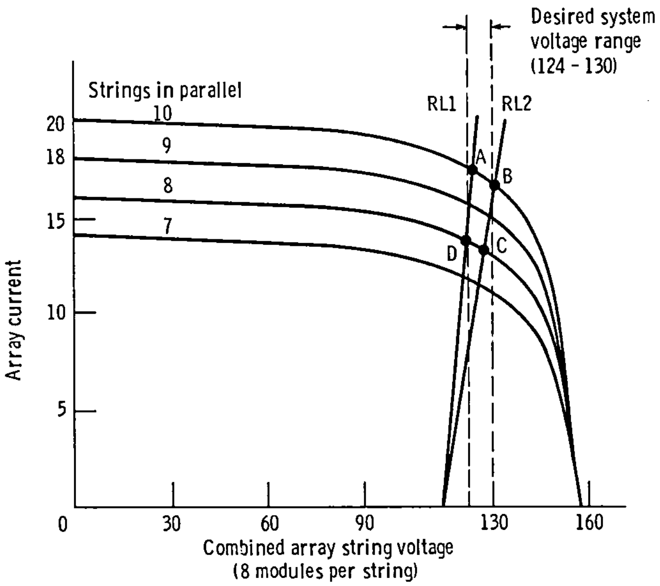

Figure 5. - Example of voltage regulation by array string switching.

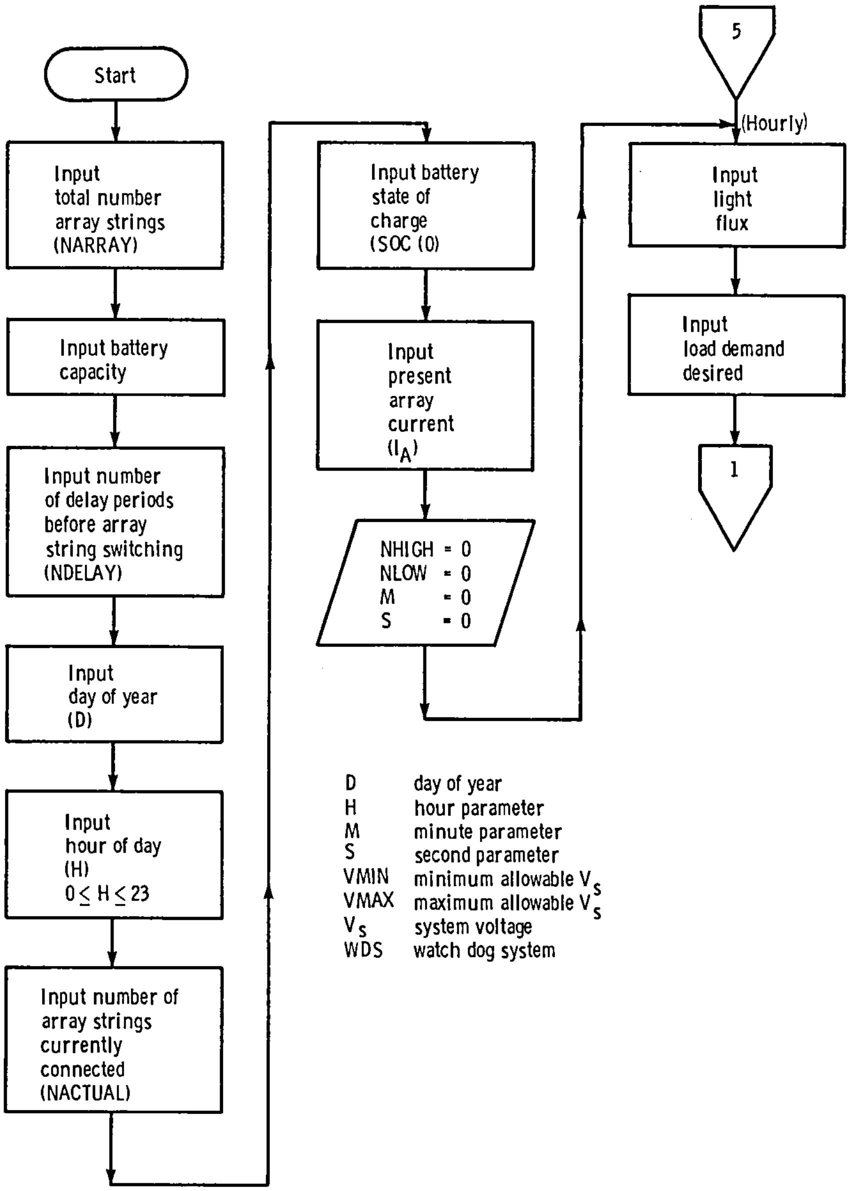

Figure 6. - Initial data requirements flowchart.

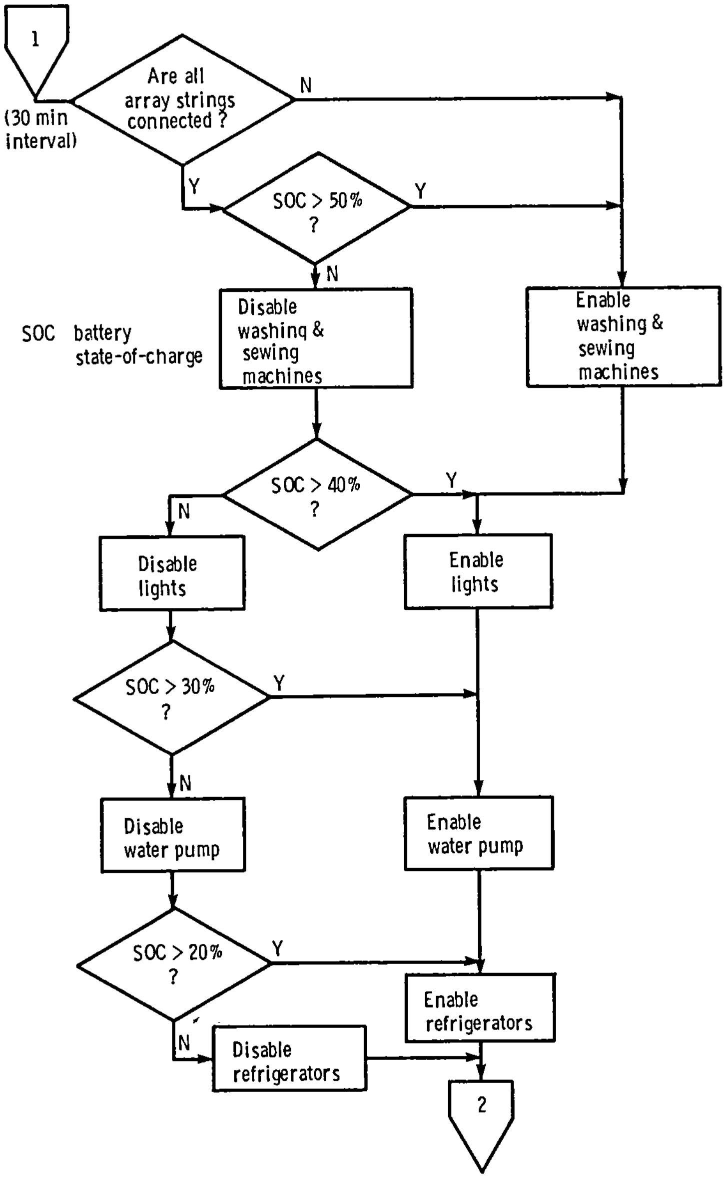

Figure 7. - Load management control flowchart.

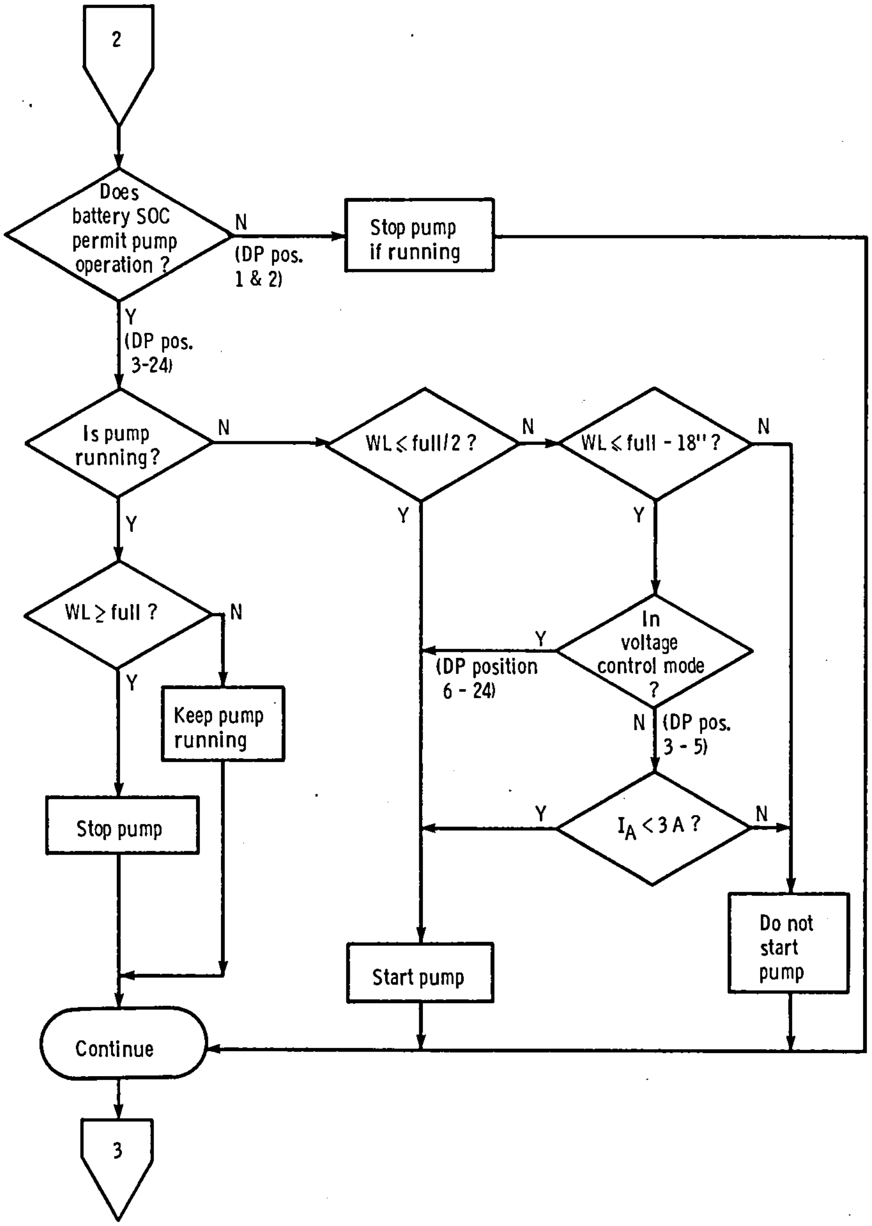

Figure 8. - Water pump control flow chart.

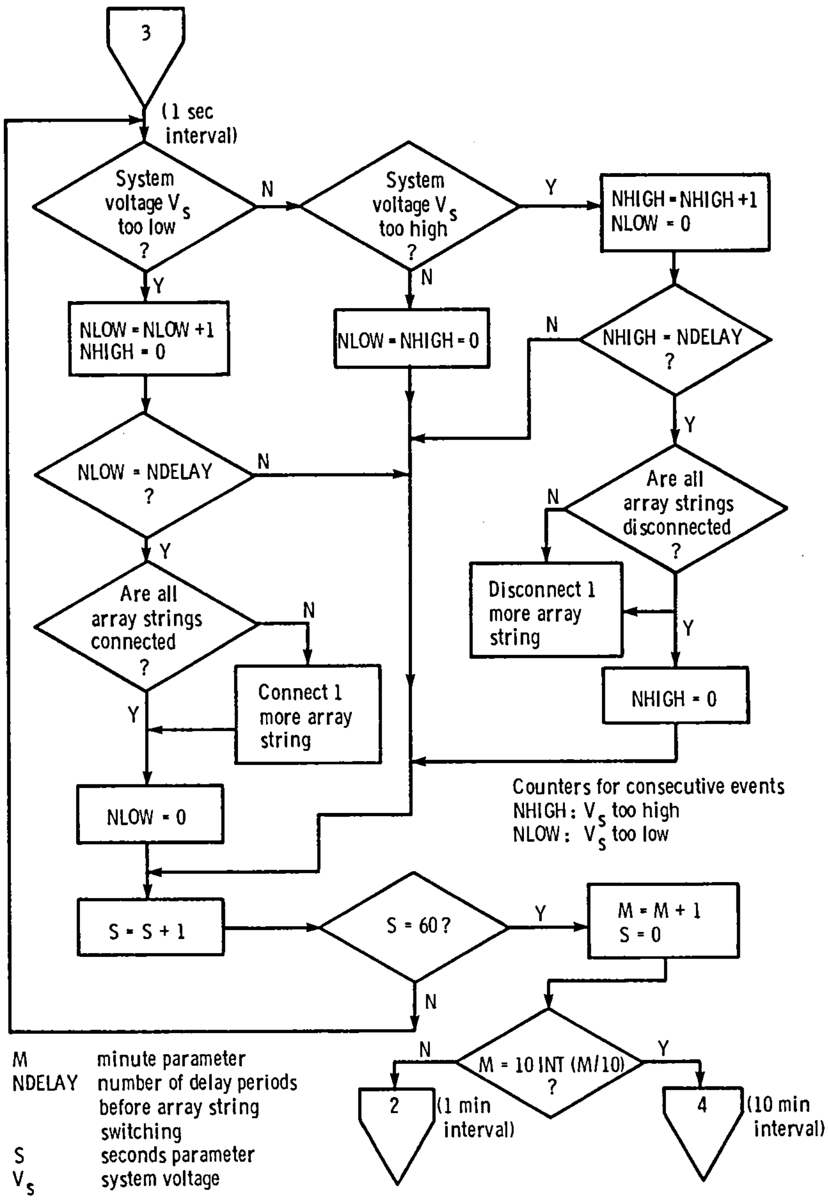

Figure 9. - Voltage regulation and timing paths flowchart.

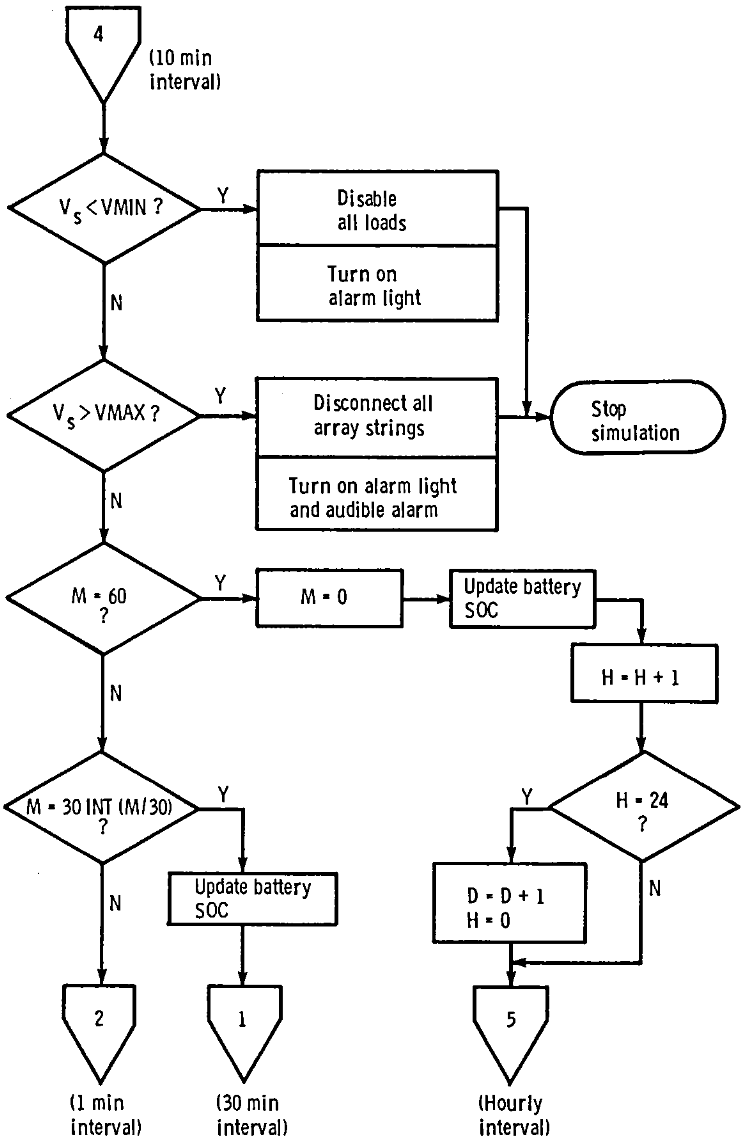

Figure 10. - Watch dog system and timing paths flowchart.

```
1          SUBROUTINE PVPSS
     C
     C              PHOTOVOLTAIC POWER SYSTEM
     C                  SIMULATION
     C
     C    JAMES CULLER & PETER P. GROUMPOS     VERSION JUNE, 1981
     C    ELECTRICAL ENGINEERING DEPT., CLEVELAND STATE UNIVERSITY
     C    CLEVELAND, OHIO 44115
     C
     C   SYSTEM DESCRIPTION
     C         BATC = BATTERY STORAGE CAPACITY (AMP-HOURS)
     C         IACONS = MINIMUM ARRAY CURRENT FOR NORMAL WATER PUMP
     C           OPERATION (AMPS)
     C         NARRAY = TOTAL NUMBER OF ARRAY STRINGS IN SYSTEM
     C         NDELAY = NUMBER OF CONSECUTIVE DELAY PERIODS BEFORE
     C           ARRAY STRING SWITCHING
     C         VSAMAX = MAXIMUM ALLOWABLE SYSTEM VOLTAGE VS (VOLTS)
     C         VSAMIN = MINIMUM ALLOWABLE SYSTEM VOLTAGE VS (VOLTS)
     C         VSMAX = MAXIMUM DESIRED SYSTEM VOLTAGE VS (VOLTS)
     C         VSMIN = MINIMUM DESIRED SYSTEM VOLTIGE VS (VOLTS)
2         COMMON /SYSTEM/BATC,IACONS,NARRAY,NDELAY,VSAMAX,VSAMIN,
         1 VSMAX,VSMIN
     C
     C   STARTING STATE
     C         D = NUMERICAL NUMBER FOR DAY OF THE YEAR
     C         H = HOUR OF THE DAY     0.<=H<=23.
     C         IA = INITIAL ARRAY CURRENT (AMPS)
     C         NACTUA = NUMBER OF ARRAY STRINGS INITIALLY CONNECTED
     C         SOC(1) = INITIAL BATTERY STATE OF CHARGE AS A
     C           FRACTION OF BATTERY STORAGE CAPACITY
     C           TYPICALLY: 0.0<=SOC<=1.0
     C         WP = WATER PUMP ON (WP=1.0) OR OFF (WP=0.0)
3         COMMON /START/D,H,IA,NACTUA,SOC(61)
     C
     C   INTERNAL PARAMETERS
     C         M = MINUTE PARAMETER
     C         NHIGH = CONSECUTIVE EVENT COUNTER FOR SYSTEM VOLTAGE
     C           TOO HIGH
     C         NLOW = CONSECUTIVE EVENT COUNTER FOR SYSTEM VOLTAGE
     C           TOO LOW
     C         S = SECONDS PARAMETER
     C         VS = SYSTEM VOLTAGE
     C         VSAVG = AVERAGE SYSTEM VOLTAGE FOR THE LAST THIRTY
     C           MINUTE INTERVAL (VOLTS)
     C         VSSUM = SUM OF SYSTEM VOLTAGES (EVERY SECOND) FOR
     C           THE PRESENT THIRTY MINUTE INTERVAL OR 1800 SECONDS
     C           (VOLTS)
     C         WDS1 = WATCH DOG SYSTEM DISCONNECT FOR LOADS
     C         WDS2 = WATCH DOG SYSTEM DISCONNECT FOR THE ARRAY
     C           STRINGS
4         COMMON /INTERN/M,NHIGH,NLOW,S,VS,VSAVG,VSSUM,WDS1,WDS2
     C
5         COMMON /LOAD/L1,R1,L2,R2,L3,R3,L41,R41,L42,R42,LP1,
         1 LP2,LP3,LP4
```

Figure 11. - Computer program listing.

```
      COMMON /WATER/SW1,SW2,SW3,WP
      COMMON /BAT/ VBAT, RBAT, UPDATE
      COMMON /SOLAR/C,T,PVIV(10,16),CC(4),TT(4),VV(10)
      REAL IA,IACONS
C  DATA INPUTS
C        1) LOADS:  L1,R1,L2,R2,L3,R3,L41,R41,L42,R42
C           (FROM "SUBROUTINE OLOAD")
C        2) WATER TANK:  SW1,SW2,SW3
C           (FROM "SUBROUTINE WATERL")
C        3) INSOLATION:  C
C           (FROM "SUBROUTINE INSOL")
C        4) CELL TEMPERATURE:  T
C           (FROM "SUBROUTINE INSOL")
C
C  SYSTEM STATE AND OUTPUTS
C        1) STATE:
C              IA (FROM "SUBROUTINE VSIA")
C              NACTUA
C              SOC(M+1) (FROM "SUBROUTINE BATTRY")
C              VS (FROM "SUBROUTINE VSIA")
C        2) LOAD PRIORITY ENABLES:  LP1,LP2,LP3,LP4
C        3) WATER PUMP ON/OFF:  WP
C        4) WATCH DOG SYSTEM DISCONNECTS:  WDS1,WDS2
C
C  THE RESULTS OF THIS SIMULATION ARE PASSED TO "SUBROUTINE
C  OUTPUT" FOR SUBSEQUENT PROCESSING AND PRINTOUT
C
C
C  HOURLY LOOP
C        OBTAIN HOURLY AVERAGE OF SOLAR POWER ON THE SOLAR
C          CELLS, C.  IT IS A FUNCTION OF:
C              1) INSOLATION
C                 A) NORMAL ON HORIZONTAL SURFACE
C                 B) TOTAL ON HORIZONTAL SURFACE (NORMAL+
C                    DIFFUSE)
C              2) SUN POSITION - AZIMUTH & ELEVATION
C                 A) DECLINATION ANGLE OF THE SUN (DETERMINED
C                    BY THE DAY OF THE YEAR)
C                 B) HOUR OF DAY
C                 C) LATITUDE OF SYSTEM LOCATION
C              3) ARRAY
C                 A) DIRECTION IT FACES (SOUTH?)
C                 B) TILT ANGLE FROM THE HORIZONTAL
C                 C) TRANSMITTANCE OF THE COVER
C                 D) CONCENTRATION RATIO
C                 E) SIZE
C                 F) FILL FACTOR (AREA OF CELLS/AREA ARRAY)
C
C        OBTAIN HOURLY TEMPERATURE OF SOLAR CELLS, T.  IT IS
C          A FUNCTION OF:
C              1) AMBIENT TEMPERATURE
C              2) WINDSPEED (ONLY COOLING FOR A PASSIVE
C                 SYSTEM)
C              3) SOLAR ENERGY ON ARRAY
```

Figure 11. - Continued.

```
      C             4) NOMINAL SOLAR CELL EFFICIENCY (FOR AMOUNT
      C                OF ENERGY ABSORBED)
      C             5) ARRAY SIZE
      C             6) THERMAL CHARACTERISTICS OF CELLS AND
      C                MOUNTING STRUCTURE
10    10   CALL INSOL
      C
      C        OBTAIN PROFILE OF THE DESIRED LOADS - HOURLY
      C             NOTE: INDIVIDUAL LOAD RESISTANCE MAY BE A
      C                FUNCTION OF VOLTAGE
      C          I. LOAD PRIORITY 1 - REFRIGERATORS
      C             (5 MOTORS @ 1/4 HP, R1 OHMS EACH)
      C             EXTERNAL CONTROLS
      C                1) INDEPENDENT TEMPERATURE REGULATING SYSTEM
      C                2) MANUAL DISCONNECT
      C             HOW MANY MOTORS RUNNING EACH HOUR ASSUMING
      C                POWER IS AVAILABLE?
      C                L1=0,1,2,3,4,5
      C         II. LOAD PRIORITY 2 - WATER PUMP
      C             (1 MOTOR @ 2 HP, R2 OHMS)
      C             EXTERNAL CONTROL
      C                1) MANUAL DISCONNECT
      C             SIMULATED CONTROL - AUTOMATIC
      C                2) WATER LEVEL IN STORAGE TANK
      C             IS THE PUMP MOTOR CONNECTED (L2=1) OR
      C                DISCONNECTED (L2=0) FOR THE HOUR?
      C        III. LOAD PRIORITY 3 - LIGHTS
      C             (53 @ 20 W, R3 OHMS EACH)
      C             EXTERNAL CONTROL
      C                1) MANUAL ON/OFF SWITCHING
      C             HOW MANY LIGHTS SWITCHED ON FOR THE HOUR?
      C                0<=L3<=53
      C         IV. LOAD PRIORITY 4 - CLOTHES WASHER
      C             (1 MOTOR @ 1/4 HP, R41 OHMS)
      C             EXTERNAL CONTROL
      C                1) MANUAL ON/OFF SWITCHING
      C                2) CUMULATIVE TIMER - 12 HRS/DAY
      C             IS THE WASHING MACHINE IN USE (L41=1) OR NOT
      C                IN USE (L41=0) FOR THE HOUR?
      C          V. LOAD PRIORITY 4 - SEWING MACHINE
      C             (1 MOTOR @ 1/8 HP, R42 OHMS)
      C             EXTERNAL CONTROL
      C                1) MANUAL ON/OFF SWITCHING
      C             IS THE SEWING MACHINE IN USE (L42=1) OR NOT
      C                IN USE (L42=0) FOR THE HOUR?
11    20   CALL DLOAD
      C
      C
      C  THIRTY MINUTE LOOP
      C        LOAD MANAGEMENT BASED ON THE BATTERY STATE OF
      C        CHARGE TO PREVENT EXCESSIVE DISCHARGE AND POSSIBLE
      C        DAMAGE TO THE BATTERY
      C
      C
```

Figure 11. - Continued.

```
C                  LP = LOAD PRIORITY
C                     = 0 FOR DISCONNECTED
C                     = 1 FOR CONNECTED
C                  SOC = BATTERY STATE OF CHARGE
C
C                  RANGE                   CONNECTED       DISCONNECTED
C                  ==============================================================
C                  0.5 < SOC               ALL             NONE
C                  0.4 < SOC <= 0.5        LP3,LP2,LP1     LP4
C                  0.3 < SOC <= 0.4        LP2,LP1         LP4,LP3
C                  0.2 < SOC <= 0.3        LP1             LP4,LP3,LP2
C                  0.0 < SOC <= 0.2        NONE            ALL
   90 IF (NACTUA .NE. NARRAY) GOTO 190
  100 IF (SOC(M+1).GT.0.5) GOTO 190
  110 LP4=0
  120 IF (SOC(M+1).GT.0.4) GOTO 200
  130 LP3=0
  140 IF (SOC(M+1).GT.0.3) GOTO 210
  150 LP2=0
  160 IF (SOC(M+1).GT.0.2) GOTO 220
  170 LP1=0
  180 GOTO 230
  190 LP4=1
  200 LP3=1
  210 LP2=1
  220 LP1=1
  230 CONTINUE
C
C
C  ONE MINUTE INTERVAL
C            WATER PUMP CONTROLS
C                  IA = ARRAY CURRENT (AMPS)
C                  IACONS = MINIMUM ARRAY CURRENT (AMPS) - SEE
C                     CASE 282 BELOW
C                  NACTUA = NUMBER OF ARRAY STRINGS PRESENTLY
C                     CONNECTED
C                  NARRAY = TOTAL NUMBER OF ARRAY STRINGS IN
C                     THE SYSTEM
C                  SOC = BATTERY STATE OF CHARGE
C                  SW1 = 0.0 WHEN WATER LEVEL ABOVE HIGH LIMIT
C                  SW1 = 1.0 WHEN WATER LEVEL BELOW HIGH LIMIT
C                  SW2 = 0.0 WHEN WATER LEVEL ABOVE MIDDLE LIMIT
C                  SW2 = 1.0 WHEN WATER LEVEL BELOW MIDDLE LIMIT
C                  SW3 = 0.0 WHEN WATER LEVEL ABOVE LOW LIMIT
C                  SW3 = 1.0 WHEN WATER LEVEL BELOW LOW LIMIT
C                     (EMERGENCY)
C                  WP = 0.0 WHEN WATER PUMP STOPPED BY THIS
C                     CONTROL
C                  WP = 1.0 WHEN WATER PUMP STARTED BY THIS
C                     CONTROL
C           OBTAIN WATER LEVEL FOR THE MINUTE
  300 CALL WATERL
  305 IF (WP.NE.1.0) GOTO 325
C
```

Figure 11. - Continued.

```
      C                CASE 1. /WP=1.0/ PUMP PRESENTLY RUNNING
      C                   KEEP IT RUNNING IF BELOW THE HIGH LIMIT
        310  IF (SW1 .EQ. 1.0) GOTO 370
      C                   STOP IT IF ABOVE THE HIGH LIMIT
        315  WP=0.0
        320  GOTO 370
      C
      C                CASE 2. /WP=0.0/ PUMP NOT PRESENTLY RUNNING
      C                CASE 2A. TEST FOR EMERGENCY USE
      C                   IF BELOW THE LOW LIMIT, START PUMP
        325  IF (SW3 .EQ. 1.0) GOTO 360
      C
      C                CASE 2B. TEST TO SEE IF TANK NEEDS FILLING
      C                   IF ABOVE THE MIDDLE LIMIT, DO NOT START PUMP
        330  IF (SW2 .EQ. 0.0) GOTO 370
      C
      C                CASE 2B1. TEST TO SEE IF ARRAYS ARE CAPABLE OF
      C                   SUPPLYING SUFFICIENT POWER
      C
      C                   IF SO, START THE PUMP
        335  IF (NACTUA .NE. NARRAY) GOTO 360
      C
      C                CASE 2B2. BATTERY NOT FULLY CHARGED
      C                   TEST TO SEE IF THE ARRAYS ARE SUPPLYING
      C                   SIGNIFICANT CURRENT TO THE SYSTEM
      C                   IF NOT, DO NOT START THE PUMP
        340  IF (IA .LE. IACONS) GOTO 370
      C                (START THE PUMP)
        360  WP=1.0
      C
        370  CONTINUE
      C
      C
      C  ONE SECOND INTERVAL
      C        OBTAIN SYSTEM VOLTAGE (VS) AND CURRENT (IA)
      C                FUNCTION OF:
      C                   1) SOLAR CELL CHARACTERISTICS
      C                   2) NUMBER OF ARRAY STRINGS CONNECTED
      C                      (NACTUA)
      C                   3) SOLAR ENERGY ON THE ARRAY CELLS
      C                   4) TEMPERATURE OF THE CELLS
      C                   5) LOAD LINE CURVE
      C                   6) BATTERY CHARACTERISTICS
      C                M = MINUTE PARAMETER
      C                NACTUA = NUMBER OF ARRAY STRINGS PRESENTLY
      C                   CONNECTED
      C                NARRAY = TOTAL NUMBER OF ARRAY STRINGS IN THE
      C                   SYSTEM
      C                NDELAY = NUMBER OF CONSECUTIVE DELAY PERIODS
      C                   BEFORE ARRAY STRING SWITCHING
      C                NHIGH = CONSECUTIVE EVENT COUNTER FOR SYSTEM
      C                   VOLTAGE TOO HIGH
      C
```

Figure 11. - Continued.

```
      C                   NLOW = CONSECUTIVE EVENT COUNTER FOR SYSTEM
      C                      VOLTAGE TOO LOW
      C                   S = SECONDS PARAMETER
      C                   VSMAX = MAXIMUM DESIRED SYSTEM VOLTAGE (VOLTS)
      C                   VSMIN = MINIMUM DESIRED SYSTEM VOLTAGE (VOLTS)
      C                   VSSUM = SUM OF SYSTEM VOLTAGES (EVERY SECOND)
      C                      FOR THE PRESENT THIRTY MINUTE INTERVAL
        500  CALL VSIA
      C
      C              VOLTAGE REGULATION BY ARRAY STRING SWITCHING
        510  IF (VS .LT. VSMIN) GOTO 560
        520  IF (VS .GT. VSMAX) GOTO 630
      C
      C                   VOLTAGE IN RANGE
        530  NLOW=0
        540  NHIGH=0
        550  GOTO 690
      C
      C                   VOLTAGE TOO LOW
      C                   (AFTER A TIME DELAY, IF THE VOLTAGE STILL IS
      C                   TOO LOW, THEN CONNECT ANOTHER ARRAY STRING
      C                   IF POSSIBLE)
        560  NLOW=NLOW+1
        570  NHIGH=0
        580  IF (NLOW .NE. NDELAY) GOTO 690
        590  IF (NACTUA .NE. NARRAY) NACTUA=NACTUA+1
        600  NLOW=0
        610  GOTO 690
      C
      C                   VOLTAGE TOO HIGH
      C                   (AFTER A TIME DELAY, IF THE VOLTAGE STILL IS
      C                   TOO HIGH, THEN DISCONNECT ANOTHER ARRAY STRING
      C                   IF POSSIBLE)
        630  NHIGH=NHIGH+1
        640  NLOW=0
        650  IF (NHIGH .NE. NDELAY) GOTO 690
        660  IF (NACTUA .NE. 0) NACTUA=NACTUA-1
        670  NHIGH=0
      C
      C                   SUM UP VOLTAGES FOR THE INTERVAL
        690  VSSUM=VSSUM+VS
      C
      C
      C  TIME UPDATE  LINE 300/MINUTE LOOP/, LINE 500/SECONDS
      C  LOOP/, LINE 750/TEN MINUTE LOOP/
        700  S=S+1.0
        710  IF (S .NE. 60.) GOTO 500
        715  S=0.0
        720  M=M+1
        730  IF (M .NE. 10*(M/10)) GOTO 300
        740  CONTINUE
      C
      C
      C
```

Figure 11. - Continued.

```
C  TEN MINUTE INTERVAL
C        WATCH DOG SYSTEM (OVER/UNDER VOLTAGE PROTECTION)
C              OUTPUT = OUTPUT RESULTS SUBROUTINE
C              VS = SYSTEM VOLTAGE (VOLTS)
C              VSAMAX = MAXIMUM ALLOWABLE SYSTEM VOLTAGE
C                 (VOLTS)
C              VSAMIN = MINIMUM ALLOWABLE SYSTEM VOLTAGE
C                 (VOLTS)
C              WDS1 = WATCH DOG SYSTEM LOAD DISCONNECT
C                   = 1.0 FOR LOADS CONNECTED
C                   = 0.0 FOR LOADS DISCONNECTED
C              WDS2 = WATCH DOG SYSTEM ARRAY DISCONNECT
C                   = 1.0 FOR ARRAY STRINGS CONNECTED
C                   = 0.0 FOR ARRAY STRINGS DISCONNECTED
  750 IF (VS .GE. VSAMIN) GOTO 790
C
C              VS BELOW ALLOWED MINIMUM, DISCONNECT ALL LOADS
C                 AND SOUND ALARM
  760 WDS1=0.0
  770 CALL OUTPUT
  780 GOTO 2000
  790 IF (VS .LE. VSAMAX) GOTO 830
C
C              VS ABOVE ALLOWED MAXIMUM, DISCONNECT ALL
C                 ARRAY STRINGS AND SOUND ALARM
  800 WDS2=0.0
  810 CALL OUTPUT
  820 GOTO 2000
  830 CONTINUE
C
C              VS WITHIN ALLOWED LIMITS
C
C
C  TIME UPDATE  LINE 300/MINUTE LOOP/, LINE 900/THIRTY
C  MINUTE LOOP/, LINE 950/HOURLY LOOP/
  850 IF (M .EQ. 60) GOTO 950
  860 IF (M .EQ. 30*(M/30)) GOTO 900
  870 GOTO 300
C
C
C  RETURN TO THIRTY MINUTE LOOP
C        UPDATE THE BATTERY - DONE EVERY 30 MINUTES
C        CALCULATE:
C              SOC = STATE OF CHARGE
C              VBAT = OPEN CIRCUIT BATTERY VOLTAGE (VOLTS)
C              RBAT = INTERNAL RESISTANCE OF THE BATTERY
C                 (OHMS)
C        AS A FUNCTION OF PAST SOC, VBAT, AND
C              VSSUM = SUM OF THE SYSTEM VOLTAGES (EVERY
C                    SECOND) FOR THE LAST THIRTY MINUTES
C              VSAVG = AVERAGE SYSTEM VOLTAGE FOR THE LAST
C                    THIRTY MINUTES
  900 VSAVG=VSSUM/1800.0
  910 VSSUM=0.0
```

Figure 11. - Continued.

```
  920  CALL BATTRY
  930  GOTO 100
C
C
C  RETURN TO HOURLY LOOP
C          UPDATE THE BATTERY AND HOUR, OUTPUT THE RESULTS,
C          GO TO THE BEGINNING FOR NEW INSOLATION AND LOAD
C          DATA
  950  VSAVG=VSSUM/1800.0
  960  VSSUM=0.0
  970  CALL BATTRY
  980  CALL OUTPUT
  985  M=0
  990  H=H+1.0
  1000 IF (H .NE. 24.0) GOTO 1030
  1010 D=D+1.0
  1020 H=0.0
  1030 CONTINUE
  1040 GOTO 10
  2000 RETURN
       END
```

Figure 11. - Concluded.

DAY = 185.

HOUR	DESIRED LOADS					LOAD MANAGEMENT				WATER PUMP				WATCH DOG		SYSTEM STATE				
	L1	L2	L3	L41	L42	LP1	LP2	LP3	LP4	SW1	SW2	SW3	WP	WDS1	WDS2	NACTUA	VSAVG	IA	SOC	VBAT
0.	1	1	3	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	115.5	0.0	0.931	115.2
1.	0	1	3	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	114.9	0.0	0.872	114.5
2.	1	1	3	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	113.9	0.0	0.872	113.8
3.	0	1	3	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	113.5	0.0	0.872	113.8
4.	1	1	3	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	113.2	0.0	0.871	113.8
5.	0	1	3	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	113.5	0.0	0.871	113.8
6.	2	1	10	0	0	1	1	1	1	1.	1.	0.	0.	1.	1.	24	112.6	0.0	0.869	113.7
7.	2	1	15	0	0	1	1	1	1	1.	1.	1.	1.	1.	1.	24	110.2	3.4	0.861	113.7
8.	2	1	8	1	0	1	1	1	1	0.	0.	0.	0.	1.	1.	24	117.2	24.9	0.869	127.9
9.	1	1	8	1	1	1	1	1	1	1.	0.	0.	0.	1.	1.	18	129.7	28.4	0.876	128.0
10.	1	1	8	1	1	1	1	1	1	1.	1.	0.	1.	1.	1.	18	129.4	38.0	0.881	128.1
11.	1	1	8	1	1	1	1	1	1	1.	1.	0.	1.	1.	1.	18	129.4	38.0	0.886	128.2
12.	4	1	8	1	0	1	1	1	1	1.	1.	0.	1.	1.	1.	18	128.8	37.1	0.888	128.2
13.	3	1	8	1	0	1	1	1	1	1.	1.	0.	1.	1.	1.	18	128.8	30.5	0.890	128.3
14.	1	1	8	1	1	1	1	1	1	0.	0.	0.	0.	1.	1.	18	129.4	18.3	0.894	128.3
15.	1	1	8	1	1	1	1	1	1	1.	1.	0.	1.	1.	1.	18	126.4	5.4	0.886	114.0
16.	1	1	8	1	1	1	1	1	1	0.	0.	0.	0.	1.	1.	24	113.3	3.4	0.885	113.9
17.	2	1	12	1	0	1	1	1	1	1.	1.	0.	1.	1.	1.	24	109.5	0.0	0.875	113.9
18.	3	1	20	1	0	1	1	1	1	1.	1.	1.	1.	1.	1.	24	108.9	0.0	0.865	113.8
19.	4	1	20	1	0	1	1	1	1	1.	1.	1.	1.	1.	1.	24	108.5	0.0	0.855	113.7
20.	2	1	40	0	0	1	1	1	1	0.	0.	0.	0.	1.	1.	24	111.2	0.0	0.850	113.6
21.	1	1	40	0	0	1	1	1	1	1.	0.	0.	0.	1.	1.	24	111.4	0.0	0.846	113.5
22.	1	1	30	0	0	1	1	1	1	1.	1.	0.	0.	1.	1.	24	111.8	0.0	0.843	113.5
23.	1	1	10	0	0	1	1	1	1	1.	1.	0.	0.	1.	1.	24	112.6	0.0	0.841	113.4

Figure 12. - Computer program sample output.

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16. Abstract

The NASA Lewis Research Center is managing the Stand-Alone Application Project for the Department of Energy (DOE). Under this project, Lewis installed, in 1978, a photovoltaic power system in an Arizona Indian village. Under a DOE funded grant from Lewis, the Energy Research Center of the Cleveland State University performed an analysis of the control subsystem of this photovoltaic power system. The four major functions of the control subsystem are voltage regulation, load management, water pump control, and system protection. This report analyzes the control subsystem functions, presents flowcharts for the control subsystem operation, and presents a computer program that models the control subsystem.

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