SOLAR PHOTOVOLTAIC POWER FOR WATER DESALINATION

by

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INTRODUCTION

There is a considerable global need for systems which can meet the drinking water requirements of small communities (2,000 people or less) from brackish water or from seawater. Because of the abundance of sunshine in most of these places, the use of solar energy for the production of potable water makes eminently good sense. Solar photovoltaic panels are an ideal source of power for the purpose, primarily because they produce electricity, which can be used to power a membrane-type desalting unit, i.e., either a reverse-osmosis plant or an electrodialysis unit. In addition, electricity is most convenient for feedwater pumping. This paper addresses considerations which arise in the design and construction of a complete solar powered water desalination system which requires no supply of fuel nor any form of backup power (grid connection or engine generator).

GENERAL SYSTEM ARRANGEMENT

Fig. 1 shows the electrical arrangement and Fig. 2 shows the fluid-flow arrangement for a representative system. A photovoltaic array charges a lead-acid battery bank directly via a diode, and the electrical load draws power directly from the battery whenever the control unit turns the load on. The load is made up of a desalination unit and a feedwater pump. The desalination unit can be either a reverse-osmosis unit or an electrodialysis unit. In either case the incorporation of direct current electric motors ensures that the desal unit is a DC load. The feedwater pump can be a DC unit also, provided that the head through which the feedwater must be lifted is not too great, (50m or less), as in the case of a seawater or a river water application. For deep well applications, an inverter will most probably be required to provide the power for an AC submersible pump. In a typical seawater desalting application, the photovoltaic array might have a peak power output of 10kW, the desalination unit would draw 2.8kW, and the feedwater pump would draw 0.5kW. The product water output rate would be a few hundred liters per hour. For a brackish water application, the desalination unit power requirement would be somewhat less for a given output rate, and the feedwater pump requirement would be greater for a deep well. The battery voltage is 240V (nominal).

CONTROL SCHEME

The design of a system of this type is based on the fact that the electrical load is interruptible because the product is stored. The function of the storage batteries in this system is to provide an energy buffer between the array and load on an hourly basis.

Since this system is intended for remote applications, it is a stand-alone system, i.e., it has no connection with utility power lines or back-up engine generators. Accordingly, the control unit is designed to carry out the necessary battery charge management both on a daily and a weekly basis, using energy from the array only. It does this by controlling the proportion of each 24-hour day for which the load is operating. Because the product is water, which is stored, long-term energy storage is not required in a system of this type. The energy storage capacity (50kWh in this example) is chosen on the basis of a 24-hour cycle, no output being obtained on completely sunless days.

The control unit senses the battery state-of-charge by measurement of its terminal voltage, and delivers an appropriate on/off signal to the load. No voltage regulators are required in this system, because the load can tolerate variation in its supply voltage. Thus, from a power conditioning viewpoint, this system has the virtues of simplicity.

The control unit uses as inputs measures of the battery voltage and current, and its output is the single on/off signal for the load. It employs discrete electronic components and integrated circuits, avoiding the complexity of micro-processor circuitry. It is comprised of three parts: a Daily Charge Controller, a Restoration Mode Controller, and a Dump Load Controller together with the Dump Load itself. The Daily Charge Controller performs the function of turning the load on and off each day. The Restoration Mode Controller performs the function of ensuring that at least every 8 days the battery is returned to full charge and given an equalizing charge for two or three hours for the purpose of maximizing battery life. The Dump Load Controller ensures that the battery charging current is kept to an acceptably low level when the battery is close to full charge, by diverting some of the array output into a variable resistive dump load. This is required at times of restoration.

LEAD-ACID BATTERY

The deep-discharge daily-cycle batteries in this system are the type normally used in electric vehicle applications, especially fork lifts and mine trucks. In service these batteries are usually discharged during an 8-hour working day, then during the following night are given a complete recharge including an equalization overcharge to ensure that all cells are in the same condition. The depth of discharge is intended to be 80%, although complete (100%) discharges are frequent in practice. In this mode of service the battery life is close to 2000 cycles.

In a photovoltaic power supply such as this, the day-to-day variability of the power source means that inclusion of a daily equalization overcharge in an efficient manner is not possible for a single-battery system. although it could be included in the split-battery scheme discussed below. Furthermore, an equalization overcharge is not required every day. Once every ten days is often enough to ensure a 2000-cycle battery life. Therefore, our control system includes the Restoration Mode Controller referred to above.

CHARGE DETERMINATION

To determine the state of charge of the battery for control purposes, the simple technique of measuring terminal voltage was chosen because, in this application, it is most accurate. Basically, we need to determine only two points in the charge-discharge cycle: the top and the bottom. Voltage sensing is most accurate for both of these. The bottom charge level is to be about 20%, this figure being recommended by the battery manufacturer. For our system it is almost always the case that the state of charge approaches 20% when the array output power is zero and therefore the net load on the battery is constant. Under these conditions a terminal voltage measurement is an accurate means of determining that a given state of charge has been reached, because the terminal voltage begins to fall quickly at low states of charge. This latter fact is used in defining the capacity of a battery, its ampere-hour rating being the number of ampere-hours which can be withdrawn before the terminal voltage falls to 1.70 volts per cell (at 25^{o}C). Voltage sensing is completely accurate as an indication that full charge has been reached, because at this point all input energy goes to electrolyte water, and there is a consequent dramatic rise in the terminal voltage from 2.4 to about 2.6 volts per cell. Our Restoration Mode Controller takes 2.5 volts per cell (300 V for the battery) as its indication that full charge has been reached.

In addition to the 230 volt load turn-off point and the 300V full-charge point, our control system uses 248 volts as a load turn-on threshold, and 284 volts as a threshold for battery charge current limiting. These latter two points are non-critical in that they do not and need not correspond to any one state of charge. The 248 volt point is reached if the state of charge is 30% and the net battery charge rate is 4kW. It would also be reached, for instance, at a state of charge of 25% and a charge rate of 5kW. Such a scheme is attractive because we want the load to be turned on either by a bright sky or a sufficiently high state of charge.

As our computer simulations have demonstrated, there will be some rare occasions when the battery charge level falls below 20%. This happens when the array has an output between 0 and 3.3kW at a time when the battery charge is just above 20%. Because the next load on the battery is then less than 3.3kW, the 230V point will not be reached until the battery charge has fallen somewhere below 20%. Typically this could happen if there are two consecutive days of low solar intensity, in which the load does not turn on until some time in the morning of the second day. Because this event is rare and is in no way harmful to the battery, its occasional occurrence is of no concern.

SPLIT BATTERY SCHEME

With a single-battery scheme, the need to enter the Restoration Mode every eight days necessarily results in the loss of some photovoltaic output which otherwise might have been put to good use. Our computer simulations have shown that less than 2% of the energy produced by the array is dissipated in the Dump Load, but this figure is misleading in that, during restoration the array is "choked off" by a temporarily elevated battery terminal voltage causing it to work at a point far from peak power. The energy lost in this way depends directly on the length of the equalization overcharge, which is arbitrarily set at 2 hours. The energy loss in restoration is effectively between 4 and 5%. The situation is analogous to that which would arise if one were collecting rainwater from a rooftop into a tank which has the requirement that every eight days it has to be filled to its brim and allowed to overflow for an hour or two. (Perhaps the tank is made from clay bricks which would crumble if allowed to dry out). At those times when the tank was full, there would be no capacity for the capture of rainfall. To remedy this problem, one would consider installing a second tank, alternately filling one then the other. For our photovoltaic system a split-battery scheme must be given serious consideration. The load would be connected to either battery at any one time, but never both together, because their states of charge would always be different. The photovoltaic array would need to be divided into a number of series strings, each of which could be switched from one battery to the other so that the proportion of array power being fed to each battery could be controlled. Thus as one of the batteries approached full charge, only the necessary amount of array would be used to complete that charge, while the larger part of the array would be beginning a charge cycle on the other battery. No dump load would be required in such a scheme, and the array and load switches would replace the dump load switches of our present design. If the two batteries were each the size of our present battery (50kWh), all of the above-mentioned 4-5% energy loss of the single battery scheme would be regained; however, the extra battery capacity would increase the total system cost by at least 5% if the array cost was not more than about $5 per watt if each of the two batteries was half the size of our proposed system, but now the internal I^2R losses of each battery would be larger, so that the 4-5% gain would be negated by a 3-4% reduction in the efficiency of each battery. The advantages of a single larger battery are that its I^2R losses are smaller in a given application, and that it stabilizes the buss voltage more.

In considering methods for regaining the energy lost during equalization, we should keep in mind that by carrying out equalization every eight days, we have already reduced the equalization charge losses to one-eighth of what they would be if complete recharging was done on a daily basis, as for electric fork lifts in regular service.

TEMPERATURE STABILIZATION

In any photovoltaic application involving lead-acid batteries, the question of maintaining an adequate battery temperature must be given careful consideration: care must be taken to ensure that the battery electrolyte is never allowed to freeze. In those photovoltaic applications where long-term storage is provided, this is done by installing a battery with sufficient capacity to ensure that at its minimum state of charge its specific gravity is high enough to prevent freezing in the lowest expected temperatures. In application such as ours where deep-discharge batteries are used, this technique would require an excessively large battery and be very uneconomical. A means for maintaining the battery temperature above a certain minimum level must therefore be employed. A practical solution to this problem is to house the batteries in a semi-underground enclosure, using the well-known fact that, in all climates, the temperature of the ground a few feet below the surface is virtually constant throughout the year. This has the further benefit of preventing the battery temperature from rising too high in the summer, thereby shortening battery life. Adequate venting is provided to prevent hydrogen build-up and hydrogen detection equipment included as an extra safety precaution.

SYSTEM SIMULATION

In order to have a sound basis upon which to choose the system design parameters, especially the battery capacity, the array size, and the array open circuit voltage, a mathematical model of the system was developed and operation of the system was simulated for a period of one year. This computer simulation utilized a SOLMET weather data tape for Albuquerque, NM, and incorporated sub-routines to separately model (i) the sky, (ii) the Mobil Tyco EFG ribbon solar cell photovoltaic array, (iii) the load, (iv) the lead-acid battery bank, and (v) the control unit. Each of these sub-routines was developed at Mobil Tyco. For a system having a 10kW array, a 50kWh battery, and a 5.5kW load, the simulation shows that the daily average energy generated by the array is 67kWh, i.e., 6.7kWh per kW of rated array power. (Photovoltaic arrays are rated under conditions of $100mW/cm^2$ insolation, which corresponds to maximum sunlight). Of this 67kWh, 1.7% is dumped, 6.6% is lost in the battery, and the remaining 91.7% (= 6.1kWh per kW of rated array power), is delivered to the load.

The average turn-around energy efficiency for the battery is 88.8%, while the overall system efficiency (energy supplied to load/energy generated by array) is 91.7%. These two figures, together with the 1.7% dumped, can be used to infer that, effectively, 40% of the energy supplied to the load by-passes the battery.

If the figure of 88.8% for the battery efficiency appears high, note that (i) Our measurements on batteries of this type have shown that the turn-around energy efficiency in a 24-hour deep-discharge cycle, including an equalization overcharge, is close to 85%; (ii) An equalization overcharge is given only once every eight days in our system.

Annual average operating time is for 19.1 hours per day, i.e., 80% of the time. We conclude that for a system of this type in a location with as much sunshine as Albuquerque, NM, actual average load power to rated array peak power should be 25% or better.

PROTOTYPE SYSTEM INSTALLATION

A prototype system of this type for seawater desalting has been designed by Mobil Tyco Solar Energy Corporation and is currently being installed near Jeddah, Saudi Arabia, on an inlet of the Red Sea. The power source is an 8kW (peak) array of Mobil Tyco ribbon photovoltaic panels. The system produces a quantity of water sufficient to meet the drinking water requirements of a community of 250 people, and also provides the power requirement of a complete digital data-logging system. The main system components are: the 8kW array, an array support structure which also serves as a sunshade for the equipment building, a 240V/45kWh lead-acid battery bank, an electronic control unit, a feedwater pump, filters and pretreatment equipment, a reverse osmosis water desalination unit, and a product water tank. An air conditioning unit and a set of fluorescent lights for the equipment building are also powered by the photovoltaic supply. The 8kW array is made up of 210 ribbon photovoltaic panels, and measures 16m x 6.7m. The salinity of the feed water is 42,000 parts per million while that of the product water is less than 100 parts per million.

REFERENCES

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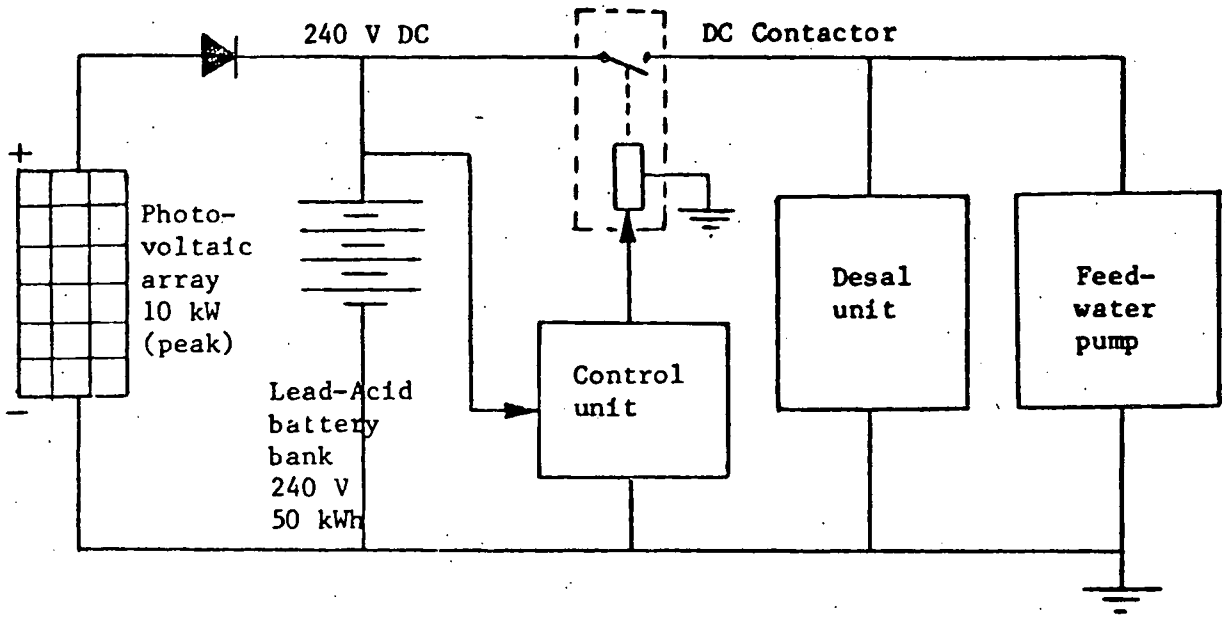

Figure 1

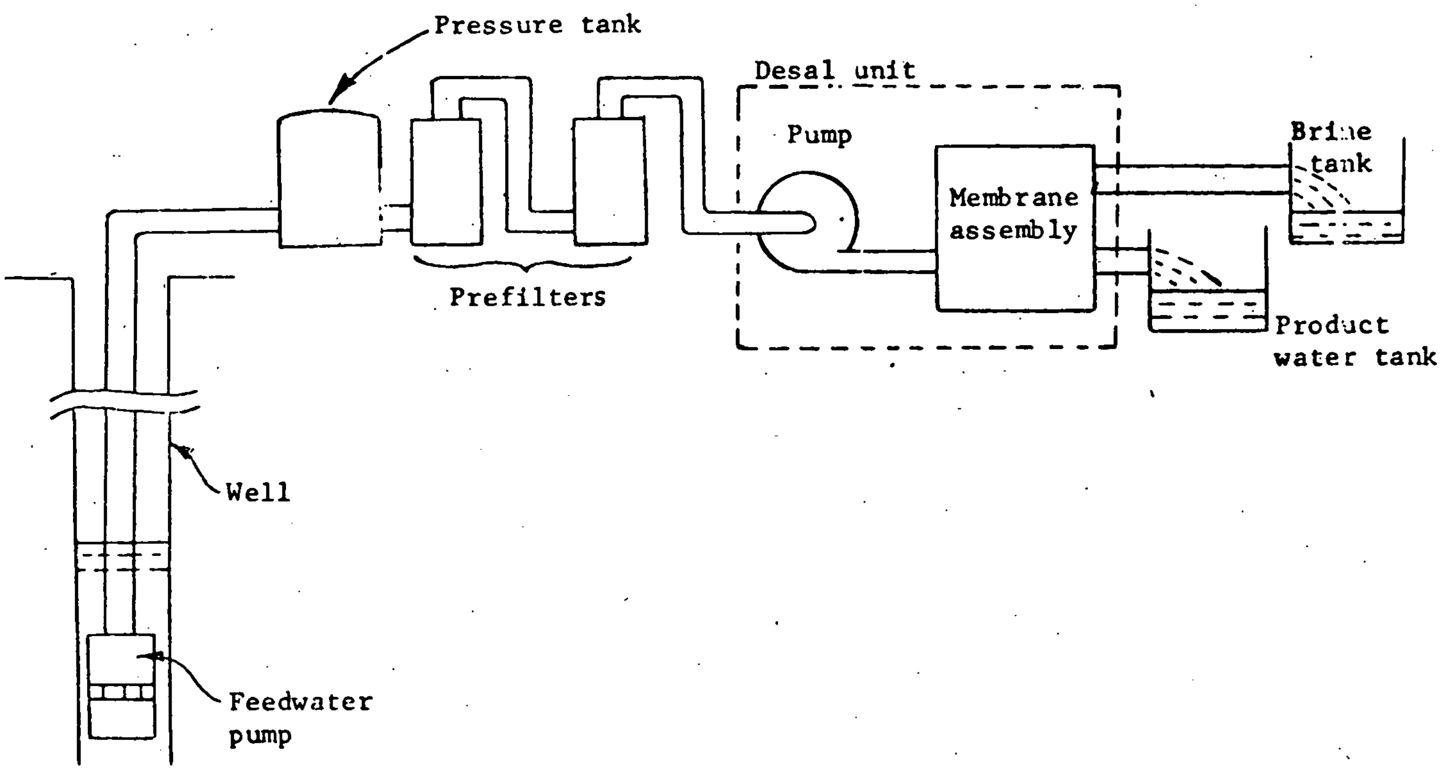

Figure 2