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DESIGN METHODOLOGY FOR PHOTOVOLTAIC PUMPING SYSTEM SUITABLE FOR RURAL APPLICATION IN NIGERIA

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ABSTRACT

Photovoltaic pumping system as an alternative source of potable water to stream water normally consumed by rural dwellers in Nigeria is considered in this paper. A general method for designing simple photovoltaic pumping systems suitable for rural application is developed. The pumping system is based on photovoltaic receiver driving electric pump. Also, information available from PV module and pump-motor manufacturers was used in the design analysis. With this method it is possible to predict the fluid flow rate at any given environmental condition. The problems of lack of potable water in the rural area and the applications of solar pump for village water supply and irrigation are discussed.

Keywords: Photovoltaic, pumping system, PV-array, PV-modules, rural area, solar.

INTRODUCTION

The continuous rise and competitive demands for fossil fuel necessitate the need for alternative source of renewable energy on earth planet. In many parts of the world there is a growing awareness that renewable energy have an important role to play in the provision of social amenities such as potable water and electricity for the rural dwellers. Among the various types of renewable energy, special attention has been given to solar energy because it is freely available. According to Bather and Caruthers (1981), solar energy is the driving force behind several of the renewable forms of energy. Solar energy is an ideal alternative source of energy because it is abundant and inexhaustible (Adu and Bolaji, 2004).

Nigeria like most tropical countries is blessed with large amounts of sunshine all year round. For instance, Nigeria receives about 490 W/m^2 of sunshine per day (Bamiro and Ideriah, 1982). From the research carried out by Fagbenle (1991), a very high insolation as much as 37639 kJ/m^2 in August, was attained in Makurdi, Nigeria. Therefore, positive results are expected from solar energy utilization in Nigeria.

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The use of photovoltaics for water pumping is appropriate as there is often natural relationship between the availability of solar energy and the water requirement. The water requirement increases during hot weather periods when the solar radiation levels are highest and the output of the solar array is at a maximum. Photovoltaic water pumping systems are particularly suitable for water supplies in remote areas where no reliable electricity supply is available.

Water supply through solar pumps is more suitable for drinking purpose than stream water, because this water is pumped from treated boreholes and wells into an overhead tank where it will finally be treated to WHO required standard before circulation. In India, more than 500 solar pumping systems have been installed for village water supplies. The report of research carried out in these villages after the installation of solar pumps, shows drastic reduction in the occurrence of water related health problems such as typhoid, diarrhea, dysentery and cholera (Thomas, 1998).

Three different photovoltaic pumping system configurations are currently in use; the maximum power point tracker (MPPT), the battery buffered system and the direct coupled system. Direct coupled systems are the subject of this paper because they are simple, reliable and the most suitable for rural application (Hsiao and Blevins, 1984).

Many researchers have in recent times investigated and proposed different methods for designing and optimizing the photovoltaic (PV) pumping system, Appelbaum and Bany (1979) analyzed a direct coupled PV pumping system under steady state conditions. Singer and Appelbaum (1993) have examined the starting characteristics of PV powered DC motors and pumps both with and without MPPT. Roger (1979) showed that a DC motor driving a centrifugal pump represents a well-matched load for a PV array because this system utilizes most of the DC power generated by the array. Anis et al. (1985) reported that a load composed at a DC motor driving a constant volume pump represents a non-matched load to a PV array because the motor driving a constant volume pump requires a nearly constant current.

The matching of a DC motor to a PV generator to maximize daily gross mechanical energy is reported by Saied and Jabori (1989). Hsiao and Blevins (1984) analyzed the performance of photovoltaic pumping system by varying the motor characteristics. In their study, hourly radiation data for a year were required, leading to extensive use of computer simulation time. In another study of solar radiation utilization by Loxsom and Durongkaveroj (1994), two straight line segments were used to represent the nonlinear flow rate versus radiation relationship. However, the nonlinear relationship among these design models is complicated, requiring numerical skill to successfully simulate systems over extended time periods. In addition, it is difficult to obtain the necessary input parameters for the motor and pump models based on available data. Therefore, there is need for simplified design model which is suitable for rural application.

The aim of this paper is to develop a general method for designing simple photovoltaic pumping systems. In addition, is to analyze the problems associated with the drinking of polluted water by the rural dwellers in Nigeria, and the possibility of using photovoltaic pumping system to alleviate the problems.

Problems of Lack of Potable Water in the Rural Area

Packaged water, commonly known as pure water was introduced in Nigeria a few years ago as a source of potable water for the teeming population. However, many rural dwellers in the country are farmers who can not afford to buy this so-called pure water. They have stream water as their only alternative source of water for drinking and for other domestic purposes. The results of the research carried out by Oguntoke and Ogunwede (2003), showed that, most stream water in Nigeria are highly polluted. Their analysis of samples of some stream water showed that turbidity, dissolved solids, chloride, iron levels, coliform count and total bacteria count in these stream water are outstandingly higher than the recommended levels for human consumption.

More often, untreated waste disposed into water bodies which serves as natural water supply for communities down stream have negative impact on consumers' health. In addition, improper refuse dumps release leachate that migrates into water sources. Leachate derived from waste dumps has been shown to contain more than 40 organic contaminants and a host of other pollutants including heavy metals. These pollutants besides degrading water resources have toxic effect on human when consumed (Oguntoke and Ogunwede, 2003). For instance, in China, higher mortality rates for stomach and liver cancers have been associated with high level of pollutants in stream water. Other health problems associated with drinking polluted water include diarrhea, cholera, intestinal worm infection and typhoid fever (Esrey et al., 1996).

METHODOLOGY

Design of Photovoltaic Pumping System

The Photovoltaic Cell Model

A photovoltaic (PV) module is a nonlinear power source. The output current and voltage depend on the radiation level and temperature. Whenever the solar radiation or ambient temperature changes, the operating point of the PV module coupled to a pump-motor will change.

To predict the performance of a photovoltaic pumping system, a mathematical solar cell model is needed. The solar cell can be represented by the equivalent circuit shown in Fig. 1. The relationship between current, I and voltage, V, is:

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{A}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where: I_L = light current (A); I_o = dark current (A); I = operation current (A); V = operation voltage (V); R_s = series resistance (W); R_{sh} = shunt resistance (W) and A = thermal voltage (V).

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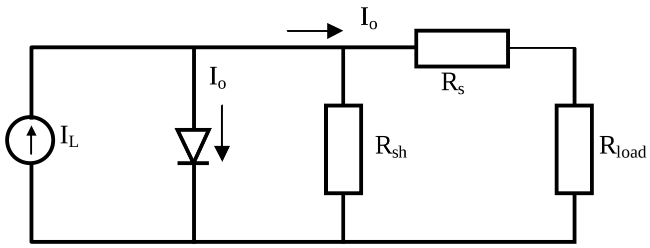

Fig. 1: Equivalent circuit of a solar cell

I_L, I_o, R_s, R_{sh}, and A are five parameters that depend on the incident solar radiation and the cell temperature. The shunt resistance R_{sh} is usually very large compared with the series resistance R_s, particularly for single crystalline silicon cells (Q-Kou et al., 1998), therefore, the term $\frac{V + IR_s}{R_{sh}}$ in Eq. (1) is negligible, which reduced the parameters to four. With this assumption, Eq. (1) can be rewritten as:

$$I = I_L - I_o \left[\exp\left(\frac{V + IR_s}{A} \right) - 1 \right] \qquad (2)$$

A method to calculate these four parameters I_L, I_o, R_s, and A is summarized in Duffie and Beckman (1991), since there are four unknown parameters, four conditions of I and V are needed. However, manufacturers usually provide I and V at only three conditions: short circuit, open circuit and maximum power point. The fourth condition comes from the knowledge of the temperature coefficients at open circuit voltage, m_{Voc} and short-circuit current m_{Isc}. The following equations are used to calculate these parameters of PV cells at a standard condition based on the experimental data provided by the manufacturer (Klein, 1996).

$$I_{L,ref} = I_{sc,ref} \qquad (3)$$

$$I_{o,ref} = \frac{I_{L,ref}}{\exp\left(\frac{V_{oc,ref}}{A_{ref}} \right) - 1} \qquad (4)$$

$$R_{s,ref} = \frac{A_{ref} \ln\left(1 - \frac{I_{mp,ref}}{I_{L,ref}} \right) - V_{mp,ref} + V_{oc,ref}}{I_{mp,ref}} \qquad (5)$$

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$$A_{ref} = \frac{\mu_{Voc} T_{c,ref} - V_{oc,ref} + E_q N_s}{\frac{T_{c,ref}\,\mu_{Isc}}{I_{L,ref}} - 3} \tag{6}$$

The subscripts oc, sc, mp, and ref refer to open circuit short circuit, maximum power and reference conditions respectively, E_q is the band gap of silicon (eV), and N_s is the number of cells in series in one module.

Whenever the solar radiation (G) or the ambient temperature (T_a) changes, the cell parameters change and can be estimated from the following equations. The cell temperature (T_c) is obtained from manufacturer supplied NOCT (Nominal Operating Cell Temperature) conditions (Duffie and Beckman, 1991; Klein, 1996).

$$T_c = T_a + \frac{G_T}{G_{T,NOTC}} \left(T_{c,NOTC} - T_a\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{7}$$

where, t is the cell cover transmittance for solar radiation, a is the cell absorption for the transmitted solar radiation and h_c is the cell efficiency at NOCT conditions.
The cell parameters at the operating cell temperature and solar radiation are then found from:

$$I_L = \left(\frac{G}{G_{ref}}\right)\left[I_{L,ref} + \mu_{Isc}\left(T_c - T_{c,ref}\right)\right] \tag{8}$$

$$I_o = I_{o,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \times \exp\left[\left(\frac{N_s E_q}{A}\right)\left(1 - \frac{T_{c,ref}}{T_c}\right)\right] \tag{9}$$

$$R_s = R_{s,ref} \tag{10}$$

$$A = A_{ref}\left(\frac{T_c}{T_{c,ref}}\right) \tag{11}$$

The cell model is summarized as follows: Eqs. (3) to (6) are used to find values of the four parameters at reference conditions. These four parameters are corrected for environmental conditions with Eqs. (7) to (11) and used in Eq. (2) which relates cell current to cell voltage.

Pump-Motor and Hydraulic System

The DC motor converts the electrical energy into mechanical energy. The pump converts the mechanical energy into hydraulic energy. Therefore the characteristics of motors and pumps can be represented by current, voltages, head and flow rate. The manufacturer normally provides the head-flow-current-voltage data for the pump-motor combination. Instead of using individual motor and pump models, the characteristics of a pump-motor combination are represented by two functions.

One is the current-voltage-head function:

$$V = f_1(I,H) \qquad (12)$$

where, the form of the function is a polynomial in both I and H, which can easily be obtained from linear regression using data supplied by the manufacturer. At any solar radiation, ambient temperature and lead the I-V-H function is used to find the I-V characteristics of the photovoltaic pumping system. I-V relationship of the PV array, Eq. (2) and the I-V relationship of the motor pump for a given head, Eq. (12), are solved simultaneously to find the system operating point.

The other motor-pump characteristic relates the fluid flow to the voltage and head as a polynomial similar to Eq. (12) and is also found by linear regression.

$$Q = f_2(V,H) \qquad (13)$$

This function indirectly relates the flow to environmental conditions because operating voltage depends on the radiation level and temperature. The operating point voltage is used in Eq. (13) to find the fluid flow rate at the specified head. Fig. 2 shows typical data from a manufacturer's catalog and the polynomial curve fits f_1 and f_2 using a 3[rd] order polynomial with cross terms (Klein, 1996).

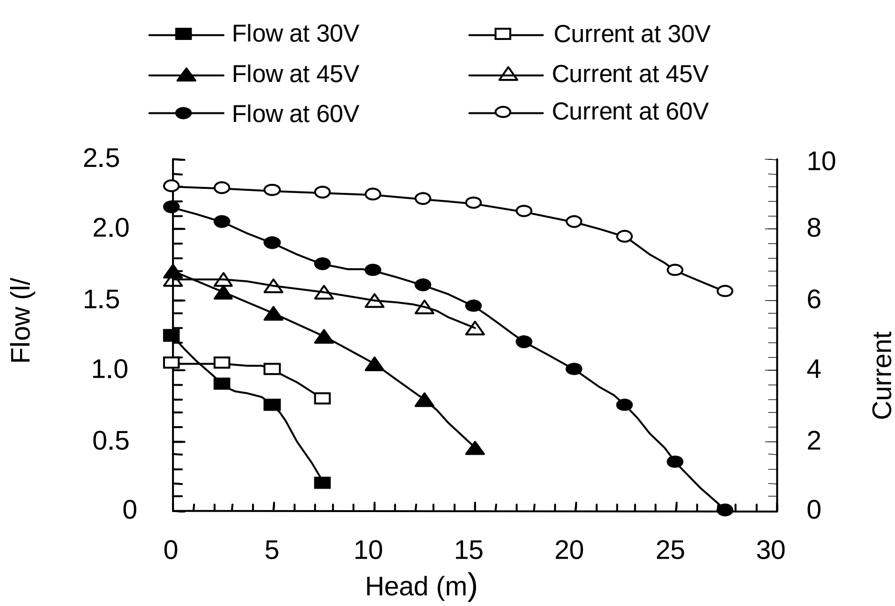

Fig. 2: Flow and current as a function of head and voltage for a typical pump-motor. The curves are based on the data obtained from manufacturer catalog (Klein, 1996).

Since it is possible to predict the fluid flow rate at any given environmental condition using various equations presented above, a procedure that estimates the performance of a photovoltaic pumping system can be developed and components can be selected for an optimal design.

Photovoltaic Array Configuration

Given a pump-motor and PV array, the number of PV modules connected in series and parallel is critical to the successful operation of the system. The objective in optimizing the configuration of a PV array is to maximize the delivered water over a time interval at a given location and known head by changing the number of PV modules that are connected in series (S) and parallel (P) for example, 24 modules there are 8 possible combinations using all 24 modules (i.e., S=24, P=1; S=12, P=2; S=8, P=3 ……. etc) and 8 combinations would normally have to be investigated. Table 1 shows the water flow rate with a fixed module configuration S=8 and P=3 at ten radiation levels and the optimum module configuration system (selected from the 8) for each radiation level and its associated flow rate. The optimal configuration does not change above a radiation level of 500W/m^2. For locations with high radiation it is clear that the optimal configuration for annual water pumped will be S=8 and P=3. For many locations a significant fraction of the monthly pumped water occurs when the radiation on the PV array has a level exceeding 500W/m^2 and S= 8, P=3 will still be the optimal configuration.

Table 1: Flow rate at various module configurations

Radiation (W/ m2)	S=8, P=3 Q (l/s)	Optimum Array Q (l/S)	S, Series	P, Parallel
100	0.000	0.000	-	-
200	0.000	0.014	24	1
300	0.104	0.163	6	4
400	0.243	0.278	6	4
500	0.369	0.369	8	3
600	0.482	0.482	8	3
700	0.582	0.582	8	3
800	0.667	0.667	8	3
900	0.738	0.738	8	3
1000	0.797	0.797	8	3

Source: Klein, 1996.

Photovoltaic Pumping System for Village Water Supply and Irrigation

A photovoltaic (PV) pumping system (Fig. 3) consists of a PV array powering an electrical motor which operates a pump. The water is pumped up through a pipe and into a storage tank. The energy from the PV array is therefore converted into the potential energy of the pumped water. This gets rid of the need for battery storage of the generated electricity, because excess water pumped during the period of high insolation will be stored for the period of low insolation.

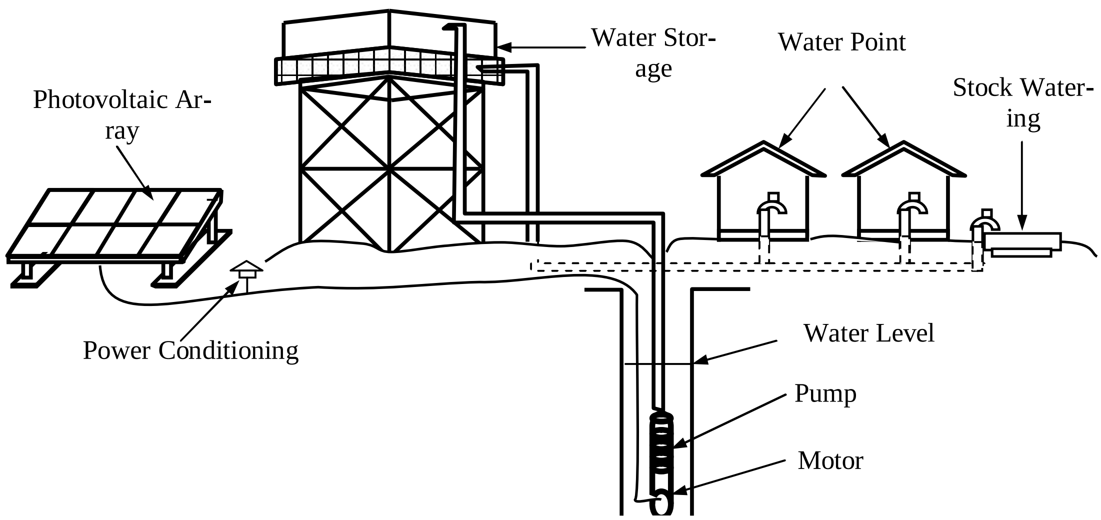

Fig. 3: Solar – powered village water supply

Solar pumps are used principally for two applications: village water supply (including livestock watering) and irrigation. These two applications have very different demand patterns. Villages need a steady supply of water whereas crops have variable water requirements during the year. During rainy seasons (which also coincides with the period of lowest solar radiation), the reduced output of the pump can be offset by capturing the rain water.

A solar pumping system for irrigation is shown in Fig. 4. In this application, the peak demand in Nigeria occurs during the dry seasons, which also coincides with the period of highest solar radiation.

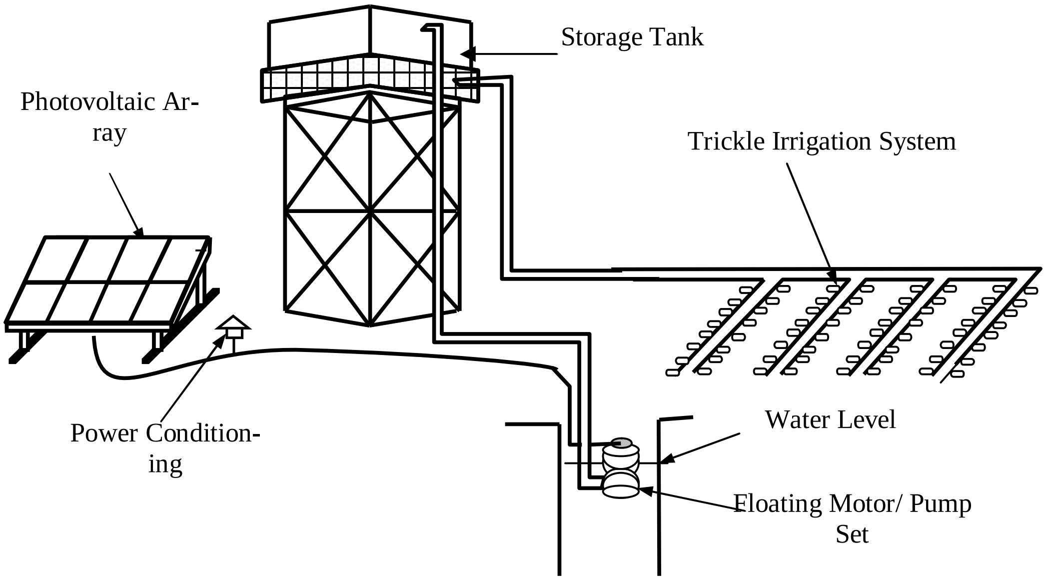

Fig. 4: Solar irrigation pumping system

Types of Solar Pump

(i) *Submerged multistage centrifugal motor-pump sets*: They are probably the most common type of solar pump for village water supply. The advantages of this type are that it is easy to install and the motor-pump set is submerged away from potential damage. The most commonly employed system consists of an a.c. pump and inverter with PV array of less than 1500W, but d.c. motors are also used.

(ii) Reciprocating positive displacement pumps: They are very suitable for high-head, low-flow applications, they are often more efficient than centrifugal pumps.

(iii) *Floating motor-pump sets*: They have a versatility that makes then ideal for irrigation pumping from canals and open wells. The pump set is portable and there is a negligible chance of pump running dry. The solar array sup port often incorporates a “wheel bar row’ type trolley to enable easy transportation

Sizing and Costing of Solar Pumps

Sizing of solar pumps could be determined by the hydraulic energy required (Tomas, 1998):

Hydraulic energy (kWh/day)

= {Volume required (m^3/day) x Head (m) x Water density x Acceleration due to gravity}

Solar array power required (kW)

$$= \frac{Hydraulic\,energy\,required\,(kWh/day)}{Average\,daily\,solar\,irradiation\,(kWh/day) \times F \times E}$$

where: F = the array mismatch factor and E = the daily subsystem efficiency.

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The total cost of a solar-powered pumping system comprises the cost of modules, pump, motor, pipe work, wiring, control system, array support structure and packaging. System with large array sizes generally has a lower cost per power out put.

CONCLUSION

Solar energy could be made to play crucial role in the supply of potable water to the rural areas. Most rural dwellers rely only on the polluted stream water in their villages for drinking and for other domestic purposes. Therefore, they are exposed to various health problems associated with drinking of polluted water. Solar pumping is an important application of photovoltaic, which does not need battery storage.

A general method for designing simple photovoltaic pumping systems suitable for rural application is developed. The method uses information available from PV module and pump-motor manufacturers. Using the equations presented in this paper, it is possible to predict the fluid flow rate at any given environmental condition. The problems of lack of potable water in the rural area and the applications of solar pump for village water supply and irrigation are discussed. Also discussed are different types of solar pumps and their suitability for different uses.

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