Optimal Performance of Mechanical Load Factor for the Solar Photovoltaic Electromechanical System

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Abstract - *In the solar photovoltaic operating system, points for the maximum electrical power, which is determined from the I-V characteristics, differs from the point of maximum mechanical power output, which is also different for motor type and parameter as well as the load torque-speed relationship. The permanent magnet motor coupled with centrifugal pump load is the most suitable for the electromechanically system of the solar photovoltaic system. Perfect matching represents the ultimate objective in terms of getting the maximum utilization of mechanical energy. There are several factors affecting the operating points of their array system. In the torque-speed relation $T=bw^r$, r load factor is varied in steps around the value 2D. When r=2, the operating point matches with P_{max} at 60% insolation levels. For r=2.1, the operating point matches at 100% insolation levels. For different insolation levels to minimize the power drop, the load factors have the different values. In order to evaluate the effect of the load factor in the exponent of the torque-speed relationship is included. The load factor enables to obtain better utilization quality by the study of its effect on the power drop at all insolation levels and helps in selection and design of such photovoltaic system.*

Key Words: Photovoltaic System, Electromechanical Load Coupling, Load Matching.

1. INTRODUCTION

The most feasible applications of photovoltaic system are the utilization of photovoltaic electricity to derive electromechanical loads. The application of a directly coupled photovoltaic (PV) electromechanical system for water pumping has received increasing attention recently because of the expected cost reduction in PV array. More than 2 billion people, mostly in developing countries, live in remote areas without access to grid-connected power. In India, there are four to five million diesel-powered water pump sets, each consuming about 3.5 kW. The requirements of PV modules are around 1000 peak MW, for converting these diesel pump sets into the PV pump system [1]. The directly coupled PV electromechanical system necessitates a complete study from a mechanical load to the PV array, but it leads to a very simple and reliable installation [2]–[8]. The PV array output is a nonlinear and time-dependent power supply that varies with solar intensity and cell temperature, so the performance characteristics of the PV-powered dc motor are different than when powered by constant voltage. The cell temperature effect on the PV array characteristics is not included in many studies [7]–[10]. In a hot climate region, the cell temperature effect on performance of the PV system becomes significant. The proper matching among the components is the main issue in a directly PV-powered electromechanical system. For PV water-pumping application, the selection of a dc motor with appropriate design parameters and pump load is also important [8]–[11]. The operating characteristics of the dc permanent-magnet motor coupled with a centrifugal pump have suitable matching with PV array characteristics [3]–[11]. It operates during most of the daytime and also has low starting torque as compared to the other directly coupled PV electromechanical systems. Fig.1 shows the basic direct coupled photovoltaic power system. In the present paper an application of the load matching formulation to a system driving a mechanical load has been discussed and analyzed.

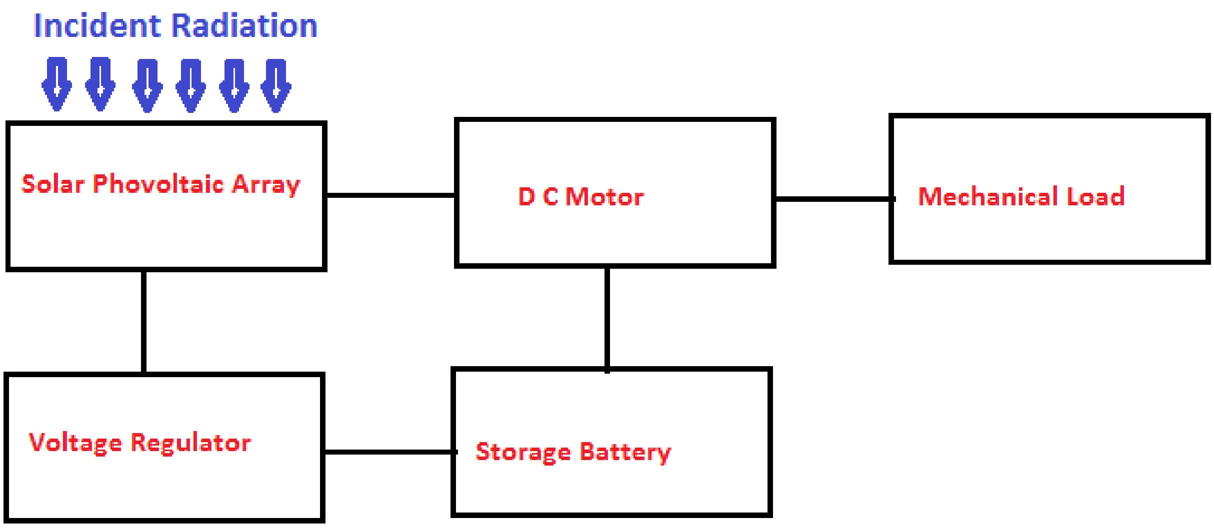

Fig. 1 Basic Direct-Coupled Photovoltaic Power System

2. PHOTOVOLTAIC GENERATOR

The current-voltage (I-V) relation for the photovoltaic generator composed of N series cells and M parallel strings, if neglecting the shunt resistance, is given by:

$$I = MI_{ph} - MI_0\left[Exp\left(\frac{q(MV+NIRS)}{AK_S TMN}\right) - 1\right] \quad (1)$$

Where, I_{ph} to the photocurrent of a cell I_0 to the reverse saturation current, q(c) the electronic change, R_S is the series resistance, KB (J/K) the Boltzmann's constant, A is the ideality factor, T(K) is the cell temperature, I(A) is the array current and r(v) is the array voltage. The effect of the cell temperature on the reverse saturation current I_0 r(2).

$$I_0(T) = I_0(T_r)\left(\frac{T}{T_r}\right)^3 exp.\left[-b\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad (2)$$

and the photocurrent

$$I_{ph}(T) = I_{ph}(T_r)[1 + a(T - T_r)] \quad (3)$$

Where, T_r is the cell reference temperature usually 25^0C.

The array maximum power at a given time can be found by differentiating the power equation with respect to current.

$$ln\left(\frac{M(I_0+I_{ph})-I}{MI_0}\right) - \frac{1}{M(I_0+I_{ph})-I}$$

$$I_{max}\left(\frac{2qR_S}{AMK_BT}\right) = \frac{1}{\frac{1}{M(I_0+I_{ph})-I}} \quad (4)$$

And $V_{max} = NI_{max}R_SM^{-1}I_{max}\ C_1^{-1}[M(I_0 + I_{ph}) - I_{max}]^{-1}$ (5)

The maximum power output is given by, $P_{max} = V_{max}$

The maximum energy which can be extracted from the solar-array throughout a day period is given by

$$E_{max} = 2\int_{t_{sr}}^{t_n} P_{max}(t)dt \quad (6)$$

Where, t_{sr} is the sunrise time and in solar noon time.

3. DC MOTOR EQUATIONS

DC motors are widely used in the direct coupled PV application for their high reliability and ease of connection. The steady state characteristics of the equation are:

$$V_a = E + I_a.Rt \quad (7)$$

Where, I_a is the armature current, Rt is the armature series resistance, E is the developed voltage.

$$E = K.F.W \quad (8)$$

Where, K is a constant, F is the magnetic flux in wb, and W is the speed of the shaft in rad/sec. The torque (N-M) developed by DC motor is given by:

$$T_d = K.F.I_a \quad (9)$$

Permanent Magnet Motor- The flux is constant. The current and voltage are computed as:

$$I_a = \frac{T_d}{KF} \quad (10.1)$$

$$V_a = KFW + \frac{T_d}{KF}\ Ra \quad (10.2)$$

Series Motor- In this motor assumption is that the saturation condition is not reached, the flux is directly proportional to the armature current.

$$F = K_1I_a \quad (11.1)$$

$$I_a = \sqrt{\left(\frac{T}{K.K_1}\right)} \quad (11.2)$$

$$V_a = (K.K_1W + Rt)\sqrt{\left(\frac{T}{K.K_1}\right)} \quad (11.3)$$

Shunt Motor- In this motor the flux is proportional to the applied voltage.

$$F = K_2I_f = K_2\frac{V}{Rt} \quad (12.1)$$

Motor terminal current is

$$I = I_a + I_f \tag{12.2}$$

$$T_d = K.K_2 \frac{V}{R_f} I_a \tag{12.3}$$

$$V_a = \sqrt{\left(\frac{R_a R_t T_d}{1 - \frac{K.K_2 W}{R_t}} \right)} \tag{12.4}$$

4. MECHANICAL LOAD EQUATIONS

The general torque-speed relationship of a mechanical load can be described as:

$$T_L = T_0 + (T_{n1} - T_0)\left(\frac{W}{W_0}\right) X \tag{13}$$

Where, T_0 & W_0 are the rated torque and speed respectively, T_{n1} is the no. of load type and X is the power which depends upon the load type

X=0 for constant torque

X=1 for viscous torque

X=2 for centrifugal load

For simplicity, the torque equation for the centrifugal load is given by:

$$T_d = A + BW^2 \tag{14}$$

Now, the current and voltage can be calculated from the Eqs. (14) and (10) to (12) for different DC motors. In all three cases, the voltage and current can be found independently of the PV modular characteristics. These are only calculated by the load and characteristics for each value of speed. And hence, it is possible to draw an I-V operating curve for the motor pump system. By drawing the operating curves of the motor on the PV module's I-V curves. The motor whose operating curves follows closely. The locus of the module's maximum power points at all irradiance levels provides the best adaptation to the module.

The total daily electrical energy which can be delivered to the motor loads assuming that it is connected to the array during the entire period is then calculated from:

$$E_L = 2 \int_{t_{st}}^{t_n} V(t).I(t)dt \tag{15}$$

The gross mechanical energy developed or given by:

$$E_D = 2 \int_{t_{st}}^{t_n} E(t).I_a(t)dt \tag{16}$$

And the useful daily mechanical energy is given by:

$$E_m 2 \int_{t_{st}}^{t_n} \lfloor A + \langle B\ W(t) \rangle^X \rfloor\ W(t)dt \tag{17}$$

Formulation for the optimization problem- The array possesses a maximum power locus it is most desirable that the operation of the load line close to the maximum power line throughout the day. In order to account for all losses, the matching factor is defined by:

$$u_m = \frac{E_M}{E_{max}} \tag{18}$$

These factors clearly depend upon the load parameters since E_{max} is fixed for the given array, and insolation & temperature profiles. Although the objective is to maximize E_m, the mechanical losses must be the part of gross mechanical power developed by the motor.

The load factor X=2 is varied in steps around the value X=2. When X=2, the operating points matches with P_{max} at 60 % insolation levels. For X=2.1, the operating points matches at 100 % insolation levels. For different insolation levels to minimize the power drop, the load factors have the different values. The load factor enables to obtain better utilization quality by the study of its effect on the power drop at all insulation levels and helps in selection and design of such photovoltaic system.

3. CONCLUSIONS

1. The paper presented a mathematical formulation of the matching of electromechanical loads coupled to a photovoltaic generator as compared to similar results reported in literature under different constraints.
2. The results obtained show that the system composed of a separately excited motor (permanent magnet motor) and centrifugal load is quite compatible to the PV array.
3. The centrifugal load offers better matching performance compared.
4. The permanent magnet motor offers higher matching performance compared to the series motor.
5. An extension of this work is to analyze the matching performance for a system with long term battery storage and more sophisticated load profile.

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