OPTIMUM LOAD MATCHING IN DIRECT-COUPLED PHOTOVOLTAIC POWER SYSTEMS - APPLICATION TO RESISTIVE LOADS

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Keywords: Load matching, Photovoltaic array sizing, Battery capacity, Maximum power tracker, Per-unit system.

ABSTRACT - In this paper the load matching factor [1, 5-7] is used as a measure for the quality of load matching to the photovoltaic (PV) array. An optimization approach is used to solve the load matching problem with the objective of maximizing the load matching factor, and consequently the PV output energy. This approach is then applied to resistive loads (with and without an internal emf) connected to the array.

Results show that optimum matching can be achieved by carefully selecting the array parameters with respect to the load parameters. The temperature of the array has little effect on the optimum matching factor. However, the optimum matching parameters are greatly affected by the array temperature. A maximum power tracker may not be needed if optimum or near optimum matching is achieved. A battery of selected parameters can be included if the load characteristic results in poor matching performance.

1. Introduction

Matching of direct-coupled loads to the PV array has been studied by many researchers [1-10]. In a direct-coupled system the array output power passes directly to the loads (Fig. 1). A battery storage may be employed to supply the loads during short periods of time.

In this paper the load matching factor [1, 5-7], as defined by the ratio of the load energy to the array maximum energy in a one day period, is used as a measure for the quality of load matching. A theoretical analysis leading to a general mathematical formulation of the load matching problem is presented. A non-linear optimization approach is used to solve the load matching problem with the objective of maximizing the matching factor, and consequently the PV output energy. This approach is then applied to general resistive loads (with and without an internal emf). Analyses are carried out to obtain the proper parameters of the battery storage needed to improve the matching factor for poor matched loads.

In order to generalize the results a per unit system based on the array maximum power point parameters at 100% SUN and 25°C is developed. The clear sky insolation model [1, 3] is adopted. The array characteristic data are obtained from the literature [2-4].

90 WM 215-4 EC A Paper recommended and approved by the IEEE Energy Development and Power Generation Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1990 Winter Meeting, Atlanta, Georgia, February 4 - 8, 1990. Manuscript submitted August 30, 1989; made available for printing December 6, 1989.

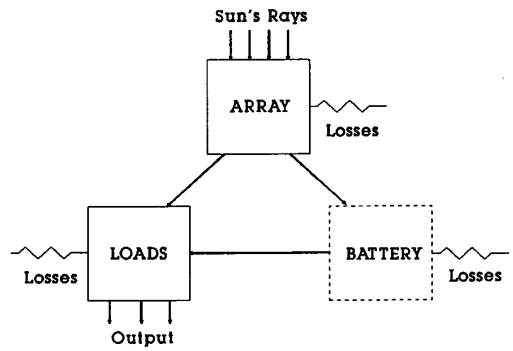

Fig. 1. The basic photovoltaic power system.

2. Array Characteristics

The general I-V equation of a solar array generator composed of N_s series cells (or modules) and N_p parallel strings, neglecting the shunt resistance effect, is expressed by:

$$V = AV_T.\ln[(I_{ph}-I+I_r)/I_r]-I.R_s \tag{1}$$

where:

$I_{ph} = I_1.N_p$, array photo-generated current
$I_r = I_s.N_p$, reverse saturation current
$R_s = R_c.N_s/N_p$, total series resistance
$AV_T = N_s.V_T$, equivalent thermal voltage

where I_1 is the photo-generated current per cell (or module), I_s is the reverse saturation current per cell (or module), R_c is the series resistance per cell (or module), and V_T is the cell (or module) thermal voltage which is equal to AkT/q; where A is the ideality factor, k is Boltzmann's constant (1.38E-23 Joule/°K), T is the absolute temperature, and q is the electron charge (1.6E-19 Coulomb).

Assuming a standard clear sky insolation model [1, 3], and a linear dependence of the light generated current on the solar density (generally valid for up to 20 SUNs), we can calculate I_{ph} by:

$$I_{ph}(w) = I_G.\sin(w) \tag{2}$$

where I_G is the array photo-generated current at solar noon, and w is the solar hour angle. Since a one hour represents a solar angle of 15 degrees, then:

$$t = t_{sr} + (w/15) \tag{3}$$

where t_{sr} is the sunrise time (equal to 6 am solar time). The output power of the array depends on the loading and can be found by multiplying both sides of Eqn.(1) by I:

$$P = I.AV_T.\ln[(I_{ph}-I+I_r)/I_r]-I^2.R_s \tag{4}$$

The array maximum power at a given time can be found by differentiating Eqn.(4) with respect to current and equating to zero. The maximum power point current, I_{mp}, can then be found by solving:

$$I_{ph} = I_{mp}+I_r\{\exp[(2I_{mp}R_s/AV_T)+ +I_{mp}/(I_{ph}-I_{mp}+I_r)]-1\} \quad (5)$$

The maximum power point voltage, V_{mp}, can then be found from Eqn.(1) by replacing I by I_{mp}. The maximum power, P_{mp}, is then given by:

$$P_{mp} = V_{mp}.I_{mp} \quad (6)$$

The input resistance of the array at the maximum power point, R_{mp}, will be defined by:

$$R_{mp} = V_{mp}/I_{mp} \quad (7)$$

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

$$E_{max} = 2\int_{t_{sr}}^{t_n} P_{mp}(t)\ dt \quad (8)$$

where t_{sr} is the sunrise time and t_n is the solar noon time.

The effect of the array temperature on the saturation current, the photocurrent, and the thermal voltage is given by [2]:

$$I_r(T) = I_r(T_o).(T/T_o)^3.\exp[-b(1/T-1/T_o)] \quad (9)$$
$$I_{ph}(T)= I_{ph}(T_o).[1+a(T-T_o)] \quad (10)$$
$$AV_T(T)= AV_T(T_o).T/T_o \quad (11)$$

where T_o is the cell reference temperature (usually 25 °C), and a and b are coefficients that depend on the type of semiconductor material used and the manufacturing process.

3. Load Characteristics

Many direct current loads can be directly connected to the PV array. In general the load I-V equation is given by:

$$V_L = f(I_L, C_1, C_2, \ldots, C_n) \quad (12)$$

where V_L and I_L are the load voltage and current, respectively, and C_i, i=1 to n are load parameters (constants). For some common loads Eqn.(12) is given below.

<u>electrolytic load</u>:

$$V_L = I_L.R_e + V_e \quad (13)$$

where V_e is the induced emf of the load and R_e is the internal resistance.

<u>resistive load</u>:

A pure resistive load is a special case in which the induced voltage is zero; for which Eqn.(13) is given by:

$$V_L = I_L.R_L \quad (14)$$

where R_L (=R_e) is the load resistance.

<u>constant voltage</u>:

$$V_L = \text{Constant} \quad (15)$$

<u>constant current</u>:

$$I_L = \text{Constant} \quad (16)$$

<u>constant power</u>:

$$I_L.V_L = \text{Constant} \quad (17)$$

<u>separately excited motor - viscous friction mechanical load</u> [10]:

$$V_L = I_L.R_a + C^2.I_L/B \quad (18)$$

where R_a is the armature resistance, C is the field constant in V.sec, and B is the mechanical load torque constant in W.sec^2.

<u>separately excited motor - ventilator type (centrifugal) mechanical load</u> [4]:

$$V_L = I_L.R_a + C^{1.5}.(I_L/B)^{.5} \quad (19)$$

where B is the load torque constant in W.sec^3.

<u>series excited motor - viscous friction mechanical load</u> [10]:

$$V_L = I_L.(R_a+R_f) + M^2.I_L{}^3/B \quad (20)$$

where R_f is the field resistance, M is the field constant in Henry, and B is the mechanical load torque constant in W.sec^2.

<u>series excited motor - ventilator type mechanical load</u> [4]:

$$V_L = I_L.(R_a+R_f) + M^{1.5}.I_L{}^2/B^{.5} \quad (21)$$

where B is the load torque constant in W.sec^3.

The total daily energy which can be delivered to the load, assuming that the load is connected to the array during the entire period, is then calculated from:

$$E_L = 2\int_{t_{st}}^{t_n} P_L(t)\ dt \quad (22)$$

where t_{st} is the time at which the array power is equal to the load minimum usable power. The time t_{st} can be obtained from:

$$t_{st} = t_{sr} + (1/15).\arcsin[I_{ph}(w)/I_G] \quad (23)$$

where I_{ph} is found by solving the array Eqn.(1) and the load equation under study for:

$$P_L = P_{st} \quad (24)$$

where P_{st} is the minimum usable power. For some electrolytic loads (and DC motors) a minimum current, I_{st} is needed to operate the load [3]. The time t_{st} in this case is found from Eqn.(23), for I_{ph} found by solving Eqn.(1) for the short-circuit current (V=0):

$$I_{sc} = I_{st} \quad (25)$$

Results will be limited to the effect of P_{st} since a relationship should exist between P_{st} and I_{st}.

4. Load Matching Factor

The efficiency of the array (the ratio of maximum power to input radiation) cannot be used, solely, to measure the performance of the PV system since a maximum power tracker is not generally employed in direct-coupled systems. Since the array possesses a maximum power line it is most desirable that the operation of the load line be close to the maximum power line throughout the day. A good measure for the quality of load matching is then the load matching factor [1, 5-7] as defined by:

$$\mu = E_L/E_{max} \tag{26}$$

The matching factor clearly depends on the load parameters since E_{max} is fixed for a given array, and insolation and temperature profile.

5. Maximum Power Tracker

The maximum power tracker (MPT) is an electronic device which can be used to operate the load at the maximum power point of the array. In other words, the MPT introduces to the array side a matching resistance equal to R_{mp} at all times. The energy which can be extracted from the array using an MPT (assuming no losses) is then:

$$E_{mpt} = 2\int_{t_{mpt}}^{t_n} P_{mp}(t)\ dt \tag{27}$$

where t_{mpt} is the time at which the array maximum power is equal to the load minimum usable power. The time t_{mpt} can be found from Eqn.(23) with I_{ph} found by solving Eqn.(4) for $P_{mp} = P_{st}$. The matching factor in the case of an MPT is given by:

$$\mu_{mpt} = E_{mpt}/E_{max} \tag{28}$$

The decision on whether to include an MPT in the system depends on the fractional energy obtained and its cost effectiveness.

6. Problem Formulation

The objective is to maximize the load matching factor and consequently E_L. This can be stated mathematically as follows:

Maximize: $\mu = f(C_1, C_2, \ldots, C_n)$ (29)

Subject to:

$$|P - P_L| \le e \tag{30}$$

$$P_L \ge P_{st} \tag{31}$$

$$I_L \ge I_{st} \tag{32}$$

$$t_{sr} \le t \le t_{ss} \tag{33}$$

where e is the permissible error in locating the array-load operating point. The solution of the optimization problem yields the optimum matching factor, μ_{opt}, and the corresponding optimum load parameters. The optimum rated power of the load can then be calculated from:

$$P_{oo} = E_{Lo}/[2(t_n - t_{st})] \tag{34}$$

and the optimum rated voltage can be obtained from the corresponding load equation. This criteria is chosen in order to minimize the deviation of the load operating power from the rated power. (Other criteria may use the point of interception of the optimum load curve and the maximum power locus of the array).

7. Per Unit System

As with any power system, a per unit has been developed for PV systems [10]. The per unit system is based on the maximum power point parameters, P_{max}, V_{max}, I_{max}, and R_{max} at 100% SUN and nominal operating temperature (normally 25 °C). These are chosen because they are usually supplied by the manufacturer of the PV modules. This approach allows the designer to easily choose the required number of modules among different manufacturers.

8. Array Sizing

The results of the optimization problem can then be used to determine the array parameters that is needed to supply the different loads. Knowing the rated parameters of the load, and the optimum per unit values, then the required total number of PV modules, n_a, the number of series modules, n_s, and the number of parallel strings, n_p, can be calculated by:

$$n_a = (P_o/P_{oo(pu)})/P_{cmax} \tag{35}$$

$$n_s = (V_o/V_{oo(pu)})/V_{cmax} \tag{36}$$

$$n_p = (I_o/I_{oo(pu)})/I_{cmax} \tag{37}$$

where P_o, V_o and I_o are the load rated parameters and P_{cmax}, V_{cmax}, and I_{cmax} are the rated power, voltage and current of the PV module as supplied by the manufacturer, respectively. This is based on the linearity of the PV generator in which we assume perfect matching of the cells (or modules) to each other in the array. Since the number of modules must be integer and satisfies:

$$n_a = n_s.n_p \tag{38}$$

then, the nearest integer values N_a, N_s and N_p which corresponds to n_a, n_s and n_p must be used such that $N_a = N_s.N_p$.

9. Battery Parameters

The next step is to find the proper battery parameters which must be connected to the system to improve the matching factor for a poor matched load and supply the load during low sun's radiation (during daytime only). Since the combined load and battery characteristic must be optimized according to the formulation given by Eqns.(29) to (33), then it follows that the optimum combined load/battery equation is given by:

$$V_L = f(I_L, C_{1o}, C_{2o}, \ldots, C_{no}) \tag{39}$$

where the C_{io}; i=1 to n, are the optimum combined load/battery parameters. The battery parameters can then be found by equating the corresponding terms of the optimum equation to the non-optimum one. An application of the required battery parameters to a general resistive load (Eqn.(13)) will be given by:

$$R_B = R_e.R_{eo}/(R_e - R_{eo}) \tag{40}$$

and

$$V_B = (V_{eo}.R_e - V_e.R_{eo})/(R_e - R_{eo}) \tag{41}$$

where V_e and R_e are the non-optimum values and V_{eo} and R_{eo} are the optimum values. For a pure resistive load, V_e is replaced by zero and R_e is replaced by R_L in Eqns.(40) and (41). The battery capacity (Wh) can be calculated from:

$$Q_B = (\mu_{opt} - \mu_L) \cdot E_{max} / (EFF_B \cdot DOD_{max}) \qquad (42)$$

where:

μ_L: the matching factor of the load,
μ_{opt}: the optimum matching factor of the combined load and battery,
E_{max}: the array maximum energy,
EFF_B: the battery efficiency,
DOD_{max}: battery maximum depth of discharge.

Equation (42) clearly shows that the poorer the matching factor of the load the larger will be the battery capacity.

10. Simulation And Analysis Of Results

The PV generator data are obtained from the literature [2-4] (Appendix). The bisection method [12] is used to determine the array maximum power point and the array-load operating point. Numerical integration is used to evaluate Eqns.(8), (22) and (27). The pattern search algorithm [11] is used to solve the optimization problem. Results are limited here to resistive loads.

10.1 Characteristics of the Array

Figure 2 shows the I-V curves of the PV array under study in per-unit at different light intensities at 25 °C. Also shown is the maximum power locus and two minimum usable power levels P_{st} (0.2 pu and 0.5 pu). Figure 3 shows the effect of the array temperature on the maximum power point parameters at solar noon. The maximum power point current is relatively insensitive to temperature, decreasing about 0.001 pu/°C. The maximum power point voltage shows a greater effect, decreasing at 0.0052 pu/°C. For maximum power the temperature coefficient is about -0.0055 pu/°C. (It should be noted that these values are slightly higher than the normal values. However, the references [2, 3] do not give the type of semiconductor used).

10.2 Pure Resistive Load

Figure 4 shows the variation of the matching factor versus R_L (pu) for different P_{st} at 25 °C. The results dictate that

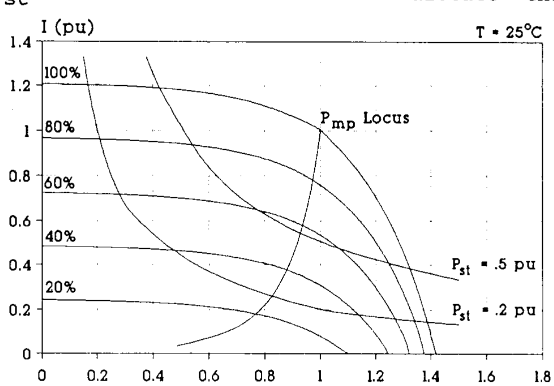

Fig. 2. The array I-V characteristics.

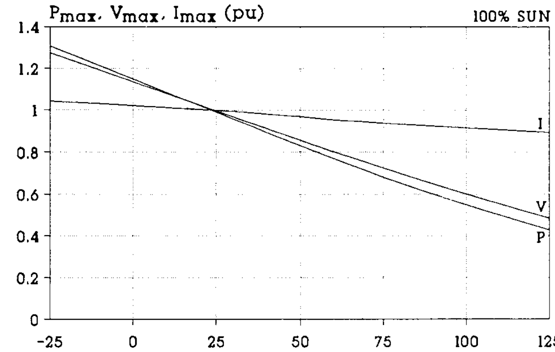

Fig. 3. Temperature effect on maximum power point parameters.

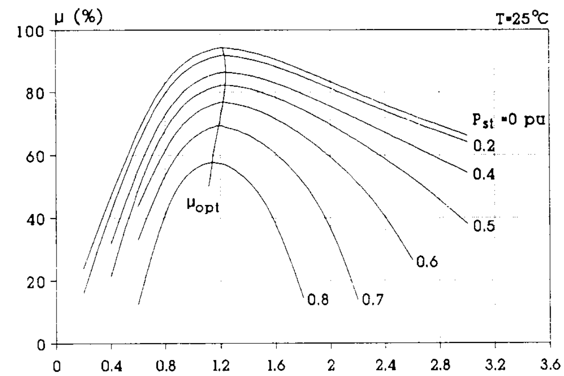

Fig. 4. Matching of a resistive load.

loading occurs within certain range of R_L or poor matching will be expected. The optimum R_L is 1.2 pu which yields an μ_{opt} of 94.34% at 25 °C. (This result is also reported in [7]).

Figure 5 shows the variation of the optimum matching factor and the corresponding load rated parameters for various P_{st}. The advantage of having a small P_{st} is obvious since more energy could be utilized. P_{oo} should be between 0.6 pu and 0.75 pu and V_{oo} should be between 0.85 pu and 0.95 pu. Figure 5 shows that an MPT will increase the matching factor by up to 5.67% compared to using an optimized value. However, if P_{st} exceeds 0.6 pu the use of an MPT will not help unless a battery is included since its matching factor drops to less than 80%. It is obvious that the MPT can be eliminated if optimum values are used in the sizing of the PV array. The effect of varying the array temperature on the matching factor is shown in Fig. 6. The optimum matching factor slightly varies with temperature, increasing at a rate of 0.043% per °C. The optimum R_L, however, decreases at a rate of .006 pu /°C. P_{oo} should be reduced at a rate of .005 pu per °C.

The optimum rated load parameters under varying temperature are shown in Fig. 7. The results show that under uncontrolled temperature (up to 125 °C) the design values should be shifted to 30 °C to minimize the deviation of the matching factor due to high temperature effect. In general the optimum load line should intercept the maximum power point of the PV array at 80% SUN at the corresponding temperature.

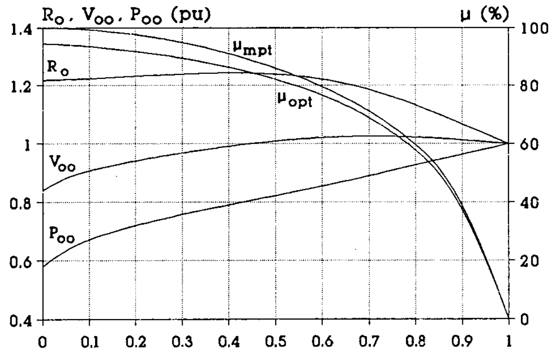

Fig. 5. Optimum matching of a resistive load.

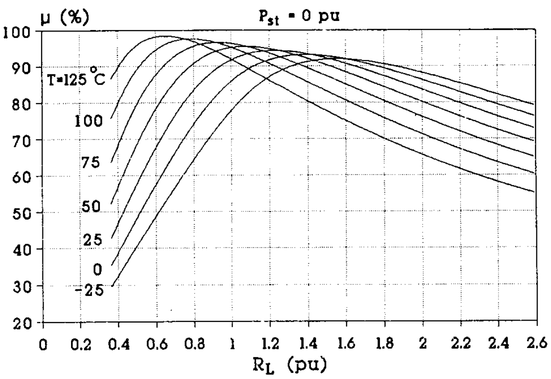

Fig. 6. Matching factor of a resistive load at different temperatures.

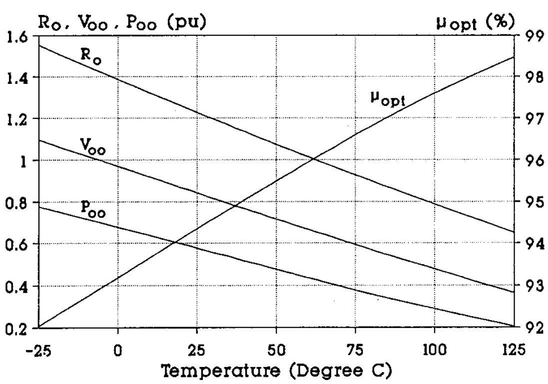

Fig. 7. Optimum matching parameters of a resistive load versus temperature.

10.3 Electrolytic load

An electrolyte load is characterized by two parameters V_e and R_e. Figures 8 and 9 show the matching factor contours as a function of V_e and R_e for P_{st} = 0 pu and 0.2 pu at 25 °C, respectively. The optimum matching factor is 99.83% for P_{st} = 0 pu. The corresponding load parameters are V_{eo} = 0.79 pu and R_{eo} = 0.243 pu. For operation close to the optimum a line segment relates the proper V_e and R_e can be extracted from Figs. 8 and 9. This can be given by $R_e = 1.18(1 - V_e)$ for V_e = 0.7 pu to 0.85 pu and R_e = 0.18 pu to 0.36 pu.

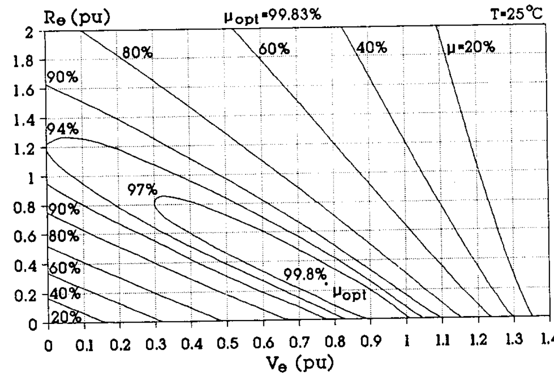

Fig. 8. Matching of an electrolytic load at P_{st}= 0 pu.

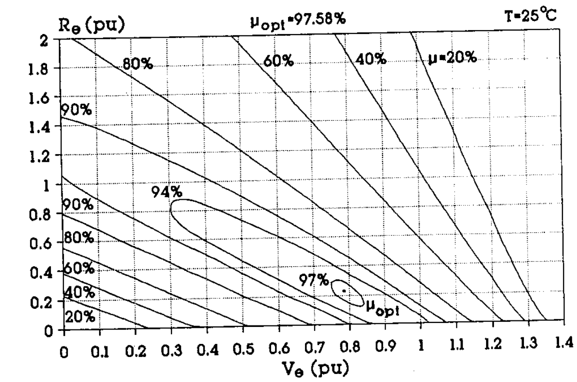

Fig. 9. Matching of an electrolytic load at P_{st}= 0.2 pu.

Figure 10 shows the variation of the optimum matching parameters at different P_{st} at 25 °C. It also gives the corresponding matching factor of an MPT. The results show that P_{st} should be small or a battery must be included. The difference between μ_{opt} and μ_{mpt} is insignificant. Figure 11 gives the load optimum rated parameters at different temperatures. V_{eo} should be reduced at a rate of 0.006 pu/°C. The optimum load line should intercept the maximum power locus of the array at 90% SUN at the corresponding array temperature. The internal emf of the load should be equal to the open circuit voltage of the array at approximately 3.5% SUN at the corresponding temperature.

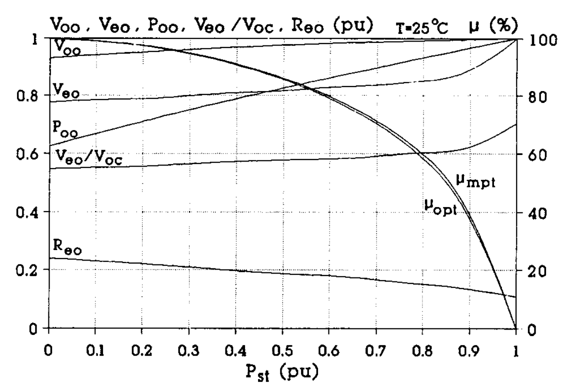

Fig. 10. Optimum matching of an electrolytic load.

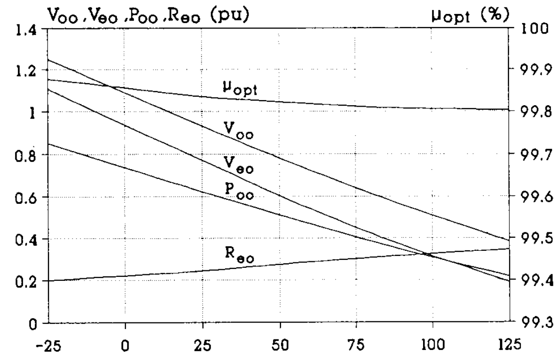

Fig. 11. Optimum matching parameters of an electrolytic load.

10.4 Calculated Battery Parameters

Figure 12 gives the proper battery parameters R_B and V_B which should be connected to the system to improve the matching factor for a poor matched resistive load. The figure is based on Eqns.(40) and (41) and for V_{eo} and R_{eo} obtained at P_{st} = 0 and 25 °C. The variation of these parameters with respect to P_{st} is insignificant. However at temperatures higher than 25 °C an account must be taken to reduce V_B by 0.005 pu /°C. As an example we assume an electrolytic load with V_e = 0.8 pu and R_e = 1.75 pu then using Fig. 12, we obtain V_B = 0.77 pu and R_B =0.277 pu. If the temperature is to increase to 50 °C then V_B should be 0.673 pu. Figure 12 could also be used for pure resistive loads. If for example R_L =1.75 pu the V_B should be 0.896 pu and R_B should be 0.277 pu.

10.5 Summary of Results

Resistive loads are optimized by selecting the load rated power, voltage and resistance with respect to those of the array. The optimum matching can be as high as 94.34% at 25 °C. Resistive loads can be considered compatible for a range of ± 25% around the optimum which maintains a minimum matching factor of 90% at 25 °C.

Electrolytic loads (and battery storage) are considered compatible with the array. The optimum matching factor is 99.83% at 25 °C. This can be achieved by carefully selecting

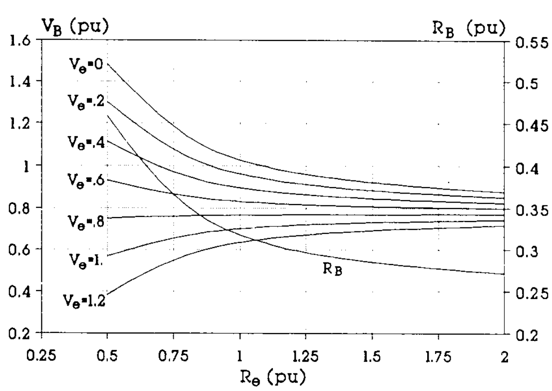

Fig. 12. Calculated battery parameters for a general resistive load.

the number of series and parallel cells of the array with respect to those of the electrolyte so that the internal emf and resistance of the load are close to the optimum values. A ± 20% deviation of those values from the optimum will maintain a minimum of 95% matching factor at 25 °C.

The optimum values of power and voltage must be reduced with the increase of the array operating temperature at approximately the same rate as P_{max} and V_{max}. Table I gives the optimum matching parameters for the two loads under study at two different ranges of array operating temperature.

Table I. Optimum matching parameters for resistive loads in per unit of the PV generator maximum power point parameters at 100% SUN and 25 °C under two ranges of array operating temperature.

LOAD / PARAMETER		0 to 50°C	50 to 100°C
RESISTIVE	R_{Lo}	1.29	1.00
	P_{oo}	0.57	0.41
	V_{oo}	0.86	0.64
	μ_{min}	92.50%	95.00%
	μ_{max}	94.35%	96.07%
ELECTROLYTIC	R_{eo}	0.21	0.25
	V_{eo}	0.79	0.48
	P_{oo}	0.67	0.41
	V_{oo}	0.94	0.64
	μ_{min}	91.00%	89.07%
	μ_{max}	99.84%	99.80%

CONCLUSIONS

Optimum matching of loads to the photovoltaic generator is most desirable for better system sizing and optimum utilization of the costly solar cell array. It was shown that optimum matching can be achieved by carefully selecting the array maximum power point parameters with respect to the load rated parameters. A maximum power tracker may not be needed if optimum or near optimum matching is achieved. A battery of selected parameters must be included to improve the matching factor for poor matched loads.

It should be noted that a slight deviation of the optimum values obtained may be expected when applying different array data. A future research work should be directed to apply these results on prototype PV modules. It will be a great advantageous to test the actual performance of these prototype modules under normal environmental conditions.

ACKNOWLEDGMENT

Thanks are due to my wife **Lucy** for her help. The support of **Drs.: F. E. Villaseca, P. P. Groumpos**, and **A. H. Qureshi** is appreciated.

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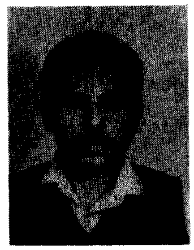
APPENDIX

The PV array data [2-4] at 100% SUN and 25 °C used for the simulation are as follows:

I_G = 13.615 Amp
I_r = 0.0081 Amp
AV_T = 23.697 Volt
R_S = 0.90 Ohm
V_{max} = 124.2 Volt
I_{max} = 11.28 Amp
P_{max} = 1400. Watt
a = 5.70E-4
b = 4400



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