THE GENERALISED RELIABILITY APPROACH FOR ARRAY-BATTERY SIZING OF PHOTOVOLTAIC SYSTEM

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ABSTRACT

A probabilistic approach to find the optimum size of a photovoltaic array and storage battery is presented. The method depends on the concept of the generalised reliability (R) and the days of autonomy (N_{ad}), i.e., and the number of survival days of the photovoltaic system under extreme weather conditions. To apply the method, the generalised reliability is extracted from meteorological data, spanning several years, consisting of one or more irradiation components, ambient temperature and the load profile. The result will be used to determine the three parameters: irradiation, temperature and load energy that define a system operating with the desired reliability.

INTRODUCTION

Although efficiencies of photovoltaic (PV) modules are in excess of 20%, commercial systems including storage are known to have a much lower overall efficiency [1]. The cost of a PV system, still very high compared to the financial strength of most developing countries, dictates that even a small percentage increase in the total system efficiency will result in a significant economic impact.

A challenging problem in the design of stand-alone storage-based PV systems is the determination of the optimum array area and battery capacity satisfying a given set of technical and economic objectives. A number of methods some based on trial and error steps and others on analytical but deterministic techniques, have been suggested and utilised. The simplest method is the worst case method in which the array is sized to satisfy the load during the critical month of the year. The battery size is then selected to cover a specified number of consecutive low irradiation days. The approach, being purely deterministic, is clearly non-optimal, as it does not take the variability of the irradiation and the array-battery relation into consideration. Another method is the load-matching approach [3] in which the ratio of the actual array energy to the maximum obtainable array energy (the array matching factor) is maximised, while system losses are minimised subject technical and economic conditions.

A probabilistic approach called the loss of load power probability method is a widely accepted method [2] that takes the variable nature of the solar radiation into consideration and the results have shown to be more realistic. In this classic approach the array is sized using the algorithm but the battery size is not included in the method. The battery size is simply selected to satisfy the average load (both day time and night time) for consecutive N_{ad} days. In this paper, a generalisation of a similar concept to determine both the array area and the battery size is given.

THE STAND-ALONE PV SYSTEM

A typical storage based PV system incorporates a PV array, a battery, power conditioning system and the load (Fig. 1).

The array is composed of modules that are basically interconnection PV cells in series and in parallel to provide the required voltage and current level. By means of the PV effect, the array produces dc power that fluctuates in response to fluctuation in the solar radiation and temperature.

The simplest system contains only the array directly connected to the load without any storage or a power conditioning. The reliability of such systems is high since the weak sub systems in PV application are the power conditioning and the battery. However, some applications may not tolerate supply voltage variation or need an ac voltage rather than the dc output of the array. In such cases, inclusion of appropriate power conditioning system is inevitable. Storage batteries enable PV systems to operate in the night as well as in a very bad weather.

By sizing is meant the determination of the correct number of the PV modules and the watt-hour (or ampere-hour) capacity of the battery for a specified load pattern. An undersized system fails to meet the load demand while an oversized system is costly and unjustifiable. Thus, an optimum sizing of the overall system is crucial both from economic and technical standpoints.

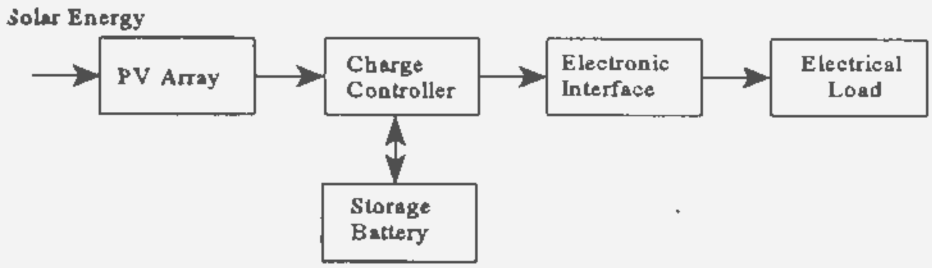

Figure 1 Storage-based stand-alone PV system

THE GENERALISED RELIABILITY (*R*)

The loss of load power probability has already been defined as the long-term average fraction of the load that is not supplied by the PV system. Reliability is the complement of loss of load power and the term is preferable since it represents the system requirement directly. Originally, the loss of load power probability was related to the minimum long-term average solar irradiation over a set of consecutive days obtainable at a given site.

The generalised reliability is an extension of the same concept that is based on not only the minimum expected tilt irradiation but also on the maximum expected ambient temperature and the maximum expected load requirement. The one-dimensional reliability is based on the minimum tilt irradiation, considering constant temperatnre and load nver a number consecutive days $1,2,...,N_{ad}$. This is basically the same as the simplified loss of load probability method. The two-dimensional reliability is based on two parameters: the minimum expected tilt irradiation and the maximum expected ambient temperature. It means the variation of the ambient temperature is taken into consideration when computing the reliability for a certain location. Here again the load is assumed to be constant through out the life-time of the system. The most complete and realistic figure is the three-dimensional reliability, here referred to as the generalised reliability, which takes variation of the three parameters (tilt irradiation, ambient temperature, and load) in to consideration to determine the reliability.

As can be seen from the foregoing arguments, it is apparent that daily figures of the three parameters must be available in order to apply the concept of number of autonomous days. Monthly figures can only guaranty a one-day reliable autonomous system.

The first step in application of the reliability concept is conversion of a statistically sufficient weather data and load profile into a joint cumulative frequency distribution. In practice, daily totals of the global irradiation (only or with the diffuse/direct component) and average maximum ambient temperature are available for 20 to 30 years. Thus the radiation components must be manipulated to get the tilt irradiation for angle around the latitude of the location, i.e., plus or minus 20 degrees, in order to allow for the seasonal variation of the optimum tilt angle. This will help to select the optimum tilt angle as the angle resulting maximum annual array output.

Depending on the availability of the computing device and the level of the accuracy required, anyone of the available tilt irradiation algorithms can be used at this step. For computation based on hourly values, the Perez [6] method is known to provide a good agreement with experimental observation. For monthly average values, the Hay method works if only global component is available and Klucher's [7] method performs better when both the diffuse and global components are available. The third component, the load variation, can not be obtained from a meteorological station but a reasonably accurate estimation of the load for each day of the year must be made. Fortunately, load profiles can be better predicted than weather data and the error incurred by assuming a monthly variation is quite negligible.

Once the daily figures of the weather and the load are found, averages of two successive days, three successive days, etc, must determined to get the cumulative frequency distributions for two-day averages, three-day averages, etc, respectively. The raw data can then be used to extract values of the desired triplet (tilt irradiation, ambient temperature, and load energy) for any specified reliability R. A computer program has been developed as part of a stand alone system design software to extract the values.

For one-dimensional problem, it is also possible to express the variation by an equation obtained through regression analysis. In such cases, useful form of the cumulative distribution is the function relating a constant value of R to the number of consecutive days, n. In other words, constant-R curves or iso-R curves along which a set of irradiation and critical day pairs are connected. Although various forms of equations are available the following is commonly used for its simplicity and ease of manipulation.

$$H(n,R) = c_o(R) + c_1(R)n + c_2(R)\ln(n) \tag{1}$$

where $c_0(R)$, $c_1(R)$, $c_2(R)$ are constants to be determined by the algorithm and they are dependent on the type of fit. Thus a site if application must be characterised be the constants for the desired level of reliability. In this paper constants for four typical levels of reliability for *Addis Ababa* (Latitude 9.03°N, Longitude 38.75°E, and Altitude 2408m) have been determined. The constants have been computed using only four years of radiation data, as it is not easy to get data of sufficiently many years. It is understood that the greater the number of years the better the accuracy of the constants in representing the available irradiation. The problem with this approach is that the equations are valid only for discrete levels of reliability, which have already been set at the outset.

A similar approach can be followed for the two-dimensional and the three-dimensional problems but the computation becomes wild and instead of extracting an equation it becomes easier to compute the values for an arbitrarily specified reliability level.

For a two-dimensional problem, a matrix with rows and columns denoting distinct levels of irradiation and temperature respectively can represent the joint-frequency distribution. Points of constant reliability define a surface. It is difficult to visualise the case for three-dimensional problem but the computation can be done in the same fashion.

THE SIZING PROBLEM

To begin with the array-battery sizing, suppose a reliability of R is given for a certain application and also that the number of autonomous days is N_{ad}. The application of the joint frequency distribution results in the minimum available plane of array irradiation $H(N_{ad},R)$, the maximum expected ambient temperature $T(N_{ad},R)$ and the maximum expected load energy $L(N_{ad},R)$. Then the array area as a function of the number of autonomous days can be given by,

$$A(N_{ad},R) = \frac{L(N_{ad},R)}{H(N_{ad},R)\eta_a\eta_i} \tag{2}$$

where η_a is the array efficiency, and η_i is the efficiency of possible power conditioning sub system. The companion battery should be able to cover the night load to maintain the same reliability during the night time and also guarantee the operation of critical day time load. The battery capacity will then be,

$$B(N_{ad},R) = \frac{L_b(N_{ad},R)}{\eta_b D_{mx}} \tag{3}$$

where $L_B(N_{ad},R)$ is the reliable night load plus the critical day load, η_b is the battery efficiency (assuming the same charging and discharging efficiency), and D_{mx} is the maximum allowable depth of discharge of the battery. Thus the overall system will have a round the clock reliability over the given number of autonomous days. It is to be noted that different reliability figures can be given for day loads and night loads and the battery capacity is chosen to reflect the night load reliability.

RELIABILITY OF A GIVEN LOCATION

Four years if radiation data for Addis Ababa, purchased from the Meteorological Service, is used to demonstrate the validity of the method. Generation of the irradiation freqnency distribution and application of the least square curve fitting techniques results in the parameters shown earlier.

Consider the monthly averages of the global irradiation and the maximum temperature recorded for Addis Ababa. Reliability with such monthly averages is applicable for one day only since the day to day behaviour of the variables can not be extracted. In such cases average figures for each day of a typical year must be provided.

Table 1: Monthly average data for A.A.

	Hg(Wh/m²)	T(°C)
Jan	4690	24.0
Feb	5904	26.0
Mar	5635	25.5
Apr	5391	24.3
May	5127	25.5
Jun	4407	23.3
Jul	3477	20.9
Aug	3632	21.2
Sep	4581	22.3
Oct	5858	23.6
Nov	5814	23.7
Dec	5717	24.0

One-Dimensional Analysis

Neglecting the variations in T and L, and deciding the range of analysis 3400 Wh/m² to 6000 Wh/m² in steps of 100 Wh/m², the reliability column shown in Table 2 can be obtained.

To design a 75% reliable system, for instance, the minimum irradiation will be 4500 Wh/m² (from Table 2) and this can be used in tilt irradiation computation and the result in Eq. 2 to determine the array area.

Table 2: Reliability column for Addis Ababa

H'	R(H>H')	H'	R(H>H')
3400	100.00	4700	58.33
3500	91.67	4800	58.33
3600	91.67	4900	58.33
3700	83.33	5000	58.33
3800	83.33	5100	58.33
3900	83.33	5200	50.00
4000	83.33	5300	50.00
4100	83.33	5400	41.67
4200	83.33	5500	41.67
4300	83.33	5600	41.67
4400	83.33	5700	33.33
4500	75.00	5800	25.00
4600	66.67	5900	8.33
		6000	0.00

Two-Dimensional Analysis

The basic assumption here is that the load variation is negligible and the reliability depends on the irradiation and temperature. Taking the same range for irradiation and the range (15-20°C) for ambient temperature, the reliability matrix can be determined as shown in Table 3.

Table 3: Reliability Matrix for Addis Ababa

H'	T 20	21	22	23	24	25	26
3400	0.00	8.33	16.67	25.00	50.00	75.00	91.67
3500	0.00	0.00	8.33	16.67	41.67	66.67	83.33
3600	0.00	0.00	8.33	16.67	41.67	66.67	83.33
3700	0.00	0.00	0.00	8.33	33.33	58.33	75.00
3800	0.00	0.00	0.00	8.33	33.33	58.33	75.00
3900	0.00	0.00	0.00	8.33	33.33	58.33	75.00
4000	0.00	0.00	0.00	8.33	33.33	58.33	75.00
4100	0.00	0.00	0.00	8.33	33.33	58.33	75.00
4200	0.00	0.00	0.00	8.33	33.33	58.33	75.00
4300	0.00	0.00	0.00	8.33	33.33	58.33	75.00
4400	0.00	0.00	0.00	8.33	33.33	58.33	75.00
4500	0.00	0.00	0.00	8.33	25.00	50.00	66.67
4600	0.00	0.00	0.00	0.00	16.67	41.67	58.33
4700	0.00	0.00	0.00	0.00	16.67	33.33	50.00
4800	0.00	0.00	0.00	0.00	16.67	33.33	50.00
4900	0.00	0.00	0.00	0.00	16.67	33.33	50.00
5000	0.00	0.00	0.00	0.00	16.67	33.33	50.00
5100	0.00	0.00	0.00	0.00	16.67	33.33	50.00
5200	0.00	0.00	0.00	0.00	16.67	33.33	41.67
5300	0.00	0.00	0.00	0.00	16.67	33.33	41.67
5400	0.00	0.00	0.00	0.00	16.67	25.00	33.33

H'	*T* 20	21	22	23	24	25	26
5500	0.00	0.00	0.00	0.00	16.67	25.00	33.33
5600	0.00	0.00	0.00	0.00	16.67	25.00	33.33
5700	0.00	0.00	0.00	0.00	16.67	25.00	25.00
5800	0.00	0.00	0.00	0.00	16.67	16.67	16.67
5900	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6000	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The (i, j) element in the matrix corresponds to the joint frequency of occurrences and probability which implies the joint probability $p(H>H', T<T')$.

Three-Dimensional Analysis

This is the most general approach representing the real scenario. Variation of all the three parameters are taken in to consideration and the result will be a reliability cube where each element in the cube corresponds to the probability $p(H>H', T<T', L<L')$. Taking the same range for irradiation and temperature and a suitable range for the load a set of reliability matrices equivalent to the reliability cube can be obtained.

In general the same reliability figures can appear in a reliability data or the particular reliability may not appear at all. An iterative computation with reduced steps in the particular variable improves the resolution with the desired result. If the additional computation is not worth for the application, interpolation can be applied for the later case while an average value can be taken for the first case.

CONCLUSION

A sizing method based on system reliability concept has been devised to determine the combination of array size and battery capacity. It is an extension of the widely used loss of power probability method. The method, called the generalised reliability method, in general depends on the three important variables (tilt irradiation, temperature, and load pattern). It relates both the array area and the battery size with the desired reliability level and the number of autonomous days. Simplified versions of the method assume a deterministic load and temperature variation.

The only assumption made to make use of the derived formula is that the load and irradiance variables are statistically independent. The assumption may not hold true for some practical applications, but the error caused will not be significant compared to more involved statistical computations.

For a small value of days of autonomy, exhaustive comparisons of all possible combinations of array size and battery capacity can be made. As the number increases, however, it becomes difficult if not impossible, to consider all combinations. Then the analytical method with acceptable level of error will prove to be advantageous.

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