

OPTIMAL SIZING OF STAND ALONE PHOTOVOLTAIC SYSTEMS: A REVIEW

M.LOKANADHAM¹, BOGGALA RAMESH²

¹Assistant Professor, Department of EEE, SVP CET, Puttur, A.P

²Assistant Professor, Department of EEE, SISTK, Puttur, A.P

Abstract: Solar energy is clean, free available, environment friendly and secure energy source. The best way to harvest the sun's power is photovoltaic technology. Stand alone photovoltaic (SAPV) systems used to electrify remote areas due to advancement in solar energy technology and substantial rise in prices of petroleum product. Many research works are carried out focusing on optimization of stand alone photovoltaic systems due to their high capital cost. This paper is to review the current research on the simulation and optimization for the stand alone photovoltaic systems in the period of (1981-2013).

Key words: SAPV systems, Optimization, Reliability power, Modelization, System cost, Size system.

1. Introduction

Energy is a vital factor for social and economic development of any country. The World Bank and International Energy Agency estimated that the world will require a doubling in installed energy capacity over the next 40 years to meet the anticipated demands of developing countries [1]. The rapid depletion and price volatility of fossil fuels resources on a worldwide basis have necessitated urgent search for new energy sources to cater to the present day demands.

Therefore, it's imperative to find alternative energy sources to cover the continuously increasing demand of energy while minimize the negative environmental impacts.

Inexhaustible sources of energy, alternatively known as renewable energy sources, are present in copious amounts and can be obtained free of cost. Solar energy system is being considered as promising power generating sources due to their availability and topological advantages for local power generation in remote areas. Utilization of solar energy has become increasingly significant attractive and cost effective, since the oil crises of early 1970s [2]. In general, photovoltaic system may be operated as a hybrid, grid connected or stand alone systems. Stand alone photovoltaic (SAPV) systems have been implemented to electrify remote areas.

However, a drawback to solar energy is their unpredictable nature and dependence on weather and climatic changes and the variation of solar energy may not match with the time distribution of load demand. The successful operation of the stand alone photovoltaic system is to find the optimum relationship between the PV array and battery storage to meet load demand. Many attempts have been made to optimize renewable systems. Among them, most studies emphasized on hybrid systems with battery, where two or more energy sources complement each other. Therefore, the sizing of battery is relatively small and the role of the battery is less important than that in SAPV system

In order to efficiently and economically utilize the renewable energy resources, one optimum sizing method is essential. The sizing optimization method can help to guarantee the lowest investment with full use of the renewable energy systems [3]. In the literature, various techniques of sizing optimization are used of SAPV systems can be applied to reach a techno-economically optimum. They must search an optimum combination of two factors: the system cost and the system reliability. The relationship between the system cost and reliability should be closely studied so that an optimum solution can be reached.

This paper attempts to show the current status of research on optimum sizing of stand alone photovoltaic systems in period of (1981-2013). Firstly, the individual components of SAPV systems are modeled. Secondly, two criteria in term of cost system and power reliability are investigated. Finally, optimization techniques and software tools are reviewed.

1.1 Modeling of photovoltaic system

The solar array is the only energy source in the SAPV system. For engineering applications, many studies used the simplified simulation models introduced the equivalent model or circuit of solar cells, such as one diode model [4,5] or two diodes model [6] which can determine the current-voltage characteristics of PV modules.

Borowy and Salameh [7] present one simplified model which the maximum power output can be calculated once the solar radiation and ambient temperature are known. PV module performance is highly

influenced by weathers conditions, especially solar radiation and PV module temperature. The PV power produced for various solar radiation and temperature are shown in these references [8, 9].

Shen [10] used the peak sun hours (PSH) to represent solar radiation so that the daily output of the solar array is easily calculated by using the peak Watt of solar array times the PSHs, where the PSHs is equivalent to the length of time in hours at a solar radiation level of 1000W/m². Diaf and al [11] estimated the power output of PV module by using the solar radiation available on the module surface, the ambient temperature and the manufacturers' data for the PV module as model inputs. A similar model described in [12], which the hourly power output PV system with an area on average day of month is given.

Zhou and al [13] presented a novel simulation model of PV array performance. Five parameters (α , β , δ , $n_{MP P}$ and R_s) are introduced to take account for all the non-linear effect of the environmental factors on PV module performance. The parameters estimation results for the selected PV modules used in this study are shown in table.1 as described in [13, 14]. All data of the novel model are normally available from the manufacture. For this reason, the novel model is more accuracy and efficient than the models described above. Using the definition of fill factor, the maximum power output produced by the PV module can be found in [15]. One simplified model for the maximum power output of PV module is used in [16] which eight parameters can be identified.

Ref	PV Type	α	β	δ	nMP P	$R_s(m\Omega)$
[13]	PV	1.21	0.058	1.15	1.17	12
[14]	MSX60	0.99	0.063	0.17	1.46	8.0
	BPSX150	1	0.066	0.13	1.50	5.1
	Pb585	1	0.093	0.44	1.10	0.4

Table.1. Parameters estimation for d ifferent PV modules .

1.2 Modeling of battery storage

Due to the intermittent nature of the solar, the instantaneous power extracted from the solar array often does not match the instantaneous load demand. As a result, energy storage systems are essential for continuous and reliable operation [17].

The lead acid battery storage is widely used in SAPV system due to their high efficiency, low cost and low self-discharge. The relativity sophisticated nature the battery makes it difficult to develop a general model. Different models for batteries are available in the literature [18, 19]. An important contribution was given by shepherd. The knowledge of internal battery process permitted to drive an empirical equation which represents a wide variety of batteries in discharge and a complete set of discharge curves. This equation uses a minimum of experimental data for the parameters fitting. Modifications to the shepherd model were proposed by Hyman to include low current effects for PV application, and were used by Facinelli for a program to simulate solar systems [20]. Most of the models require the knowledge of appropriate parameters; excepting the Monegon model and Copetti model [9, 19-21] do not keep the parameters fixed. Thereby, they must fit for each battery design, the values used in charge also differs from those used in discharge. They are non linear equation, which takes into account not only the charge and discharge but also the overcharge. Although this model is widely used but it not takes account the self-discharge rate. In [22] uses three properties of the battery, i.e the state of charge (SOC), the float charge voltage (or terminal voltage) and the battery lifetime but in [16] utilize the state of charge and the float charge voltage only. Several factors that affect the battery behaviors have been taken into account, such as the charging current rate, the charging efficiency and the self-discharge rate. In [8], the accumulator is modeled by two electrical non linear elements: a voltage source representing the open-circuit voltage (V_1) of the accumulator and an internal resistance (R_1) for the different losses, as shown in figure.2. This model develops different equations for charging and discharging. This is basically the energy balance equation computing the value of the state of charge (SOC) increment as the energy increment in a differential of time taking into account self-discharge and charge and discharge efficiency.

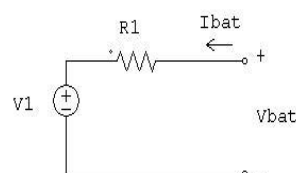


Fig.2. Lead-acid accu mulator modeling [8].

In order to increase the cycle of the battery, it's necessary to keep the battery from being overcharged or undercharged. So the state of charge is held in a limited range:

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (1)$$

1.3 Modeling of inverter

The inverter modelling is based on the energy efficiency curve. This inverter model has been deduced from the normalized of the efficiency curve of a rated power inverter. The inverter energetic performance is not constant [6].

2. Stand alone PV system modeling

Modelization is an essential step before any phase of optimal sizing. Various modeling techniques are developed, to model SAPV system components. This SAPV system typically consists of PV array, a controller, battery storage and inverter for AC loads, as shown in figure.1.

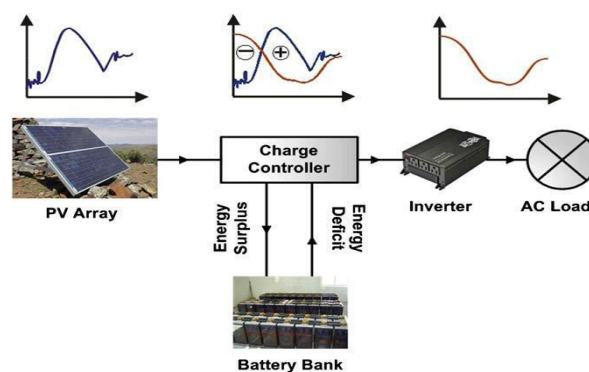


Fig.1. Stand alone photovoltaic system [56].

In order to predict the SAPV system performance, individual components should be modeled first and then their combination can be evaluated to meet the load demand.

2.1 Power reliability criteria

Due to the intermittent nature of solar radiation, the power system reliability analysis is usually considered as an important step in any such system design process. The most popular method is the loss of power supply probability (LPSP) [23, 24], which can be defined as the probability that an insufficient power supply results when the system is unable to satisfy the load demand [15]. Some papers used the loss of load probability (LOLP) [25, 26] as the key of the power reliability of SAPV system because the merit of a SAPV system should be judged in terms of the reliability of the electricity supply to the load. LOLP is defined as the ratio between the energy deficit and the energy demands both on the load, over a long period of time [27]. The way to calculate this probability is based on a simulation with real-time solar radiation data for a given photovoltaic array peak power and storage capacity. The disadvantage of this method is that it's necessary to know daily radiation data for a long period of time [28]. In [29] compared their results by those obtained in [10, 30] on the basis of the loss of load hours (LOLH). There may find a situation during which the demand is low and the excess energy generated from PV system can not be utilized for charging when the battery is already full. Therefore, a new factor named unutilized energy probability (UEP) is used in [31] show that the most suitable combination can be selected depending upon the choice of minimum UEP or minimum levelized energy cost (LEC) from the set of combinations. The choice of these factors depends on interest of the design. In [32] the residue of generated power is described as the percentage of the surplus of energy produced (PSEP) which is defined as the report between the sums of the surplus of the energy produced and the consumer's total need.

2.2 System cost criteria

It's judicious that economic analysis should be made while attempting to optimize the size of the proposed system. Various costs are used to evaluate different option for energy system. The levelized energy cost (LEC) is often the preferred indicator. LCE is defined as the ratio of the total annualized cost of system to the annual electricity delivered by the system [33]. A stand alone photovoltaic/wind used to satisfy the requirement of typical residential home 3kWh/day located in Corsica Island which the LCE is utilized as cost

criteria [34]. The net present cost and life cycle cost are widely used as economic evaluation [35, 36].

3. Criteria for SAPV system optimizations

In order to select an optimal combination of a SAPV system to meet the demand, evaluation may be carried out on the basis of power reliability and system cost.

Sizing methods can be classified as follows:

3.1 Intuitive methods

A simplified calculation of the size of the system is carried out without establishing any relationship between the different subsystems or taking into account the random nature of solar radiation [41]. These methods can be based on the worst month method. This usually results in an over/under sizing of the designed system which results in a low reliability of the system. In [42], an optimum design of a SAPV system for residential uses in Dhaka is presented. The main objectives have been the search for the best suited tilt angle, battery size, array size and parameters for optimum performance, to solve the problem of delivering electrical power at minimum life cycle cost. The influence of tilt angle on sizes of the SAPV systems was investigated for the given load demand, the optimal size of solar array and battery was obtained when the tilt angle was adjusted in accordance with seasons, which complicates the installation of the solar array.

3.2 Numerical methods

A system simulation is used in this case. For each time period considered, usually a day or an hour, the energy balance of the system and the battery load state is calculated. These methods offer the advantage of being more accurate and the concept of energy reliability can be applied in a quantitative manner. These methods allow optimizing the energy and economic cost of the system. The disadvantage of such method is the need to have available hourly or daily radiation series for long periods of time [41].

In [43], a new optimal sizing algorithm for solar array and battery capacity is developed. This algorithm would provide us with the optimum balancing parameter for any SAPV application and for every month of the year. In order to size the solar array and battery capacity, two factors are considered: the life cycle cost of the system should be as small as possible and an acceptable performance for LOLP should be determined. The authors in [26] presented to select the optimum tilt angle, photovoltaic array area and battery storage capacity of SAPV system located in Greek Island. This method uses monthly average meteorological data. The optimum system selected is that with the minimum life-cycle cost and loss of load reliability, which is most appropriate for solar energy system. In [28] an optimization of PV system in Algeria is developed. The sizing criterion is the LOLP. For a given LOLP, there are many combinations of photovoltaic array peak power and battery capacity. The optimum PV configuration is selected based on the minimum total system cost where the sizing curves for 12 sites in Algeria have been presented. In Sudan [25] an optimum design for SAPV system is developed based on a clear sky model to estimate solar radiation in areas at latitudes greater than 10°N, where measured data are not available. In this study, the author used the monthly average radiation and chosen that the optimum configuration for array and storage sizes based only on the LOLP where the cost of energy was not taken into account. This may cause errors in calculating the optimum PV system size. The effect of maximum cell temperature and different load profiles in the system size are also investigated in this paper.

An optimized sizing method of an autonomous photovoltaic system is applied to a case study located in Corsica [39]. In this research, the sizing curves for a daily load of 1kWh and for the four profiles types are presented. It shows that the temporal distribution of the load has an important influence on the battery energy state variation and induces some difference in the characteristics of the PV system according to the load profile type. In the other hand, the influence of the time step of the system simulation has been discussed. Using hourly data is recommended. The optimum configuration is selected based on the cost of energy only while the LOLP was not considered. A simulation model for sizing of stand alone solar PV system with interconnected array in Delhi is done using the loss of power supply probability (LPSP) [44]. Based on the concept of fuzzy random variable representation of cloudiness index, the global solar radiation data is generated. A linear programming approach is used to evaluate the optimal sizing of stand alone PV system with array made of interconnected modules. The number of PV modules and battery capacity in the solar PV system with fixed and tilted aperture and single axis tracking aperture array configurations are selected based on the minimum system cost.

A new sizing approach of a SAPV system for three locations in UK is presented in [45]. The monthly average daily radiation of the worst month is assumed for the calculation of the minimum required PV generator size. The worst month, for the case of constant load, is the month with the minimum monthly average daily radiation. The same method is used to determine the battery size and the minimum required number of storage days is calculated for each particular each year of the used historical data. In [10], optimal sizing of typical

house in remote areas in Malaysia is investigated. Different size combination of solar array and battery can meet the given load for the desired loss of power supply probability (LPSP). The cost function of the SAPV system is defined. To determine the optimal size combination, the function cost equation is partially derived and has to be solved graphically. The tangent point of the two curves corresponds to the optimum size of solar array and battery. Uses graphical solution rather than an accurate relation to gives the optimum size of SAPV system makes this method inaccurate of the calculated size.

Due to multidimensional nature in optimum problem, a suitable methodology to deal this problem will be one able to solve multi-objective optimizing heuristics methods as Genetic Algorithm (GA) and Artificial Neural Network (ANN) [46]. In Algeria [46], an optimization is done based on the numerical method. An ANN model has been used for improving the analytical method of LOLP curves. The same concept used in [48], the proposed methodology works without any information of the relationships between the different variables and sources of information studied. The presented method reports an improvement in results respects to an analytical method studied. An ANN model used to predict the optimum size of the PV array in terms of the optimum storage battery, LOLP and the clearness index yearly average. The proposed method has an advantage to predict the future optimal configuration or sizing of energy system's components [49]. ANN has been used in prediction of total daily solar radiation in isolated areas where data records are not always available as developed in [50].

Analytical methods

By the use of equations these methods try to describe system size as a function of reliability. The main disadvantage of these methods is that either they are not accurate enough or they require the determination of coefficient for expressions for each location [41]. A first attempt has been done by Macomber [51], based on the assumption that the daily solar irradiation is an uncorrelated Gaussian variable having a mean of horizontal daily irradiation and a variance of σ . Both are input to the model [27]. In [52] a simplified method for the optimal sizing of a photovoltaic system is presented for Italian meteorological data but we can be applied to any geographical area where the formulae for the optimal value of the PV area and battery storage value are developed. Further drawbacks of this method are: the assumption that all the energy produced by the photovoltaic array passes through the battery and the use of initial investment as the economics criterion which does not take into account the effect of the number of battery replacement. In [53] a simple analytical method which allows one to predict the fraction of the load covered by a photovoltaic system as a function PV array area, battery storage capacity, meteorological parameters and the user's load. Two cases are discussed. In SAPV system, we impose the minimum fraction of the load which must be covered by the system. In the case of fuel generator plant, the objective of the sizing procedure is to analyze the cost of the energy produced by the plant as a function of the size of the PV system.

The author in [54] presents a model for the LOLP derived by approximating the probability density function of the difference between the daily PV array outputs and the load with two events and by assuming the daily storage charge/discharge process can be represented as a one step Markov process. The analytic models for designing optimal SAPV systems are based on the theory of stochastic processes [55]. The LOLP is used as reliability factor. Once the storage size-collector area characteristic curve is known, economic optimization is defined as the total system cost which can be assumed by a linear combination of storage and PV costs. In [27], a variety of numerical and analytic models for calculating the LOLP are described and evaluated using data for three different climatic condition in Spanish locations (Madrid, Murcia and Santander). For each location, the analytic model requires as input four different coefficients.

A sizing procedure based on the observed time series of solar radiation for UK is described in [56]. This method is based on a direct use of solar radiation data near the site where the PV system is to be installed. The authors calculate the average of the obtained solar radiation series and divided this series in two climatic cycles. The first climatic cycle contains the days with average solar radiation equal to or higher than the calculated overall solar radiation average and the second climatic cycles contains the days which have average solar radiation lower than the calculated overall solar radiation average. Unlike the traditional methods based on loss of load probability (LOLP), the reliability of supply (LPSP) enters in this method through the length of the time series of data used in the analysis. This approach offers several advantages over the traditional LOLP based methods. It obviates the need to produce synthetic time series of solar radiation data. The concept of reliability is also brought closer to the user's experience, by being linked to duration of time over which the system is expected to operate with 100% reliability.

In [57] an optimization of SAPV system is developed based on the criterion of minimum embodied energy. Both crystalline based and thin film PV modules in collaboration with plomb-acid batteries are examined while two different cases are investigated, the first considering an Island area of high solar potential and the second an Island area of medium solar potential. The most interesting finding concerns the fact that in all cases examined, the contribution of the battery component exceeded 27% of the life-cycle energy

requirement, hence reflecting the difference between grid-connected and stand alone configurations. In [58], a novel analytical method has been developed for determining the optimal sizing of a stand alone PV system based on reliability and cost by using monthly mean daily data of solar radiation and other meteorological parameters. Algebraic equations for optimal PV array area (A), optimal useful battery storage capacity (C_u) and the constant of integration (k) has been formulated. PV array area and useful battery storage capacity were determined by the intersection of a certain cost line with desired LLP curve, as shown in figure.3. For $k=c_3$, the straight line is tangent to the LLP curve at a single point $P_{opt}(C_{u,opt}, A_{opt})$ which is the optimum point for best possible combination of A and C_u . The developed model involves the energy demand for the calculation of required optimal parameters. This method is more constructive due to incorporation of many useful variables namely desired LOLP values, latitude clearness index of location, load demand, unit cost of PV array and battery capacity.

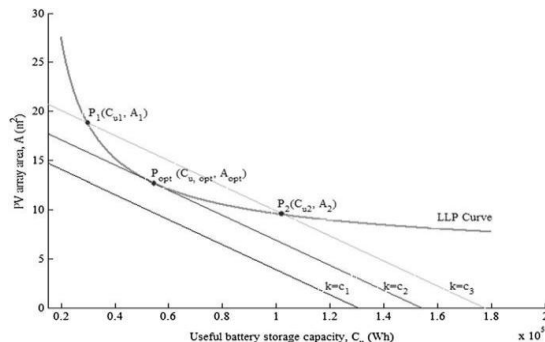


Fig.3.LLP curve and cost lines with various combinations of A and C_u [58].

4. Stand alone PV systems size optimizations

Various optimisation techniques for SAPV system have been reported in the literature. The size optimization of such system can only assure the low investment with full use of the system component. Optimization makes the system functional at the most favourable condition in terms of investment and power reliability. This can be carried out by the use of empirical models. Based on the reviewed work we found that there are three major PV system sizing procedures [37]. The use of one or other will depend on the initial data available.

In addition to the sizing methods, it's essential for the designers to choose an appropriate optimization technique and take into account the most influential parameters which are suitable for the system sizing. Many optimal sizing techniques were developed based on the worst month scenario [27, 38]. Yearly average month method and worst month method were investigated in [38]. The time-series simulation method which uses a time scale of 1h and 1 min is presented in [39]. The model proposed in [7] was based on long-term hourly solar radiation data and peak load demand data of the chosen site. Typical meteorological year data or long period meteorological data were employed by [40].

5. Simulation and optimization software tools

Simulation programs are the most common tools for evaluating performance of utilized systems. By using computer simulation, the optimum configuration can be found by comparing the performance and energy production cost of different system configuration. Several software tools are available for designing of stand alone electric generation system [2, 35]:

HOMER (Hybrid Optimisation Model for Electric Renewable), developed by NREL (National Renewable Energy Laboratory, USA). It is able to optimize hybrid systems containing a PV generators, batteries, wind turbines, hydraulic turbine, AC generators, fuels cells, electrolyzers, hydrogen tank, AC-DC bidirectional converters and boilers. The load can be AC, DC, and /or hydrogen loads, as well as thermal loads. Depending on the number of variables used, the simulation can take a long time. HOMER uses hourly simulation for arriving at optimum target. It has been used in renewable energy system [59, 60].

HYBRID2 was developed by the Renewable Energy Research Laboratory (RERL) of the University of Massachusetts. The hybrid systems include three types of electrical loads, multiple diesel generators, multiple wind turbines of different types, PV generators, battery storage, four types of power conversion devices and fuel cell or electrolyzers can be modelled in the software. The simulation is very precise, as it can define time intervals from 10 min to 1 h. NREL recommends optimizing the system with HOMER and then, once the optimum system is obtained, improving the design using HYBRID2.

HOGA is a hybrid system optimization program developed by the Electric Engineering Department of the University of Zaragoza (Spain). It allows optimizing of hybrid systems consisting of a PV In [63] developed an automated Microsoft Excel Spreadsheet that can be used to design a solar-PV generator, batteries, wind turbines, hydraulic system and analyse its economic efficiency. A turbine, AC generator, fuel cells, electrolyzer, MATLAB fitting tool was used to fit the resulting hydrogen tank, rectifier and inverter. The loads can be AC, DC and /or hydrogen loads. The optimization is carried out by means of Genetic Algorithms, and can be mono-objective or multi-objective. The simulation is carried out using 1h sizing curves to derive general formulas for the optimal sizing of PV arrays and batteries as utilize in [64].

Based on the detailed illustration given above, many case studies of projects following these

intervals, during which all of the parameters remained constant. An optimized system by HOGA is presented in [61].

methods of optimizations and software tools have been published. Some of those studies are presented in table .2.

PHOTOV-III is a numerical code which used to generate PV-BAT configurations able to guarantee zero load rejection (100% energy autonomy) for a given area and time period examined. The computational algorithm PHOTOV-III is used in [57, 62].

References	Project location	Load type	Design capacity	Software tools
Kaldellis and al.[57]	Rhodes island, Greece	≈ 4.7MWh/yr	865W solar-PV at panel tilt angle of 60° (24V, 160Ah) battery	PHOTOV-III
Silva and al.[59]	Tocantins, Brazil	23.8kWh/day	6.28kW solar-PV, 16 pieces with battery (12V, 220Ah)	HOMER
Karghouli and al.[65]	Southern Iraq	Health clinic load of 31.6kWh/day	6kW solar-PV, 80 pieces with battery (6V, 225Ah)	HOMER
Ahammed and al.[66]	Bangladesh	*Rural electrification board *Electrification of rural markets: ex:24fluorescent lights	*solar-PV 250.000W with 5.000 number of SHS. *7 solar modules (50W _p), 7 pieces with battery (12V, 100Ah)	-
Salam and al.[67]	Sohar, Oman	Lighting load of 1.56kWh/day	0.7kW, 4 pieces with battery (6V, 360Ah)	HOMER

Table.2. Some SAPV systems projects.

6. Conclusion

Stand alone photovoltaic (SAPV) systems is recognized as a viable solution to electrify rural off-grid locations. This paper summarizes existing research of optimal sizing of SAPV systems in the period of (1981-2013). This review includes the modelling components, size optimization and the software tools of SAPV systems. Most of the commonly used criteria that evaluate the system power reliability and system cost are investigated. Various optimization techniques have been reviewed including intuitive methods, numerical methods and analytical methods. The numerical methods are widely used rather than the others.

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