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Methodology, Simulation and Optimization of Hybrid Solar / Wind Power System

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Abstract: *Solar energy is a clean, inexhaustible, abundantly and universally available source of energy. Wind energy is clean, cheap and ecofriendly renewable source. Hybrid solar and wind generation power system increases reliability and reduces the dependence on one single source. Good compensation characteristics are usually found between solar energy and wind energy. A model was designed and optimized for designing hybrid solar-wind system employing battery bank for calculating the system optimum configuration ensuring minimum cost of the system while satisfying the custom required loss of power supply probability (LPSP). A method for computation of the optimum size of a battery bank and the PV array for a standalone hybrid Wind /PV system has been developed. Long term data of Wind Speed and irradiance level was considered for every hour of a year. For a desired load and LPSP, an optimum number of batteries and PV modules were computed based on the minimum cost of the system using MATLAB R2007a (Version 7.4). The mathematical model for characterizing PV module and Wind generator was developed. Graphical optimization for the number of battery and PV module has been carried out to minimize the cost of system for desired LPSP*

Key words: *Hybrid generating system, Optimization, Loss of power supply probability*

I. Introduction

We all know that the world is facing a major threat of fast depletion of the fossil fuel reserves . Most of the present energy demand is met by fossils and nuclear power plants. A small part is met by renewable energy technologies such as wind, solar, biomass, geothermal etc,. After a short time there will be severe shortage of these fuels. Most of the research is about to conserve the energy and how to utilize the energy in better way. Research has also been into the development of reliable and robust systems to harness energy from nonconventional energy sources .Among them ,the wind and solar power sources have experienced a remarkably rapid growth in the past 10 years. The solar energy and Wind energy has been listed as the promising alternative sources for the future as the energy available from them is free and clean. By complimenting the properties of solar and wind energy sources for certain locations, a Hybrid PV/Wind system with storage banks presents an unbeatable option for the supply of small electrical loads at remote locations where there is no utility grid power supply.

Methodology for optimal sizing the wind /PV hybrid system was given by Borowy and Salmeh [1] that calculates the optimum size of a battery bank and the PV array for a hybrid system based on the minimum cost of the system using graphical construction technique. Based on Genetic algorithm technique optimum match design sizing method for hybrid solar wind system was developed by Hongxing *et.al* [2]. Diaf *et.al* [3] presented a mathematical models for characterizing PV module, wind generator and battery considering various types and capacities of system devices and the configuration that meet the desired system reliability by changing the type and size of the devices system. Wang and Singh [4] presented the optimal design of an autonomous hybrid generating system including different power sources such as wind turbine generator, photovoltaic and storage batteries. A constrained mixed-integer multi-objective particle swarm optimization (CMIMOPSO) algorithm was adopted to derive non dominated solutions for the optimal design. Due to its simple operations and good convergence performance, PSO has turned out to be outstanding heurists for numerous complex engineering design problems and also an optimization procedure was developed to simultaneously minimize the system cost as well as maximize the system reliability. A probabilistic approach based on the convolution technique to assess the long term performance of a hybrid for both standalone and grid-linked applications was provided by Tina *et.al*. [5].This approach uses energy index of reliability (EIR) directly related to energy expected to estimate energy performance of hybrid solar-wind power system (HSWPS) for the reliability analysis. Yang and Burnett [6] used simulation model for analyzing the probability of power supply failure in hybrid photovoltaic wind power generation systems incorporating a storage battery bank and also analyzes the reliability of the systems, for the loss of power supply probability (LPSP) analysis. The Hourly mean solar radiation (HMSR) and standard deviation are used to simulate the radiation over a year. The major objective of this study was to take a multidisciplinary approach to problem solving which accounts for reliable system design .The objective functions were number of battery and number of PV module. 8736 irradiance level and wind speed data for a year was used for optimal design model of hybrid system. Wind turbine and PV power output were matched to a given load demand that was a load of a year. For every hour of a typical day in each month, power output of both a wind turbine and a PV module were calculated. Then for a given loss of Power Supply Probability, the combinations of a number of PV modules and a number of batteries were also calculated. The choice of the optimum number of PV modules and batteries was based on the minimum cost of the system.

Nomenclature

A Current change temperature coefficient at reference insolation (Amps/^{o}C)
β Voltage change temperature coefficient at reference insolation (Volts/^{o}C)
I Module Current (Amps)
Imp Module Maximum Power Current (Amps)
Isc Module Short Circuit Current (Amps)
S Total Tilt Insolation (W/sq.m)
Sref Reference Insolation (W/sq.m)
Rs Module Series Resistance (Ohms)
T Cell Temperature (^{o}C)
T_A Ambient Temperature (^{o}C)
Tref Reference Temperature (^{o}C)
Δ*T* Change in Cell Temperature (^{o}C)
V Module Voltage (Volts)
Vmp Module Maximum Power Voltage (Volts)
Voc Module Open Circuit Voltage (Volts)
Ppv Power generated due to PV module (KW)
V Wind speed at projected height, H (m/s)
Vi Wind speed at reference height, Hi (m/s)
α 1/7, Power law exponent
Pr Rated electrical power (KW)
Vc cut in wind speed (m/s)
Vr rated wind speed (m/s)
Vf cut off wind speed (m/s) (1)
Pw power generated by Wind turbine (KW)
$E_{B(t)}$ energy stored in batteries at any time t (KW)
E_{Bmin} battery minimum allowable energy level (KW)
η_{in} efficiency of the inverter
ηbatt,in round-trip efficiency of the batteries
EB(t) energy stored in batteries in hour t(KW)
EB(t-1) energy stored in batteries in previous hour(KW)
EL(t) load demand in hour t. (KW)
Ew(t) energy generated by wind turbine(KW),
EPV(t) energy generated by a PV module (KW)
NPV number of PV modules in a PV Array
LPSP loss of power supply probability
LPS(t) loss of power supply at hour t.
T period of time

II. Renewable Power Generation Methodologies

2.1 Solar power Generation

Solar energy has been used in many traditional technologies for centuries and has come into widespread use where other power supplies are absent, such as in places far off from the national electrical grid and in space. Solar array connected in suitable module is a source of supply. Solar array modules are arranged so that there are sufficient series connected solar cells to generate enough voltage to charge a battery. Modules are arranged in series to increase the system voltages and in parallel to increase the system output current.

Calculation of the PV Module Average Power Output. The power output of the PV module P(s*)* is a product of the module output voltage and output current. The equivalent circuit of a PV module used is shown in Fig 1. PV module represents the fundamental power conversion unit of a PV system.

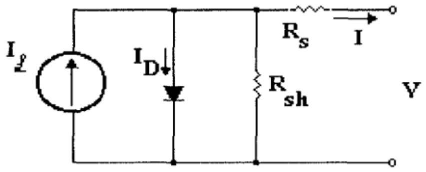

Fig 1. Equivalent Circuit of a PV Module.

In the calculation of the power output of a module, we assumed that a maximum power point tracker will be used. Manufacturers of PV modules supply information on the maximum power point voltage and current at reference temperature and irradiance. The module equivalent circuit output current ‘I’ can be expressed as a function of the module output voltage V.

$$I(V) = I_{sc}\left\{1 - C_1\left[\exp\left(\frac{V + \Delta V}{C_2 V_{oc}}\right) - 1\right]\right\} + \Delta I$$

where:

$$\begin{aligned} C_2 &= \frac{V_{mp}/V_{oc} - 1}{\ln\left(1 - I_{mp}/I_{sc}\right)} \\ C_1 &= \left(1 - I_{mp}/I_{sc}\right)\cdot \exp\left[-V_{mp}/\left(C_2 \cdot V_{oc}\right)\right] \\ \Delta I &= \alpha\left(S/S_{ref}\right)\Delta T + \left(S/S_{ref} - 1\right)\cdot I_{sc} \\ \Delta V &= -\beta \cdot \Delta T - R_s \cdot \Delta I \\ \Delta T &= T - T_{ref} \\ T &= T_A + 0.02 \cdot S \end{aligned} \qquad (1)$$

Then module output voltage and Power generated are calculated using the formulas given below.

$P_{pv} = V*I - I^2 R_S$

MATLAB R2007a program is used for the calculation of solar power and the Graph is plotted between the solar power and the solar radiation as shown in fig 2.

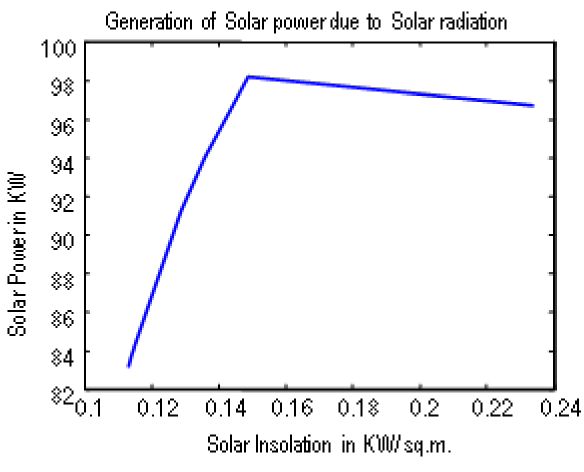

Fig 2. Variation of solar power with solar Radiation for 100W SPV array

2.2 Wind electric system

Wind energy is ample, renewable, widely distributed, clean, and works against the greenhouse effect if used to replace the use of fossil-fuel. Wind power is used in large scale wind farms for national electrical grids as well as in small individual turbines for providing electricity to rural residences or grid-isolated locations. The speed of Wind is a random process therefore modeling of wind speed should describe in such a way to satisfy its random nature. The wind speed data were recorded near the ground surface. It should be converted to hub height using the required formula.

Calculation of Wind speed
The formula used for the calculation of wind speed is given as below

$V = Vi\,(H/Hi)^{\alpha}$ (2)

Calculation of available Wind generator power is performed with the help of following formulas. The available wind generator power output is a function of the wind velocity. This wind power is calculated for each hour of a typical day in every month.

$Pw = Pr\,(V-Vc) / (Vr-Vc)$ for $(Vc \leq V \leq Vr)$ (3)

$Pw = Pr$ for$(Vr \leq V \leq Vf)$
$Pw = 0$ otherwise

The plot of wind power versus wind velocity is illustrated as shown in Fig 3 .

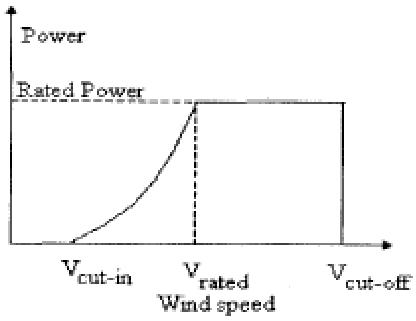

Fig 3. Power Wind Speed characteristics

2.3 Model Used for Solar/ Wind Hybrid System.

The initial cost of the renewable generation facilities is quite expensive and there is also maintenance cost. Thus it is desirable to make use of renewable in an appropriate fashion in order to achieve a cost effective and reliable autonomous hybrid power generation system (Fig 4). A suitable combination of these power sources is able to reduce the generation costs as well as enhance the overall system reliability. In this project the calculation of the optimum number of photovoltaic modules and batteries was based upon a Loss of Power Supply Probability (LPSP) concept and the economics of the system.

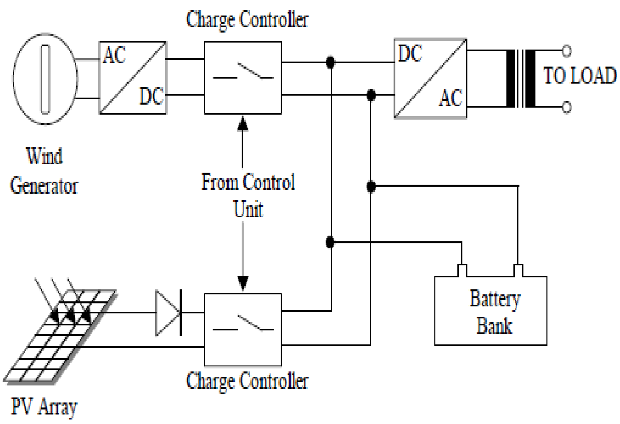

Fig. 4. Wind/PV Hybrid system

Loss of Power Supply Probability (LPSP)

Loss of Power Supply Probability can be defined as the long-term average fraction of the load that is not supplied by a stand-alone system.Energy is stored in batteries when the generated power by the wind turbine and PV array is greater than the load. When the power generated is less than the load, the energy is taken from the batteries. The state of charge of the batteries was used as a decision variable for the control of the overcharge and discharge. The case of overcharge may occur when high power is generated by the photovoltaic and wind

turbine, or when low load demand exists. In such a case when the state of charge of the batteries reaches the maximum value B_{max} the control system intervenes and stops the charging process.
On the other hand, if the state of charge decreases to a minimum level B_{min} the control system disconnects the load. This is important to prevent batteries against shortening their life or even their destruction**.** In terms of state of charge of batteries, the loss of Power Supply Probability can be therefore defined as:

LPSP = Pr {$E_{B(t)} \leq E_{Bmin}$; for $t \leq T$) (4)

i.e. the probability of the state of charge at any accumulative time *t*, within the time period *T*, to be less or equal than the minimum level E_{Bmin}.

Simulation Model

The performance of batteries is complicated and cannot be precisely predicted for uncontrolled charge/discharge cycles in stand-alone systems. Moreover, the battery capacity is defined in terms of the amount of energy that can be extracted, not the amount that is actually stored. Therefore, the battery charge efficiency was set equal to the round-trip efficiency, and the discharge efficiency was set equal to 1. The inverter is rated in terms of the peak load demand. The efficiency of the inverter is a function of the ratio of actual load to the inverter's rating. In this paper, we used a constant value of inverter efficiency based on the average load demand.

Derivation of the Simulation Model

The energy generated by wind turbine and PV array for hour t , EG(t) can be expressed as follows:

$EG(t) = Ew(t) + NPV \times EPV(t)$ (5)

Since we assumed that the battery charge efficiency is set equal to the round-trip efficiency and the discharge efficiency is set equal to 1, we considered two cases in expressing current energy stored in the batteries for hour t. If the generated energy from the wind turbine and PV array exceeds that of the load demand, the batteries will be charged with the round-trip efficiency.

$EB(t)=EB(t-1)+(EG(t)-EL(t)/\eta in.).\eta batt,in$ (6)

When the load demand is greater than the available energy generated, the batteries will be discharged by the amount that is needed to cover the deficit. It can be expressed as follows:

$EB(t)=EB(t-1)-\{EL(t)/\eta in-EG(t)\}$ (7)

Constraints

The energy stored in batteries at any hour t is subject to the following constraint:

$EBmin \leq EB(t) \leq EBmax$ (8)

The generated power is subjected to following constraint

$EG(t) > EL$.

When the available energy generated and stored in batteries is insufficient to satisfy the load demand for hour t, that deficit is called as Loss of Power Supply for hour t and can be expressed as:

$LPS(t)=EL(t)-\{EG(t)+EB(t-1)-EBmin\}\eta inv$ (9)

The Loss of Power Supply Probability for a considered period of time T is the ratio of all LPS(t) values for that period to the sum of the load demand. This can be defined as-

$LPSP=\sum LPS(t)/\sum EL(t)$ for$(1 \leq T)$ (10)

Once the available energy generated from both a wind turbine and a PV module was determined in the previous steps for every hour of a typical day in each month, different combinations of the number of PV modules and the number of batteries could be calculated for a desired LPSP.

Optimization Technique used

Graphical optimization is performed for the calculation of optimum number of PV modules and batteries for different values of loss of power supply probabilities. The costing is performed for different number of batteries and PV modules. Then graphs are plotted taking number of batteries on x axis and LPSP, cost on Y axis. The same procedure is done for number of PV modules. Variation of LPSP is observed for different values of PV modules .Then graph is plotted taking number of PV modules on X axis and Cost and LPSP on Y axis. Optimized values are obtained at the intersection of the graphs. The optimal point will give the optimized design number of objective variables.

III. Results and Discussions

The specifications used for the PV module considered in the program are as given below.

Table 1. Specifications of PV module

Vsc (v)	Isc (A)	Vmax (v)	Imax (A)	Pmax (W)	Cost ($)
21	6.5	17	5.73	100	6500

The specifications used for Wind turbine are as follows

Table 2. Specifications of the Wind turbine.

Pr (KW)	vc (m/s)	Vr (m/s)	vf (m/s)	H(m)	Hi (m)
6	2.5	10	25	20	8

3.1 Optimization of battery number for IEEE hourly load pattern

The results of optimization of battery number are summarized in Table 2. As we go on increasing the generation capacity by increasing number of battery, we are improving the loss of power supply probability. By considering the cost variation Hybrid system is optimized with the help of graphical optimization technique.

Solar and Wind speed Data used for IEEE hourly load pattern

Fig 5 & 6 shows meterological parameters i.e. 8736 solar irradiation level and Wind speed data of an year for IEEE hourly load pattern

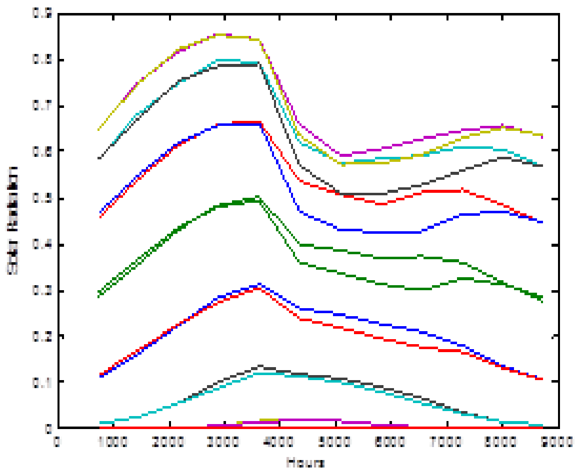

Fig 5. Solar radiation data for IEEE hourly load system

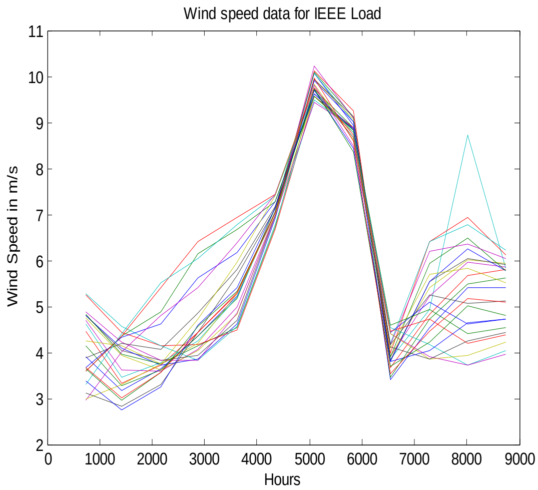

Fig 6. Wind speed data for IEEE hourly load system

The results of optimal sizing for IEEE hourly load pattern are given in Table 3. In the Fig. 7, the optimal design number for battery is coming as 4 and corresponding optimized cost of 4 batteries will be $ 6000.

Table 3. Optimal sizing results for number of batteries for IEEE load

Npv	Nbat	Cbat (Ah)	LPSP	Price (1500 US $ / KW / battery)
10	2	100	0.7025	3000
10	3	100	0.6867	4500
10	4	100	0.6709	6000
10	6	100	0.6393	9000
10	8	100	0.6077	12000
10	10	100	0.5762	15000
10	12	100	0.5446	18000

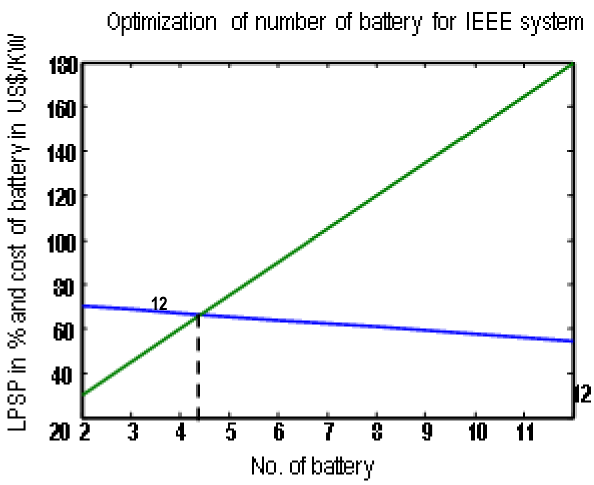

Fig 7. Optimization of battery number for IEEE hourly load system

Optimization of number of PV module for IEEE hourly load pattern system.

As we increase number of PV modules by keeping number of battery constant LPSP is decreasing i.e it is improving.The results obtained are given in Table4. As seen from Fig.8, the optimal design number for PV module is coming as 10 and the optimized cost of 10 PV modules will be 65000 $.

Table 4. Optimal sizing results for number PV modules for IEEE load

Npv	Nbat	Cbat (Ah)	LPSP	Price (6500 US $ /KW /PV module)
6	5	100	0.6836	39000
8	5	100	0.6694	52000
10	5	100	0.6551	65000
12	5	100	0.6409	78000
14	5	100	0.6266	91000

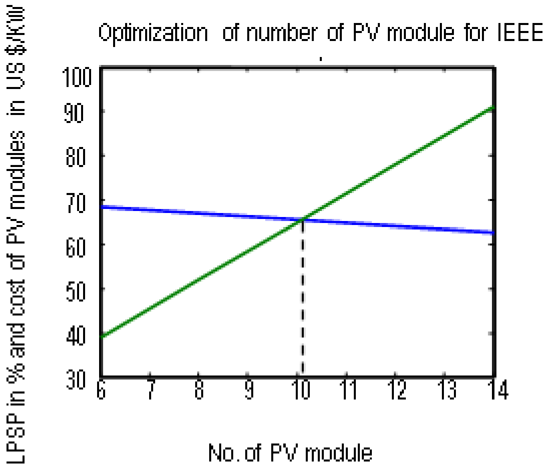

Fig 8. Optimization of PV module number for IEEE hourly load system.

IV. Conclusion

A methodology for calculation of the optimum size of a battery bank and the optimum size of a PV array in a hybrid wind/PV system for a given load is interesting because it allows to study technico-economic aspects of a hybrid system with two renewable system (Wind generator and Solar module) and electrochemical storage system (battery bank). It is based on the use of long term data for both wind speed and irradiance levels. The power outputs of both the wind turbine and the PV module were calculated. For a given Loss of Power Supply Probability, a different combination of the number of PV modules and the number of batteries was calculated. An optimum design choice depends on the relative costs of a PV module and a battery. We assumed that total cost of the system is linearly related to both the number of PV modules and the number of batteries. The minimum cost will be at the point at which cost line and the LPSP line are intersecting. The optimal design value for number of battery is 4 which costs 6000$ for IEEE. The optimal design number for PV module in IEEE system is 10 with optimized cost 65000 $. By increasing the number of objective variables i.e. battery number, PV module number decreases loss of power supply probability and improves the reliability of the Hybrid system. With the help of optimization technique we have been able to reduce the cost of hybrid system. The optimum mix of PV modules and batteries depends on the particular site, load profile, and the desired reliability of the hybrid system. The results obtained depend upon the quality of the simulation model and the representivity of the data.

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