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Design and Optimization of Wind-PV-Battery Hybrid System Suitable for Low Wind Speed Area

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Abstract

Renewable system is playing an important role to generate electricity at remote location where grid extension and electricity generation from fossil fuel is not an economical option.Combination of two or more renewable resources can generate a better solution because of their complementary nature of occurrence, such combination is known as Hybrid System. Current paper discusses a techno- economic analysis of PVWind battery hybrid system suitable for low wind speed area where set of feasible solutions are obtained to satisfy the load demand. The minimum battery size has been identified on battery size vs. total generated power and all such points are represented on graph known as design space. Optimum configuration identified for only PV-Battery system is 1.50 kW PV array, 1.01kWh battery capacity and cost of energy is 10.72Rs/kWh. While for PV-Wind-Battery system the optimum configuration is 1.43 kW PV array, 600 W wind turbine, 18.1 kWh battery capacity with cost of energy is 20.30 Rs/kWh. Inputs to the model are one year monthly averaged solar radiations and wind speed data with daily load demand of 5kWhr/day.

Keywords:*Design space, Renewable hybrid system, system sizing, Blade element momentum theory*

1. Introduction

Nearly 50 % of India's rural population, around 80 million households has little or no access to grid-based electricity. This unmet electricity demand and Indian Governments ambitious target of generating over150 GW Renewable energy by 2020 presents the huge opportunities for Distributed renewable energy systems

Ease of availability, negligible fuel cost, environmentally friendly nature, ease of extensibility etc. are the main advantages of renewable energy systems. The power available from renewable resources is stochastic in nature however some renewable resources like solar and wind are complementary to each other. By hybridizing such complementary nature of resources a cost effective and reliable power generation solutions is possible at remote location and applicable for several applications such as public area lightening, schools, health clinics, water pumping, water purification, rural telephony etc. Proper sizing is the key requirement for designing the hybrid system. Sizing of hybrid system involve Design of individual component, its simulation and followed by its optimization. Reviewing the several literatures the common issues in hybrid system sizing are as follow:

- The uncertain nature of resources puts restriction on selection of individual component size, sometimes which leads to oversize the system and increase the system cost.
- Energy coming from PV- Wind resources fluctuates with respect to time although it satisfies load demand, sizing an external storage device for such fluctuation and given power reliability is crucial task.
- Mutual dependence between V_c, V_r, and P_r is not taken into account by various models which leads to erroneous sizing.[3]
- Coefficient of performance C_p of small wind electric generators (SWEG) is lower as compared to the large wind turbines so its need to improve $C_p$especially in low wind speed regimes. [2]
- Energy loss in part loads operation of wind turbine because of not optimum selection of rotor diameter with rated wind generator. [3]
- The cost per kW of small wind electric generator (SWEG) are more expensive as compared to large wind turbines.[2]
- Initial investment cost of hybrid system is rather high, proper system integration will help to reduce system cost.

Proper modeling of each individual system component can helps to minimize these issues. Designing a model for particular application is done on the basis of availability of data, complexity of model and desired accuracy. Power curve model of wind machine is important for the power performance prediction of wind turbine. (Sohoni et al.(2016)) Studied various power curve modeling methods and conclude that polynomial approximation based power curve models in which power output relates to the rated(V_r) , cut in(V_c) , cut off (V_f) wind velocities and rated power (P_r) have been use widely for predicting the power during initial resource assessment and designing a small system. These models generate less accurate results but main drawback of this model is that they don't take care of mutual dependence between V_c, V_r and P_r values. (Notton et al., 2001) examined five different normalized power curve models for different wind turbines in order to predict their power output and conclude that power curve profile of the wind turbine must be imperatively specified during sizing of isolated hybrid system.

Another important concept relating to the power of wind turbines is the optimal tip speed ratio, which is defined as the ratio of the speed of the rotor tip to the free stream wind speed. If a rotor rotates too slowly, it allows too much wind to pass through undisturbed, and thus does not extract as much as energy as it could within the limits of the Betz Criterion. On the other hand, if the rotor rotates too quickly, it appears to the wind as a large flat disc, which creates a large amount of drag. The rotor Tip Speed Ratio, TSR depends on the blade airfoil profile used, the number of blades, and the type of wind turbine. (Roy et al., 2009) employed a power coefficient (C_p) v/s tip speed ratio (λ) characteristics of wind turbine to predict the power performance of wind turbine which is modeled by blade element momentum methodology. In time series simulation varying the generator rating with rotor diameter is necessary to minimize part load operation of turbine and to get an optimum solution, which can be done by integrating and simulating the above parameters.

Modeling of each component is followed by the proper sizing of it. Sizing provides the flexibility to designer to choose proper combination of system component with desired reliability and less system cost. Typically Deterministic and probabilistic are the two primarily sizing approaches used for designing and simulation of hybrid system (Deshmukh and Deshmukh et al., 2008). In deterministic approaches sources and demand considered as deterministic quantities and variation with respect to time is assumed to be known. In this methods the chronological sequence of data is extremely important sometimes calculations based on the worst case scenario (worst month) can be used in designing the system (Protogeropoulos et al.,1997Cleik.,2003; Morgon., 1996) however design obtained by this kind of methodologies tends to be oversized because of the worst case has low occurrence of probability or the average values not constant values all the time. In probability based approaches energy generated by power source and load demand considered as random variables. (Yang et al., 2008) sizes the wind PV and battery bank system for standalone applications by keeping the LPSP as a design constraint.

A graphical representation of all designed possible option is known as design space. For isolated power system the representation of design space is used for optimization of PV battery system by (Arun et al.,2007) and wind battery system by (Roy et al., 2009). In this paper set of feasible configuration of Wind-PV-Battery system is calculated to satisfy 5kWh daily load at respective site by analyzing manufacturer supplied power curve. Adesign space approach is proposed for Wind-PV-Battery isolated hybrid system by incorporating effect of varying rotor diameter.

2. Modeling of Hybrid System

Hybrid solar-wind system consists of PV array, wind machine, battery for energy storage, inverter, charge controller and power cables. The PV panel and wind turbine together generate power to satisfy the load demand. To generate more accurate results, incorporate system losses and different system characteristics into model. Individual component should be modeled initially and then their combination can be evaluated to satisfy the desired load output. Thus a Mathematical modeling of PV power generation, WT power performance and system energy balance is necessary. Following section discuss a detail mathematical modeling of each component.

2.1 Modeling of PV Array

Power generated by PV panel is depends upon various parameters ambient temperature, voltage and current characteristics, solar irradiation, wind speed etc.The power generation by the photovoltaic system is given as (Sreeraj et al., 2010).

$$P_{PV} = \eta_p A_p I_T \ldots\ldots\ldots (1)$$

Where η_p is the PV system efficiency, I_T is the total radiation incident on tilted surface (W/m^2) at particular time step, and $A_P$is the total PV panel area (m2). The effect of temperature on module efficiency is given by following equations

$$\eta_p = \eta_r\left[1 - \alpha\left(T_c - T_{cref}\right)\right]\ldots\ldots\ldots (2)$$

Where η_r is the PV module reference efficiency, α is the temperature coefficient power and its value is ,T_{cref} is the reference solar cell temperature and T_c is the solar cell temperature. Solar cell temperature further expressed as

$$T_c = T_a + [(NOCT - 20)/800]I_t \ldots\ldots (3)$$

Where$T_a$represents the ambient air temperature while NOCT is the nominal operating cell temperature.

Total incident radiation on tilted surface is calculated as (Sukhatme et al., 2006)

$$I_t = \left(I_g - I_d\right)r_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I_T\left(\frac{1-\cos\beta}{2}\right)\ldots\ldots\ldots (4)$$

Where Ig is the hourly global radiation received on flat surface (W/m^2),Id diffuse radiation (W/ m^2), ρ is the ground reflectivity,r_b is the tilt factor and β is the angle of inclination. The module efficiency of PV array is decreases by 3% - 5% per day due to dust particle. So incorporating the effect of dust particle on PV module efficiency is necessary. In Current model 3% dust effect is considered.

2.2 Modeling of Wind Turbine power curve

To calculate the optimum configuration of wind PV battery system primarily the simulation done with manufacturers supplied power curve. The W200 wind turbine model is selected for analysis which is taken from WISH energy Pvt. Ltd Pune. The product of generator efficiency and coefficient of power is kept constant and supplied power curve is modified further way and it shown as below

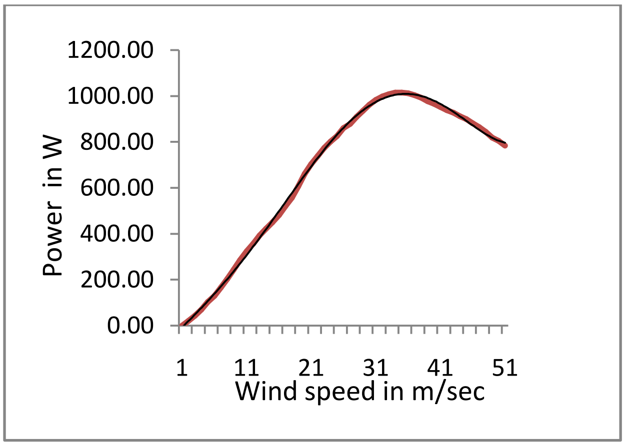

Fig 1: Analysis of Manufactured power curve

The polynomial equation of power curve W200 is used for further analysis is as below

$y = .00003v^5 - 0.0028v^4 + 0.0772v^3 - 0.3524v^2 + 29.25v - 37.484$ …….. (5)

R^2=0.9987 ……. (6)

The deterministic constant which represents the variability of polynomial equation around the mean value. So here it is represents that polynomial curve an varies only by 1 %with the manufactured supplied power curve. Respective polynomial equation is taken for the simulation purpose and system sizing is carried out for given load demand. To analyses the effect of changing rotor blade diameter and to finding out optimum rotor diameter for given rated wind machine blade element momentum theory is used.

2.3Effect of change in blade diameter by using blade element momentum (BEM) theory

Power performance of wind machine depends upon various subcomponents, rotor dia., gear transmission, electrical generator and different control mechanism employed. So to predicted power generated by wind machine, behavior of these subcomponent need to integrate and incorporate into various models .The power coefficient (C_p) vs. tip speed ratio (λ) characteristics model using the blade element momentum methodology is employed in current paper. (Roy et al., 2009).

The coefficients of power C_p is calculated for each rotor diameter by varying the tip speed ratio is as given below

$$C_p = \frac{B}{\Pi R^2}\int_{r_h}^{r_t} c_i\,\lambda_{ri}(1-a_i)^2\frac{F_{li}}{\sin\Phi_i}\left(1-\frac{F_{di}}{F_{li}}\right)dr \quad ……(7)$$

Where λ is tip speed ratio at ith element from hub of the turbine, r_h and r_t the radii at wind machine hub and blade tip respectively and B is the total number of blades. F_{di} and F_{li} are the coefficients of drag and lift forces respectively at element i, $\Phi$is relative flow angle which the angle between relative wind velocity and plane of rotation.$a_i$is the axial induction factor.

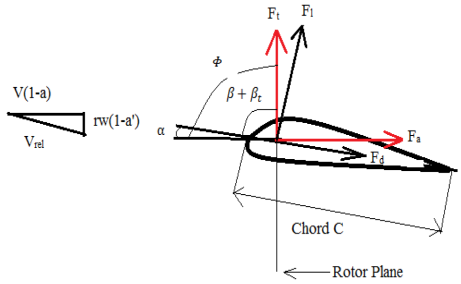

Fig 2: Blade element geometry with associated forces and angles.

By using C_p-λcharacteristics, mechanical power generated by the wind rotor shaft (P_m) at different velocities is given by(Roy et al., 2009)

$$P_m = \begin{cases} \frac{1}{2}\rho A V^3 C_{pmax} & V_c \le V \le V_r \\ P_r V_r & \ll V \ll V_f \\ 0 & V \ge V_f \end{cases} \quad ……. (8)$$

P_r is generated power by wind machine at rated speed V_r. Torque is available at output shaft of wind machine is as given below

$$P_t = P_m \eta_m \quad ……. (9)$$

Electrical generator power outputP_g from wind machine is as follow

$$P_g = P_t - P_{loss} \quad …… (10)$$

Where
P_{loss} is the total generator loss in wind machine.

2.3 Wind-PV –Battery hybrid system configuration and energy balance

The schematic of PV- wind- battery isolated hybrid power system is shown in above fig 3. Wind machine, AC load is attached to the AC bus while PV panel, battery bank and dump load is attached to the DC bus. A bidirectional inverter separates the two buses and transfers the energy from dc to ac and vice versa. By using energy balance principle the time series simulation of overall system is performed to find out the size of minimum battery where the average power generated by each power source is know from the available wind speed and solar radiation data and power source capacity. The dump load is provided in system to withdraw the excess power when battery gets fully charged.

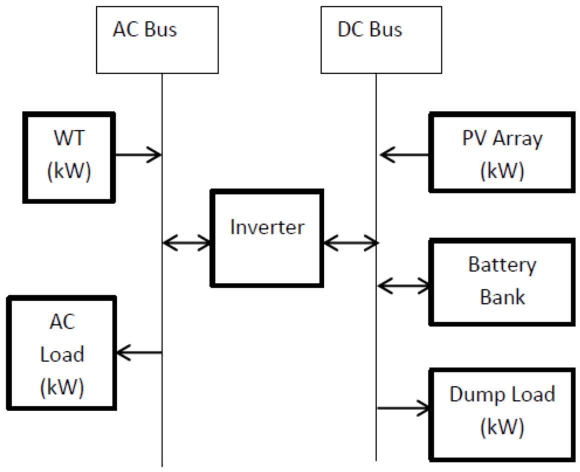

Fig3: Graphical representation of wind-PV-battery isolated hybrid power system.

Power dispatchstrategy of a wind–PV- battery hybrid system is as follow (Sreeraj et al., 2010):
$P_{net}(t)$ is the total power from wind turbine and Photovoltaic Panel. When this P_{net} (t) > load demand D (t) then power available for charging the battery is given as
$P_{net}(t)$=[power generated by PV panel + (power from wind turbine-AC load) * converter efficiency]

$$Pnet(t) = [\Sigma P_{pv}(t)+(\Sigma(P_{wt}(t)-D(t))\ k(t)] \quad \text{..... (11)}$$

Where k (t) = converter efficiency

$K_{(t)} = \eta$ when $P_{wt}(t) > D(t)$ ...... (12)
$K_{(t)}=1/\eta$ otherwise

If the battery is fully charged and excess power generated by the sources are available at DC bus then this excess simply sent to the dump load so the change in battery charge at each time step is equal to Net power available at battery size minus dumped power at each time step

$$D_{qB}(t)/dt = (P_{net}(t) - P_{du}(t))\ f(t) \quad \text{....... (13)}$$

Where f(t) is the battery charging and discharging efficiency

$f(t)= \eta_c$ when $P_{net}(t) \geq 0$
$f(t)= 1/\eta_c$ when $P_{net}(t)<0$

The changes in battery size at each time step is described as follow

$$q_B(t+\Delta t) = q_B(t) + \int_t^{t+\Delta t}(P_{net}(t) - P_{du}(t))f(t)dt \ldots\ldots (14)$$

With using the equation (10) in equation (13) we get a battery size as particular time step is as follow

$$q_B(t+\Delta t) = q_B(t) + \int_t^{t+\Delta t}\left([Ppv(t) + \left((Pwt(t) - D(t)\right)k(t)\right] - P_{du}(t)\Big)f(t)dt \ldots\ldots (15)$$

Some constraint has to be taken into consideration when finding out the minimum battery size those are as below

$$q_B(t) \geq 0 \quad \text{.......... (16)}$$

$$q_B(t=0) = q_B(t=T) \quad \text{..........(17)}$$

Equation (16) ensures the battery charge level is always positive within the time interval T and equation (17) represents the battery state of energy at start is equal to the battery state of charge at the end of time. if the initial and final charge level of battery is not equal then the battery charge will accumulate or deplete over the time. Then required battery capacity is determined as

$$B_r = \frac{\max(q_B(t))}{DOD} \quad \text{...... (18)}$$

Where DOD is the allowable depth up to which battery can discharge. The optimization variable are the initial battery energy $q_B(t=0)$ and the power dumped at each time step $P_{du}(t)$. The proposed methodology helps to identify the set of possible and impossible combination of PV panel and WT turbine rating with respective battery size for satisfy the load demand.

2.4.1System Optimization

The set of all possible combination which can satisfy the load demand forms a design space. After finding out the design space next objective is to find out the minimum energy cost generated by hybrid system.

$$COE = \frac{\sum ACC + \sum AOM}{E_{Delivered}} \quad \text{..... (19)}$$

Where AOM is the annual operating and maintenance cost, And E total supplied energy to meet the load, ACC is the capital cost over the year which is calculated as follow:

$$ACC = \sum_i C_{0i}.CRF_i \quad \text{...... (20)}$$

Where C_{0i} is the capital cost of i^{th} system component like PV panel, Wind turbine, battery bank, inverter etc.

$$CRF_i = \frac{d(1+d)^{n_i}}{(1+d)^{n_i}-1} \quad \text{......... (21)}$$

CRFi is system components capital recovery factor and which is depends upon rate of discount (d) and life function(n)

2.5 Sizing curve and design space

Whenever total rating (PV+wind) is increases from P_{min} the battery size get reduced to satisfies a required load demand in such conditions excess energy need to dump, by varying the total rating higher than the P_{min} minimum battery size is obtained at each rating. the curve which represents locus of minimum storage capacity is called as sizing curve. It divides design space into two regions one is feasible and other is infeasible. Feasible design option are shown above the sizing curve and remaining region except of sizing curve is infeasible.

3. Illustrative Example

PimpriChinchwadcollege of engineering situated at Akurdi station at mean see level of 580 m $(18^0 32' N, 73^0 51' E)$ Nigdi Pune is chosen for study. The hourly load variation at particular day in Heat power lab no.101 of mechanical department is shown in fig below

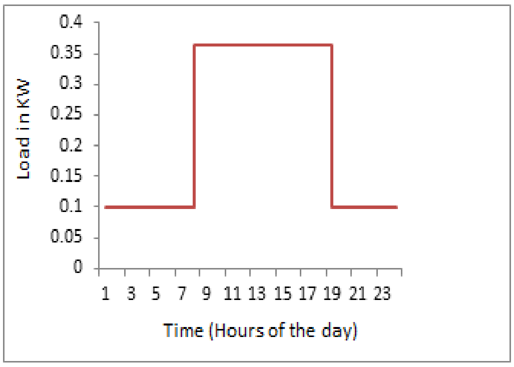

Fig4: Hourly load variation at Heat power lab no.101

The average and peak load during a representative day are 0.210 kW and 0.365 kW respectively the daily energy requirement is 5 kWh. The solar radiation and wind speed resource data for the entire year 2016 is measured with the help of data monitoring device placed at PCCOE rooftop (25 m from ground level). The monthly average hourly estimated wind speed (m/sec) for 24 hours over the year as shown in following fig 5 .the average wind velocity over the entire is observed between 2-4 m/s at mast height. The wind speed with standard deviation for particular month of June is shown in fig6, the wind speed at turbine height Z is calculated by following correlation

$$v = v_i \left(\frac{Z}{Z_i}\right)^{\alpha} \ldots\ldots (22)$$

Where α is known as power law index,(A.Mani)

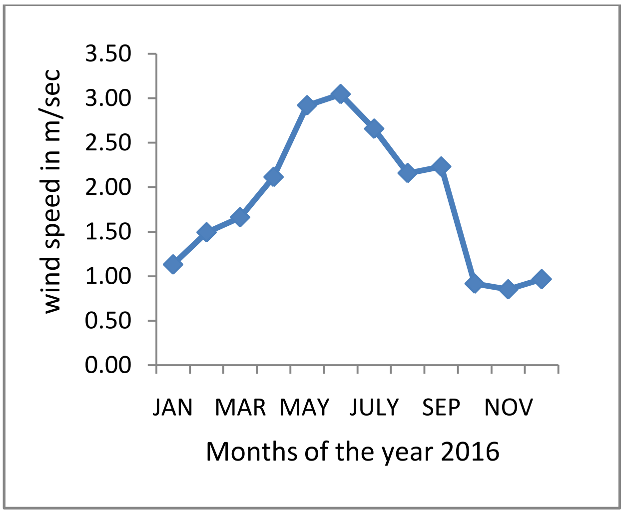

Fig5: Monthly average of hourly estimated wind speed (m/s) for entire year.

The monthly average daily global solar radiation for the year 2016 is as shown in following fig 6 .The maximum monthly averages daily global solar radiation about 724.82 W/m2 is observed in year 2016.

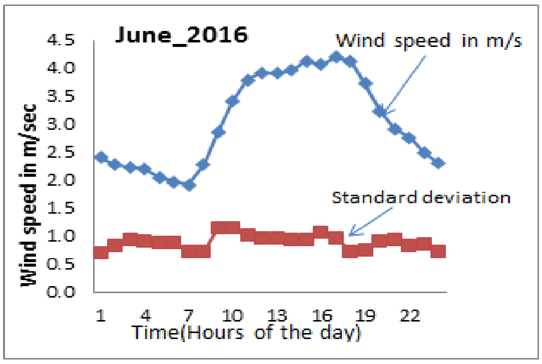

Fig6:Wind speed (m/s) and standard deviation graph in month of June 2016

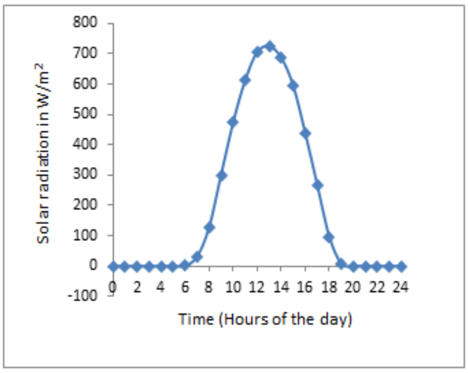

Fig7: Monthly average of hourly estimated solar radiation (W/m²) for entire year2016

4. Results and Discussion

4.1 PV-Battery system

The set of PV array, battery combinations has simulated to satisfy the entire load demand during the year. PV array rating is varied from 0.250 kWp to 2 kWp. Minimum battery capacity required to satisfy the load is determined and sizing curve of the system is generated from locus of all such points (possible combinations). The minimum battery capacity required to satisfy the load demand is continuously decreasing till a certain point and after this it will remains constant. This is because the mismatch between generated energy and load demanddue to no solar radiation during night time. The optimum configuration of PV –battery system to satisfy entire load demand during the year is 1.35 kWp PV array with 2.658 kWh battery capacities. The minimum cost of energy is determined for optimum configuration is 11.75Rs/kWh. From fig this optimum combination represents the maximum amount of storage with minimum PV array capacity. The minimum cost of energy is observed is 10.72 Rs/kWh forsizing1.5 KW PV capacity. The detail cost analysis is shown in table no. 1

Table1: Cost analysis of PV-battery system

PV (kW)	Battery size(kWh)	COE(Rs/kWh)
1.365	2.658	11.83
1.425	1.75	11.14
1.500	1.017	10.72
1.725	1.013	11.92
1.800	1.012	12.32
1.950	1.009	13.13

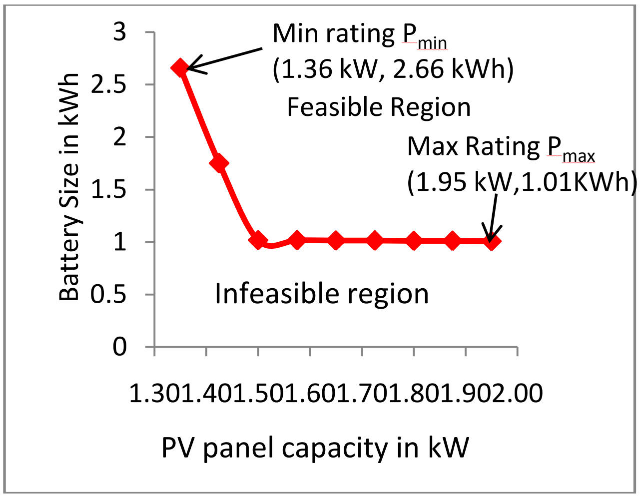

Fig8: Sizing Curve for PV-Battery system

4.2 PV-Wind–Battery system

In this section Power generated by wind turbine with conventional power curve and with changing blade diameter is analyzed. The minimum battery requirement for each combination of total generator power with varying diameter is identified3.2.1 Simulation with Conventional wind turbineSelection of conventional wind turbine with given rotor diameter is taken such a way that it at least produce power equivalent to or greater than the required load demand. So W200 wind turbine model which generate maximum peak power of 600 W at rated velocity Is selected for given problem. The optimum configuration of PV –Wind-battery system to satisfy entire load demand during the year is 1.82 kW total generators rating with 3.985 kWh battery capacity. The cost of energy generation with this optimum configuration is 20.30 Rs/ kWh. The set of minimum battery sizes for different PV and wind combinations are simulated and plotted in below fig.9

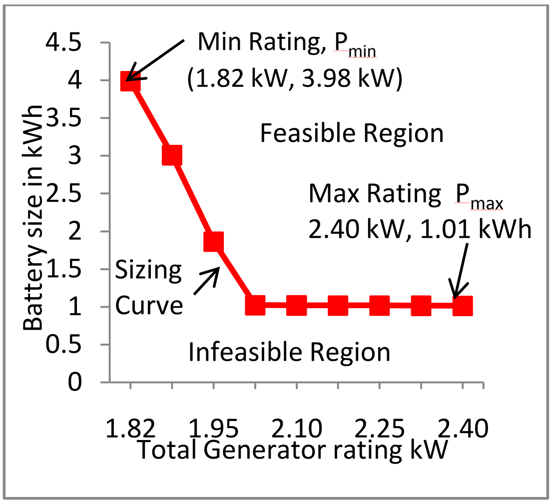

Fig9: Sizing curve for Wind-PV-Battery hybrid system.

Also a simulation is done with 2kW Wind machine and two 600W wind machine. Optimum battery size is obtained for combining PV panel with these machines and sizing curve with respect to total generator rating is plotted in given fig10

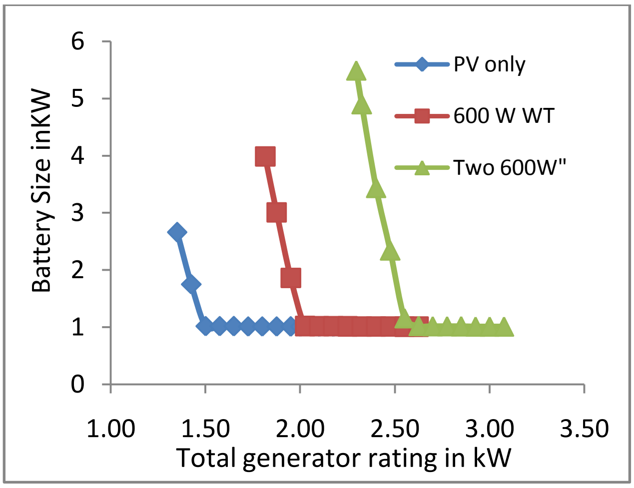

Fig10: Sizing curve with different generator rating of wind turbine

PV-battery system gives a economical solution as compared to other combinations.

4.3 Simulation with varying Blade Diameter

Swept area of wind turbine is increased by increasing its rotor diameter due to this it is possible to extract maximum power at available wind speed. There is restriction on selection of minimum and maximum rotor dia because small rotor dia is fail to capture the adequate energy to meet the demand load while the hub height of turbine puts restriction to choose maximum diameter. The 3m minimum and 5m maximum rotor diameter is selected for given simulation.

Table2: Input parameters used for system

Module efficiency	15%
Nominal operating cell temp(NOCT)	47^0
Turbine hub height (m)	10 m
Power law index	0.46
Swept area (m^2)	5.8
Cut in wind speed(Vc) m/s	3.1
Rated wind speed(Vr) m/s	11.6 to 13
Cut-off wind speed(Vf) m/s	16 to 18
Battery charging and discharging efficiency (%)	90
Depth of discharge (%)	60

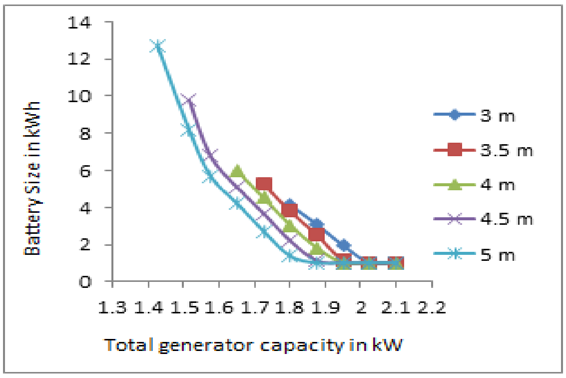

Fig11: Battery size vs total generator rating with varying blade diameter.

The battery size is continuously decreases as increase the blade diameter of 600 W rated wind turbine. This will happens till total generator rating below 2 kW after 2kW total generation the battery size will remains constant and that will be 1.005 kWh.

Table3 Battery size variation with same generator rating at varying rotor diameter.

Diameter (m)	Total(kW)	Battery(kWh)
3	1.8	4.12
3.5	1.8	3.799
4	1.8	3.051
4.5	1.8	2.211
5	1.8	1.387

Conclusion:

1. A techno economical study of Wind PV-battery hybrid system with varying blade diameter of wind turbine is taken place at PCCOE (PimpriChinchwadcollege of engg) location. As blade diameter increase through a certain limit battery size will get reduced to some extent and further it keep constant.
2. The optimum configuration corresponding to PV-battery system with no wind turbine it is an economical solution than the PV wind Battery hybrid system for current location.
3. The set of possible solution to satisfy load demand at given resource condition is identified and Generated the sizing curve which is further helps to designer to choose optimum combination of wind PV battery system for current location.

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