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A WIND-BATTERY OPTIMAL DESIGN ALGORITHM FOR POWER GENERATION SYSTEM

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ABSTRACT

This paper presents an optimal design with improved algorithm for optimal sizing of the standalone wind-battery power generation system, reporting minimum total cost of the system with satisfying the requirement of power supply reliability. The adopted method is found to be superior over earlier traditional methods. The energy storage system using a kinetic battery model may act as a source or a load according to the wind power output and loading conditions. Battery lifetime decides the lifetime of the system. The method proposed increase the lifetime of the system considering all the battery constraints.

Keywords: wind-battery power system, optimal sizing method, power supply reliability.

1. INTRODUCTION

Generation of power from renewable is now a day's more in practice. Renewable energy does not count any environmental pollution and fuel cost. Various resources such as wind, photovoltaic (PV), hydro are used for electricity generation today. Energy crises and environmental problems faced by the mankind today has given rise to the distributed generation (DG) based on renewable [1]. Remote areas and isolated regions are getting benefited by the use of renewable today. Grid electricity is unable to reach these areas hence many small scale projects related to renewable are going on in the country to satisfy the needs of people regarding electricity [2]. However, these sources are uncertain in their nature and their outputs are fluctuant. To overcome this we need large capacity energy storage systems while in stand-alone mode. We need to design the system optimally [3], thus sizing the system will not only reduce the cost of the system but it will also improve its power supply reliability. Many single and multi-objective optimal sizing methods are used for stand-alone hybrid power generation system. Minimizing the system cost, with acquiring power supply reliability is the main object for optimization in single-objective optimal sizing method. Many methods such as enumerative methods, linear methods, iterative algorithms or genetic algorithms are used in optimization process [4]. Obtaining the optimal size by minimizing the system cost and satisfying the requirement of power system reliability is a traditional method and some of the factors are not considered in these traditional methods

a) Battery's charge /discharge current, rate, cycles as they can affect the lifetime of the battery [4].

b) Full utilization of the characteristics of wind and battery [6].

This work will try to include these factors and acquire reasonable model working in stand-alone mode. Battery parameters and wind power generation will be focused equally in the optimization process of this optimal sizing algorithm, unlike traditional method which focuses only on the system cost and the power supply reliability [5].

The organization of paper is as follows, II. Wind-Battery Model III. Energy Management Strategy IV. Optimal Sizing Methodology of the System V. conclusion

2. THE WIND-BATTERY SYSTEM MODEL

A small wind-battery system is shown in Figure-1. The wind turbine and battery-bank are coupled to the DC bus and further mathematical models of each component are explained,

i) Wind power generation model [4] [13]**:** The output power curve of a wind turbine is as shown in Figure-2 and it is described as

$$P_{wt} = \begin{cases} 0 & v_w < V_{ci} OR v_w > V_{co} \\ P_{wt\_r} \dfrac{v_w - V_{ci}}{V_r - V_{ci}} & V_{ci} \le v_w \le V_r \\ P_{wt\_r} & V_r \le v_w \le V_{co} \end{cases} \tag{1}$$

Where v_w is wind speed, V_r is the rated speed, V_{ci} is the cut-in speed, V_{co} is the cut-out speed and P_{wt_r} is the rated output power of the wind turbine.

ii) Battery model: The proposed model is based on the concept of the battery given by Manwell and McGowan. The concept

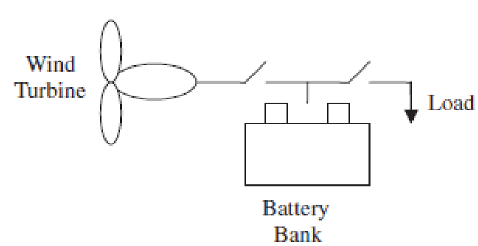

Figure-1. Small wind-battery system.

explains the battery as a two tank system based on electrochemical kinetics. One tank contains the energy readily available i.e. available energy' and the other tank contain 'bound energy' i.e. Energy which is chemically bound and will not be readily available for use. Figure-3 well explains the outline of the battery model. The maximum capacity of the battery is the total amount of energy the two tanks of the battery can contain [7]. The maximum battery capacity is denoted by Q_{max} . Q_1 and Q_2 are the available and bound energy, therefore

$$Q = Q_1 + Q_2 \quad (2)$$

Q_1 and Q_2 denotes the energies at the beginning and similarly the energies at the end are given using the parameters (c) is the capacity ratio, (k) is the rate constant, P_{bs} is the power in or out of the battery bank and Δt is the time step. The end energies are denoted by Q_{1_end} and Q_{2_end} [7].

Maximum charge and discharge power is also derived from the parameters listed above. The batteries terminal voltage V_{bs} is expressed as under [4].

$$V_{bs} = E_{bs} - I_{dch}R_0 \quad (3)$$

Where, R_0 = internal resistance

I_{dch} = discharge current
E_{bs} = effective internal voltage

3. ENERGY MANAGEMENT STRATEGY

In a stand-alone mode when power generated by the wind turbine is less than the load demand, the battery will be discharged. The power flow is expressed as

$$P_L(t) = P_{wt}(t) + P_{bs\_dch}(t) \quad (4)$$

And if total power generated is more than the load demand, the battery will be charged by excess power

$$P_L(t) = P_{wt}(t) - P_{bs\_ch}(t) \quad (5)$$

Where $P_L(t)$, $P_{wt}(t)$ are demand power of load and output power of wind turbine and $P_{bs\_dch}(t)$, $P_{bs\_ch}(t)$ are discharge and charge power of battery.

4. OPTIMAL SIZING METHODOLOGY

A. Evaluation indices for the proposed method

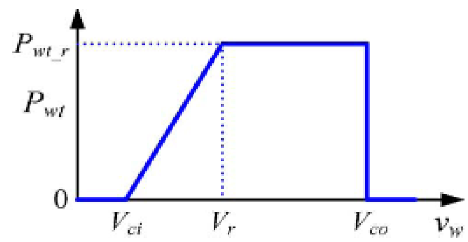

Figure-2. Output power curve of wind turbine.

a) Power supply reliability: The loss of power supply probability (LPSP) of the load evaluates the power supply reliability of the system and is given by

$$LPSP = \frac{\sum_{i=1}^{N}[P_L(t_i) - (Pwt(t_i) + P_{bs\_dch}(t_i))]}{\sum_{i=1}^{N} P_L(t_i)} \quad (6)$$

Here $t_1 \sim t_N$ is the operating time of the system.

The operating time here is 8760 hours (N=8760) and the daily operating time is 24 hours. LPSP should be very small, if LPSP = 1 then load is not satisfied but if LPSP = 0 then load is satisfied [8].

b) Total cost of the system: The stand alone system includes following costs. I. initial investment cost II. Operation and maintenance cost III. Replacement cost [9].

a. The initial investment cost of the DG is given by C_i.

$$C_i = (N_{wt}C_{wt} + N_{bs}C_{bs})\, f_{cr} \quad (7)$$

Here N_{wt}, N_{bs} are the number of wind turbines and C_{wt}, C_{bs} are the prices of wind turbine and battery, f_{cr} is the capital recovery factor used to calculate the present value and it is defined as

$$f_{cr} = \frac{r(1+r)^{L_p}}{(1+r)^{L_p} - 1} \quad (8)$$

Where L_p is the project lifetime and r is the real interest rate.

b. Operation and maintenance cost of the DG is given as C_{OM}.

$$C_{OM} = C_{wt\_OM}t_{wt} + C_{bs\_OM}t_{bs} \quad (9)$$

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Where C_{wt_OM} , C_{bs_OM} are the operating and maintenance cost of wind turbine and battery per unit time and t_{wt} , t_{bs} are operating time of wind power generation and battery.

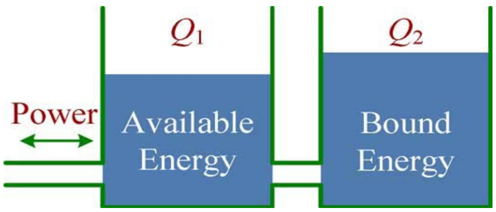

Figure-3. Kinetic battery model concept.

c. The replacement cost is given as C_R

The cost is considered only if the project lifetime exceeds the DG lifetime and is as given

$$C_R = C_{wt\_R} + C_{bs\_R} \tag{10}$$

Where C_{wt_R} , C_{bs_R} are the replacement cost of wind turbine and battery respectively.

The total cost (C_A) of the system is given

$$C_A = C_i + C_{OM} + C_R \tag{11}$$

Government's subsidy and credit is important and give more accurate results when considered.

B. Constraints for the proposed method of optimization

i. Maximum installed capacity of DG: The capacity is constrained by the installed area. Usually, the interval between two wind turbines must be 6-10 times the rotor diameter in the direction of prevailing wind and 3-5 times of the rotor diameter in the vertical direction of prevailing wind [4]. Thus the maximum number of installed wind turbines is given as N_{wt} for a region with area S_1, length *L*, and width *W*. the equation is as given

$$N_{wt} \le \left[\frac{L}{(6-10)d}+1\right] \cdot \left[\frac{W}{(3-5)d}+1\right] \tag{12}$$

d is the rotor diameter similarly the installed capacity for battery is given as

$$N_{bs} \le [S_2 / S_{bs}] \tag{13}$$

S_2 is the area for installation of battery and S_{bs} is the area of single battery required for installation.

ii. Minimum installed capacity of DG: It is expected to minimize the battery's charge/discharge cycles fully utilizing the renewable energy. The system is required to satisfy the average load demand [10]. When there is excess of wind generation load is satisfied and that excess energy is stored in the batteries and that batteries are supposed to satisfy loads at low and no wind conditions. Battery should guarantee the load to work at least λ days. The minimum number of wind turbines and battery installed are determined by

$$N_{wt} \ge \int_{t_{m2}}^{t_{m3}} P_L(t)dt \Big/ \int_{t_{m2}}^{t_{m3}} P_{wt}(t)dt \tag{14}$$

$$N_{bs} \ge \frac{\lambda . W_{Ld}}{\eta . C_{bs} . V_{bs} . DOD_{\max}} \tag{15}$$

Where W_{Ld} , η are the daily energy consumed by load and discharge efficiency of the battery, DOD is the depth of discharge of the battery and C_{bs} , V_{bs} are the capacity and voltage of single battery.

iii. Operating reserve capacity of system: It is the surplus available source which is acquired when there is sudden increase in the load demand or unexpected decrease in power output. That will be expressed as follows

$$\sum P_{DG} \ge (1+\mu\%)P_L \tag{16}$$

P_{DG} , μ , P_L are the total output power of DG, operating reserve ratio and average power of load.

iv. Battery charge and discharge constraints: Following constraints are taken into consideration during energy conversion in order to optimize the battery's charge and discharge state. a) Battery state of charge (SOC) [13] b) charge and discharge rate (r_{ch}, r_{dch}) c) charge and discharge current (I_{ch}, I_{dch}) d) charge and discharge power d) battery's charge/discharge cycles (N_C). The constraints and their limits are as given below

$$\begin{aligned}
& SOC_{\min} \le SOC \le SOC_{\max} \\
& r_{ch} \le r_{ch_R}, r_{dch} \le r_{dch_R} \\
& I_{ch} \le I_{ch\max}, I_{dch} \le I_{dch\max} \\
& 0 \le P_{bs_ch} \le P_{bs_ch\max} \\
& 0 \le P_{bs_dch} \le P_{bs_dch\max} \\
& N_C \le N_{C\max}
\end{aligned} \tag{17}$$

Where,

r_{ch_R}, r_{dch_R}, $I_{ch\max}, I_{dch\max}$, $N_{C\max}$ can be obtained from the manufacturer. While rest limits can be calculated according to the battery's model. If all these constraints

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are satisfied then battery's charge and discharge state is optimized increasing the battery's lifetime.

v. Performance constraints: In this method higher power supply reliability is achieved by using battery as energy storage. In this study minimizing the system cost is the final objective considering other factors as the constraints

LPSP is used to characterize power supply reliability. LPSP need to satisfy

$$LPSP \le \lambda_L \tag{18}$$

Where λ_L is the allowable LPSP of the load.

C. Objective function

Minimizing the total cost is the objective and it is expressed as

$$\min f = \min(C_i + C_{OM} + C_R) \tag{19}$$

Equation (19) is universal if (18) is satisfied.

D. Optimal sizing strategy in stand-alone mode

LPSP can be calculated for every probable combination according to the output models of the system and battery's charge and discharge constraints. The combinations with LPSP satisfying (18) are chosen.

Program flowchart for the proposed optimal sizing method is as sown in Figure-6. Here we have assumed wind speed data and load data.

The yearly data for each hour is considered for both wind speed and load demand. Figure-4 and Figure-5 represents the respective data. The wind turbine and battery parameters are as listed in Table-1 and the respective values of the variables mentioned in different steps adopted in optimization is listed in Table-2. The flowchart represents the steps for optimal sizing of the wind-battery system. *i* and *j* represents the number of wind turbines and number of batteries. We consider some minimum and maximum number of wind turbines and battery and among them the best combination is chosen with less LPSP and minimum cost.

For example suppose if we have to design a system for given particular region we acquire minimum wind turbines 3 and maximum WT 23 (difference 20) and minimum batteries 71 and maximum batteries 500 (difference 429 ≈ 430) then the total no of combinations is 430*20 which equals 8600 combinations. Now we have to choose best among these combinations. Considering all the data given above we get optimized results for these particular combinations and the best combination among them is then chosen. Optimized results are as shown in Table-3.

Table-1. Main parameters of Wind Turbine/Battery [4].

Wind Turbine	Battery
Rated power : 35kW	Rated capacity : 600Ah
Cut-in speed : 3m/s	Rated voltage : 2V
Cut-out speed : 25m/s	Minimum state of charge : 35%
Hub-height : 24m	Round-tip efficiency : 85%
Rated power wind speed : 11m/s	Max charge/discharge rate : 0.5A/Ah, 0.5A/Ah
Rotor diameter : 19.2m	Max charge/discharge current :100A/75A
Survival wind-speed : 52.5m/s	Self discharge rate : 1%
Blade length : 9m	Dimensions (length/ width/ height) : 215mm/ 193mm/ 710mm
Cost : 25000 $(average)	Cost : 150 $(average)

Table-2. Value of mentioned variables [4].

Given region				Coefficients of battery			Reference for performance constraints
S_1 (m^2)	L (m)	W (m)	S_2 (m^2)	Q_{max} (Ah)	c	k	λ_L
10000	500	200	1000	720	0.34	0.98	0.05

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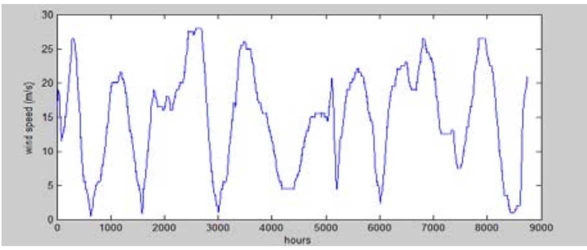

Figure-4. Assumed wind speed data.

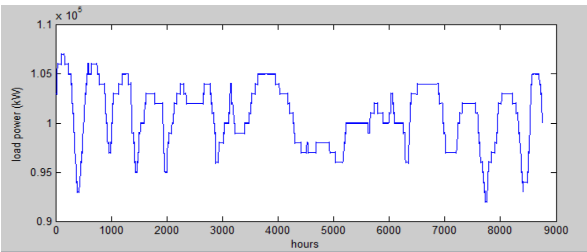

Figure-5. Assumed load demand.

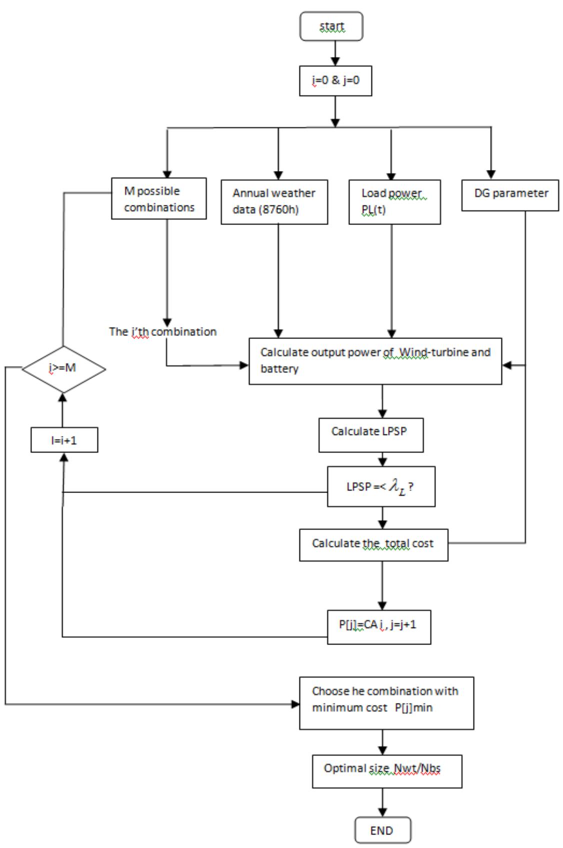

Figure-6. Optimal sizing algorithm.

Table-3. Optimized results for stand-alone mode.

Number of wind turbines	Number of batteries	LPSP	Optimized cost ($)
23	496	0.1274	649400

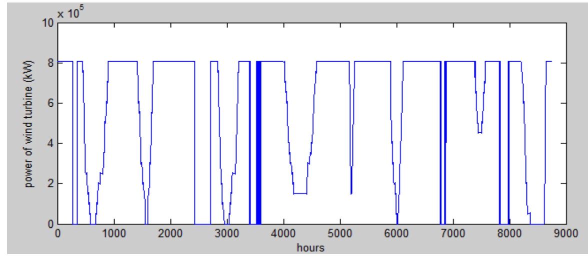

Figure-7. O/P curve of wind power generation (WPG).

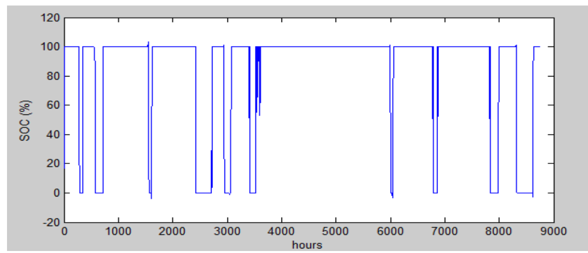

Figure-8. SOC of the battery.

4. CONCLUSIONS

The above optimal sizing algorithm is designed for multiple WT's and batteries giving the best possible combinations among the given. The proposed system can benefit the industries where there is requirement of continuous power supply and chances of failure for example, Textile industries. This system can also prove beneficial to remote areas and areas prone to wind energy availability. According to the regional configurations the method can provide optimized results. Accurate and reasonable optimal sizing model is established. Battery's state of charge, charge/discharge current/rates/cycles are considered thus optimizing battery states and increasing its lifetime. In future different storage devices can also be added and optimized results be obtained. Some results are shown to validate the proposed method. The proposed method is improved method than the traditional methods in practice as follows:

a) The method gives a more accurate and optimal model considering the required installation area of DG and the reserve capacity of the system.
b) In the stand-alone mode, the battery capacity is utilized to its full extent to satisfy the demand.
c) All the battery constraints SOC, charge/discharge rate, charge/discharge cycle, charge/discharge current are considered thus helping to optimize the battery states of charge/discharge. We also get a prolonged battery lifetime.

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