CHEMICAL ENGINEERING TRANSACTIONS Volume 18, 2009
Editor Jiří Klemeš
Copyright © 2009, AIDIC Servizi S.r.l., ISBN 978-88-95608-04-4 ISSN 1974-9791
DOI: 10.3303/CET0918105

Design of Wind Power Generation Systems for Industrial Application Incorporating Resource Uncertainty

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The technical challenge in designing an onsite power generation system incorporating renewable energy technology for overall sustainability is the inherent unpredictability of the renewable resource. Integration of a battery bank as energy storage can alleviate the mismatch between the load and power generation. By accounting for the system operating and geometrical constraints, the entire set of feasible design options can be identified on a plot of battery capacity vs. rated power of wind generator. Such a diagram is known as the design space. The present study illustrates the generation of design space for different reliability levels for wind-battery systems using chance constrained programming. The proposed approach can generate and evaluate a range of possible design alternatives which can speed up the decision making process and also provide a clear understanding of the system design limitations.

1. Introduction

Reliance on conventional fossil fuel energy to satisfy the growing electricity demand is not sustainable. One of the options for sustainability is to generate power utilizing renewable energy sources. In order to integrate renewable energy based power systems, its economic competitiveness and uncertainty in availability compared to conventional fossil fuel based power generation is a subject of concern. Optimum choice of equipment size, system design and consideration of uncertainty of the resource can promote competitiveness of these technologies. This paper proposes the design space methodology for sizing and optimizing a wind-battery power system by incorporating the uncertainty of the wind resource in the design stage. The methodology originally derives inspiration from design and optimization of heat exchanger networks in chemical process plants (Poddar and Polley 1996, Muralikrishna and Shenoy 2000). The application of design-space approach in identifying the optimum design options has also been demonstrated in the case of solar water heating systems (Kulkarni et al. 2007), standalone battery integrated diesel generator power system (Arun et al. 2008) and wind – photovoltaic hybrid system (Roy et al. 2007).

2. Mathematical model of Wind – battery system

The wind-battery system consists of the wind turbine rotor, transmission system, electrical generator and battery bank. The mathematical model of each of the above sub-components is described below:

Please cite this article as: Roy A., Kedare S.B. and Bandyopadhyay S., (2009), Design of wind power generation systems for industrial application incorporating resource uncertainty, Chemical Engineering Transactions, 18, 647-652 DOI: 10.3303/CET0918105

2.1 Wind turbine rotor and transmission system

The fundamental rotor performance representation, known as the power coefficient (C_p) vs. tip speed ratio (λ) characteristic can be obtained from the Blade Element Momentum (BEM) theory. The turbine modeled is a horizontal axis three-bladed upwind rotor with a NACA 23015 aerofoil section. From the knowledge of blade geometrical parameters such as rotor diameter, blade pitch angle, chord and twist distribution and aerofoil characteristics, the C_p - λ characteristic can be obtained. The rotor C_p - λ model was validated with the field test results reported by Anderson et al. (1982). Maximum power extraction from the wind can be achieved by a variable speed configuration in which the tip speed ratio is maintained constant at λ_{opt} which corresponds to the maximum power coefficient (C_{pmax}). The power extracted by the rotor (P_{rot}) at any wind speed (V) with respect to the cut-in (V_c), rated (V_r) and cutoff (V_f) velocities can be expressed as

$$\begin{aligned} P_{rot} &= P_{rot\_r} && \text{whenever } V_r \le V \le V_f \\ &= (1/2)\rho A V^3 C_{p\max} && \text{whenever } V_c \le V \le V_r \\ &= 0 && \text{otherwise} \end{aligned} \tag{1}$$

where P_{rot_r} is the power extracted by the rotor at the rated wind speed (V_r) also designated as the low speed shaft rated power. It is assumed that power control above rated wind speed is done by progressively yawing the turbine rotor out of the wind in such a manner that $P_{rot} = P_{rot\_r}$. Mechanical efficiency (η_m) of the drive train can be modeled using Eq (2) with the assumption that the transmission loss is proportional to P_{rot_r} (Johnson, 1985).

$$\eta_m = \frac{P_{rot} - qrP_{rot\_r}}{P_{rot}} \tag{2}$$

where q is the number of gear stages and r is the constant of proportion for the power loss per stage.

2.2 Electrical generator

In the present study a self excited induction generator has been considered in which the reactive power is supplied by charged capacitor banks connected across the stator terminals. The capacitor current can be controlled so as to allow a variable frequency generation. With known values of generator circuit parameters and given input wind torque, the output power can be determined from the equivalent circuit model of the induction machine. In order to supply a load that requires a constant frequency, the variable voltage variable frequency output of the generator needs to be converted into constant voltage constant frequency by means of a power electronic device consisting of an AC-DC and DC-AC converter. By integrating the rotor, transmission and generator model the power output characteristics of the wind machine can be obtained. It is assumed that at rated condition the generator three phase voltage is 415V and the frequency of current is 50Hz for a 4-pole electrical machine.

2.3 System modeling following a probabilistic approach

The components of a standalone wind - battery power system connected in a parallel fashion is shown in Figure 1. The load dispatch is such that, whenever excess power is available after meeting the load, it is stored in the battery bank and when generation from the wind turbine is insufficient to meet the demand, energy is drawn from the battery, provided the battery has not reached its depth of discharge (DOD). When the battery is fully charged, any excess power available is dumped. There is a loss of load if at any instant there is no or less generation from the wind turbine and the battery bank is fully drained. Power transfer across the battery bank (dQ_B/dt) can be calculated by

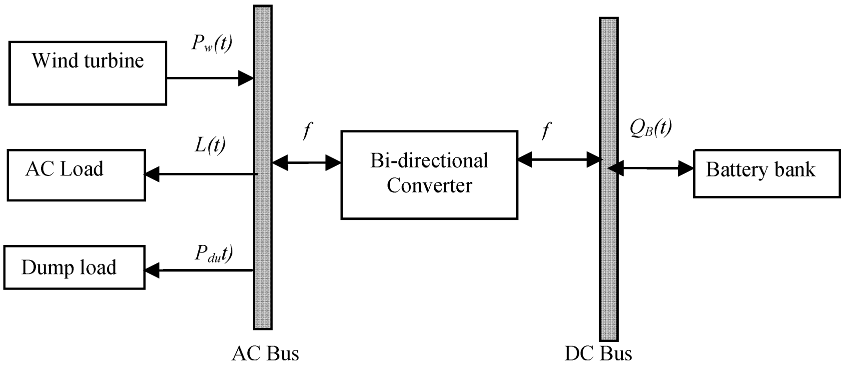

Figure 1 Schematic of a standalone wind-battery power system

considering the balance between the power supplied by the wind turbine ($P_w(t)$) and the load ($L(t)$) at a given instant t as :

$$dQ_B/dt = [P_w(t) - L(t) - P_{du}(t)]f \tag{3}$$

$$\begin{aligned} \text{where} \quad f &= \eta_c \quad \text{whenever} \quad P_w(t) \geq L(t) \\ &= 1/\eta_d \ \text{whenever} \ \ P_w(t) < L(t) \end{aligned} \tag{4}$$

η_c and η_d represent the charging and discharging efficiency of the battery bank and bi-directional converter, while $P_{du}(t)$ is the power which may be sent to dump loads, whenever the generation exceeds the demand. It is assumed that η_c and η_d and therefore f do not vary within the time step. The hourly wind speed is treated as a stochastic variable which follows a Weibull distribution. Assuming that power generated by the wind turbine (P_w) also follows a Weibull distribution, the density function and cumulative density function (CDF) of the power generated by a given turbine can be derived from the density function of wind speed and the functional relation between the power generated and the wind speed (Papoulis et al., 1984). The CDF of the power function may be given by:

$$F(P_w) = 1 - \exp\left[-\left(P_w/ac^3\right)^{3/k}\right] \quad \text{where} \quad a = (1/2)\rho AC_p\eta_0 \tag{4}$$

k and c represent the shape and scale parameters of the wind speed distribution and η_o is the combined efficiency of transmission and generator system. Assuming that the demand at a given time step is deterministic, the load can be met if power supplied by the system ($P_s(t)$) is equal to or greater than the demand as expressed by the following chance constraint (Charnes and Cooper, 1959).

$$Prob[P_s(t) \geq L(t)] \geq \alpha \tag{5}$$

The system sizing therefore corresponds to a specified value of α. Since, power may be supplied to the load through the combined sources of battery bank and the wind turbine, for a small time step Δt Eq. (5) may be expressed as follows:

$$Prob\left[P_w(t) \leq L(t) + \frac{Q_B(t+\Delta t)}{f(t)\Delta t} - \frac{Q_B(t)}{f(t)\Delta t}\right] \leq 1-\alpha \tag{6}$$

It may be observed that Eq. (6) represents the CDF of P_w. Knowing the distribution function of power, the deterministic equivalent of Eq. (6) in terms of the battery energy values may be expressed as:

$$Q_B(t+\Delta t) = Q_B(t) + (ac^3(-\ln\alpha)^{3/k} - L(t) - P_{du}(t))f\Delta t \tag{7}$$

The storage capacity for a given rating of the wind generator capable of meeting the specified load may be obtained by solving Eq. (7) over the entire horizon (T). The required battery bank capacity (B_r) is then obtained as follows:

$$B_r = \max\{\, Q_B(t)\} / DOD \tag{8}$$

For each value of generator rating considered, the associated minimum battery bank capacity is obtained by minimizing the storage capacity given by Eq. (8). The optimization variables are the initial battery energy, $Q_B(t=0)$ and the power dumped at each time step ($P_{du}(t)$), subject to the constraint of non-negativity of the battery state of energy ($Q_B(t) \geq 0$), non-negativity of the power dumped ($P_{du}(t) \geq 0$), and the equality of the battery energy at the start and end of the time horizon ($Q_B(t=0) = Q_B(t=T)$). The latter constraint suggests that the battery being an energy storage device, in a given time horizon, no net energy is supplied to or drawn from the battery bank. The above procedure obtains the minimum battery capacity for a given generator rating. In order to find the minimum wind generator rating (P_{min}), the power dumped at each time step $P_{du}(t)$ in Eq.(7) should be minimum (ideally equal to zero).

3. Illustrative Example

An average hourly power demand profile of a chemical plant located in Maharashtra, India is shown in Figure 2 (Sridhar, 2004). Figure 3 shows the hourly mean and standard deviation of wind speed (CWET, 2001) on a representative day for a sensor height of 25m near the plant location. For a chosen reliability level (α), and with known resource and demand profiles, the minimum wind generator rating (P_{min}) and the associated battery bank size can be found (Section 2.3). The time step of simulation is 1h and the time horizon is 1 day. The battery – converter system net charging and discharging efficiency is taken to be 85%, while DOD of the battery is 60%. The turbine has a hub-height of 40m and the power law index for the site is 0.13. For ratings greater than P_{min}, the minimum battery capacity required may also be determined from the system mathematical model. The loci of all such minimum battery requirement - wind turbine rating points plotted on a battery size vs. wind turbine rating diagram is known as the sizing curve and is shown in Figure 4. It can be seen that the sizing curve shows a minimum and maximum value of wind turbine rating for a given α. In the present example, the minimum wind turbine rating required to supply the load is 36.1 kW along with a battery bank of 62 kWh This corresponds to a reliability level of 0.6. It may be noted that the P_{min} point is numerically close to the daily average load demand. This provides a check on the result obtained.

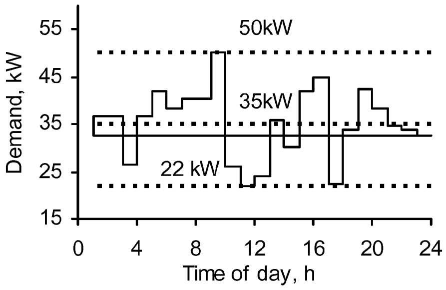

Figure. 2 Daily load variation

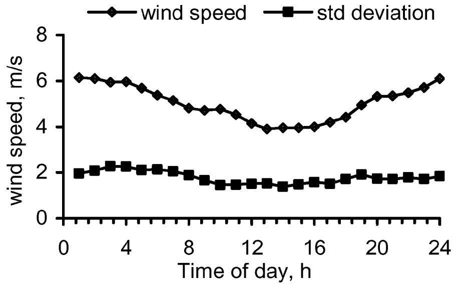

Figure. 3 Daily wind speed variation

For values of α greater than 0.6, the minimum generator rating required increases while the maximum generator rating decreases. This is because, typically, with an increase in the confidence level (α), the power produced by the wind turbine decreases (Eq. 4). It may be clarified that the rotor diameter varies with different values of α as well as along the sizing curve for a given α. By tracing a particular constant reliability line (e.g. α=0.65) it may be seen that with an increase in the generator rating from P_{min}, there is a resulting decrease in storage requirement which is due to the higher energy produced over the time horizon by a generator of higher capacity. For a rated power of 50 kW, the battery capacity required is least. If the wind turbine rating is increased beyond 50 kW, the storage requirement increases. This may be justified because the maximum rotor diameter being constrained by the hub height, an increase in the rated power leads to an operation with higher rated wind speed. This results in de-rating of the turbine at relatively low wind speeds leading to an increase in storage requirement.

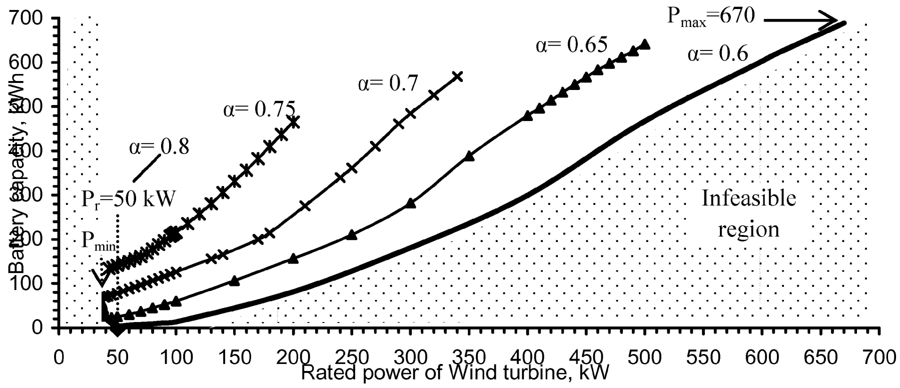

Figure.4 Sizing curve and design space for different reliability levels

Thus, for α = 0.6 to 0.7, the sizing curve shows an optimum battery capacity; however for α greater than 0.7, the optimum battery capacity coincides with the minimum generator rating point. This difference in the nature of the sizing curves is attributed to the tradeoff between the incremental energy available from a relatively higher generator rating and the energy lost due to de-rating of the turbine with an increase in rating. The maximum generator rating which will suffice the load is 670 kW with an associated battery bank size of 690 kWh. The region enveloped by the sizing curve is the area in which a feasible configuration may be designed and is hence the feasible design region; whereas the area below the sizing curve (excluding the sizing curve) will not meet the load energy requirement and is hence the infeasible design region (shown by the shaded area). The maximum confidence level for which a feasible system may be designed is 0.8. For confidence level greater than 0.8 the demand can not be met by any combination of wind turbine rating and battery capacity.

4. Conclusions

The effectiveness of design space approach in solving a multi-parameter design problem is demonstrated. Through the application of the proposed ideology the system designer can first choose the system reliability level and then the combination of wind turbine rating and battery capacity which can at the best realize the system design objective. By application of chance constrained programming approach it was possible to account for the uncertainty in resource availability. The system reliability can be further enhanced by installing the system in a better wind regime or by increasing the hub-height of the turbine. A system designer may therefore explore the practicality of the chosen configuration by referring to the design space. The methodology is adaptable to the chosen time horizon, not restricted by non-linearity in system sub - component models, overall generic by nature and can be conveniently solved on a computer.

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