Risk Assessment Study of Loss Profit for Integrated Maintenance Policy Based on Power Generation for a Wind Turbine

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Abstract: This paper deals the risk assessment of the type of preventive maintenance action impact for an integrated maintenance optimization problem for a wind turbine power generation. A jointly optimization is made in order to establish an economical energy production policy and to determine the risk assessment for a loss profit of maintenance strategy. The objective of this study is at first, to present an analytical model which studies sequentially an economical power generation plan and an optimal maintenance strategy for randomly failing wind turbine system with variable failure rate and minimizing the total cost of production, storage and maintenance. Secondly, analytical study were developed to determine the risk assessment for the quality of preventive maintenance action impact. In order to illustrate the developed model, numerical results are presented.

Keywords: Risk, Loss Profit, Maintenance, Production, Optimization.

1. INTRODUCTION

The renewable energies have become increasingly complex in response to economic growth and continuously increasing power demand. The wind and solar energies are considered among the renewable energies that have become the most efficient to achieve sustainable development. The renewable energies technologies and equipment's are generally operated under more or less stationary conditions and influenced by several factors. [1] showed the variations of wind speed from season to another and from day to day. In the last years, the renewable energy has become one of the efficient ways to reach sustainable development but it is influenced by several factors in terms of reliability deterioration. Among these factors, we can consider that the variability of wind has a significant impact on the wind turbine equipment availability and the random variation of the climate is considered as constraint for the application of maintenance actions (preventive and corrective maintenances).

Concerning maintenance strategies in the energy generation, the operation and maintenance is considered as a sizeable share of a wind turbine generating. [2] determines the availability of the wind turbine according to the distance to shore, average (offshore) wind speed and of course amount of money to be spend for maintenance. [3] proposed a life cycle cost (LCC) analysis with strategies where CMS improved maintenance planning for a single wind turbine onshore and a wind farm offshore by studding different cases based on real data from Olsvenne2 at Naumlsudden (Gotland, Sweden) and Kentish Flats, in the U.K. [4] studies the wind power operations and the different critical factors that have significant impact on the turbine's reliability and maintenance. [5] proposed several analytical models for predicting the lifetime of a sys-tem and developed an operation and maintenance strategy by quantifying risks and uncertainties based on the lifetime prediction.

The optimization of financial risks is considered the key of the business development. Therefore, the enterprises must realise higher performances and quality of products/services, lower costs, sustainability control, etc. [7]. That is why the risk assessment is considered a part of the performance measurement (PM) [8]. Risk identification and assessment give a more specific indication on where to focus the actions [9] which, should it occur, will have an effect on achievement of one or more objectives. The assessment of risks helps managers in decision making process in the production policy and maintenance strategy.

The previous works treated the production and maintenance problem of the power generating system. In this context, firstly, this paper proposes an economical production plan for a wind turbine power generation and secondly, to determine the loss profit risk of an imperfect preventive maintenance strategy based on the obtained production plan

The remainder of the paper is organized as follows: Section 2 is presented the mathematical model of the problem which consists to minimize simultaneously the total average production and maintenance cost of the wind turbine system under operational and service level constraints. An analytical study is developed to determine the analytical expressions of the components of total cost and constraints. A numerical example is discussed in section 3.

2. MODELING PRODUCTION/MAINTENANCE PROBLEM

Our model is a finite-horizon, we are concerned with the problem of jointly optimal energy production and maintenance planning problem formulation of a manufacturing system composed of a wind turbine that considered as energy recovery device provided by the Kinetic energy of wind and which provisions the load when there is a lack of electricity, and stores the surplus in battery system for energy storage when the power generated exceeds the load.
The wind turbine is subject to a random failure. The failure rate λ(t) increases with time and according to the production rate . That's why; a preventive maintenance action is planned according to the production rate in order to reduce the ma-chine failure and to improve the overall reliability and availability of the wind turbine.
Our objective is to establish simultaneously an economical production plan and an optimal preventive maintenance strategy of a wind turbine satisfying the randomly power demand with a given service level over a finite time horizon. The use of the production plan in maintenance strategy is justified by the fact of taking into account the natural influence of the production rate on the evolution of the failure rate of the wind turbine.

2.1. Problem Formulation

The wind turbine power generation system that minimizes the total costs over a finite horizon $H=N.\Delta t$; taking into consideration the requirement of satisfying the fluctuating demand and the constraints on major variables.
The problem can be stated as follows:

$$Min\ f\left(W,B\right)=Min\sum_{k=1}^{N}f_k\left(W,B\right)+\varphi\left(j\right)$$
$$=Min\left[Cs\cdot E\left[B^v\left(H\right)\right]+\sum_{k=1}^{N-1}Cp\cdot E\left[W_v\left(k\right)\right]+Cs\cdot E\left[B^v\left(k\right)\right]+j\times M_p+M_c\times A_j\right] \quad (1)$$

$$B^v\left(k\right)=B^v\left(k-1\right)+w_v\left(k\right)-P_d\left(k\right) \quad (2)$$

$$Prob(B^v\left(k\right)\geq 0)\geq\theta,\ \forall k\in\{1..H\} \quad (3)$$

$$0\leq C_p\leq C_{p\max} \quad (4)$$

Where $\left\{f_k\right\}$ denotes functions that represent the output power and battery storage costs with *Cp*: production unit cost and *Cs*: storage unit cost, $\left\{\phi\left(j\right)\right\}$ denotes functions for maintenance costs with *Mp*: preventive maintenance cost and *Mc*: corrective maintenance cost. The paper set defines the virtual amount of stored energy for each time period *k* (2). The constraint (3) imposes the service level requirement for each period and denotes the lower physical limit of storage variables. The constraint (4) defines the maximum or the optimal value of the performance coefficient *Cp*. Note that for a simple wind turbine; physically it's impossible to recuperate more that 59% of the kinetic energy of wind [6].

2.2. Power generation policy

The inventory and production variables are stochastic and their statistics depend on the probabilistic distribution function of the demand.

$$B(k) = \max(B^v(k), 0)$$
$$B^v(k) = B^v(k-1) + w_v(k) - P_d(k) \tag{5}$$

Where:

$B(0) = B_0$; $P_d(k)$ is the electric power demand at period *k*.

The average amount of energy stored during period k is given by:

$$E\left[B^v(k)\right] = \int_{(k-1).\Delta t}^{k.\Delta t} t.B^v(t)\,dt \tag{6}$$

- Average output power

Respecting the wind turbine efficiency constraint, the performance of every period *k* cannot exceed a given maximal performance factor $C_{p\max}$.

Considering the wind speed passing through the turbine is uniform as *V*, with its value as V_1 upwind, and as V_2 downwind at a distance from the rotor. Extraction of mechanical energy by the rotor occurs by reducing the kinetic energy of the air stream from upwind to downwind.

The extractable power from the wind turbine can be expressed as:

$$P_O = \frac{1}{2} \cdot \rho \cdot S \cdot V^3 \cdot \frac{1}{2} \cdot (1 - b^2) \cdot (1 + b) \; ; b = {V_2}/{V_1} \tag{7}$$

The average output power by time unit of the wind turbine can be calculated using the following equation:

$$P(V) = \int_{LB}^{LH} \frac{df(V)}{dV} P_O(V)\,dV \tag{8}$$

With:

$\frac{df(V)}{dV}$: The Weibull probability density function associated with the wind speed random variable V_w is given by:

$$\frac{df(V)}{dV} = \frac{h}{A}\left(\frac{V}{A}\right)^{h-1} \exp\left(-\left(\frac{V}{A}\right)^h\right) \tag{9}$$

LB: minimal velocity of the wind turbine started the production

LH: maximal velocity

Consequently, the average output power during period k is expressed as follows:

$$E\left[W_v(k)\right]=\int_{(k-1).\Delta t}^{k.\Delta t} t\cdot P(V)\,dt=\int_{(k-1).\Delta t}^{k.\Delta t} t.\left[\left(\int_{LB}^{LH} P(V)\right)dV\right]dt=\int_{(k-1).\Delta t}^{k.\Delta t} t.\left[\left(\int_{LB}^{LH}\frac{df(V)}{dV}\cdot P_O(V)\right)dV\right]dt \qquad (10)$$

- Service level

In order to solve our optimization problem, we transform the service level constraint into a deterministic equivalent constraint by specifying certain minimum cumulative output power quantities that depend on the service level requirements.

$$Prob(B(k)\geq 0)\geq\theta,\ \forall k\in\{1..N\}$$

For $k=0,1,..,N$, we have:

$$W_v(k)\geq\varphi_d^{-1}(\theta)\cdot V_d-B^v(k-1)+E\left[P_d(k)\right]\ \text{ with } k=1,...,N \qquad (11)$$

Where
V_d : variance of demand at period k
φ_d : cumulative Gaussian distribution function with mean $E\left[P_d(k)\right]$ and finite variance $V_d\geq 0$

3. LOSS PROFIT RISK FOR MAINTENANCE STRATEGY

The maintenance strategy under consideration characterized by an imperfect preventive maintenance strategy with the delay of reparation of each failure is not negligible. The reparation delay influenced on the production policy by decreasing the quantity of production in the period where we will do the repair. Consequently, some customer demands are loosed for different periods. The objective of this section is to study the assessment of risk of loss profit due to the imperfect maintenance actions. Assuming *j* is the optimal number of preventive maintenance actions during the finite horizon H=N.Δ. The replacement or the preventive maintenance actions are practiced at periodic time's *m.T* with m: 1,…*j* restores the state of machine between two states "as good as new" and "as bad as old". In this case, the failure rate $\lambda(t)$ can be written as $\lambda(t^+)=(1-\lambda_0)\,\lambda(t)$ and λ_0 is a random variable.

The risk of loss profit is evaluated according to the optimal number of preventive maintenance actions *j* and the quality level of preventive maintenance that depend to the value of the random variable λ_0.
Assuming that R_t the necessary time units to repair the machine at each failure,
Let $R(PM(J^*))_{/Mi}$ be the risk assessment for loss profit due to imperfect preventive maintenance.

We consider $\overline{A}_H\,(U,J)$: average number of failure during *H*.

$$\overline{A}(U,N)=\sum_{i=0}^{N-1}\left[\sum_{k=In(i\times\frac{T}{\Delta t})+1}^{In((i+1)\times\frac{T}{\Delta t})}\int_0^{\Delta t}\lambda_k(t)\,dt\right]+\sum_{k=N\times T}^{H.\Delta t}\int_0^{\Delta t}\lambda_k(t)\,dt \qquad (12)$$

With :
The failure rate $\lambda\,(t)$ can be written as:
$\lambda(t^+)=(1-\alpha).\lambda(t)$
Where α is a random variable that follows a Bernoulli distribution, $\alpha\in[0,1]$.
In the case of imperfect maintenance, the failure rate is expressed as follows:

$$\lambda_k(t)=\lambda_{k-1}(\Delta t)\left(1-\left\lfloor \frac{k-1}{\left(\left\lfloor \frac{k-2}{T} \right\rfloor+1\right)T} \right\rfloor\right)+\frac{U_k}{U_{max}}\lambda_n(t)+\left\lfloor \frac{k-1}{\left(\left\lfloor \frac{k-2}{T} \right\rfloor+1\right)T} \right\rfloor.(1-\alpha).\lambda_T(\Delta t) \quad (13)$$

With: $T=\frac{N\cdot\Delta t}{j}$

Assuming that D_t the downtime, the loss of production during is given by the following relation:

$$D_t = \overline{A}_H (H).R_t \quad (14)$$

The production quantity during (H- D_t) is given by the following relation:

$$C=\frac{\sum u^*(k)\times(H-D_t)}{H} \quad (15)$$

Lp: loss of production:

$$Lp=\sum_k u^*(k)-C \quad (16)$$

Risk assessment:

$$R\left(PM\left(j^*\right)\right)=\frac{Lp}{\sum_{k=1}^{N-1} u^*(k)} \quad (17)$$

4. Numerical Example

A simple example of a hypothetical wind farm, whose sales are strongly influenced by the fluctuation of demands (Electricity of housing) and the storage level, is not perfectly known. In this example, we left on the use of such a wind turbine type WT6000 having the following characteristics: Power: 6000 W to 12 m/s; Startup speed: 2,5 m/s; Nominal speed: 12 m/s; Survival speed: 65 m/s; Rotor diameter: 5,5 m; Mean wind speed: 6 m/s; Battery Voltage: 12V, Battery Capacity: 100Ah. The remainder of the input data is presented below: Production cost of a KW of energy: *Cp* =3 *mu (monetary units);* Storage cost of 1 KW: *Cs* =6 *mu;* Customers' satisfaction degree (required service level): θ_1=100%. The random demand of electricity is characterized by a Normal distribution with mean and variance given respectively by $\hat{P}_d$ and $V_d = 10$. From the average wind speed (6 m/s), we established the Rayleigh distribution of wind using the formula of Weibull probability density with parameters *A*=6 and *k*=2.

Figure1 shows the average power random demand during the finite horizon.

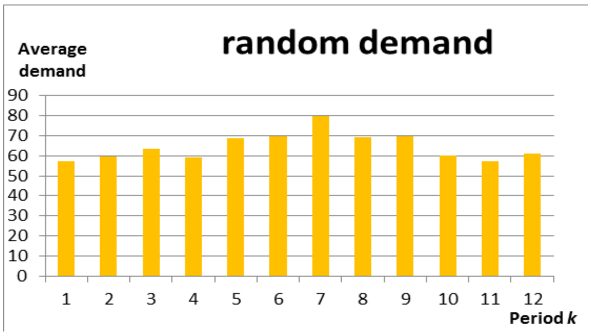

Figure 1. Average power random demand

For the maintenance strategy, the Weibull scale and shape parameters are respectively $\beta=100$ and $\alpha=2$.
The optimal production plan is presented in figures 2 and figure 3 presents the curve of the average total maintenance cost, $\varphi(j)$, as function to j. The optimal number of preventive maintenance action that equals to $j^*=3$. It means that over the finite horizon H of 12 periods. A preventive maintenance actions must be down every $T^*=H/j^*=4$, with a minimal average total cost of maintenance action equals to $\varphi^*=21.63934$ *mu* and with a risk assessment is equal to

$$R\left(PM\left(N^*\right)\right)=\frac{Lp}{\sum_{k=1}^{H-1}u^*(k)}=0,30\%$$

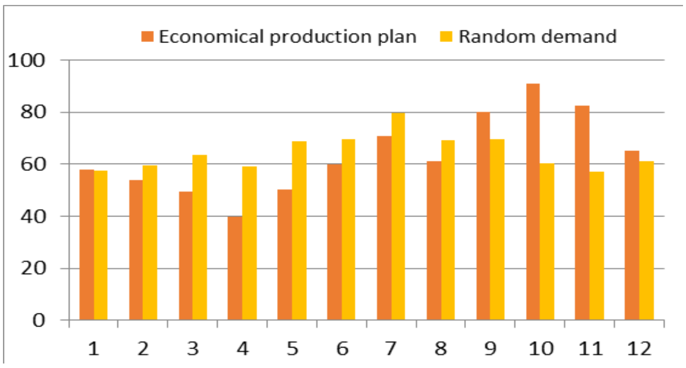

Figure 2. Average output power

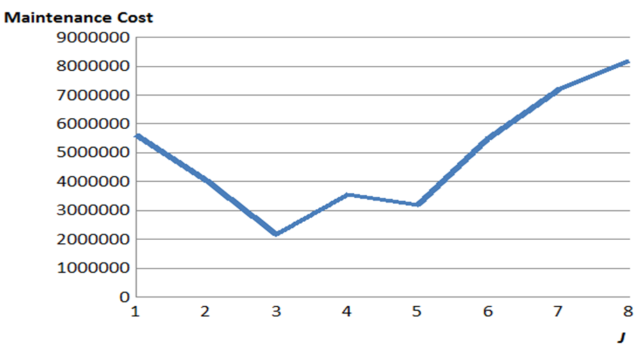

Figure 3. Average total cost of maintenance

4. CONCLUSION

This paper discussed the risk assessment of lost profit for a wind turbine system. An integrated maintenance optimization strategy is developed in order to minimize the total cost of production and maintenance and to satisfy the random demand with a given service level. Firstly, we have determine the optimal power generation plan and secondly we have studied the risk assessment of loss profit according to the optimal number of preventive maintenance actions determined for the case of imperfect maintenance policy.

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