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**JOINT DYNAMIC PRODUCTION LOAD SHARING
AND MAINTENANCE SCHEDULING FOR OPTIMAL
OPERATION OF A FLEET OF ASSETS:
APPLICATION TO A WIND FARM**

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A fleet of systems that is used to meet a demand for production that varies over time is considered. For example, a wind farm consisting of N wind turbines under contract with a customer must produce and supply a given power to the grid. To guarantee the power delivery availability, the wind farm is over-dimensioned with respect to the contractually binding power production. However, when producing the deterioration phenomenon worsens with the production level, leading an increased deterioration rate. Hence this study proposes a load-sharing decision rule based on prognostic information for a wind farm. The load-sharing decision rule redistributes the production objective on each wind turbine through the so-called control level according to its degradation state and corresponding expected production at each time when the prognostic information is available. The optimal control level of each wind turbine at each decision time is optimized according to both the production objective and the expected degradation. A global model is developed including all these features and implemented to solve the joint production/maintenance optimization problem by simulation. Simulations results show how the joint load sharing/maintenance approach allows to reach an optimum operation at the farm level.

Keywords: Maintenance; Production Load Sharing; Prognostic and Health Management; Wind turbines (WTs)

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1. Introduction

For the fleet consisting of a set of identical systems, the mission of each time unit is shared by all the survival systems to achieve the global objective. Due to all kinds of stochastic effects, the degradation level of each identical systems may develop randomly, despite under the same environment with the same assigned load. In order to keep the degradation levels of all systems in prescribed a range, it is necessary to redistribute load among systems with different degradation levels meanwhile fulfill the global objective. In order to ensure the maximum capacity and the lifetime of the water filtration, a load-sharing modelled is proposed where the component degradation can be adjusted by regulating the load exerted on the component in [1]. In [2] two classes of models accounting for the effects of load history: tampered failure rate model and cumulative exposure model. In [3] a periodic inspection and maintenance strategy is proposed, where a failed component is rectified or minimally repair according to its age. In [4] a load-sharing systems with identical components subject to continuous degradation is considered, where the relationship between the degradation rate and load stress levels is described by a log-linear link function. In [5] a parallel system that is subject to both failure dependence through load sharing and economic dependence through maintenance set-up costs is modelled by a Markov Decision Process.

In this study, a wind farm consisting of N wind turbines that under contract with a customer must produce and supply a given power to the grid. To guarantee the power delivery availability, the wind farm is over-dimensioned with respect to the contractually binding power production. In such a context, an interesting issue to investigate is the dynamic deterioration-based decision-making for the optimal production level dispatch and assignment to each of the turbines within the farm, and at the same time, for the maintenance scheduling on the wind turbines. The manager of the wind farm has to control and distribute the production demand according to the contract and the actual state of each wind turbine. Hence, how to balance the control strategy and the maintenance policy is the common challenge for the system of systems [6,7]. In this paper, we develop all the modelling features required to propose a first overall model for this problem. A global model is developed including all these features and implemented to solve the joint production/maintenance optimization problem by simulation.

2. Model description

The idea is to request that the highly deteriorated turbines produce at a low level, whereas the less deteriorated turbines could produce at a higher level so that the turbines all reach a deterioration level requiring maintenance at the same time and maintenances can be grouped, see 1.

2.1. *Production-dependent deterioration model*

Each wind turbine is subject to a deterioration phenomenon combining a continuous graceful deterioration process and a shocks process. For a given system within the fleet, the graceful deterioration process and the severity of the shocks both depend on the production level assigned at this system: the production-dependent deterioration model is developed in the paper for the particular case of a Gamma deterioration process and a homogeneous arrival process for the shocks with random amplitudes.

We assume that a WT is subject to continuous random cumulative degradation $X(t)$ from 0 to a failure threshold x_F . The graceful degradation over a time period $(0, t_k)$ is modeled by a non-stationary Gamma process where the degradation increments over $(t_i, t_{i+1}), i \in \{1, \dots, k\}$ are gamma distributed with shape parameter $\alpha(t)$ and scale parameter β . Further, the effect of the load distributed on each wind turbine affects on degradation is discretized by limited level $\rho_i > 0, i = 1, 2, 3, \dots$, referred to "control level" in this study:

$$\alpha(t) = \alpha_0 t^{\rho_i}, \quad (1)$$

where α_0 is the baseline shape parameter; i is corresponding to the control level at time t . The shock is modelled by a Poisson with random amplitudes. The arrival rate is related with the control level through an increasing real function $\lambda(t) = f(\rho_i)$; the shock amplitude is dependent on the present degradation level $X(t)$. The introduction of the shock is to describe the random phenomena of the offshore environment and the effect on the wind turbine under different control levels.

2.2. *Production assignment process*

The production in a period is the cumulative production of all the survival WTs. Each control level corresponds to a production rate. We assume that the higher level of control will produce more energy than a lower level on the

same wind turbine. The production demand is constant over an interval of length T_{prod} , and updated to a new value every T_{prod} . Hence the required production level of each period is not constant from the perspective of both the wind energy practice and the flexibility of the proposed model. Each time the production demand changes, a new production level is re-allocated to each turbine. This allocation is decided using the conditional survival probability (i.e. the predicted remaining useful life, RUL) at the end of the next production period: the proposed RUL-based production allocation rule states that the conditional failure probability should be below a threshold for all the systems in the fleet, and that the failure risk is equally shared by all the systems.

$$R_i(kT_{prod}, j|(k-1)T_{prod}) = \mathbf{P}\{T_{i|\rho_j} > kT_{prod} | T_{i|\rho_j} > (k-1)T_{prod}\} \quad (2)$$

where $R_i(kT_{prod}, j|(k-1)T_{prod})$ is the conditional survival probability of wind turbine i given wind turbine i survives at $(k-1)T_{prod}$ and the control level j with the corresponding parameter ρ_j . $T_{i|\rho_j}$ is the conditional life of wind turbine i given the current control level j . The RUL of each wind turbine is computed at the beginning of a production period, based on its monitored deterioration and on the planned production level for the system on the next period. The realized production could be more than the production objective, while the uncompleted production objective will result in a penalty.

2.3. Maintenance policy and decision making

The maintenance decision-making step is synchronized with the production allocation step. The remaining useful life of each system is computed at the beginning of each production period. If a system is not able to survive the next production period when producing at the lowest possible level, then a replacement decision is made for this system. The threshold for the survival probability below which a maintenance decision is made is the maintenance decision variable to be optimized, referred as failure risk threshold η . Opportunistic maintenance can also be considered at this stage, aiming at grouping maintenance operations among systems in the fleet to save set-up costs.

- At the beginning of each production period, calculate the survival probability of each wind turbine with the minimal control level, i.e., ρ_1 . If $R_i(kT_{prod}, j|(k-1)T_{prod}) < \eta$, then wind turbine i will be preventively maintained.

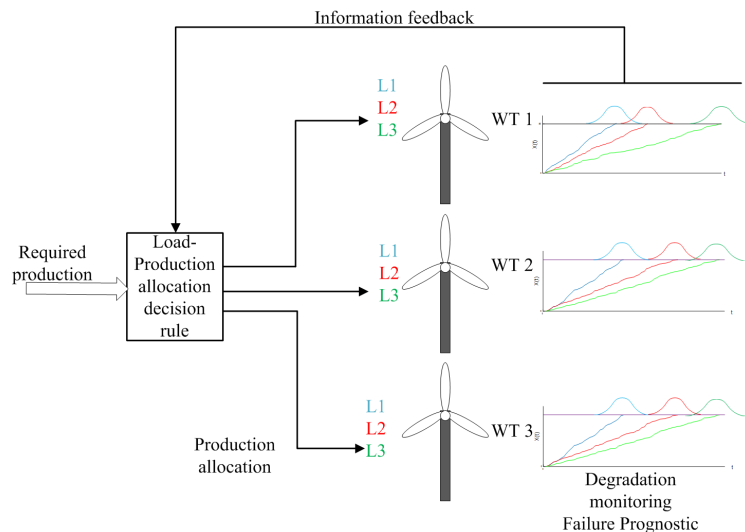


Figure 1. Flowchart of the production-degradation allocation and maintenance policy)

- For the resting wind turbine which satisfy $R_i(kT_{prod}, j|(k - 1)T_{prod}) > \eta$, allocate the production on each wind turbine according to the following rule:
 - Calculate all the possible combinations of wind turbines with their own control level.
 - Find the combinations which satisfy the required production level and calculate the variance of predicted degradation of each combination.
 - Choose the combination of wind turbine with the minimal variance as the control level of each wind turbine for the production period.
 - If no combination satisfies the required production, then organize preventive maintenance. Failure occurs during production will be correctively maintained.

Figure 2 gives an example of 3 WTs. The inspection information of each WT is available at time $t = k\tau, k = 1, 2, \dots, K$, where τ is the time interval when the information is available and $K = T_{prod}/\tau$. Hence at time t , simulate the production with the percentiles 0.01 corresponding to each control parameter of each wind turbine. It is clear that at the beginning

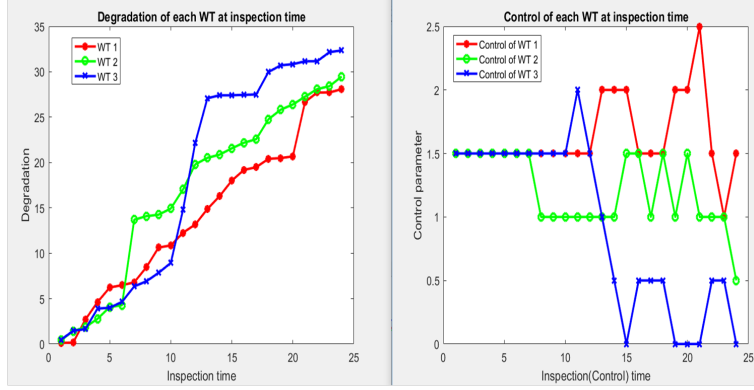


Figure 2. An example of production-degradation trajectory of 3 wind turbines with optimal control level

the degradation of 3 WTs are similar. But as time goes on, the difference of degradation increases. The changing of the control level balance the difference among different wind turbines.

2.4. Decision and Optimization

The failure risk threshold η affects on the number of maintenance activity and maintenance setup. In this study, we choose η as the decision variable to be optimized. The total maintenance $MCost(T)$ is calculated as

$$MCost(T) = N_p C_p + N_c C_c + N_s C_s \quad (3)$$

The total profit $Profit(T)$ according to the contract is calculated as

$$Profit(T) = P_g C_g - P_{un} C_{Pe} \quad (4)$$

The average unit cost is calculated as

$$EC(T) = \frac{Profit(T) - MCost(T)}{E(T)} \quad (5)$$

where N_p , N_c and N_s are the cumulative number of preventive maintenance, corrective maintenance and maintenance setup respectively. C_p , C_c and C_s are the cost of preventive maintenance, corrective maintenance and maintenance setup respectively. P_g and P_{un} are cumulative extra production and uncompleted production. C_g and C_{un} are unit profit of extra production and unit penalty of uncompleted production respectively.

3. Case study

3.1. Parameters setting

The size of the wind farm is $N = 5$. Hence at the beginning there are 5 new WTs in the farm. The shape parameter $\alpha = \alpha_0 t^{\rho_i}$, where $\alpha_0 = 0.02$ and $\rho_i \in \{1, 1.5, 2, 2.5\}$ corresponding to each control level (further the unit production rate). The scale parameter $\beta = 2$ is constant. The arrival rate $\lambda(t) = f(\rho_i) = 30/\rho_i$. The required production level of different production period is [525, 350, 420, 525, 630, 700, 700, 630, 525, 420, 420, 350] which is corresponding to monthly energy requirements. The preventive maintenance cost C_p , corrective maintenance cost C_c , set up cost for each maintenance activities C_s and the unit profit of extra part of production C_g and the unit penalty of uncompleted production C_{pe} are considered as the following three cases: Case 1: [100,120,50,1,2]; Case 2:[100,150,100,1,2]; Case 3:[100,120,100,1,2].

3.2. Simulations and analysis

The simulation results with η takes values from 0.1 to 0.9 are shown in Table 1. Among the three cases, the setup cost of Case 1 is lowest. The corrective maintenance cost of Case 2 is expensive. As η increases, the probability of preventive maintenance increase. Hence the group maintenance can take the chance to save the setup cost and the probability of failure during production decreases. Thus the average unit cost is decreasing. However, when η is as high as 0.9, some unnecessary preventive maintenances are incurred, thus the cost increase. Overall, the degradation and production allocation rules have balanced the difference of each wind turbines and guaranteed the performance at a good level. It can explain why the different cost setting doesn't change the optimal η very much.

Table 1. The effect of η on different cost cases

η	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
N_p	85	89	95	101	109	113	121	130	146
N_c	71	63	58	53	46	32	28	23	6
N_s	39	37	37	33	30	31	33	39	47
N_{pe}	572	534	525	501	413	378	396	415	437
N_g	3401	3325	3271	3198	3122	2986	2845	2683	2589
$EC(T)$ of Case 1	1.6713	1.6053	1.6089	1.5914	1.5624	1.4460	1.5057	1.5857	1.7155
$EC(T)$ of Case 2	2.0793	1.9793	1.9679	1.9154	1.8504	1.6970	1.7547	1.8497	1.9985
$EC(T)$ of Case 3	1.8663	1.7903	1.7939	1.7564	1.7124	1.6010	1.6707	1.7807	1.9505

4. Conclusion

In this paper, a global model is developed including all the features about load-sharing system, such as the required production, control level and degradation, and implemented to solve the joint production/maintenance optimization problem by simulation. The maintenance decision is made on both the conditional survival probability on given control level and the predicted production. The simulation results show how the joint load sharing/maintenance approach allows to reach an optimum operation at the farm level. However, the case with only 5 wind turbines is considered, which is limited. Further, the randomness of the wind may affect the control level, which is not included in this study. In the future, it would be interesting to relax these limits.

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