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ScienceDirect

IFAC-PapersOnLine 49-28 (2016) 073–078

Investigation on the use of energy efficiency for condition-based maintenance decision-making

Anh HOANG, Phuc DO and Benoît IUNG

Université de Lorraine, CRAN, UMR 7039, Campus Sciences, BP 70239,
Vandœuvre-lès-Nancy Cedex, 54506, France
(anh.hoang, phuc.do, benoit.iung @univ-lorraine.fr)

Abstract: Condition-based maintenance (CBM) has been introduced in industrial systems to maintain preventively the correct equipment at the right time with regards to its current health "condition" represented mainly the conventional indicators such as oil temperature, harmonics data, vibration, etc. The monitoring of these indicators is done through sensors or inspection tasks leading to incorporate in the maintenance optimization models, additional costs related to CBM. Nevertheless, while this practice is quite mastered in terms of benefits and costs, it is not well adapted to face now the new challenge encountered by the "industry of the future" such as the sustainable one. Indeed CBM indicators and maintenance cost model are not really taken into account today emergent indicators (and their impacts) related to energy consumption, energy efficiency or footprint tracking. In that way, this paper is investigating the interest to use energy efficiency (EE) for CBM decision-making. Investigation is consisting first to propose a new EE-based CBM model by using energy efficiency indicator (EEI) which is defined as the amount of energy consumption to produce one useful output unit. The proposed model leads to consider energy directly in the maintenance optimization. An extension of an existing CBM by integrating energy consumption in optimization model is also investigated in the way to compare the new CBM approach with conventional (extended) one. The comparison step is developed on the case study of the TELMA platform allowing to assess the impact of EE on existing CBM strategies and to conclude on the interest of a new EE-based CBM practice both in terms of cost and efficiency.

Keywords: Energy Efficiency, condition-based maintenance, cost model, energy cost, decision-making.

1. INTRODUCTION

Maintenance decision-making plays an important role during operating of industrial system in order to maintain it for providing its product/service with the expected performances while minimizing maintenance costs and relative consequences cost like downtime, customer penalty (Fritzsche et al. 2014). This decision can result from different strategies, such age-based maintenance, time-based maintenance and condition-based maintenance (CBM) (Do et al. 2015). It is pointed out in (Shin and Jun 2015) that CBM is a better strategy with regards to these previous ones because the maintenance action is decided at the right time on the basis of real monitored "conditions" of the industrial system. Indeed CBM is performed after one or more indicators show that equipment is going to fail or that equipment performance is deteriorating (indicator value is over a threshold). The monitoring of these indicators is done "on-line" through sensors or "off-line" by inspection tasks leading to incorporate in the maintenance optimization models, additional costs related to CBM.

The monitored conditions are materialized most of the time by an acquired signal which is corresponding to noise level, temperature, reactive power, vibration, etc. (Ben et al. 2015; Sun et al. 2014; Wang, 2002). From this data and "isolated" level, additional considerations are also addressed in CBM. Indeed, at component or system level, CBM can be used for tracking a global performance (resulting from data vs. information aggregation). For example, (Muchiri et al., 2013) is studied the performance degradation to control the component mission achievement. (Banks et al. 2014) proposed with CBM strategy to track the performance degradation for a vehicle at the system level. The tracking results can be also used by on-line prognostic system (Zhou et al. 2014). At this time, these conditions are very conventional and not well adapted to control also the system in link with performances expected, for example, by the new challenge of "industry of the future". Indeed, such challenge imposed, at least, to be consistent with sustainability requirements (industrial ecology) to preserve the environment (Iung & Levrat, 2014). One pillar of sustainability is related to energy mastering and mainly Energy Consumption (EC) and Energy Efficiency (EE) such as focused in this paper.

Nevertheless indicators such as EC, EE are not really taken into account in CBM and just a little in maintenance decisions in general. For instance, (Xu & Cao 2014) proposed to use EE performance as an objective for maintenance by updating periodic maintenance on EE evolution, but mainly on mastering the deterioration of machine tool (a Markov process application). In (Shafiee, et al 2015), deterioration level of multi-bladed wind turbine system can be used to rise/trigger the unplanned maintenance action for any failure items, while electrical energy as the useful output of this system is not fully taken into account. So

10.1016/j.ifacol.2016.11.013

EE is seen only as the auxiliary result of these previous CBM plans. In addition, energy can be saved by optimal periodic preventive maintenance (Mora at al. 2013) or can impact preventive maintenance by considering energy consumption in the case of minimal repair (Yildirim & Nezami 2014). To summarize, EE in link with maintenance is mainly considered as an item to adapt a preventive maintenance plan in terms of scheduled one but not in case of CBM strategy.

To face the previous issues, the objective of the paper is to investigate on the use of EE for condition-based maintenance. The paper focus on (i) an EE-based CBM enabling the consideration of EEI in maintenance decision making for supporting sustainability requirement and (ii) an analytical cost model including the energy cost under the constraint of different maintenance actions. This model provides global cost to highlight the benefits of new EE-based CBM in comparison with an extension of an existing CBM policy. The extension is required to be able to compare the two CBM ways (new and conventional one) under energy consideration.

For constructing the contributions of the paper, section 2 is describing the system and related assumptions as well as the deterioration modelling. The section 3 is developing the new proposed EE-based CBM approach and the cost model for maintenance optimization step. To highlight the performance of the proposed EE-based CBM approach, an extension of an existing CBM approach by integrating energy consideration in the maintenance model is developed and presented in appendix A. These proposals are applied in section 4 in a case study which is the TELMA platform materializing an industrial process processing metal sheet. The application aims to assess the extended model, and to compare the proposed EE-based CBM approach with an existing one in order to study the interest of the new EE-based practice in terms of cost and efficiency. Finally, section 5 provides conclusions and prospective.

2. SYSTEM MODELLING AND ASSUMPTIONS

2.1 General assumptions

Consider a single-component system which is gradually subjected a degradation phenomenon. The condition (degradation) is described by scalar random variable X_t. In the absence of repair or replacement actions, the evolution of the system degradation is assumed to be strictly increasing. Therefore, the system is considered as failed as soon as the deterioration value overs a critical threshold L, which can be selected by economical or technical reasons. These failures of system are automatically recorded.

It is shown in (Hoang at al. 2014) that the energy consumption may vary over time and depend on different factors such as the deterioration level of the system, the required useful output, etc. In this work, it is assumed that:

- The energy consumption during one time unit (from t to $(t+1)$), denoted by $E(t)$, depends not only on the state of system but also on the useful output.

$$E(t) = f(t, X_t, O(t)) \qquad (1)$$

where $O(t)$ is the useful output during one time unit (from t to $(t+1)$).

- The deterioration evolution of the system does not depend on its useful output.

It is also assumed that the inspection operations can only be planned at regular intervals. Two kinds of inspection operations are considered herein. The deterioration inspection operation provides the current state/condition of the system and each deterioration inspection operation costs C_i^D. The energy consumption inspection provides the current energy consumption and we have to pay a cost C_i^E for each operation. From a practical point of view, monitoring the deterioration level of a system is usually more complex than measuring its energy consumption. It may be reasonable to assumed that $C_i^E \le C_i^D$. It is important to note that a sensitivity analysis to the energy inspection cost is presented and discussed at Section 4.2

2.2 Deterioration modelling

To describe the deterioration process of a such system, Gamma process is widely selected and successfully applied in various industrial system (Van Noortwijk, 2009). In that way, in this paper the increment in the deterioration level of the system during $(t - T_i)$ time units follows Gamma probability density with shape parameter $\alpha(t - T_i)$ and scale parameter β:

$$f_{\alpha(t-T_i)}(x)=\frac{\beta}{\Gamma(\alpha(t-T_i))}(\beta x)^{\alpha(t-T_i)-1}(e)^{-\beta x} \qquad (2)$$

By the modelling, the deterioration speed and its variance are $\alpha\beta$ and $\alpha\beta^2$ respectively. Various deterioration behaviours can be modelled by changing the couple of parameters.

The system degradation behavior and the energy consumption are illustrated in Fig. 1

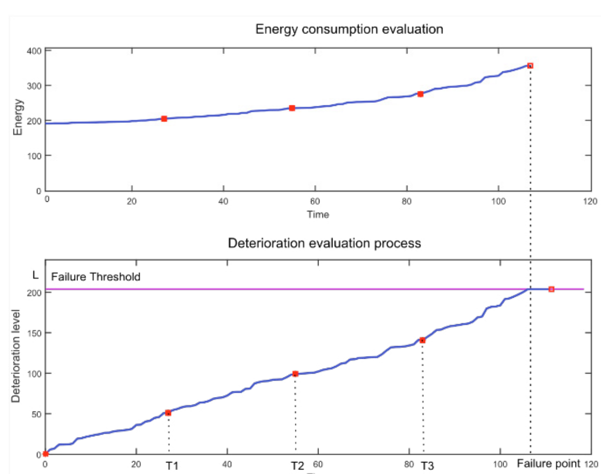

Fig. 1 Degradation evolution and energy consumption

3. EE -BASED CBM MAINTENANCE POLICY

3.1 Energy efficiency indicator