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Post-Prognostics Decision for Optimizing the Commitment of Fuel Cell Systems ⋆

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Abstract: In a post-prognostics decision context, this paper addresses the problem of maximizing the useful life of a platform composed of several parallel machines under service constraint. Application on multi-stack fuel cell systems is considered. In order to propose a solution to the insufficient durability of fuel cells, the purpose is to define a commitment strategy by determining at each time the contribution of each fuel cell stack to the global output so as to reach the demand as long as possible. Two algorithms making use of convex optimization are proposed to cope with the assignment problem. First one is based on the Mirror-prox for Saddle Points method and second one uses the Lasso (Least Absolute Shrinkage and Selection Operator) principle. Results based on computational experiments assess the efficiency of these two approaches in comparison with an intuitive resolution performing successive basic convex projections onto the sets of constraints associated to the optimization problem.

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1. INTRODUCTION AND RELATED WORK

In the context of the decline of fossil fuel resources, the use of fuel cells appears to be of growing interest as a potential alternative to conventional power systems (Jouin et al., 2013). Fuel cells can be used in many applications, such as stationary ones for domestic use, but also in transportation and portable power applications (Borup et al., 2007). Fuel cells suffer however from insufficient durability. In fact, their lifetime reaches between 1500 and 3000 hours, whereas 5000 hours are required for transportation applications and up to 100000 hours for stationary ones. Improvement of their performance, reliability and lifetime is then an important challenge (Borup et al., 2007), for which techniques of Prognostics and Health Management (*PHM*) can help. It has been pointed out by Jouin et al. (2013) that researches in PHM dealing with fuel cells have been mainly focused on data acquisition and data processing. Less attention has been paid to condition assessment and diagnostics and very few works address prognostics and decision making. Papers taking into account the decision part propose furthermore only corrective actions (see (Bosco and Fronk, 2000) and (Wells and Parr, 2004)), for which physical parameters (such as inlet and outlet gas flows, pressures and temperatures, single cell and stacks voltages or current) are controlled to master each fuel cell operating conditions as accurately as possible. These corrective actions correspond to real-time control (from nanoseconds to seconds), necessary to compensate the natural fluctuation of fuel cells parameters and to avoid too early irreversible degradations. At each time it allows also to set the operating current to meet the needs in power for each fuel cell. Decision making addressed in this paper differs from the studies proposed so far. Larger scale of time (hours to weeks) is indeed considered and decision comes within the scope of Prognostic Decision Making (PDM), which aims at choosing an appropriate system configuration (Balaban and Alonso, 2012). The system considered here is composed of several fuel cells, used in parallel to provide a global power output. The problem is to provide the power output value for each fuel cell as a function of time, on the basis of a global power demand. Target application considered here is based on stationary power generation for domestic usage, also known as micro combined heat and power (micro-CHP).

In order to deliver suitable power outputs, fuel cells are used in the form of stacks, composed of many individual connected cells. Each stack is supposed to be independent, but the multi-stack fuel cell system has to deliver a given global power output based on a need of energy. At each time, the total provided power output is the sum of each output of the stacks that are currently running. Each fuel cell stack is able to deliver an output that can vary continuously and take any value within a given interval. The optimization problem consists in determining the appropriate output for each fuel cell stack during the whole production horizon. All the stacks are not supposed to be running at each time if the target output can be reached by using only a subset of them. All the stacks may moreover not be always available if their end of life has been reached.

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Considering a global needed power output, the multi-stack system useful life depends not only on each stack useful life, but also on both the schedule and the operating condition settings that define the contribution of each stack over time. The same statement applies to batteries in a health management context. Saha et al. (Saha et al., 2012) have for instance addressed the maximization of the battery charge used while constraining the probability of a battery shut off in flight for electric unmanned aerial vehicles. Predictions on remaining battery life are used to optimize mission plans without exceeding the available battery charge. In a same way, we propose to use prognostics results in the form of RUL to maximize the global useful life of a multi-stack fuel cell system under service constraint.

A similar problem has been addressed in (Herr et al., 2014a) and (Herr et al., 2014b), where the purpose was to define a schedule of machines that maximizes the production horizon, based on the knowledge of each machine remaining useful life (RUL) in a PHM framework. In these studies, machine throughputs have been considered to be in a discrete domain. It has been shown in (Herr et al., 2014b) that optimal solutions can be found in limited time only for small size instances considering a very limited number of machines, very few throughput values and short production horizons. An other study considering this time machines whose performances can vary continuously between two bounds has been proposed in (Herr et al., 2015). The considered model has been built to fit the fuel cells behavior, but the proposed resolution approach gives suboptimal solutions and is limited to systems of reasonable size. In order to overcome these two limitations, we propose in this paper to change totally the paradigm of the resolution and to build the solutions globally on the whole production horizon. Contribution of each machine during its lifetime is considered as a whole and optimized on the whole horizon. Each machine contribution is determined through convex optimization, whose interest is to allow the solving of big optimization problems in limited time.

The considered scheduling problem is proposed to be addressed via optimizing a composite function subject to several constraints due to fuel cell intrinsic characteristics. Two different algorithms are developed and used to define the contribution of each fuel cell stack to the global output over the whole production horizon. First one is based on the Mirror Prox method proposed by Nemirovski (2004) as a variant of the Mirror Descent developed by Nemirovsky and Yudin (1983) to minimize a smooth convex function subject to convex constraints. Estimation of the variable is efficient in that it depends very little on its dimension. This is why these methods can be used to solve big optimization problems (Beck and Teboulle, 2003). Second resolution method is based on a penalization through an ℓ_1 norm, which has been extensively studied in many domains such as artificial intelligence for machine learning, statistics, image processing or data analysis (Donoho and Elad, 2003; Candès et al., 2008). We propose to use a variant of the Lasso (Least Absolute Shrinkage Operator) algorithm, proposed by Tibshirani (1996) as a method for sparse model selection in statistics.

The organization of the paper is as follows: the tackled problem is first described in Section 2, with a brief presentation of the application framework and the optimization problem. After a mathematical formulation of the problem, resolution methods are then described in Section 3. Efficiency of these methods is assessed through simulation results in Section 4. Conclusion and future work are finally given in Section 5.

2. PROBLEM STATEMENT

The application addressed in this paper is based on a multi-stack fuel cell system which is supposed to meet energy requirements for domestic usage in a stationary power generation framework. This system is supposed to be composed of m fuel cell stacks M_j $(1 \leqslant j \leqslant m)$. All the stacks are supposed to be always supplied with raw material required for the energy conversion. They can be used simultaneously and independently from each other.

This corresponds to a parallel machines system, in which each machine is supposed to be able to deliver power outputs P_j that can vary continuously within a given power output range $[P\text{min}_j; P\text{max}_j]$. For each machine M_j $(1 \leqslant j \leqslant m)$, the minimal power output $P\text{min}_j$ is supposed to be strictly greater than zero and constant over time. The maximal power output $P\text{max}_j$ decreases with time when the machine M_j is used. The range of available power outputs depends then on the time t: for each machine M_j, $0 < P\text{min}_j < P_j(t) < P\text{max}_j(t)$. Useful life of each power output P_j, $RUL_j(P_j)$, is moreover limited by the decrease of $P\text{max}_j$ of equation $P\text{max}_j(t) = a_j \cdot t + P\text{max}_j(0)$, with $a_j < 0$.

At each time, the global outcome $P\text{tot}$ is the sum of each stack power contribution. During the whole production horizon, denoted H, this global outcome has to reach a given load demand $\sigma(t)$. In the stationary power generation framework considered here, this demand is supposed to be constant over time. Storage being not considered in this study, overproduction is lost. Stop-and-start of fuel cell stacks have moreover to be avoided as far as possible. Stopping and restarting a fuel cell can indeed induce considerable damage and lead to premature aging (Borup et al., 2007). Change of power output during the use of fuel cell stacks is however still authorized.

Considering these assumptions, the point is to manage the system by defining the commitment of fuel cell stacks so as to reach the demand as long as possible. During the whole production horizon, the purpose is then to define at each time each stack contribution to the global power output.

3. RESOLUTION

A mathematical formulation of the problem making use of convex elements is first defined. Two different convex resolution methods are then proposed to cope with the assignment problem. First one is based on the Mirror Prox method and second one makes use of the Lasso technique to optimize the commitment of machines.

3.1 Mathematical formulation

Let $f_j(t)$ $(1 \leqslant j \leqslant m,\ 0 \leqslant t \leqslant T)$ be the vector defining the evolution over time of the power output delivered by the machine M_j, with T the length of the

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