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Particle filter based hybrid prognostics of proton exchange membrane fuel cell in bond graph framework

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ABSTRACT

This paper presents a holistic solution towards prognostics of industrial Proton Exchange Membrane Fuel Cell. It involves an efficient multi-energetic model suited for diagnostics and prognostics, developed using some specific properties of Bond Graph (BG) theory. The benefits of Particle Filters (PF) are integrated with the BG model derived fault indicators named Analytical Redundancy Relations, for prognostics of the Electrical-Electrochemical part. The hybrid prognostics involves statistical degradation model obtained using real degradation tests. Prognostics problem is formulated as the joint state-parameter estimation problem in PF framework where estimations of state of health (SOH) is obtained in probabilistic domain. This in turn is used for prediction of Remaining Useful Life (RUL) under constant current as well as dynamic current solicitations. The SOH estimation and RUL prediction is obtained with very high accuracy and precise confidence bounds. Moreover, a comparative analysis with Extended Kalman Filter demonstrates the usefulness of PF.

1. Introduction

Addressing the issue of sustainable energy requirement has become a major challenge, especially as the world faces major decline of the available fossil energy resources and global warming. Usage of hydrogen as the energy source and development of Proton Exchange Membrane Fuel Cell (PEMFC) has emerged as one of the promising solutions and a potential alternative to the fossil energy (Ziogou et al., 2011). However, several factors inhibit the wide utility of PEMFC such as irreversible degradation mechanisms, multiple impairments etc. These manifest in form of deterioration of the carbon support, the dehydration of the membrane, a catalytic degradation and the ripening of the platinum particles (Martínez et al., 2008; Schmittinger and Vahidi, 2008). These phenomena generate voltage drops which are difficult to forecast when a constant or variable profile of load (current) is considered (Pei and Chen, 2014). Most of the phenomena described above are mutually dependent and understood with insufficient clarity. The presence of irreversible degradation severely affects the useful life of PEMFC and leads to inefficiency, reduced lifespan, lesser power density and high maintenance cost (Venkatasubramanian, 2005). This in turn reduces the reliable deployment of PEMFC, thus preventing its widespread use. The latter has led to an urgent need of effective pro-active maintenance strategies against the traditional preventive action ones. The latter lead to enhancement in the useful life of PEMFC and reduction in the maintenance cost. The issue of useful life assessment is best addressed from the perspectives of Prognostic and Health Management (PHM) (Dai et al., 2013; Jardine et al., 2006). For instance, knowledge of the Remaining Useful Life (RUL) of a fleet of energy sources (e.g. batteries (Hu et al., 2014; Ng et al., 2014) and PEMFC (Chen et al., 2015)) leads to good estimation of the power that can be delivered to adapt the energy distribution. This enhances the service time of the system and economic investment.

Thus, the core problem at hand can be seen in two folds: complex and mutually dependent multi-energetic physics of PEMFC along

Abbreviations: ARR, analytical redundancy relations; BG, bond graph; BG-LFT, bond graph in linear fractional transformation; DM, degradation model; DPP, degradation progression parameter; EE, electrical-electrochemical; EKF, extended kalman filter; EOL, end of life; ESCA, electro-chemical active surface area; FC1, fuel cell under constant current load; FC2, fuel cell under variable current load; GDL, gas diffusion layer; I-ARR, interval valued analytical redundancy relations; OCV, open circuit voltage; PDF, probability density function; PEMFC, proton exchange membrane fuel cell; PF, particle filters; PHM, prognostic and health management; *RA*, relative accuracy; RMAD, relative median absolute deviation; *RMSE*, root mean square error; RUL, remaining useful life; SIR, sampling importance resampling; SOH, state of health.

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Notations

I_0	Exchanged current in PEMFC
I_{fc}	Load Current in PEMFC
I_L	Limiting Current in PEMFC
$Rohm$	Global Resistance
n_s	Number of cells in a stack
U_{fc}	Stack Voltage sensor
θ^d	System parameter under degradation
θ_n^d	Nominal value of θ^d
$\Delta\theta$	Additive uncertainty on θ
δ_θ	Multiplicative uncertainty on θ
$r_n(t)$	Numerical evaluation of the nominal part of ARR
y_k^d	Measurement of prognostic candidate $\theta^d(or, \alpha)$ at discrete time k
γ^d	Degradation progression parameter associated to θ^d
$\hat{X}$	Estimated value of species X
X^*	True value of species X
σ_X	Standard deviation value of random specie X
σ_X^2	Variance of population values of X
N	Number of particles in PF
w_k^i	Weight of i^{th} particle at discrete time k
$w^d(t)$	Noise associated with the measurements y_k^d
α	Bounds of true RUL in $\alpha - \lambda$ metric for RUL assessment
α	State of health indicator
β	Rate of change of α
ξ_k	Normally distributed artificial random-walk noise

with the irreversible degradation mechanisms involved, and the requirement of efficient assessment of the RUL for development of efficient pro-active maintenance strategies.

Recently, Jha et al. (2016) proposed a hybrid prognostics methodology where benefits of Bond graph (BG) modelling technique and Sequential Monte Carlo based *Particle filters* (PF) were integrated for efficient prognostics. As such, statistical or empirical *degradation models* (DM) could be exploited along with information obtained from physics based models.

This paper implements the methodology proposed in Jha et al. (2016) in the context of PEMFC. As such, a holistic solution is developed towards aforementioned issues related to PEMFC. The first issue is tackled in BG framework where mutually-dependent complex dynamics of PEMFC is systematically modeled and graphically represented. The second issue of prognostics is addressed for the electrical-electrochemical (EE) part of PEMFC in PF framework. To that end, the electrical global resistance parameter is considered uncertain. Also, based upon the aging tests conducted in real time, the global resistance and limiting current are considered as the principle system-parameters undergoing significant degradation. To achieve a robust detection of degradation beginning, uncertain BG model named BG in Linear Fractional Transformation (BG-LFT) (Sié Kam and Dauphin-Tanguy, 2005), is developed for the EE part. This enables a robust detection of degradation-beginning in form of an incipient parametric fault. Thereafter, prognostics is exercised using PFs.

To this end, a *fault model* is constructed in state space modelling the dynamics of state of health (SOH) evolution. The latter is inspired from the DM and observation equation is obtained from the uncertain BG derived fault indicators or Analytical Redundancy Relations (ARRs). This way, the ARR used as the degradation indicator, is further exploited to obtain SOH evolution information. Using PF algorithms, SOH estimation is obtained along with the estimation of the associated unknown parameter that influences the degradation evolution. The latter is tracked to obtain the SOH in probabilistic terms. These estimations are projected in future, to achieve RUL predictions of the EE part of PEMFC. The methodology is applied on real degradation data sets under constant and dynamic load (current) profiles.

Various motivations for the development of this work are:

- There are very few existing model-based works that propose efficient prognostics for PEMFC. Wang et al. (2011) proposes physics based DM of the Electro-Chemical Active Surface Area (ECSA), used for damage tracking and prediction using Unscented Kalman Filter. However, ECSA is only one of the many factors that influence the damage progression. As such, more efficient approaches are needed. (Chen et al., 2015) proposed a rapid lifetime prediction formula to estimate the voltage drop rate. However, with only a linear DM employed, it required further investigation.
- Recently, (Jouin et al., 2014a,b, 2015) have efficiently exploited PFs for efficient prognostics of PEMFC. Therein, DM considered is purely empirical in nature, employing a model fitting log-linear DM. As such, it lacks the insight into the physics of the phenomenon. On the contrary, in this work, based on aging tests, SOH is considered to evolve linearly. Moreover, although the DM is statistically derived, the measurement of degradation state is obtained from the ARR which reflects the energetic assessment of EE part. As such, understanding of the underlying physics is not compromised during the process of prognostics.
- Contrary to constant current solicitations, dynamic solicitations are more representative of the current load profiles encountered in practice (residential applications under changing weather-temperature conditions (Oh et al., 2012)). The latter have not been studied much (Bressel et al., 2016b). In fact, presence of variable speed of degradation progression, reduces the effectiveness of model based approaches for prognostics. Moreover, machine learning techniques remain useful to a limited extent as they require many examples/samples of similar degradation patter. In this context, this paper shows that PFs are able to estimate the damage pattern efficiently and generate precise RUL predictions.
- Interestingly, the issue of PEMFC prognostics based in BG framework has not even been attempted. For instance, although Saisset et al. (2006) and Peraza et al. (2008) develop a detailed PEMFC BG model, they are not suited for diagnostics or prognostics. Ould-Bouamama et al. (2013) develops Signed BG model of PEMFC, but for diagnostics purposes only.

The scientific interests and novel contributions of this paper are listed as follows.

- BG model of industrially oriented PEMFC is developed with efficient functional decomposition suited for diagnostics and prognostics.
- An efficient robust detection of parametric-degradation-beginning is achieved by development of BG-LFT model of the electrical-electrochemical part.
- Benefits of BG modelling technique and Monte Carlo framework are integrated for estimation of SOH and RUL prediction in PEMFC context.
- The method is applied on EE part of PEMFC under: (i) constant current load stack solicitation, (ii) Dynamic (variable) current load solicitations, using real/experimental degradation data sets.
- The SOH estimator is replaced with Extended Kalman Filter (EKF) for constant current load case and the performance is compared with that of PF.

Besides this introduction section, Section 2 discusses the background and related works, Section 3 details the BG model of the PEMFC, Section 4 builds the BG-LFT model of the EE part and