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A dynamic prognosis scheme for flexible operation of gas turbines

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HIGHLIGHTS

- A prognosis scheme for predicting the performance of gas turbine components is presented.
- The proposed prognosis scheme takes into consideration flexible and dynamic operating conditions of gas turbines.
- The performance of the scheme is tested under transient conditions of gas turbines.
- The proposed scheme is utilized to detect and forecast compressor fouling and turbine erosion.

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ABSTRACT

The increase in energy demand has led to expansion of renewable energy sources and their integration into a more diverse energy mix. Consequently the operation of thermal power plants, which are spear-headed by the gas turbine technology, has been affected. Gas turbines are now required to operate more flexible in grid supporting modes that include part-load and transient operations. Therefore, condition based maintenance should encapsulate this recent shift in the gas turbine's role by taking into account dynamic operating conditions for diagnostic and prognostic purposes. In this paper, a novel scheme for performance-based prognostics of industrial gas turbines operating under dynamic conditions is proposed and developed. The concept of performance adaptation is introduced and implemented through a dynamic engine model that is developed in Matlab/Simulink environment for diagnosing and prognosing the health of gas turbine components. Our proposed scheme is tested under variable ambient conditions corresponding to dynamic operational modes of the gas turbine for estimating and predicting multiple component degradations. The diagnosis task developed is based on an adaptive method and is performed in a sliding window-based manner. A regression-based method is then implemented to locally represent the diagnostic information for subsequently forecasting the performance behavior of the engine. The accuracy of the proposed prognosis scheme is evaluated through the Probability Density Function (PDF) and the Remaining Useful Life (RUL) metrics. The results demonstrate a promising prospect of our proposed methodology for detecting and predicting accurately and efficiently the performance of gas turbine components as they degrade over time.

1. Introduction

The ever-growing demand for environmental friendlier and more efficient power generation sources has triggered a diverse family of challenges that have to be met by gas turbines which are the prime movers of thermal power plants. One of these challenges involves the development of high fidelity, accurate and computationally efficient health monitoring, diagnostic and prognostic schemes for ensuring a reliable and effective gas turbine asset management [1].

Efficiency still remains as one of the top priorities of gas turbine manufacturers and users. However, there has been a significant shift towards products that can operate with increased reliability and flexibility in load following and grid supporting roles. A significant part of this shift is due to the fact that gas turbine power plants have to compensate for intermittent renewable energy sources in a more diverse energy mix. This new type and mode of gas turbine operation has been recently implemented in the Siemens Flex-Power™ [2] and GE's FlexEfficiency™ [3] technologies. A typical gas turbine operating profile is shown in Fig. 1.

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Nomenclature

Acronyms

AB	Accuracy Bounds
DI	Diagnostic Index
EoL	End of Life
ERUL	Equivalent Remaining Useful Life
GPA	Gas Path Analysis
ISA	International Standard Atmosphere
NN	Neural Networks
OF	Objective Function
PDF	Probability Density Function
RUL	Remaining Useful Life

Symbols

a	coefficient of linear regression model
l	time length of diagnostic window overlap (h)
L	time length of diagnostic window (h)
$\dot{m}$	mass flow rate (kg/s)
n	total number of operating points
N	corrected shaft rotational speed
p	probability
P	pressure (Pa)
q	total number of diagnostic windows
t	time instant (h)
T	temperature (K)
$\mathbf{u}$	ambient and operating conditions vector
W	component work (W)
x	variable
$\mathbf{X}$	component characteristics vector
$\mathbf{Y}$	measurement vector

Greek

α	upper and lower accuracy bound
Γ	mass flow capacity
Δ	deviation
ϵ	average prediction error
η	isentropic efficiency
μ	mean
π	pressure ratio
σ	spread

Subscript

amb	ambient
c	compressor
cl	clean
d	diagnosis
deg	degraded
des	design point
e	effective
f	fuel
inj	injected
lreg	linear regression
p	prognosis
pred	predicted
pt	power turbine
r	reference engine
ref	reference
t	turbine
th	thermal
thr	threshold
1-6	engine gas path station

The recent trend for increased flexibility in gas turbine operation implies that the engines are required to start up and shut down faster, and at the same time produce power at high thermal efficiency. Since the power output available from renewable energy sources is prioritized in the grid, the gas turbines will have a supporting role for fulfilling the energy demand depending on the wind capacity and the solar radiation. Consequently, majority of the gas turbine's new operating profile will be dominated by part-load operation, followed by fast start ups and shut downs as depicted in Fig. 1. This increased demand on the gas turbine flexibility has motivated the gas turbine community to evaluate the effects of this transition in terms of accuracy of diagnostic and prognostic schemes.

Apart from a limited number of works in the literature [4–7] most diagnostic and subsequently prognostic schemes have been developed based on the steady state performance operation. Moreover, in dynamic operating conditions the useful life of gas turbine components is consumed faster than the steady state and the maintenance intervals suggested by manufacturers [8] are brought out forward, as shown from Fig. 2. The peaking unit given in Fig. 2 refers to a unit where its operational profile is characterized by an increased number of start ups and shut downs which characterize the transient conditions. The midrange unit refers to a unit that is dominated by part-load operations with a smaller number of start ups and shut downs, and the continuous unit refers to a unit that operates most of its lifetime at base load mode.

The problem of prognosis deals with prediction of the future condition of a system. The most common issue in prognostics deals with calculation of the Remaining Useful Life (RUL) [9,10] of a life limited component of the system. In particular, for gas turbine prognostics there are several available methods, such as model-based [11], data-based [12,13] and statistical [9,14] approaches, although these schemes are *only* tested and developed when diagnosis is performed at steady state conditions. The capabilities of a prognosis scheme for implementing the engine's dynamic transient performance information has to be further investigated. Among a wide selection of methods, such as exponential models [15] and particle filtering [11,16] that are applied for prognostics of various energy systems the most common method for gas turbine prognosis is trending through regression fitting of gas turbine component degradations as developed in [9].

In comparison to our earlier works on transient diagnostics [17,18], in this study the proposed adaptation method is further developed and implemented for gas turbine prognostics. Specifically, the proposed prognosis scheme is not continuous as suggested in [9], where all the past diagnostic results under steady state operation were used to fit a multiple regression model based on a data skewness criterion. In contrast to [9], in this study a linear regression method is implemented that is based on a local window-based segment. Furthermore, the proposed scheme takes into consideration the transient operations, variable ambient conditions as well as multiple component degradations.

Our proposed prognosis scheme within a local window-based segment is fundamentally different from the conventional forecast of engine health and RUL based on pattern recognition methods that utilize the entire historical operating data of the engine. The main reason for this change in the prognosis approach lies in the fact that most existing gas turbine prognosis schemes [1,12,13] rely on diagnostic methods that have been tested only for steady state operating conditions. In addition, for model-based diagnostic