CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333144

Integrated Condition Monitoring For Plant-Wide Prognostics

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The use of Condition Monitoring (CM) in the power industry is well established, with traditional manual analysis increasingly giving way to intelligent, automated analysis. Further, there is a growing interest in the extension of such CM systems to derive prognostic information for asset management. It is common however for CM applications to be retrofitted to existing equipment, to monitor a particular component or subsystem, resulting in several isolated CM systems attached to a larger system from which it is not trivial to extract plant-wide prognostic information.

The extension of CM applications to deliver prognostic information is an area of current research in the nuclear industry as operators seek to maximise the operational life of ageing plants. The interdependence of multiple safety critical systems, each of which is monitored individually, is a critical challenge in determining the health of a life-limiting component which may be part of a chain of monitored sub-systems. The generation of new information about plant-wide state, based on subsystem prognostics and monitoring, can help inform operation and maintenance.

This paper describes two CM systems used to monitor key systems on the UK fleet of Advanced Gas-Cooled Reactors, at different ends of the coolant cycle in the reactor. The first system monitors vibrations of the gas circulators used to pump coolant into the core, while the second system monitors the thermal power of the fuel channels inside the core. The systems make diagnoses of anomalies in their respective data-sets, however a fault in the gas circulator would directly affect the cooling of the core, potentially affecting the fuel channels further along the coolant loop. The paper discusses how closer integration of the outputs of each system may better inform the prognostic information about the plant, by identifying related anomalies and providing corroborating information to better inform prognostic estimates.

1. Introduction

Condition Monitoring (CM) has been used extensively in many industries, including the power industry, to provide asset health information about a wide range of assets. Initial implementations of CM focussed on the detection and classification of anomalies, ideally before but often after they occur. A preferable scenario for the asset owner or operator is an estimate of when a fault is likely to occur, which has recently seen an increased move towards prognostic health estimation in the CM field.

The highly specific nature of many CM analyses however can often result in isolated systems, used to monitor or estimate the Remaining Useful Life (RUL) of individual systems with little or no interaction with other monitoring systems. Two pieces of equipment in same plant for example, may have two individual CM systems which both provide estimates of prognostic health of their respective components. The outputs from these systems may be considered, at a high level, in the decision making of the operation of the wider plant, however it is unlikely that the two systems directly interact to provide updated estimates of shared parameters.

Recent interest in Prognostic Health Monitoring (PHM) in the nuclear industry has become particularly relevant as many Generation II reactors approach, and in some cases exceed their original design lives. A combination of economic, political and safety drivers have resulted in programs in the United States (Coble, 2012) and the extension of safety cases for continued operation of plants in the UK, amongst other countries. Key to such programmes are the development of CM and prognostic models which allow estimates of the structural state and likely performance of critical components such that a high degree of

Please cite this article as: Wallace C., Costello J., West G., Mcarthur S., Coghlan M., 2013, Integrated condition monitoring for plant-wide prognostics, Chemical Engineering Transactions, 33, 859-864 DOI: 10.3303/CET1333144

confidence can be assigned to continued safe operation of the plant and are increasingly able to make estimates about component health and plan maintenance accordingly.

CM and prognostic systems are to a very large extent characterized by the information and data available to them, in order to generate models of behavior, make diagnoses and estimate component health. Often the most advanced knowledge about a system however will not be the raw data from a sensor, which may be an input into a CM or prognostic system, but the output of a CM algorithm designed to analyze this data. To achieve the best possible CM estimate of health and by extension RUL, every useful data source should be included, especially where analysis of one set of data may better inform the analysis of another or there is a physical relationship between the two systems.

This paper describes two CM applications developed for the Advanced Gas-Cooled Reactor (AGR) in the UK, both of which have potential for extension into prognostic health estimates of their respective components but by virtue of their location and function in the plant, may benefit from integration and sharing of information. The paper discusses the key functions of these systems and considers where they would be of benefit in a prognostic role. After considering the general issues associated with the sharing of CM information for the purposes of PHM, the potential benefits for the two AGR CM systems in the event of such a sharing framework are discussed.

1.1 Advanced Gas-Cooled Reactor Condition Monitoring

The AGR is the second generation of civil nuclear reactor in the UK and uses graphite bricks to form the core structure, supporting fuel and control assemblies, and for neutron moderation (Steer, 2005). A CO_2 coolant at 30 bar is pumped around the core by eight gas circulators, transferring heat from the fuel assemblies, which contain ceramic UO_2 pellets, to the boilers.

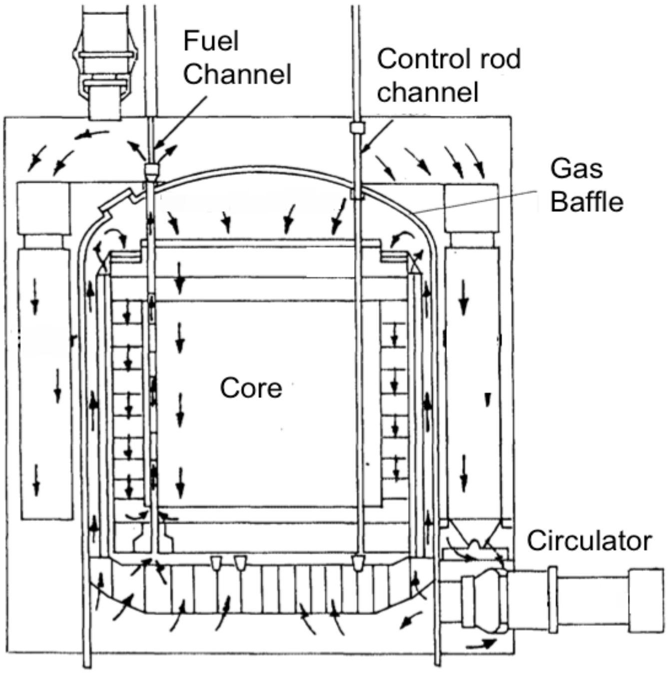


Figure 1: An overview of the AGR core structure, highlighting the gas flow of coolant through the core. Image courtesy EDF Energy.

The graphite core is the principal life-limiting feature of the AGR, as during operation, radiolytic oxidation causes weight loss and dimensional change in the graphite resulting in a loss of structural strength and loss of moderation. Inspections of the graphite core occur when the station is offline, approximately every three years. These inspections are used to justify continued operation are complemented by CM, to provide estimates of component health when the reactor is online.

The economic and safety-related benefits of extracting component health information when the reactor is online have resulted in an increased use of CM on key core systems. The systems described in Table 1, all developed at the University Of Strathclyde, are designed as decision support tools for the engineers who operate AGR stations and involve strong collaboration at each stage of design, development and deployment. Only recently however has work begun to look at interaction between systems with overlapping scopes, initially between the BETA and IMAPS systems (Wallace, 2011), where contextual information is now presented to the users of either system.

1.2 Integrated Advanced Gas-Cooled Reactor Condition Monitoring

As the systems described in Table 1 are extended towards to PHM, it has been proposed that an early investigation of the process of sharing CM information and conclusions between systems may enhance the future utility of the systems. For this reason, the remainder of this paper will discuss the general considerations involved in sharing the outputs of two or more CM systems by describing the potential integration of the ROMAAN and IMAPS systems described above.

Table 1: AGR CM Systems

System	Component	Status	Notes
BETA	Fuel Channels	Deployed	A rule based system for detecting damage to graphite fuel channels based on refuelling data
IMAPS	Whole Core	Deployed	A visualisation and observation storage application for AGR related CM analyses
ROMAAN	Gas Circulators, Turbine Generators	Test Deployment	A rule based system for automatically analysing and managing rotating machinery vibration alarms
DMF	Whole Core	Prototyping	An agent-based system for integrating CM analyses and managing reactor data

2. Gas Circulator Monitoring

Gas circulator units represent a key operational asset in the AGR, facilitating the flow of coolant CO_2 through the reactor core channels. Eight of these units are fitted to each core, with the circulation function of each focused on a particular cluster of channels. Monitoring of the circulators is a point of interest for the operator due to increased focus on extension of life in the UK nuclear industry. Intelligent techniques have been applied to the circulators and steam turbine generators (Costello, 2012) in the Rotating Machinery Alarm Analyst (ROMAAN) toolkit, developed by the University of Strathclyde and EDF Energy.

2.1 Monitoring of gas circulators

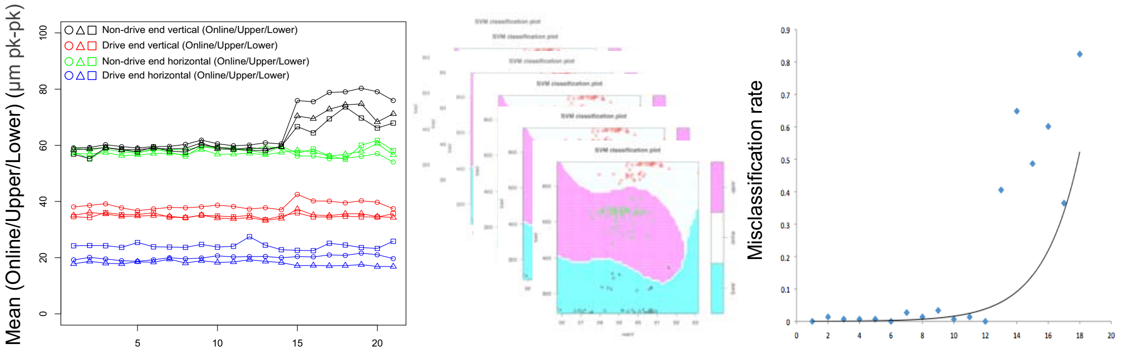
Condition Monitoring of gas circulators, as a member of the rotating plant item asset family, is rooted in vibration analysis (Randall, 2004). Operating speed component vectors and frequencies are compared with driving operational parameters and benchmarks in order to reason about circulator performance and health. Experts in the discipline are tasked with monitoring the performance of the circulators from these signals, and reasoning about future operating regimes for each asset.

Due to the nature of AGR operation, the duty cycle of the circulators is variable, with events such as maintenance and online refueling causing non steady state periods of behavior. Recent data-intensive investigations have illustrated the potential information available from the vibration response of the circulators and a refueling classifier (Costello et al., 2012) was constructed from sample historical data, which showed promise as a benchmark of asset behavior regimes. This classifier provides a unique phase space view of the interdependence of vibration response and load regime during refueling system events, and defines refueling normality on an individual asset basis which could allow engineers to track any potential behavior change between refueling events and schedule maintenance accordingly.

2.2 Example analysis

A key potential area in improving the monitoring of the circulators units is the identification and mapping of the observed vibration response to a performance or health metric, allowing for the long-term operation of individual asset instances to be reasoned about. Numerous data-driven techniques exist that have seen application to long-term asset analysis, including algorithms from machine learning such as support vector machines (SVM) (Kim et al., 2008), relevance vector machines (Di Maio et al., 2012), and both standard (Gouriveau and Zerhouni, 2012) and novel neural approaches (Zio et al., 2012). In order to facilitate any predictive calculations, one of the major obstacles to overcome in data-driven approaches is the availability of fully labeled reliability and remaining useful life data. For a large number of assets in function-critical scenarios (including NPP coolant pumps such as AGR circulators), the acquisition of full failure data remains difficult.

Extending the SVM-based refueling classifier discussed earlier (Costello et al., 2012), an examination of example historical data of a single circulator unit was made to demonstrate the usefulness complimentary approaches would have within an integrated monitoring platform. Refueling is often made during periods of low reactor power, allowing the operator to replenish fuel without ceasing generation completely. This provides a useful, semi-regular event during which the vibration monitoring systems used on the circulators remain recording data, providing insight into the response of the machines. Identified in (Costello et al., 2012), the chronological evolution of the SVM hyperplanes suggested a potential emergent vibration behavior (illustrated in Figure 2) with continued circulator use between refueling events, pointing towards an evolution of machine state. This provides an illustration of the type of observed metric or residual an integrated system would examine when making system-wide conclusions. Each data tick in Figure 2 represents a refueling event in time, with the separate classified behaviors of 'Online', 'Upper' and 'Lower' each corresponding to the circulator operating states experienced during the event. The example behavior could be used to flag an anomalous vibration profile, as a deviation from the observed 'normal' circulator classifier model, to the decision support systems used by engineers in order to prompt further investigation. While there is an observed change consistent with continued operation, any condition metric of the circulator from this machine view remains censored, a concept discussed in (Heng, 2009). In order to construct a performance model for the circulators, it is argued there is some value in analyzing outputs from other reactor sources.



Refuelling event index Event classifier evolution Refuelling event index

Figure 2: Evolving vibration profile of circulator across multiple refuelling events, showing the characteristics of the primary vibro-acoustic observables and misclassification rates.

2.3 Gas Circulator Prognostics

As the circulators supply coolant to the core, there is an implicit dependence between the performance efficiency of the gas circulators and the regulation of the reactor operating temperature. Data from both systems therefore could potentially inform analyses regarding the condition or future condition of each other. For example, a circulator unit displaying features of degradation in its vibration profile can be expected to drop in performance, thus failing to sufficiently supply coolant and negatively impacting on the core. Conversely, unexpected features identified in key reactor core parameters could yield information about an underperforming gas circulator where there is a thermal dependency.

3. Fuel Channel Power Monitoring

Each AGR reactor contains approximately 300 fuel channels, for each of which a neutronics model is used to estimate the theoretical neutronic power. Every 7-10 days, a comparison of this value is made with the measured thermal power of the channel, based on a thermocouple in the fuel assembly. These comparisons are made in order to detect problems with fuel cooling or damage to fuel causing excessive heat. The deviation between the neutronic and thermal power, known as the Channel Power Discrepancy (CPD) is typically +/- 3 %, normally as a result of modeling errors or for operational reasons. Values larger than this are identified by engineers for further analysis as they potentially indicate fuel cooling problems.

3.1 Channel Power Analysis

The CPD values, an example of which are shown in Figure 3 are analyzed by applying a filter to the data and extracting values greater than the limits set by the station engineer for further analysis. Normally some other event, such as a refueling of a fuel channel can be identified as the cause for the anomalously large CPD, as new fuel alters the local flux profile. It can however require significant time for the engineer to identify an event which explains the anomaly. Further, the limits used in the analysis are coarse and consider only a 'High' or 'Low' evaluation of the CPD, rather than attempting to identify more subtle trends in the data which may indicate other performance issues.

3.2 Channel Power Discrepancy Prognostics

It can be observed in Figure 3 that most channels exhibit a similar trend over time in CPD, if not absolute value, as a result of the operational state of the reactor. The CPD data shown in Figure 3 are all in the vicinity of the same gas circulator, which is the dominant provider of coolant to that section of the core. It has been proposed that an understanding of the operating performance of the local gas circulator for a particular region of the core may allow some prediction of the deviation from predicted neutronic power.

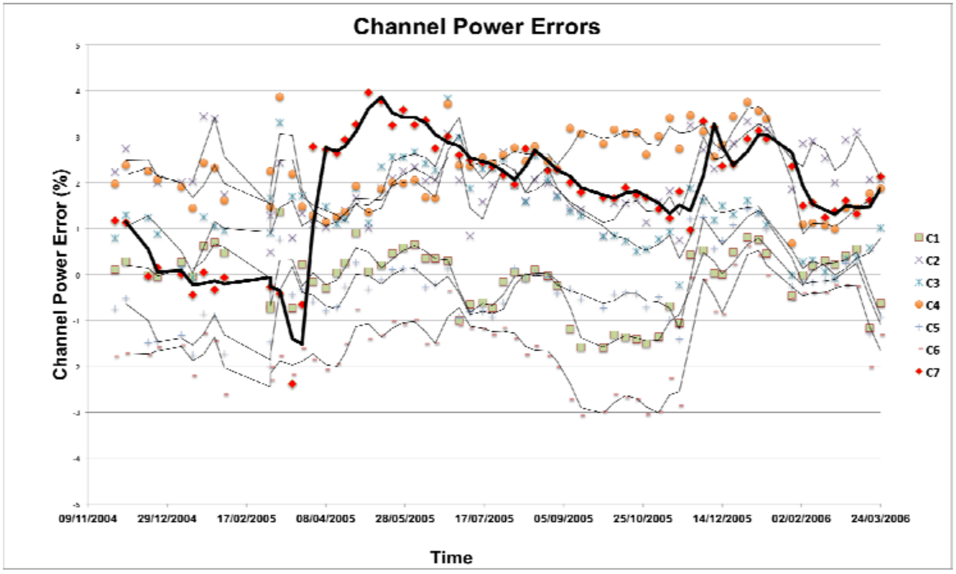


Figure 3: An example of channel power errors for a selection of channels. The data indicated by the bold line shows the effect of refuelling on the CPD of a channel – specifically, it causes a large step change

Such forecasting of coolant related impact could allow for more detailed analysis of the CPD data by generating expected ranges of errors, rather than the existing, coarse limits. The knowledge derived from conclusions of the ROMAAN system could potentially provide a source of information for more detailed analysis of CPD data. Forecasting envelopes of expected CPD for example, based on the performance of the gas circulators or other anomalies or behaviors identified by the ROMAAN system would allow for a more comprehensive analysis. This could help predict anomalous CPD values before they are detected by the weekly analysis, providing increased confidence in the knowledge of the health of the fuel.

4. Integrated Condition Monitoring For Prognostics

With CM deployment often applied on a component-by-component basis, there is the potential for information regarding systems as a whole being missed or not fully exploited. Deployed systems are often tailored to meet the requirements of legacy data infrastructures, largely operate independently and tend not to share conclusions. It is proposed that there is the potential for a wealth of previously unknown metrics to be discovered through taking an integrated approach to whole system prognostics.

In many situations there are clear benefits to sharing information between CM systems, as there will often be overlapping scopes of different systems, therefore movement towards such integration seems logical and desirable. In general however, it is important however that the there is no increased dependency of one system to another, as the standalone integrity of each system is crucial to their continued use and the reliability placed on their conclusions. That is, a failure in one system may be allowed to remove some functionality from another system (the functionality provided by the failed system), however the failure of one system should not compromise the complete functionality of another system.

Similarly, the sharing of information or data between two or more CM systems must be carefully analyzed in order to check for logical consistency and to ensure that the conclusions made by systems are not unduly affected by potential errors in other systems. For example, an error in one system may lead to a particular bias in one type of conclusion, which is used as a fact by another system, which then alters it's own conclusions and may then feed back into the system which made the original error, potentially amplifying the original error. The sharing of CM conclusions between different CM systems will require a framework for making information available. An example of a proposed infrastructure, comparing an integrated approach with a conventional CM system is illustrated in Figure 4. The framework must be capable of interpreting information from multiple systems and translating this content into a form other systems can utilize, analogous somewhat to an Application Programming Interface used to provide developers access to software. Some work towards such a framework has already been developed (Wallace, 2012) as mentioned earlier to provide closer integration between the IMAPS and BETA systems, by means of a distributed, intelligent agent based system which uses a well defined ontology to share information in a form that can be stored, shared and reasoned upon.

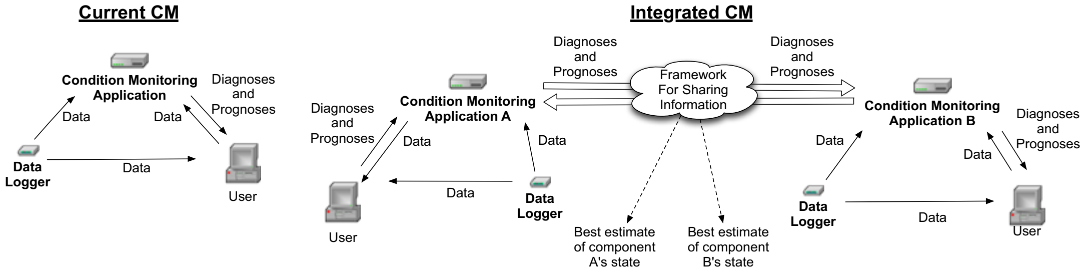


Figure 4: Comparison of the current CM approach taken and the proposed integrated infrastructure, which is argued to provide more information regarding complex system prognostics

4.1 Integrated Condition Monitoring For Advanced Gas-Cooled Reactor Prognostics

As the core of an AGR cannot be replaced, failure data for prognostic analysis is not available for either the core or critical components. It is proposed however that a 'best estimate' of both core and asset health state can be inferred through the combination of analyses from different intelligent systems. Circulator performance, for example has an implicit effect on the condition of the graphite, as improper cooling results in undesirable conditions within the core. Any change observed in reactor parameters corresponding with a change in circulator profile can be investigated further, with suitable focus on the component asset and reactor area in particular. Conversely, having input from the reactor conditions to the ROMAAN systems could provide feedback on the asset performance previously unavailable through vibration analysis alone.

5. Conclusions and Further Work

This paper has described the reasons and potential benefits of introducing sharing of information between CM systems monitoring different components on the same plant, such that prognostic information derived therefrom will be more accurate. The integration of several AGR monitoring systems, along the principles described in this paper is currently being investigated.

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