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Fault Monitoring and Accommodation of the Heat Exchanger Parameters of Triga-Mark II Nuclear Research Reactor using Model-Based Analytical Redundancy

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ABSTRACT

One of the major challenges in instrumentation is to identify wrong data (signal) measurements and perform their validation. This can be done by regularly ensuring a correct operation of the different process components, particularly those having great importance for safety, in order to detect, isolate and identify any possible degradation or fault. This operation, known as on-line fault monitoring, should be done as early as possible, before any fault causes failure in equipment which can lead to the downtime of the plant and even to severe catastrophes and disasters. Therefore, these consequences influence negatively on productivity, availability and environment. At Triga-Mark II nuclear research reactor, the heat exchangers are provided for removing generated heat from the reactor pool water throw cooling circuits. Therefore, the monitoring of the evolution of thermo hydraulic parameters is necessary to ensure the safety of the reactor. Among several developed techniques, analytical redundancy has been recognized as an effective method for fault monitoring. It is the process of identifying a faulty instrument in a system through a comparison of its output to an estimate data. This estimation is based on the model and the measurements provided by the data acquisition chains of the existing sensors during all the operating modes of the installation. In our case, we are limited to mathematical models and Kalman filter approaches. In this paper we review the state of the fault monitoring and some model based analytical redundancy techniques for the heat exchanger, and present experimental results on their application to temperatures and flow rates of the cooling system of Triga-Mark II research reactor core.

Nomenclature

Subscripts - *h*: *hot*, *c*: *cold*, *i*: *inlet*, *o*: *outlet* and $n = h$ or c

Notation	Designation
A_n	Heat transfer (exchange) surface area of the fluid n, $[m^2]$.
c_{pn}	Specific heat of the fluid n, $[J/(Kg°C)]$.
C_n	Heat (thermal) capacity or specific heat capacity of the fluid n, $[W/°C]$.
F_c	Correction factor, [.].
k	Discrete Time.
$\dot{m}_n$	Mass flow rate of the fluid n, $[Kg/s]$.
N	Sample number of the data set.
$\dot{Q}_n$	Heat transfer rate or heat power of the fluid n, $[W]$.
R	Heat transfer rate ratio, [.].
T_{ni}, T_{no}	Inlet and outlet temperatures of the fluid n, $[°C]$.
U_n	Overall heat transfer coefficient of the fluid n, $[W/(m^2 °C)]$.
v_n	Volume velocity, $[m^3/s]$.
V_n	Volume of the fluid n, $[m^3]$.
ε_n	Effectiveness of the fluid n of the heat exchanger, [.].
ρ_n	Density of the fluid n, $[Kg/m^3]$.

Acronyms

Abbreviation	Designation
*ANN*s	Artificial Neural Networks.
AR	Analytical Redundancy.
CM	Combined Method

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ε-NTU	Effectiveness - Number of Transfer Units.
FA	Fault Accommodation.
FDD	Fault Detection and Diagnosis.
FDe	Fault Detection.
FDi	Fault Diagnosis.
FDI	Fault Detection and Identification (Isolation).
FM	Fault Monitoring.
FR	Flow Rate.
FS	Fault Supervision.
HB	Heat (Thermal) Balance.
HE	Heat Exchanger.
HTR	Heat Transfer Rate.
KF	Kalman Filter.
LMTD	Log-Mean Temperature Difference.
LS	Linear System.
LSE	Linear State Equation.
MAE	Maximum Absolute Error.
MAE (%)	Percent Maximum Absolute Error.
MFR	Mass Flow Rate.
NR	Nuclear Reactor.
NRR	Nuclear Research Reactor.
RMSE	Root Mean Square Error.

1. Introduction

The conventional approach followed in a *nuclear reactor* (*NR*), is to monitor the value of some important parameters, like neutron flux, temperature, *flow rate* (*FR*), *pressure*, *level*, *loose part*, *etc*., and to generate alarms if certain thresholds values of these parameters are exceeded. Moreover, the preventive maintenance strategy consists in systematic tests and calibration of all sensitive and critical instruments, such as sensors (Balaban et al., 2009), radiation detectors, actuators, *etc*. This procedure is performed periodically (annually or monthly) during the scheduled shutdown state of the plant. Unfortunately, this operation requires significant resources and time, in order to isolate the faulty instruments, then to return them back to full service. In addition, it is not an optimal methodology because the function conditions are only checked cyclically. Therefore, faulty component can continue to operate for unknown periods up to the calibration intervals. This means, wait and the degradation continue till it causes a loss of function.

Due to the progress of technology, nuclear plants are becoming more complex, automated and large in scale. Usually including large number of *instrumentation*, *measurement chains* and *computers*, *etc*. So, the information delivered by processes instrumentation from different parts of the plant might be excessive, and therefore even skilled operators cannot properly analyze and interpret it.

*NR*s are expected to be operated with high performance level of reliability, availability and safety for extended periods of time (Isermann and Ballé, 1997). So, avoidance of the occurrence of unexpected failures has thus become a subject of major attention. Hence, automatic monitoring systems are necessary tools and have become an issue of primary importance in modern process to support and to help the operators in their tasks (Olivier-Maget, 2007). More monitoring benefits are cited in (International Atomic Energy Agency, 2008; Ma and Jiang, 2011). In addition, the current generation of *NR*s has passed its mid-life, and an enhancement of plants performance monitoring is necessary to their continued safe operation.

Important applications on the monitoring of processes and equipment in *NRs* have been performed with success in many different fields, such as: *reactor internal parts vibration monitoring* (Basseville and Nikiforov, 1993; Kolbasseff and Sunder, 2003), *loose part monitoring* (Young Woo Chang et al., 2004; Ma and Jiang, 2011), *instrumentation* (*e.g.* sensors, actuators) *monitoring* (Fantoniet al, 2003; Ma and Jiang, 2011), *reactor core parameters monitoring* (Ma and Jiang, 2011), *transient identification* (Ma and Jiang, 2011), *equipment* (*e.g.* rotating machinery) *condition monitoring* (Basseville and Nikiforov, 1993; Ma and Jiang, 2011; Ma, 2015), *etc*.

*HE*s (Ramesh et al., 2003; Zapata et al., 2009; Varbanov et al., 2010; Theodore, 2011; Bergman et al., 2011; Rathakrishnan, 2012; Thulukkanam, 2013) are widely used and play an important role in numerous industrial systems and processes (Kakaç et al, 2012), such as *motor vehicles* (*e.g.* cars, trains, ships, *etc*.), *air-conditioning systems*, *chemical and process industries* (Persin et al, 2002), *Power plants* (Rathakrishnan, 2012) *NRs* (Laubscher and Dobson, 2013). In *NR*s, a heat exchanger (*HE*) is provided for removing heat from the reactor core. The water is pumped through it and the heat is transferred from the hot to the cold fluid loop. When *HE*s are in use, they are always vulnerable to degradations which are non-periodic and non-stationary processes, and depend upon the variation of their internal coefficients vs. time. Among these impoverishments, the occurring of *fouling* (Gudmundsson et al, 2009; Theodore, 2011; Rathakrishnan, 2012; Thulukkanam, 2013), so that the metal that separates hot and cold fluids in the HE: (*i*) accumulates deposits from the fluids, (*ii*) creates biofilm and (*iii*) starts to corrode. As consequence of fouling accumulates, the decrease of the heat transfer and increases of the pressure which influence negatively on heat exchange efficiency and finally will increase the thermal load and energy cost (Kakaç et al, 2012; Thulukkanam, 2013). Measurements of *thermo hydraulic parameters* of the *HE* are necessary to know its health and follow its dynamic state evolution. In addition, validation of measurement of these parameters underwrites that the used sensors; their associated cables and instrumentation operate correctly which contribute to the safety improving of the *HE* and finally of the reactor.

Sensors and *radiation detectors* and their *instrumentation chains* are used to measure critical plant parameters which are a required acknowledge for the safe and economical of nuclear plants systems operation, such as in the shutdown system envisaged by *Safety and Control Rod Acceleration Movement* (*SCRAM*) (Kasinathan et al, 2009). They should be in healthy condition. Theirs faults are one of the most common industry processes problems and their detection has been an area of an active research.

According to the literature, numerous technologies have been developed to the *fault monitoring* (*FM*) of industrial plant systems. So, the sample group of methods of monitoring is considerable (Isermann and Ballé, 1997; Persin et al, 2002). These methods distinguish themselves according to various criteria: the dynamics of the process (discreet, continuous, hybrid, linear or non-linear), the implementation of the monitoring system (on/off-line), the nature of the information (qualitative and/or quantitative), and the type of use (centralized or distributed).

The aim of the current work is to monitor some parameters of the *HE*s of *Triga-Mark II* (*Training Research and Isotope Production General Atomic*) *NRR* at *LENA* (*Laboratorio Energia Nucleare Applicata*), particularly, *inlet* and *outlet temperatures* and *FR*s of both streams using *analytical redundancy* (*AR*) methods, particularly these based on mathematical model applied on *linear systems* (*LS*s).

In this paper, we concentrate our study on the *Kalman Filter* (*KF*) which is considered as the best estimator for *LS*s. In addition, we use some other well-known mathematical approaches for estimation comparison and combination to be applied later in monitoring and accommodation. This paper is organized in five sections described as follows. It starts with an introduction in Sec. 1. In Sec. 2 we describe *Triga-Mark II* reactor at *LENA* and its main hydraulic system. Sec. 3 illustrates the fault, the *FM* and the main elaborate monitoring procedures ready for application. Sec. 4 deals with the physical theory of mathematical modeling methods to use for predicting temperatures and *FR*s of the *HE*. Results of estimation and a scheme for the fault detection (*FDe*), location and accommodation are presented and discussed in Sec. 5. Finally a conclusion and perspectives are stated in Sec. 6.