Applications of Digital Reactivity Meter based on Kalman Filtering Technique in Indian Nuclear Reactors

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Abstract

A reactivity meter based on Kalman filter algorithm is developed in Reactor Control Division, Bhabha Atomic Research Centre, for providing the reactor operator with a direct, online, real-time indication of the absolute reactivity status of the reactor core under all states of the reactor from shutdown through start-up to power operation. The reactivity meter has potential applications such as estimation of reactivity perturbations around critical conditions, indication of point of criticality during reactor startup, shutdown margin monitoring, worth computation and calibration of reactivity devices, detection of inadvertent insertion/removal of reactivity under subcritical conditions etc., thereby improving the overall safety in reactor operation. This article summarizes the applications of the reactivity meter in Indian nuclear reactors, and its effectiveness in such applications as experimentally established. It also looks at the regulatory benefits and support to utility in economization of plant operation.

Introduction

In reactor operation or experiments, signals indicating reactor power (or neutron flux) and reactor period are generally used for direct information on the state of the reactor. However, the most important time dependent parameter is the reactivity, and in the past few decades, many techniques were proposed by researchers for on-line dynamic computation of reactivity from the above mentioned signals. Many nuclear reactors worldwide are equipped with such reactivity meters. Most of these digital reactivity meters employ reactivity estimation based on inverse point kinetic equations or otherwise based on reactor period. However, these algorithms demand an accurate knowledge of the model parameters, which is difficult to provide in many cases. Also they do not have any direct provision to eliminate noise content in the data, and hence fail miserably in estimation of subcriticality when the noise content in detector signal is large compared to the neutron flux level. This is where the Kalman Filtering algorithm, with its inherent ability to work with even highly noisy input signals and uncertain plant parameters, serves as a promising candidate.

The Kalman Filter is a recursive stochastic estimator algorithm, which uses a mathematical model of the process to predict the instantaneous values of all the process variables (in the form of a vector called the 'state'); including those which cannot be directly measured [1]. It further corrects these predicted values using a feedback of the error between the available measurements from the actual process and the predicted outputs, through an optimally computed feedback gain K. This predictive-corrective process, with in-built noise filtering capability resulting from the recursive optimal computation of the feedback gain, repeats in each cycle of the algorithm execution as shown schematically in Fig. 1.

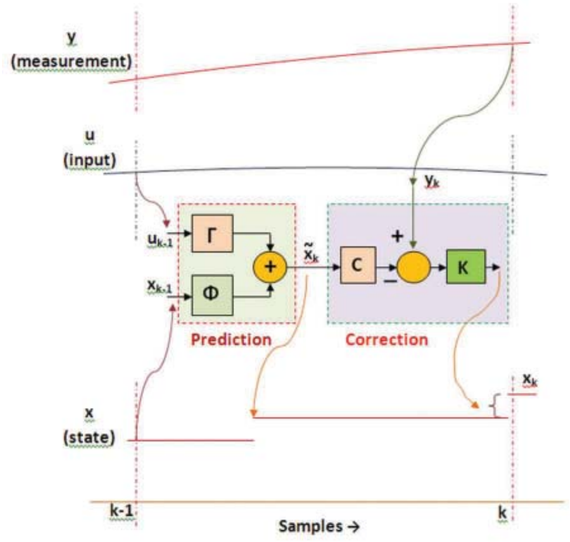

Fig. 1: Schematic representation of Kalman filter algorithm

A reactivity meter based on this algorithm is developed in Reactor Control Division, Bhabha Atomic Research Centre, for providing the reactor operator with a direct, online, real-time indication of the absolute reactivity status of the reactor core under all states of the reactor from shutdown through start-up to power operation, unlike the conventional reactivity meters effective only during power range operation [2]. The reactivity meter employs an embedded system hardware consisting of processor with add-on data acquisition and analog output cards. It accepts the signals corresponding to reactor power from the neutronic channels, and provides indication of the estimated reactivity through a dedicated Graphical User Interface (GUI) panel as shown in Fig. 2, and/or an analog meter mounted on the control panel in Main Control Room. The reactivity meter algorithm adopts the point kinetics model of the nuclear reactor in standard state space form, with neutron life time and delayed neutron data specific to the reactor as the design data [3]. In order to use the model for subcriticality indication, the source term is explicitly modeled in terms of a known initial stable subcriticality and corresponding steady state power level for any reference subcritical condition, which form two additional design parameters for the meter.

During the past decade, efficacy of this reactivity meter in estimation of core reactivity under different operating conditions has been demonstrated in various nuclear reactors. Vast operational experience from these exercises has proved that the meter is a very handy tool in applications such as estimation of reactivity perturbations around critical conditions and indication of point of criticality during reactor startup, shutdown margin monitoring, worth computation and calibration of reactivity devices, detection of insertion/removal of small amounts of reactivity under subcritical conditions etc. The applications of the reactivity meter in Indian nuclear reactors, and its effectiveness in such applications as experimentally established, are touched upon in the forthcoming sections.

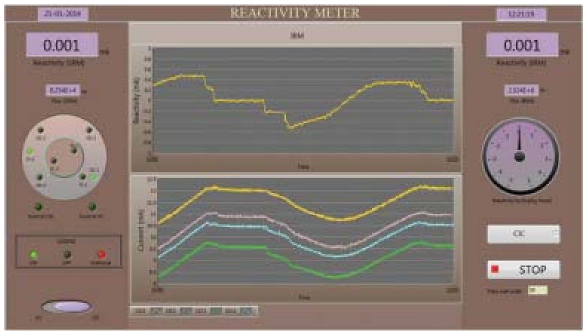

Fig. 2: Screenshot of the reactivity meter GUI

Indication of point of criticality during reactor startup

The reactivity meter can effectively be used during startup operation of nuclear reactors, including first startup, to monitor the approach to criticality. Fig. 3 shows the response of the reactivity meter during the first approach to criticality of a critical facility in Trombay. The meter had been indicating the instantaneous shutdown margin while withdrawing a control rod in small steps. As the rod approached its critical position, indicated reactivity also approached to zero. When the rod position attained 771 mm, the estimated reactivity was close to zero, indicating the criticality. Subsequently when the rod was driven further out and kept at 792 mm for about 5 minutes, it indicated a

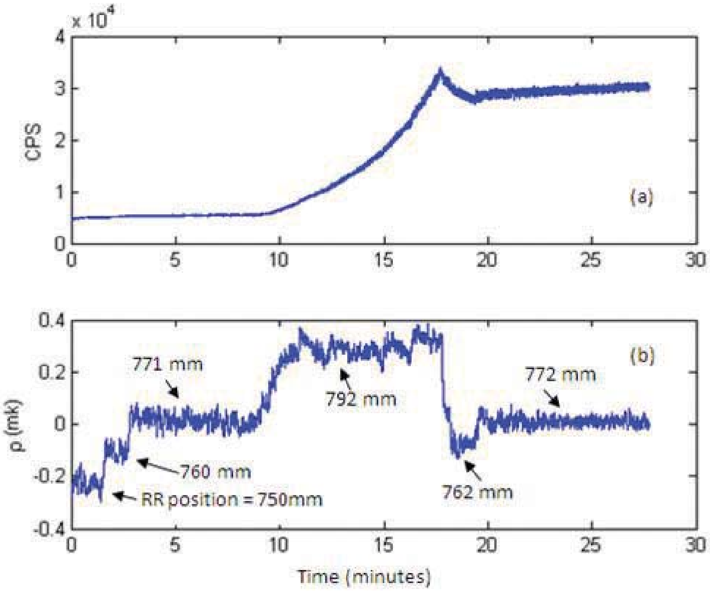

Fig. 3: Response of the meter during approach to criticality.

supercriticality of about 0.3 mk. During this phase, the reactor was declared critical. Afterwards the rod was driven down to 768 mm during which the indicated subcriticality was about -0.08 mk. Soon the rod was driven slightly out to 772 mm, on which the reactivity indicated was zero. Reactor was operated at critical steady state with the rod at 772 mm as shown.

Subcriticality Monitoring

Real–time indication of subcriticality is a challenging problem, essentially due to the difficulties in modeling the neutron source strength with sufficient accuracy, and also due to the high fluctuations in neutron signals measured in subcritical systems. The Kalman filter algorithm has inherent capability to work with stochastic signals and hence addresses the latter issue efficiently. Former issue is taken care of by an explicit modeling of the neutron source in terms of any known initial subcriticality as mentioned previously. Efficacy of the meter in indication of subcriticality has been validated in research reactors and critical facility at Trombay and in Fast Breeder Test Reactor (FBTR), Kalpakkam.

Fig. 4 depicts the performance of the meter in the critical facility during a transient involving lowering of control rod followed by dropping of safety rods. Prior to the transient, the meter indicated that the reactor was subcritical by about 2.9 mk. When the control rod reached core bottom, indicated subcriticality was about 7 mk. Subsequently when the shut off rods reached core bottom, the indicated subcriticality was stabilized at 63 mk. These figures were found to be in very good agreement with the values calculated by the reactor physicists. It is also established that the Reactivity Meter can indicate the reactivity even under a prolonged shutdown, thus providing valuable information of the shutdown margin of the reactor.

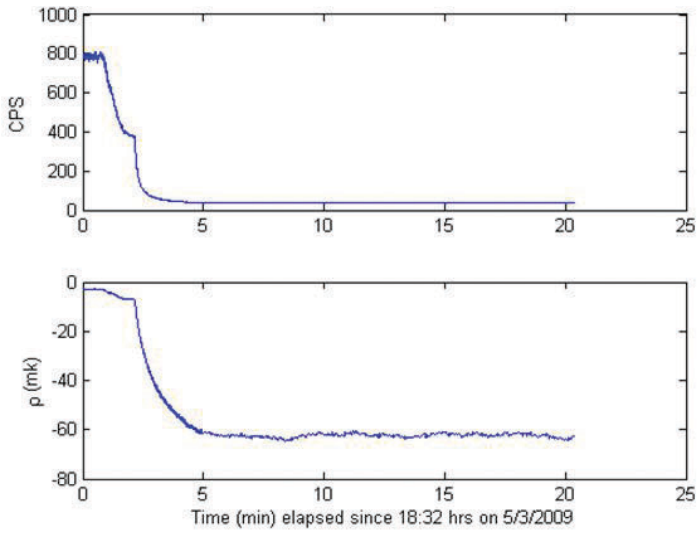

Fig. 4: Subcriticality indication in the critical facility during the lowering of regulating rod followed by reactor trip.

Worth Computation and Calibration of Reactivity Devices

Experiments conducted in different reactors demonstrate the capability of the meter to serve as a handy tool for direct online computation of the worth of different reactivity devices and their calibration. Outcome of one such exercise in the critical facility is depicted in Fig. 5. It shows the worth estimation when two shutoff rods were withdrawn sequentially. With both the shutoff rods at core bottom, reactivity indicated was -90 mk. When first rod was fully retracted, it was about -57.75 mk which shows that its worth is 32.25 mk. When the second rod was fully withdrawn, reactor was still subcritical by about 31 mk. This indicates that the worth of the second rod, with the first one at top, is 26.75 mk.

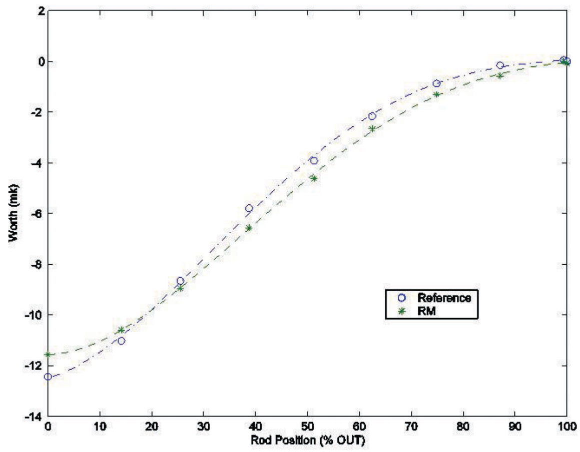

Fig. 7: Comparison of the calibration curves generated from reactivity meter readings and physics computations.

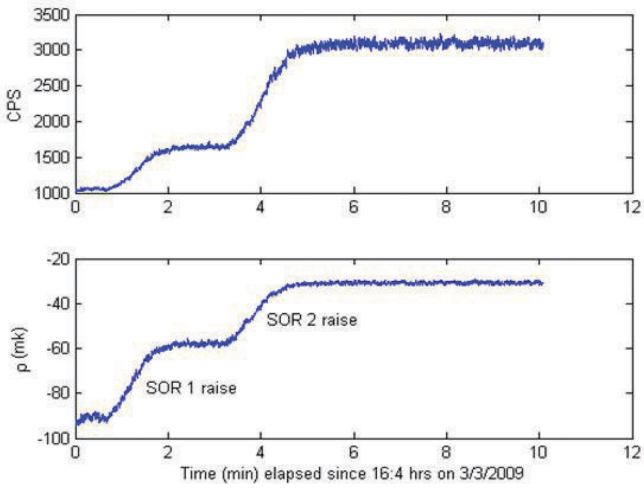

Fig. 5: Online estimation of shutoff rods' worth in critical facility.

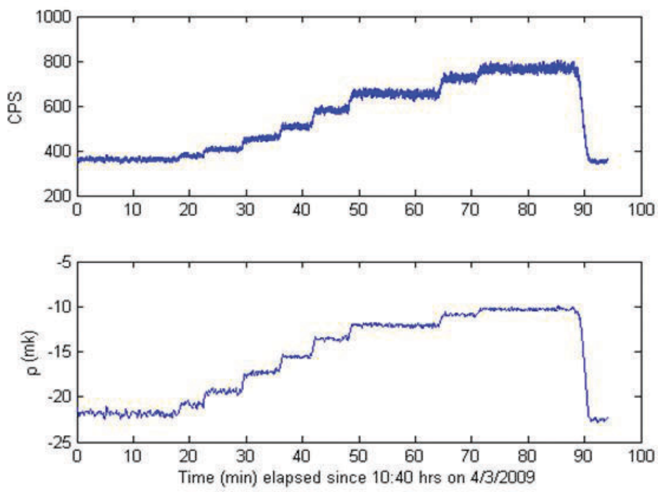

Fig. 6: Indicated reactivity during regulating rod calibration exercise in critical facility.

Likewise, Fig. 6 depicts the response of the meter during step by step withdrawal and subsequent insertion of the regulating rod in the critical facility. Prior to the withdrawal of the regulating rod, the indicated subcriticality was 22.6 mk. The regulating rod was withdrawn in steps of about 100 mm till it reached the core top when the subcriticality indicated was 10.8 mk. Hence, the worth of the rod as indicated by the reactivity meter is 11.8 mk, against the calculated worth of 12.6 mk. From the reactivity estimated by the meter at different rod positions, the calibration curve of the rod was plotted off–line. Fig. 7 compares this calibration curve, with that generated from the physics calculations.

Detection of reactivity changes during fuelling operations

The feasibility of using the reactivity meter for the purpose of measuring the reactivity during shutdown, fuel handling and startup of the reactor was established in FBTR. Measurement of reactivity during fuel handling operations was of prime significance. During the fuel handling campaign, various fuel sub assembly transfer operations were carried out. While transfer operation is in progress the changes in core reactivity values were estimated online by the reactivity meter. From the results obtained, it was concluded that the meter is very effective in indication of the worth of fuel pins. Subsequently it was proposed to connect the meter as a diverse measuring instrument to the existing reactivity meter which is effective only in the high power range. Fig. 8 depicts the response of the meter during this fuel handling operation, which indicates that the meter recognizes each incident of fuel pin removal / insertion, and provides a direct indication of the worth of individual pins.

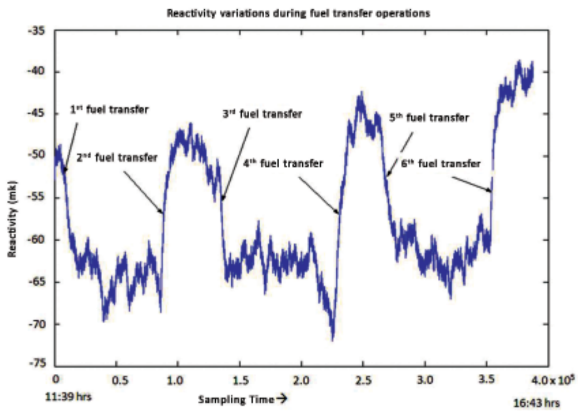

Fig. 8: Response of the meter during fuel handling operations in FBTR.

Drop Time Monitoring of Safety Rods

In PFBR, there are two independent, fast acting, and diverse shutdown systems, the first comprising of nine Control & Safety Rods (CSRs) and the second consisting of three Diverse Safety Rods (DSRs). Monitoring of the drop-time performance of the DSRs is an important design requirement, however, design does not provide for direct sensing of top and bottom positions of DSRs due to physical restrictions on layout and unfavorable environmental conditions. Therefore, the drop time of DSRs will be monitored in PFBR using the reactivity meter, based on the principle that the drop-time can be found out from the record of reactivity change subsequent to the dropping of

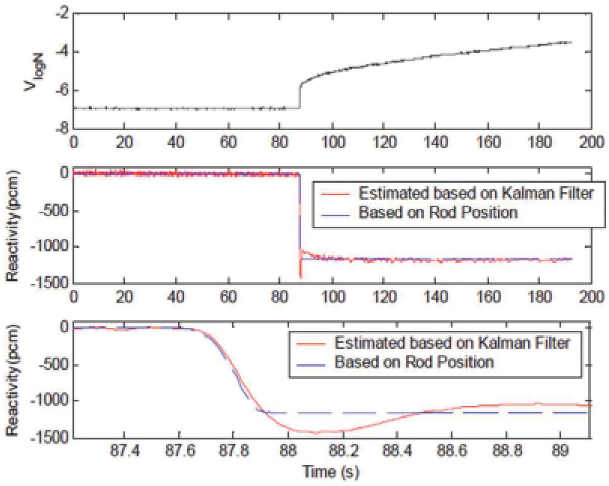

Fig.9: Estimated and actual reactivity during a rod drop in FBTR

the rods since the change in reactivity status of the core on shut-off rod drop is equal to the worth of the shut-off rod. The efficacy of the reactivity meter in estimation of rod drop time has been demonstrated through offline analysis as well as rod drop experiments in FBTR. Fig. 9 depicts the time variations of neutronic signal, estimated reactivity and the reactivity computed from the rod position, during dropping of a shutoff rod in FBTR. The deviation between rod drop time inferred from the reactivity values estimated by the reactivity meter and the drop time inferred from rod position signal is found to be less than 20 ms, which is considered acceptable for sensing of rod drop time [4].

Concluding Remarks

The applications of the reactivity meter based on the Kalman filtering technique have generated remarkable confidence in its usage. The reactivity meter facilitates continuous surveillance of the core reactivity status from shutdown through the start-up and power range operation of the reactor. Since it always indicates the true state of the reactor, shutdown margin is always directly known, and not inferred by status of reactivity devices as it happens in PHWRs today. The meter assists the operator in monitoring the shutdown margin, detection of any inadvertent introduction of reactivity into the core and in assessment of any requirements of addition of boron in the moderator, thereby improving the overall safety in reactor operation.

There is generally a stipulation by regulator that Minimum Shutdown margin of 10 mk must be maintained during shut down at all times. There are no means available in Indian reactors to verify this stipulation. Hence it is always up to utility to show the regulator by calculations that this stipulation is being met. The situation becomes even more complicated when the reactivity in the reactor can change substantially due to change in temperature and Xenon concentration. If an online reactivity meter is installed in the plant it provides direct monitoring of the reactor status, thus enabling regulator o monitor the specified Shutdown margin criterion.

The Reactivity Meter can offer the best protection against inadvertent criticality happening in a nuclear reactor. Reactivity Meter can be used to generate an alarm whenever Reactor keff exceeds 0.99 or is within 10 mk of becoming critical. This indirectly provides regulatory benefits by improving safety.

Specification of shutdown system is often made in terms of speed of actuation of device i.e. Shutoff rods insertion time or injection time in case of liquid poison system. These are again indirect means of ensuring safety, true parameter for reactor being the negative reactivity insertion time. With the reactivity meter regulator can now insist on measure of negative reactivity insertion time.

The reactivity meter can effectively provide a direct estimate of the variations in xenon load subsequent to a reactor trip. This will aid the operator in restarting the reactor prior to a poison out, or in delay of boron addition to maintain adequate Shutdown margin and will also provide more time to the utility whereby it can optimize the amount of boron to be added; in fact in most of cases the plant may be able to skip the boron addition completely. This provides two benefits, first, it will reduce load on resin used in boron removal system which will reduce the radioactive waste. Second, it will reduce the startup time for the reactor as boron removal time will be reduced drastically in most of the cases.

The capability of the reactivity meter in online monitoring of sub criticality status of the reactor cores can be exploited to extend its application to the monitoring of spent fuel storage pools. With dedicated neutron detectors strategically located inside the spent fuel storage pools, sub criticality status of the pools can be monitored continuously thereby enhancing the safety of the storage pools.

Finally, it is convincingly felt that a reactivity meter is a very useful and convenient instrument for reactivity measurements during the physics experiments. It provides direct reactivity measurement in many experiments with great convenience and accuracy, which would not be possible through conventional means.

Acknowledgement

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