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Reactimeter dispersion equation

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Abstract

The aim of this work is to derive and analyze a reactimeter metrological model in the form of the dispersion equation which connects reactimeter input/output signal dispersions with superimposed random noise at the inlet. It is proposed to standardize the reactimeter equation form, presenting the main reactimeter computing unit by a convolution equation. Hence, the reactimeter metrological characteristics are completely determined by this unit hardware function which represents a transient response describing the processes on delayed neutrons after a stepped power leap. It is shown that the amplitude-frequency response of the reactimeter linear unit allows inlet additive noise to be considered as white. For such conditions, reactivity dispersion expressions were obtained for an exponential and discrete representation of the delayed neutron transient response. The dispersion amplification factors were calculated for a number of known delayed neutron constant systems. The dispersion equation implementation in the reactimeter composition makes it possible to reflect the uncertainty in a real-time reactivity assessment. A number of tasks and directions for further studies and developments have been indicated.

Keywords: Reactimeter; Metrology; Dispersion equation; NPP instrumentation and control.

Introduction

Metrological reactivity measurement support is an important aspect of nuclear safety in NPP operation. There are a number of domestic and international standards formulating requirements for the neutron flux measuring channels and sensors [1–5]. Standardized methods for calculating metrological characteristics of measuring channels as well as relevant industry regulative documents have been developed [6–11].

Reactivity assessment errors were analyzed from various viewpoints in a number of papers (A bibliographic database covering domestic and foreign publications on this subject from 1954 to the present day is described in [12] and posted on the Internet). To meet the requirements of modern metrology, it makes sense to carry out such an analysis on the basis of standard metrology models used for normalization of metrological characteristics [13].

One of the main metrological models is the linear convolution equation used to describe the links of a measuring channel. Based on this equation, the theory of dynamic measurements is constructed [14,15], a typical example of which is the reactivity measurement. The reactimeter equation in the form of a convolution integral is proposed in [16]. This integral is always implicit in the inverted kinetic equation formulation and discretization but its direct consideration gives an opportunity to use the known relations between the input/output signal dispersions of the measuring converter for the error estimation. The dispersion equation hardware–software implementation in the reactimeter composition makes it possible to reflect the uncertainty in a real-time reactivity assessment. In this paper, the dispersion equation is derived for reactimeter analog and discrete models in the presence of additive noise in the input signal.

Standardized reactimeter metrological model

The traditional form of the reactimeter equation is quite complex and involves a large number of parameters complicating its metrological analysis. For example, in [17], the following form of the reactimeter equation was used

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(henceforward all the symbols are conventional):

$$\rho(t_j) = 1 + \frac{1}{v(t_j)}\left(\frac{l}{k\beta}\frac{v(t_j) - v(t_{j-1})}{\Delta t} - \sum_{i=1}^{6} C^*_{ij} - S^*\right),$$

$$C^*_{ij} = C^*_{i,j-1}\exp(-\lambda_i \Delta t) + \frac{\beta_i\lambda_i}{\beta}\int_{t_{j-1}}^{t_j} v(\tau)\exp\left(-\lambda_i(t_j - \tau)\right)d\tau,$$

$$C^*_{i0} = v(t_0)\beta_i/\beta.$$

However, to simplify the calculations, the multiplication factor, $k = 1/(1–\rho)$, was adopted equal to 1, which is obviously contrary to the meaning of the reactivity (ρ) measurement, resulting in a distortion of its assessment and the relevant metrological indexes.

In order to simplify the reactimeter equation structure, it was proposed in [16] to use the integral nuclear reactor kinetics equation written for the power change rate:

$$n(t)r(t) = \upsilon(t) + \int_0^t h(t-\tau)\upsilon(\tau)d\tau - Q(t), \quad (1)$$

where $n(t)$ is the actual power; $\upsilon(t)$ is the power change rate; $Q(t)$ is the independent source intensity. The reactivity in the Λ-scale ($r = \rho/\Lambda$) is obviously interpreted as the probability of prompt neutron reproduction equal to the difference between the probability of neutron generation and the probability of survival: $r = 1/\Lambda - 1/l$, where Λ is the generation time; l is the prompt neutron lifetime. This definition is fully consistent with the traditional understanding of reactivity as a measure of a nuclear reactor deviation from the critical state, differing only in the normalization:

$$\rho = (k-1)/k = 1 - \Lambda/l = \Lambda r.$$

This normalization brings the reactivity dimension to the reciprocal time units, allowing the reactivity in the Λ-scale to be treated as the relative rate of processes on prompt neutrons, $r(t) \equiv v_{pn}(t)/n(t)$, and ensuring its direct comparability with the inverse period, $\alpha(t) = v(t)/n(t)$, which has a meaning of the relative reactor power change rate for all the processes.

Eq. (1) unifies the direct and inverse problems of nuclear reactor kinetics, reducing both the power assessment (direct problem) and reactivity assessment (inverse problem) to the calculation of the delayed neutron integral (DNI),

$$I_{dn}(t) = \int_0^t h(t-\tau)\upsilon(\tau)d\tau,$$

which expresses the current rate of the delayed neutron number increase/decrease. The theoretical form of the delayed neutron integral kernel is expressed through the delayed neutron constants:

$$h(t) = \sum \delta_i \exp(-\lambda_i t),\ \delta_i = \beta_i/\Lambda. \quad (2)$$

This function is a transient response describing the delayed neutron generation process after a stepped power leap and can be considered as a hardware function of the reactimeter linear link, i.e., DNI unit. In general, exponential form (2) is not mandatory. For calculations or hardware implementation, any appropriate approximation can be used, e.g., a series of discrete samples derived from theoretical expression (2) or in the process of identifying the transient response [16,18]. In the latter case, a non-trivial problem of restoring the parameters of theoretical exponential representation (2), i.e., the delayed neutron constants, is removed.

For the purposes of the metrological analysis, the structure of Eq. (1) can be simplified further by representing it in the form of a convolution equation as a model of the linear function generator with the input signal, $v(t)$, and the response, $f(t) = r(t)n(t) + Q(t)$:

$$f(t) = \int_0^t [\delta(t-\tau) + h(t-\tau)]\upsilon(\tau)d\tau. \quad (3)$$

Eqs. (1) and (3) contain a single ‘parameter’ which determines the reactimeter metrological properties, i.e., the delayed neutron integral kernel and provide a simple calculation of the metrological characteristics specified by modern standards.

In Eqs. (1) or (3), the major component of the reactimeter (traditionally considered as a nonlinear function generator) turns out to be the linear convolution unit for calculations of the delayed neutron integral. In addition, Eqs. (1) and (3) provide a number of other advantages in terms of the adequacy of the numerical simulation, hardware implementation and reactivity experiments, automatically ensuring the essential requirement of metrological support for operating NPPs, i.e., comparability of ‘measured and calculated’ reactivity [11], e.g.:

- in modeling reactivity effects, the consistency of the calculational and experimental results is provided based on unification of the direct and inverse problems of nuclear reactor kinetics; the measurements and calculations are reduced to the delayed neutron integral evaluation (the same computational scheme is applicable to accounting for several fissile nuclides as well as distributed nuclear reactor dynamics models).
- physically unobservable delayed neutron-induced processes (i.e., changes in the delayed neutron precursor concentrations) are excluded from consideration, thus eliminating the problem of their metrological analysis;
- for integrated nuclear reactor kinetics equations, there is no problem of rigidity requiring special methods for numerical implementation of the corresponding differential equations;
- reactivity of the steady state exit time does not depend on any parameters and is determined only by measured values: $r(0) = v(0)/n(0)$;
- there is no need for the kinetics equation linearization which is usually postulated as a mandatory step in the analysis of problems with variable reactivity; the corresponding source of error disappears as well;
- it becomes possible to quickly adapt the reactimeter to the actual reactor conditions by identifying the delayed neutron transient response in reactor operating modes [16,18].