WIDE-RANGE FISSION CHAMBERS SIGNAL SIMULATOR

I.V. Alyaev, N.A. Selyaev, Yu.A. Paryshkin, V.A. Fedorov
National Research Nuclear University MEPhI
115409, Russia, Moscow, Kashirskoe shosse, 31
nselyaev@yandex.ru

ABSTRACT

Fission chambers (FC) signal simulators are a useful means to test neutron flux instrumentation channels of the reactors control and protection systems (CPS). Well-known signal simulators do not provide a secondary equipment testing in all modes of measurement. A wide-range simulator that simulates a full range of FC signal changes (pulse, fluctuation, current) was designed. The simulator takes into account the statistical nature of neutrons detection in the FC, including the shape of the pulse and the spectrum of the pulse amplitude distribution. The simulator uses the principle of mathematical simulation of the fission chambers signal with real-time calculations using the FPGA.

The wide-range simulator reproduces a FC signal in the range of ten orders without switching ranges or playback modes while ensuring very good linearity. It allows to generate both static and dynamic test signals such as: stair-step, linearly and exponential varying signals, exponential varying signals with a linearly changing period or a signal change simulating the response of the nuclear reactor power to a given reactivity response. Continuity of reproduced signals and the ability to playback dynamic effects makes it possible the simulator using to check the algorithms of cross-linking of measuring paths, reactivity and period measuring tools and to monitor the operation of interlocking and alarm CPS functions.

This article discusses the simulator`s software and hardware, its features and specifications, user interface and example of the simulator using to check the neutron flux monitoring channels.

Key Words: simulator, fission chamber, pulse, campbelling mode, neutron flux monitoring

1 INTRODUCTION

The main task of the control and protection system (CPS) is to ensure the safe operation of nuclear reactors. The neutron power reactor facility, the period its changes and the entered reactivity value should be continuously monitored. All of these parameters can't be controlled without measuring the neutron flux density. Fission chambers (FC) are widely used to measure the neutron flux in power and research nuclear reactors.

The range of neutron flux density changes is more than 11 orders of magnitude when reactors power is changed from subcritical state to the nominal level. None of the methods of measuring the neutron flux density with the help of FC can cover such a large range. Therefore wide-range channels or a few measuring channels with overlapping ranges with "cross-linking" of the results of neutron flux density measurement obtained by using different methods (pulse, fluctuation and current) are used to control the reactor power.

Using the NPP equipment with a variety of methods for measuring the neutron flux density, including fluctuation channels that operate on the Campbell principle or based on multithreshold comparators, led to the inability of reliable control of the secondary equipment parameters using standard measuring tools and the need for FC signals simulators. These simulators must replicate real fission chamber signals throughout the operating range of the neutron flux density both static and dynamically changeable.

In addition FC signal simulators are an indispensable tool in the development of new hardware for the neutron flux monitoring because in some cases they eliminate the testing with the use of reactor by moving them to the laboratory.

2 EXISTING SOLUTIONS ANALYSIS

The simplest solution is to use separate devices for each FC signal processing method. For example, to check the secondary equipment working in current mode, you can use the standard small currents sources, to test secondary equipment operating in a pulse mode with a fixed threshold of discrimination you can use a conventional pulse generator with a current-voltage converter, and for the secondary equipment operating in the fluctuation mode testing noise generators can be applied. There are measuring tools that combine several separate functions, such as "Autotest-M" complexes [1], which can generate both a constant current and a pulse current signals. In spite of its seeming simplicity, this solution has the following drawbacks:

- at least a couple of different measuring instruments is required;
- often conversion functions of secondary equipment are not explicitly specified, it does not allow to verify the metrological characteristics of the secondary converters;
- secondary equipment can include different correction function taking into account the random nature of the pulses occurrence and the FC signal amplitude spectrum;
- the noise "colouring" can be very critical to check the channels based on fluctuation methods.

The second way is to use specialized devices, which simulate with some approximation FC signals. One of them, DVD based electroinic pulser, was developed and presented [2]. The device generates signals which simulate the neutron and gamma radiation using recorded on DVD-ROM original data. The main disadvantage of this device is the limited counting rate of 10^6 s^{-1} and a fixed duration and shape of the pulses.

Simulators, built on the principle of mathematical modeling of the FC signal where the output is calculated as the sum of the signals from the individual pulses provide more flexibility in modeling FC signals in the pulse mode. The noise that simulates the alpha and gamma background can be added to this signal. An example of such simulator is the one developed during the ITER project work [3].

The advantage of such type of simulators is the possibility of generating a random pulse sequence with predetermined variable shape, random amplitude described amplitude spectrum, and their superpositions. The disadvantages include the signal model calculation time (at high count rates a few tens of minutes), the absence of the voltage-to-current converter, the limitation on count rate range (from 10^3 to 10^8 c^{-1}) and the problem of the limited signal playing time which is only 1.5 s. The problem with the calculation speed of the signal model was solved in simulators Desktop Digital Detector Emulator family of DT5800 / DT5810 [4] signal by using FPGA for real time calculation. Both simulator types let you to add a noise component to the output signal.

The inability to reproduce the signals corresponding to the changing of the pulse counting rate with time is also a disadvantage of nearly all existing fission chamber signal simulators. Such signals are very important for testing the reactivity and period gauges and for operation control of CPS channels which generate interlocking and alarm signals.

The wide-range simulator was designed to test the electronic equipment of the neutron flux monitoring channels that use different methods of the fission chambers signals processing. The simulator reproduces the signal of a real fission chamber in the range equivalent pulse count rate from 1 to 10^{10} pulses/s in both static and dynamic modes.

3 THE WIDE-RANGE FC SIMULATOR

3.1 The simulator structure

The block diagram of the FC simulator is shown in Fig. 1. The simulator consists of the following components:

- personal computer (PC);
- chassis NI PXIe-1071 with modules FPGA FlexRIO NI PXIe-7966R and DAC NI PXIe-5451;
- the signal interface device, including pulse and current voltage to current converter, switch, master controller.

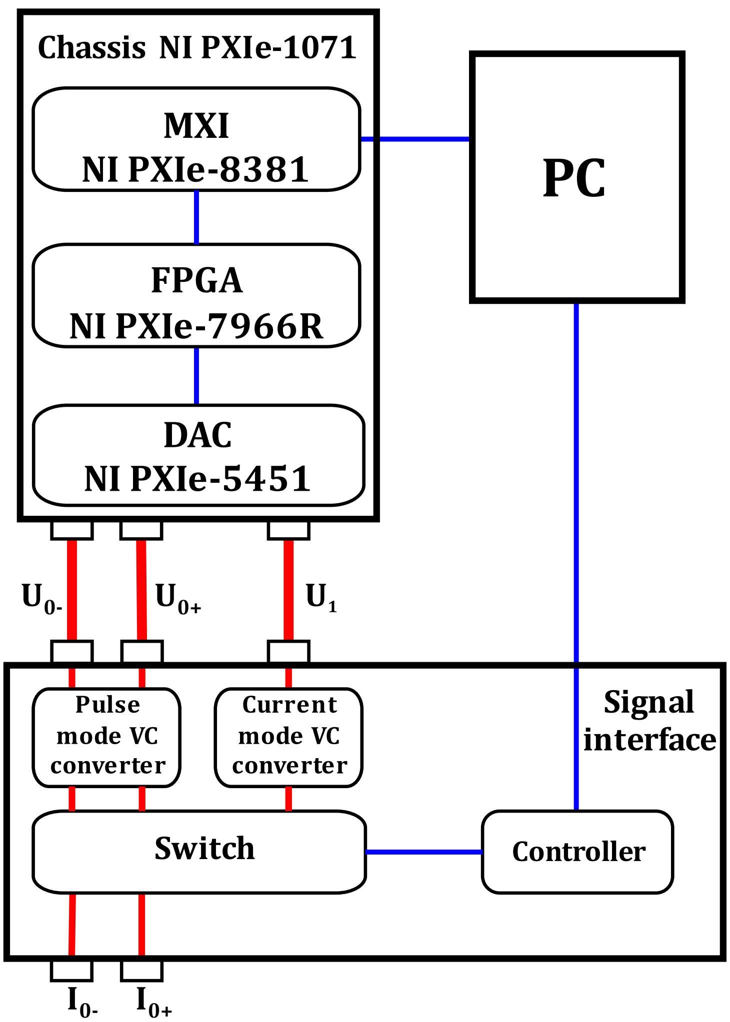

Figure 1. The block diagram of the wide-range FC simulator

Parameters of the generated impact (the shape and amplitude spectrum of the pulses, parameters of the noise component and parameters of dynamically changing effects) are set using a PC. After this the calculation of the pulses number with Poisson distribution within each time cycle is performed. The time cycle may be only 10 ns to ensure accurate reproduction of dynamic effects. The calculation time of these impacts is no more than a few minutes, even when it is necessary to calculate such effects as reactivity or exponentially varying signal with a linearly variable period for test lasting for hundreds of seconds.

Further calculation FC signal model is performed using the FPGA in real time during playback signal. The application of FPGA allows to calculate simultaneously up to 30 uncorrelated pulses. This allows calculation of the signals at loadings of up to 10^9 s^{-1} and with a slight deviation from the mathematical model up to 10^{10} s^{-1}. At the same time a constant component that occurs at high count rates can be excluded to avoid going beyond the DAC dynamic range.

The FPGA simultaneously calculates the current value corresponding to the number of pulses in the reproduced time cycle. This is necessary to restore the DC component of the output current signal when operating in a wide-range mode is performed.

The generation of computed digital signals is performed by using the generator NI PXIe-5451. The pulse-fluctuation voltage signal which was converted into a differential current signal is mixed with the DC component obtained by converting of the second channel voltage signal into a current. The current mode voltage-to-current converter operates in the range from 10^{-10} to 10^{-3} A without subbands switching at very good linearity. Voltage-to-current converters allow to work with the secondary equipment that has input impedance up to 10 kOm.

3.2 FC signal calculation

Fission chamber signal is a random sequence of current pulses occurring at a gas ionization by high-energy fission fragments which arise in the interaction chambers radiator with neutrons. Random time intervals between pulses are subordinated an exponential distribution with directly proportional mean to the neutron flux density. Pulses amount that occur within a certain time interval is described by the Poisson distribution.

The pulses shape depends on a number of parameters such as the FC geometry and gas filling, as well as the connection line and its matching. Analytical calculation of the pulse shape is quite complex and can be produced only in the simplest cases. That is why the pulse form is defined as the numerical array, obtained from processing of experimental signals of fission chambers.

The pulse charge is also a random value and is specified by charge distribution spectrum. Signal amplitude spectrum depends on many factors. The FC spectrum is split at two parts - the part related to the neutron registration and the noise component which is determined by the gamma and alpha background.

Pulse shape and amplitude spectrum of the particular FC type can be measured with the use of additional measuring instruments, such as a mobile automated complex for FC diagnostic [5]. The simulation of any FC signal over the entire range of its work becomes possible after the normalized impulse response to act of gas ionization by one neutron, amplitude spectrum of these pulses and noise component would be described.

In general, the applied signal FC calculation algorithm is similar to the algorithm described in [3, 4], but with increased number of units for calculation separately uncorrelated pulses, as well as the changes needed to generate dynamically varying signals.

3.3 Simulator user interface

The simulator operation is controlled by a PC. Fig. 2 shows the user interface of software signal simulator. Before signal generation the user must choose a signal generation mode (current, counting, counting-campbelling or wide-range mode) and following parameters:

- the pulse form;

- the pulse duration;

- the amplitude spectrum (including mean charge);

- the type of count rate time dependency (time-varying or static);

- parameters of time-varying signals.

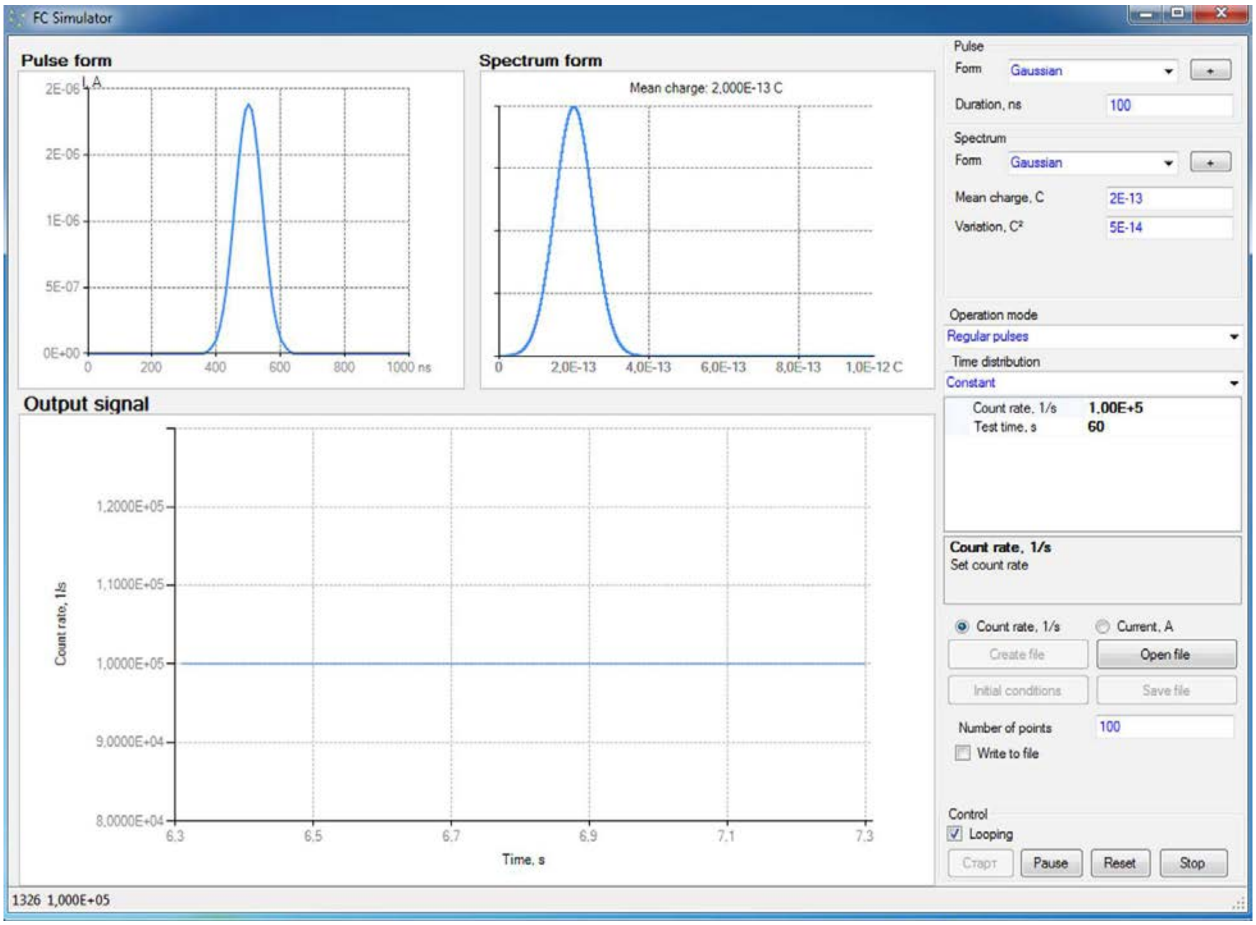

Figure 2. Fission chamber simulator user interface

The user can set the generated impact value in terms of FC current (neutron component) or equivalent count rate (the number of neutrons registration per time).

When the user sets a shape and spectrum of pulse he has the choice to select "standard" forms (Gaussian, exponential (sawtooth), rectangular), to set the shape and spectrum by hand (using the built-in editor) or to select it from the FC database. The ability to combine the spectrum, for example by defining it as a sum of exponential and Gaussian, is provided. To simulate the presence of a gamma background, the user can set the DC current and its fluctuations, which will be added to the signal due to the neutron component of the output signal of the fission chamber.

To specify a dynamically changing signal, the user must set the initial value of the signal and parameters of signal change in the time (rate of changing, period or reactivity). The user also should enter the time of reactivity input when the generate of the reactivity impact. The program uses the 6- and 24-group kinetic reactor model in the calculation of test actions simulating neutron flux density change with the introduction of reactivity.

After setting the test action parameters the program performs calculation file with random distribution of pulses in time. During the playback the current value of the output signal is displayed on the graph of current, frequency, or count rate depending on the selected mode. The user has the possibility to pause the signal reproduction. This feature is useful for recording the individual control points or for verification interlock and alarm CPS channels.

3.4 The simulator metrological characteristics

FC Simulator has the good metrological characteristics and can generate the following test impacts:

- constant current signal from $1 \cdot 10^{-10}$ to 1×10^{-3} A with maximum relative error ±1 %;
- regular current pulses with frequency from 1 to 10^7 Hz with maximum relative error ±0,05 %;
- simulation of real FC signals with equivalent count rate from 1 to 10^{10} pulses/s with integral nonlinearity ±1 % and maximum relative error ±1 % in counting-campbelling mode and ±5 % in wide-range mode.
- pulse duration from 50 ns to 1 μs with step of 10 ns;
- amplitude spectrum resolution is equivalent to 4096 channels;
- pulse charge from 10^{-15} to 10^{-12} C with integral nonlinearity 0,1 % and maximum relative error ±1 %;
- standard deviation of pulse shape and spectrum form less than 0,05 %;
- rate of counting rate (for linearly-varying signals) $\pm 1 \times 10^{-3}$ A/s (for current mode) or $\pm 1 \times 10^{5}$ s^{-2} (for for other simulating modes), period (for exponentially-varying signal) in range ± (1…400) s with maximum relative error 0,2 % in current, counting and counting-campbelling modes and 5 % in wide-range mode;
- reactivity from -20 to +0,9 β with maximum relative error 0,1 % for counting and counting-cambelling modes and 1 % for current or wide-range modes.

The test impacts duration is limited only by PC memory. At this 1.2 GB of memory corresponds to the duration of 60 s with a minimal time step. The minimum time step is only 100 ns. It allows playback of dynamically changing signals with excellent accuracy. Tests can be played ones or cyclically.

All the above parameters have been confirmed by the tests. Monitoring results of pulse shape and spectrum form are shown in the Fig. 3 as example.

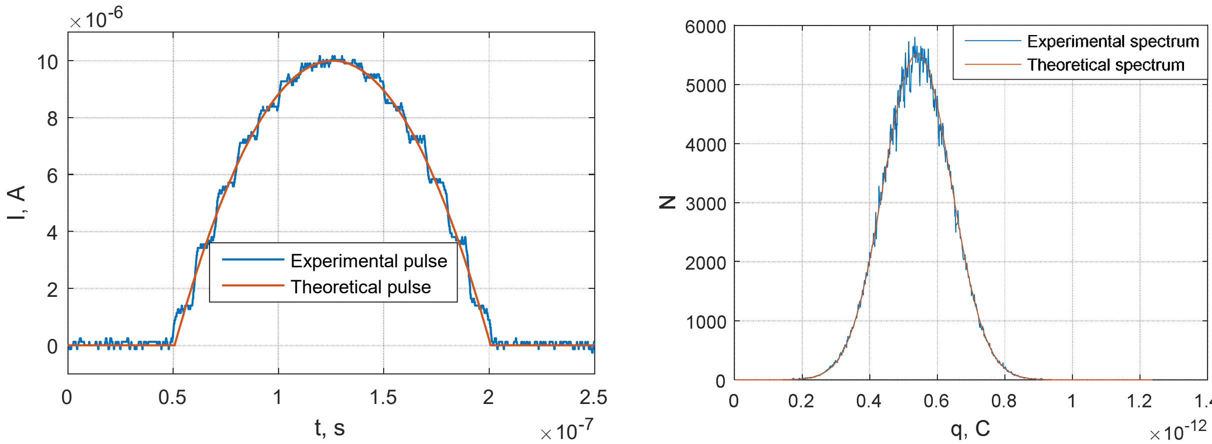

Figure 3. Metrological characteristics monitoring of pulse shape and spectrum form

3.5 The test of neutron flux instrumentation channel

The simulator was tested during the metrological verification of various types of neutron flux monitoring secondary equipment. The most interesting of simulator using as a device for verification of wide-range channels were the tests of multichannel block of fission chambers signal processing BCSP.

The BCSP [6] is a complex component of subcritical monitoring and reactor start-up systems and combines the secondary FC signals converters with computers of period and reactivity. Each BCSP contains several neutron flux density measurement channels. Its characteristic feature is using different FC signal processing modes: counting mode, counting-campbelling mode, current mode, wide-range mode. Since the BCSP is used as a means of monitoring the safety limits of the reactor operation, therefore, the linearity and indissolubility of the conversion characteristics of the measuring paths in a wide range is of paramount importance.

The following verification procedures were performed with the use of the wide-range FC signal simulator:

- the check of the DC, counting-campbelling and wide-range measurement chains;
- the check of the measuring chains time constant in different ranges with the use of stair-step signals;
- the verification of period measurement functions by giving the exponential varying signals;
- the verification of reactivity measurement functions by giving signals that simulate the response of the reactor power on the impact by reactivity according to a predetermined reactor model;
- the control of operation of emergency alarm by the power (current) with the use of linearly changing signals;
- the control of operation of emergency alarm by the period with the use of exponentially varying signal with a linearly varying period.

The fission chamber signals simulator allowed to perform all the checks of the BCSP and verify its metrological characteristics. The most revealing, from the point of view of using the simulator as a wide-band oscillator of test signals, were the results of monitoring the linearity of counting-campbelling and wide-range channels. The only one mode of FC signal generation was used for testing for ten decades without any ranges switching. It was determined during the tests that the relative error and linearity of measurement chains BCSP in all modes do not exceed of specified limits.

The ability to generate dynamically changing signals made it possible to verify of the BCSP functions for calculating the period and reactivity, as well as the functions for generating an alarm signal for exceeding the power and period. The duration of continuously generated dynamic test impact reached 400 s at the time of period calculator verification. At the same time the preparing of this test impact took only a few minutes.

4 CONCLUSION

The developed FC signal simulator combines the best properties achieved in simulators with signal model calculation as the sum of individual pulses. Unlike existing simulators, it significantly expands both the lower and upper limits of the reproduced counting speed range. The ability to work in a single wide range without any range switching makes it possible to apply it for testing of wide-range neutron flux monitoring channels including counting, campbelling and current working modes and its combination or overlapping. In addition, the simulator implements the functions of generating dynamically changing signals corresponding to a stair-step, linear and exponential change in the neutron flux in time, as well as the possibility of generating signals simulating the response of a reactor to the reactivity introduction. The flexibility of fission chamber signal modeling algorithms and parameters allows to use simulator for verification of both neutron flux monitoring secondary equipment and spectrometric or dosimetric devices.

The metrological characteristics of the wide-range fission chamber simulator were confirmed during the tests. The using of the simulator for testing of existing neutron flux monitoring channels confirmed its functionality abilities.

5 REFERENCES

1. G.N. Alexakov, S.N. Grouzdev, N.A. Selyaev, A.G. Ter, V.A. Fedorov, "The "Avtotest" System for the NPIC Equipment Diagnostics Automation", *Proceeding of NPIC&HMIT 2004 ANS/ENS Embedded Topical Meeting*, Columbus, September 19-22, pp.127-133 (2004).
2. S. Morris, R. Pratt, M. Hughes, R. Kouzes, K. Pitts, E. Robinson, "DVD Based Electronic Pulser", *IEEE Transactions on Nuclear Science,* **Vol. 4(53)**, pp.2303-2306 (2006).
3. A.V. Batyunin, V.A. Vorobyev, S.Yu. Obudovsky, S.A. Shvikin, Yu.A. Kaschuck, "Fission Chamber Simulator for Data Acquisition Performance Tests", *Proceeding of Conference on Advancements in Nuclear Instrumentation, Measurements Methods and their Applications ANIMMA-2013*, Marceille, June 23-27, (2013).
4. A. Abba, F. Caponio, A. Cusimano, C. Tintori, "Dual channel fast digital detector emulator with analog input", *2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC),* California, October 31 – November 7, pp. 1-3 (2015).
5. E.S. Martazov, "Diagnostic performance of neutron FC using a mobile automated PIK monitoring complex", *Proceedings of the RAS session and business program* "*Territory of NDT in 2016*", pp.184-188 (2016).
6. V.P. Alferov, A.V. Kudryavtsev, Yu.A. Parishkin, V.A. Fedorov, A.B. Dmitriev, K.I. Yakovlev, "Applicaton of Modern Tools for NPP Neutron Monitoring Systems Upgrading", *Proceeding of NPIC&HMIT 2000 ANS/ENS Embedded Topical Meeting*, Washington, November 12-16, pp.393-401 (2000).