Performance Evaluation of Newly Developed EIS/IIS Utilizing Digital Signal Processing

Authors: *Ryuki Tanaka*, Ryo Konishi*, Tetsushi Azuma**, Makoto Sasano**, Cheol Ho Pyeon****

Energy Systems Center, ** Advanced Technology R&D Center, * Kyoto University*

Abstract

Nuclear power generation is garnering attention as a way to realize a carbon-neutral society, and against that backdrop Mitsubishi Electric is developing new models of nuclear instrumentation equipment for Pressurized Water Reactors (PWR) that actively incorporate digital signal processing technology as a new approach, aiming for the sustainable development of nuclear power business in the future.

For the Ex-core Instrumentation System (EIS), signal processing with analog circuits has been the mainstream choice in order to apply specific processing methods to signals from neutron detectors. Amid that trend, we have achieved digitalization, which is rare, even globally.

For the In-core Instrumentation System (IIS), we have developed a signal processing unit compatible with Self Powered Neutron Detectors (SPND), which have not been previously applied in domestic PWRs, and confirmed that the specified performance can be achieved.

1. Introduction

Due to increasing demand for decarbonized power sources in recent years, global expectations have risen for construction of advanced nuclear reactors, particularly small modular reactor (SMR), for nuclear power plant. Mitsubishi Electric is participating in development of the SMR-300 small modular reactor by the US company Holtec International, and is in charge of equipment design of the Instrumentation and Control (I&C) system that handles reactor control and automation of operation(1). In the small modular reactor market, it is important to create economic advantages during construction as a factor differentiating from conventional large reactors. Therefore, we are promoting the development of I&C systems that actively incorporate digital technology with the aim of reducing initial costs and maintenance costs.

Among I&C systems, EIS and IIS, which have core monitoring functions, are two of the main instrumentation equipment (Fig. 1). The EIS contributes to reactor protection, monitoring, and control by measuring neutrons that leak from the reactor using neutron detectors installed around the reactor pressure vessel. The IIS enables monitoring the core in detail by measuring neutrons inside the reactor using neutron detectors installed inside the reactor core.

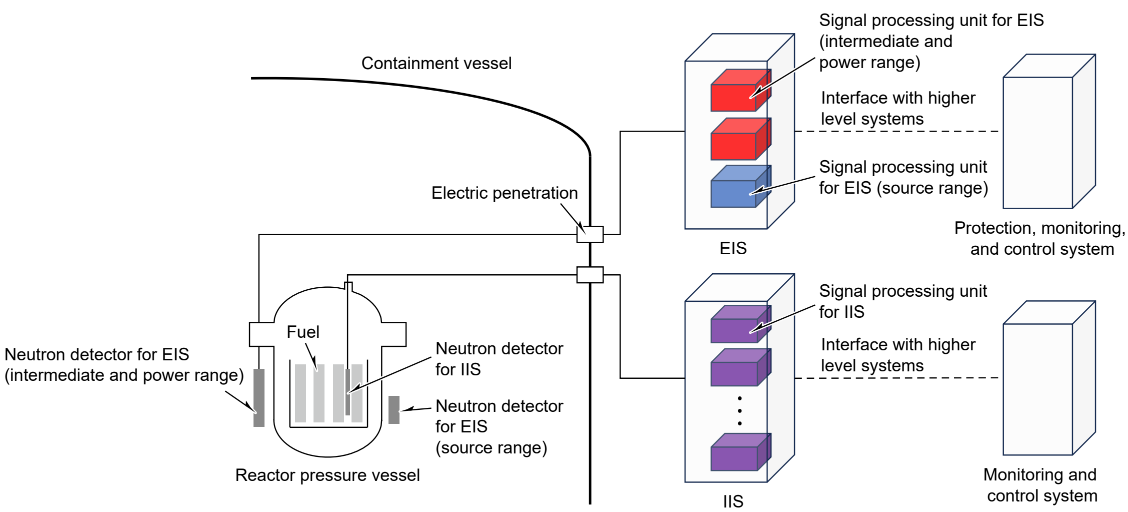

Fig. 1 System configuration of EIS and IIS

In small modular reactors overseas, there is a possibility of using neutron detectors and detection methods that differ from those in existing domestic PWRs for which Mitsubishi Electric has supplied equipment. In addition, there is a need to reduce construction and maintenance costs, including both existing domestic PWRs and advanced nuclear reactors, and to address these needs, we are developing new models of EIS/IIS that utilize digital technology[2].

2. Signal Processing and Digitalization in Nuclear Instrumentation System

In nuclear instrumentation system that monitors reactor power and status, signal processing of detector output signals is essential for measuring the neutron flux incident on neutron detectors installed inside or external to the reactor core.

2.1 Digitalization of signal processing methods and related issues

Conceptual diagrams of signal processing methods developed for nuclear instrumentation system and related issues are shown in Fig. 2 and Fig. 3.

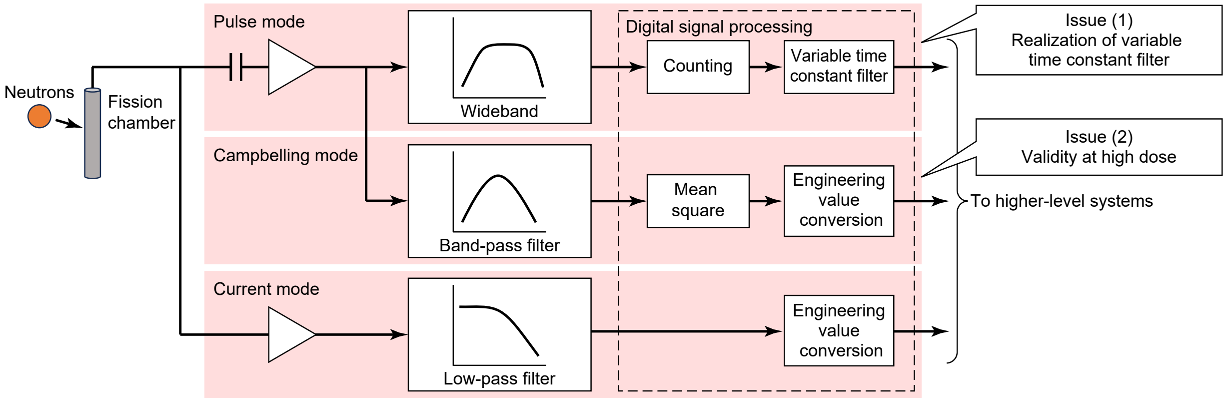

Fig. 2 Conceptual diagram of signal processing methods and issues for EIS

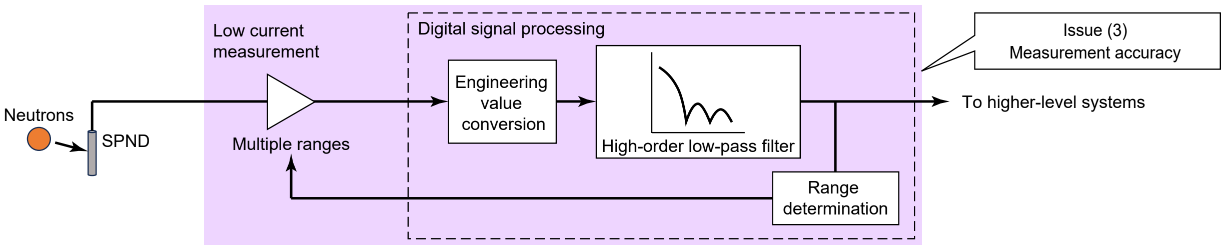

Fig. 3 Conceptual diagram of signal processing methods and issues for IIS

Neutron detectors for EIS include BF3 proportional counters, fission chambers, and uncompensated ionization chambers. Three different measurement methods are used according to neutron flux and detector characteristics: pulse mode, Campbelling mode, and current mode. Among these, digital signal processing technologies for pulse mode and Campbelling mode suitable for fission chambers were newly developed for EIS successor models. In realizing digital signal processing technologies suitable for both measurement methods, there are the following respective issues:

Issue (1) (pulse mode): Realization of digital filters (variable time constant filters) that meet required accuracy regardless of count rate

Issue (2) (Campbelling mode): Validation of signal processing methods for output signals from neutron detectors in high-dose-rate conditions

For IIS neutron detectors, top-mounted fixed in-core instrumentation that inserts SPNDs from the upper part of the reactor for improved safety has recently become mainstream in newly constructed PWRs. The detector signal range of SPNDs is typically small at approximately 1nA to 1μA and requires ensuring accuracy over a wide dynamic range. Therefore, IIS compatible with SPNDs has the following issue:

Issue (3) (low current measurement): Ensuring measurement accuracy suitable for low current applications and achieving the required dynamic range.

These issues and their corresponding solutions are described in detail in sections 2.2, 2.3, and 2.4.

2.2 Approach to Issue (1) (pulse mode): Modeling of analog circuits and recurrence formula expression

With pulse mode, a count rate proportional to reactor power is obtained by determining the number of pulse signals generated when neutrons react in the detector. However, signals occur randomly, so when signal occurrence frequency is low, variations in count rate become large during short-term measurements, and that is unsuitable for reactor protection and monitoring. Therefore, with the typical pulse mode in EIS, processing is performed while varying the time constant so that the standard deviation meets the required accuracy regardless of the magnitude of the count rate. Mitsubishi Electric has previously realized this processing using a dedicated analog circuit (logarithmic amplifier) that utilizes the exponential characteristics of transistors. This also has the characteristic of fast response when changing from low count rates to high count rates.

When digitalizing the pulse mode, the issue was to reproduce characteristics similar to the aforementioned logarithmic amplifier through digital signal processing. Therefore, digitalization was achieved by modeling the analog circuit of a logarithmic amplifier using ideal transistors and expressing the relationship between input and output as a recurrence formula for minute steps (Fig. 4)[(3)].

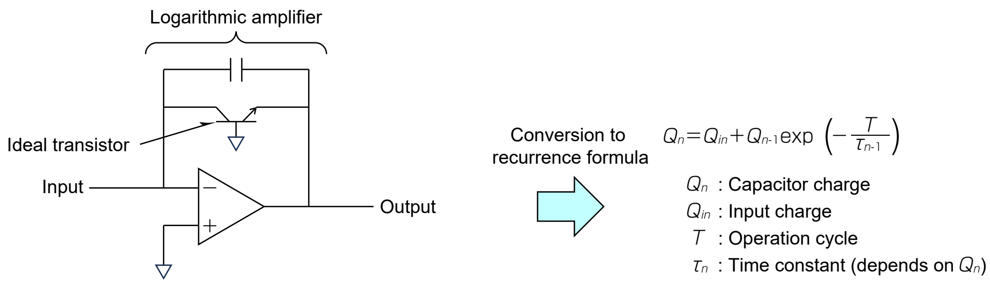

Fig. 4 Modeling of logarithmic amplifier analog circuit

2.3 Approach to Issue (2) (Campbelling mode): Model-based design enabling system verification

In developing EIS and IIS, evaluation using actual signals is difficult because measurements in high neutron irradiation fields cannot be easily performed. Since the detector signals are also complex, conventional methods for EIS digitalization design validity in particular could only perform static confirmation using normal test environments or simulated signals, and that was a hurdle for the development and verification of signal processing methods.

Therefore, model-based design was applied to reproduce neutron detectors, analog circuits, digital signal processing, and even higher-level control and monitoring systems in digital space (MATLAB/Simulink)[*1] (Fig. 5). This enabled not only efficiency improvements in implementation design and the development process for digital signal processing methods, but also system-level validation. Dynamic and high-dose simulated signal confirmation, which could not be performed until the actual equipment test stage, was implemented at the design stage, confirming the validity of signal processing logic including the Campbelling mode for EIS, which had previously been an issue.

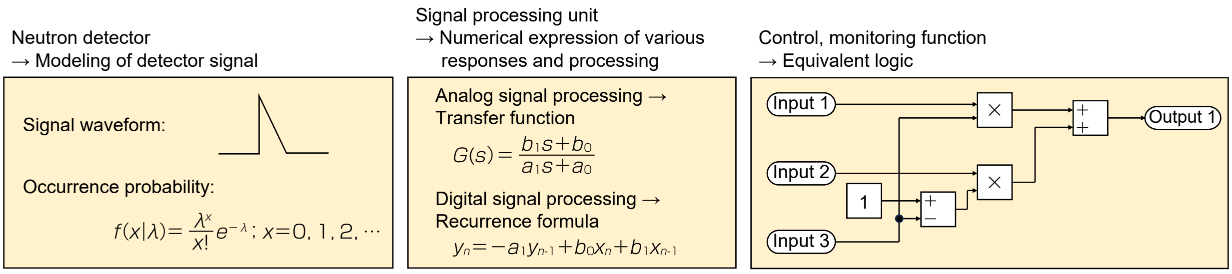

Fig. 5 Application of model-based design

*1 MATLAB and Simulink are registered trademarks of The MathWorks, Inc.

2.4 Approach to Issue (3) (low current measurement): Application of automatic range switching method

To ensure measurement accuracy corresponding to the required dynamic range while targeting low currents for measurement, an automatic range switching method was developed that continuously measures while appropriately switching the amplification factor of the first-stage amplification circuit.

Generally, in low current measurement circuits that ensure high accuracy, a long time that cannot be ignored in measurement is required until the output voltage settles, when the amplification factor of the first-stage amplification circuit is switched. With the developed method, this settling time was significantly shortened through analog circuit innovation, and continuous measurement was achieved by digital-signal filtering of short-term data immediately after switching[4].

3. Miniaturization of Nuclear Instrumentation Equipment through Digitalization

Signal processing units for EIS and IIS were each prototyped. These units employed the digital signal processing logic described in section 2.3 (Fig. 6 and Fig. 7). The board area required for signal processing circuits was significantly reduced by implementing the signal processing logic in one computing element (Field Programmable Gate Array (FPGA)). This enabled the signal processing circuits, the main elements of nuclear instrumentation equipment, to be consolidated into a single unit, realizing miniaturization of nuclear instrumentation equipment.

Fig. 6 Prototype of signal processing unit for EIS

Fig. 7 Prototype of signal processing unit for IIS

4. Performance Evaluation and Validity Confirmation

Performance of the signal processing units was evaluated by inputting simulated signals to the prototypes. Results were obtained where measured values matched well with design values, as described in section 4.2. This confirmed validity of the digital signal processing logic and feasibility as a product.

4.1 Evaluation results for EIS signal processing unit

The input/output characteristics of pulse mode and Campbelling mode are shown in Fig. 8, and the evaluation results of the time constant in the pulse mode are shown in Fig. 9. The generation probability of input signals was set to a Poisson distribution with count rates of 1cps (count per second), 10cps, ..., or 10^6cps. As a result, linearity was obtained in the expected range for input/output characteristics, and for response time, response was confirmed to be proportional to the reciprocal of the count rate as designed.

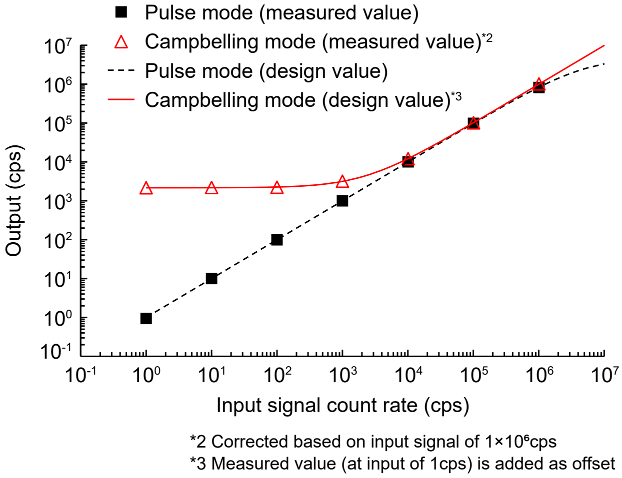

Fig. 8 Evaluation results for input/output characteristics

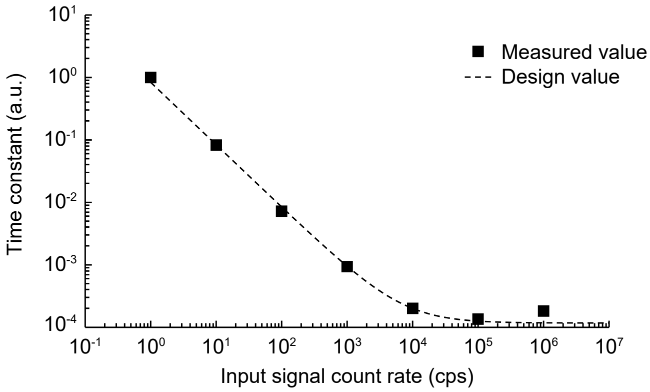

Fig. 9 Evaluation results for response time of pulse mode

4.2 Evaluation results for IIS signal processing unit

To evaluate the automatic range switching function implemented with digital signal processing, current source input was used, and the calculation results inside the unit were recorded when the amplification factor of the analog circuit switched from high range to low range due to range switching (Fig. 10). The output before and after range switching was seamless, which confirmed the effectiveness of the automatic range switching function.

Also, the attenuation amount representing the filter effect for AC signals at 5 to 25Hz was evaluated as an evaluation of the noise removal performance of the high-order low-pass filter (Fig. 11). The attenuation amounts at the measured frequencies matched well with the design values that considered the characteristics of both the analog and digital filters, confirming that the filter with high noise removal performance functioned as designed.

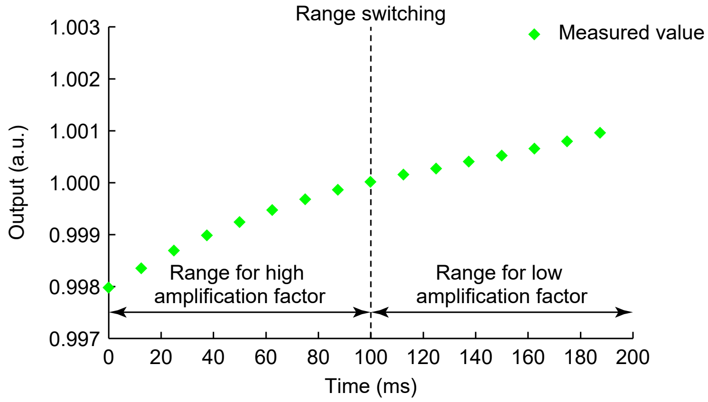

Fig. 10 Evaluation results for automatic range switching function

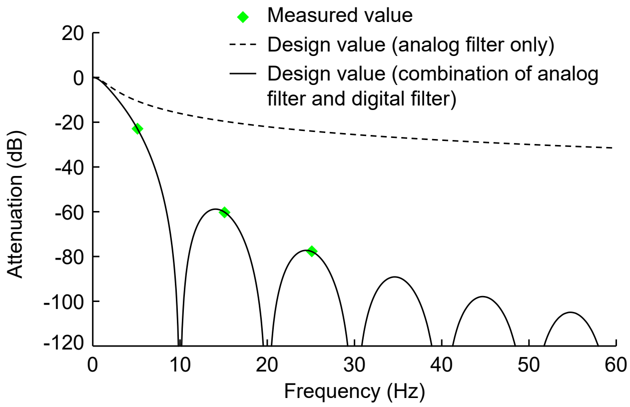

Fig. 11 Evaluation results for high-order low-pass filter

5. Conclusion

This paper has described the developed signal processing technology and its evaluation results, as performance evaluation for the new model of nuclear instrumentation system equipment. By applying this newly developed digital signal processing technology, it will be possible to realize equipment suitable for advanced nuclear reactors. Since validity of basic performance has been confirmed, we will proceed with environmental testing and acquisition of US certification in the future, and advance development toward commercialization.

Also, for the purpose of evaluating characteristics of neutron detectors used in IIS, neutron irradiation tests(5) using the Kyoto University Research Reactor are being conducted through joint research with Kyoto University, and evaluation is being performed using the signal processing units described in this paper. Similarly, experiments using the same research reactor are planned for evaluating measurement methods for EIS. We plan to describe these results in another paper.

Some of the results related to IIS described in this paper were obtained as a result of the Ministry of Economy, Trade and Industry’s “Nuclear Industry Infrastructure Strengthening Project.”

References

(1) Hamaya, Y., et al.: Instrumentation and Control System for Small Modular Reactor “SMR-160”, Mitsubishi Denki giho, 95, No. 11, 686–689 (2021)
(2) Local Digital Ex-core Instrumentation System for Small Module Reactor, Mitsubishi Denki giho, 99, No. 1, 1-1-03 (2025)
(3) International Application No.: PCT/JP2024/040975 (application date: Nov. 19, 2024)
(4) International Publication No.: WO2024/150353 (publication date: Jul. 18, 2024)
(5) Pyeon, C. H., et al.: Development of Compensation Method for Faster Measurement with SPND, KURNS Prog. Reports 2022, CO12-8, 242(2023) https://www.rri.kyoto-u.ac.jp/PUB/report/PR/ProgRep2022/CO12.pdf