Development of a fiber-optic system for testing instruments for monitoring nuclear power plants

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Abstract. The necessity of testing the equipment for monitoring the operation of nuclear power plants is justified. It is proposed to use optical fiber and pulsed laser radiation for these purposes. It is established that optical fiber is more resistant to radiation than other communication systems. The design of a fiber-optic emergency simulator is developed. The calculation of its characteristics is carried out. Their experimental research was carried out. It was found that with an optical signal delay of 98.6 microseconds, the loss is –26 dB with an uneven frequency response of ±2 dB. This makes it possible to test the entire set of equipment that uses optical signals used to control a nuclear power plant.

1. Introduction

Reduction of fuel reserves led to the development of nuclear energy [1-7]. Nuclear energy is a dynamically developing high-tech field with broad prospects for progress [8-13]. The environmental problems associated with this atomic energy [14-22], because of its great prospects, are relegated to the background.

The use of nuclear power plants (NPP) also remains relevant on sea vessels, both civil and military, which, in turn, leads to both the emergence of a number of new types of nuclear power plants and the modernization of existing ones [4, 11-13, 20, 23-26].

One of the main problems arising during the operation of nuclear power plants is their safe operation. One of the main conditions for the safe operation of nuclear power plants is the flawless operation of the reactor cooling systems, for the control of the operation of which reliable equipment must be used. For cooling in nuclear power plants, the so-called "heavy" water is most often used, the flow rate of which and its parameters are controlled using flow meters, the principle of which is based on the phenomenon of nuclear magnetic resonance (NMR) [11-13, 25, 27].

In an emergency in a nuclear reactor there is a sharp increase in the level of ionizing radiation, which affects the "heavy" water of the reactor cooling system. It has been experimentally established that in this case there is a shift in the timing of the appearance of the NMR signal in the recording system and a change in signals appearance. This shift happens once. By measuring this one-time shift (time interval) between the recorded NMR signals and comparing it with the one previously
To keep the operating parameters of the time domain measurement system in working order, it must be checked and tested regularly \[11-13, 19-21, 27, 28\]. Since mobile objects, as a rule, have a large amount of various kinds of interference for the transmission of NMR signals, fiber-optic communication lines (FOCL) are most often used in these systems \[29-32\]. The FOCLs developed at present are insensitive to powerful electromagnetic radiation, contact interference arising during transient processes in ship power plants, etc \[29-37\]. Therefore, to test the system for measuring time intervals, it is more expedient to use devices based on fiber-optic communication lines and laser radiation. At present, a large number of models of various lasers have been developed, which makes it possible to eliminate many problems in the creation of such devices.

2. Development fiber-optical emergency simulator

A during developing fiber-optic systems for various purposes for objects with nuclear power plants, it is necessary to take into account the effect of \(\gamma\)-radiation, which can have a negative effect on FOCL \[33-35\]. In this regard, in the developed fiber-optic simulator, it is advisable to use a single-mode fiber with a pure quartz core. At present, relaxation constants are determined in NMR-based flowmeters, and the flow of "heavy" water is also recorded in a wide frequency band from 3 to 40 MHz at a modulation frequency \(f_m\) of a constant magnetic field in the range from 10 to 50 Hz. The time interval between the recorded NMR signals is from 0.01 to 0.05 s, and the range of time of the possible delay of the NMR signal when the state of "heavy" water changes is from 40 to 130 \(\mu s\).

The inclusion of the simulator in the information transmission line can introduce the minimum possible loss for the attenuation of the transmitted NMR signal to ensure the required measurement accuracy when testing the control system of the nuclear power plant, especially when it operates at the "edges" of the dynamic range of measurements. Distortion of the form of the transmitted signal is impossible, since this will instantly degrade the accuracy of measurement of the relaxation constants, as well as the very time interval between signals, which characterizes changes in "heavy" water. In Figure 1 shows as an example the line shape of the NMR signal from "heavy" water, recorded at a frequency of \(f_{nmr} = 4573\) kHz with a modulation frequency of \(f_m = 16.3\) Hz.

![Figure 1. The NMR signal from «heavy» water in wide registration band.](image)

For accurate measurement of relaxation times \(T_1\) and \(T_2\), an NMR signal with a large number of damped "wiggles" of oscillations is required. Such signals should be transmitted without distortion of the form to the processing device (the calculator of the reactor compartment and to central computers of the ship), in which \(T_1\) and \(T_2\) will be determined and the corresponding conclusions and recommendations will be issued.

It should also be noted that in order to objectively check the operation of the NPP control system using NMR flowmeters-spectrometers, it is necessary to cover the entire range of variation of the delay times \(\tau_d\). As part of solving this problem, the task was to develop six simulators. for different
values of τd, which are about 40, 50, 75, 100, 110 and 130 μs. Also, simulators should work stably in the temperature range from 278 to 318 K. The developed simulators can be placed on one rack and in turn connected to the information transmission system. In the presented work, a FOCL-based simulator is developed on the basis of a passive fiber-optic delay line with an optical isolator switched on at the input to exclude reflected signals.

The signal attenuation was calculated for the developed design of the simulator. All intrinsic losses \( A_\Sigma \) in the fiber are defined as follows:

\[
A_\Sigma = a_a + a_d + a_i + a_{ex},
\]

(1)

where: \( a_a \) – takeover loss; \( a_d \) – scattering loss; \( a_i \) – impurity losses; \( a_{ex} \) – additional losses.

Absorption losses are defined by the following expression:

\[
a_a = 8.69 \frac{\pi \tg(\delta) n_1}{\lambda},
\]

(2)

where: \( n_1 \) – refractive index of the core, for the fiber we have chosen is 1.4676; \( \tg(\delta) \) – dielectric loss angle tangent (2.510−12), then absorption losses for operating wavelength (\( \lambda = 1310 \) nm) constitute \( a_a = 0.076 \) dB/km.

The scattering loss is determined by the following formula:

\[
a_d = 4.34 \times 10^3 \left( 8 \pi^3 \frac{n_1^2 - 1}{3 \lambda^2} \kappa \beta T \right),
\]

(3)

where: \( T \) – fiber core manufacturing temperature; \( \beta = 8.1 \times 10^{-11} \) m²/H – compressibility factor. The calculated value for operating wavelength is \( a_a = 0.234 \) dB/km.

To transmit NMR signals in NPP control systems use single-mode optical fibers of the firm Corning SMF-28e+ with a operating wavelength of 1310 nm are used, therefore, for them, the loss of extraneous material and additional losses are very small compared to the estimated \( a_a \) and \( a_d \).

Then all your own losses will be \( A_\Sigma = 0.31 \) dB/km. In addition to these losses, there are back losses on four additional compounds (FC-APC connectors) \( a_c = 4 \times 0.2 = 0.8 \) dB. Loss in optical insulator 0.41 dB. Then all the losses associated with switching on the fiber-optic simulator will be:

\[
a_{im} = (a_a + a_d) \times L_{op} + 1.21,
\]

(4)

where: \( L_{op} \) – fiber length.

For a system energy margin of 2 dB, let us determine the maximum possible length \( l_{max} \) of the regeneration section of the fiber-optic delay line:

\[
l_{max} = (A_{max} - M - n_{pc} a_{pc})/(\alpha + \frac{n_{nc} a_{nc}}{l_{ct}}),
\]

(5)

where: \( n_{pc} \) – number of connectors; \( a_{pc} \) – loss in detachable compounds; \( l_{ct} \) – face-to-face cable length (\( l_{ct} = 63000 \) m); \( a_{nc} \) – loss in integral compounds (when welding face-to-face cable lengths \( a_{nc} = 0.05 \) dB), \( \alpha = a_{im} \) for calculation of \( L_{op} = l_{ct} \); \( M \) – system attenuation margin at the regeneration section (\( M = 2 \) dB); \( A_{max} \) – maximum closed attenuation value of instrumentation.

Thus, the value \( l_{max} = 124900 \) m. The results obtained indicate that there are great opportunities for using this type of fiber for the production of simulators based on fiber-optic communication lines for signal delay.
3. Experimental results and discussion

To check the correct functioning (measurement of delay times $\tau_d$) of the developed fiber-optic simulators and study their dynamic characteristics, an experimental setup was created, the block diagram of which is shown in Figure 2.

![Figure 2. The design Scheme of the Simulator Test Facility.](image)

To measure the dynamic characteristics of simulators in an experimental setup, the Agilent MS07954B oscilloscope in the block diagram is changed to an Agilent PXA N9030A spectrum analyzer. In the case of $K_n$ noise figure measurements, the Agilent MS07954B oscilloscope in the block diagram is replaced by an Agilent PXA N9030A Spectrum Analyzer, and an Agilent E82570 Signal Generator is replaced by an Agilent N4002A SNS Series Noise Source.

In Figure 3 shows, as an example, the results of measurements of the delay times $\tau_d$ for three simulators (values 49 $\mu$s, 75 $\mu$s and 98.6 $\mu$s). The upper signal on the oscillogram was obtained without including the simulator in the measurement circuit shown in Figure 2, the lower one with the simulator turned on.

Analysis of the signals obtained during the experiment shows a decrease in power. Thus, when a FOCL-based simulator is included in a fiber-optic NMR signal transmission system for testing nuclear power plant control systems, the transmitted signals will need to be amplified to ensure the required accuracy during measurements. The measured dynamic characteristics of fiber-optic simulators showed that all the developed designs have a dynamic range of at least 56 dB, which is quite easy to implement in practice.

An important characteristic when transmitting optical signals over fiber-optic lines is the intrinsic noise of an additional device connected to the communication line. The noise figure $K_n$ of the developed simulators was investigated by the $Y$-factor method in the frequency range from 3 to 44 MHz.

In Figure 4 shows the experimental dependence of the noise figure $K_n$ on the input signal frequency $F$ for three values of $\tau_d$, obtained during the experiment.

Based on the data obtained during the experiment, it was found that the noise figure varies in the range from 23 to 28 dB. For the frequency range $F$ from 18 to 42 MHz, the nonlinearity of $K_n$ is no more than 1.5 dB. In the specified frequency range, it is most convenient to test the control system for nuclear magnetic meters of NPP parameters. In this regard, when designing nuclear magnetic counters for these control systems, developers are advised to choose the frequency of recording the NMR signal in the range from 18 to 40 MHz in order to be able to qualitatively check its performance.
Figure 3. Temporary passage of the optical signal through a simulator with different lengths of fiber – optical L: a) – corresponds to L = 10 000 m (τ_d = 49.6 μs), b) - L = 15 000 m (τ_d = 75.0 μs), c) - L = 20 000 m (τ_d = 98.6 μs).

Figure 4. The dependence of noise coefficient K_n on the frequency of the input signal F. Graphs 1, 2 and 3 correspond τ_d in a μs: 49.6; 75; 98.6.

4. Conclusion
The results obtained in the course of the experiment showed sufficient reliability of the developed simulator based on FOCL, intended for testing the operation of time intervals meters in NPP cooling systems.

The conducted studies of the parameters of simulators based on FOCL showed that they can also be successfully used for testing equipment of radar stations, since the noise figure of the developed simulator, as shown by additional studies, in the frequency range from 2 to 18 GHz, varies by no more than 17 dB (the maximum allowable value for these devices is 27 dB). This shows the wide functionality of the developed equipment.
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