Control and instrumentation (C&I) systems in nuclear power plants should have high reliability and high maintainability, and adopting automatic control systems should reduce an operator’s workload. For this purpose, a new digital control complex system was adopted in the ABWR (Advanced Boiling Water Reactor) to make the human-machine interface more helpful and to expand the scope of automatic control to the plant start-up and shutdown operations and automatic operation after a scram. The new digital control complex system in the ABWR has shown good performance during commercial operation. The next generation ABWR, the ABWR-II, has been under development for a decade in Japan. This ABWR-II will offer improved plant economy, greater safety, easiness of operation and maintenance, and flexibility in the fuel cycle strategy. For the C&I system, a highly reliable design above that of ABWRs is adopted for the ABWR-II. This paper describes and compares the features of the next C&I system of the ABWR-II.

KEYWORDS: New digital control complex system, Transient mitigation system, Gamma Thermometer

I. Introduction

Control systems of nuclear power plants must support operators in making qualified decisions and efficient operations during plant start-up, shutdown and normal operations and surveillance testing.

A new digital control complex system was adopted in the ABWR to make the human-machine interface more widely useful and to expand the scope of automatic control.

Digital technology has been gradually applied more widely to improve the human-machine interface, and the reliability and maintainability of individual plant systems. The goal of implementing digital technology is to facilitate monitoring and operation of plants. Progress in applications of digital technology to BWRs and the characteristics of the latest digital C&I system are described below.

Table 1 shows the progress in applications of digital technology. Digital technology was first applied to second generation C&I systems in Japan. At this early stage of progress, a redundant digital system was developed and applied to the major control systems of the plant. This provided a drastic improvement in reliability and control performance of the plant. Then, a digital radiation monitoring system and an optical information transmission system were incorporated into the plant. The optical information transmission system, in particular, had many characteristics superior to those of ordinary electronic transmission systems including its superb noise resistance and the large transmission capacity. A nuclear power plant usually involves tens of thousands of pieces of plant information, which are transmitted simultaneously to the main control room. Hence, optical transmission is expected to be more and more common in future power plants.

Accordingly, the optical information transmission system and digital processing technology have first been applied to every possible part of the radioactive waste processing system. Then, to improve the reliability and maintainability of nuclear power plants, digital technology has been applied gradually to non-safety-related systems such as the turbine/generator auxiliary systems and reactor non-safety-related systems. For the ABWR, digital technology was applied to the control and instrumentation facilities of the entire plant, including the neutron monitoring system, the safety protection system, the reactor recirculation internal pump control system, and the control rod control system.

Table 1. Progress of Digital Technology and Application

<table>
<thead>
<tr>
<th>Phase of Progress</th>
<th>1st generation (first used domestically)</th>
<th>2nd generation (improvement and standardization)</th>
<th>3rd generation (ABWR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Machine Interface System</td>
<td>Conventional system</td>
<td>Main console + large panel</td>
<td>Main console + subpanel</td>
</tr>
<tr>
<td></td>
<td>2 CRT displays for operation monitoring</td>
<td>5 LCD displays for operation monitoring</td>
<td>Flat-panel displays</td>
</tr>
<tr>
<td></td>
<td>- Touch operations using CRT display</td>
<td>- Flat-panel displays</td>
<td>- Optical information transmission for Radioactive waste processing system and radiation monitoring system</td>
</tr>
<tr>
<td></td>
<td>Control Systems</td>
<td>Conventional system</td>
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<td></td>
<td>Analog equipment</td>
<td>Digitized technology for safety-related systems</td>
<td>Digitized technology for safety-related systems</td>
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<td></td>
<td>Digitized technology for non-safety-related systems</td>
<td>Optical information transmission for safety-related systems</td>
<td>Optical information transmission for safety-related systems</td>
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<td></td>
<td>Optical information transmission for non-safety-related systems</td>
<td>Optical information transmission for non-safety-related systems</td>
<td>Optical information transmission for non-safety-related systems</td>
</tr>
<tr>
<td></td>
<td>Electronic transmission (conventional)</td>
<td>Optical information transmission for safety-related systems</td>
<td>Optical information transmission for non-safety-related systems</td>
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II. ABWR C&I System

Fig.1 is a schematic representation of the new generation integrated digital C&I system. The system aims to attain high system reliability and maintainability based on digital control and optical transmission technologies applied to the C&I system, including safety-related systems.

I. Human-Machine Interface

Fig.2 shows the advanced human-machine interface for the ABWR. The design philosophy for this system has two main points: 1) to further facilitate and ensure monitoring and operations, and 2) to make plant operations more efficient. To attain these goals, the control board configuration used consists of a main control console and a wide display panel. The wide display panel simultaneously presents important information on the plant to all of the operators involved, while the main control console provides integrated information for normal monitoring and operation.

The main control console has flat-panel displays, which are intended to be used in plant specific operations such as those done during periodic inspections. These technologies have reduced the size of the human-machine interface area.

Fig.3 shows an example of a flat-panel display screen with touch operation capability, which is installed on both the main control console and the wide display panel. The flat-panel display presents screens with superior visibility. This is due to the thin film transistor (TFT) color device used in the display. The flat-panel display is in the latest device technology 10-inch diagonal class, which means that currently there is a steady supply of such devices. Flat-panel displays of this class are used in various systems of plants, including safety-related systems, for the purposes of monitoring and operations. Plant diagrams presented on the display allow operators to select equipment and operational modes by touching the surface of the panel. Measurement data screens presented on the display allow operators to see how physical quantities being monitored are changing. This human-machine interface functions independently of the CRT displays driven by the process computer. This
deliberately makes operating and monitoring activities redundant.

2. Digital Neutron Monitoring System

A neutron monitoring system (start-up range monitor and power range monitor) measures levels of neutron flux. Its goal is to monitor all the power ranges of nuclear reactors from the start-up range to the power range.

For ABWRs, with implementation of a digital system, the following have been made possible: 1) improvement of the reliability and maintainability of the neutron monitoring system; 2) automation of part of the calibration capability of the local power range monitor (LPRM); and 3) addition of a self-diagnostic capability to the monitoring system.

The digital power range monitor uses a special high-performance digital filter with fine frequency-response characteristics. This improves the signal processing capability as well as noise resistance.

Then the flat-panel displays have made the human-machine interface compact, but powerful.

3. Digital Safety Protection System

Japanese manufactures have gained much experience in full-scale applications of digital control technology as well as optical information transmission technology to various control systems. Additionally, digital components have been incorporated into the safety protection system of the ABWR. Reliability and sufficient validity are required of the safety protection system. In regard to this theme, an application have been made based on both the results of joint research with electric power companies, and the results of a validation test under the supervision of the Nuclear Power Engineering Corporation.

Realizing a digital safety protection system means a system is constructed on the basis of microprocessors instead of conventional relays and analog instruments. A system so constructed facilitates the use of more highly reliable logic “2 out of 4” instead of conventional logic “1 out of 2/twice,” and allows any one channel to be isolated from the others for maintenance. Thus, the system is able to contribute to improvements in plant maintainability and availability.

In addition to the digital control technology mentioned above, the safety protection system also employs optical transmission technology to send and receive signals to and from many spots in the system. What is more, the system is provided with the flat-panel displays in its human-machine interface. These displays provide touch operation support for display of the plant status, and allow for operation of particular equipment manually.

III. ABWR-II C&I System

The next generation ABWR, the ABWR-II, has been under development for a decade in Japan. This ABWR-II will offer improved plant economy, greater safety, easiness of operation and maintenance, and flexibility in the fuel cycle strategy. For the C&I system, a more highly reliable design above that of ABWRs is adopted for the ABWR-II. That is, a flexible integrated digitalized system is applied in the C&I system of the ABWR-II.2 It should be noted, however, that some components of the C&I system are more sophisticated and highly reliable from the viewpoint of reliability and effectiveness as described below.

1. Advanced Human-machine Interface

Investigation of regular outage maintenance of operating ABWRs pointed out some improvements to the ABWR plant human-machine interface. That is, the ABWR human-machine interface is good enough for start-up, shutdown and usual operations, however, for regular outage some improvements are needed.

- Efficiency of assistant operator and inspection team
- Visualization of inspection and maintenance status
- Judgment support of work conditions
- Efficiency of system inspection
- Improvement of the C&I maintainability

These improvements will be applied to the ABWR-II plant human-machine interface.

2. Advanced Control System

A symptom-based transient mitigation method for feedwater system failure has been developed. This method will be able to monitor plant primary parameters and control other systems, if necessary, as the top plant control system in order to avoid unnecessary plant shutdown when controlling reactor water level.

A representative system is the automatic power output adjustable device. This system outputs operating signals of the recirculation flow and control rods, etc. and controls the reactor power in case of feedwater system failure, based on various pieces of information about core status and the control rods.
3. Transient Mitigation System

This system has been developed to reduce ΔMCPR (minimum critical power ratio) for the most severe transients as below:

a. power load rejection without bypass (ΔMCPR = 0.13)

b. loss of feedwater heating (ΔMCPR = 0.14).

To reduce these ΔMCPR, this system is equipped with the function to open the relief valve as soon as the power load rejection without bypass is detected and also to activate insertion of the selected control rods or RIP run back signals as soon as loss of feedwater heating is detected from a change of feedwater temperature.

As a result of applying this system, ΔMCPR can be reduced to 0.08 for item a and 0.10 for item b.

4. Gamma Thermometer

Conventional BWR flux monitoring systems use both fixed and traverse neutron sensitive fission chambers. Fixed LPRMs provide signals proportional to the local neutron flux at various locations within the reactor core. Traversing in-core probes (TIPs) provide indications of axial power signals for calibrating the LPRMs. Recently, it has been proposed to replace the existing TIP system with a system based on a fixed in-core gamma thermometer. The developed gamma thermometers (GT) was tested at Tokai 2 of Japan Atomic Power Co. and at Kashiwazaki Kariwa Nuclear Power Plant Unit Number 5 (K5) of Tokyo Electric Power Co. Latest test results at K5 are described here.

The simplified sketch shown in Fig.4 illustrates a GT. In the GT, core metal is heated by gamma rays. The generated heat is proportional to the power of the adjacent fuel rods. The heat generated in the core metal is permitted to escape to a heat sink though a heat path. The temperature drop along that heat path is directly proportional to the heat rate from gamma heating. Each differential thermocouple (TC) embedded in the gamma thermometer measures the temperature drop along the heat path and produces a signal which is proportional to the local power.

The signal U from the TC, the output voltage from the differential thermocouple (in millivolts), is given in following formula,

\[
U = \frac{S_0 \times w}{1 - \alpha S_0 \times w}
\]

where \(w\) is the gamma energy deposition (W/g), \(S_0\) is the sensitivity (mVg/W), and \(\alpha\) is a small adjustment factor for nonlinearities. The sensitivity \(S_0\) is calibrated based on the heat deposited by the heater in operation.

The configuration of the data acquisition and calibration system (DACS) is shown in Fig.5. The TC input unit collects the analog signals from the TCs and converts them to digital data after rejecting electric noise contained in the signals. Also, the data processing unit has other functions such as the detection of anomalous GTs and bypass management of the detected anomalous GTs.

The heater controller which is linked with the calibration controller via the system interface controls the DC suppliers to output the regulated current to the heaters. The new sensitivity \(S_0\) is calculated based on the amount of the heat deposited by the heater in the data processing unit. The gamma energy deposition \(w\) and the detection results of anomalous GTs are transmitted to the core monitoring system (CMS).

During the K5 in-plant test, the GTs were loaded in a
1/8 reactor core region and their output data were collected for a whole cycle. Fig.6 shows a comparison of the GT and its adjacent LPRM outputs in start-up operation, where GT relative power is obtained through the following two steps.

1) The gamma energy deposition data (with delayed gamma compensation) are converted to the adjacent fuel bundle power by using the GT response factors to fuel power.

2) The equivalent LPRM data are calculated from the adjacent fuel bundle power with the LPRM response factor to fuel power.

The GT and LPRM outputs in Fig.6 agree quite well with each other. The differences between them are less than 2% through the start-up operation except during and after rapid power changes. The same results are obtained for other GTs at different positions. These results show that the GTs, like LPRMs, have a linear characteristic for local power and can be used to calibrate LPRMs.

The developed GT system was finally verified at K5 for the core monitoring application.

This system can be applied to commercial nuclear power plants.

5. Advanced Sensor Technology

Investigations on present instrumentation methods of nuclear plants and studies on applications of ray technology-based sensing or transmission methods have been done on:

- a. the present sensor
- b. the field bus method
- c. the ray fiber dyne method
- d. ray sensing instrumentation

As a result of these investigations, the ray fiber instrumentation system has been selected for the ABWR-II design.

IV. Conclusion

This paper described the features of the next C&I system for ABWR-II. Some components of the C&I system have been more sophisticated and reliable from the viewpoint of reliability and effectivity. In-plant testing was done for a gamma thermometer and good performance was obtained.

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