Hitachi's Technologies for Instrumentation and Control Systems to Fulfill High-performance and Highly-reliable Nuclear Power Plants

Shin Hasegawa, Dr. Eng.
Tatsuto Sugiura

OVERVIEW: Comprehensive plans are in place to enhance nuclear power plant operation to achieve higher performance, including longer fuel cycle operation and uprating the reactor's rated thermal power output. Similarly, many plants have been upgraded by replacing component and/or equipment that have obsoleted. In an environment in which new operating phases coexist with both new replaced equipment and existent equipment, it is necessary to have an instrumentation and control system capable of monitoring and properly controlling a wide range of state conditions from the equipment level to the plant level in order to obtain maximum performance from the plant while ensuring that its operating state remains stable and highly reliable. By constantly employing the state-of-the-art digital technologies, Hitachi has developed instrumentation and control technologies for achieving highly efficient and reliable nuclear power plants.

INTRODUCTION

THE function of an I&C (instrumentation and control) system is similar to that of the human brain and nervous system. When the system sends a command signal from the control unit (brain) to operate a pump, the pumped fluid (blood in the case of a human body) moves around the plant. If a sensor (sensory organ) detects an abnormal condition, the system operates to prevent the further propagation of the condition by initiating an appropriate control operation or interlock.

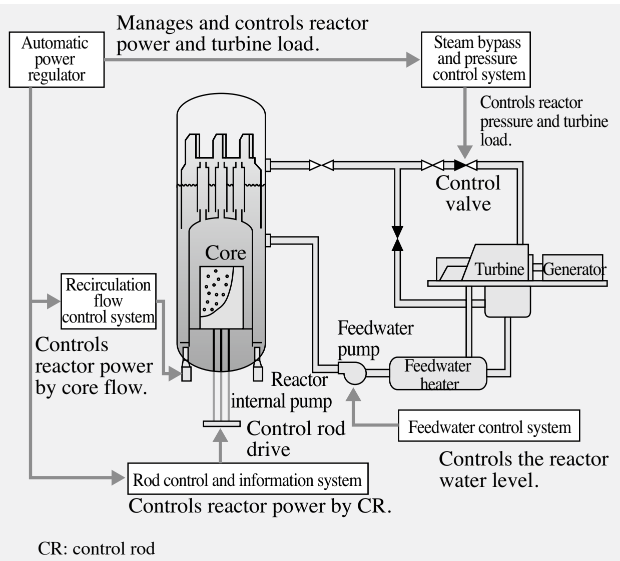

Fig. 1—Overview of ABWR Primary Control System.
These control systems work together to control the plant power and other vital parameters.

Because nuclear power plants use the energy of nuclear fission as their heat source, one of the safety functions of the I&C system is to shut down the reactor by using hydraulics to insert all the control rods into the core quickly (called a "scram").

In addition to this safety protection system, another important control function in nuclear power plants is what is called the "primary control system." The primary control system of BWRs (boiling water reactors) consists of the RFCS (recirculation flow control system) which controls the reactor recirculation flow, the FWCS (feedwater control system) which controls the feedwater to the reactor, the SB&PC (steam bypass and pressure control) system which controls the pressure in the reactor, the RC&IS (rod control and information system) which controls and monitors the normal operation of the fine motion control drive, and the APR (automatic power regulator) which manages the above control systems to regulate the power. Fig. 1 shows an overview of the primary control system in an ABWR (advanced BWR).

The functions of the primary control system include controlling the plant's power and various process parameters to keep them within a given range during normal operation, and ensuring that safety margins are maintained and scrams avoided by measures such as temporarily decreasing the plant's power during the transient condition between normal operation and abnormal conditions that require a scram to be performed. To reduce any unnecessary loss in availability, the plant power is restored to its normal level as soon as adequate safety is confirmed after a transient condition.

As discussed above, the primary control system has a significant relationship with the operation and operating practices of the overall plant because it directly handles the plant power output. Particularly in recent times, plans to adopt operating practices that affect the overall plant operation, including longer fuel cycle operation and uprating the rated thermal power output of the reactor, have been put in place to improve the efficiency of the nuclear power plant. Moreover, equipment replacement programs have been carried out at many plants to improve reliability and performance.

In an environment in which new operating phases coexist with both new replaced equipment and existent equipment, it is necessary to design and develop the I&C system based on a full understanding of plant operation practices, and to supply instrumentation systems capable of accurately monitoring a wide range of state conditions from the equipment level to the plant level and a primary control system that can control the plant appropriately in order to obtain maximum performance from the plant while ensuring that its operating state remains stable and highly reliable.

This article discusses recent trends in the operation of nuclear power plants, their relationship with I&C technologies, and what Hitachi is doing to meet the associated needs (see Fig. 2). The article also describes several specific I&C products and solution examples.

TRENDS IN PLANT OPERATION

The objective currently sought in plant operation is to achieve highly efficient operation with an adequate level of safety and reliability while also targeting improvements in economic performance through better efficiency, rationalization, and similar.

The following formula defines the capacity factor (availability) as an index of plant operational

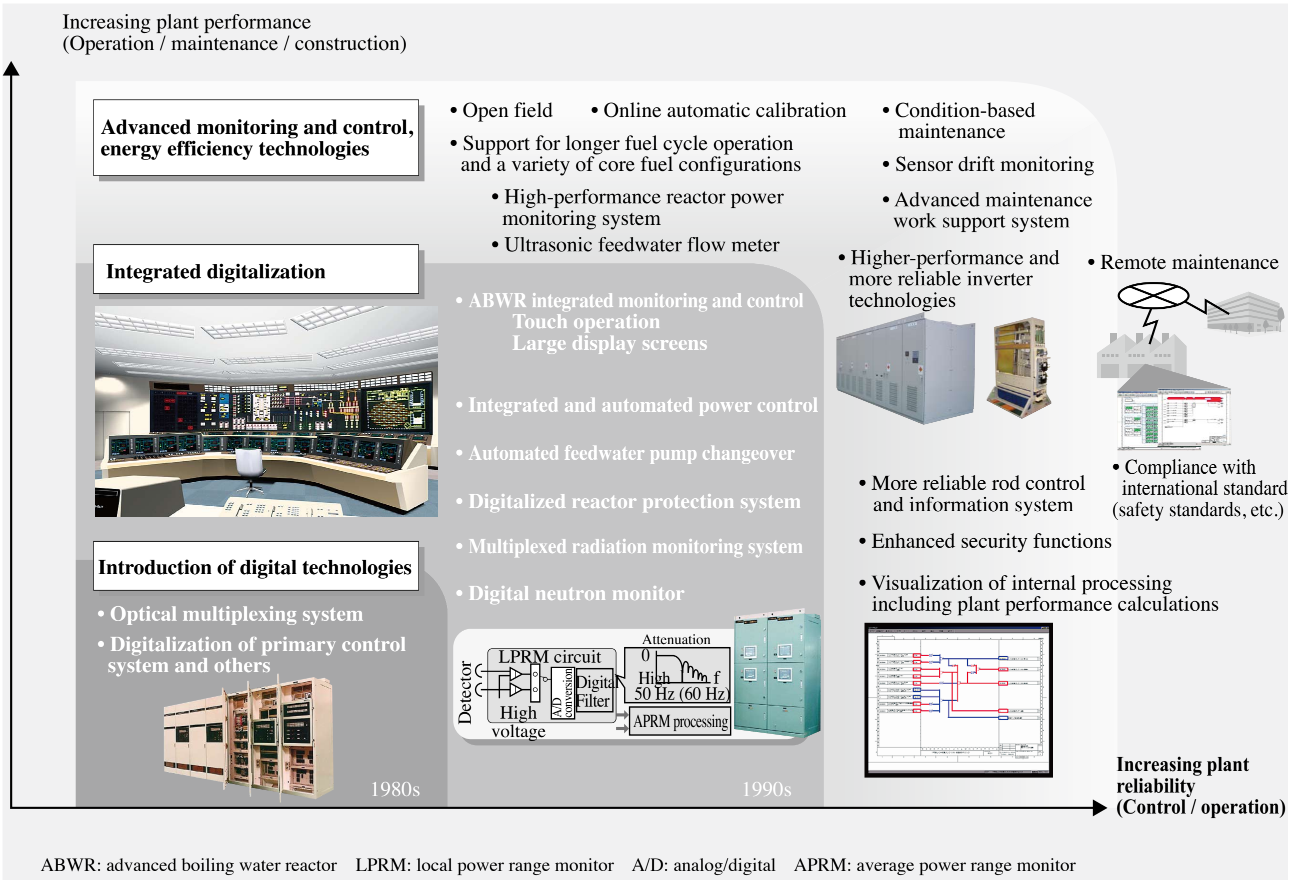

Fig. 2—Development of I&C (Instrumentation and Control) Technologies for Nuclear Power Plants.
Instrumentation and control technologies for nuclear power plants have been subject to ongoing improvements, including incorporating advances in digital control technology, with the aim of further improving reliability and performance.

$$\text{Capacity factor (\%)} = \frac{\text{Net electricity generated for the time considered (kW}\bullet\text{h)}}{\text{Energy that could have been generated (kW) at continuous full-power operation during the period (h)}} \times 100$$

performance:

Therefore, the higher the value of the numerator (the amount of electricity generated during the time period), or the longer the time during which electricity is generated, the greater the capacity factor, indicating that the plant is being operated at a high level of efficiency.

In general, if reliability of equipment is increased, then plant shutdowns at times other than the fuel outage period will become less frequent. Accordingly, the net electricity generated will increase and the capacity factor will improve. Other than improving equipment reliability, however, further improvement of the capacity factor requires drastic measures to change the basic operation of the plant. Key elements of this approach include: (1) longer fuel cycle operation, (2) power uprating, and (3) rationalization of maintenance. Fig. 3 shows the relationship between these measures in terms of time and power output.

The aim of longer fuel cycle operation is to extend the traditional operation cycle from about 13 months to a target of more than 18 months by fuel improvement and other measures. Power uprating means improving the electrical power output by operating the reactor with a higher level of thermal power output than that authorized when the reactor was originally approved. Although rationalizing maintenance involves a combination of different strategies, in terms of time and power output, the intention is simply to increase the net electricity generated for a certain period of time by shortening the fuel outage period by a reasonable amount. These strategies are not mutually exclusive and can be combined to achieve more effective and higher-performance plant operation.

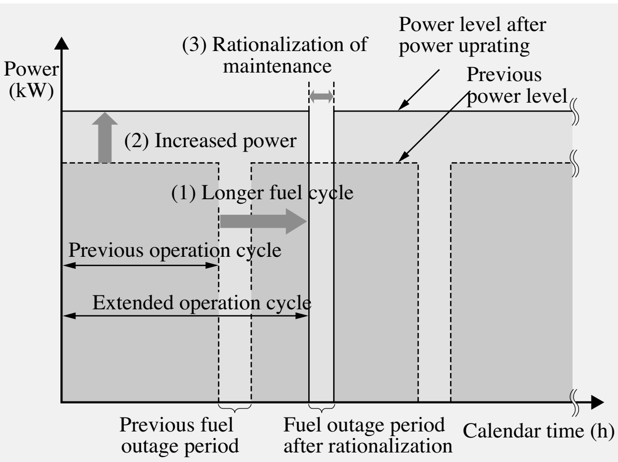

Fig. 3—Strategies for High-performance Operation.
The power axis represents the measures to improve power and the time axis represents improvements in the capacity factor of the plant through adopting longer fuel cycle operation and rationalization of maintenance. The area of the rectangular region enclosed by the operation cycle and the power during operation represents the product of power multiplied by time. Accordingly, larger areas indicate higher performance.

Along with the directly applicable technologies, which include fuel technologies for achieving longer fuel cycle operation and higher power output, and individual technologies for rationalizing maintenance and ensuring that specific units of equipment satisfy their specifications, implementing these strategies will also increase the importance of the I&C systems such as the primary control system.

In increasing power output, for example, because increasing power causes many power-related parameters (such as feedwater flow rate and steam flow rate) to increase also, the control parameters controlled by the primary control system will cover a wider range. The “normal operation state” referred to above will consequently be expanded, and the control range will therefore include operating conditions outside what has been experienced in the past. Because longer fuel cycle operation will tend to cause the absolute value of the void reactivity coefficient (one of the negative feedback gains associated with the core power) to grow, internal parameters that characterize the plant dynamics are likely to expand into new regions. For this reason, Hitachi has ideas that, in addition to improving the reliability and performance of the equipment associated with the primary control system, it is also necessary to provide technologies for analyzing plant dynamics and safety that can assess the operability and safety in these new operating regions, and monitoring technologies that can monitor operating conditions in the plant with high accuracy.

Based on these ideas, Hitachi has developed and installed systems that use the state-of-the-art information technology such as RFID (radio-frequency identification)(1) and supplied solutions for technical applications, including the development of I&C technologies for ABWR plants(2) (see Table 1). The following section gives examples of these solutions.

EXAMPLE SOLUTIONS

Supporting Technologies for Plant Performance Analysis and Plant Operation

APR simulation

One of the notable control algorithms used in the APR (automatic power regulator) is criticality control. Hitachi's criticality control algorithm uses period signals to switch between the "continuous," "sub-step," and "step" control rod withdrawal modes. In this control method, the control rod withdrawal sequence (the withdrawal sequence for the control rod group and the amount of withdrawal) is prepared off-line based on information on the characteristics of the core to be controlled. When actual control operation is invoked, the APR controls the withdrawal of the control rods as specified by this sequence using the rod control and information system based on the neutron flux signal and other process signals.

The key to the success of this control method lies in the advanced configuration and verification of the sequence. For this purpose, Hitachi has developed a three-dimensional, multi-energy group kinetic analysis code and a dynamics analysis code for the heatup of the reactor to rated temperature and pressure(3). These technologies were verified at the Shika Nuclear Power Station Unit No. 2 of Hokuriku Electric Power Company(4).

Table 1. Examples of Solutions for More Reliable and Higher-performance Plants

Application examples of solutions in individual technological fields are listed.

Technological field	Example
Supporting technologies for plant performance analysis and plant operation	• APR simulation • Plant operator training simulator
Advanced monitoring technologies	• High-performance reactor power monitoring system • Latest process computer
Technologies for higher performance	• High-performance inverter
Control technologies for higher reliability	• RIP-MFG system • Highly reliable control rod operation and monitoring

APR: automatic power regulator RIP: reactor internal pump
MFG: motor-fluid coupling-generator

Future core operation is expected to become complicated due changes expected in the near future including the adoption of mixed-fuel reactor cores using uranium-plutonium mixed oxide fuel, cores designed for longer fuel cycle operation, and power uprating. To cope with these changes, more sophisticated analysis methods are being used on the core. Considering these trends in core operation, Hitachi has developed a plant dynamics analysis technology that is an enhancement of the previous APR-related analysis technology. Fig. 4 shows example analysis results by the dynamics analysis code for the APR which is intended for use in the next generation plants. The results show that the analysis can reproduce the dynamics of the actual plant with good accuracy.

Plant operator training simulator

Safe operation of nuclear power plants requires not only improved reliability in machine systems but also more reliable human systems (such as training). Hitachi's latest plant simulator has the following characteristics and provides optimal equipment for plant operator training.

(1) Emulation of actual plant software logic

Hitachi has developed an emulation technology to run the same software logic, which is loaded on the digital controllers in the real plant control equipment, on PCs (personal computers) in real time. As the logic from the actual plant is used, detailed systems behavior including the HMI (human machine

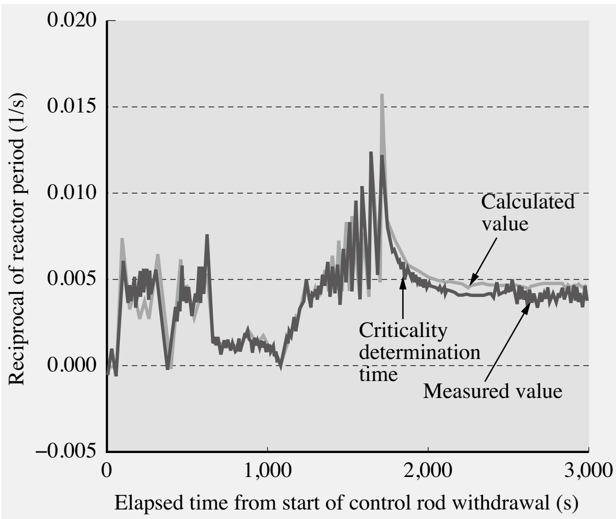

Fig. 4—Example Simulation of Criticality Control.
This graph shows a comparison between the measured and calculated values of the reciprocal of reactor period in the region around criticality and indicates that they are in good agreement.

interface) screen is precisely reproduced.

(2) Process simulation

Hitachi has produced a dynamics model that can reproduce plant behavior with a high degree of accuracy based on simulation technologies developed in the past. Used in combination with the plant software emulation technology in (1) above, the model can accurately reproduce the behavior of the plant being simulated.

Advanced Monitoring Technologies

High-performance reactor power monitoring system

The MUR (measurement uncertainty recapture) type uprating is one of the categories of methods for uprating power output defined by the U.S. Nuclear Regulatory Commission. The measurement accuracy of the reactor feedwater flow rate is a significant factor in the uncertainty of thermal power measurement. This method involves improving this accuracy and using the additional margin to justify an increase in the power output in a way that does not compromise safety. Hitachi has been looking at technologies for improving the accuracy of reactor feedwater flow rate measurement using ultrasonic flow meters since the late 1980s and has deployed the technology at various times in Japan(5).

In particular, Hitachi independently evaluated the performance of the chordal ultrasonic feedwater flow meter which has become the de facto standard for ultrasonic feedwater flow meters used for MUR-type power uprating in the USA, and is the only Japanese manufacturer to have installed the flow meters in actual plants. These meters are still in operation.

A welded structure called the "chordal spool" is a distinctive feature of the ultrasonic feedwater flow meter and requires high-level processing technology, not only to ensure the integrity of the welding, but also to meet the measurement accuracy requirements (see Fig. 5). Hitachi has established technology for spool manufacture through trial production of spools in expectation of future deployment in Japan.

The thermal power output is one of the parameters specified in the application for regulatory approval at plant installation. Once a license has been granted for the reactor to operate at its rated thermal power, appropriate monitoring and management of the thermal power level has a direct influence on the level of performance at which the plant operates.

Hitachi has established MUR-type power uprating as its ultimate goal. In addition to undertaking ongoing technical studies aimed at achieving this goal, the company also currently intends to include it as the core of its solution technologies for thermal power supervisory control in its range of advanced thermal power control technologies, integrated, for example, by incorporating it into the APR system described above.

Latest process computers

Process computers started as data loggers used to calculate plant performance and reactor core performance. Since the accident at the Three Mile Island nuclear power plant in the USA, however, their monitoring function has been significantly reinforced. In the 1980s, process computers also took on the role of supervisory control of the overall nuclear power plant as the highest-level device in the automation system, and this remains one of their functions. Recent years have seen the adoption of distributed control systems using general-purpose technologies in which the various servers, which are defined according to their roles, are connected over standard open networks. The latest process computer technologies are discussed below.

(1) Visualization of internal processing in process computers

On conventional process computers, users were not able to view the internal computational processing directly. However, a demand emerged to be able to display the process of internal computational processing to handle situations such as when the automation process was stalled for some reason or to check the operation of the plant

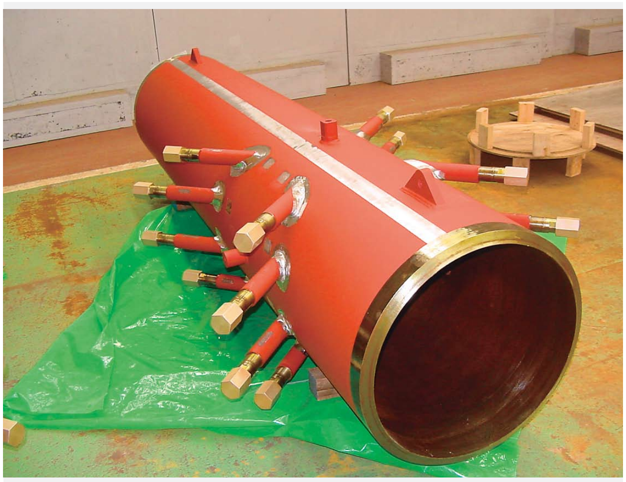

Fig. 5—Chordal Spool for Ultrasonic Feedwater Flow Meter.
This spool is girth-welded to the feedwater main pipe. Transducers for transmission and reception of ultrasonic wave are installed on the bosses regularly arranged around the both sides of the spool.

performance calculation. To satisfy this demand for "visualization" functions, process computers are now able to represent this computational processing in a human-friendly graphical language and display the progress of the processing on program diagrams.

(2) Security measures for important functions

The process computer systems that perform supervisory control of the nuclear power plant require a high level of security. The latest systems have enhanced security measures such as being able to set the security level independently for each function and only allowing users to perform operations that are permitted based on their security level which is obtained by IC (integrated circuit) card authentication.

Technologies for Higher Performance

Inverters that can operate at high efficiency even at low speed are widely used for motor control because of the significant power savings they provide. In BWRs, they are used for reactor recirculation pump motor control and have contributed to stable operation since their first application in actual plants in the early 1990s. Recently, a highly reliable high-voltage direct inverter that does not need an output transformer was developed for nuclear power applications and has completed factory tests (see Fig. 6).

In addition to providing redundancy in the control circuits, this inverter equipment allows use of main circuit backup systems (a single backup main circuit is provided for a number of different main circuits) to further improve reliability.

In the future, the technology is expected to expand its application in nuclear power plants in and outside Japan for equipment upgrades to existing BWRs and other purposes with the aim of reducing the in-plant load and improving maintainability.

Fig. 6—High-voltage Direct Inverter for Nuclear Power Applications.
Multiple cell inverters (photograph on right) are combined to drive the motor directly without requiring an output transformer.

Control Technologies for Higher Reliability

RIP-MFG system

A RIP-MFG system is a system in which a MFG (motor-fluid coupling-generator), which is already used in conventional BWRs, is used as the variable frequency power source for the RIP (reactor internal pump) in the recirculation flow control system which is an important part of the power control system in an ABWR[(6)].

The system configuration of the RIP-MFG system, which combines a variable frequency function with a buffer function for frequency perturbations caused by mechanical inertia, allows equipment to be rationalized without compromising tolerance of transient events. This system symbolizes Hitachi's uniqueness.

In the development of the RIP-MFG system in particular, Hitachi has engaged in a steady series of activities to ensure reliability and to address permit and license issues. These include various desk studies during the conceptual design phase, establishment permit safety analyses, the development of mechanical-electrical system interaction analysis code which was designed to simulate the combination of the RIP and MFG, and planning an integrated test for the actual machine at the factory prior to the delivery to the site.

As a result of this work, a factory integrated test for the RIP-MFG system to be incorporated into the Shimane Nuclear Power Station Unit No. 3 of The Chugoku Electric Power Co., Inc. was conducted in October 2008. The results showed a good agreement between the simulation results from previous preliminary studies and the dynamics of the actual machine (see Fig. 7).

It is expected that these simulation techniques and factory test data will improve the efficiency of the on-site pre-operational test and further improve reliability.

Highly reliable control rod operation monitoring

The rod control and information system controls and monitors the insertion and withdrawal of control rods, and is an important system that impacts directly on reactor power control. Hitachi has developed a highly reliable rod control and information system which has significantly reduced the number of parts and decreased the malfunction by using IMs (induction motors) in place of the step motors previously used in ABWRs to drive the control rods.

Because the system switches the power supply to the IM on and off to control the position of the control rods, the main technical issues for this system are the response speed of on-off control and how to reduce the noise that occurs at power supply switching. To resolve these technical issues, Hitachi used its ingenuity to satisfy the control specifications associated with noise and response speed by adopting a thyristor semiconductor device or SSC (solid state contactor) as the on-off control element (see Fig. 8).

As with the RIP-MFG system, an integrated test was carried out combining the control system with the IM-FMCRD (IM-driven fine-motion control rod drive system). The control characteristics were verified by analyzing the data acquired from the test.

By combining the results of this testing with the APR simulation technique described earlier, Hitachi also plans to evaluate the effect that the control rods have on the reactor output control characteristics when IM-FMCRD is used.

To improve maintenance, the system also allows users to view the status of the various subsystems from a central location by collecting data in a supervisory maintenance system via a high-speed optical network.

Fig. 7—RIP-MFG System for the Shimane Nuclear Power Station Unit No. 3 of The Chugoku Electric Power Co., Inc.
An integrated test was conducted after the actual system was assembled in the factory and connected to the RIP in the RIP test center used for RIP performance testing.

CONCLUSIONS

This article has discussed recent trends in nuclear power plant operation, how these relate to I&C technologies, what Hitachi is doing to satisfy the associated requirements, several specific I&C products, and example solutions.

Hitachi's I&C technologies have been continuously developed in various different ways through the experience it has gained since the completion of the first ABWR, including the completion of the Hamaoka Nuclear Power Station Unit No. 5 of Chubu Electric Power Co., lnc. and the Shika Nuclear Power Station Unit No. 2 of Hokuriku Electric Power Company (a full-plant ABWR), and the construction of the Shimane Nuclear Power Station Unit No. 3 of The Chugoku Electric Power Co., Inc.

Specific examples of this work include the development of the advanced simulation technique for the APR and new process computers as well as the successful integrated test of the RIP-MFG system.

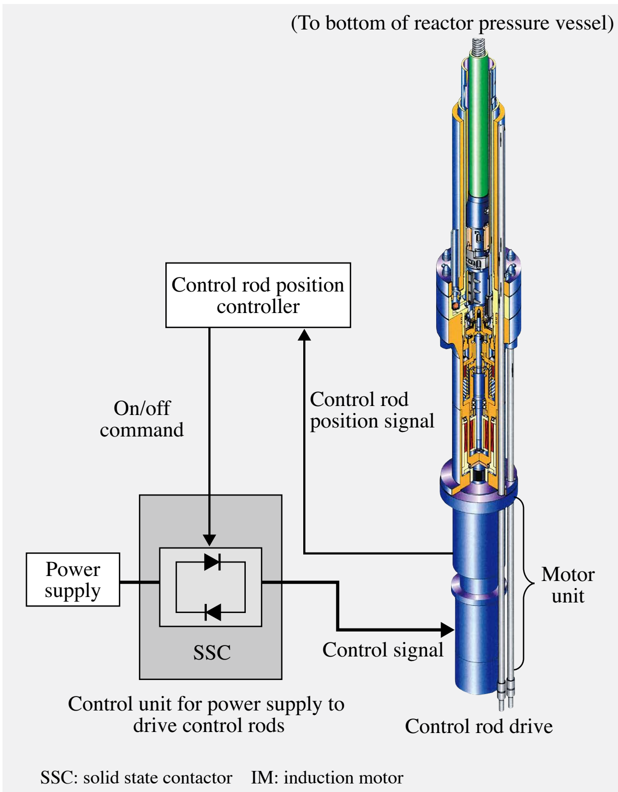

Fig. 8—Structure of IM-driven Control Unit for Control Rod Operation Monitoring System.
Control rod position control is performed by switching the power supply to the IM and brake on and off at the appropriate timings by sending commands to the SSC.

I&C technologies involve the latest IT (information technology) and are subject to rapid technological innovation, and particular skills are required to keep up to date with these trends while also producing products that are acceptable to the nuclear power industry.

Based on the belief that I&C technologies are critical products serving as the brain and nervous system of nuclear power plants, Hitachi will follow its tradition and contribute to society by ensuring the safe, stable and high-performance operation of nuclear power plants by developing new technologies and supplying solutions.

REFERENCES

(1) K. Onda et al., "Development of Advanced RFID Application Systems for Nuclear Power Plants," Hitachi Review **57,** pp. 254-261 (Oct. 2008).
(2) T. Seiji et al., "Advanced Supervisory and Control Systems for Nuclear Power Plants," Hitachi Review **50,** pp. 79-83 (Aug. 2001).
(3) Y. Ishii et al., "Plant Simulation System for Developing ABWR Automatic Power Regulator System," Journal of Nuclear Science and Technology **46,** No.1 (2009).
(4) F. Yoshimori et al., "Evaluation of Start-up Test for Shika Nuclear Power Plant Unit No. 2," 2006 Fall Convention of Atomic Energy Society of Japan (Sep. 2006) in Japanese.
(5) S. Hasegawa et al., "Experience and Accuracy Evaluation on High-accuracy Ultrasonic Flow Meter for Reactor Feedwater in Hamaoka Unit No. 5," Chubu Branch, Thermal and Nuclear Power Engineering Society (Mar. 2008) in Japanese.
(6) A. Mizuide et al., "The Application of Motor Fluid Coupling Generator to the Power Supply of Reactor Internal Pump," ICONE 9 (Apr. 2001).

ABOUT THE AUTHORS

Shin Hasegawa, Dr. Eng.

Joined Hitachi, Ltd. in 1995, and now works at the Control & Instrumentation Design Section, Nuclear Plant Control & Instrumentation Engineering Department, Hitachi-GE Nuclear Energy, Ltd. He is currently engaged in instrumentation and control planning for nuclear power plants. Dr. Hasegawa is a member of the Atomic Energy Society of Japan (AESJ) and The Society of Instrument and Control Engineers.

Tatsuto Sugiura

Joined Hitachi, Ltd. in 1994, and now works at the Nuclear Power Control and Instrumentation Systems Engineering Department, Information & Control Systems Division, Information & Telecommunication Systems. He is currently engaged in the design of monitoring and control equipment for nuclear power plants. Mr. Sugiura is a member of the AESJ.