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An Intelligent Human-Machine Interface for Next Generation Nuclear Power Plants

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Abstract

The intelligent human-machine interface (HMI) has been developed to enhance the safety and availability of a nuclear power plant by improving operational reliability. The key elements of the HMI are the large display panels which present synopsis of the plant status and the compact, digital work stations for the primary operator control and monitoring functions. The work station consists of four consoles such as a dynamic alarm console (DAC), a system information console (SIC), a computerized operating-procedure console (COC), and a safety related information console (SRIC). The DAC provides clean alarm pictures, in which information overlapping is excluded and alarm impacts are discriminated, for quick situation awareness. The SIC covers a normal operation by offering all necessary plant information and control functions. In addition, it is closely linked with the DAC and the COC to automatically display related system information under the request of these consoles. The COC aids the operator with proper emergency operation guidelines so as to shutdown the plant safely, and it also reduces his physical/mental burden by automating the operating procedures. The SRIC continuously displays safety related information to allow the operator to assess the plant status focusing on plant safety. The proposed HMI has been validated and demonstrated with on-line data obtained from the full-scope simulator for Yonggwang Units 1, 2.

I. Introduction

A nuclear power plant (NPP) has been developed under the principles pursuing safety as the most important goal from early year of development because of the release of radioactive materials. One of the principles is "proven technology" which is that all technologies related to safety of an NPP should be validated and verified at the same or related industries. This important principle has contributed to enhancement of NPP safety, of course. However, from early 1980s, it has been recognized that NPP designers cannot adopt remarkably progressing new technologies, especially computer science, digital control, human engineering, and artificial intelligence, properly because of the "proven technology" principle. TMI accident demonstrated that various and much information using alarm tiles, indicators, and control devices more than a few thousands may influence negative effects on NPP safety. Therefore, the necessity to develop a main control room (MCR), which is simpler and easier to operate, has been increased.

According to this necessity, large programs on advanced control rooms (ACRs) are underway in the active areas: the Nuplex 80+ developed by ABB-CE, [1] the main control room (MCR) of N4 developed by Framatome, [2] the MCR of AP600 developed by Westinghouse, [3] the advanced boiling water reactor (BWR) control room developed by international team of BWR manufacturers, [4] the MCR for next generation pressurized water reactors (PWRs) developed jointly by Japanese five PWR utilities and Mitsubishi group, [5] an Integrated Surveillance And Control System (ISACS), which has been developed as a part of the OECD Halden Reactor Project. [6]

In those MCRs, digital technology and automation enable one or two operators to operate an NPP in a normal state. In addition, human factors are incorporated in the design of control room layout and information presentation. However, several issues should be addressed for the ACR design including (1) reliability problem of a digital system, (2) information hierarchy problem, and (3) user-machine problem. There are no obvious solutions for these issues and each country should address these problems to fit in their characteristics. In this paper, an intelligent human-machine interface (HMI) will be proposed which is designed for Korean operators by addressing the above issues.

II. Layout of Human-Machine Interface

The proposed HMI consists of four large display panels (LDPs), two operator work stations, one supervisor work station, one safety advisor work station, and one auxiliary control station, as shown in Fig. 1. The LDPs are placed on the front walls of the MCR and present operating staffs with common information to be shared in order to prevent a lack of communication, to increase competence as an operating crew, and to maintain a normal state without other information sources. Two operator work stations can be used independently, but all monitoring and control functions for plant operation can be executed on a single operator work station. The major role of supervisor work station is to provide the proper coordination and direction of control operation. It is until two operator work stations fail to function that supervisor work station is employed for plant operation. Safety advisor work station is equipped for a safety advisor, a technical advisor, and other operating crews who will participate in operation in an emergency state. A hardwired auxiliary control station exists between two operator work stations to bring the plant to safe shutdown and keep it there, under all operating conditions, in case of the unavailability of the controllable work stations.

III. Development Strategies of Intelligent Human-Machine Interface

III.1 Plant Status Monitoring and Control

The LDPs present dynamic display of key operating information. This key information was selected on the basis of following criteria: (1) Should the information be monitored in "electricity generation," "safety," and "residual heat removal" respect? (2) Should the information be grasped before the operator starts his tasks after operating crew's shift? and (3) Should the information be frequently used during plant operation? According to those criteria, following key information is displayed on the LDPs: critical function alarms related to plant safety and performance, system alarms, key operating variables, operating margin, plant performance parameters, and operator's sharing information.

The SIC displays piping and instrumentation drawings (P&IDs) to provide the operator with system information required for status monitoring. The operating status of equipment, active paths, and necessary operating variables are dynamically displayed in the P&IDs. The plant information was organized in a four-level hierarchy, as shown in Fig. 2. On the basis of this hierarchy, success paths are also provided on the SIC for the operator's quick recovery action. Success paths are a kind of map that bridges from systemic level to functional level to inform the operator of the plant functional status. A control action is performed using soft control after equipment/component to be controlled is selected on a P&ID, which provides a good sense of control because the effect of a control action is displayed on the same P&ID so that the operator can confirm feedback from the plant. The SIC is closely linked with the DAC and the COC to present related P&ID information under the request of these consoles.

The SRIC continuously displays safety related information that is essential for plant safety. If the usage of the SIC is impossible because of earthquake or other causes, equipment-level monitoring and control functions are carried out on the SRIC.

III.2 Alarm Processing

In order to provide necessary information effectively in the CRT-based alarm system, alarm information should be organized hierarchically and generated alarms should be processed. The hierarchy is an inherent characteristic of a large process plant and serves functional abstraction of the plant physical status. From this point of view, all the alarms were organized in a four-level hierarchy in the DAC as shown in Fig. 2, together with the additional, six critical safety function alarms. The hierarchy was established on the basis of the physical and functional importance of alarms to show the propagation of alarm impacts from equipment level to plant functional level.

Alarms are generated following "dark board at power" concept and the number of alarms generated is reduced by applying signal validation before alarming and by providing dynamic setpoints contingent on applicable operating mode. After individual alarms are generated, unnecessary alarms for acquiring and understanding plant behavior are eliminated followed by the suppression of less important alarms. Finally, the residual alarms are prioritized.

The DAC assigns one of three discrete priority levels to individual alarms according to urgency of recovery actions and severity of their impacts. For the dynamic prioritization, system-oriented prioritization is performed followed by mode-oriented prioritization. And then, individual alarm priority is determined by synthesizing system-oriented priority with mode-oriented priority. System-oriented prioritization aims to identify the importance of the alarm within the system to which it belongs. In this step, the importance of the system itself in plant function is not considered. Mode-oriented prioritization aims to identify the importance of the system to which the alarm belongs in current operating mode because its importance is dynamically varied depending on operating modes.

III.3 Automation of Operating Procedure

The hard copy operating procedures exist for virtually all aspects of reactor operation including emergency response. These procedures written sequentially, however, may not be possible to implement in the situation that many complex knowledge-based tasks should be performed simultaneously. Because of that, the computerized procedure system, COC, has been developed.

Each step of operating procedures is composed of perception, judgment, and control. Because a perception is to simply detect parameter values or equipment/component status by the human sensory systems, there are no qualitative portions in this task. Therefore, a perception was readily automated as a kind of soft automation. Judgment is mainly a cognitive action to compare current states with predetermined states in operating procedures. Quantitative judgment can easily be automated because it has deterministic characteristic. In the case of automation of qualitative judgment, fuzzy logic is used to evaluate qualitative rules by adopting the algorithm embedded in the Operator Aid SYStem (OASYS). [7]

The information processing model developed by Rasmussen was utilized to decide the level of hard automation during procedure execution. [8] The three categories of skill-, rule-, and knowledge-based behaviors were chosen based on the model. To distinguish skill- and rule-based behavior from knowledge-based behavior, task-verb analysis was performed. Table I shows the classification of three kinds of behavior in the EOPs using task verbs. In Table I, there is no conflict in automating skill- or rule-based tasks because only binary states are possible. So, skill- and rule-based tasks were automated with the operator's intervening opportunity in the procedure execution at any time if necessary. On the other hand, in the case of knowledge-based tasks, there are several technical problems such as software reliability in automating the tasks. Therefore, manual control is more appropriate in knowledge-based tasks, so long as proper information is provided. On the basis of this philosophy, the kind of information, that would be provided during knowledge-based tasks, was determined.

IV. Validation and Conclusions

As the result of abnormal and emergent event simulation, the number of alarms displayed was reduced by ~59% on the average. In addition, the proposed HMI provides the operator with clean alarm pictures for the earlier termination and mitigation of an event even when there are enormous alarm influxes in the conventional alarm system. The time response for completing the required actions under emergency conditions was observed to evaluate the effect of the intelligent HMI on the operator's performance during the SGTR scenario. The result shows the operator using the hard-copy EOPs is ~27% later than the operator using the HMI in stabilizing plant conditions, as shown in Fig. 3. This time reduction was achieved by automating skill- and rule-based tasks and by providing proper information timely for knowledge-based tasks. In conclusion, a key advantage of the proposed HMI would be its capability to support intelligent decision making by the operator in the whole spectrum of reactor operation, especially in interpretation and planning in non-routine situations such as handling plant disturbances.

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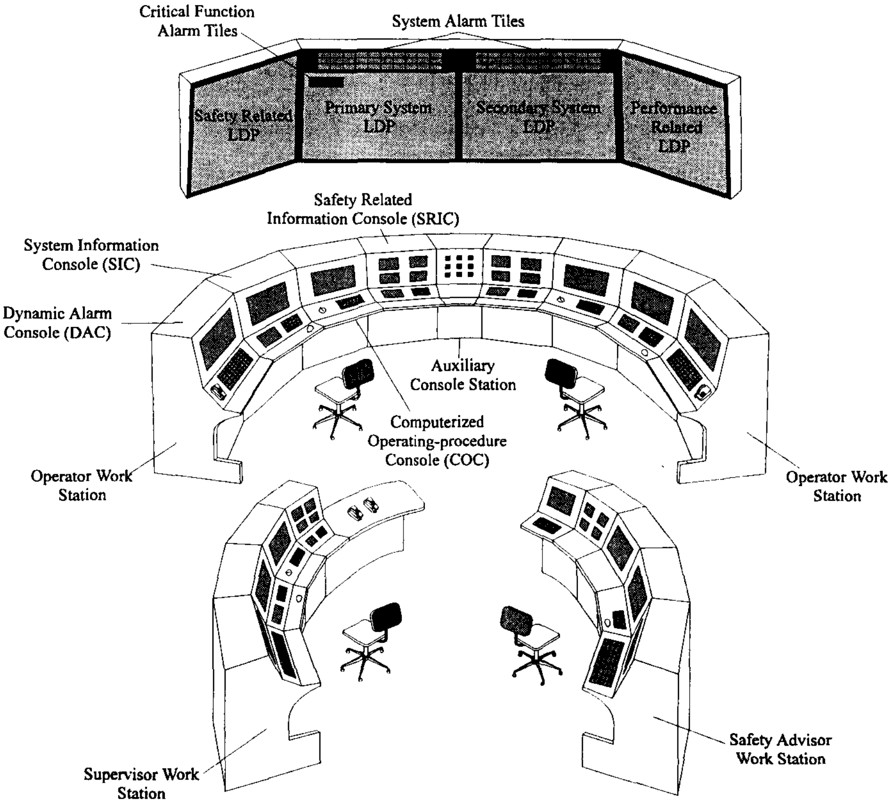

Fig. 1. Intelligent human-machine interface overview

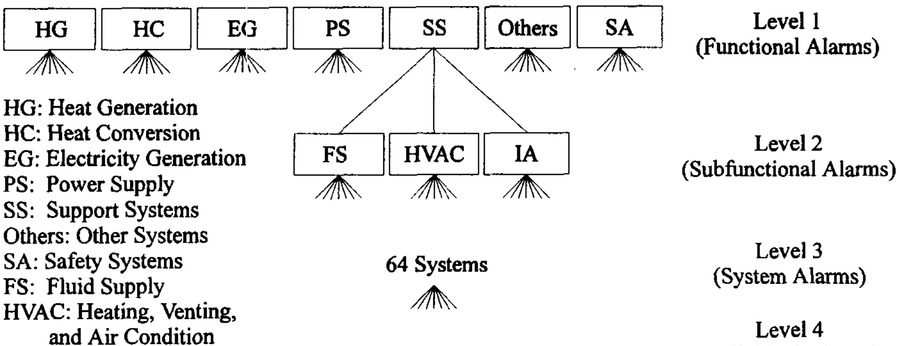

Fig. 2. Hierarchical structure of plant information

Table I. Classification of the operator's behavior in the EOPs

Category	Task
Skill- or Rule-based Behavior	Restore power to all AC emergency busses Load equipment on busses (D/G) Energize/Deenergize detector Transfer nuclear recorders to source range scale Shutdown unnecessary equipments Actuate letdown, charging, makeup, boration, feedwater, component cooling water, safety injection, residual heat removal system, etc. Open/Close valves Start/Sop pumps Start/Sop diesel generator Start/Sop fans Turn on/off pressurizer heater Actuate engineered safety feature signal Perform steam dump
Knowledge-based behavior	Cooldown RCS temperature Depressurize RCS pressure Maintain SG level Maintain pressurizer level Depressurize SG pressure

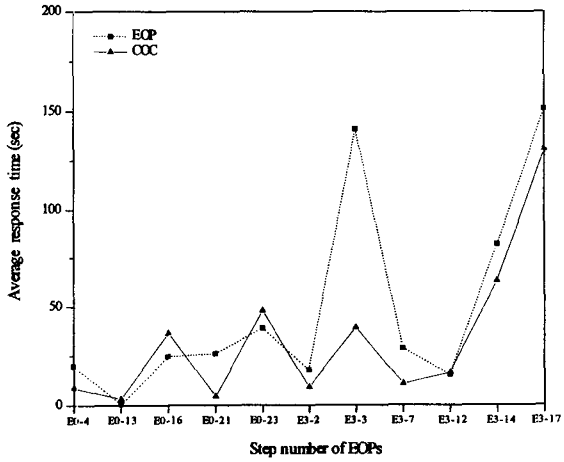

Fig. 3. Operator's average response time at the SGTR scenario