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Assessment of Signals Reliability for Instrumentation and Control System for Nuclear Power Plants

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Abstract
Since digital technologies have been improved, the analog systems in nuclear power plants (NPPs) have been replaced with digital systems. Recently, new NPPs have adapted various kinds of digital instrumentation and control (I&C) systems. The digitalized Instrumentation and Control system can provide more powerful overall operation capability, and user friendly man machine interface. The operator can obtain more information through digital I&C system. However, while I&C system is the heart of the nuclear power plant, three issues are encountered: (1) software common cause failure, (2) the interaction failures between operator and digital instrumentation and control system interface, (3) the non detectability of software failure. These failures might defeat defense echelons, and make the Diversity and Defense in Depth (D3) analysis be more difficult. These three weak point are more related to I&C system signals reliability. The I&C system consists of 30 sub-systems lies in 183 I&C cabinets, which are analyzed and mapped to the sub-systems. As reliability of systems and signals is considered one of the most important safety design requirements, this paper is a deep and comprehensive analysis to I&C sub-systems signals reliability. That paper presents an assessment to the reliability of Instrumentation and Control system "I&C" signals of a nuclear power plant. This reliability assessment is based on analyzing the Instrumentation and Control system using top down approach.

1. Introduction

Nuclear power plants (NPPs) rely on I&C systems for protection, control, supervision and monitoring. A typical unit has approximately 10 000 sensors and detectors and 5000 km of I&C cables. The total mass of I&C related components is on the order of 1000 tonnes. This makes the I&C system one of the heaviest and most extensive non-building structures in any nuclear power plant. No globally comprehensive statistics are available on the numbers of plants with fully analog, fully digital or hybrid I&C systems. However, approximately 40% of the world's 439 operating power reactors, accounting for nearly all of the 30 countries with operating NPPs, have had some level of digital I&C upgrade to, at least, important safety systems. From another perspective, 90% of all the digital I&C installations that have been done have been modernization projects at existing reactors. 10% have been at new reactors. Of the 34 reactors currently under construction around the world, all of those for which construction began after 1990 have some digital I&C components in their control and safety systems.

In order to group the I&C systems, we define a category for the high level I&C

systems by applying the diversity and defense-indepth (D3 in short) criteria. The I&C systems are implemented in the form of cabinets. So, it is necessary to figure out how many cabinets exist and where they are installed. After investigating the I&C cabinets, we map the cabinets to the systems. Finally, each system and cabinet is analyzed in terms of a signal interface between them. With this analysis, we can figure out a relationship between the systems. This paper presents the results from performing these procedures by means of presenting an overview of the I&C systems.

We can find an introduction to the I&C systems of Nuclear Power Plants from IAEA-TR-239 (1984) and IAEA-TR-387 (1999). These reports deal with many items such as the overall I&C requirement, concept, instrumentation, safety and control functions, control room, design and so on. These reports also present examples of I&C systems from some countries in annexes. The examples are introductory and conceptual.

It has been a generic approach to classify systems and equipment in a NPP into safety-related functions and non-safety-related functions. The I&C systems and equipment related to performing safety functions are classified into electrical class 1E (1E in short) and the non-safety systems and equipment into electrical non-class 1E (N1E in short). These terms are defined in IEEE Std. 100 (2000). By applying the D3 criteria to the design of I&C systems, as shown in NUREG/CR-6303 (1994), a control system (CS), a protection system (PS) and a monitoring system (MS) are required as a minimum to maintain the plant in a safe state.

The CS not only controls the plant automatically into a desired state but also provides a means to supportmanual controls. The CS should be designed to minimize a demand for the activation of the PS. The CS is categorized into a process control and an on–off control.The process control determines a certain range of values for afinal actuation signal through a predefined algorithm. The on–offcontrol simply sends a two-state signal to a component such as avalve, pump, fan, damper, etc. based on the combination of a commandfrom other I&C systems or the operators. Since we do notcredit the CS in mitigating a design bases event (DBE), it is classifiedinto an N1E system.

The PS basically provides two functions: one is to shut downthe reactor by interrupting the power to the control element drivemechanism (CEDM) and the other is to actuate the engineeredsafety features (ESF) systemsby initiating the ESF actuation systems(ESFAS) signals to the systems. These functions are automaticallyand continually operating in order to limit the consequences of certainplant accident conditions. The PS is required as a 1E system. As a diversemeans to mitigate the event of an anticipated transient withouta scram, a diverse protection system (DPS) is provided as an N1Esystem.

The MS monitors the status of the NPP and alerts the operatorto take an action corresponding to the plant status. For this, thereare various monitoring systems in the NPP. They usually conveyinformation and alarms to the video display units (VDUs) and printers.There are a 1E MS and an N1E MS. The 1E MS is designed for apost-accident monitoring, so it should withstand both during andafter a DBE. The N1E MS is designed to effectively and efficientlyaid the plant operators to safely operate the plant by promptly providingthe plant information encompassing all of the plant statusesincluding normal and abnormal operation modes, so it is huge andcomplex [1,2].

The basic function of an I&C systemis intrinsically separated intothree parts: receiving signals, processing logics, and outputting signals.It is obvious that all the I&C systems intrinsically contain thesethree parts in each system. There are dedicated cabinets,called process instrumentation cabinets, to collect rawsignalsfrom the process instrument transmitters that are spread all overthe plant. They convert the signals into a proper range of signals anddistribute them to the PS, CS, MS and indicators in the main controlboard (MCB) and remote shutdown panel (RSP). These cabinets collectand distribute most of the process instrument signals such asthe temperature, pressure, flow, level, etc. There are other specialcabinets to collect specific signals such as the in-core and ex-coreneutron flux and RCP speeds. So, we need to define an instrumentationsystem (IS) to group the cabinets and systems that receiveand process the input signals.

2. Nuclear Power Plant Instrumentation and Control System

Used in virtually all systems of an NPP, instrumentation and control “I&C” may encompass more then ten thousand devices per plant. Though the cost of I&C equipment comprises only a small fraction of an NPP”s total capital equipment in a plant. Nuclear facilities such as power reactors, research reactor, fuel fabrication, and spent fuel storage facilities use temperature, pressure, and radiation sensors to monitor, control, and protect plant safety.

Together with a chain of electrical and electronic components and dozens of cables and connectors, a sensor makes up what is known as an instrumentation channel. Part of instrumentation channel is normally located in the process a harsh environment and the rest resides in instrument cabinets usually located in an air conditioned room in a mild environment. For example, in the case of a temperature sensor, the sensor itself, its thermo well, junction box, cables, and connectors are in the field. The same is true for pressure and different pressure sensors, which are normally connected to the process using sensing lines. Each sensing line typically includes isolation and equalizing valves, condensation pots, check valves, snubbers, and other components. Likewise, the transmitter and its electronics, the cables and connectors that bring the pressure signal from the transmitter to the instrument cabinets in the control room area, and the core exit thermocouples and ex-core flux monitors, all are continually subject to the heat, humidity, radiation,

temperature cycling, vibration, and other taxing influences of the environments.

Nuclear Power Plant Instrumentation and Control Systems consists of four major parts: Reactor Instrumentation System, Reactor Control System, Safety Protection System, and Monitoring System [3,4].

2.1. Reactor Instrumentation System

2.1.1. Instrumentation Skeleton Outline

The reactor monitors the major parameters in the operation condition of the NPP, such as the neutron flux, the position of control rods, the differential pressure in the core, the coolant temperature at the hot plenum and fission products from failed fuel.

2.1.2. Instrumentation Design and Process

It has been a generic approach to classify systems and equipment in a NPP into safety related functions and non safety related functions. The I&C systems and equipment related to performing safety functions are classified into electrical class, and the non safety systems and equipment into electrical non class[10]. The overall diagrams of Instrumentation system is shown in fig. 1.

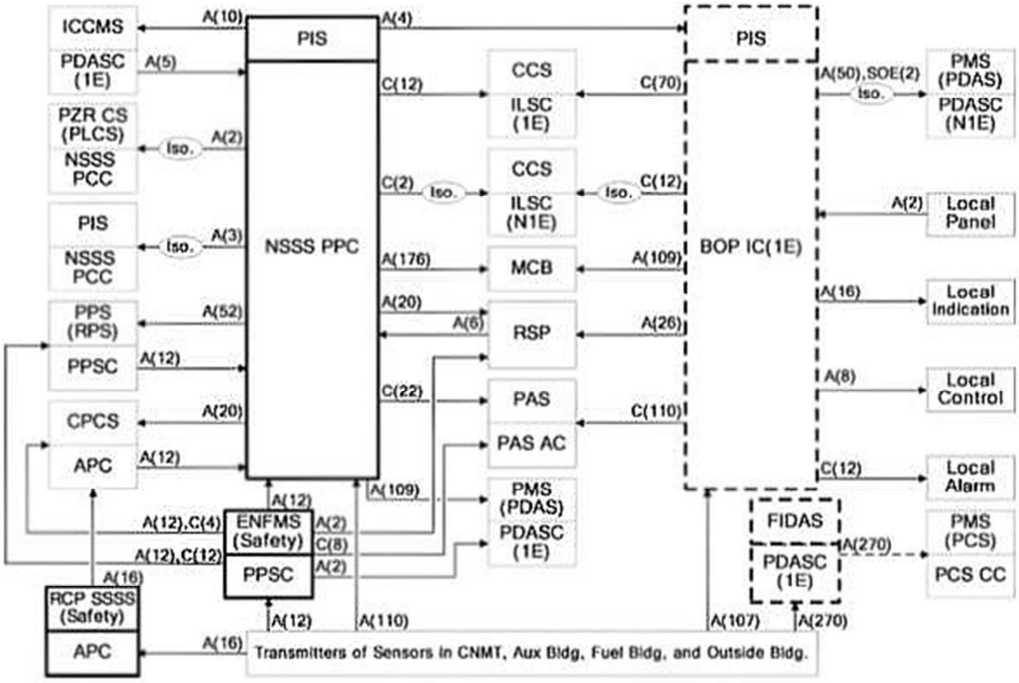

Fig. 1. *The Signal interface of the Instrumentation System*

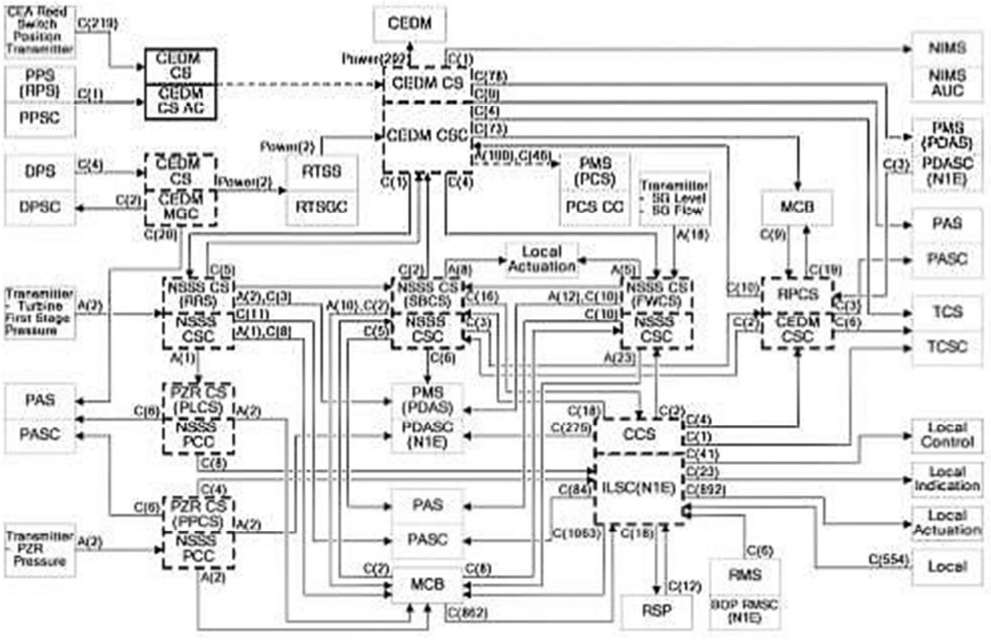

Fig. 2. *The Signal interface of Control System*

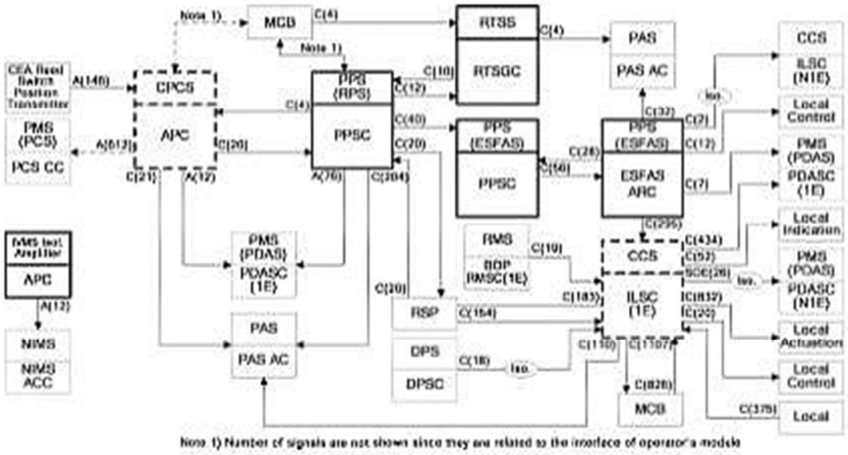

Fig. 3. *The Signal Interface of Protect System*

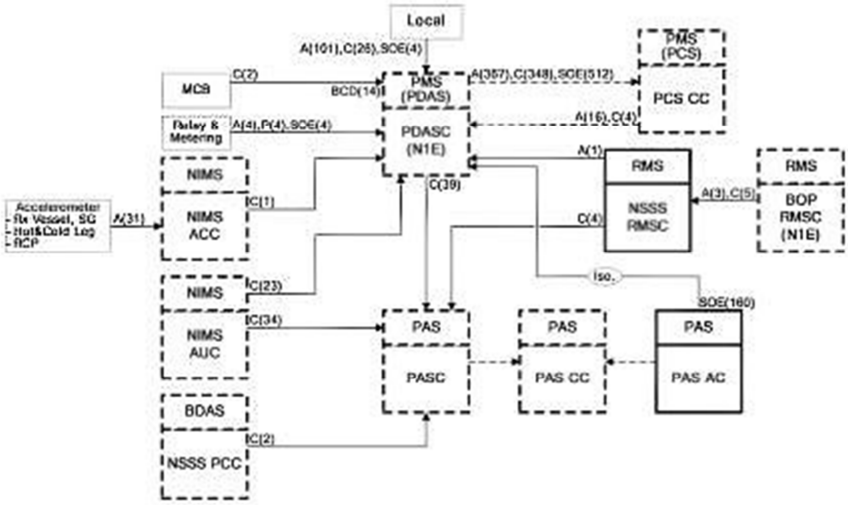

Fig. 4. *The Signal Interface of Monitoring System*

The control rods position instrumentation monitors the position of 16 pairs of control rods. The position of control rods is measured by the encoder sensor in the control rod drive mechanism and the signal from this instrumentation is used for the reactor control system.The core differential pressure instrumentation detects a decrease in primary coolant flow in the reactor core. Also, it measures the differential pressure between the inlet and outlet of the core, and the signal from this instrumentation is used for the safety protection system.The fuel failure detection system detects the failure of coated fuel particles by detecting short life fission products. The initial failure fraction in the coating layer of the coated fuel particles shall be less than 0.2% in terms of the sum of heavy metal contamination.

The process instrumentation system “PIS”:acquires most of the process signals such as temperature, level, pressure, flow, etc. It also acquires signals from the I&C systems and transmits them to other I&C systems, as a messenger, for some process signals, the PIS checks their set point. There are many process signals that are not acquired by the PIS, these are directly acquired and processed by the systems that require them.

There are three dedicated systems for processing specific signals: an ex-core neutron flux monitoring system “ENFMS”,fuel building emergency ventilation actuation signal “FIDAS”, and a reactor coolant pump “RCP”, we will discusses the function of them in details:

1. Ex-Core Neutron Flux Monitoring SystemENFMS: provides ex-core neutron flux information through three kinds of channels: four safety channels, two start up channels, and two control channels. They safety channels provide information that represents the range of 10^{-7}% thro ugh 200% full power acquired from the fission chamber to the I&C systems as shown in fig. 1. Especially, the safety channels A and B are capable of monitoring the flux for 182 days after a loss of coolant accident or min steam line break. The start up and control channels are non-safety channels. The start up channels acquire maximum 2000 counts per second from the boron trifluoride proportional counter and the control channels acquire maximum 125% operating range from the uncompensated ionization chambers. These channels provide the acquired information to the I&C systems.
2. Fuel Building Emergency Ventilation Actuation Signal FIDAS: provides in core neutron flux information by

acquiring microampere signals from the in core neutron flux detectors and converting them to voltages. The fixed in core detectors are self powered rhodium neutron detectors and consist of 45 detector string; each string has five rhodium neutron detectors and one background detector, for a total of 270 detector signals. One fixed in core detector string and core exit thermocouple is insulated within a same cable. It is capable of providing a low impedance to the detector and an over voltage protection at the input terminal to prevent the in core detector from over charging when the signal processing circuitry is disconnected. It also filters the signals to eliminate a signal noise. It's signals are sent to the PCS for monitoring a statues of the in core see fig. 1.

3. Reactor Coolant Pump RCP: provides speed information by acquiring a radio frequency from proximity probes attached to the RCP shaft, converting it to a pulse signal, and sending to other I&C systems.

2.2. Reactor Control System

The control system of NPP consist of an operational mode selector, a reactor power control system and a plant control system. Microcomputers are used for the plant control system and the reactor power control system. An operational mode selector supervises them.

2.2.1. Control Skeleton Outline

The reactor power control device consist of a reactor power control system and a reactor outlet coolant temperature control system. The reactor power and reactor outlet coolant temperature control systems are cascade connected: the latter is an upper control system to give demand to the power control system. It also designed to specify the operational condition, such as the demand of the control system and the reactor scram point of instrumentation.

2.2.2. Control System Design and Function

It consist of several systems, andwe will discussesthe function of most of them in details:

1. Reactor Protection System RPS: reactor protection system automatically regulates the reactor power to follow the turbine load changes by keeping the main steam pressure and reactor coolant average temperature T_{avg} within the programmed values by means of a reactivity control by utilizing the control element drive mechanism "CEDM". It receives the T_c and hot leg temperature T_h from NSSS to calculate the T_{avg}, neutron flux from the reactor monitoring system "RMC" to calculate the reactor power, and the turbine first stage pressure as the turbine load index. It sends the T_{avg}, power and index to the SBCS and FWCS. Also, it send the following signals to the CEDM:
   - A CEA motion command for maintaining the T_{avg}, automatic withdrawal prohibit command due a high deviation of the T_{avg} from a specified reference, and an automatic motion inhibit command due to a CEA deviation.
   - It sends the $T_{avg}$to the PLCS;
   - It sends the information and alarms to the PCS via the PDAS.
   - It provides a status, record and manual control means for the MCB.
2. Steam Bypass Control System SBCS: Steam bypass control system follows a load rejection of any magnitude including a turbine trip from 100% power and a loss of one of two operating feedwater pumps without tripping the reactor or lifting the "PZR" safety valves, by regulating the steam flow, controlling the pressure, generating a turbine bypass demand signal, or initialing the "RPCS".
   - It sends a "CEA" command whenever the reactor power falls below 15%;
   - It also provides a means for manually controlling the reactor coolant temperature during a plant heat up and cool down;
   - It receives the PZR pressure and steam header pressure signals from the "NSSS", a condenser available signals from the "BOP", and turbine bypass permissive signals from "MCB".
3. Feed water Control System FWCS: feed water control system maintain the SG water level by regulating the feedwater flow rate with other control systems in the event of a reactor trip, loss of one of two operating feedwater pumps and a high SG down comer water level.
   - It receives the SG water level, steam flow, total feedwater flow and down comer feedwater flow signals from the transmitters.
   - It receives a neutron flux signal from the RPS to transfer low and high power level control modes and a T_{avg} for post trip feedwater control.
   - It also receives the reactor tripped signals from the "CEDM".
   - It sends the steam flow signals and reactor tripped signals received from the "CEDM" to the "SBCS".
   - It sends signals related to the steam and feedwater to the "MCB" and "PDAS".
   - It sends alarms to the "PAS" and "PDAS".
   - It provides a manual control capability for the "MCB".
4. Reactor Power Cutback System RPCS:reactor power cutback system responds to a minor plant perturbation[7,8].
   - It responds to large plant imbalances such as a large turbine load rejection, turbine trip or loss of one of two operating feedwater pumps.
   - It generates signals to the "CEDM" to drop a pre selected numbers of " CEA", which result in a rapid reactor power reduction.
   - It conjunction with the "SBCS" sends signals to the "TCS" to rebalance the turbine and reactor power following an initial reduction in the reactor power as well as to restore the steam generator water level and pressure to their normal values.

5. Turbine Control System TCS: turbine control system is a complex and total system that provides functions for controlling, protecting and monitoring components related to a turbine operation. The control and protection functions are performed by the three redundant modular microprocessors installed in the "TCSC". They output actuation signals to the turbine based on a 2-out of 3-voting logic[9].
   - The control function controls the speed and load of turbine, the limit of the main steam pressure, load runback and setback, and a megawatt feedback, with four operating modes: a backup in emergency cases, semi automatic for a manual, automatic to follow targets, and a remote by a dispatch system.
   - The protection function protects the turbine from an over speed, power load unbalance, and an intercept valve trigger.
   - It sends "SOE" signals to the "PDAS".
   - The monitoring function is performed by the computer in the "cc".
   - It displays information and controls equipment via the plasma touch panel and "VDU".
6. Computer Control System CCS: computer control system controls most of the motor operated components in the plant by receiving process signals from the PIS, statues from the components to be controlled, and commands from the I&C systems, MCB, and RSP via the HL. However, specific components such as the CEDM,PZR heater and spray, turbine and feedwater pumps are not controlled by the "CCS" but by the modulating CS dedicated to these components.

2.3. Safety Protection System

The safety protection system consist of the reactor protection system and engineered safety features actuating system. The reactor protection system ensures the integrity of the core and reactor coolant pressure boundary under abnormal operational conditions. The engineered safety features actuating system prevents fission products from being released into the environment due to an accident, such as a rupture of the primary concentric hot gas duct.

2.3.1. Safety Protection System Skeleton Outline

The reactor protection system inserts the control rods into the core to ensure the integrity of fuel and protect the reactor coolant pressure boundary under abnormal operating conditions. The logic circuits of this system have two trains, which receive the signals from the reactor and process instrumentation, and send the signals in case of reactor scram.

The engineered safety features actuating system sends the signals actuating the engineered safety features, such as the isolation valve of containment vessel, the auxiliary cooling system and the emergency air purification system. The engineered safety features protect the reactor, the reactor coolant pressure boundary and the containment vessel boundary, and prevent large amounts of fission products from being released outside the reactor facility. This system consists of logic circuits having two trains, which receive the signals from the reactor and process instrumentation, and actuates the engineered safety features.

2.3.2. Safety Protection System Design

The RPS protects the reactor core and coolant pressure boundary and the "ESFAS" prevents a radioactive material release to the environment. The "PPS" receive four redundant signals for the PZR pressure, SG level of pressure and differential pressure, containment pressure, and refueling water tank level from the "NSSS". It receives four redundant neutron flux power signals from the "ENFMS". The "RPS" and "ESFAS" perform a similar logic as follow:

- receiving four redundant signals from the NSSS,PPC and ENFMS, determining the pre trip and trip condition by comparing them to predetermined fixed and variable trip set points in the bistables, and generating an initiation signal with a 2 out of 4 coincidence logic.
- The RPS sends the initiation signal to the "RTSS", and the "ESFAS" to the "ARC".

The logic trains of the reactor protection system are set with two parallel systems and each logic trains is connected to the circuit breaker with two series. Each logic train sends a signal in case of a reactor scram independently.The signals isolating the containment vessel activate to close the isolation value of the containment vessel in order to prevent fission products release in a depressurization accident. These signals also activate to stop the air supply and exhaust in the ventilator and air conditioner in the reactor building system and to start up the emergency air purification system.

The signals starting up the auxiliary cooling system, which are the signals for a reactor scram, active to start up the auxiliary cooling system so as to remove residual heat in case of a reactor scram except for the case of the depressurization accident or an auxiliary heat exchanger heat transfer tube rupture accident.The signals isolating the auxiliary cooling water line activate to stop the auxiliary cooling system and to close the valve of the containment vessel connected to the auxiliary heat exchanger and the valve of the primary coolant pressure boundary connected to the primary helium purification system.

CPC, core protection calculator receive four redundant signals for the PZR pressure, T_c , and T_h from the PPC, CEA positions from the RSPT, RCP speed from the SSSS and the neutron flux power from the ENFMS.It sends the CWP signal to the PPS for the following events:

- DNBR pre trip; LPD pre trip;
- CEA group out of sequence or sub group deviation;
- RPC, CEA deviation within sub group.

The RSPT power supply modules reside in the CPCS. The four CPC operator's modules are located in the MCB. Each module consists of a plasma display unit with a touch screen, pushbuttons, function keys and indicator lights to display parameters and statuses, support a change of constants and enable a trip bypass.

2.4. Monitoring System

Standard core monitoring System are designed with an emphasis on normal of Nuclear Power Plant. Their purpose is to provide necessary support for reactor operators and other operating personnel during the fuel cycle. After each fuel reloading, and to the larger extent during the plant commissioning, a variety of start up tests need to be carried out and evaluated. For technical reasons, the access to standard monitoring systems is very limited. Non standard measurement and evaluation systems are highly specialized devices designed with an emphasis on start up tests performance and evaluation. They are capable of high frequency sampling processing and communication of hundreds of technological signals with required accuracy and low communication delay.

2.4.1. Monitoring System Skeleton Outline

Although not absolutely essential to plant operation, the function of the Radiation Monitoring System is to monitor radiation levels at selected plant locations. If these levels exceed predetermined normal or safe values, alarms are activated and in some cases automatic protective functions initiated. Thus the system serves to:

- Warn of any radiation health hazard
- Give an early warning of a plant malfunction
- Initiate automatic protective functions.

The computer collects data from many locations within the plant and then processes it to provide a variety of information:

- To enable the operator to have a good understanding of the plant's operation as he needs it for making decisions.
- To provide a historical record to the plant's engineering staff to help analyze the plant's operation and for permanent record retention.
- To help analyze malfunctions and help plan the recovery from significant malfunctions.

2.4.2. Monitoring System Design

It consist of several systems, and we will discusses the function of most of them in details:

1. Plant Monitoring System PMS: plant monitoring system, receives thousands of signals from the I&C systems, computes various and complex logics, and sends the calculated results to the VDUs and printers in the MCR and offside facilities including the EOF. It plays a major role in providing the plant operation staff with a bulk of plant information.
2. PRMS: monitors the gross and specific isotope gamma activities of the primary coolant in the chemical and volume control system and sends the monitored data to the RMS to display it on the VDUs.
3. PCS: promptly provides wide range and in depth plant information to the operators through VDUs. The information is provided by displaying, alarming, logging, reporting, trending, recording and retrieving historical data, etc. The PCS processes more than eight NSSS applications such as the critical function monitoring system, core operating limit supervisory system, and CEA monitoring system, RPC application, PPS and CPC channel deviation monitoring system, data snapshot application, etc. The COLSS calculate the reactor power with a more sophisticated algorithm than that of the CPCS, while the CPCS calculates it with a simple and fast algorithm. The PCS processes the BOP application to monitor the performance the BOP systems. The PCS consists of hot standby dual computers, mass data storage devices, display generators, input/output switch boxes and so on. Only one of the dual computers sends display information to the display generators via the input/output switching boxes. Each computer contains and processes about 9000 points in the database including input points from the PDAS and calculated points by the applications in the PCS.
4. ALMS: the alms monitors the occurrence of a fluid leakage by detecting a high frequency caused by the leakage. For this, the 16 acoustic emission sensors installed in the leakage are of the SGs, reactor, hot and cold leg, and RCP and 3 accelerometers installed in the PZR safety valve send signals representing a series of waves caused by a leakage of fluid or gas to the ALMS preamplifiers in the containment. The NIMS alarm unit interfaces with the preamplifiers to acquire the signals and then performs a signal conditioning such as an amplification, band pass filtering and root mean square calculation, and compares them to their set point for an alarm initiation. It provides alarms not only to a local panel of the cabinet but also to the PDAS and PAS.
5. LPMS: It monitors the presence of loose parts inside the primary and secondary side of the reactor coolant system by detecting an impulse caused by these parts. For this, the 12 accelerometers installed at the lop and bottom of the steam generator and the reactor send signals representing a series of waves caused by the presence of loose parts of the LPMS amplifier in the containment. The MINS alarm unit interfaces with the preamplifiers to acquire and process the signals. When the CEA moves, the LPMS module in the NIMS alarm unit inhibits an alarm, by receiving the signals for the CEA movements from the CEDM. The NIMS analysis computer interfaces with the alarm unit to receive alarm pulse signals and then the NIMS analysis computer validates them and activates the alarms when validated. It also controls a gain and band pass of the NIMS alarm unit.
6. PAS: It receives alarm contact signals from the I&C systems and indicates the alarm conditions by lighting alarm window tiles located in the MCR. It also sends the alarm conditions to the VDUs and printers. There are about 600 lamp box windows and 260 status windows in the MCR. The windows are colour codes to alert operators to important alarms by adopting a prioritization system: red for first priority, amber for second, white for third and blue for an ESF actuation. There is also a device for an audible alarm. It also displays alarm information on the VDU in the control room.

3. Conclusion

The advanced I&C design concept and requirement can be referred to in Maillart (1999). However, a paper that introduces an overall implementation of I&C systems is rarely found. This paper has value in presenting an overall implementation of the I&C systems without omitting the I&C cabinets. The 30 I&C systems are implemented in 183 cabinets. In order to deliver an overviewof the I&C systems, this paper applies the criteria ofD3and the top-down approach to group the I&C systems and then maps the cabinets to the systems. These were found to be a proper way to establish an overview of the I&C systems and their implementation.

Based on the top down approach, a reliability assessment ofthe I&C signal in presented in this paper. As I&C of NPP has 30 sub-systems mapped into about 183 cabinets, signal between such huge number of cabinets may be lost, changed, conflicted, interfered with other signals, or generated before or after the required time. These signals problems affect the whole I&C reliability and consequently system safety.

The contribution of this paper is an assessmentto the signals reliability based on the analysis to sub-systems inter-relation in different cabinets to stress weak points in design to enhance the whole I&C reliability.This paper also presents an interface between the systems and the cabinets. The number of interface signals between them is not precise in this paper because changes are always occurring in the plant, but the numbers show the complexity of the interface. The results of the interface analysis will be used for upgrading the I&C systems. This paper shows a proper method for analyzing these I&C systems.

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