Design of Electrical Human Performance Optimization Training Facility

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1. Introduction

Performance improvement of nuclear power plant (NPP) personnel through training is crucial for maintaining plant safety and reliability. Achieving high level of workforce competency promotes quality and safety culture in meeting the objective of eliminating incidents/events resulting from human errors. Thus, the purpose of this study is to define the requirements and design the facility for the Human Performance Optimization (HPO) training of NPP electrical workforces.

2 Analysis of Design Requirements for HPO Electrical Training Facility

According to the licensee event reports(LER) and failure modes and effect analysis (FMEA) report, human error is about 60% of the electrical and I&C failures in the nuclear power plants (See Table I). This result and Ref.[1,2] also support the importance of human performance optimization.

2.1 General Design Requirements

The HPO electrical training facility shall be designed to meet the measurable objectives of the HPO training plan and manual [3]. The HPO Facility shall be designed to perform representative operation of the medium voltage (MV) motors for the engineered safety feature actuation systems (ESFAS) [4]. The operations shall include normal, abnormal and emergency conditions. Provision shall be made for monitoring and recording trainee's actions during interaction and training session with the HPO facility.

2.2 Functional Design Requirements

The HPO training facility shall functionally and physically be an exact replica of the actual 'MV motor protection and control system' in the plant. The functional, performance and interface requirements of the actual 'MV motor protection and control system' shall apply to the HPO training facility. The actual plant operating procedures for normal, abnormal and emergency conditions shall be applicable to the HPO training facility. The training facility shall be configurable so that abnormal scenarios and fault conditions observed in the actual plant can be simulated with the HPO facility for training purpose [5]. The training support system (TSS) shall be designed as part of the HPO training facility and shall be used to monitor the status of all the MV motor protection and control system [6].

3. Design of HPO Electrical Training Facility Design

The types of accidents were classified by analyzing NRC's electrical equipment-related event records reports over the past 20 years. Based on the results of the survey and design requirements, functions and specifications required for HPO training facilities were defined and designed accordingly.

3.1 Analysis of Electrical Failure Records

The NRC Licensee Events Report [LER] from 2000 to 2020 was analyzed [7,8]. A total of 200 electrical failures were extracted and classified according to their causes. The results are shown in Table I and Fig.1.

Table I: Cause of Failure and Occurrence Frequency

S/N	Cause of Failure	Frequency of Occurrence	%
1	Human Error	114	57.0
2	Component Failure	55	27.5
3	Inadequate Maintenance Procedure	6	3.0
4	Inadequate Procedure	5	2.5
5	Inadequate Design	5	2.5
6	Environmental Transients	4	2.0
7	System Failure	2	1.0
8	Natural Phenomenon	2	1.0
9	Lack of Understanding	2	1.0
10	Undefined	5	2.5
	Total	200	100

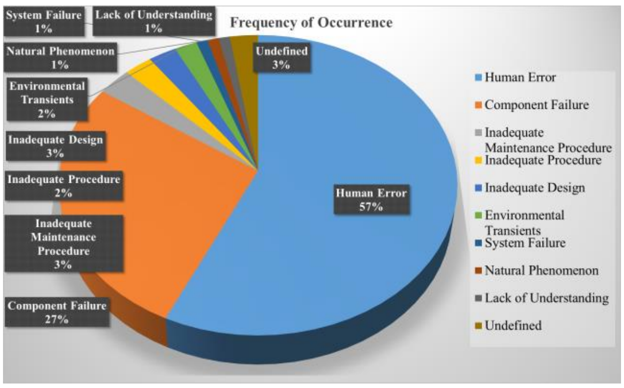

Fig.1 Cause of Failure and Occurrence Frequency

3.1 System Architecture and Functions

The HPO electrical training facility consists of electrical distribution system, electrical control and monitoring system (ECMS) and training supervisor station (TSS). The electrical distribution system is sub divided into 4.16kV switchgear (SWGR) and 408V load center (LC). The 4.16kV switchgear consists of one incoming feeder and two outgoing feeders. One of the two outgoing feeder furnishes power to 4.0kV medium voltage motor and another furnishes power to 480V LC. The incoming feeder receives 4.16kV power through a disconnection switch through a 22.9kV/4.16kV step down transformer. The 480V LC consists of one incoming feeder and four outgoing feeders. Two of the four outgoing feeders supply power to 460V motors. Remaining two outgoing feeders supply power to non-motor loads. One is the feeder for 480V-380/220V step down transformer and another non-motor feeder is a spare feeder. The ECMS consists of digital integrated protective relays and control and monitoring computer including network cables and control and monitoring program. TSS is a part of the HPO training facility and consists of computer and training program. TSS is out of scope of electrical training facility [9].

The HPO training facility is the functional and physical replica of the actual '4.16 kV power distribution system for medium voltage (MV) motor and non-motor load system' in the plant. The training facility shall have similar equipment layout arrangement with the actual system and have no new Human Factors Engineering (HFE) issues that may impair training and cognitive skill development.

The HPO Facility shall be designed to perform representative operation of the medium voltage (MV) motors for the engineered safety feature actuation system (ESFAS) systems. The operations shall include normal, abnormal, and emergency conditions. Provision shall be made for monitoring and recording trainee's actions during interaction and training session with the HPO facility. Safety class of the electrical HPO training facility is non-class 1E.

3.2 Technical Specification

The 4.16kV SWGR consists of main bus, incoming feeder and outgoing feeders. All feeders are equipped with a vacuum circuit breaker (VCB) and digital protective relay. The current transformers (CT), voltage transformers (VT), zero sequence current transformers (ZCT) and surge suppressor (SS) are provided for each feeder as required. Each feeder is protected by dedicated relay, and VCB is controlled and monitored from ECMS.

The 480V load center (LC) is fed from the 4.16kV SWGR and supply power to 460V motor load and 480V non-motor load. The 480V LC consists of main bus, incoming feeder and outgoing feeders. The incoming feeder and one outgoing feeder are equipped with air circuit breaker (ACB). The outgoing feeder equipped with ACB supply power to 460V motor; greater than 60hp and smaller than 250hp. Remaining outgoing feeders are equipped with molded circuit breaker (MCCB) and supply power to the motor load not greater than 60hp or non-motor load not greater than 100kW. The actual plant operating procedures for normal, abnormal and emergency conditions are applicable to the HPO training facility. The 480V motor drives the lubrication pump of the 4.0kV motor. So the feeder breaker of 460V motor and the feeder breaker of 4.0kV motor shall be interlocked. The training facility is configurable so that abnormal scenarios and fault conditions observed in the actual plant can be simulated with the HPO facility for training purpose. Additional provisions are made on the training system design for interface with a Training Supervisor Station (TSS). The TSS is designed as part of the HPO training facility and used to monitor the status of all the MV motor protection and control system. The TSS is designed to perform HPO training system control functions including initiation of system fault conditions [10].

3.3 Design Verification and Validation

After design the HPO training facility verify the design document whether the requirements are fully satisfied by the design documents [11]. Requirements can be classified into measure of performance (MOP) and measure of effectiveness (MOE) [12]. Then validate the operational requirements and other requirements than technical requirements.

The HPO training system control functions of the TSS include:

- Work instructions
- Protective relays set point modification
- Voltage level control
- Events monitoring and recording
- Fault conditions initiation

Provisions shall be made for seeding and simulating the hardware fault conditions in each component and module in the HPO MV motor protection and control system training facility. The modules include; component control (CC), sequence control logic (SCL) for circuit breaker, integrated motor protection relay (MPR), electrical control and monitoring system (ECMS). The hardware fault conditions include:

- Power supply failure or degradation
- Over load
- Short circuit fault
- Open circuit fault
- Ground fault
- Component Failure

The design shall allow for the following software fault conditions to be seeded and simulated in the ECMS, and MPR modules:

- Logic failure
- Out-of-range operating parameter
- Digital processor failure
- Loss of communication

The design shall provide for human errors to be demonstrated during:

- Start and stop of motor
- Reacceleration of motor
- Trouble shooting
- Set point modification
- Fault reset
- Component repair or replacement
- Design vulnerability tracking
- Review and confirm of discrepancy between drawing and installed component

4. HPO Electrical Training Scenario

The scenarios provided in the training manual include the representative functional failure behavior of the MV motor protection and control system [13]. The scope covers the training assignments for the members of the training group identified in the HPO facility Hands-on Evaluation Plan which comprises the instructor, evaluator, and the trainees (Team leader, Worker A and Worker B).

4.1 Role Play Training (RPT)

For the evaluation items specified in Appendix A Table II, the operator's human performance (situation awareness, work load, etc.) is measured and controlled using HPO facilities to properly maintain and achieve operation and maintenance in the role-playing practice. The electrical HPO training program is conducted in English to improve personnel performance in preparation for overseas dispatch. Participating personnel are:

- Evaluators: HPO expert, ergonomic expert
- HPO Instructor
- HPO training facility evaluator

4.2 Equipment used

- HPO training equipment
- Video/Audio Recorder
- Time meter

4.3 Evaluation Tool

- SART (Situation Awareness Technique) [14]
- NASA-TLX (National Aeronautics and Space Administration Task Load Index) [15]
- BARS (Behaviorally Anchored Rating Scale)[16]
- Questionnaire on inconsistencies in human performance and current evaluation issues

4.4 Practice and Evaluation

The general evaluator explains the overall evaluation requirements for the purpose, method and points to be noted to the HPO subject immediately before the evaluation begins. Evaluation assistants are educated on human performance, the practice and evaluation methods required for this evaluation.

After a certain period of time, various situations are developed according to the planned scenario, and the trainees perform the operation according to the situation of the HPO training facility. In the process of the trainee performing driving actions according to the scenario, the evaluator records the specific matters while observing the trainee (action, conversation, etc.) with the current issues of the evaluation in mind.

If the general evaluator determines that all measures for the planned scenario have been completed, the evaluation is completed, by distributing situational awareness, workload and a questionnaire to the source.

4.5 Debriefing

After collecting the questionnaire filled out by the trainees, the evaluator and the trainees gather together to use the completed questionnaire to perform debriefing on the evaluation issues. When performing debriefing, the evaluator prepares and organizes the matters related to the problems related to the HPO facility equipment. This is after conducting an in-depth discussion on the evaluation issues by referring to the matters written by the evaluator, questions and questionnaires of the evaluator.

4.6 Practice Scenario

The scenario is written so that representative operation and maintenance tasks of HPO facilities can be performed using cases of sudden stoppage of representative 4.16kV MV motor protection and control systems and incidents of ECMS failure. It is used to develop a scenario for HPO training facilities by analyzing cases of emergency stop due to failure of electrical facilities of nuclear power plants at home and abroad derived from licensee event report (LER) and operation performance information system (OPIS) statistics, types of electrical failures and derived cases of shutdown investigations and failure types. The list of HPO verification facility scenarios is as sown in Appendix A Table II.

5. Conclusions

As shown in Table I, human-related events are the cause of more than half of the electrical faults in nuclear power plants. Accordingly, the purpose of this study is to improve the performance of electrical personnel working in nuclear power plants. This paper elaborates the process and results of design of electrical training facility for HPO. The electrical training facility for HPO was designed according to systems engineering approach for the fulfillment of stakeholder requirements.

According to the analysis of electrical equipment failure cases and human error cases, breakers, emergency generators and motors accounted for more than 50% of the frequency in both cases [17]. That's why the medium voltage motor protection and control system was selected as an HPO training facility. Until now, individual device-level training or test facilities have been used by utility companies to train operation and maintenance personnel. However, this HPO training system is an exact replica of the actual medium voltage network in nuclear power plants.

Acknowledge

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Appendix A , Table II: List of verification for HPO facility scenarios

SN	Fault Condition	Scenario	Method
1	Ground fault in the motor feeder cable by insulation failure	Vacuum Circuit Breaker(VCB) for motor feeder trip	Manual
2	Surge Arrester(SA) grounding failure	Motor feeder VCB open by ground fault relay trip.	Manual
3	Motor overload	VCB trip by overcurrent relay	TSS
4	Short circuit in the switchgear bus or feeder cables	Incoming feeder VCB trip or branch feeder VCB trip	TSS
5	Overvoltage or under voltage of switchgear bus	Motor stop by feeder breaker trip or fail to motor start	TSS
6	Circuit breaker stuck and motor over temperature	Motor feeder VCB do not open then incoming feeder VCB trip.	Manual
7	Circuit breaker's trip or closing coil open	Motor feeder VCB is not opened or closed.	Manual
8	Loss of DC power source for the circuit breaker control circuit	Motor feeder VCB is not controlled and protective relays loose power.	TSS
9	Switchgear's VT fuse open	VCBs are all tripped by undervoltage relay activation. But measured bus voltage is normal	Manual
10	Lubricant oil pump interlock circuit open	Motor was started but lubricant pump is not operating. Then motor is tripped by over temperature	Manual /TSS
11	Misconnection of the CT for differential current relay	Fail to motor start without fault in the motor. Bus voltage is normal	Manual
12	Component Control System circuit error	Switchgear and motor circuit is normal but motor is uncontrollable.	TSS
13	Poor coordination of overcurrent relays	Incoming and branch feeder VCB trip simultaneously.	TSS
14	Improper relay setting	Motor feeder VCB trip without over load/over current.	TSS
15	Discrepancy between drawing and installed components	Relay setting was conducted according to the drawing. But relay is tripped without any fault.	Manual & TSS
16	Reclosing of VCB without reset of field lockout relay	After repair reclosing is impossible	TSS