Transient Simulation and Performance Analysis of KALBR Simulator for PFBR Operator Training

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Abstract—Transient Simulation and Analysis is the most important phase in the integrated performance testing of a Full Scope Replica Operator Training Simulator. Transient Analysis is performed as per ANSI 3.5 standard to analyze the dynamic behaviour of the simulated process models. The degree of accuracy of the models is checked before the deployment of the simulator. This paper deals with Transient Analysis with respect to Steam Water System (SWS) of Kalpakkam Breeder Reactor Simulator for the event originating from the interconnected sub systems and the associated components. The dynamic behaviour of SWS in response to one primary pump trip and one BFP trip is analyzed in this paper. It discusses about the methodologies adopted to capture the simulated parameters, comparison of test results and the associated system dynamics with respect to each affected sub system. It also covers verification & validation process, tuning and implementation of simulator for training purpose.

Index Terms—Full scope operator training Simulator, Human error, KALBR-SIM, Nuclear Power Plant, Prototype Fast Breeder Reactor, Transient Analysis and Safety Control Rod Accelerated Movement.

I. INTRODUCTION

The use of Full Scope Training Simulator has become an essential element of the operator training programme as a means of minimizing risk and improving the performance of the operator. Every effort is on towards improving the safety of the plant by improving the knowledge and the skill set of the operators. Statistical analysis and experience in plant operation indicate that human error is the main cause of concern for most of the accidents that take place in the nuclear power plant. The Full Scope Training Simulators are used to provide a comprehensive training and retraining on full spectrum of the plant including normal operation, reactor startup operation, abnormal and emergency conditions of the plant. Apart from the training on normal operation, the ability to train the operator on accident conditions that are critical to the plant safety using training simulator is gaining more importance in the present scenario. Essentially, the simulators are built with process models with high accuracy to replicate the actual situation of the plant under both normal and abnormal conditions.

At the international level, concentrated effort is being made to reduce the human error through improved plant monitoring and control system, Human Machine Interface (HMI) system, well documented plant
procedures and efficient information management system. Here, the Operator Training Simulator plays a significant role in developing various skill sets required to operate the plant and thus enhancing the operational ability and minimizing the human error [8]. In the actual power plant, the operator rarely gets the opportunity to carry out the diagnosis on plant conditions and apply the emergency operating procedure following an incident or event (i.e. abnormal condition). The Full Scope Training Simulator provides a platform to try, operate and experience such emergency situations towards improving the performance of the operators. Such knowledge enhancement could be possible only with the introduction of Full Scope training simulators in the training program.

II. BRIEF DESCRIPTION ON KALBR-SIM

KALBR-SIM is a Full Scope Replica Operator Training Simulator, built to replicate Prototype Fast Breeder Reactor (PFBR) in order to train the operators. (Refer Fig.1 for details). It is an engineering product designed and developed by synergizing the effort of all the system experts available in the related areas at Indira Gandhi Centre for Atomic Research (IGCAR). The main objective is to provide a Virtual Control Room environment to operate, practice and train the operators on all possible reactor states and apply normal & emergency operating procedures wherever required. It also facilitates conducting transient/scenario based training to study and understand the plant dynamics.

III. BRIEF DESCRIPTION OF PROTOTYPE FAST BREEDER REACTOR (PFBR)

Prototype Fast Breeder Reactor (PFBR) is a 500 MWe capacity, pool type reactor, utilizing sodium as the main heat transport medium. The reactor core consists of fuel sub assemblies made up of (Uranium, Plutonium) mixed oxide fuel. The heat transport system consists of primary sodium circuit, secondary sodium circuit and steam water system. Steam and water system employs once through type steam generators producing super heated steam at very high temperature & pressure and adopts a reheat and regenerative cycle using live steam for reheating. Fig.2 shows PFBR flow sheet. Energy conversion and transfer is done through Electrical System using 500 MWe capacity Turbo Alternator set with a plant efficiency of 40% [1]. The process simulation details are derived from the Prototype Fast Breeder Reactor systems. The scope of simulation for operator training purpose has been drawn based on the past operational experience and general training requirements.

IV. BASIC REQUIREMENTS FOR A TRAINING SIMULATOR

Building a training simulator needs certain fundamental requirements to be fulfilled with respect to system requirements and resources (Refer Fig.-3). 1. The very purpose for which the Training Simulator is to be developed i.e. Training Requirements. 2. The availability of human resource i.e. the domain experts based on system design & analysis and operational experience and modeling experts with adequate knowledge to build the models. 3. Providing the supporting systems in terms of Hardware and Software platforms using which the process models can be developed i.e. Computer based Development Platform. 4. The Training platform on which the developed models can be ported installed and commissioned. It includes providing an environment exactly matching the plant Main Control Room to impart training to the operators on various
events with respect to the plant states. It is called replicated control room. 5. The final one is a strong Verification and Validation team of experts to qualify the models for the intended purpose. The experts are required to guide and evaluate the models with respect to the reference plant which is mandatory to meet the training requirements. Here the Fig.4 refers to Training Platform on which the operators can be trained.

V. HARDWARE AND SOFTWARE ARCHITECTURE

The physical components of Hardware Architecture comprises of Control Panels, Operator Information Consoles, Input/Output systems, Instructor station, Simulation Computers, Simulation Network and Power Supply & Distribution system. The Simulation Computer executes various mathematical models of reactor sub-systems in real time[5]. It takes the input from Control Panel and Operator Console through I/O Systems, processes them and responds by giving the information to I/O system for display on indicator/meters, recorders and raise alarms in real time. The training simulator Control Panels are replica of the Plant Control Room Panels made up of mosaic tiles with grid structure. The Operator Console caters to overall monitoring of the plant using the most important and frequently used signals and controls. (Refer Fig-4)

The software architecture is depicted in Fig.5. The software architecture of simulator consists of four major components namely, process modeler, logic modeler, virtual panel modeler and instructor Module. The Process Modeler is used for developing process models, Logic modeler is for developing system logic circuits, Virtual Panel (VP) Modeler is for developing Virtual Control Room Panels for monitoring the
simulated process parameters and the Instructor Module is for creating plant related scenarios and run the simulator to train the operators.

All other modules are supporting modules like MDSM (Messaging and Data Sharing Mechanism) for establishing communication between Process, Logic, VP, DB etc, IC Logger to save and restore information about the state of the simulator, Executive to control and synchronize the operation of various simulator components, and DB server to store and retrieve all the data pertaining to simulated models.

VI. DESIGN AND DEVELOPMENT OF A TRAINING SIMULATOR

The design and development of a Training Simulator involves three basic functional models to be built namely, the Process Model which deals with process components with respect to reference plant, the Logic
Model which deals with logic and controls associated with the components with respect to reference plant and the Virtual Panel Model which represents the Control Room panel for monitoring and controlling the system parameters. Essentially, the above three modules are developed based on the inputs collected through technical discussions, design and operation documents, system drawings, isometric drawings and PID diagrams. Refer Fig. - 6&7 for details.

Once the models are built and tested for satisfactory operation, all the modules are integrated and tested. Invariably, some of the modules have been developed using indigenous/conventional tools and many are developed in-house based on the uniqueness of the system (Internal and External models). Essentially, all the models are brought into the same environment for ease of handling. The integrated testing is carried out to check the integrated performance under steady state first and the gross errors if any are brought to the notice of the developer. A systematically developed model will pass through this test more easily.

![Fig.6. Basic Functional Models](image)

![Fig.7. Steps involved in building the simulator](image)

**VII. DEVELOPMENT OF PROCESS MODELS AND ASSOCIATED PLANT DYNAMICS**

The design and development of KALBR-SIM includes modeling of various reactor subsystems (Refer Fig.8) like Neutronics, Primary & Secondary Sodium, Decay Heat Removal, Steam & Water, Electrical, Fuel
Handling and PFBR Instrumentation & Control systems. The development work is carried out in collaboration with various system experts available in the centre. All the plant conditions that are mandatory for training the operators are included in the simulator development. The important plant operating conditions that are taken into account for modeling of PFBR Operator Training Simulator include, Reactor Start up Operation, Power Rise Operation, Full / Partial Power Operation, Reactor Criticality (Hot, Cold and First Criticality), Fuel Handling Operation, Reactor Trip under various conditions, Shut down of Reactor, Reactor Power Setback etc[6]. Refer Fig.9 for details. Simulation of transient conditions and related incidents and malfunctions such as failure/ tripping of pumps, heat exchangers, malfunction of valves, control systems etc affecting the system performance by altering the normal operation have also been modeled in KALBR-SIM.

VIII. INTEGRATION OF VARIOUS PROCESS MODELS

Process models can be broadly classified into two categories, Internal models which are developed using the inbuilt components and devices in a tool and the External models which are developed in-house using system transfer functions considering various transient conditions. Internal models include Steam Water System simulation and Electrical System simulation and the external models include Neutronics Model, Primary & Secondary Heat Transport System, Fuel Handling System Model, Core Temperature Monitoring System, Safety logic system etc. All the models are brought into simulator environment by interfacing the modules and integrated together to form the Full Scope Training Simulator. (Refer Fig.10 for details).

IX. NEED FOR TRANSIENT SIMULATION AND ANALYSIS

The transient simulation helps in understanding the dynamic behaviour of the plant in a time frame extending from few seconds to tens of seconds. Fundamentally the plant design safety limits are fixed by the design experts, based on the transient analysis study conducted extensively, taking into consideration the various
interconnected system behaviour. The ultimate goal is to safeguard the plant and the personnel under all normal and abnormal conditions of the plant.

The dynamic simulation study using training simulator can provide the operators, an opportunity to understand the system dynamics, the equipment performance and changes that would occur in the system with indicative parameters like pressure, level, temperature, flow etc with respect to time. The operator can understand the system behavior and subsequent level of stabilization after being subjected to a disturbance like pump trip or pump seizure etc and visualize and gain more insight about the plant dynamics. This will help the operator to make quick and accurate decisions towards improving the performance and safety of the plant.

X. PERFORMANCE TESTING

As the main purpose of the simulator is for training the operator, the developed models are subjected to performance testing. It includes testing under steady state and transient/disturbed condition of the plant. The performance accuracy has to be maintained within the stipulated limits, in order to qualify the simulator for training purpose. The following paragraphs describe the various categories of transients and analysis carried out on the KALBR simulator.

XI. IDENTIFICATION OF BENCHMARK TRANSIENTS

The Bench Mark Transients represent a list of important transients identified for simulation, based on the Preliminary Safety Analysis Report [4]. They are used for evaluating the process models and further qualification of the simulator for the purpose for which it has been built. As per the Preliminary Safety Analysis Report, the Design Basis Events are grouped into four categories viz. Cat-1, Cat-2, Cat -3 and Cat-4 starting from more frequently occurring incidents to less frequently occurring incidents [3]. Category-1 events indicate the normal operations that would take place in any plant like Reactor Start up, Shut Down, Full Power Steady State Operation and Part Load Operation etc. Category -2 events indicate a situation, arising due to failure of coolant pumps, causing main core cooling affected, like - Primary Sodium Pump Trip, Secondary Sodium Pump Trip, Boiler Feed Pump Trip, and Condensate Extraction Pump Trip due to pump fault or motor fault. Category-3 events indicate severe situation which can impair the core cooling at a faster rate like - Primary Sodium Pump Seizure, Secondary Sodium Pump Seizure etc. Category-4 events indicate the rare events that would occur due to material defect like Primary Pipe Rupture, causing heavy reduction in the coolant flow through the core (Refer Fig.11 for details). Exposure to such occurrences and events will essentially improve the understanding of the plant personnel about the system dynamics and actions to be taken. (Refer TABLE I for details).

Here the Incidents / Events and Malfunctions are chosen from the above referred document i.e. Preliminary Safety Analysis Report for inclusion in the training simulator.
A systematic training on the events causing transient situation in the plant will prove its worth once the trained operators are deployed in the actual plant. The list of Bench Mark Transients that are considered for qualifying the simulator for training purpose include continuous withdrawal of one CSR, One primary sodium pump trip, One primary sodium pump seizure, Primary pipe rupture, One secondary sodium pump trip, One boiler feed pump trip, One condensate extraction pump trip etc[2].

The Instructor Station facilitates, loading of plant scenarios for performance study and system analysis. It also provides a platform for conducting training sessions for the operators and monitoring of simulator operations and operator actions / response [1].

The important features that are available in the Instructor Station include loading of various reactor states, capturing of relevant process signals, forcing a specific condition of a process etc.

The commands like RUN, STEP, BACK TRACK, FREEZE, REPLAY and SNAPSHOT are operable from here. (Refer Fig.12 for details)

### A. Analysis of One Primary Pump Trip Event

The primary heat transport system of PFBR consists of main components such as the Core, Primary Sodium Pumps (2 Nos), Intermediate Heat exchangers (4 Nos), Cold Pool and Hot Pool of sodium. The primary pumps take the suction from the cold pool sodium at 397 Deg C and discharge the sodium to the grid plate from where the flow is distributed through the core. The sodium flowing through the core removes the heat generated in the core and gets collected at hot pool at 547 Deg C. The hot sodium from the hot pool enters the IHX through the sleeve valve located at the top and leaves the IHX through the sleeve valve located at the bottom after transferring the heat to the secondary sodium. This cycle keeps repeating. The event, One Primary Pump Trip refers to failure of one of the main coolant pumps whose discharge is directly connected to the core, affecting the heat removal from the core.

<table>
<thead>
<tr>
<th>Category</th>
<th>Occurrence</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat - 1</td>
<td>&gt; 1</td>
<td>Normal operation, planned startup and shutdown</td>
</tr>
<tr>
<td>Cat - 2</td>
<td>10^{-2} cf&lt;1</td>
<td>Off-site power failure, pump trip</td>
</tr>
<tr>
<td>Cat - 3</td>
<td>10^{-4} cf&lt;10^{-2}</td>
<td>Station black out, Pump seizure</td>
</tr>
<tr>
<td>Cat - 4</td>
<td>10^{-6} cf&lt;10^{-4}</td>
<td>Primary Pipe Rupture, SSE (safe shutdown earthquake).</td>
</tr>
</tbody>
</table>
Here, the occurrence of one primary sodium pump trip (belonging to Cat-2 Event) is simulated by loading the appropriate scenario belonging to primary sodium system selected from the Instruction Station [3].

XII. PARAMETER PROFILES AND ANALYSIS

For analysis purpose, preparations are made in advance to generate profiles by capturing the Process Simulator Signals. The parameters include reactor inlet/outlet temperature, flow through the core, Hot/Cold pool sodium temperature, secondary sodium inlet/outlet temperature of intermediate heat exchanger, feed water inlet temperature, flow, pressure and steam outlet temperature, flow and pressure of Steam Generator etc. Simulator Test Screens and Main Flow Sheet Mimic diagrams (Refer Fig.13) are used for checking the dynamic changes in the systems parameters on the occurrence of an incident. (Refer Fig.14 and Fig.15 for details).

It can be observed from the profiles, that the incident leads to slow reduction in speed of the tripped pump. This results in reduction in flow supplied by the pump under consideration. As both the pumps (PSP-1 &2) are operated in parallel, the flow supplied by the running pump increases to a maximum of 126% momentarily [4]. The flow through the tripped pump reduces gradually from 100 to 0 and then reverses with a flow halving time of 8 sec. Actually the operating pump feeds both the core flow and the bypass flow through the tripped pump causing the reverse flow.
Ultimately a reduction in core flow is observed with the running pump maintaining a constant speed. This reduction in cooling causes the temperatures to shoot-up in the core which can be measured through mean temperature, Delta Theta (CSAM) - temperature raise in central subassembly and Delta Theta (M) - temperature raise in mean core outlet. Automatic Reactor Trip (SCRAM - Safety Control Rod Accelerated Movement) is initiated on sensing the critical parameters crossing the stipulated limits to safeguard the plant. The thresholds are chosen in such a way that they are very close to the normal operating level taking into account the fluctuation in the signal around the mean values, operational margins and error in setting the threshold.

XIII. SCRAM PARAMETERS

For each system, the important system parameters are identified and included as SCRAM parameters. These parameters, on crossing the first threshold limit, trigger an alarm in the Local Control Centre and Control Room and on crossing the second level of threshold limit will introduce a reactor trip or SCRAM. This is mainly to limit the critical parameters (clad and fuel temperature) crossing the stipulated Design Safety Limits. The important parameters are \( N_p \) – Pump Speed and Power to flow ratio including the above mentioned parameters [4].

Under normal condition of operation, the power to flow ratio is about 0.99 and the speed is 100\% (590 RPM). When the pump trip occurs, the pump speed reduces slowly and reaches less than 97.5 \% affecting the
total flow through the core. A “Pump speed off normal” alarm is initiated at this point and SCRAM is ordered when the pump speed reduces below 95%. As it causes reduction in total flow for the given power, Power to Flow ratio shows an increasing trend.

Subsequent to SCRAM, the operating primary sodium pump speed is reduced to 20% and the secondary sodium pumps are run down to 20% due to sympathetic safety action. The speed of the running primary sodium pump is increased to 40% manually on integrity considerations of the hydrostatic bearing of the pump.

The Decay Heat Removal System is enabled by opening the dampers and the decay heat is removed from the core. On steam water system side, both the boiler feed pumps are run at reduced speed automatically due to controller action. When the steam outlet temperature at the outlet of steam generator reaches 402 deg C, the turbine is tripped automatically releasing the steam through the turbine bypass system.

The following table indicates the parameters causing SCRAM with the limits specified w.r.t time (Refer TABLE-II for details).

The parameters are redundant, keeping safety as the ultimate goal. If the SCRAM does not occur in the first instant, then the next parameter will take care of the automatic tripping of the plant, safe guarding the reactor.

A. Analysis Of One Boiler Pump Trip Transient (Not Taken Over By The Standby Pump)

The Boiler Feed Pump is the main component in the feed water system which is a part of steam water system. There are totally 3 Nos. of BFP- Boiler Feed Pumps (2 turbine driven and 1 Motor driven) of 50% capacity each, deployed in the feed water circuit [7].

Under normal condition of operation only 2 nos. of turbine driven BFPs will be running, taking suction from the deaerator. The pump discharge will flow through 2 sets of High Pressure Heaters connected in parallel for regenerative feed heating. The preheated feed water will enter the Steam Generators -8 Nos. through the Flow Control Station and the cycle repeats (Refer Fig.16 for details).

Here, the One BFP Trip Event originates from the balance of plant and does not cause any direct SCRAM order on the reactor.

As per the design philosophy, tripping of one of the running BFPs leads to starting of standby BFP as per the system logics and belongs to Cat -1 event. The same event gets converted into Cat-2 event when the standby also fails to take over following one BFP trip. The occurrence of One BFP Trip event with standby not taking over is simulated by loading the appropriate scenario belonging to Steam Water/Feed Water System selected from the Instruction Station.

The following paragraphs detail out the Simulation and Analysis of One Boiler Pump Trip Event combined with failure to start of Standby BFP Pump. In this case, one can observe from the captured profiles that an immediate reduction in feed water flow to 55% occurs as a step change. It causes partial loss of heat sink in the SG which in turn causes the secondary sodium temperature to rise [3]. This reduction in cooling does affect the primary outlet temperature of the Intermediate Heat Exchanger leading to increase in core inlet and outlet temperature (Refer Fig.17).

An alarm is initiated at the first level at 402 deg C and SCRAM is ordered when the core inlet temperature exceeds the specified limit i.e. 407 Deg C. The temperature rise in cold pool causes introduction of negative reactivity feedback and hence reduction in reactor power [3]. This can be observed from the simulated parameter profiles in Fig.18 & 19.

<table>
<thead>
<tr>
<th>S.NO</th>
<th>SDS acting</th>
<th>Parameter name</th>
<th>Parameter Description</th>
<th>SCRAM initiation time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SDS-1</td>
<td>$N_p$</td>
<td>Pump speed</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>SDS-1</td>
<td>$P/Q$</td>
<td>Power to Flow ratio</td>
<td>1.95</td>
</tr>
<tr>
<td>3</td>
<td>SDS-2</td>
<td>$\theta_{LSM}$</td>
<td>Central Subassembly Outlet Temperature</td>
<td>1.92</td>
</tr>
<tr>
<td>4</td>
<td>SDS-2</td>
<td>$\Delta T_{LSM}$</td>
<td>Temperature raise in Central Sub assembly Outlet</td>
<td>2.89</td>
</tr>
<tr>
<td>5</td>
<td>SDS-2</td>
<td>$\Delta T_m$</td>
<td>Temperature raise in Mean Core outlet</td>
<td>11.07</td>
</tr>
</tbody>
</table>

TABLE-II. SCRAM PARAMETERS
After SCRAM, on ensuring that reactor shutdown systems have operated, the primary and secondary sodium pumps are run down to 20% and boiler feed pump is run down to 15% due to controller action. At the SG outlet, the steam temperature starts falling, following the SCRAM and when the temperature reaches 420 deg C, turbine trip is initiated. The simulated results are compared with the predictions made in the Preliminary Safety Analysis Report by the designers. The simulated parameters are found to be within the permitted error limits defined by the ANSI – 3.5 standards.

Fig.16. Feed Water System

Fig.17. One BFP trip Flow graph

Fig.18. One BFP trip Power graph
XIV. VALIDATION OF PERFORMANCE OF PROCESS MODELS

The evaluation of process model performance is yet another milestone to be crossed in the development of training simulator. The process models are subjected to Verification & Validation (V&V) process in order to ensure that the original design requirements are incorporated successfully and the user requirements are met. Essentially, it is a methodology adopted to qualify the Training Simulator for the intended purpose. In the present setup, the Training Simulator needs to pass through two V&V Committees i.e. Local Verification & Validation Committee (LVVC) and an External Verification & Validation Committee (EVVC). Basically the performance of process models under steady state condition and transient conditions are demonstrated to the Design Experts belonging to Local Verification & Validation Committee. Here, the mass balance, thermal balance and the plant dynamics are checked as a first level of approval. At this stage small modifications, tuning of components and controls are carried out to achieve the required performance. Once approved, the second level of approval is obtained from the External Verification & Validation Committee (constituted by the experts from various other units of Department of Atomic Energy) through a detailed demonstration of the process models. This includes various plant operating states like plant startup, power raise (part load and full power), steady state and emergency conditions. Normally technical minutes of meetings are prepared to record the comments offered by both the expert team for further incorporation and testing. In such cases approval is obtained after the implementation of the comments. The V&V documents are prepared and submitted for approval based on the demonstration and detailed presentation to the LVVC and EVVC.

XV. STANDARDS FOLLOWED

The standards ANSI 3.5 – 1998 edition and IAEA – TECDOC – 995 / 1411 are referred for building and testing the operator training simulators. The standard provides general guidelines for conducting performance testing on the Training Simulator and a methodology for testing the suitability of a Full Scope Operator Training Simulator for the intended purpose. Essentially, the plant safety, equipment availability, and efficient operation are kept as common goals to be achieved. The error limits specified by the standard indicates an allowance of 1 – 2% for the steady state operation. Normally, the performance test results under steady state conditions are evaluated adhering to the reference standard. Large deviations are not observed as the Modeling and Simulation is subjected to rigorous V&V process. Slight deviations outside the stipulated boundaries are corrected by tuning the models. The error limits specified for transient condition is 10-15 %.

XVI. CONCLUSION

As the Training Simulators are increasingly used for training the plant personnel, qualifying the simulators based on a set of Bench Mark transients has become a mandatory requirement. Strict adherence to the standards and the Verification & Validation process helps in maintaining the required degree of accuracy of the Operator Training Simulators. The transient simulation and performance analysis study ensures that the simulated process models represent the real systems under consideration with an acceptable degree of
accuracy. Training the operator on transients and related plant dynamics adds yet another dimension to the knowledge gained by the operator. The knowledge on system dynamics that are critical to plant safety and the plant response to disturbances that arise from the changes in the state of components and equipments are equally important for efficient monitoring and control of the plant. It is highly essential to train the operators on various plant states and the associated plant dynamics. A Full scope Replica Operator Training Simulator caters to such requirements and provides a strong platform for imparting the plant knowledge to the operators. The significant advances in Computer Science & Technology have also played a major role in realizing the Real Time Full Scope Replica Operator Training Simulators.

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