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SIMULATION OF BOILER FEED PUMP USING CONTROLLER PROGRAM: A CASE STUDY OF SAPELE POWER BOILER FEED PUMP

Ogheneakpobo Jonathan Eyenubo[1]; Ebimene Ezekiel Ebisine[2]; Ufuoma Jeffery Okieke[3]
[1-3] Department of Electrical/Electronic Engineering, Delta State University, Abraka, Nigeria.

Corresponding author: ojeyenubo@delsu.edu.ng

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ABSTRACT

The goal of this work is to simulate the Sapele Power Plant Boiler Feed Pumps (BFPs) using CODESYS software for the simulation of BFP controlled by a proposed PLC system. The boiler pressure, level, feed stream flow, and primary heat transport (PHT) pressure BFP were restored to their optimal levels within a few seconds after the trip. During the simulation, the BFP goes into standby mode after 14 seconds. The results obtained show the boiler pressure rose to 40.3 kg/cm^{-1}s^{-2} and remained stable for 147 seconds, as opposed to 55.9 kg/cm^{-1}s^{-2} in 25 seconds under the same conditions. The flow rate of the feed water shows a decrease of -0.172 m at 50 seconds. The boiler pressure rose further to 44 kg/cm^{-1}s^{-2} at 175 seconds, which corresponds to a specific gravity value of 59.5 kg/cm^{3} at the same time. At 146 seconds, the feed water hits the trip setting of -2.85m due to the low specific gravity (SG) level. Thus, a further increase reached a fluctuation level of -10m at 200 seconds. The PHT was 88.5 kgcm^{-1}s^{-2} at 146 seconds, contrary to the expected pressure of 105.6 kgcm^{-1}s^{-2}. This change after 146 seconds results from a generator trip. The pressure increases to 90.2 kg/cm^{3} at approximately 148 seconds and subsequently decreases to 48 kg/cm^{3} consequently opening the condenser steam discharge valves (CSDVs) and atmospheric steam discharge valves (ASDVs) during the simulation state.

Key words: *Boiler Feed Pumps; Programmable Logic Controller; Main Steam Valve; Feed Pressure; Machine Control Center; Boolean Algebra.*

1.0 INTRODUCTION

Historically, process control was performed manually, which was an arduous endeavour. But relays were inadequate to fulfill the demands of the twenty-first century; thus, a more rapid solution was necessary. In order to modify the control logic, it was sufficient to replace the entire hardware cabling. This was both tedious and time-consuming. Engineers at last devised the PLC after much effort (Fathahillah et al., 2020). PLC was able to facilitate the revolution of changes that optimized performance and profitability because it provided solutions to many of the key operational barriers: speed, flexibility, safety, and distance difficulties associated with them. The emergence of PLCs and their related technologies has led to the death of tedious manual hardware relay-wired control systems and collapsed the entire system into a “microprocessor-based system" of BFPs, as exemplified in Figures 1 and 2.

The advent of microprocessor technology in the late 1960s brought about significant alterations in terms of operation and control. This technology is computer-based, meaning that the processing logic and data control are combined into a single integrated circuit (Szcześniak and Szcześniak, 2022.). It plays a crucial role in enabling various operations and control functions to achieve significant improvements that benefit industries in multiple ways. These include enhanced control, operation, and maintenance flexibility of the process control system; reduced space requirements for the control system; simplified and less complex wiring systems; improved programming versatility and system expandability; increased interaction between operators and the process; faster control system response times; improved overall plant productivity; and reduced maintenance and troubleshooting time (Wikarek and Sitek, 2019). The processing unit executes specified arithmetic and logical operations on input data and generates output that is functional.

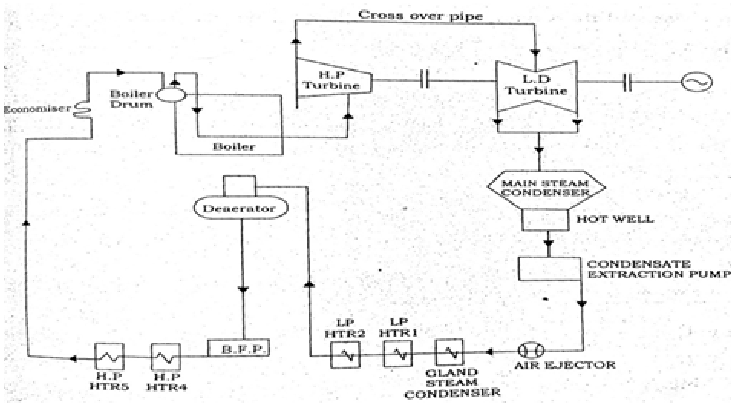

Figure 1: Diagrammatic arrangement of a typical Sapele Steam Power Plant 120MW (non-reheat) system Feed Water Flow, showing the Boiler feed Pump (BFP).

Figure 2: Boiler Feed Pump (BFP)

Ladder logic diagram language is a basic tool controller that incorporates physical and logical commands (tags) to format and prepare commands or feedback (visual, audio, or documents) that can be displayed on control monitors or sent as inputs to other controllers through communication lines (Gharieb, 2006). According to Szcześniak et al. (2022), the program's presentation and structure of ideas are highly significant. So, depending on the operation you want the program to handle, you should keep an eye on the markup commands and colours it uses. This implies that, depending on the intended operation that the program will manage, one should pay attention to the markup commands and colours used in the program. In order to increase clients' enthusiasm for using the controller on a regular basis for new projects, it must include current or up-to-date information, tagging format, and colour coding on the operation being carried out by the users (the operator). This will help to clearly define what is needed in terms of operation and control.

Programmable controllers are utilized in several sectors of industry, including power generation, vehicle painting, and food packing, among others, with the aim of augmenting and broadening production capabilities. In contrast to electromechanical devices, PLCs use integrated circuits to accomplish control operations, making them a solid-state member of the computer family. According to Lohstroh et al. (2020) and Lee and Zheng (2007), industrial machinery and processes can be controlled by storing instructions that encompass several functions, including sequencing, timing, counting, arithmetic, data manipulation, and communication.

1.1 Programmable Logic Controllers

The investigation of the programming paradigm employed by PLCs, as specified in the IEC 61131-3 standard, is deemed essential due to its inherent significance in the nature of these controllers. The comprehensive analysis of IEC 61499 is an event-driven extension of IEC 61131-3 due to its limited implementation in industrial applications. Thramboulidis (2013), Zoitl and Vyatkin (2009), and Vyatkin (2013) have detailed work for a more extensive exploration of software engineering in industrial automation.

When contrasting generic embedded control systems with PLCs, it becomes evident that PLCs provide a more organized and restricted framework for the purpose of design. This is supported by established and widely used design patterns (Bolton, 2015; Lewis, 1998; Webb and Reis, 2002). PLCs can be programmed using various languages that operate at different levels of abstraction. These languages include:

i. Structured text, which is imperative and based on the PASCAL programming language;

ii. Instruction lists, which are similar to assembly language;

iii. Ladder diagrams, which are based on ladder logic and are commonly used for hardwired relay circuits;

iv. Function block diagram, which is a graphical language;

v. Sequential Function Charts, which are graphical and similar to Petri Nets.

2. 0 METHODOLOGY

2.1 The proposed system

The suggested system is a microprocessor-based program model designed for internal switching. It utilizes a PLC native language called ladder logic diagram, as shown in Figure 3, which adheres to the IEC 61131-3 standard for programmable logic controllers. The purpose of this system is to:

The control task is described as follow:

Discuss the lines pertaining to process inputs and outputs.

Program set points are defined based on the process operating limitations and alarm set points.

The program logic should be sequenced in accordance with loops and sub-loops.

Lastly, develop and build a visualization window that facilitates increased operational interaction by means of a human-machine interface.

The program is developed within a programming device, commonly referred to as a programmer unit, which is equipped with a preloaded CODESYS runtime and an integrated development environment. Figure 3 depicts a fundamental block diagram of a prevalent PLC system.

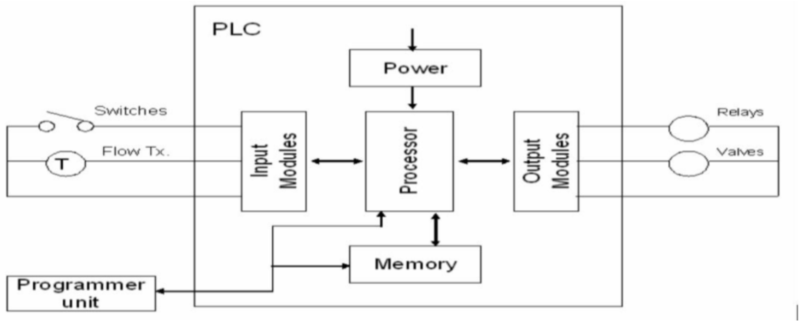

Figure 3: PLC schematic block diagram

The control program is split into five main loops, which are further broken down into parts and solutions that define the control jobs and ensure high safety integrity and availability. These are the loops:

i. Press to begin
ii. Command to start or stop
iii. Last Version Out
iv. The last command to start or stop
v. Logic for Start/Stop

2.1.1 Release the Start Loop

The pump release to start is the primary loop that defines the pump availability. This is an all AND configuration that confirms that every condition or availability limit necessary for safe operation of the pump is met. Table 1 shows all release conditions necessary to establish the pump to begin. Address in PLC, input type, comment (set-point), PLC wiring type, and logic state.

Table 1: Press to begin

Name of input	Address	Type	Comment /Set-point	PLC wiring	Logic state
DP	1.1.3	Bool	Boiler drum pressure > 40kg/hr.	Normally open	0
DL	1.1.4	Bool	Boiler drum level<Max (+1.8m)	Normally Close	1
DTL	1.1.5	Bool	Deaerator storage tank level >min (0.6m)	Normally open	0
WIVH	1.1.6	Bool	Motor winding temperature very high(>90℃)	Normally close	1
BT	1.1.7	Bool	Motor and pump bearing temperature very high (>100℃)	Normally close	1
FWDP	1.1.8	Bool	Feed Water deferential pressure across strainer < max(1Kg/CM²)	Normally open	0
RR	1.1.9	Bool	Revers rotation	Normally close	1
LTL	1.1.12	Bool	Lub. Oil talk level >min (2ft)	Normally open	0

2.1.2 Command Start/Stop

The start/stop command loop is an integrated loop that consists of an internal (memory) and external input signal configured by a combination of an AND, OR, and EXOR gate configuration to form a security as well as a control loop for pump start-up or stop signals that enable operation of the pump either via manual or auto mode, considering every other pump availability condition as well as other advanced conditions necessary for pump start or trip position. All basic conditions and their signal positions in the program for a start/stop command loop are shown in Table 2.

Table 2: Command Start/Stop

Name of Input	Address	Type	Comment /Set-Point	PLC wiring	Logic state
SWITCH/HOLD	2.1.1	Bool	Start/stop switch	Normally open	0
MAS	1.1.12	Bool	Manuel/Auto Select	Normally open/close	1 or 0
ASM	1.1.10	Bool	Automatic standby monitoring (ASM)	Normally open	0
RELEASE	2.1.0	Bool	Release To Start (output of 1 above)	Normally open	0

2.1.3 Last Version Out

The final release loop is an internal/external AND configuration program input signals loop designed to ensure the third level of integrity of pump protection, a kind of double checking of the availability and start/stop command input signals. Table 3 below shows all conditions and their signal positions in the program for the last version.

Table 3: Last Version Out

Name of Input	Address	Type	Comment /Set-point	PLC wiring	Desired run state
Start/stop command	3.1.0	Bool	Pump start/stop input signal (output of 2 above)	Normally open	0
LOP	1.1.1	Bool	Auxiliary Lubrication oil pressure >min(1kg/cm^2)	Normally open	0
FWP	1.12	Bool	Feed water pressure > min (80kg/cm^2)	Normally open	0

2.1.4 Last Command: Start/Stop

The final start/stop command is an all-internal program action AND to yet reconfirm that all conditions are correct (depending on the operation mode selected) at a 4[th] level, completing the start/stop logic and giving the final output command for breaker open/close. Table 4 below shows all conditions and their signal positions in the program for a final start/stop loop.

Table 4: Last Command Start/Stop

Name of Input	Address	Type	Comment	PLC wiring	Desired run state
Start/Stop_Logic	1.1.12	Bool	Supervisory logic output (output of 5 below)	Normally open	0
F_Release	4.1.0	Bool	Final release out (as from 3 above)	Normally open	0

2.1.5 Logic for Start/Stop

This is an all internal and more complex loop comprising multiple gates, timers, and counter configurations, with its input and output connected to the other loops. It serves as an intermediate loop with functions that include those shown in the flow chart in Figure 4.

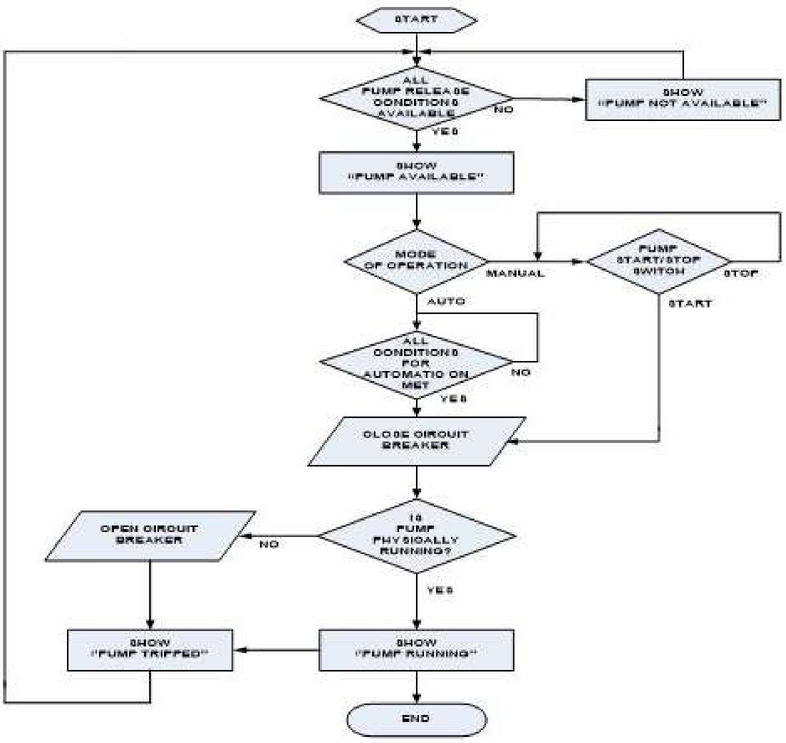

Figure 4: Flowchart

2.2 Control Set Point Monitoring

The process set points are monitored by a set of discrete input devices, including switches, pressure switches, thermocouples, flow switches, and so on, that are installed in specific points throughout the plant and designed to change position when within or outside of the desired process parameter value (set point) as specified in the logic. The positions are fed into the logic as 0 or 1 by the PLC's input module (depending on the value of the process parameter in relation to the set point). Before being used as a logic input in the loops, these input signals are first processed through a particular piece of logic that eliminates transitory actions and controls fluctuation using unique logic conditions, counters, and on-delay/off-delay timers.

2.3 Simulation

The motor logic simulation is executed using the CODESYS integrated development environment. This involves the use of two primary travel situations, each of which is assessed according to five designated criteria. The following section presents the simulation outcomes for several operational scenarios. This study examines the correlation between the overall boiler and plant system, with particular emphasis on the boiler's level and pressure. Furthermore, it evaluates the condition of the BFP by examining the motor winding, bearing temperatures, and rotation direction. The auxiliary systems of the BFP, such as the pressure in the PHT and steam flow, are also accounted for; thus, investigating the feed water parameters, specifically the differential pressure after strainers (flow) and pressure, which are essential in deciding when the pump release begins during startup.

A choice can be made between a remote or local location for the pump's circuit breaker system and the operational status of the pump, which includes the position of the on/reset switch and the mode of operation. One of the study's objectives is to confirm that the lubricating pump's operation is consistent with the BFP output. Consequently, the system readiness to be added to the logic ladder includes making sure the input and output signals are intact.

3.0 RESULTS AND DISCUSSION

These findings are based on simulated studies that made use of the CODESYS IDE. The goal is to make it easier for water to circulate in a secondary circuit so that heat may be extracted from a PHT circuit. First, the boiler feed pump is turned on in the simulation, and then, 14 seconds later, the standby pump is turned on.

3.1 Boiler Pressure

A reduction in feed water flow results in a higher PHT mean temperature, thus restoring heat transfer to the secondary side. Furthermore, as feed water has a lower enthalpy compared to that in a steam generator, the reduction in feed water flow increases steam formation. This results in increased boiler pressure. Table 5: Boiler pressure increases to 40.3 $kgcm^{-1}s^{-2}$ at 25 seconds as against 55.9 $kgcm^{-1}s^{-2}$ in 25 seconds under unautomated conditions. Boiler pressure stabilizes at its normal value after the standby pump comes on, as depicted in Figure 5.

Table 5: Variables /Parameters for scenario trips and standby after 14 secs

Time (Secs) [B.P]	Boiler Pressure [Pressure ($kgcm^{-1}s^{-2}$)]	Time (Sec) [B.L]	Boiler Level [Deviation from normal level (m)]	Time (Secs) [F.L]	Feed Flow [Flow Rate (Kg/Sec)]
0	40.0	0	0.0	0	92.0
60	39.9	50	-1.4	50	104.0
120	40.03	110	0.01	110	98.0
190	40.04	180	0.08	180	92.0
250	40.01	230	0.06	230	90.0
320	40.0	290	0.02	290	91.0
390	40.0	350	-0.19	350	91.50
470	40.1	410	0.0	410	92.0
		480	0.0	480	92.0

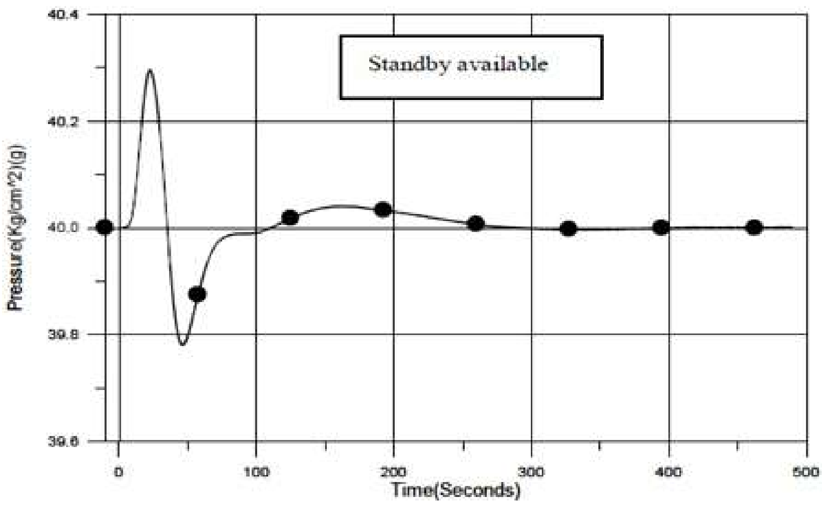

Figure 5: Steam generator pressure variation with the time

3.2 Boiler Level

With a decrease in feed water flow, the level starts reducing and reaches -0.172 m at 50 sec. Figure 6. Standby pumps start after 14 seconds, causing the level to start rising. However, an increase in feed flow results in the collapse of voids, hence the level tends to decrease again. As the feed flow stabilizes, the level rises to the set point after an overshoot.

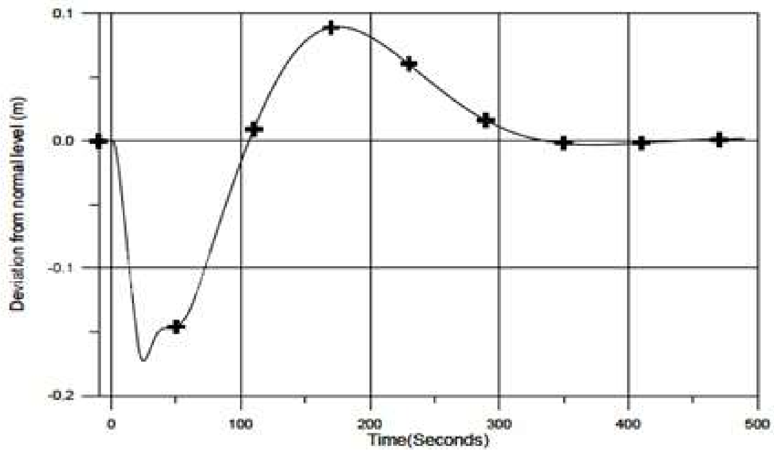

Figure 6: Steam generator level variation

3.3 Feed Flow

Following the 50% feed pump trip, the feed flow reduces, as shown in Figure 7. Due to a decrease in the boiler level, the boiler level control program causes the feed valve to open to a greater extent, resulting in higher feed flow under automated conditions. Hence, feed flow gets to nearly 65% of the initial value. Once the standby pump starts after 14 seconds, feed flow increases and reaches a value higher than normal flow at 100% FP because of boiler level response. Finally, the feed flow decreases to a stable value, which was not achievable through the manual processes depicted in Table 6 for variables and parameters.

Table 6: Variable/Parameters

Time (Secs) [B.P]	Boiler Pressure [Pressure ($kgcm^{-1}s^{-2}$)]	Time (Sec) [B.L]	Boiler Level [Deviation from normal level (m)]	Time (Secs) [F.L]	Feed Flow [Flow Rate (Kg/sec)]
0	40.0	0	0.0	0	92.0
60	40.0	50	-1.0	20	59.0
120	40.02	110	-2.0	40	59.0
200	43.0	180	-6.8	60	59.0
270	43.20	230	-9.0	90	59.0
350	38.40	290	-9.0	120	59.0
		350	-5.0	150	59.0
				170	56.0
				240	35.0
				260	50.0
				280	42.0
				320	43.0

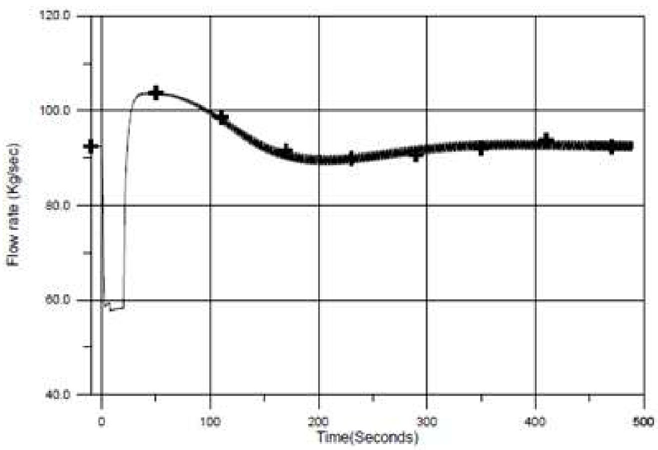

Figure 7: Feed flow to steam generator

3.4 Primary Heat Transport (PHT) Pressure

Due to the partial loss of heat sink, PHT pressure rises slowly (Figure 8) to 88.2 $kgcm^{-1}s^{-2}$ at 10 seconds. A rise in the primary pressure is seized by the PHT pressure controller by the action of feed and bleed valves. Due to this rise in primary pressure, the bleed flow rate increases to 16 kg/sec, and hence the bleed condenser level also rises. Once the boiler feed flow is restored, PHT pressure decreases to its normal operating set point. As a result, PHT feed flow increases. PHT pressure shows stabilized behaviour.

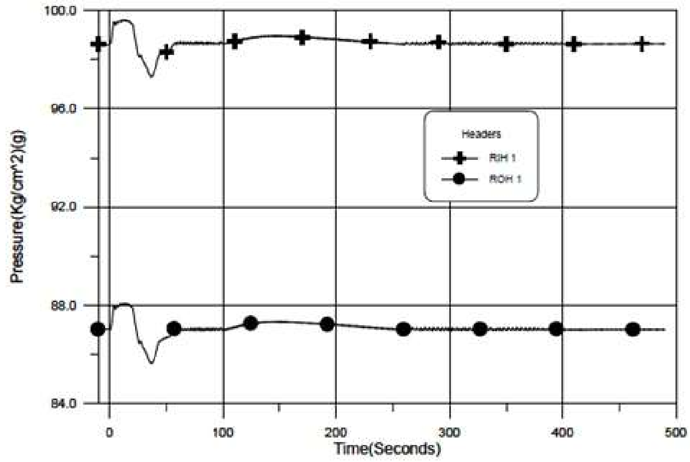

Figure 8: PHT pressure variation

3.5 Primary Heat Transport (PHT)

Pressure rise in PHT pressure is arrested by the feed and bleed system (Figures 10 and 11 of PHT). Pressure does not rise beyond 88.5 $kgcm^{-1}s^{-2}$ till 146 sec. After 146 seconds, the PHT pressure variations are due to a generator trip. Pressure rises to 90.2 $kg/cm^{-1}s^{-2}$ at around 148 sec and then falls to 48 $kg/cm^{-1}s^{-2}$ due to the opening of CSDVs and ASDVs. Pressure started rising at around 180 due to the opening of CSDVs and ASDVs. Pressure starts rising at around 180 sec due to the reduced rate of cooling of PHT and finally settles to its normal operating value.

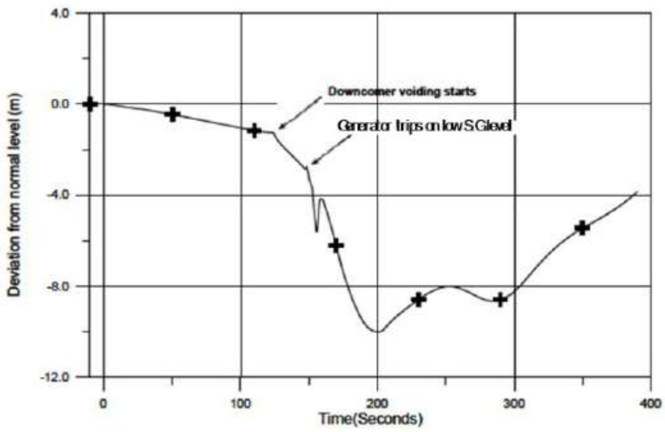

Figure 9: Boiler level deviation room normal

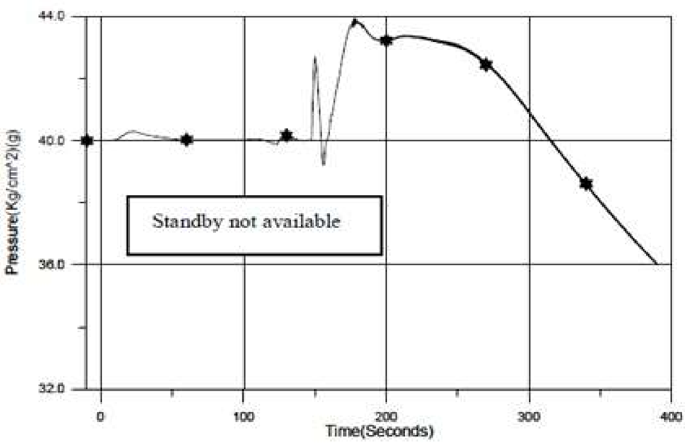

Figure 10: Boiler pressure variation

4.0 CONCLUSION

The effects of simulated BFP models were used to see how well they worked. It was planned that when the first BFP goes off after 14 seconds, the standby BFP will turn "ON." Simulation of the BFP system was carried out, as some important variables, such as boiler pressure, boiler level, feed flow, steam flow, and PHT pressure, were obtained. These are measurements for checking how the BFP worked, and the results show that the boiler pressure rose when the first BFP tripped. At 25 seconds, the pressure in the boiler rose to 40.3 $kgcm^{-1}s^{-2}$. The boiler pressure, however, stayed normal after the backup pump turned on. The boiler level rises to a pre-set point after the feed flow stabilizes. This was at the level when it dropped to -10 m at 200 s and then started to rise again. As soon as the standby pump turns on after 14 seconds, the feed flow goes up until it's higher than usual at 100% FP. As soon as the standby pump is activated, the steam flow resumes to its initial level. The generator tripping resumes at approximately 146 seconds, and the steam flow experiences a brief decline followed by a subsequent surge owing to the discharge of ASDVs and CSDVs. When these valves are closed, the flow of steam is practically non-existent, which hinders the operation of the BFP. Thus, the boiler input flow is reinstated, and the PHT pressure returns to its standard operating range. PHT input flow consequently increases. The PHT pressure exhibits a state of stability. Generally, the results indicate that the implementation of BFP enhances its functionality and diminishes the need for human involvement. Thus, this drastically reduces the likelihood of industrial accidents due to the reduced level of human contact with the BFP.

Acronyms

ASDV	Atmospheric Steam Discharge Valve
ASM	Automatic Standby Monitoring (breaker statues monitor)
AFAP	As fast aspossible
BFP	Boiler Feed Pump
BPC	Boiler Pressure Control
BOOL	Boolean algebra
BPC	Boiler Pressure Control
BT	Motor/pump Bearing Temperature
CSDV	Condenser Steam Discharge Valve
DL	Boiler Drum Level
DP	Boiler Drum pressure
DTL	Deaerator Tank level
ESV	Emergency (steam) Stop Valve
FP	Feed Pressure
FWDP	Feed Water; Across Strainer Differential Pressure (DP)
FWP	Manual/Automatic Select
GB	Generator Breaker
HM1	Human Machine Interface
IEC	International Electrotechnical Commission
LDP	Lub. Oil pump; Across Strainer
LLDL	Ladder Logic Diagram Language
LOP	Lub. Oil Pressure
MAS	Manual/Automatic Select
MCC	Machine control Canter
MSV	Main Steam Valve
OL	Aux. Lub oil tank level
PHT	Primary Heat Transport
PLC	Programable Logic Controller
RIH	Reactor (Boiler) Input Header
ROH	Reactor (Boiler) Output Header
RR	Reverse Rotation
WTVH	Motor Winding Temperature Very High
SG	specific Gravity
WCET	Worst-case execution time
FWF	Feed water flow
BF	Boiler feeder
BP	Boiler pressure
SG	Specific gravity

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