MINIMIZATION OF START-UP TIME OF SOJITZ KELANITISSA COMBINED CYCLE POWER PLANT

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the Master of Engineering in Energy Technology

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Abstract

There are only three combined cycle power plants in Sri Lanka. Ceylon Electricity Board owns one power plant, and private companies own the other two. Combined cycle power plants start-ups can be divided into three categories such as hot, warm and cold. Most of the start-ups are hot start-ups due to varying demand in the Sri Lankan's grid system. During start-up, power plant run at part load, which is inefficient. Because a portion of the steam generated is directed to the atmosphere during boiler warming up, it is essential to reduce the combined cycle power plants' start-up time. This thesis focuses on optimising hot start-up time without compromising equipment reliability.

The thesis is carried out on a combined cycle power plant in Sri Lanka. Parameters during hot start-ups between 2019 and 2021 were collected in a minute interval. After analysing the start-ups in 2019 and 2020, several experiments were carried out during 2020 and 2021 hot start-ups. For this purpose, the start-up operation was divided into sub-operations, and four critical operations which have a significant impact on start-up time were identified.

Operations such as G.T. Loading, High Pressure (H.P.) start-up vent operation, High Pressure (H.P.) steam bypass valve operation and new vent system operation were analysed, and the best optimum operation pattern was identified.

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List of Abbreviations

Abbreviation	Description
ACF	Activated Carbon Filter
APRDS	Auxiliary Pressure Reducing & De–Superheating
BHEL	Bharat Heavy Electricals Limited
BWRO	Brackish Water Reverse Osmosis
CEB	Ceylon Electricity Board
CEMS	Continuous Emission Monitoring System
CWST	Clarified Water Storage Tank
DCS	Digital Control System
DM	Demineralization
DMF	Dual Media Filter
ESV	Emergency Stop valve
FSNL	Full Speed No Load
GE	General Electric
GT	Gas Turbine
HP	High Pressure
HRSG	Heat Recovery Steam Generator
IGV	Inlet Guide Vane
LLP	Low Low Pressure
LP	Low Pressure
MOV	Motor Operated Valve
OEM	Original Equipment Manufacturer
PST	Permeate Storage Tank
RO	Reverse Osmosis
RSD	Reserved Shutdown
SH	Super Heater
SWAS	Steam Water Analysis System
SWRO	Sea Water Reverse Osmosis
ST	Steam Turbine

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1. INTRODUCTION

1.1 Overview

Currently, there are only three combined cycle power plants in Sri Lanka.

1. Kelanitissa Combined Cycle Power Plant [Ceylon Electricity Board (CEB) owned]
2. Sojitz Kelanitisssa Combined Cycle Power Plant
3. Yugadanavi Combined Cycle Power Plant

The CEB has planned to construct more combined cycle power plants in Sri Lanka in the future.

Generally, the combined cycle power plant can be started and quickly loaded compared to the Rankine cycle power plant with only a boiler and Steam Turbine (ST). Starting a boiler consumes significant time due to the preparation of firing and warming up of boiler. In a combined cycle power plant, the boiler is used to extract waste heat from the Gas Turbine (GT) exhaust. So, preparation for firing does not take a long time. Only warming up and achieving the steam condition takes significant time.

1.2 The Objective of the Project

This thesis was done in a combined cycle power plant in Sri Lanka and, the rated capacity of the plant is 163 MW having one Gas turbine, Heat Recovery Steam Generator (HRSG) and steam turbine.

1.2.1 Present scenario

Currently, start-ups perform according to the manufacturer recommendations. It leads to more time and energy consumption during start-up, because the recommended start-up procedure is typical for combined cycle power plants, and it only considers the stress of the equipment not the start-up time. The operation of some equipment can be optimised to reduce start-up time and it indirectly reduces the start-up fuel consumption.. For example, the diverter damper's operation, the start-up vent operation, and the Bypass valve operation can be optimised.
When these operations optimise, the stress on the equipment may become significant. It is essential to consider stress on the equipment and follow Original Equipment Manufacturer‘s

(OEM's) guidelines to minimise the stress while reducing the start-up time which is the main objective of the research.

1.2.2 Proposed system

This research's main objective is to develop a start-up procedure that minimize the start-up time while maintaining the stress on equipment within the OEM recommended level during start-up. Mostly, the equipment subjects to severe stress during start-up. Mainly, the steam turbine is experiencing more stress than other equipment in a combined cycle power plant due to significant variation in operational parameters such as steam temperature, pressure, rotor surface temperature, and rotor mean temperature.

If the steam turbine rotor warms up slowly, the equipment's stress can be minimised, but it leads to long start-up time and higher start-up fuel consumption.

Further, before steam admits to the steam turbine, gland steam must be established to prevent atmospheric air ingress into the steam turbine, which causes thermal stress on rotor and blades. The gland steam auxiliary header's temperature must be increased to a certain level before admitting gland steam. This operation takes time, and it leads to a delay in other operations.
This research will identify such operations and recommend the best way to perform those operations so the start-up time can be minimized while maintaining the stress level of the equipment within the OEM recommended value.

1.3 Data Gathering

Electronic devices measure all the data, such as operational parameters (pressure, temperature and flow rate), and those values are stored automatically in the Digital Control System (DCS) at the Control Room. Then, the required data for the analysis are extracted by using excel.

Other parameters, such as start-up time and fuel consumption, are calculated using the data from DCS. Further, standard curves are collected from OEM.

Data from 2019 to 2021 start-ups, including Hot, Warm and Cold start-up, were used to analyse.

Table 1.1 Number of Start-ups

	2021	2020	2019
Hot Start-up	41	36	37
Warm Start-up	4	6	7
Cold Start-up	7	12	8

1.4 Methodology

As the first step, the existing start-up procedure and the recommended procedure are analysed. Before the start-up was divided into the following operations:

- Start-up of gas turbine and loading
- Start-up HRSG and warming up
- Start-up of steam turbine and loading

Furthermore, the primary operations were divided into the following sub-operations:

- High Pressure (HP) Start-up Vent operation
- Gland Steam Operation
- HP Bypass Valve Operation
- Inlet Guide Vane (IGV) Operation
- New Vent Valve Operation
- Downstream Drains Operation
- Diverter Damper Operation

Then, each operation was analysed individually during start-ups, including Hot, Warm and Cold start-ups. Several trials were carried out to obtain the optimum operation of each system. Microsoft Excel was used for most of the analysis.

2. LITERATURE SURVEY

2.1 Combined Cycle Power Plant

Combined cycle power plants employ more than one thermodynamic cycle. Most commonly, it incorporates the Brayton cycle and the Rankine cycle. The waste energy in the Brayton cycle uses in the Rankine cycle. So, the overall efficiency of the plant improves. Generally, the combined cycle power plant consists of gas turbines, heat recovery steam generators, and steam turbines.

The thermodynamic cycle upon which a gas turbine operates is called the Brayton cycle [1]. A simple gas turbine is an internal combustion engine that consists of three basic components a compressor, a combustion chamber and a turbine. Ambient air is compressed in a multistage axial compressor and fed into the combustion chamber. Fuel s injected into and burnt with this air in the combustion chamber to produce a high-temperature mixture of air and fuel combustion products. The hot gas flow then expands through the turbine, which produces work. A portion of the turbine's power drives the compressor, and the excess power drives an electric generator.

The thermodynamic cycle upon which the steam turbine operates is called the Rankine cycle [2]. In a combined cycle power plant, the gas turbine's flue gas sends through the heat recovery steam generator where the high-pressure superheated steam is produced. This steam is utilised to drive a steam turbine.

The steam turbine drives an electrical generator to produce electricity.
Advantages of Combined Cycle Power Plant [3]:

- Low Installation cost.
- Higher efficiency among all practical power cycles
- Low auxiliary power consumption/MW (about 2-3%).
- Less Manpower/MW ratio.
- High Reliability and Availability.
- Clean operating conditions.
- Less Gestation period.

- Fast starting characteristics.
- Less water requirement.
- Fewer pollution problems.
- Flexibility in locating power plant.
- Fuel flexibility.
- Less space requirement / MW.
- Gas Turbine can be operated as Peak Load plant and Steam Turbine as Base load plant by supplementary firing in HRSG unit.

2.2 Gas Turbine

Figure 2.1 Gas Turbine (Original in Colour)

The gas turbine is an internal combustion engine uses in various industries, including power generation industries. The first gas turbine design was successfully done by Sir Frank Whittle (England). He developed a working gas turbine in 1937, used to drive turbojet aero plane. According to the Brayton cycle, the gas turbine operates, proposed by an American mechanical engineer George Brayton in 1870 [4].

The Brayton Cycle comprises four reversible processes. Those are [4]:

1. Isentropic Compression
2. Constant Pressure Heat Addition
3. Isentropic Expansion
4. Constant Pressure Heat Rejection

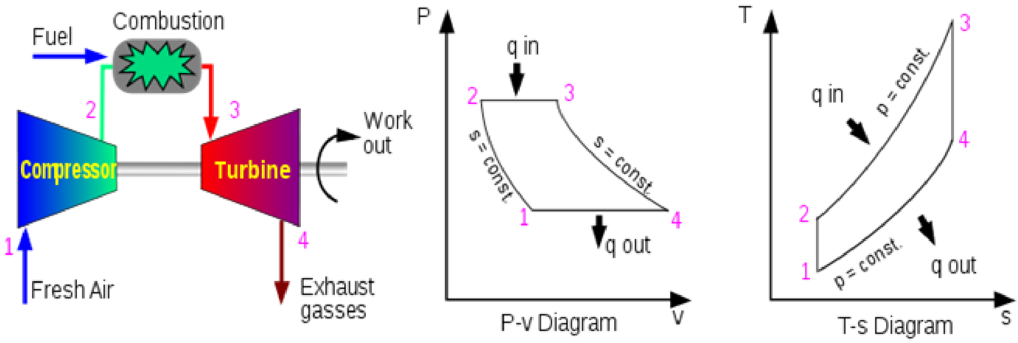

Figure 2.2 Element of gas turbine and P-v and T-s Diagram [4].

2.3 Heat Recovery Steam Generator

Generally, the boiler uses in industries incorporate flue gas that contains waste heat is called Heat Recovery Steam Generator (HRSG). Like boilers, HRSG transfers heat energy in the flue gas to water and generates steam which drives the steam turbine [5].

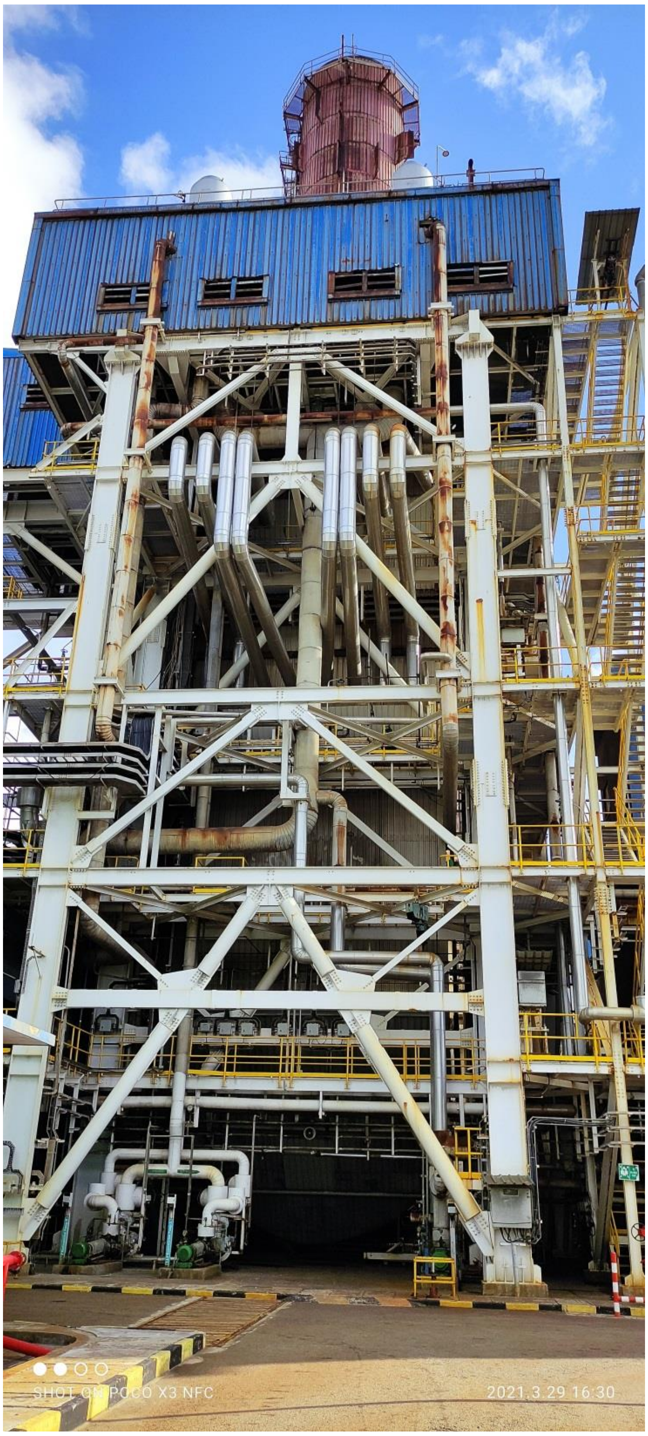

Figure 2.3 Heat Recovery Steam Generator (Original in Colour)

2.4 Steam Turbine

Steam Turbine is a prime mover which converts the thermal energy in the high pressure, high-temperature superheated steam delivered by the boiler into mechanical energy, and the low-temperature steam exhausted from the turbine is discharged to a condenser.

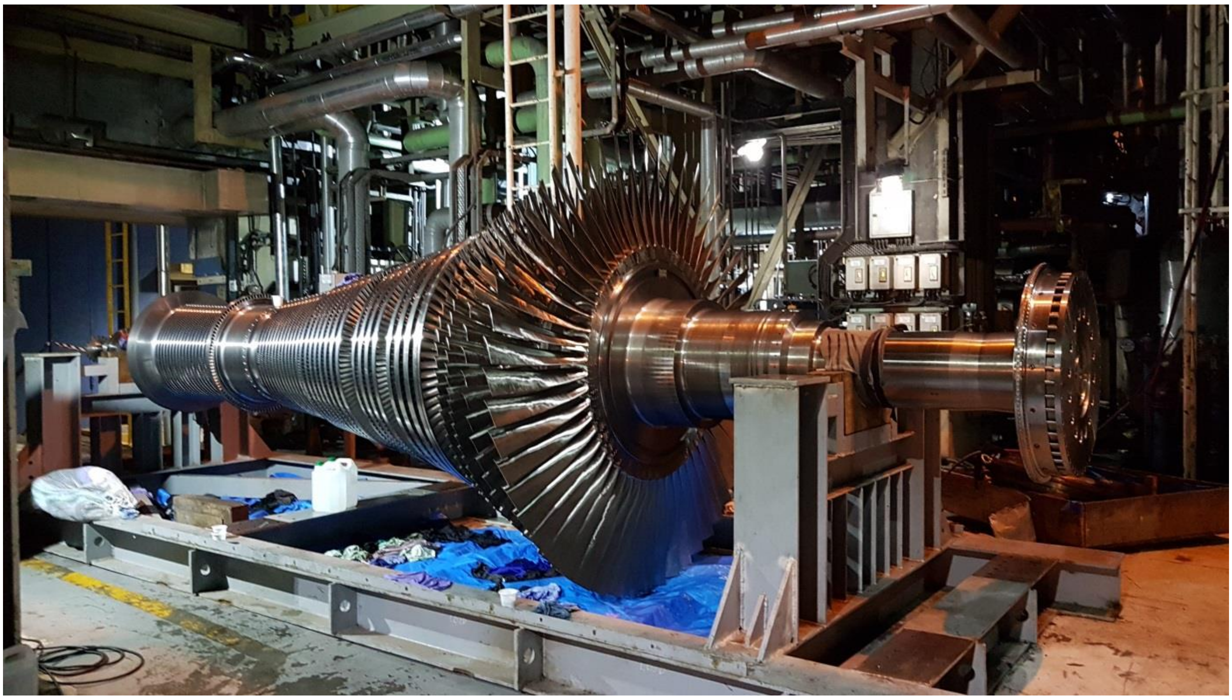

Figure 2.4 Steam Turbine (Original in Colour)

2.5 Start-Up of a Combined Cycle Power Plant

The combined cycle power plants are famous for a fast start-up compared to simple cycle steam power plants.

The start-up of a combined cycle power plant can be divided into mainly three operations. Those are [6]:

1. Gas turbine start-up
2. Heat Recovery steam Generator (Boiler) warm-up
3. Steam Turbine start-up

The gas turbine can be started and reached full load within a short time. However, when it comes to boiler warm-up and steam turbine start-up, it takes a significant amount of time. Usually, gas turbines can reach full speed no load (FSNL) condition from turning gear within 14 minutes. Heat recovery steam generator warming up can take vary according to the shutdown time. When a plant keeps at stop condition for more time, then the warming up time also takes more time.

3. COMBINED CYCLE POWER PLANT OVERVIEW

3.1 Plant Overview

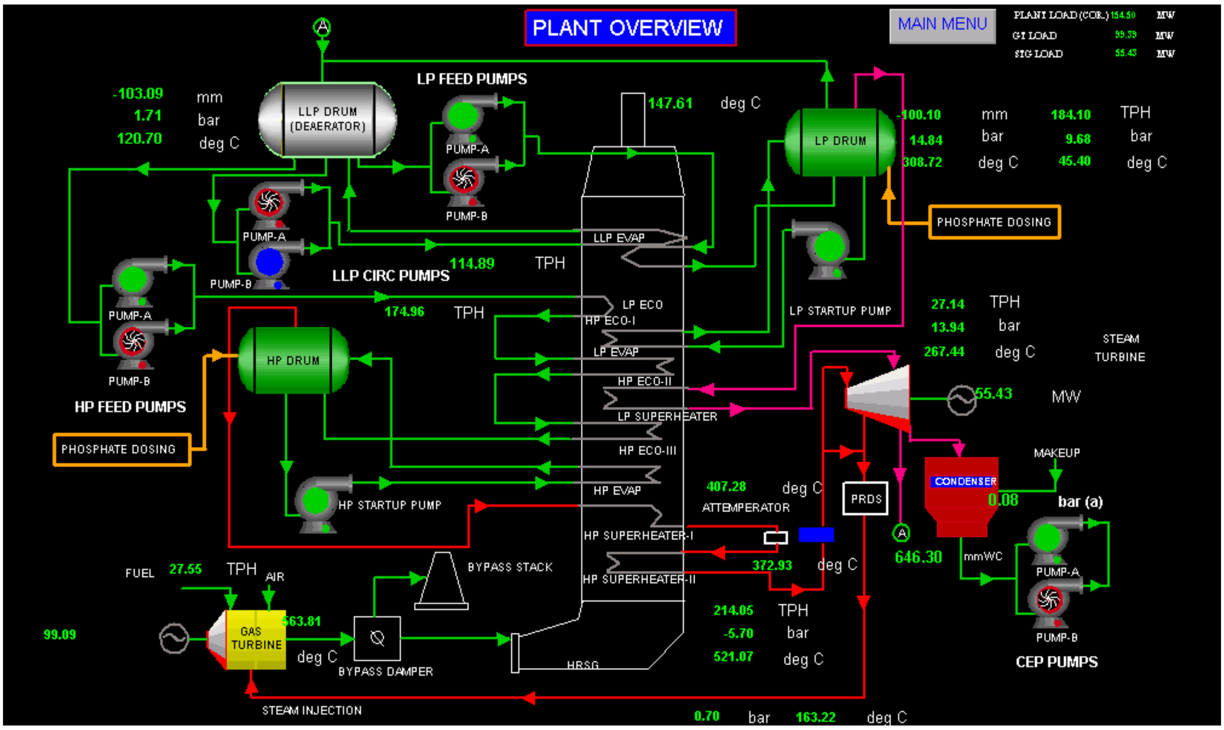

Figure 3.1 Plant Overview (Original in Colour)

The plant is a combined cycle power plant owned by Sojitz Corporation, and the rated capacity is 163 MW. The plant consists of one frame 9E, General Electric (GE) designed, and Bharat Heavy Electricals Limited (BHEL) manufactured gas turbine whose capacity is 110 MW, one Seimens designed BHEL manufactured steam turbine whose capacity is 57 MW, and one vertical Larsen and Turbo's 100 bar and 186TPH Heat Recovery Steam Generator.

Apart from GT, ST, and HRSG, the plant consists of a water treatment plant, fuel oil system, cooling water system, Steam Water Analysis System (SWAS), and Continuous Emission Monitoring System (CEMS).

High-speed diesel is the fuel uses for power generation. The diesel mixes with compressed air and burns inside the gas turbine combustion chamber. The part of the energy from the combustion is used to drive the gas turbine, which is coupled with a generator. The exhaust gas from the gas turbine goes through the HRSG (boiler), where the waste heat in the gas turbine exhaust is transferred to the water, produces high pressure superheated steam which runs the steam turbine to generate power.

3.2 Gas Turbine

The Gas Turbine is BHEL supplied Model PG 9171 E machine, and the rated capacity is 114 MW [7]. The Gas Turbine and its compressor are mounted on the single shaft. The exhaust end of the GT rotor is coupled with the Generator. The complete machine is installed in four enclosures, namely, the Accessory Compartment, Turbine Compartment, Load Coupling Compartment, and Generator Compartment. All enclosures have ventilation fans and are CO_2 protected with the provision of annunciations and isolations.

The PG 9171 E (Frame 9E) is a simple-cycle, single-shaft gas turbine with a 14 combustor, reverse-flow combustion system. The MS9001 gas turbine assembly consists of six major sections [8]:

- Air inlet
- Compressor
- Combustion system
- Turbine
- Exhaust
- Support systems

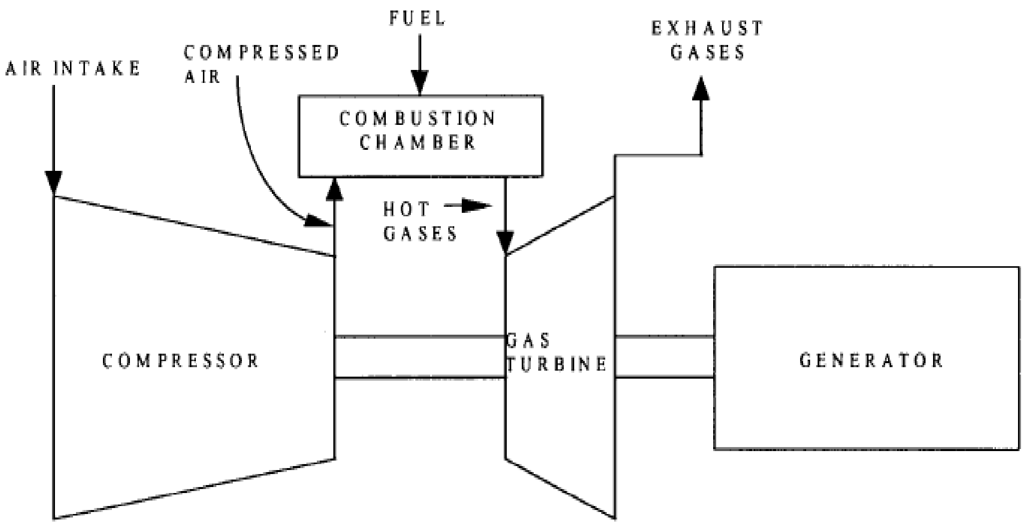

Figure 3.2 Components of gas turbine [8].

The Gas Turbine has a starting electric motor and a torque converter as starting device. Air intake to the compressor is through frame-mounted static filters. The fuel is received at fuel skid and passes through Low Pressure (LP) fuel filter, shaft driven warren fuel pump, HP fuel filter, flow divider and 14 numbers of annular combustors. The lube oil system comprises three lube oil pumps (one is AC driven, one is shaft driven, and the other one is DC driven) and two number jacking oil pumps (one AC & another DC driven) for Generator bearings. There are two hydraulic pumps – AC motor-driven & shaft driven. Cooling water is supplied from an off-base cooling water system. Further, the start-up and load control are with the help of a liquid fuel bypass control valve.

The generator is air-cooled and has a brushless excitation system, and the air intake is through frame-mounted static filters and is once through. The generator's power evacuation is via one step-up transformer (10.5 kV/220 kV). Isolation between generator and transformer is through one isolator and SF6 breaker. One Unit Auxiliary Transformer-1 (UAT-1), a step-down transformer (10.5 kV/6.6 kV), is located between the GT Generator and Main GT Transformer.

3.2.1 Air inlet system

Gas turbine air inlet system comprises of multi-stage inlet air filter house, inlet ducting and inlet plenum [9]. Atmospheric air is taken through the filter house located outside of the gas turbine building. Fine dust particles in the air up to 5 microns are removed in the filter house and sent to the compressor through the inlet duct and inlet guide vane. Then the air is compressed in the compressor and directs to the combustion chamber, where atomised fuel is mixed and ignited. After that, the combusted air is directed to the turbine, where the chemical energy is converted into mechanical energy and drives the gas turbine generator. The exhaust from the gas turbine is directed to the HRSG through the exhaust duct and diffusor.

Figure 3.3 Gas Turbine Filter House (Original in Colour)

3.2.2 Compressor

The compressor is an axial-flow compressor located after the inlet guide vane and comprises 17 stages of rotor and stator blades. The primary function of the compressor is to supply high-pressure air to the combustion chambers. A portion of compressed air is used as cooling air for the turbine nozzles, turbine wheels, transition pieces, and other portions of the hot gas path.

3.2.3 Combustion System

The combustion system is a reverse-flow type with 14 combustion chambers arranged around the compressor discharge casing periphery. This system also includes fuel nozzles, spark plug, ignition systems, flame detectors, and crossfire tubes. The function of the combustion system is to supply heat energy to the gas turbine cycle. This is accomplished by burning fuel mix with compressor discharge air. The hot gas generated from burning fuel in the combustion chambers is used to drive the turbine.

3.2.4 Turbine

The turbine has three stages. The energy in the combusted high-pressure air is converted to mechanical energy by the turbine, which is coupled with a generator.

3.2.5 Exhaust system

The exhaust system consists of an exhaust frame and diffuser. The flue gas discharged from the turbine third stage enters the diffuser section where the flue gas's velocity is reduced, and pressure is recovered. Then the flue gas is directed to the HRSG through the exhaust duct.

3.2.6 Support system

The support system helps to operation and protection of the entire gas turbine. The support system consists of the following:

- Lubricating oil system
- Hydraulic oil system
- Trip oil system
- Fuel system
- Cooling and sealing air system
- Cooling water system

- Starting system
- Variable inlet guide vane system
- Ventilation system
- Gas turbine compressor water wash system
- Fire protection system

3.2.7 Lubricating oil system

The system is a closed-loop, forced feed system including a lube oil tank, main lube oil pump (shaft driven), auxiliary lube oil pump, jacking oil pump, emergency lubricating oil pump, coolers, filters and protection devices such as pressure relief valve, bearing header pressure regulating valve and lube oil temperature regulating valve. The lube oil system functions are lubricating the shaft, including accessory gearbox and supply oil for hydraulic system, trip oil system, and torque convertor.

Lubricating oil is circulated to the three main turbine bearings, generator and exciter bearings, and the turbine accessory gear.

3.2.8 Hydraulic oil system

The system supplies high-pressure fluid to operate the control components such as fuel stop and control valve assembly, fuel oil bypass valve assembly and variable inlet guide vane mechanism. The system consist main hydraulic supply pump, an auxiliary supply pump, filters, a transfer valve, hydraulic supply manifold assembly and accumulator manifold assembly.

3.2.9 Trip oil system

The trip oil for the turbine is taken from the lubricating oil system, and the system causes component devices to trip in an emergency.

3.2.10 Fuel oil system

A liquid fuel system pumps and distributes fuel as supplied from off base fuel forwarding and filtration units to fourteen nozzles of the combustion system. The fuel flow is then divided into fourteen parts using a flow divider and supplied to the combustion chambers. The system includes a low-pressure fuel strainer, fuel oil stop valve, liquid fuel pump, fuel pump discharge relief valve, fuel bypass valve assembly, electrohydraulic servo valve assembly, hydraulic oil filter, high-pressure fuel filter, flow divider, magnetic pickups and selector valve assembly.

3.2.11 Cooling and sealing air system

Compressed air from the gas turbine compressor issued for pressurising the bearing seals in the gas turbine, cooling of various parts of the turbine section and supplying operating air for air operated valves. Cooling and sealing air is provided from two connections on the compressor casing at the fifth stage and is directed externally to each of the three bearings.

3.2.12 Cooling water system

The cooling water system is a closed cooling water system designed to accommodate the turbine's heat dissipation requirements, the generator lubrication system, the generator cooling system, and the atomising air cooler.

The cooling water system consists of on-base and off-base mounted components. The on-base mounted components include the heat exchangers, flow regulating valves, orifices, hand-operated valves, and off-base components, including radiator banks, fin fans, cooling water pumps and surge tank.

Cooling water is circulated through lube oil heat exchangers to keep the lubricant in the system at a required temperature and through atomising air cooler to maintain the temperature at a required level. Apart from that, the cooling water is supplied to the jackets surrounding the turbine support legs.

3.2.13 Starting system

The starting system in a gas turbine rotates, cranks, and brings to operating speed before firing. This is accomplished by an induction motor operating through a torque converter. The starting system's primary function is to accelerate the turbine up to self-sustaining speed from where the turbine can accelerate on its own to the full speed.

During start-up, the starting system provides three main functions:

- Start the gas turbine rolling (a breakaway from standstill)
- Accelerate the turbine to a speed where it can be fired

- Further, accelerate the turbine to a self-sustaining speed (a speed at which gas turbine develops net positive power output)

3.2.14 Variable inlet guide vane

Variable inlet guide vanes prevent any possible compressor pulsation during start-up and shutdown and operation under partial load conditions. The vanes are automatically positioned within their operating range (34 – 84 DGA) to control system operating temperature limits for normal loaded operation or the control system pulsation protection limits during the start-up and shutdown sequences. When the turbine is reset, the IGVs are at the designed closed position. The closed IGV angle position is determined to limit the airflow through the compressor during the accelerating and decelerating sequence. Apart from the above functions, the IGV can be modulated to control gas turbine exhaust temperature.

A hydraulic oil system operates the inlet guide vane, and a SPEEDTRONIC control system controls it.

3.2.15 Ventilation system

The ventilation system is provided for the accessory, turbine, exhaust, load gear, and generator compartments. The primary purpose of the system is to remove heat dissipated from the equipment inside the compartments.

3.2.16 Gas turbine compressor water wash system

Over the period, the gas turbine can experience a loss of performance due to contaminants' deposits on the internal components such as compressor rotor and stator blades. These deposits can be cleaned with a water-detergent solution by using a water wash system. The system consists of on-base components, including motor-operated water injection valve and water manifold spray nozzles, and off-base components including a water storage tank, a detergent tank, temperature sensors, centrifugal water pumps and a positive displacement detergent pump.

3.2.17 Fire protection system

The fire protection system for gas turbine comprises detection and extinguishing system. The heat detectors are used to detect the fire, and carbon dioxide gas is used for extinguishing the fire. The system works if fire detects and includes addressable fire alarm panel AFP-300, heat detectors, carbon dioxide cylinder bank and addressable monitor modules. The protection is provided to the accessory compartment, turbine compartment, load compartment, generator compartment and inside the generator.

3.3 Heat Recovery Steam Generator

The type of Heat Recovery Steam Generator (HRSG) uses in the plant is unfired, dual pressure, top supported with natural circulation, and capable of operating under sliding mode. The HRSG aims to recover waste energy in the flue gas discharged from the gas turbine. The HRSG consists of mainly three circuits [10]: High Pressure (HP) Circuit, Low pressure (LP) Circuit and Low Low Pressure (LLP) circuit. The HRSG (boiler) in the plant works on a natural circulation principle. A specially designed ejector is provided to ensure smooth circulation through all the evaporators.

The steam is generated in the HRSG in two pressure levels. One is called low pressure (LP) steam at 14.75 bar(a), and the other is called high pressure (HP) steam with the pressure value sliding based on load requirement. The full-load steam parameter is about 104.75 bar (a) and 518 ° C temperature.

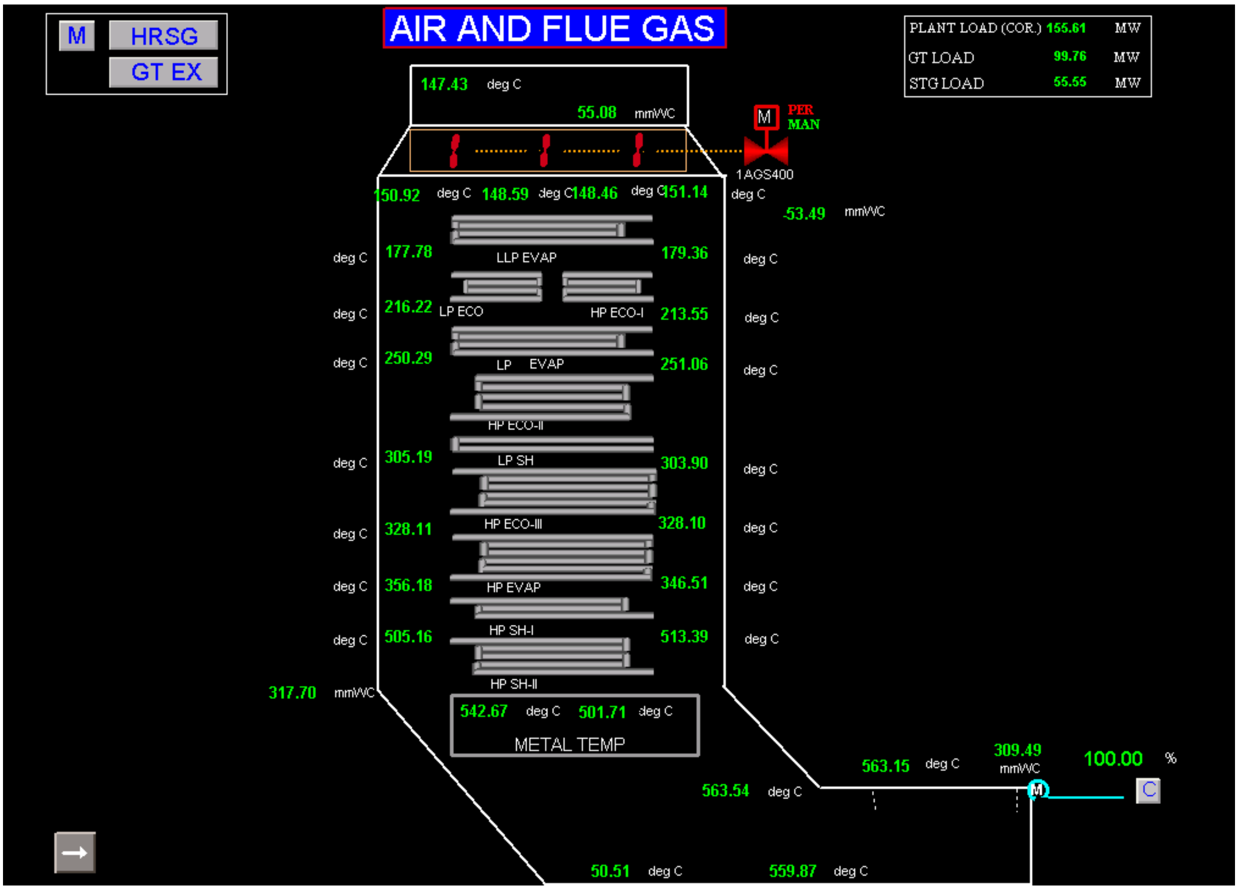

Figure 3.4 Layout of Heat Recovery Steam Generator (Original in Colour)

3.3.1 High-Pressure (HP) circuit

The high-pressure circuit comprises three economisers, an evaporator and two superheater coils. Apart from the heat exchanger coils, the HP circuit consists of an HP drum, high-pressure boiler feed pumps, HP start-up pump, Attemperator, start-up vent, ejector and downstream drains [11].

The HP economiser recovers the remaining heat contained in the flue gas after the HP evaporator tube coils. The HP evaporator produces steam through a natural circulation loop to and from a high-pressure boiler drum. The Superheater coil heats the saturated steam from the high-pressure drum to the required level.

The HP drum functions are to ensure good mixing of feed water and water from the evaporator, constitute a water reserve required for the controlled circulation system, allow water expansion during start-up, ensure water and steam separation, and dosing of chemicals for maintaining steam purity.

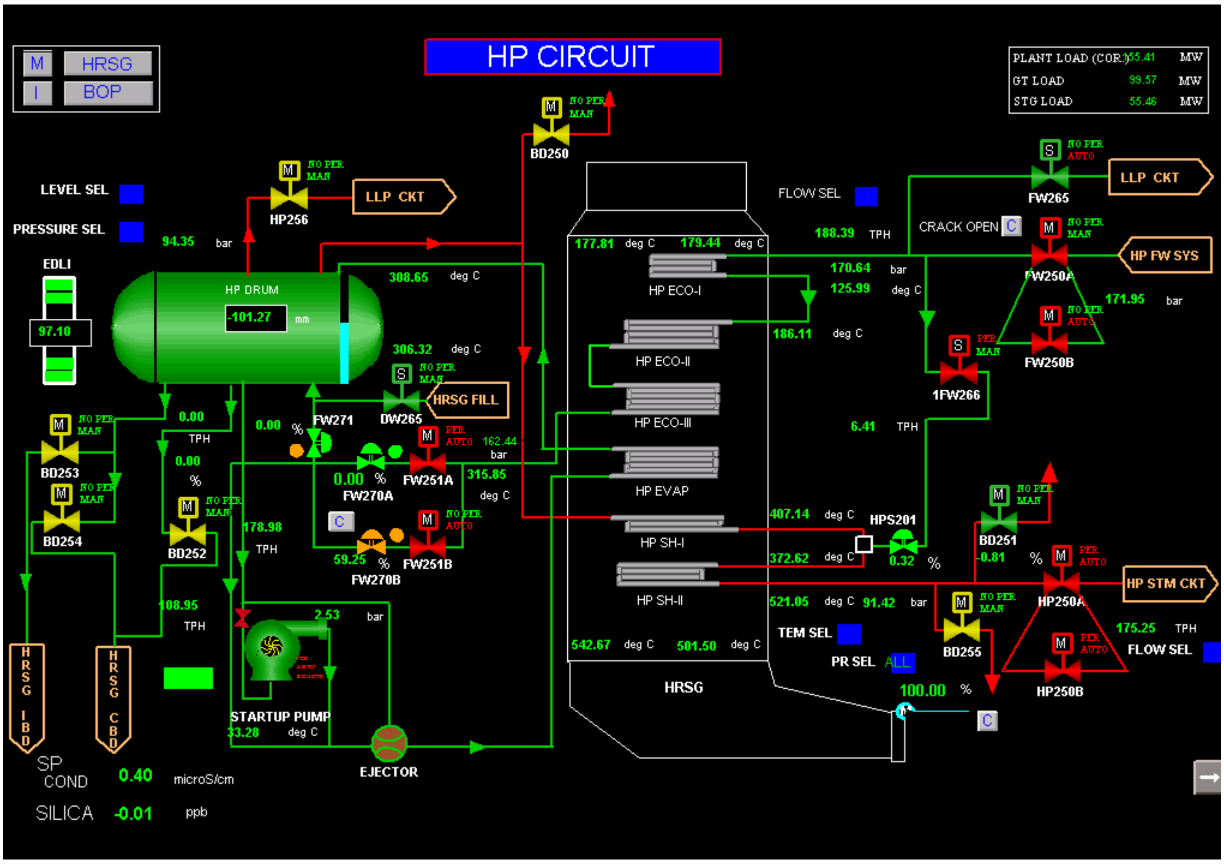

Figure 3.5 HP Circuit (Original in Colour)

The HP circuit's water is drawn from the LLP drum using an HP boiler feed pump through HP Economiser-1, 2 & 3. The portion of the water is circulated through the HP evaporator circuit to the HP drum by an ejector, and the remaining portion is sent directly to the HP drum. The saturated steam draws from the HP drum top circulated through HP Super Heater (SH) module 1 & 2, where the around 100 bar and 520 °C superheated steam is generated and directed to the steam turbine.

3.3.2 Low-Pressure (LP) circuit

The low-pressure circuit comprises one economiser, one evaporator and one superheater module. Apart from the heat exchanger coils, the LP circuit consists of an LP drum, Low-pressure boiler feed pumps, LP start-up pump, start-up vent, ejector and downstream drains [11].

The LP economiser recovers the remaining heat contained in the flue gas after the evaporator tube coils. The LP evaporator produces steam through a natural circulation loop to and from a low-pressure boiler drum. The superheater coil heats the saturated steam from the low-pressure drum to the required level.

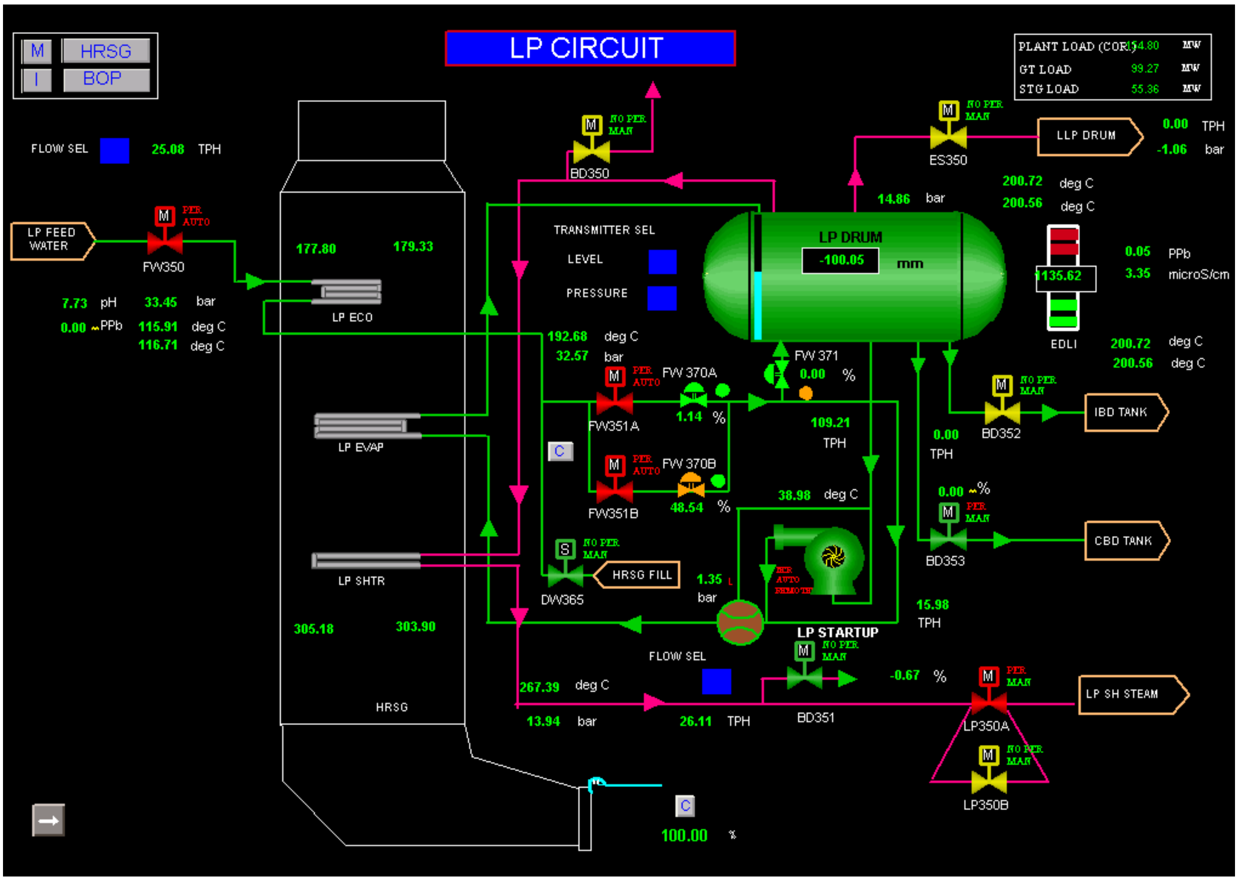

Figure 3.6 LP Circuit (Original in Colour)

Water for the LP circuit is drawn from the LLP drum using an LP boiler feed pump through LP Economizer. The portion of the water is circulated through the LP evaporator circuit to the LP drum by an ejector, and the remaining portion is sent directly to the LP drum. The saturated steam draws from the LP drum top circulated through the LP superheater module, and 14 bar and 270 °C superheated steam is generated and directed to the steam turbine.

3.3.3 Low, low pressure (LLP) circuit

A low-low pressure circuit comprises an evaporator module. Apart from the evaporator circuit, the LLP circuit consists of an LLP drum and LLP recirculation pumps [11].

The LLP evaporator recovers the remaining heat contained in the flue gas after LP and HP economiser bundles. The LLP evaporator produces saturated steam (130 °C temperature) through a forced circulation loop to and from the LLP boiler drum.

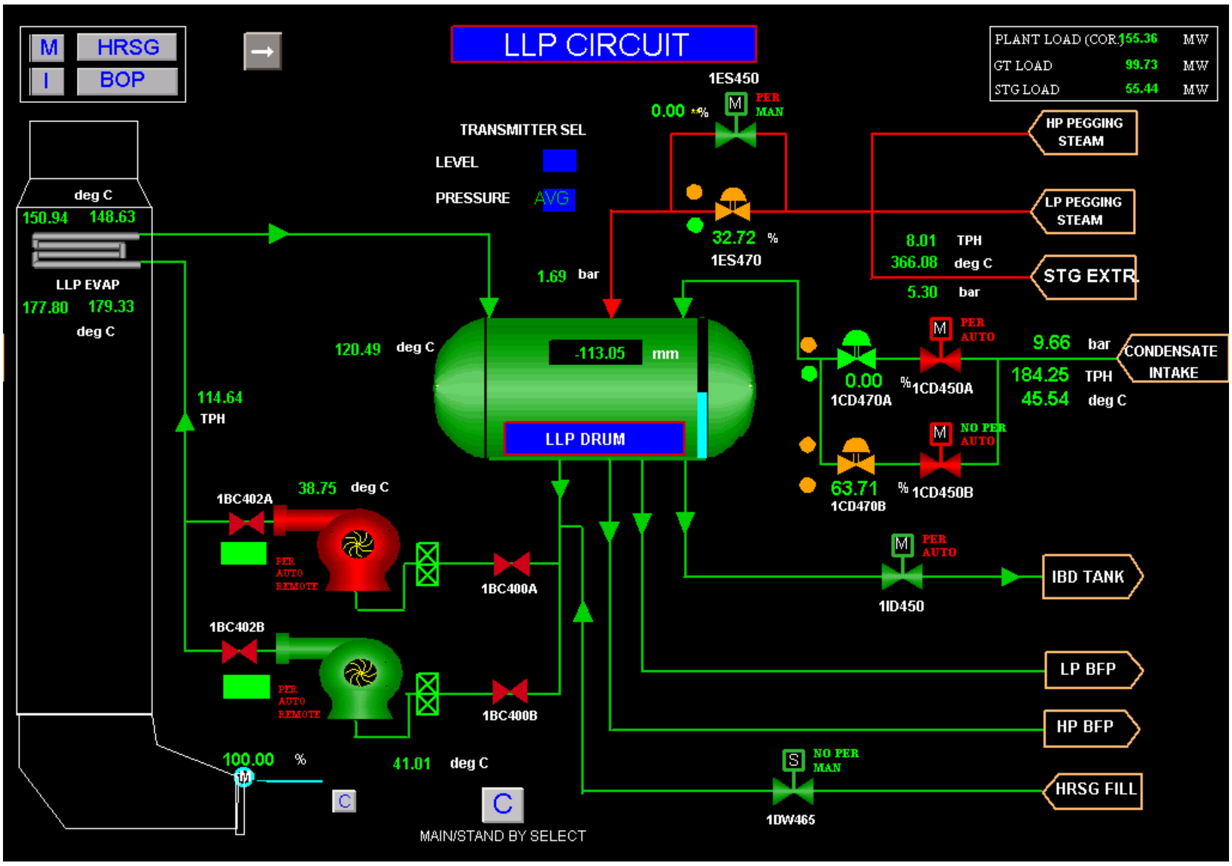

Figure 3.7 LLP Circuit (Original in Colour)

Water for the LLP circuit is drawn from Condenser hot well using condensate extraction pumps directly to the LLP drum.

3.4 Steam Turbine

The steam turbine uses in the plant is Siemens designed BHEL manufactured HNK 71/3.2-4. The inlet HP steam temperature is 515 ° C, and the inlet HP steam pressure is 99.75 bar (a). The inlet LP steam temperature is 254 ° C, and the inlet LP steam pressure is 12.9 bar (a).

The steam turbine consists of the following components [12]:

- HP turbine
- LP turbine
- HP & LP Emergency stop valves
- HP & LP Governor Valves
- Gland steam system

- HP & LP Bypass system
- Lube oil system
- Jacking oil system
- Turning gear system
- Control oil system
- Condenser
- Condenser vacuum system
- Steam turbine drains

3.4.1 HP steam path through turbine

The HP steam coming from the HP circuit is divided into two identical streams and passes through Emergency Stop valves (ESV) and Governor valves to the HP turbine. There are two ESV and governor valve in the HP steam system.

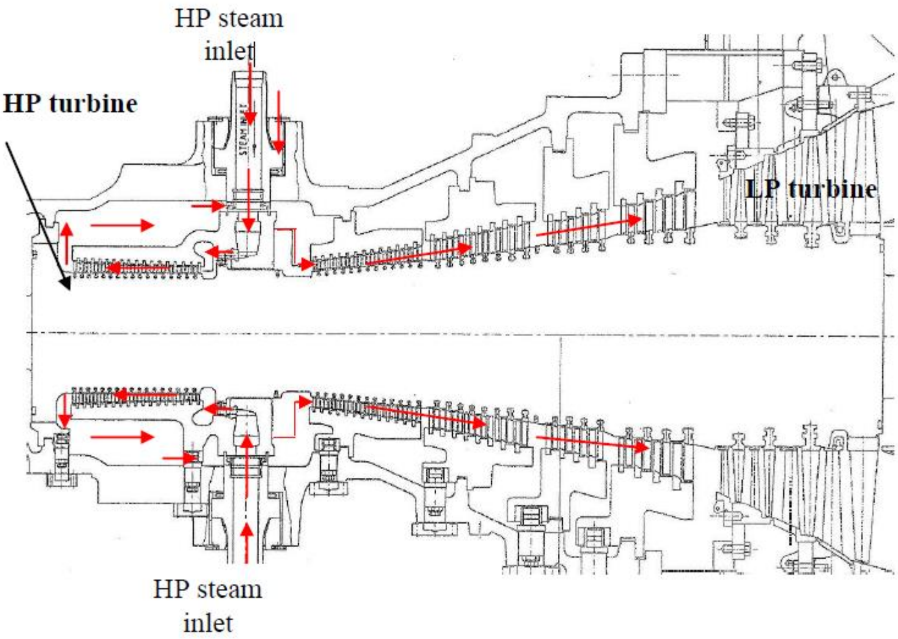

Figure 3.8 HP Steam Path through Turbine [13].

3.4.2 Operation of HP ESVs and governor valves

The HP ESVs open after achieving steam qualities such as temperature, pressure and steam chemical parameters, including pH, conductivity and silica. Apart from the steam qualities, two criteria are called X1 & X2, have to be satisfied.

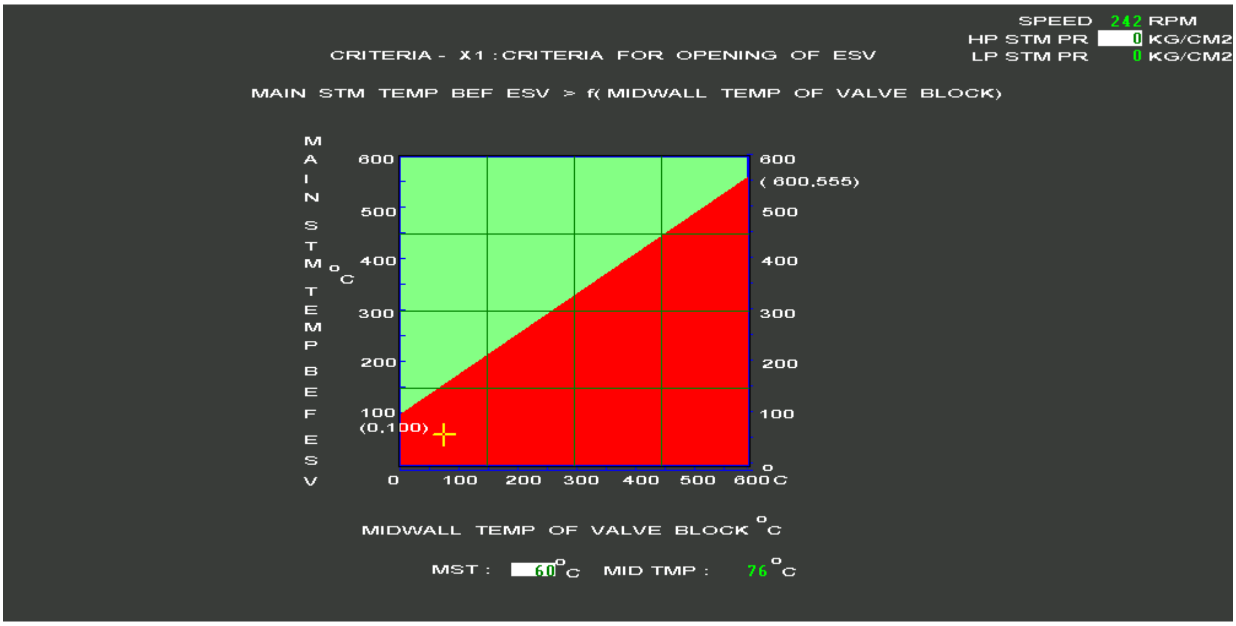

Figure 3.9 X1 Criteria (Original in Colour)

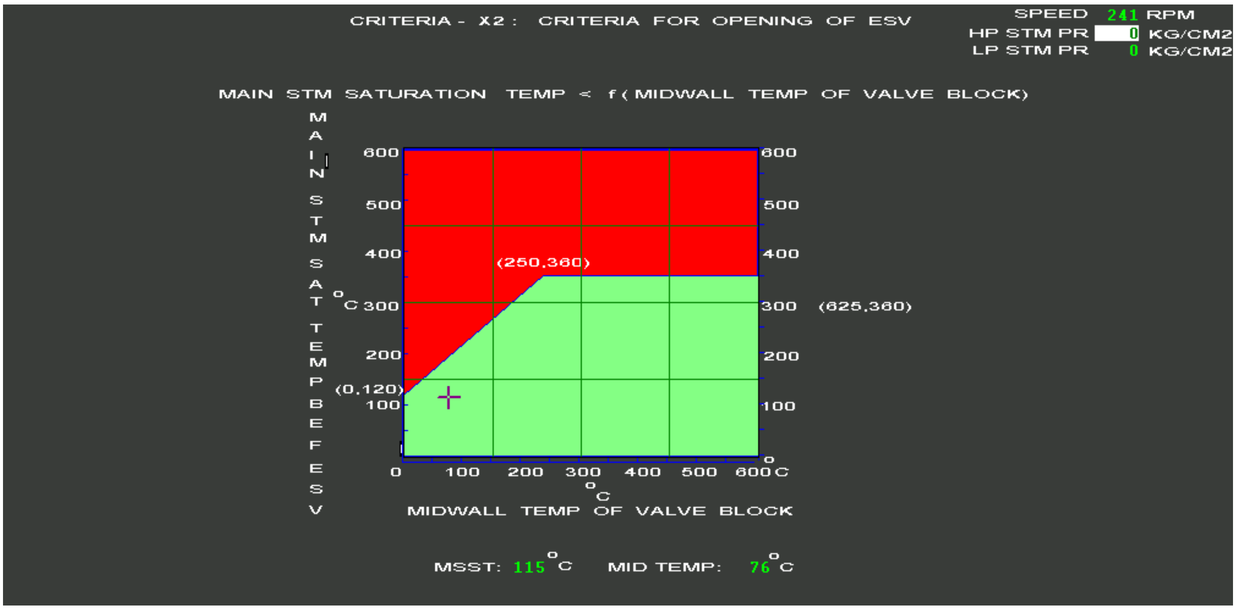

Figure 3.10 X2 Criteria (Original in Colour)

Table 3.1 Steam Conditions during Start-up

Start-Up Type	Steam Temperature/ (°C)	Pressure/ (bar)
Hot	450	55
Warm	390	55
Cold	390	55

After opening ESVs, governor valves open, and the steam turbine speeds up to 600 rpm and then to 3000 rpm (full speed). There are two criteria, X4 & X5 have to be satisfied to open governor valves, and X7 criteria have to be satisfied to speed up to rated speed.

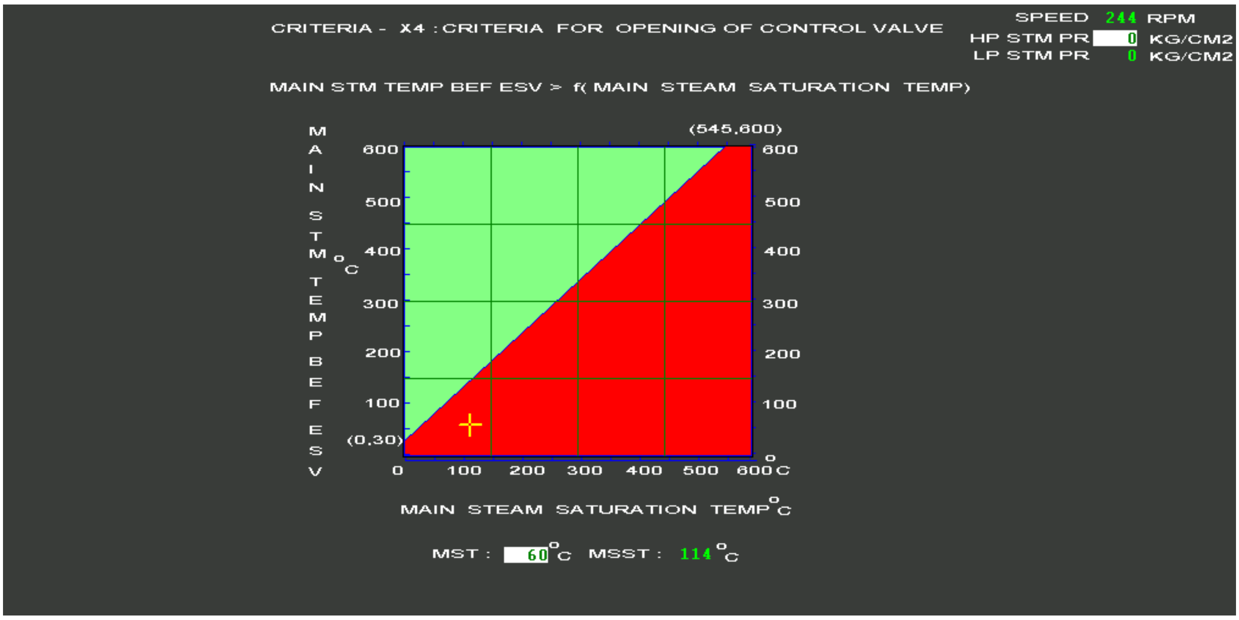

Figure 3.11 X4 Criteria (Original in Colour)

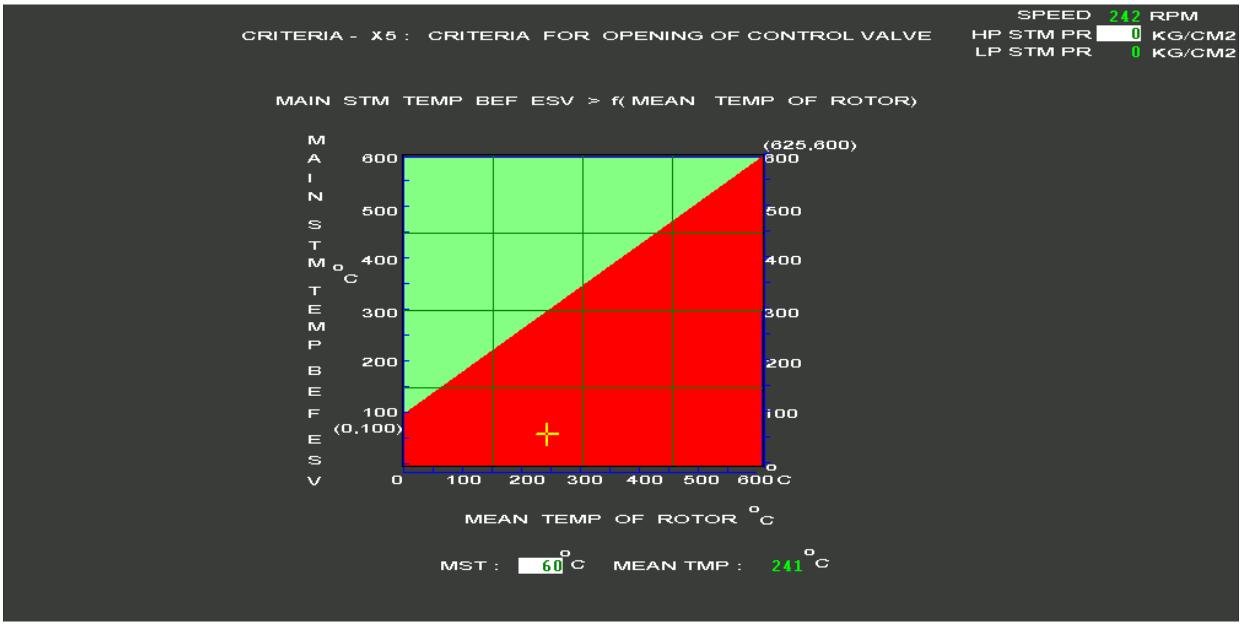

Figure 3.12 X5 Criteria (Original in Colour)

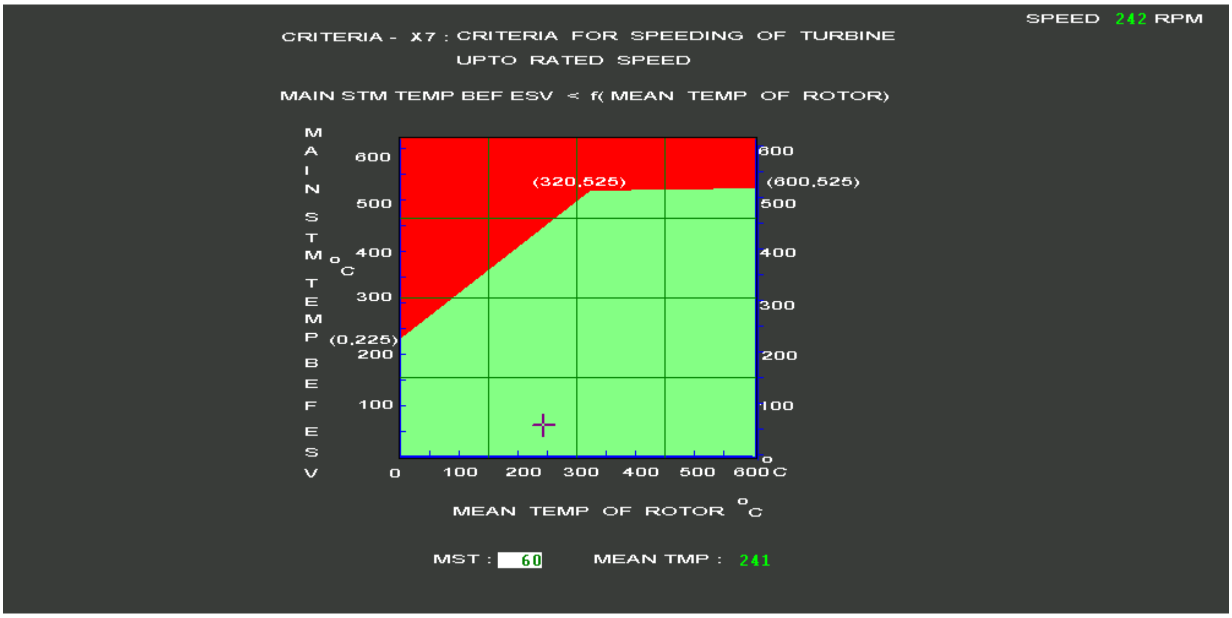

Figure 3.13 X7 Criteria (Original in Colour)

3.4.3 LP steam path through turbine

The LP steam coming from the LP circuit passes through ESVs and Governor Valves to the LP turbine. There are only one ESV and governor valve in the LP steam system. The LP ESV and governor valve open after achieving steam qualities such as temperature, pressure and steam chemical parameters, including pH, conductivity and silica. The LP steam flows through the LP portion of the turbine, and it mixes with the expanded HP steam which comes from the HP turbine. After that, exhaust flow to the condenser

3.4.4 Gland steam system

This system aims to prevent leakage of steam from the HP gland into the atmosphere and prevent atmospheric air ingress into the LP turbine through the LP gland. The HP Gland is located at the front end of the turbine, and the LP gland is located at the rear end of the turbine.

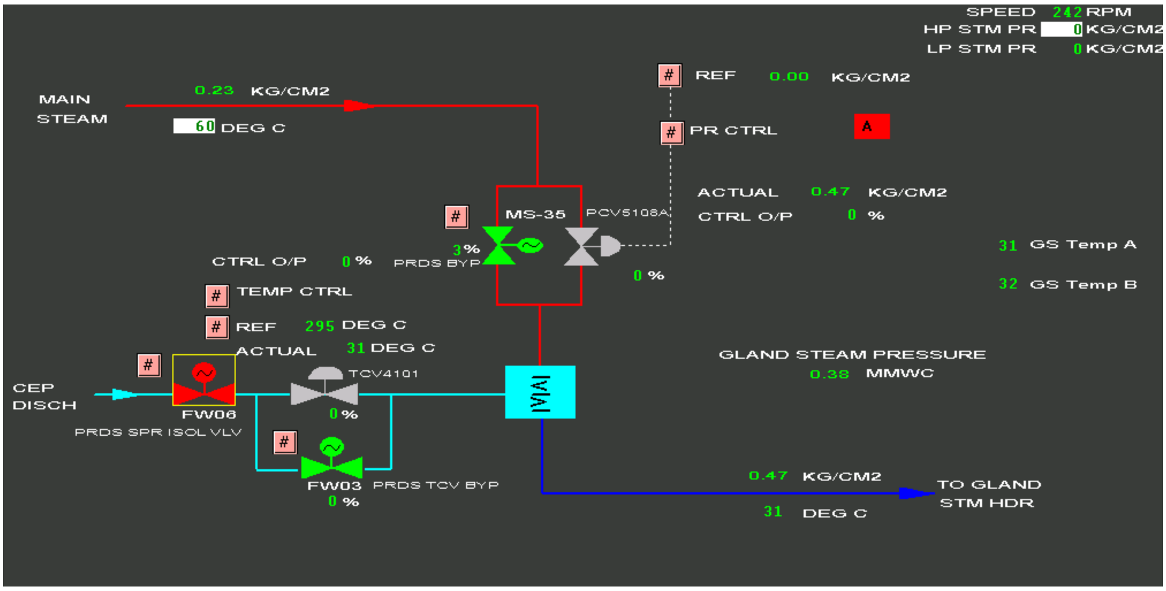

Figure 3.14 Auxiliary Pressure Reducing & De–Superheating (APRDS) System (Original in Colour)

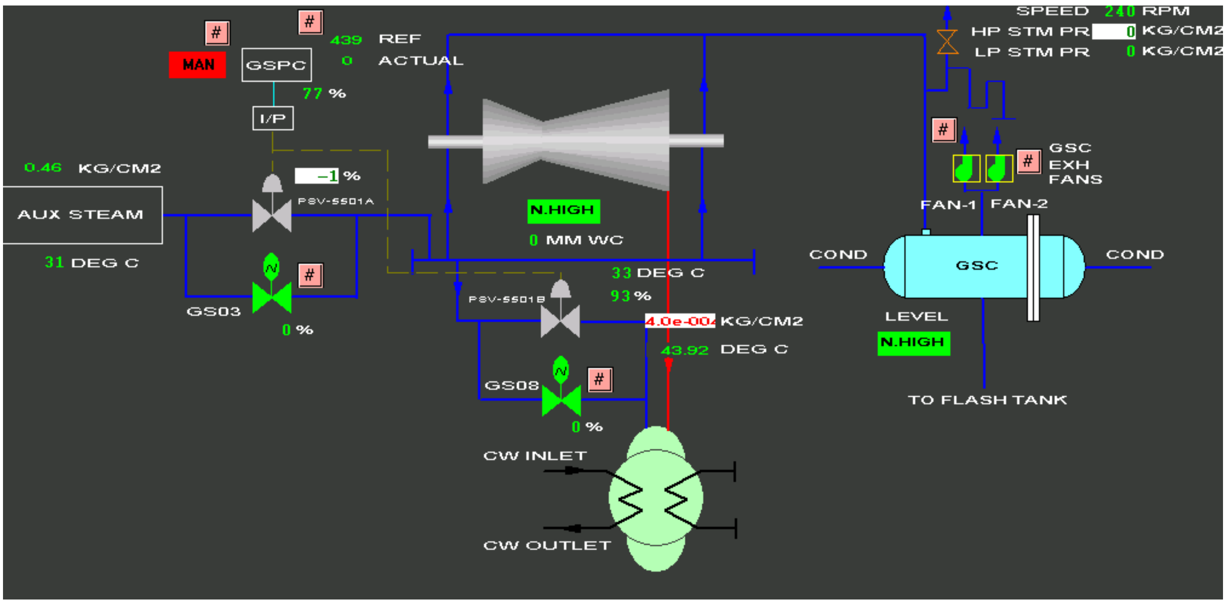

Figure 3.15 Gland Steam System (Original in Colour)

Gland steam system comprises gland steam APRDS header and control valves and gland steam main header and control valves.

Before admitting the gland steam to the gland steam main header during start-up, the gland steam APRDS header temperature should be increased above 280 °C. Achieving APRDS temperature is accomplished by heating the gland steam APRDS header using HP main steam. Generally, this operation takes a significant amount of time during all the start-up.

During start-up, PVC5501A CV is at the close position; after opening the HP Main steam valve, the PSV5108A CV opens to warm up the gland steam APRDS header. After PARDS header temperature reaches 280 ºC, the PCV5501A opens and establishes gland steam pressure. Generally, the gland steam header pressure has to be maintained between 400 – 600 mmWC.

When ST load increases, the leak-off steam through the gland is sufficient to maintain gland steam header pressure. So, the supply from the gland steam APRDS stops.

3.4.5 Condenser and make-up system

The surface condenser furnish comprises a single shell, single pressure, two passes, and rectangular type with divided water boxes, and located below the steam turbine, with condenser tubes' axis normal to the steam turbine's longitudinal axis. The condenser is provided with 6006 m2 of effective heat transfer area equally divided into two tubes bundles.

The condenser's primary function is to condense steam from the steam turbine exhaust and provide a condensate storage chamber. The condenser's secondary function is to deaerate & reheat the condensate water internally.

Circulating water flows inside the tubes while steam condenses outside the tubes. The total of 9420 impingement tubes of 25.4 mm O.D is 90-10 Cu-Ni (SB 111 C70600) are there in two tube bundles. The condenser shell is rectangular & is fabricated from carbon steel plates.
The condenser is designed for 14055 m^3/hr of circulating water flowing inside the tubes at an inlet temperature 31.5 ℃ & to maintain an operating pressure of 0.078 bar(a) at the turbine exhaust neck when condensing 180240 kg/hr steam.

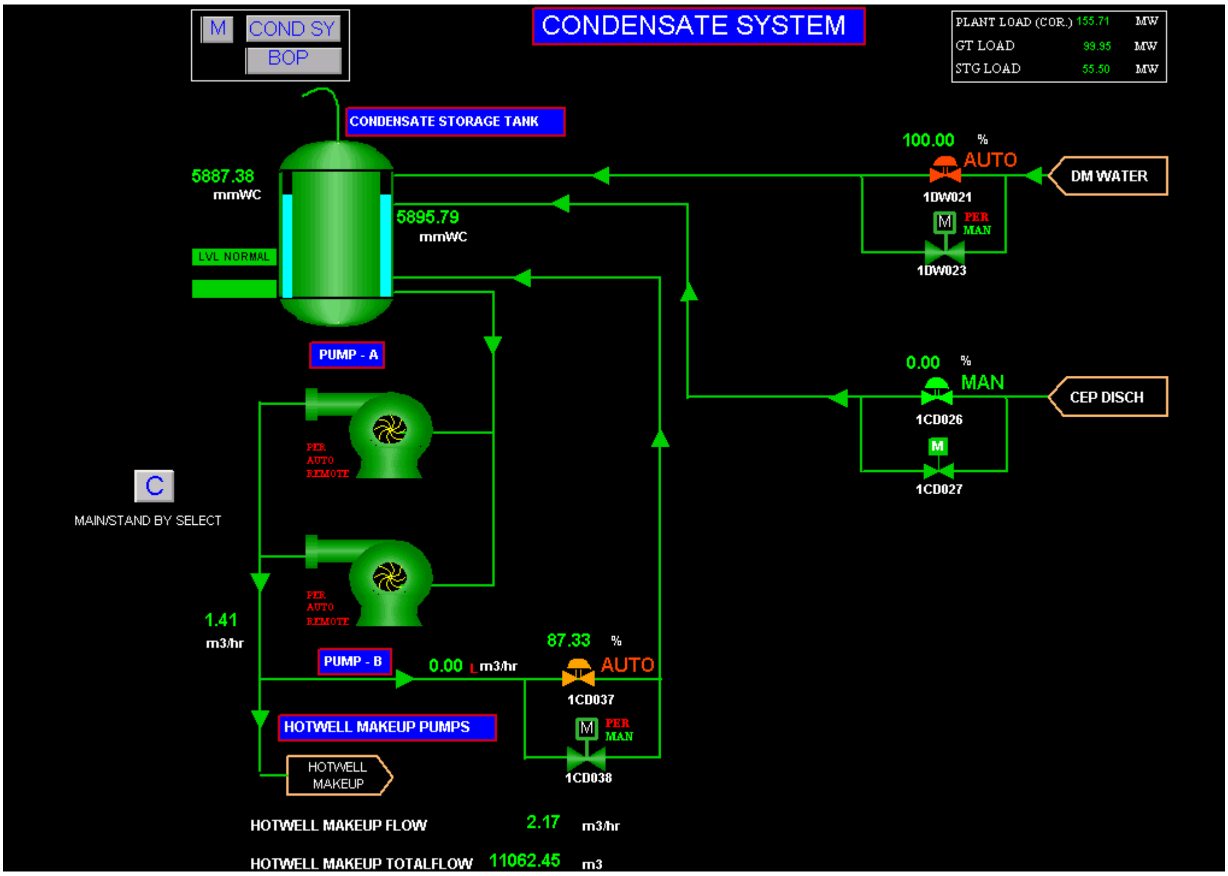

Figure 3.16 Condenser Make-up system (Original in Colour)

The condenser hot-well is sized for a retention capacity of 11 m^3 of condensate. The makeup water provided from hot-well makeup pumps saturated with oxygen is let into the condenser through a STROKE make sprayer. The sprayer makes the makeup water atomise into fine droplets, thereby allowing dissolved oxygen in makeup water to get separated. This gas escapes the condenser through the air off-take pipe, which is connected to vacuum pumps.

The steam dumping provisions are made in the condenser to recover steam that has been bypassed around the steam turbine generator. The condenser is provided with flash tanks to receive drains from the HP/LP extraction piping.

3.4.6 Condenser vacuum system

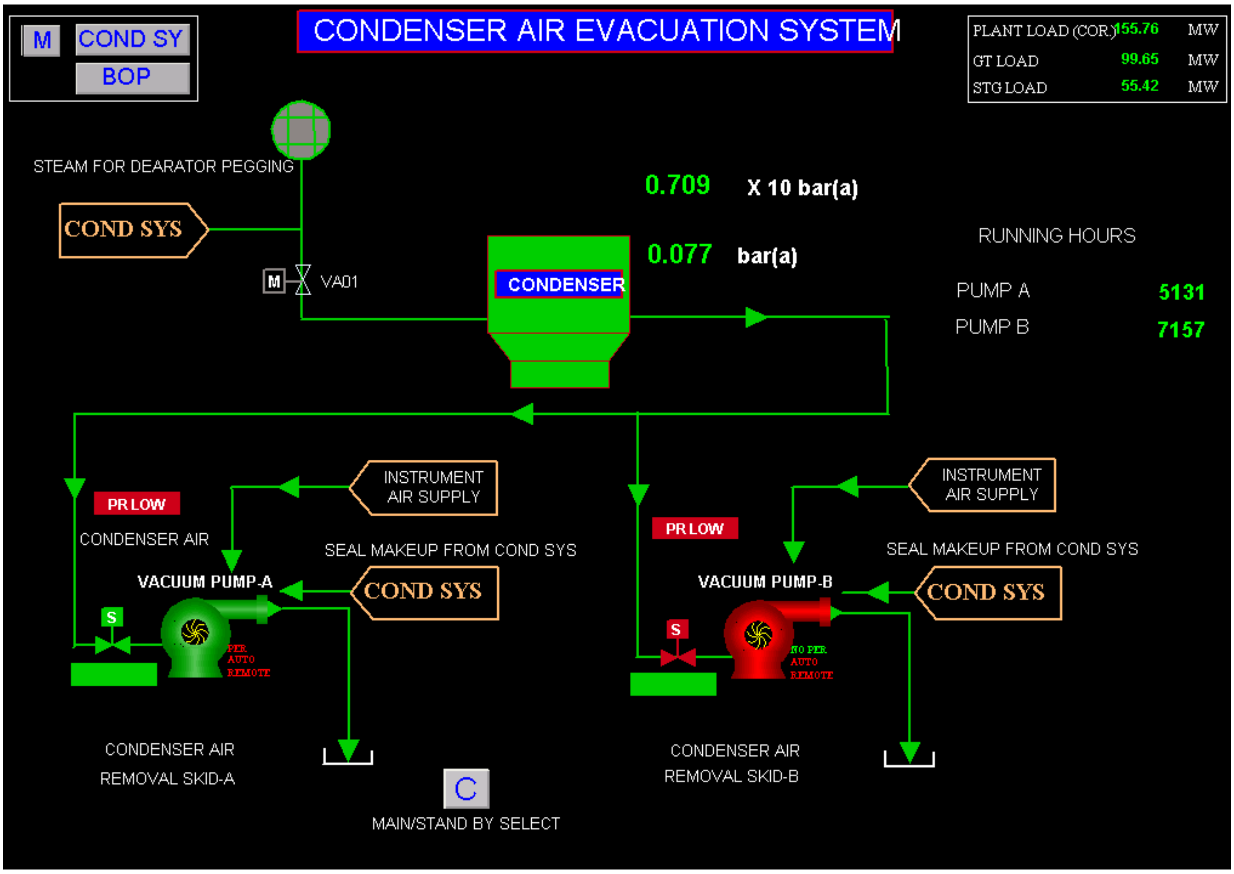

Figure 3.17 Condenser Air Evacuation System (Original in Colour)

The vacuum system is provided to the condenser to remove non-condensable gases when steam condenses and maintain condenser pressure at the required level. The system consists of two vacuum pumps and their accessories and a vacuum breaker valve.

During start-up, one vacuum pump starts after gland steam establishes, and the start condition for the vacuum pump satisfied. The second vacuum pump starts when condenser pressure falls below 0.8 bar (a). When the condenser pressure reaches the 0.2 bar (a) vacuum breaker closes, and the steam bypass operation can be started. Once the condenser pressure reaches 0.07 bar (a) standby vacuum pump stops.

3.4.7 Lube oil system

The lube oil system functions are to lubricate the shaft and supply low-pressure control oil for the hydraulic system. The system comprises a lube oil tank, main lube oil pump (shaft driven), auxiliary lube oil pump, emergency lubricating oil pump, lube oil coolers, lube oil filters, and protection devices [13]. The system supplies lube oil to one turbine thrust bearing, two turbine journal bearings, two generator journal bearings, and one exciter journal bearing.

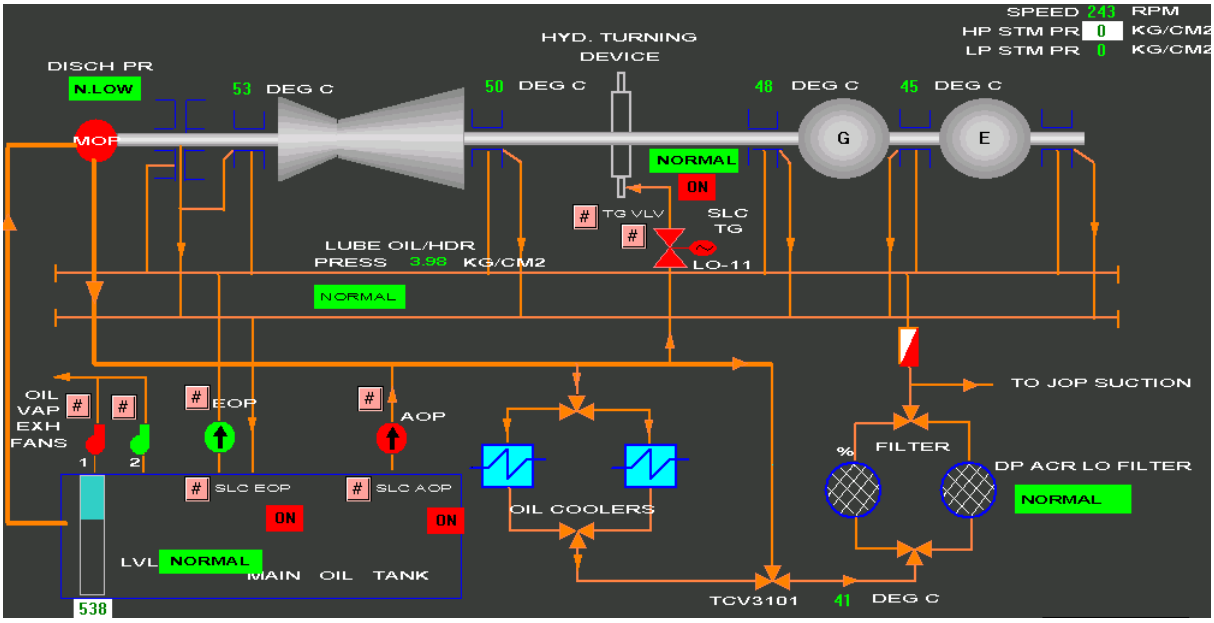

Figure 3.18 ST Lube Oil System (Original in Colour)

Two jacking oil pumps draw oil from the lube oil tank and supplies to the journal bearings to lift the turbine and generator shaft during turning gear operation. Apart from this, lube oil discharge is used to turn the turbine during the turning gear operation. A turning gear Motor Operated Valve (MOV) and impulse turbine have been provided to accomplish turning gear operation.

3.4.8 Control oil system

The purpose of the control oil system is to operate steam turbine ESVs and governor valves. The system consists of two systems:

1. Primary control oil system – The system incorporates a low-pressure lube oil system, and the low-pressure control oil system achieves the protection of the turbine.
2. Secondary control oil system - The system incorporates a high-pressure control oil system, and the operation of the ESVs and governor valves is achieved by the high-pressure control oil system.

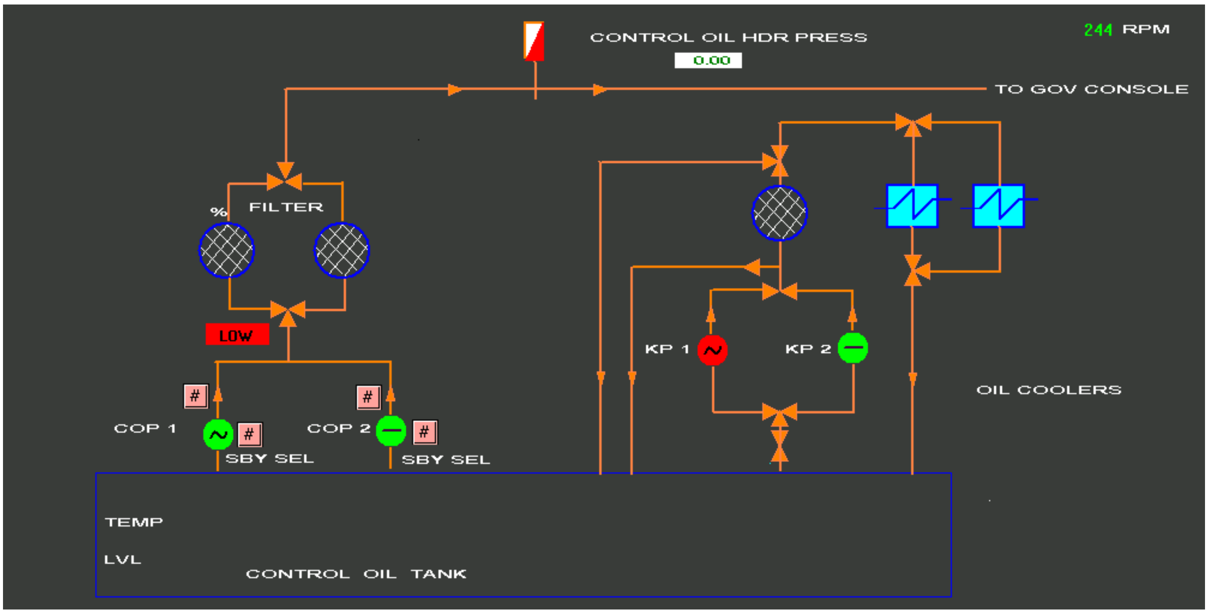

Figure 3.19 ST Control Oil System (Original in Colour)

3.4.9 HP and LP steam bypass system

Achieving steam conditions such as temperature, pressure, and chemical parameters, including pH, conductivity, and silica, is vital during start-up before admitting steam to the steam turbine. This protects the turbine in the long run. The steam bypass system is used to achieve steam parameters during the start-up by dumping steam into the condenser.

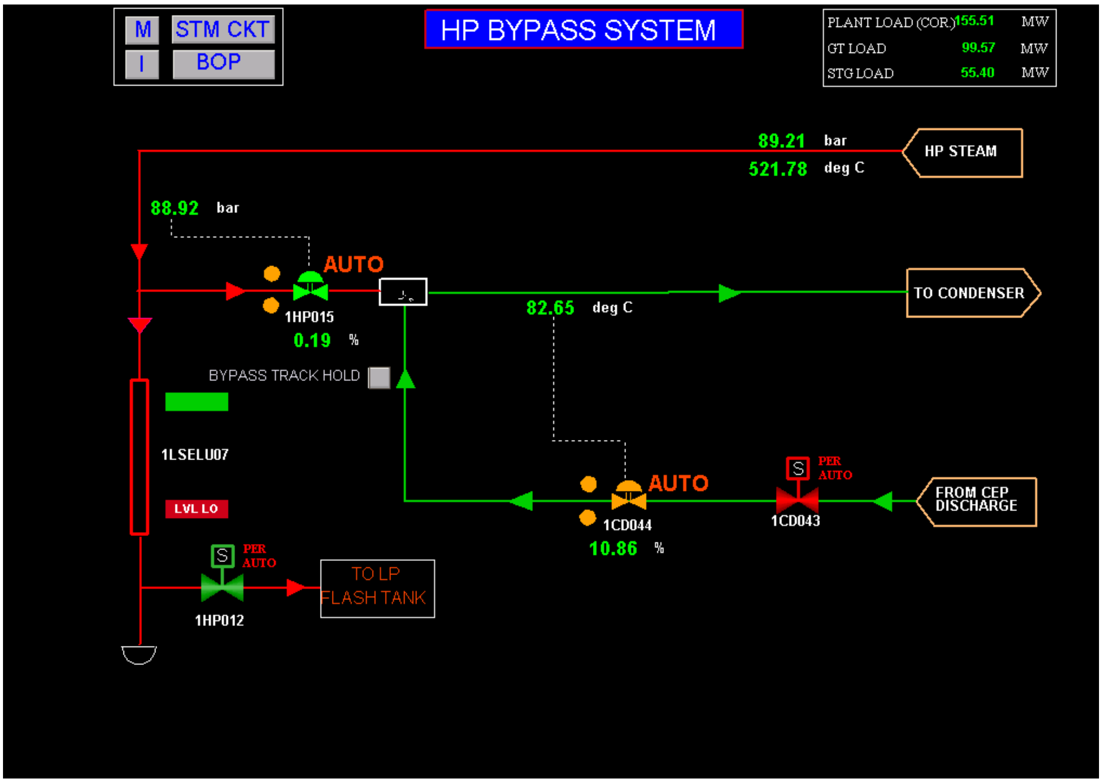

Figure 3.20 HP Bypass system (Original in Colour)

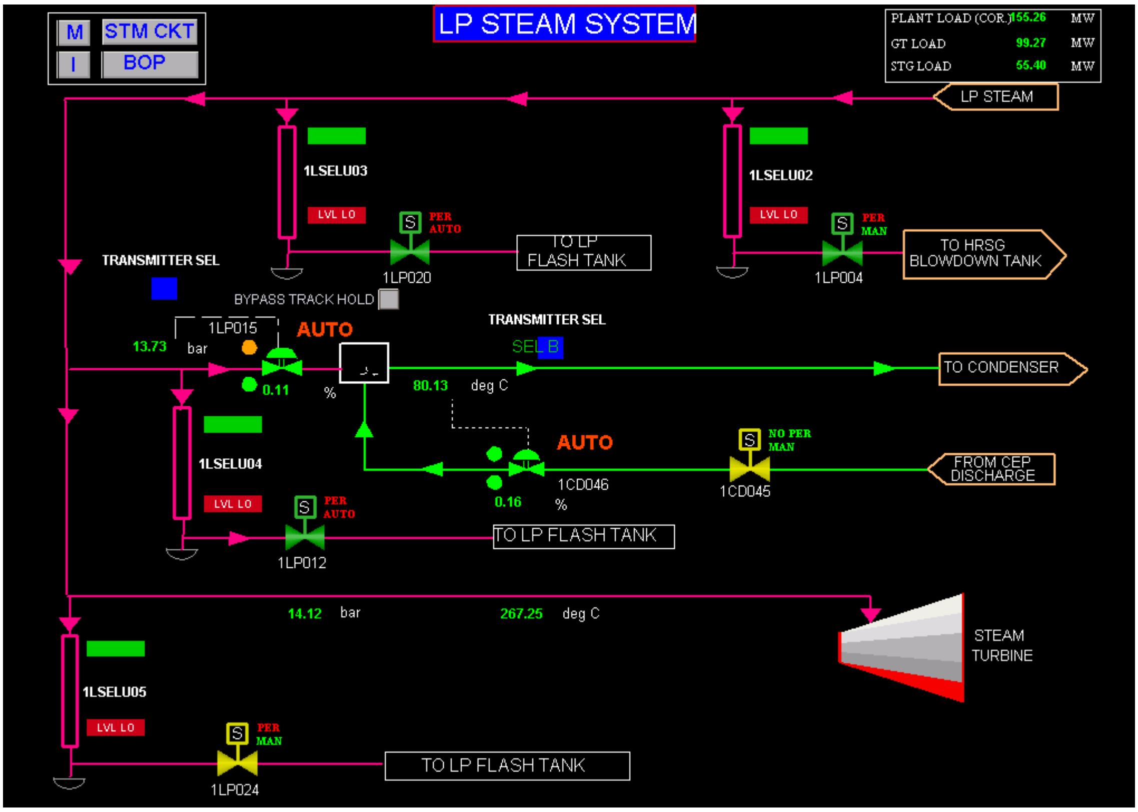

Figure 3.21 LP Bypass System (Original in Colour)

3.4.10 The operating mode of the ST Governor valve

Steam Turbine Governor Valve can be operated in three different modes.

1. Speed Control
2. Valve Lift Control
3. Inlet Pressure Control

ST speed up to rated speed before synchronisation on speed control mode soon after ST synchronisation turbine is in speed control mode. Then, the valve lift reference setpoint increases to 28%. Then, the Control mode will change over to valve lift, and ST can be loaded up to full load through valve lift. The Governor valve can be open and close according to the operator requirement in the valve lift mode.

When the steam pressure comes to a particular value, the valve lift mode can be changed to inlet pressure control mode, and this can be achieved by changing the valve lift and inlet pressure reference.

The valve lift set point and inlet pressure control set point have to be changed to full fill below requirement.

(HP valve lift ref set + Speed controller out)> Inlet pressure controller out (but this difference should be minimum to avoid sudden closure of governor valves)
When this condition achieves, the control mode will change to inlet pressure control mode.

3.5 Water Treatment Plant

The water treatment plant supplies the water for the boiler. The raw water draws from the Kelani River, and it goes through a treatment process, including clarification, filtration, and demineralisation. The water treatment plant mainly consists of the Pre-treatment system, Reverse Osmosis (RO) system, and Demineralisation (DM) system. The pre-treatment system comprises of clarifier, clarifier water storage tank (CWST), Chemical dosing system, filter feed pumps, dual media filters (DMF), activated carbon filter (ACF), and cartridge filter. The RO system consists of Brackish Water Reverse Osmosis (BWRO) Booster pumps, Sea Water Reverse Osmosis (SWRO) feed pumps, BWRO system, SWRO System, and Permeate storage tank (PST) [14]. The demineralisation system comprises a DM plant supply pump, mixed bed, and de-mineralise water storage tank.

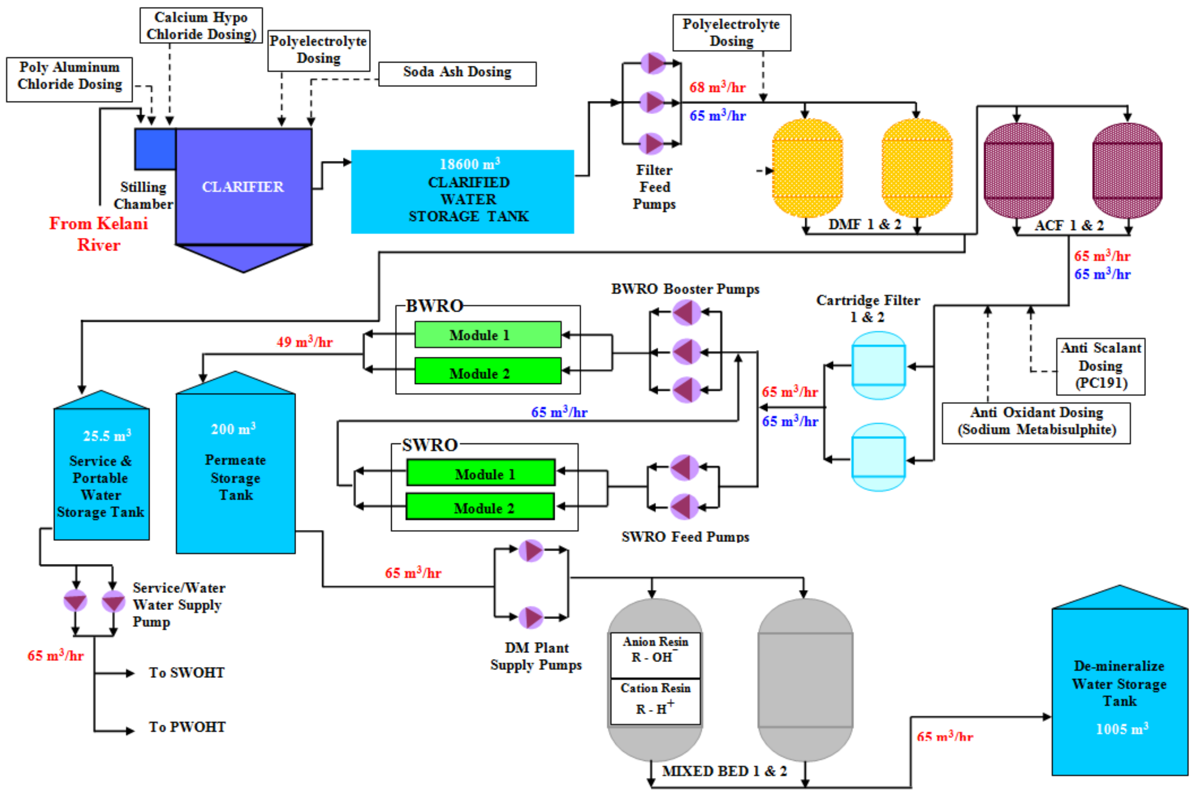

Figure 3.22 Layout of Water Treatment Plant (Original in Colour)

The plant's raw water is drawn from the Kelani river and circulated through a clarifier where the suspended particles and microbiological contaminants in the raw water are removed before storing in the clarified water storage tank (CWST). Removing of suspended particles in the raw water is achieved by coagulation and flocculation process, and poly aluminium chloride as coagulant and polyelectrolyte as flocculant is used.

The microbiological contaminants are removed by dosing calcium hypo chloride. Soda ash is injected at the discharge of the clarifier to control pH.

The water stored in the CWST is pumped to Dual Media filters (DMF), activated carbon filters (ACF), and cartridge filters using three filter feed pumps. A dual media filter consists of sand and anthracite, and it removes remaining suspended particles in the raw water. Activated carbon filter removes dissolved organic chemicals such as Cl, H_2S, lead, Cu and Hg. Cartridge filter removes fine suspended particles range from 0.2 µm to 100 µm.

Discharge from the cartridge filters pumps using booster pumps to the reverse osmosis (RO) system where dissolved solids in the feed water are removed and stores in the permeate storage tank (PST).

The PST water is pumped by using demineralisation plant supply pumps to the mixed bed, consisting of anion exchanger resin and cation exchanger resin. A mixed bed removes ions such as sodium and silica in the permeate water. The discharge of the mixed bed is stored in the De-mineralise water storage tank.

3.6 Fuel Oil System

The fuel oil system supplies the high-speed diesel (HSD) required to operate the Gas Turbine. The fuel system comprises of three major systems [15]:

1. Raw Fuel system
2. Fuel Treatment system
3. Fuel forwarding system

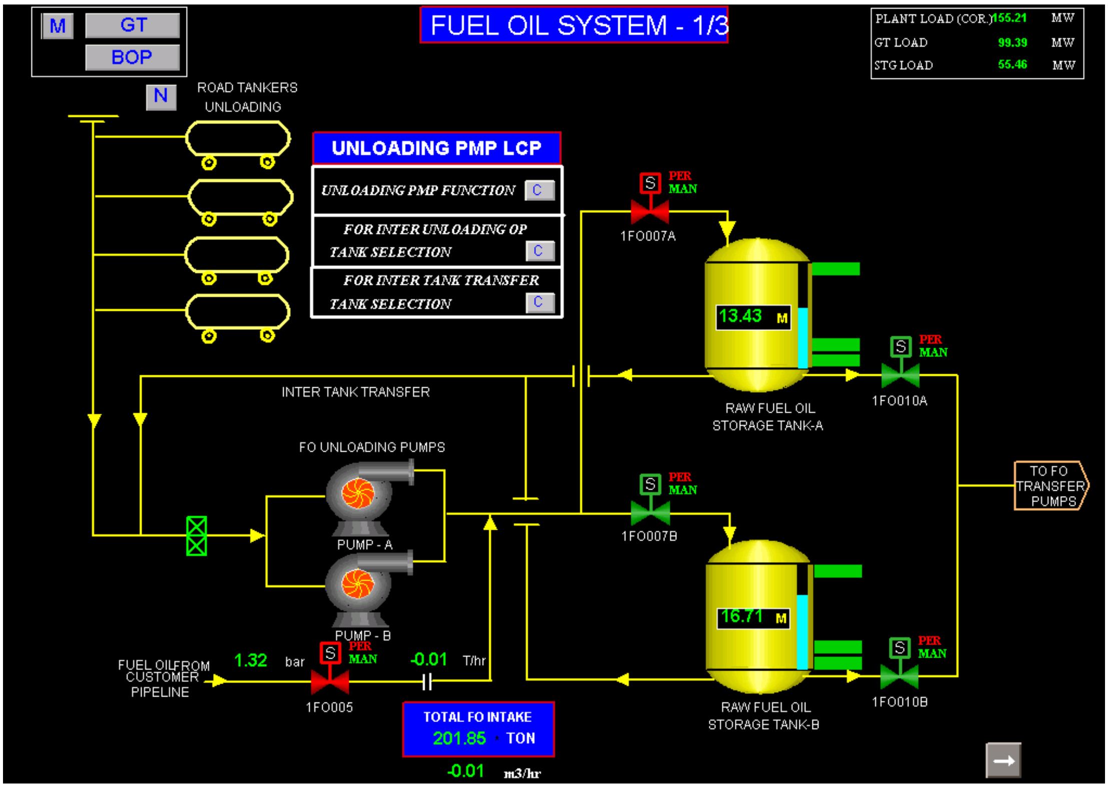

Figure 3.23 Raw Fuel Oil System (Original in Colour)

The raw fuel system consists of two storage tanks where the customer's fuel is stored for treatment purpose.

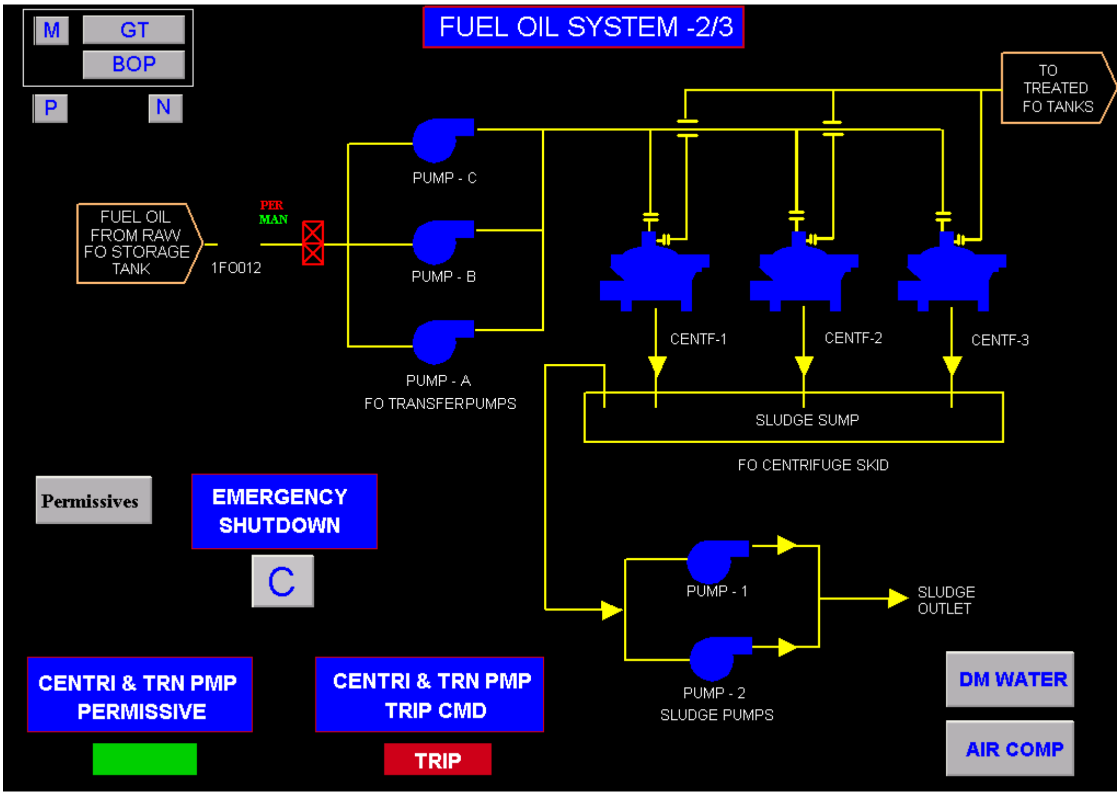

Figure 3.24 Fuel Oil Treatment System (Original in Colour)

Fuel oil Purification System in Fuel Oil Pump House area consists of (3X50%) Centrifuges (Separators), and each capacity is $20m^3/h$. With the (3X50%) transfer pumps. 100-micron duplex filter is at the suction line of the pumps. Each centrifuge has a flow meter to measure the oil passed out from the unit. The fuel oil centrifuges purify the raw fuel oil delivered by Ceylon Petroleum Corporation before sent to Gas Turbine.

(2X100%) A sludge pump will run to remove the wastewater and sludge in the sludge sump. The wash water is used to remove Sodium, Potassium and Vanadium salts in Raw Fuel oil and flush the impurities inside the centrifuge while the bowl flushes. After analysing the Fuel oil sample, we can inject wash water to the fuel oil supply line, whether any salts are available.

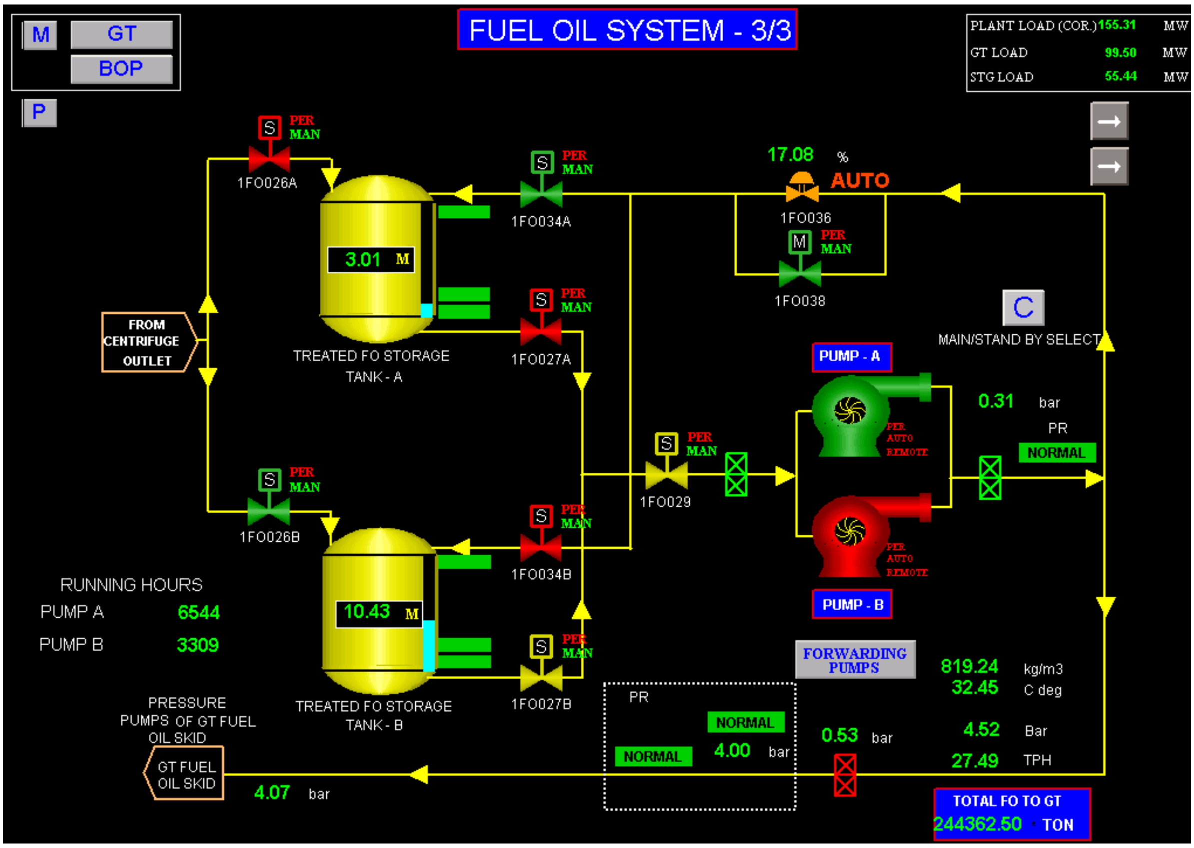

Figure 3.25 Treated Fuel System (Original in Colour)

The Fuel Forwarding System provides clean fuel to the Gas Turbine and comprises two treated fuel oil storage tanks of 5853 m^3 capacity and two fuel forwarding pumps with 42 m^3/hr capacities at 70 M head. These pumps supply fuel from the tank farm area to GT fuel skid, where 20-micron duplex filters at the pump suction and 20-micron duplex filters at the pump discharge are located. One re-circulation valve located before the GT fuel skid bypasses the gas turbine skid and sends the fuel back to the treated fuel tank.

This pneumatic control valve controls fuel pressure as 3.5 kg/cm^2 at the GT fuel skid inlet. The pneumatically operated fire protection valve at the outlet of the treated fuel oil storage tank closes in case of fire.

One density meter and one flow meter are provided at the GT fuel skid. At the downstream of the flow meter, there are 5-micron duplex filters. There are six numbers of nitrogen-filled accumulators connected parallel to the fuel line downstream to the duplex filters.

3.7 Steam Water Analysis System

Maintaining boiler water chemistry is vital to safeguard equipment from failure. The plant comprises a Steam Water Analysis System (SWAS) to accomplish this. The system consists of a wet panel (conditioning unit) and a dry panel (analysis unit). The samples, including feed water and steam from various boiler points, are taken and analysed parameters such as conductivity, pH, silica, dissolved oxygen, eliminox, sodium, and phosphate [16].

3.8 Continuous Emission Monitoring System

The continuous emission monitoring system aims to monitor the SOx, NOx, oxygen, and particulate matter in the flue gas emitted through the HRSG stack [17].

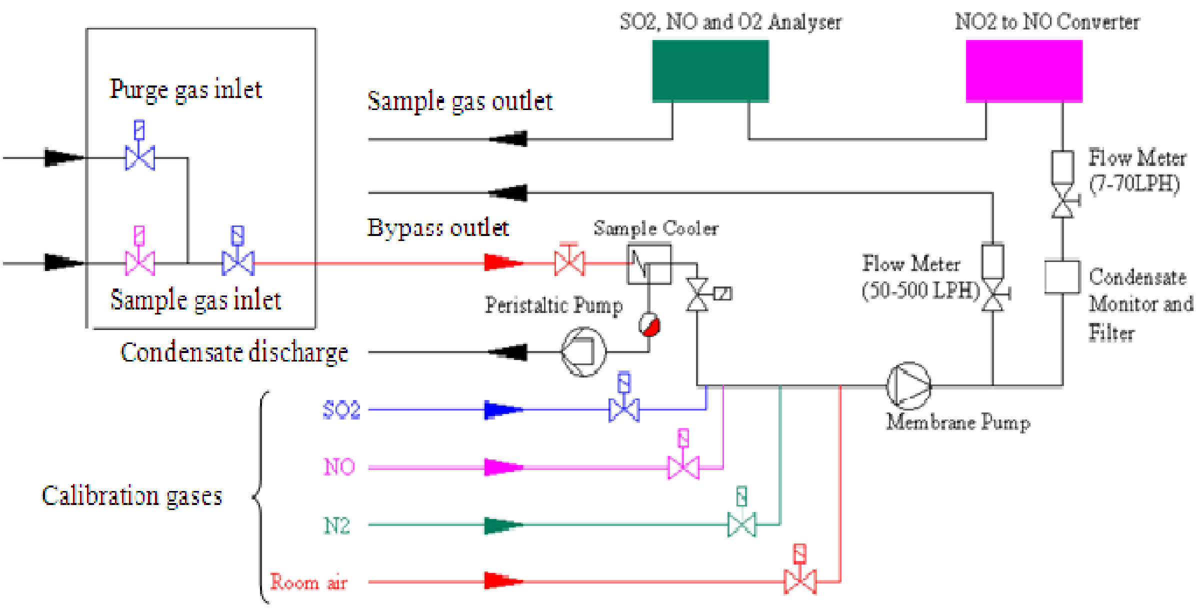

Figure 3.26 Layout of the Continuous emission Monitoring System (Original in Colour)

4. PLANT START-UP

4.1 Introduction

Starting a combined cycle power plant does not consume much more time than power plants with only boilers and steam turbines. Because the gas turbine in the combined cycle power plants can be started and synchronised in 15 minutes, it consumes a longer time than gas turbine when it comes to HRSG and ST. Starting time of HRSG and ST depends on reserved shutdown (RSD) time, which means the time between the gas turbine de-synchronise to the next gas turbine synchronise.

According to the RSD time, the start-up can be categorised into three types:

1. Hot Start-up
2. Warm Start-up
3. Cold Start-up

4.1.1 Hot start-up

When the RSD time is below 8 hours, then the start-up is called a hot start-up. It means the HRSG and ST are in hot condition. So, it does not take a long time to start the plant and reach full load. The recommended time for a hot start-up is 95 minutes (GT start to full load). The plant can be started within less time than the recommended time by optimising some operations such as gas turbine loading, start-up vent operation, steam bypass system operation and additional steam vent operation during start-up.

4.1.2 Warm Start-up

When the RSD time is between 8 to 48 hours, the start-up is called a warm start-up. It means the HRSG and ST are in warm condition. So, it takes a longer time than a hot start-up. The recommended time for a warm start-up is 165 minutes (GT start to full load). The plant can be started within less time than the recommended time by optimising some operations such as gas turbine loading, start-up vent operation, steam bypass system operation and additional steam vent operation during start-up.

4.1.3 Cold Start-up

When the RSD time is above 48 hours, then the start-up is called a cold start-up. It means the HRSG and ST are in cold condition. So, it takes a longer time than a hot and warm start-up. The recommended time for a cold start-up is 195 minutes (GT start to full load). However, a considerable amount of time can be saved by optimising some of the operations such as gas turbine loading, start-up vent operation, steam bypass system operation and additional steam vent operation during start-up.

4.2 Start-up Procedure

The plant start-up can be divided into three groups:

1. Gas Turbine start-up
2. HRSG Start-up
3. Steam Turbine Start-up

Above three operations are carried out one after another. As the first step, gas turbine starts and synchronizes with the grid. While gas turbine loading carries out, boiler (HRSG) warming up starts. Steam turbine start-up begins once the steam parameters reach the required level.

4.2.1 Gas turbine start-up

Generally, the gas turbine start-up is automatic through a SPEEDTRONIC control system (Mark V). So, the operator intervention is minimal during start-up.

<u>The gas turbine Start-up sequence</u>

1. Start command to the gas turbine.
    a. Hydraulic Oil Pump (L4HQZ) starts,
    b. Starting Motor starts (L4CR).
    c. Torque Converter Clutch engages, and speed begins to increase.
    d. Atomising Booster compressor starts (L4AB).

2. At the speed of 8.33%, the L14HT relay actuates, and the following equipment is ON or OFF.
    a. Load compartment Fan (L4VGZ1) ON
    b. Generator compartment Fan (L4VGZ2) ON
    c. Turning Gear motor (L4TGIX) OFF
    d. Jacking oil pump (L4VGZ2) OFF

3. Speed increases to10% & actuates14HM speed relay. Purging Cycles begins.
    a. Open cycle purging timer: 1 minute (T2TV)
    b. Combined cycle purging timer: 3 minutes (T2TVC).

4. Torque Converter solenoid valve 20TU-1 energises (Preparation for firing)
    a. The turbine slows down.
    b. The turbine slows down for 2 minutes.

5. At the end of 2 minutes timer, the firing cycle begins.
    a. Fuel Stop Valve (SOV 20FL) opens
    b. Fuel Pump clutch engages (SOV 20CF-1)
    c. Admits firing value of fuel to FSR 17.56%
    d. Flame is detected, 2 of 4 flames detect (T28FDX) for 1 second.
    e. Check for any fuel / hot gas leaks in the turbine compartment after firing.

6. After 2 seconds, fuel cuts down from 17.56% to 14.4% FSR for warm-up.
    a. Warm-up timer: 1 minute.
    b. At the end of the warm-up, Ignition goes off.

7. Speed up to 14 HA
    a. The fuel increase rate: 0.05%/s/s.
    b. The solenoid valve L20TUIX de-energises and closes to increase the Turbo converter pressure and increase the turbine speed.
    c. Turbine reaches 50% speed (14HA)

8. Acceleration up to 14 HC (60% speed)
    a. HP Acceleration control adjusts to 0.31%/s/s of FSR.

b. Turbine speed reaches to 60% (14HC) & 14HC relay actuation
c. Starting Electric Motor goes off for cooling down.
d. Turbo converter Solenoid valve L20TUIX energises, opens the valve and drops the pressure.

9. Turbine speed reaches 85%
    a. IGV regulates from 34º to 57º.

10. Turbine Speed reaches 95% (14HS)
    a. Compressor bleed valves close
    b. Auxiliary oil pump (AOP) stops,
    c. Exhaust Flame Blower Fans start one after the other, 10 sec after the first fan.
    d. Aux Hydraulic Oil Pump (AHOP) stops
    e. The generator Field breaker closes, and voltage builds up. (Make sure synchronising switch on Auto)

11. Turbine Speed reaches 100% (FSNL)]

12. GT Generator Circuit Breaker closes, and GT Load increases to 12 MW.

4.2.2 HRSG start-up

Starting time of HRSG differs according to the type of start-up (Hot, Warm & Cold), but the start-up procedure is almost identical for all types. According to the start-up type, the HRSG parameters such as drum pressure, temperature, and water level vary significantly.

<u>HRSG Start-up Sequence</u>

1. Preparation

   The following systems must be ready before the start-up of HRSG.

   - Plant auxiliary system
     - Water supply system
     - Chemical dosing system
     - Sampling system
     - Wastewater system
     - Closed cooling water system

- Condenser system
- Feedwater system
- Drains
- Live steam system
- Steam by-pass system
- HRSG

2. Boiler Filling

   The boiler filling procedure differs according to the start-up type. The boiler can be filled with feed water at atmospheric temperature during the cold start-up, but the boiler metal temperature must be below 100 ºC to prevent thermal shock or water hammering with flashing. However, the boiler must be filled with warm water in the hot well where the water temperature is above atmospheric temperature (around 40 -45 ºC) when it comes to warm and hot start-up. Boiler filling consists of three steps.

   - Step -01 LLP circuit filling

     During Cold start-up, the LLP circuit is filled with the demineralised water in the DM storage tank, where water is at atmospheric temperature.

     During Warm & Hot start-up, the LLP circuit is filled with condensate water in the hot well where the water temperature is around 45 ºC.

   - Step-02 LP circuit filling

     During Cold start-up, the LP circuit can be filled with the demineralised water in the DM storage tank or LLP drum water.

     During Warm & Hot start-up, the LP circuit must be filled with water in the LLP drum where the water temperature is around 100 - 120 ºC.

   - Step-03 HP circuit filling

     During Cold start-up, the HP circuit can be filled with the demineralised water in the DM storage tank or LLP drum water.

     During Warm & Hot start-up, the HP circuit must be filled with water in the LLP drum where the water temperature is around 100 - 120 ºC.

3. Boiler preparation

It is vital to prepare the boiler before start it. This allows a safe and proper operation of equipment during warming up.

Boiler preparation consists of:

- Boiler filling
- Feedwater pumps line up
- Prepare auxiliary circuits
- Prepare boiler valves position
- Feedwater control stations line up
- The lineup of drains and vents
- Boiler damper (Diverter Damper) closed fully

4. Boiler start-up
    - GT start
    - Diverter damper open
    - GT loading
    - Open HP and LP main steam valves
    - Open HP and LP by-pass valve after steam parameters reach a sufficient value.

4.2.3 Steam turbine start-up

Before starting the steam turbine, achieving the required steam parameters is essential. This is accomplished through the steam by-pass operation. Mainly, in combined cycle power plant ST start and synchronising takes significant time only during cold start-up due to lower steam turbine rotor surface and mean temperature. Warming up the steam turbine and reaching the required level of rotor surface and mean temperature is always challenging during cold start-up. However, it is easy during warm and hot start-up because the steam turbine is in warm condition. Still, it takes a considerable amount of start-up time.

<u>The steam Turbine start-up sequence</u>

1. Start CW System, ACW system, CCW System and Condensate water system.
2. Start Lube Oil system and Turning Gear Operation.
3. Gland Steam Lined Up / Operation.
4. Start Condenser Vacuum Pumps Operation and vacuum pulling.
5. Line up Vacuum Breakers.
6. Start HP & LP Bypass Operation

7. Start Control Oil Operation and Steam Turbine Resetting
8. Steam Admission and Rolling of Steam Turbine.
9. Steam Turbine speed increases to 600 rpm
10. Steam turbine speed increases to 3000 rpm
11. Steam turbine generator circuit breaker closes and loading

5. COMBINED CYCLE POWER PLANT SHUTDOWN

5.1 Introduction

A good shutdown is essential for a good start-up of the combined cycle power plant. Operational parameters such as steam drum pressure, temperature, water level, steam turbine rotor surface, and mean temperature should be at optimum level to perform a successful start-up. The shutdown procedure should be analysed, and implementing a successful shutdown procedure is vital for optimising start-up.

5.2 Normal shutdown Procedure

Shutdown sequence

- Ensure HP By-pass valve & LP By-pass valve set point is at 85 bars & 17 bars, respectively.
- Make sure Inlet Pressure Reference Set Point at 65 bars and Governor Valve wide open.
- Reduce Plant Load Set Point gradually (5MW per 5 minutes) until GT load reach 45MW.
- Change HP By-pass valve & LP By-pass valve set point is at 70 bars & 14 bars respectively.
- Maintain drum levels at appropriate states.
- Bring Valve Lift Set Point close to Valve Lift Reference Point.
- Change IPC to Valve lift mode.
- Close Governor Valve gradually reduces the ST load while reducing the Plant Load SetPoint.
- Bring ST load below 10MW.
- Issue ST Shutdown command from Pro-control.
- After ST stop, Change plant load set point to 12MW.
- Close HP and LP main steam valves.
- Box-up all the circuits (HP, LP & LLP).
- Stop the gas turbine.

5.3 Proposed Shutdown Procedure

1. Reduce Plant Load Set Point gradually (5MW per 5 minutes), maintaining GT load 50MW to keep the steam temperature above 450 ºC as possible.
2. Gradually increase HP & LP drum level set point to a safe level which will make drum control easier during next start-up.
3. Close attemperator manual valve when plant load reaches less than 120 MW. Confirm attemperator flow 0 TPH.
4. Open PCV5108A when plant load reaches 100 MW to keep APRDS temperature 280 °C, then maintain gland steam header pressure 400mmWC to 600mmWC.
5. Switch off Sliding Pressure Mode when ST Inlet Pressure Reference reaches 75 bar.
6. Close LP CV by monitoring LP Drum pressure.
7. Manually open LP Bypass Valve around 10 – 20 % when the LP CV position reaches around 30 - 40 %, and the LP drum pressure around 13 bar. Then, Change LP Bypass to Setpoint to 12 bar and auto mode, and gradually closes the LP CV to Zero.
8. Change HP Bypass set to point to 75 bar when ST Actual Inlet Pressure reaches 75 bar and gradually increases the ST Inlet Pressure Reference setpoint to around 78 – 80 bar to close the HP CVs. Monitor HP Bypass Valve Operation. Maintain Main steam temperature above 450 ºC and maintain lower margin.
9. Change ST Mode to Valve lift when ST load reaches 20 MW [At this moment HP CVs up to HP CV-01 to 25 mm and HP CV-2 to 35 mm
10. Gradually close the HP CV by reducing valve lift set point
11. Issue ST shutdown command from Pro-control
12. Change plant load set point to 12MW
13. Box up drums while GT in operation and fill HP drum level to 50mm and LP drums level to 0 mm accordingly.
14. Issue GT stop command.

6. OPTIMISATION OF DIFFERENT OPERATIONS

6.1 Gas Turbine Loading

Gas turbine load and loading rate determine the rate of steam temperature increment. However, the optimum load should be selected to achieve steam conditions without time delay and fuel loss. If the GT is loaded to a higher load before ST GCB closes, the fuel loss becomes more. If the GT is loaded to a lower load than required, the start-up time increases. This leads to again more fuel loss and inefficient operation due to part load.

6.2 HP start-up vent operation

The HP Start-up vent is located at the HP superheater-2 outlet. The start-up vent's primary purpose is to vent steam during start-up to achieve the required steam temperature after HP superheater-2 and open during sudden pressure increment of HP drum to prevent stress on the drum wall. HP superheater - 2 outlet temperature increment rate can be increased by fully opening HP start-up vent during start-up, but it will significantly reduce drum pressure. So, it is vital to find optimum start-up vent operation to reduce start-up time and save start-up fuel. Experiments were carried out during all type of start-up to determine the optimum operation of the start-up vent. For this purpose, parameters such as HP start-up vent valve open percentage, HP steam flow rate, HP drum pressure, and HP superheater outlet temperature were extracted from the DCS database using excel.

After analysing the data, the optimum HP start-up vent open percentage and HP steam flow were found. Further, the point at which the HP Start-up Vent operation starts is determined.

6.3 Downstream drains operation

The downstream drain system is provided to drain condensate water from the steam line. Generally, all the steam drains were fully opened during hot start-up. It leads to steam loss and high noise during start-up. Several trials were carried out to determine the drains valves' position during start-up, especially a hot start-up. Drains on the HP circuit and LP circuit were closed one by one during trials, and the parameters such as gland steam temperature increment rate and start-up time were analysed to check the effects of the operations carried out during the trials.

6.4 Gland steam operation

The gland steam system is designed so that no HP steam from the HP gland (at the front end of the turbine casing) escapes into the turbine area atmosphere and prevents any atmospheric air ingress from LP Gland (at the rear end of the turbine casing) into the LP Turbine.

There are two essential circuits in the gland steam system. One circuit controls the steam pressure. It connects the front and rear turbine glands and ensures steam extracted from the HP gland is fed into the LP vacuum glands. The pressure level in this circuit is slightly above atmospheric pressure. Two gland steam valves achieve pressure control. One valve (PCV 5501A) delivers steam into the circuit during the start-up of the turbine, the other gland steam valve (PCV5501B) relieves excess steam, typically when the quantity of steam extracted from the HP glands is higher than the quantity of steam fed into the LP glands. This condition occurs during all operational modes when there is a higher steam inlet.

The steam delivered into the gland steam circuit during start-up or shut down is taken from an HP steam header. The excess steam extracted from the circuit is passed into the main condenser.

The second gland steam system is the vent steam circuit. The piping of this circuit connects the front and rear turbine glands. The vent steam sections of the glands are in the outer-facing sections. The pressure in the vent steam circuit is slightly under atmospheric pressure. This means that steam and some amount of air are extracted from the last LP gland section. This design ensures that no steam escapes into the atmosphere. The gland steam condenser provides the vacuum pressure in this vent circuit. The steam that enters the gland steam condenser is condensed, and a motor-driven fan blows out the non-condensable gas (air).

Regular gland steam operation during start-up

During starting of the HRSG and HP steam line warming upstage, the Gland steam header drains MS-37, MS-38, GS-04, GS-05 & GS-09 to be opened to warm up the Gland Steam line, if the HP steam pressure at 20 bar Gland steam system can be charged by the opening of APRDS pressure control valve PCV-5108A, GS Pressure control valve PCV-5501A and spill overpressure control valve PCV 5501B gradually to warm up the APRDS line and gland steam line.

Start one of the Gland steam exhauster Fan for STG from the Pro-control system and put other fans on Auto / SLC ON.

Both control valves are opened manually (pay more attention to this stage as only one controller controls both control valves, PCV-5501A and 5501B). Before admitting the steam to the gland steam system, it is vital to verify that the vacuum breaker manual valve and vacuum breaker at the opened position. (In case if the steam admits to the turbine glands with vacuum breaker close position, the LP turbine rupture disk can be popped off)

APRDS control valve set point to be set at 3.0 bars and GS pressure control valve pressure set point to be at 300 mmWC.

Gland steam header temperature control valve set point to be at 320 °C and controller on Auto / SLC ON.

Once the Gland steam temperature reached more than 200 °C, all the drain valves mention in the above chart related to the Gland steam system can be closed, then put APRDS and GS Pressure control valves on Auto and observe the header pressure and Temperature.

Till the Steam Turbine rolled up and higher load on Generator, the gland steam spill over valve may not open. The spill over valve will open when the GS header pressure above 300mmWc. Make sure to close the Vacuum breaker valve after vacuum pulling started.

6.5 HP bypass operation

During start-up, this system improves the steam quality and controls the steam pressure of the HRSG outlet, requiring admitting steam into the Steam Turbine by dumping steam into the condenser through the HP bypass valve.

Further, this system controls the HRSG outlet pressure during sudden load drops in the steam turbine.

<u>Normal operation</u>

1. Before starting bypass operation following conditions must be satisfied.
   - Condenser cooling water system in operation at least with one pump.
   - ACW system in operation and both vacuum pumps sealing water coolers are line up.
   - Condensate Water System in Operation and both Vacuum Pumps sealing water tanks within operating limit.

2. After pulling the condenser vacuum, HP bypass control valves can be taken into service at the condenser backpressure of 0.2 bar. HP bypass initially will be at 52 to 55 bar, and this operation will continue till the following chemical parameters being achieved.
   - HP Steam Cation Conductivity < 0.2 μS / cm, Silica < 20 ppb and pH 8.8 – 9.2

3. When HP bypass in operation, HP steam temperature and pressure will be improved. Steam Turbine rolling steam condition as follows:
   - HP Steam Temperature 390 °C and Pressure 55 bar (cold & warm start-up)
   - HP Steam Temperature 450 °C and Pressure 55 bar (Hot start-up)

4. Once the Steam parameters achieved and Steam Turbine synchronised, the plant load can be increased gradually. As the plant load increases, the HP bypass set points can gradually increase until both HP bypass valve fully closed.
   - The final set point of the HP bypass is 100 bar.

6.6 Inlet guide vane operation

Variable Intel guide vanes are provided on the turbine to prevent any possible compressor pulsations during start-up and shutdown and operation under partial load conditions. The vanes are automatically positioned within their operating range in response to the control system operating temperature limits for normal loaded operation or the control system pulsation protection limits during start-up and shutdown sequences.
When the turbine is resting, inlet guide vanes (IGV) are at the designed closed position. This closed position limits the airflow through the compressor during the accelerating and decelerating sequence.

Before starting the steam turbine rolling, steam parameters such as temperature and pressure should be at the required level. This value varied according to the start-up type and provided by OEM.

Table 6.1 Start-up Types and HP Steam Parameters [13].

Start-up Type	HP Steam Temperature/ ºC	HP steam Pressure/ bar
Hot	450	55
Warm	390	55
Cold	390	55

It is challenging to control HP steam temperature at the required level by only adjusting the gas turbine load. So, it can be achieved by controlling GT exhaust temperature. GT exhaust temperature can be controlled by controlling GT air flow rate. The inlet guide vane must be modulated to get the required GT exhaust temperature by controlling the GT air flow rate.

Parameters such as GT exhaust temperature and ST inlet temperature were collected and analysed to determine the required curve to control the ST inlet temperature by controlling GT exhaust temperature.

6.7 New venting operation

Achieving ST inlet temperature and Gland steam temperature take a significant portion of the start-up time. This depends on the steam flow rate through the main steam line up to the ST inlet. There is a vent before the ST emergency stop valve to vent steam before start HP bypass operation, but that is not enough to maintain a sufficient steam flow rate to heat the steam line after the main steam valve.

A new venting operation was introduced to increase the steam flow after HP main steam valve. The new vent line (4 inches) is located near the ST inlet, and it is capable of contributing around 20 TPH steam flow rate during start-up. It increases the rate of ST inlet steam temperature rising.

6.8 Diverter damper operation

The purpose of the diverter damper located in the gas turbine's exhaust side is to direct flue gas from the gas turbine to HRSG or bypass stack. During start-up, the damper keeps close to HRSG until GT synchronise. This is to prevent overheating of the HRSG heat exchanger module. This operation leads to loss of energy in the GT flue gas through the bypass stack. HRSG heat exchanger module such as economisers must be filled sufficiently to keep open diverter damper to the HRSG side. So, the energy in the flue gas can be recovered. However, during a hot start-up, this damper cannot be kept open from the GT starting. Because just after GT start, the flue gas temperature is less than the HRSG module skin temperature. So, if the damper is kept open during that period, the steam temperature inside the HRSG superheater module will decrease. So, a point at which the diverter damper can be opened to HRSG to prevent steam temperature drop inside the module has to be found out.

Parameters to analyse and determine the optimum point to operate diverter damper were collected from the DCS database. The parameters which were taken to analyse are GT exhaust temperature and HP superheater-2 outlet temperature.

7. ANALYSIS AND RESULTS

7.1 Gas Turbine Loading

Before the Experiment, on 28th September 2018, the gas turbine was loaded initially to 40 MW before reach gland steam APRDS header temperature 280 °C, and then the load increased to 54 MW.

Three experiments were carried out, and parameters such as GT load, HP superheater-2 steam temperature, HP steam temperature at ST and fuel consumption during start-up were collected and analysed.

Experiment – 01

On 08th July 2020, GT load was increased to 56 MW before reach gland steam APRDS header temperature 280 °C.

Experiment – 02

On 29th July 2020, GT load was increased to 54 MW before reach gland steam APRDS header temperature 280 °C.

Experiment – 03

On 28th November 2020, GT load was increased to 60 MW before reach gland steam APRDS header temperature 280 °C.

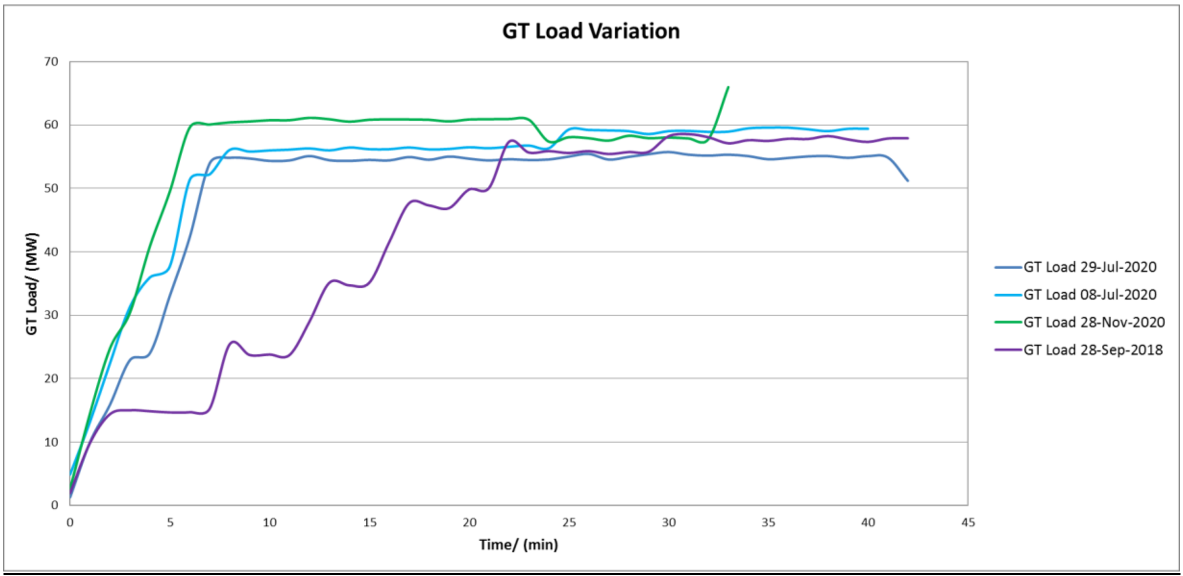

Figure 7.1 GT Load variation before the experiment and during the experiment

On 28th September 2018, GT load was increased to 54 MW, but the loading rate is low compared to other days. When it compares to other startups, on 28th November 2020, the GT load was increased to 60 MW within six minutes. So, the loading rate and the load is higher on 28th November 2020.

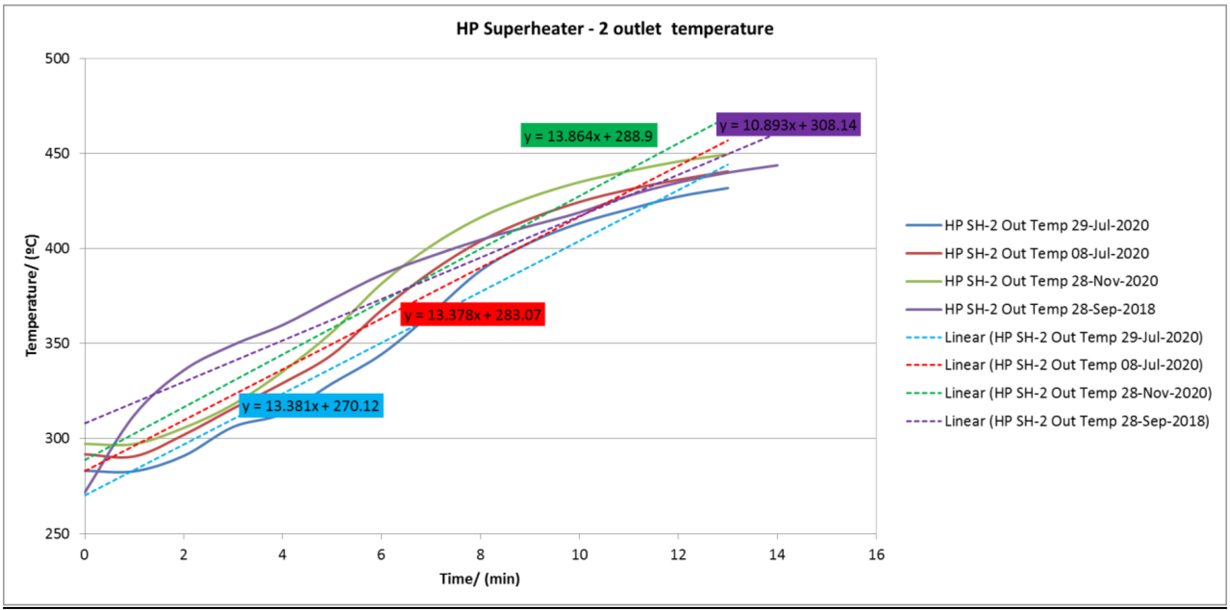

Figure 7.2 HP superheater – 2 outlet temperature before and during the experiment

The HP superheater-2 outlet temperature gradient (10.893 °C/min) is very low on 28th September 2018 where the GT loading rate and the load is low.

The HP superheater – 2 outlet temperature gradient, which is 13.864 °C/min, is higher on 28th November 2020. This is due to the higher load and loading rate of GT.

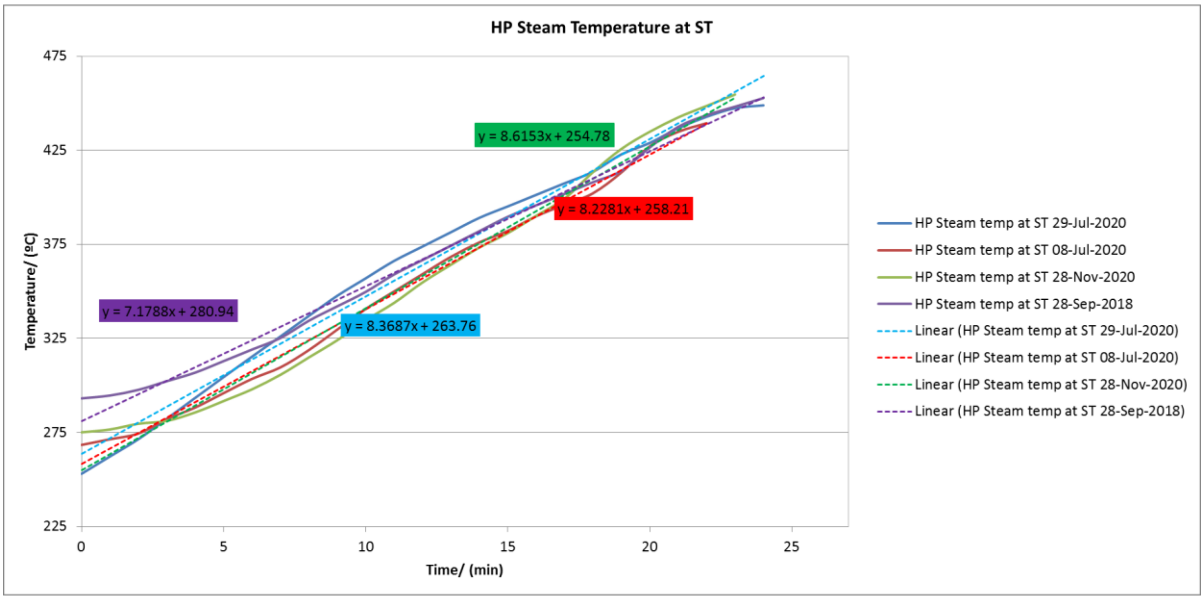

Figure 7.3 HP steam temperature at ST before and during the experiment

The gradient of HP steam temperature at ST (7.1788 °C/min) is low on 28th September 2018 compare to other start-ups. The gradient of HP steam temperature at ST, which is 8.6153 °C/min, is higher on 28th November 2020. This is due to the higher load and loading rate of GT.

Table 7.1 Time taken to reach different level during hot start-ups

	GT Synch to Gland Steam APRDS 280 ºC Time/ (min)	GT Synch to HP Steam 450 ºC Time/ (min)	GT Synch to ST Synch Time/ (min)
28-Sep-2018	27	43	55
08-Jul-2020	18	33	40
29-Jul-2020	17	31	41
28-Nov-2020	12	23	32

The time taken to reach gland steam APRDS temperature 280 ºC, HP steam temperature 450 ºC and ST synchronization with grid from GT synchronization is 12 min, 23 min and 32 min respectively. The time taken to reach different level has decreased on 28th November 2020.

Table 7.2 Fuel consumption during hot start-ups

Date	Fuel/ (MT)
28-Sep-2018	3.40
08-Jul-2020	3.19
29-Jul-2020	3.49
28-Nov-2020	3.20

According the table 7.2, the fuel consumption on 28th September 2018 and 28th November 2020 are 3.4 MT and 3.2 MT respectively. The fuel consumption is low on 28th November 20220.

7.2 HP Startup Vent Operation

Four experiments were carried out to find the optimum way to operate HP start-up vent during hot start-up.

Experiment -1

On 7th January 2021, the HP start-up vent kept open until HP steam bypass operation begins.

Experiment – 2

On 2nd March 2021, the HP start-up vent kept open until gland steam APRDS temperature reaches 280 °C, which is before HP steam bypass operation begins.

Experiment – 3

On 4th March 2021, the HP start-up vent kept open until HP superheater – II outlet temperature reaches 450 °C, which is before HP steam bypass operation begins.

Experiment – 4

On 9th March 2021, the HP start-up vent kept open until HP superheater – II outlet temperature reaches 440 °C, which is before HP steam bypass operation begins.

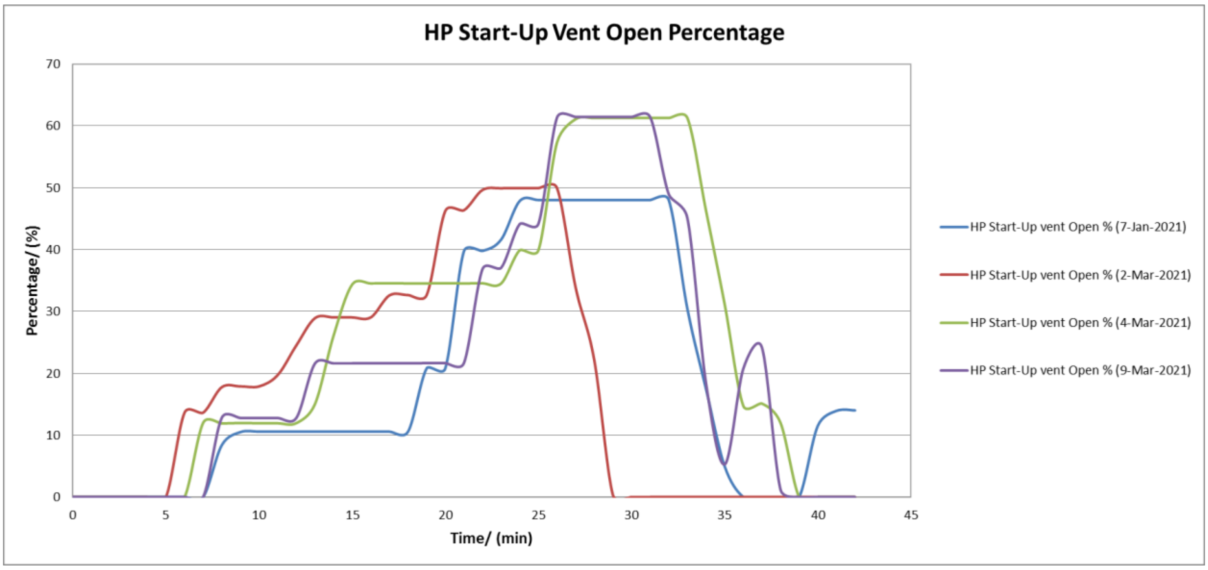

Figure 7.4 HP start-up vent open percentage

Above figure 7.4 represents the operation pattern of the start-up vent during hot start-ups. According to the figure, start-up vent was opened and closed earlier on 02nd March 22021, and the maximum open percentage is 50%. But, during other start-ups, start-up vent was kept open for a longer period and the maximum open percentage is 60%.

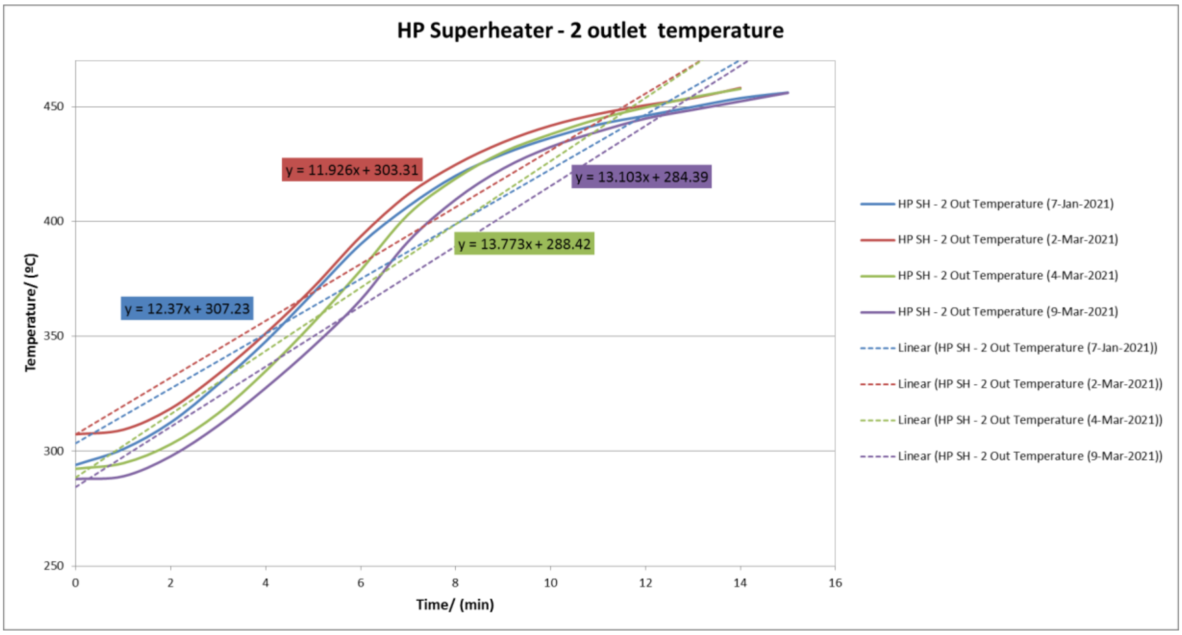

Figure 7.5 Variation of HP Super Heater – 2 outlet steam temperature

According to figure 7.5, the HP superheater-2 outlet temperature gradient is 11.926 °C/min, which is low on 02nd March 2021 compare to other start-ups due to less opening percentage of start-up vent. Steam flow rate reduces when restrict the opening of start-up vent.

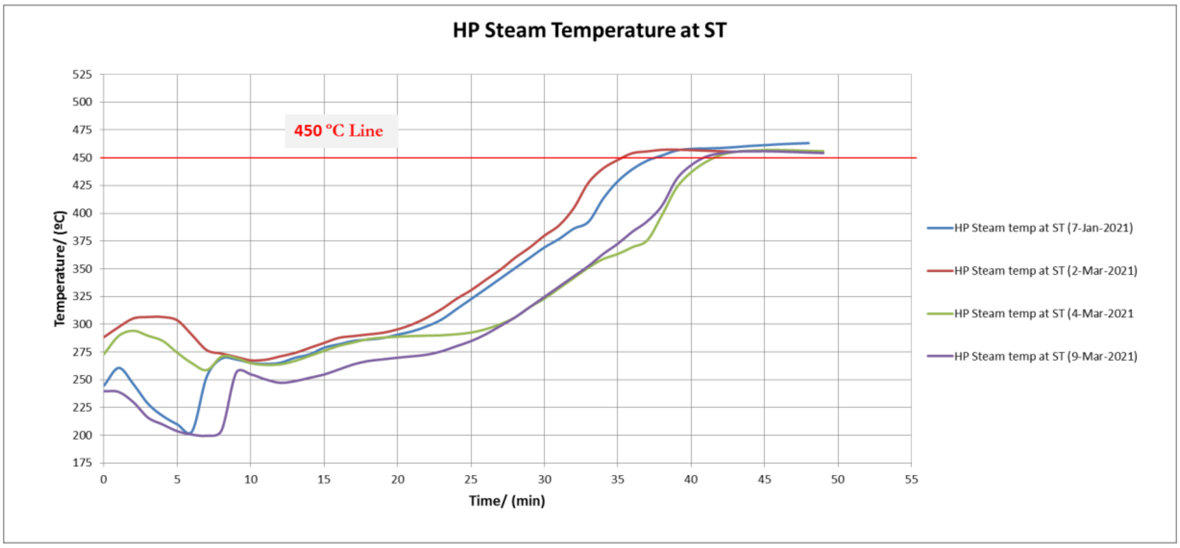

Figure 7.6 Variation of HP steam temperature at ST

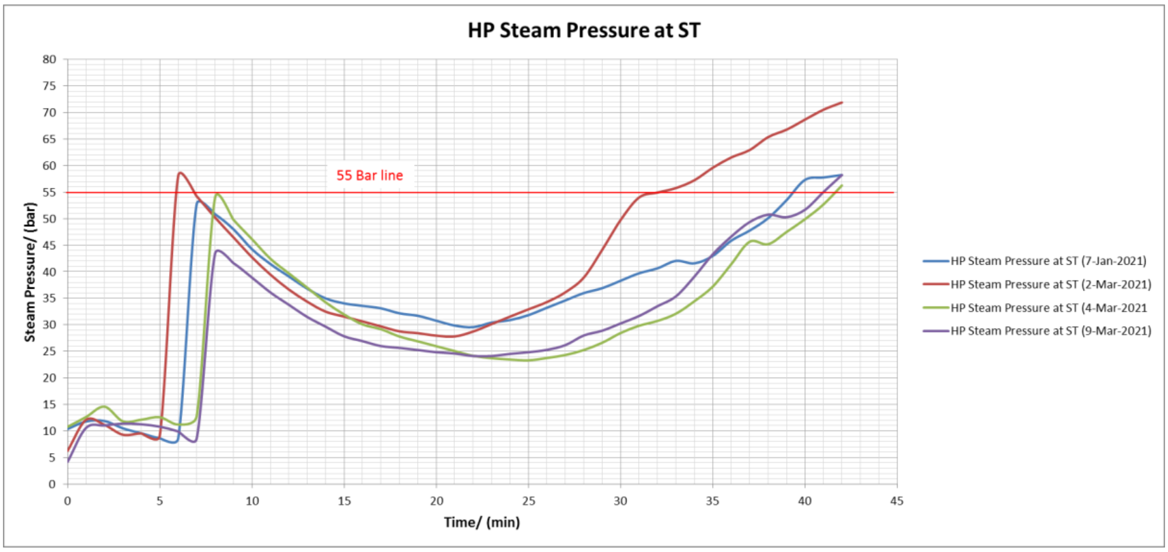

Figure 7.7 Variation of HP steam pressure at ST

According to the above figure 7.6 & 7.7, HP steam temperature at ST and HP steam pressure at ST reached their required value earlier on 2nd March 2021 compare to other dates.

On 2nd March 2021, the HP start-up vent was closed when gland steam APRDS temperature reaches 280 °C, which is well before HP steam bypass operation begins. This operation helped to increase the HP steam pressure to 55 bar earlier than other start-ups.

7.3 HP Bypass Valve Operation

Before starting the research, the HP Bypass valve pressure setpoint rate was low. Figure 8.8 shows the increment of HP Bypass valve pressure setpoint rate during hot start-up.

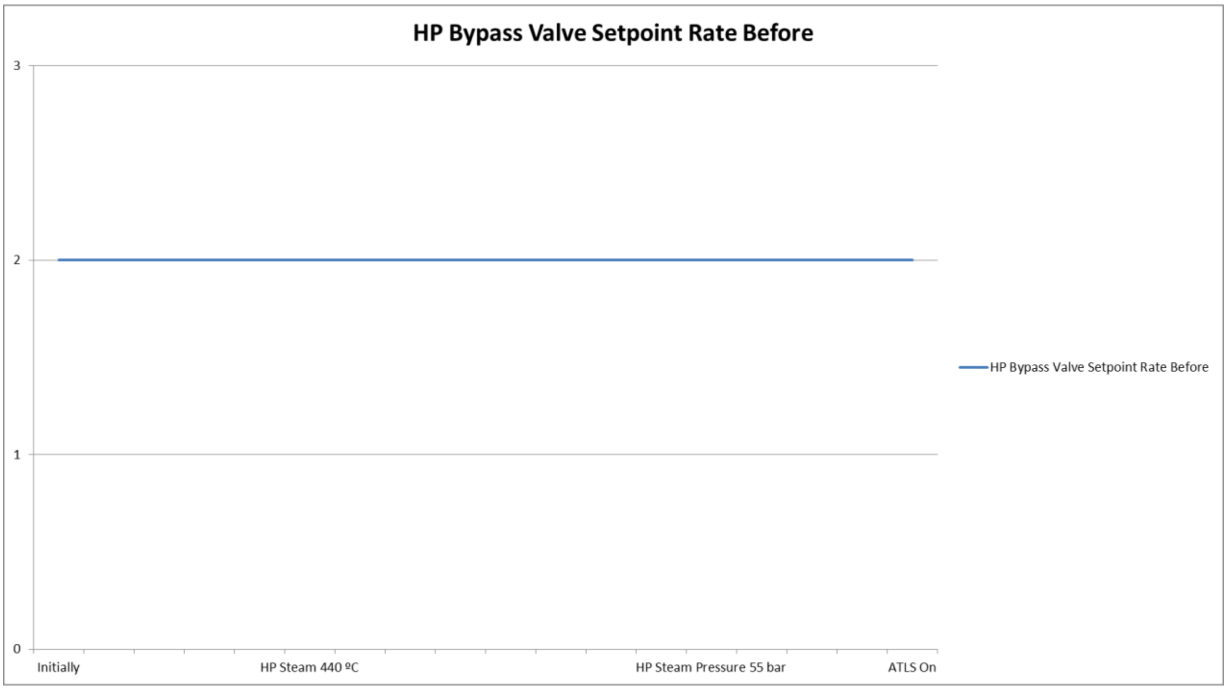

Figure 7.8 HP Bypass valve pressure set point rate

Initially, the HP Bypass Valve auto opens after the condenser vacuum reaches less than the 0.2 bar, and the pressure set point of the HP Bypass valve increases 2 bar/min up to Automatic Turbine Loading System (ATLS) starts.

Two experiments were carried out to determine the optimum pattern of the HP bypass valve operation during hot start-ups.

<u>Experiment – 01</u>

On 27th January 2021, the HP Bypass valve set point increasing rate was changed to 4 bar/ min after HP steam temperature reaches 450 °C, and it was kept as 4 bar/min until ATLS on.

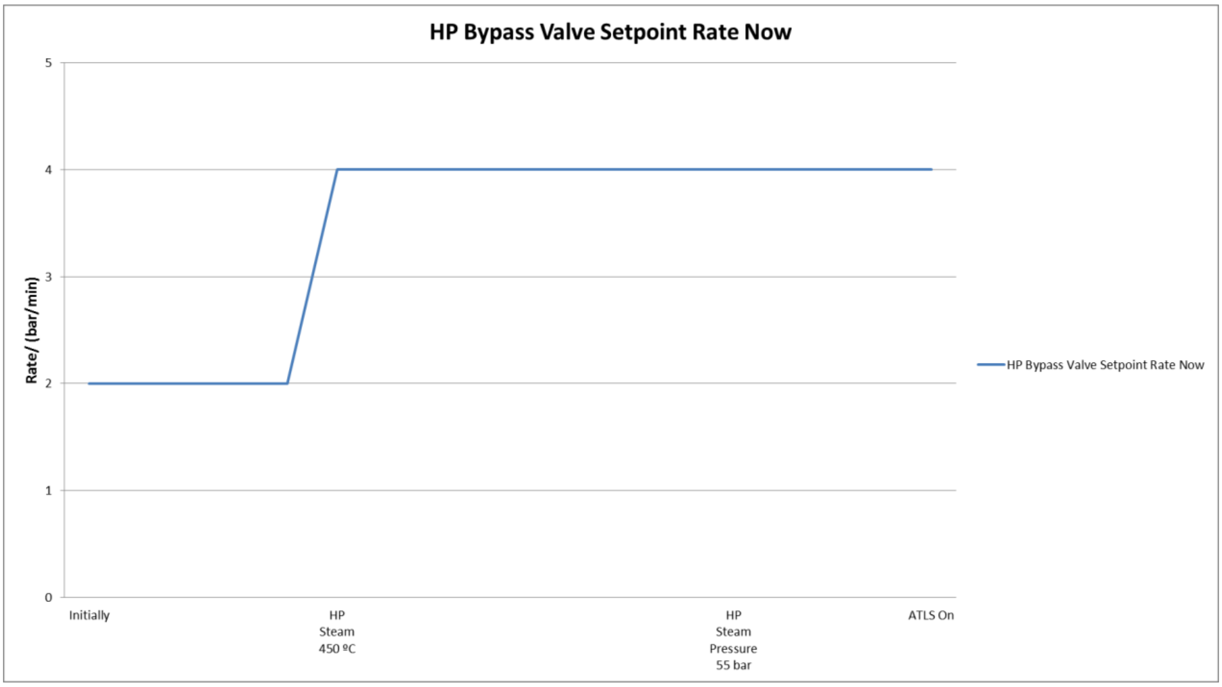

Figure 7.9 HP Bypass valve pressure set point rate

<u>Experiment – 02</u>

On 25th February 2021, the HP Bypass valve set point increasing rate was changed to 4 bar/ min after HP steam temperature reaches 440 °C, and it was kept as 4 bar/min until HP steam pressure at ST reaches 55 bar. Then, the set point was changed to 2 bar/min and kept until ATLS on.

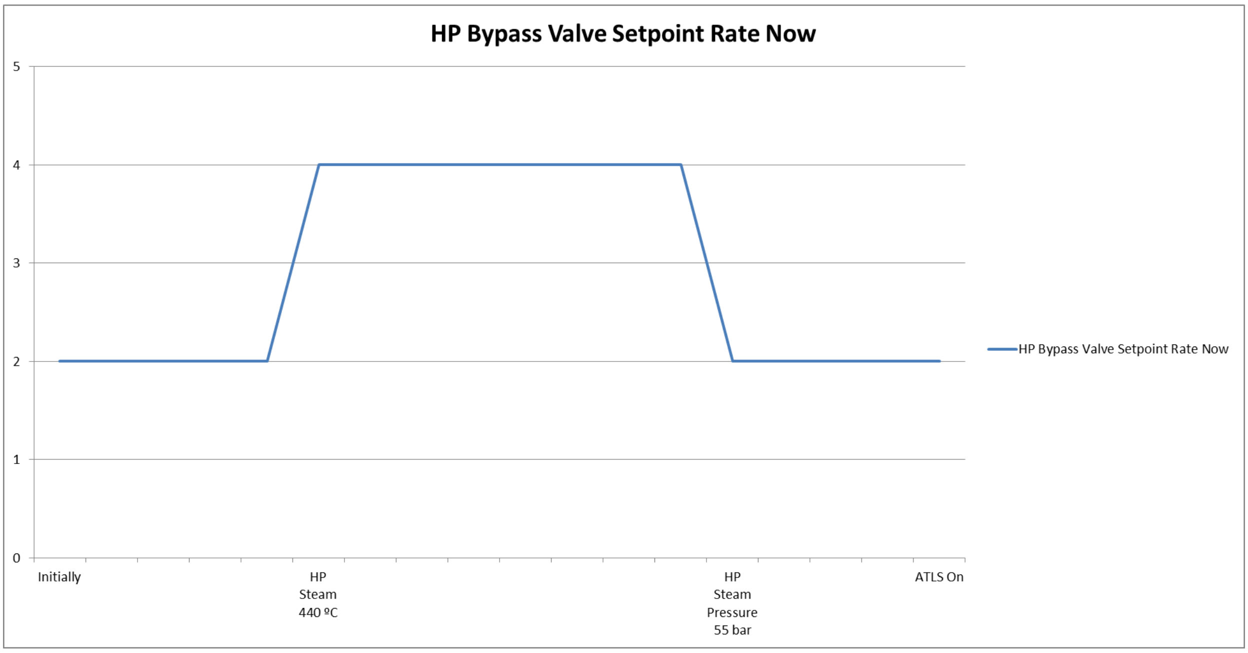

Figure 7.10 HP Bypass valve pressure set point rate

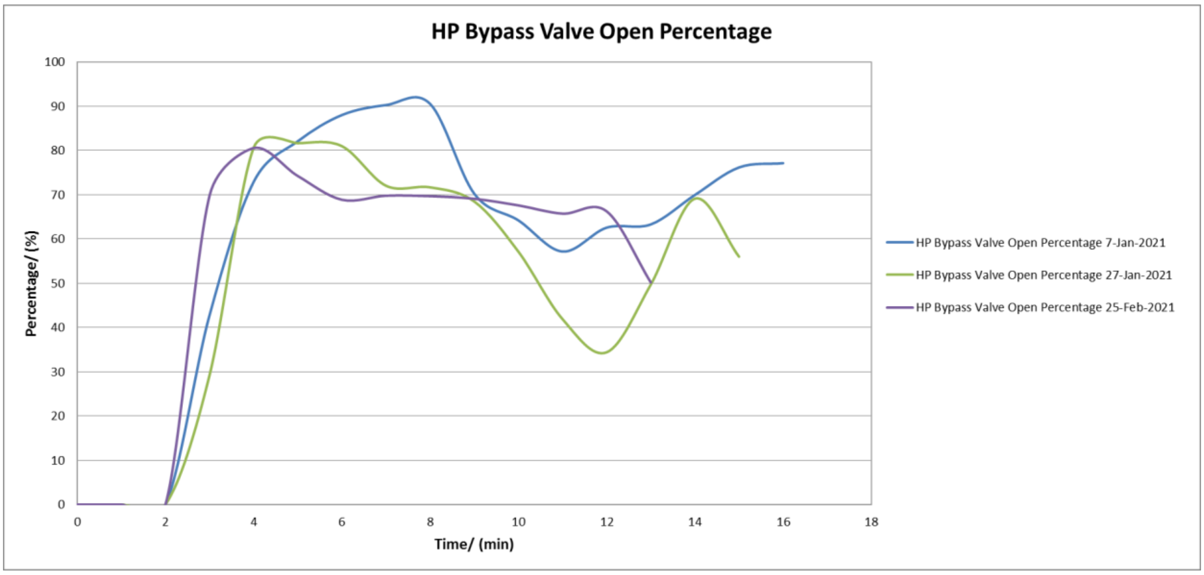

Figure 7.11 HP Bypass valve open percentage

Figure 7.11 represents the operation patter of steam bypass system. According to the figure, HP bypass valve was closed at a slow rate.

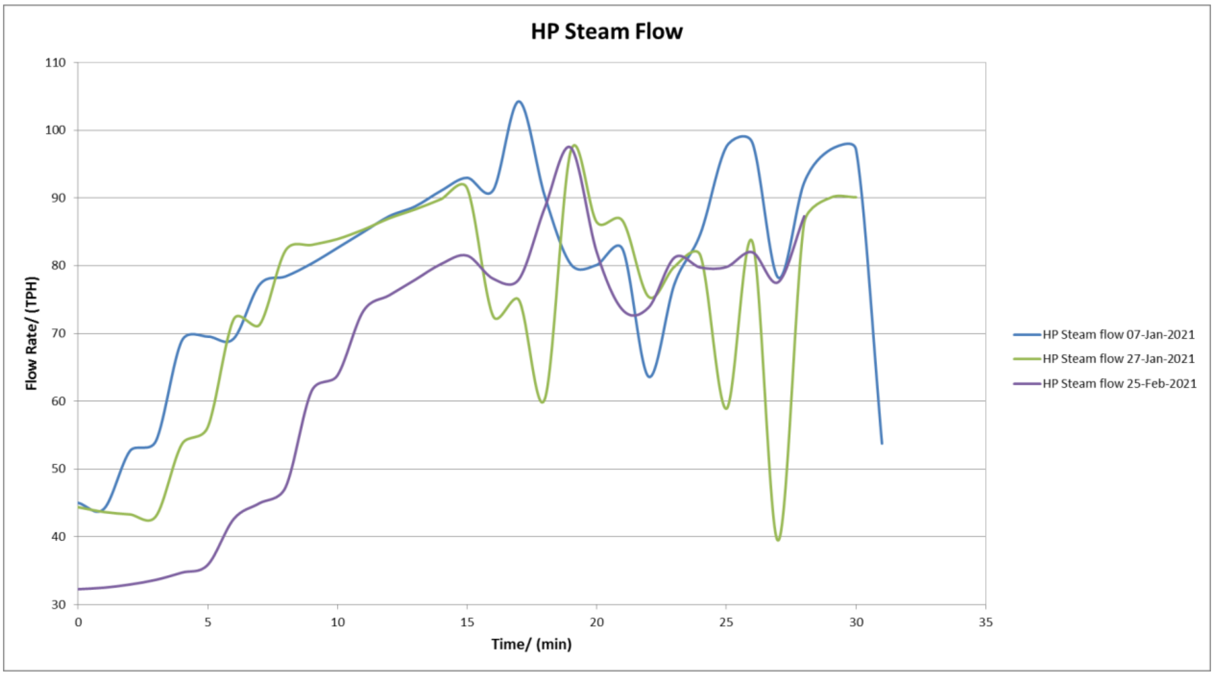

Figure 7.12 HP steam flow rate

Figure 7.12 describes the steam flow variation with time during hot start-ups. According to figure7.11, the HP bypass valve open percentage is minimum on 25th February 2021 compared to 7th Jan 2021 & 27th Jan 2021. This leads to less steam bypass to condenser through HP bypass valve, which can be seen in figure 7.12.

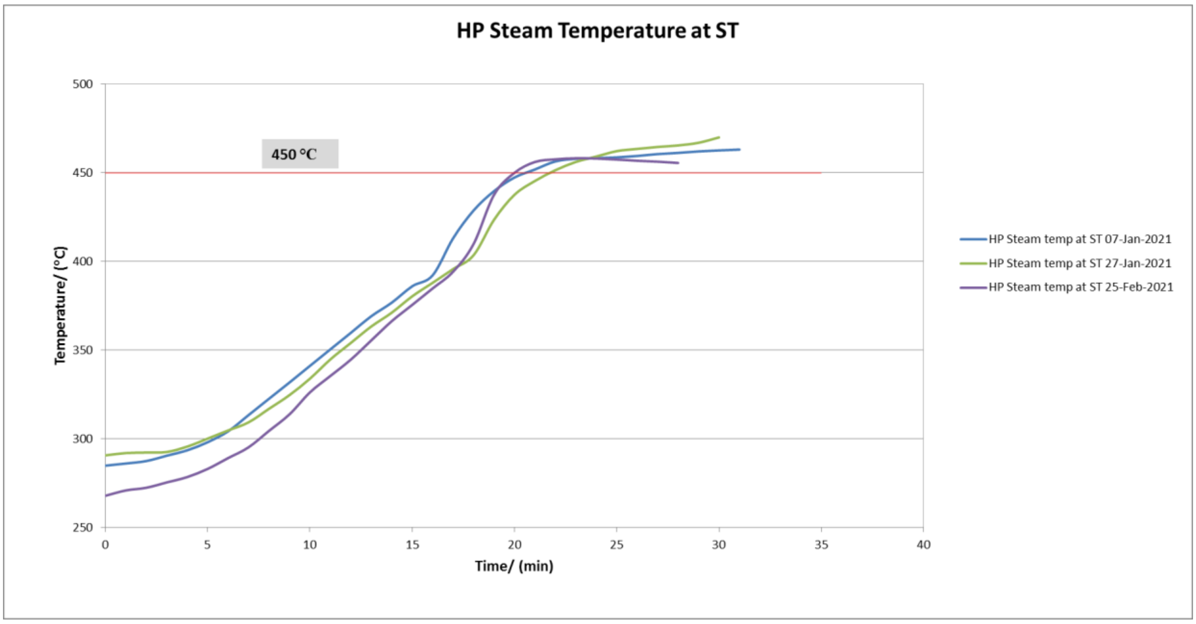

Figure 7.13 HP steam temperature at ST

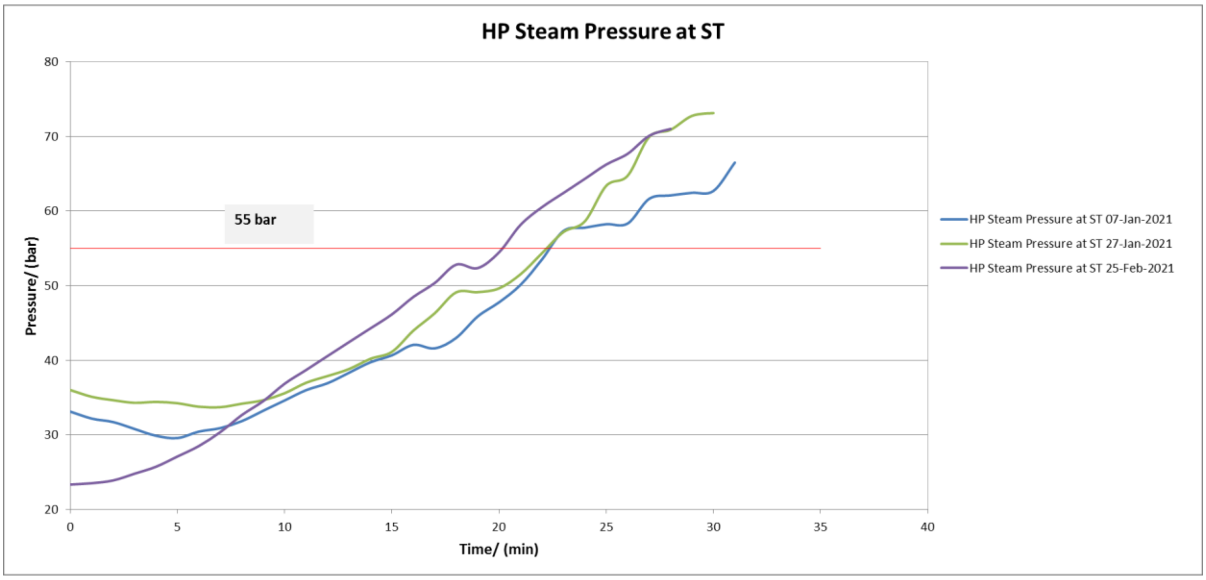

Figure 7.14 HP steam pressure at ST

According to Figures 7.13 which describes the variation of HP steam temperature at ST & 7.14 which explains the variation of HP steam pressure at ST, HP steam parameters such as steam temperature at ST (450 °) and steam pressure at ST (55 bar) required to ST rolling were achieved well before on 25th Feb 2021 compared to 7th Jan 2021 & 27th Jan 2021.

7.4 Introduction of New Venting System

Three different hot start-up data were collected and analyzed to check the new steam vent system's behaviour. Further, two experiments were carried out to find the optimum operation pattern of the new vent system.

On 16th Jul 2020 & 2, the hot start-up was carried out without the new vent system.

<u>Experiment - 1</u>

On 4th Mar 2021, the hot start-up was carried out with the new vent system, but the vent valve was closed just after the HP bypass operation started.

<u>Experiment - 2</u>

On 20th Mar 2021, the hot start-up was carried out with the new vent system, but the vent valve was closed just after HP steam temperature at ST reached 450 °C, which is after HP bypass operation started.

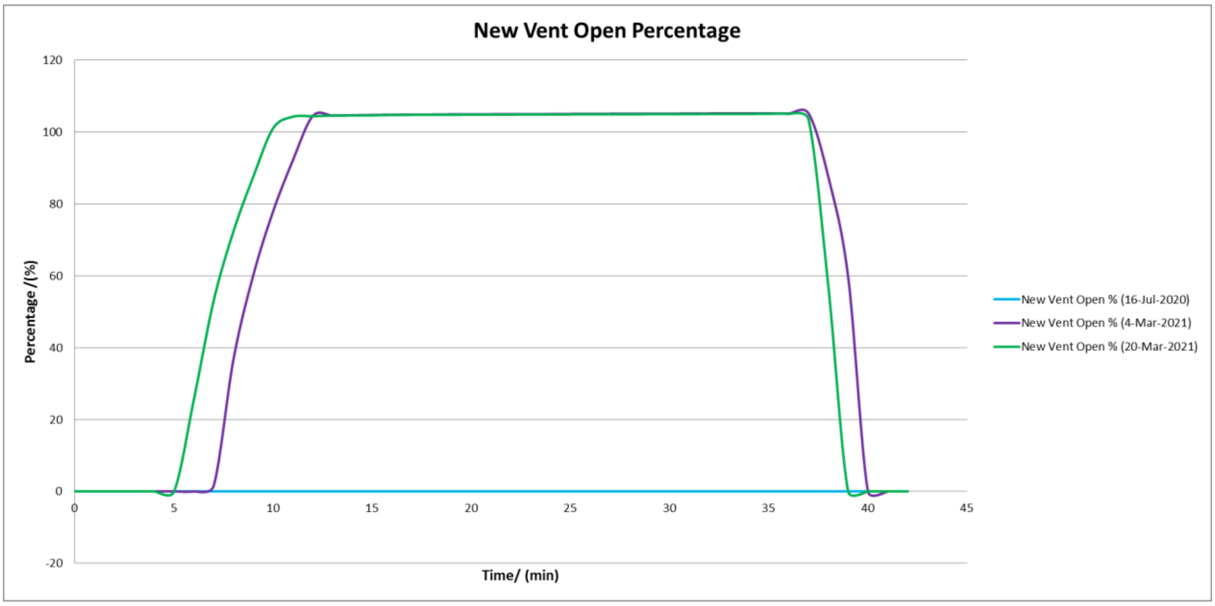

Figure 7.15 New Vent Open Percentage

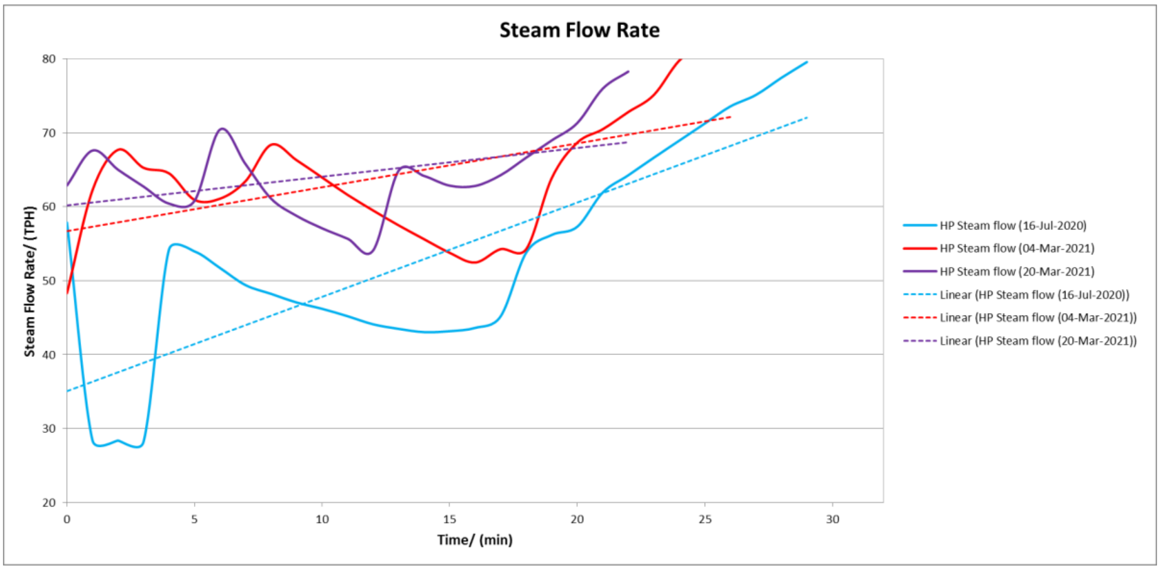

Figure 7.16 HP steam flow before and after the introduction of the new vent

Figure 7.16 describes the steam flow variation with time during hot start-ups. According to the above figure 7.16, the steam flow has increased after introducing the new vent system on 20th March 2021 and 04th March 2021.

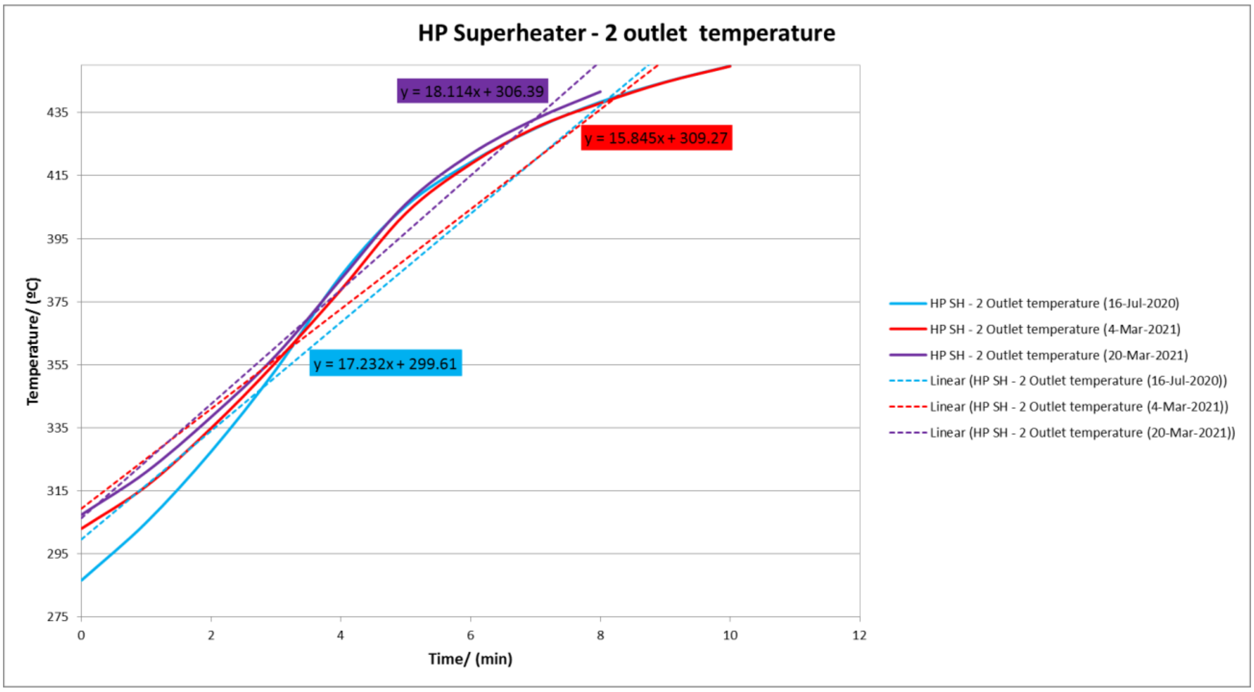

Figure 7.17 HP superheater – 2 temperature before and after the introduction of the new vent

Compared to the three start-ups, the gradient of HP superheater -2 outlet temperature (18.114 °C/min) is higher on 20th March 2021 than the other start-ups.

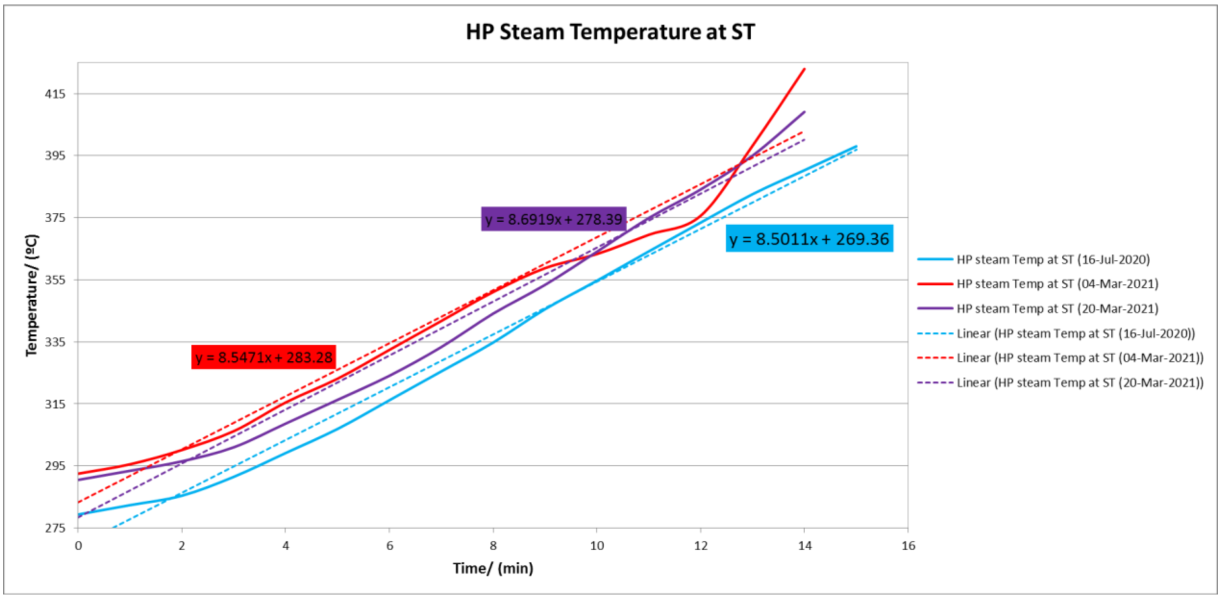

Figure 7.18 HP steam temperature at ST before and after the introduction of the new vent

Compared to the three start-ups, the gradient of HP steam temperature at ST is higher on 20th March 2021 than the other start-ups.

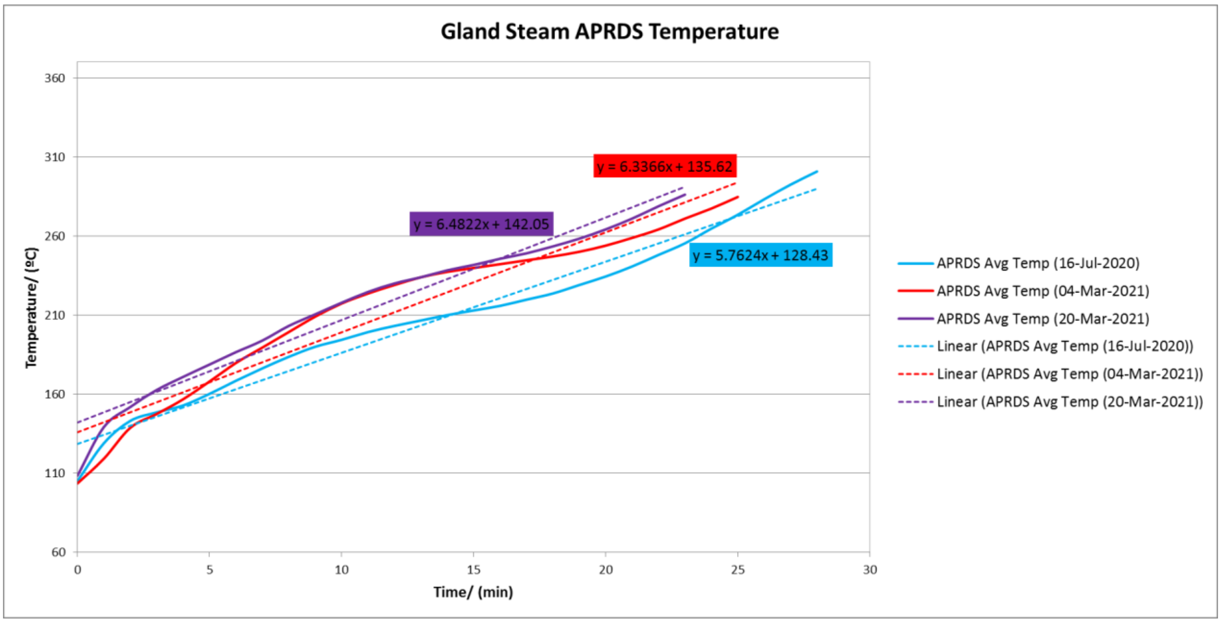

Figure 7.19 Gland steam APRDS temperature before and after the introduction of the new vent

Compared to the three start-ups, the gradient of gland steam APRDS temperature is higher on 20th March 2021 than the other start-ups.

7.5 Comparison of Hot Start-up Time

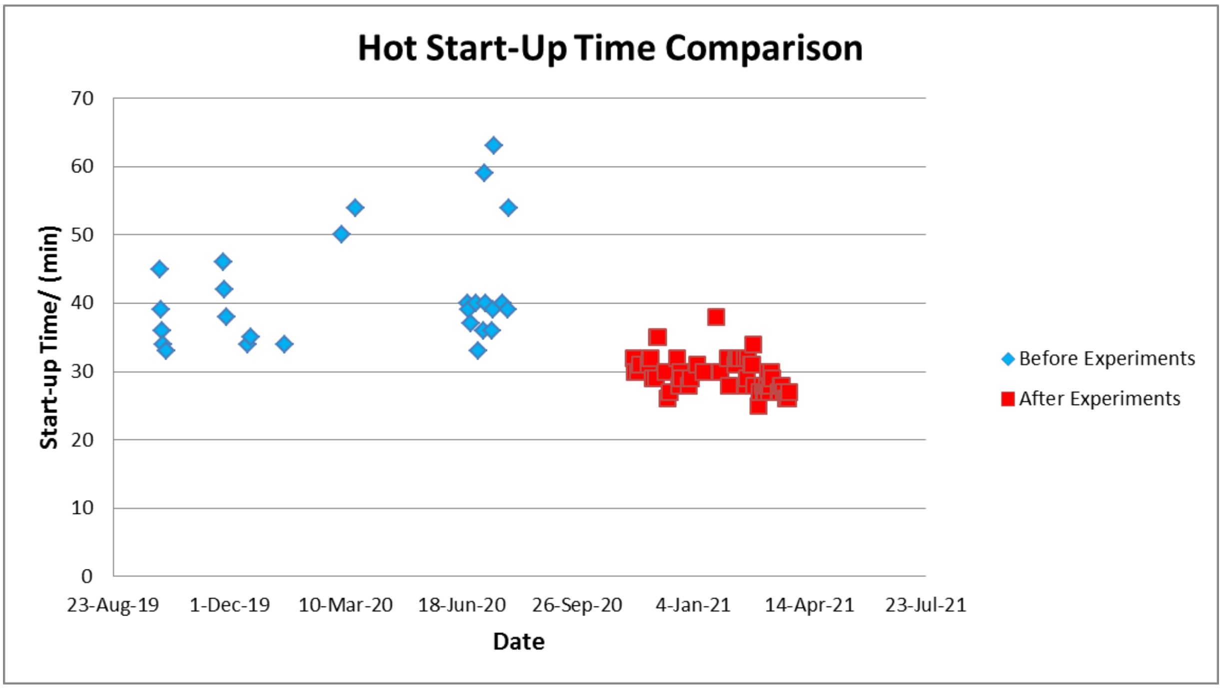

Figure 7.20 Hot Start-up time before and after research

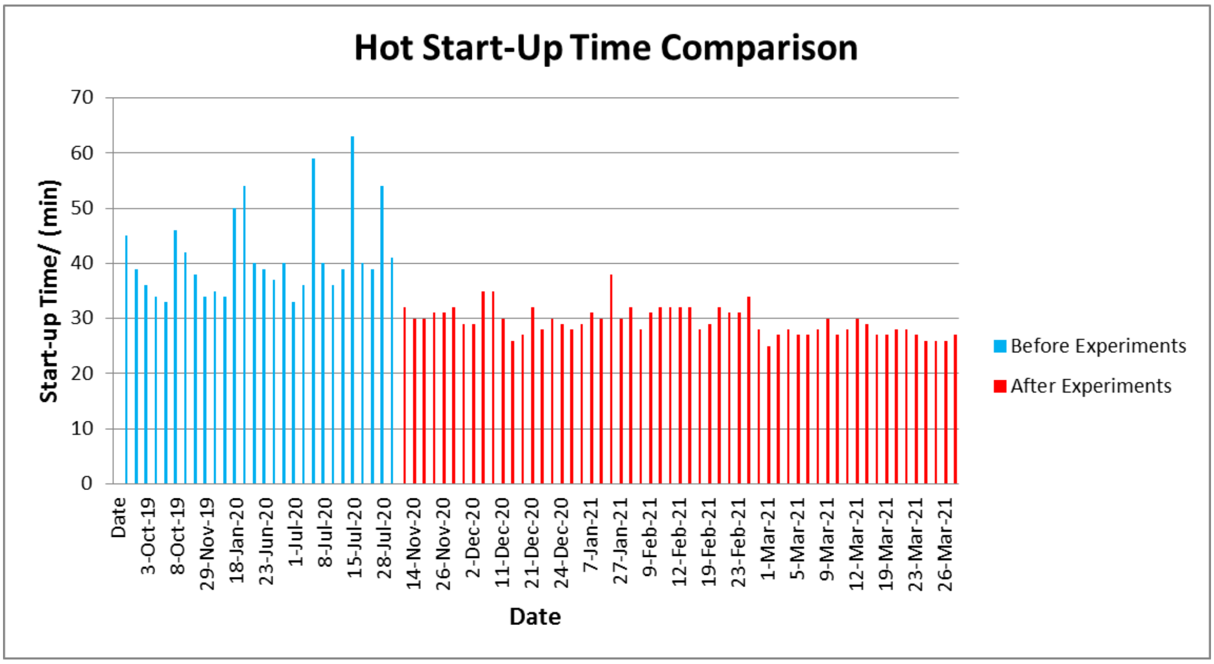

Figure 7.21 Hot Start-up time before and after research

According to figure 7.20 & 7.21, hot start-up time has decreased significantly. Before the research, the average hot start-up time was 41 minutes, and it reduced to around 29 minutes.

8. CONCLUSIONS AND RECOMMENDATIONS

When a combined cycle power plant run at part load portion of the waste heat in the flue gas release to the atmosphere through bypass stack, another portion of the energy dump as steam through steam drains, vents and steam bypass. Combined cycle power plants operate at part load during start-ups. So, energy can be saved by reducing start-up time.

Gas turbine load and loading rate have a significant effect on the hot start-up time. However, when GT load increases, fuel consumption also increases. Waiting time at part load should be minimised to reduce fuel consumption. GT has to be loaded quickly (GT is capable of fast loading) to a high load.

A significant amount of hot start-up time is utilised to warm up HRSG and achieve gland steam APRDS temperature (280 °C), the Steam temperature at ST inlet (450 °C) and steam inlet pressure (55 bar). These steam conditions can be achieved by optimising the operation of some equipment such as HP start-up vent, HP steam Bypass and additional vents. Steam flow should be maintained at a higher level to reach steam temperature quickly, but it leads to a delay in achieving the required steam pressure.

HP start-up vent located at the end of the superheater module near the HRSG helps to reach the super heater module outlet temperature to the required value quickly. However, it does not improve the ST inlet's temperature gradient because it is a little far away from HRSG. The steam temperature has to be achieved through the steam bypass system. However, steam bypass operation can be started once the gland steam established. Gland steam can be admitted to gland steam main header once gland steam APRDS header temperature reaches 280 °C. A new vent system apart from the vent before ESVs can improve the rate of gland steam temperature rise.

All the steam vents and bypass should be closed to achieve the required steam pressure. Nevertheless, there should be a point where the different vents, such as HP start-up vent and vents before ST can be closed, and HP bypass closing rate also determines the pressure rising rate. Once gland steam APRDS header temperature reaches the required value, the HP start-up vent can be closed slowly to increase the HP steam pressure. After steam bypass operation started, steam can be dumped through the bypass valve to the condenser to acquire steam temperature quickly.

However, the opening of the HP bypass valve reduces the HP steam pressure. So, before achieving the required steam temperature, the bypass valve can be closed at a slow rate, and after achieving the temperature, the bypass valve can be closed at a higher rate to achieve steam pressure.

Heat Recovery Steam Generator and steam turbine may experience stress due to changes in the start-up procedure. While optimizing operations such as start-up vent operation and steam bypass system operation, the Original Equipment Manufacturer's standard curves for steam temperature, steam pressure and positive pressure gradient curve for HP drum were followed. For instance, optimizing start-up vent operation affects the HP drum positive pressure gradient. So, start-up vent operation was modified by considering the positive pressure gradient curve for HP drum (refer below figure 8.1).

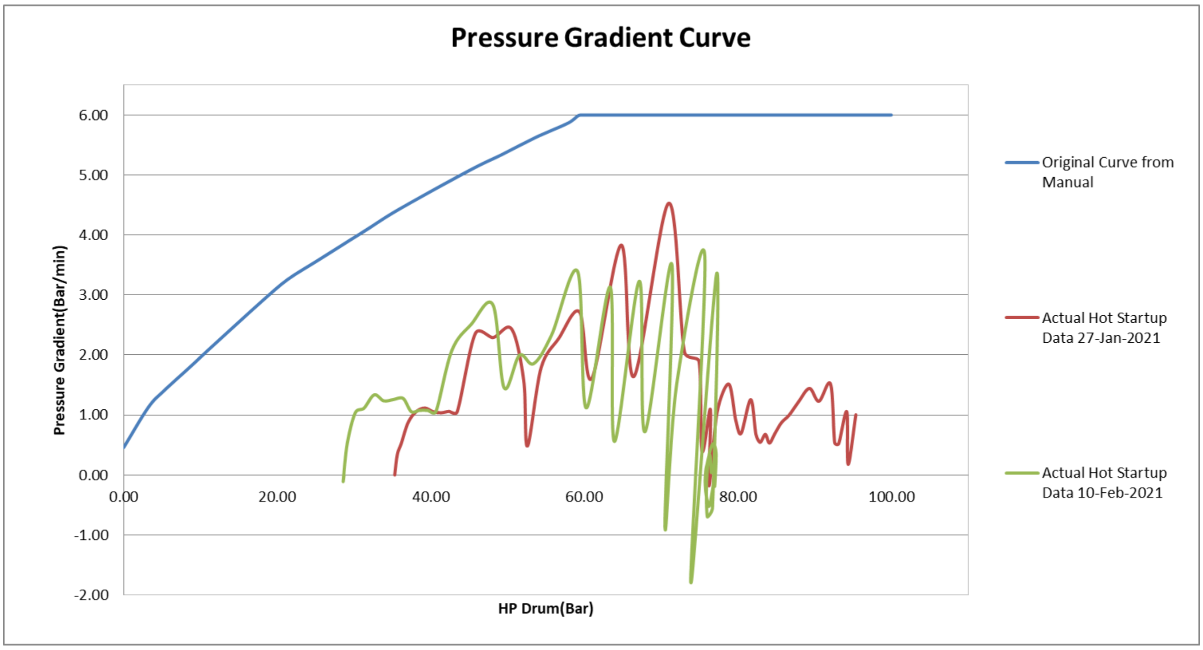

Figure 8.1 HP Drum Positive Pressure Gradient

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Appendix A: GT Load

Time /(min)	GT Load 29-Jul-2020 / (MW)	GT Load 08-Jul-2020 / (MW)	GT Load 28-Nov-2020 / (MW)	GT Load 28-Sep-2018 / (MW)
0	1.3	4.892	2.619	1.970
1	9.995	13.208	14.526	9.868
2	15.893	22.432	24.77	14.412
3	22.924	31.316	30.395	15.019
4	24.014	35.966	40.872	14.868
5	33.055	37.697	49.491	14.680
6	42.317	51.352	59.611	14.713
7	53.96	52.221	60.075	15.276
8	54.83	56.077	60.415	25.432
9	54.716	55.813	60.556	23.734
10	54.339	55.993	60.755	23.809
11	54.414	56.115	60.755	23.728
12	55.094	56.305	61.133	28.997
13	54.442	56.002	60.906	35.124
14	54.339	56.455	60.528	34.718
15	54.49	56.191	60.831	35.131
16	54.414	56.181	60.868	41.521
17	54.943	56.455	60.868	47.678
18	54.528	56.153	60.821	47.311
19	55.019	56.229	60.566	46.890
20	54.688	56.493	60.868	49.830
21	54.414	56.341	60.906	50.055
22	54.602	56.569	60.944	57.339
23	54.48	56.758	60.831	55.657
24	54.566	56.332	57.382	55.883
25	55.019	59.29	58.071	55.582
26	55.435	59.215	57.92	55.883
27	54.556	59.139	57.542	55.423
28	54.972	59.027	58.298	55.733
29	55.397	58.563	57.92	55.770
30	55.737	59.027	58.033	58.214
31	55.322	59.063	57.883	58.553
32	55.17	58.913	57.769	58.064
33	55.322	58.951	65.971	57.123
34	55.094	59.48		57.603
35	54.602	59.593		57.489
36	54.802	59.584		57.828
37	55.048	59.319		57.790
38	55.094	59.027		58.252
39	54.83	59.404		57.725
40	55.094	59.404		57.339

Appendix B: HP Superheater – 2 Outlet Temperature

Time /(min)	HP SH-2 Out Temp 28-Sep-2018 /(°C)	HP SH-2 Out Temp 08-Jul-2020/(°C)	HP SH-2 Out Temp 29-Jul-2020/(°C)	HP SH-2 Out Temp 28-Nov-2020/(°C)
0	271.757	291.733	283.098	297.197
1	312.359	290.656	282.815	297.161
2	335.915	301.988	290.904	305.616
3	349.290	315.829	306.158	317.973
4	359.736	329.186	313.03	335.253
5	373.218	344.172	328.998	356.062
6	386.198	367.57	344.361	381.52
7	395.908	387.68	365.645	401.322
8	404.554	403.834	388.355	416.327
9	411.817	415.55	403.078	426.902
10	418.926	424.436	413.269	434.862
11	427.780	431.002	420.604	440.701
12	434.720	436.128	427.283	445.747
13	439.880	440.532	431.74	449.554

Appendix C: HP Steam Temperature at ST

Time /(min)	HP Steam temp at ST 29-Jul-2020/(°C)	HP Steam temp at ST 08-Jul-2020/(°C)	HP Steam temp at ST 28-Nov-2020/(°C)	HP Steam temp at ST 28-Sep-2018/(°C)
0	198.8	260.094	275.064	325.033
1	198.674	261.321	276.567	324.576
2	198.668	262.45	279.6	324.126
3	198.559	263.808	281.109	323.688
4	246.827	265.322	285.636	323.202
5	253.008	268.351	291.674	322.709
6	262.222	271.369	297.923	322.253
7	271.401	274.411	305.62	321.866
8	282.278	282.068	314.86	321.488
9	293.365	288.23	324.005	321.051
10	304.414	295.894	334.643	320.730
11	315.267	303.452	343.846	317.452
12	326.017	309.58	354.719	301.172
13	336.93	318.77	364.12	293.515
14	347.618	329.66	373.275	293.093
15	356.895	340.622	380.924	294.618
16	366.168	349.923	390.114	297.647
17	373.795	359.129	399.306	302.228
18	381.425	368.336	413.351	306.794
19	389.059	376.021	425.677	312.906
20	395.134	382.111	434.839	319.062
21	401.266	389.899	442.452	325.181
22	407.429	396.05	448.557	334.355
23	413.551	402.12	454.608	342.023
24	422.795	413.194	457.636	349.686
25	428.882	427.085	458.246	358.961
26	436.694	434.785	458.116	366.610
27	442.785	439.392	459.632	374.282
28	447.339	442.423	461.16	381.974
29	448.873	445.454	462.026	389.606
30	451.88	448.471	462.624	395.730
31	453.4	449.975	463.421	401.881
32	454.863	451.483	464.065	407.993
33	455.976	452.879	464.94	414.070
34	456.714	455.885		426.507
35	457.255	457.402		437.444
36	457.68	458.909		443.616
37	457.907	460.061		448.172
38	457.918	460.862		452.726
39	458.094	461.342		454.233
40	458.173	461.654		457.264
41	458.338			458.782
42	458.335			459.995

Appendix D: APRDS Average Temperature

Time /(min)	APRDS Average Temperature 08-Jul-2020 /(°C)	APRDS Average Temperature 29-Jul-2020 /(°C)	APRDS Average Temperature 28-Nov-2020 /(°C)	APRDS Average Temperature 28-Sep-2018 /(°C)
0	171.875	103.0275	184.082	236.329
1	179.199	102.539	192.383	237.793
2	184.082	102.539	199.219	239.258
3	187.9885	102.051	207.5195	240.234
4	192.383	102.051	214.3555	241.700
5	195.8005	102.051	222.168	242.188
6	199.219	102.051	229.4925	243.164
7	202.1485	102.539	236.8165	243.652
8	206.543	135.254	245.117	244.629
9	211.914	161.133	253.9065	244.629
10	217.7735	183.1055	262.6955	245.117
11	223.633	199.219	272.949	244.141
12	231.4455	213.867	282.715	240.723
13	238.281	228.0275	292.4805	236.817
14	247.559	241.211	301.2695	232.910
15	256.836	255.3715	306.1525	230.469
16	267.09	268.5545	308.594	229.004
17	276.8555	280.2735	310.0585	228.516
18	287.1095	290.527	307.129	229.493
19	295.8985	301.2695	305.1755	230.957
20	306.641	310.0585	305.176	233.399
21	314.9415	311.0355	305.176	237.793
22	323.7305	312.0115	301.758	243.164
23	331.0545	314.453	298.828	248.536
24	338.3785	318.8475	301.27	253.906
25	348.6325	324.219	298.34	261.719
26	355.957	329.59	299.3165	270.996
27	361.8165	320.801	299.805	283.203
28	359.8635	302.7345	300.781	293.457
29	348.633	295.41	304.199	304.688
30	339.844	288.086	306.1525	299.805
31	330.5665	283.6915	308.1055	295.410
32	319.336	282.715	309.5705	299.317
33	317.871	282.7145	310.547	304.688
34	311.035	282.7145		310.059
35	302.7345	282.2265		316.895
36	295.4105	282.2265		325.196
37	293.9455	282.715		332.520
38	293.9455	283.6915		340.332
39	294.4335	284.668		346.680
40	293.457	286.621		349.122

Appendix E: Hot start-up time before the experiment

Date	Hot Start-Up time before experiments/ (min)
1-Oct-19	45
2-Oct-19	39
3-Oct-19	36
4-Oct-19	34
5-Oct-19	33
8-Oct-19	46
26-Nov-19	42
27-Nov-19	38
29-Nov-19	34
17-Dec-19	35
20-Dec-19	34
18-Jan-20	50
7-Mar-20	54
19-Mar-20	40
23-Jun-20	39
24-Jun-20	37
26-Jun-20	40
1-Jul-20	33
2-Jul-20	36
7-Jul-20	59
8-Jul-20	40
9-Jul-20	36
14-Jul-20	39
15-Jul-20	63
16-Jul-20	40
23-Jul-20	39
28-Jul-20	54
29-Jul-20	41

Appendix F: Hot start-up time after the experiment

Date	Hot Start-Up time after experiments / (min)
13-Nov-20	32
14-Nov-20	30
17-Nov-20	30
19-Nov-20	31
26-Nov-20	31
28-Nov-20	32
30-Nov-20	29
2-Dec-20	29
3-Dec-20	35
4-Dec-20	35
11-Dec-20	30
12-Dec-20	26
14-Dec-20	27
21-Dec-20	32
22-Dec-20	28
23-Dec-20	30
24-Dec-20	29
31-Dec-20	28
1-Jan-21	29
7-Jan-21	31
12-Jan-21	30
23-Jan-21	38
27-Jan-21	30
2-Feb-21	32
3-Feb-21	28
9-Feb-21	31
10-Feb-21	32
11-Feb-21	32
12-Feb-21	32
17-Feb-21	32
18-Feb-21	28
19-Feb-21	29
20-Feb-21	32
22-Feb-21	31
23-Feb-21	31
24-Feb-21	34
25-Feb-21	28
1-Mar-21	25
2-Mar-21	27
4-Mar-21	28
5-Mar-21	27
6-Mar-21	27
8-Mar-21	28
9-Mar-21	30

10-Mar-21	27
11-Mar-21	28
12-Mar-21	30
13-Mar-21	29
18-Mar-21	27
19-Mar-21	27
20-Mar-21	28
21-Mar-21	28
23-Mar-21	27
24-Mar-21	26
25-Mar-21	26
26-Mar-21	26
27-Mar-21	27

Appendix G: HP Bypass valve open percentage

Time /(min)	HP Bypass Valve Open Percentage 7-Jan-2021 / (%)	HP Bypass Valve Open Percentage 12-Jan-2021/ (%)	HP Bypass Valve Open Percentage 27-Jan-2021/ (%)	HP Bypass Valve Open Percentage 25-Feb-2021/ (%)
0	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	42.826	74.213	29.281	69.841
4	72.922	78.429	80.647	80.533
5	82.074	78.194	81.624	74.208
6	87.994	79.195	80.948	68.849
7	90.247	80.608	72.011	69.766
8	90.497	69.557	71.660	69.656
9	70.192	57.974	68.456	69.066
10	64.183	66.226	57.114	67.578
11	57.147	56.497	41.875	65.720
12	62.547	71.645	34.389	66.235
13	63.281	63.147	49.686	50.169
14	69.933	70.317	69.090	
15	76.151	75.490	55.988	
16	77.118	52.315		
17	81.209			
18	10.954			

Appendix H: HP Drum Pressure

Time /(min)	HP Drum Pressure 7-Jan-2021 /(bar)	HP Drum Pressure 12-Jan-2021/(bar)	HP Drum Pressure 27-Jan-2021/(bar)	HP Drum Pressure 25-Feb-2021/(bar)
0	33.721	30.811	36.929	24.262
1	33.202	29.933	36.055	24.385
2	32.643	29.178	35.533	24.724
3	31.705	28.835	35.353	25.619
4	31.326	28.476	35.493	26.657
5	31.386	28.456	35.513	27.937
6	32.304	29.540	35.313	29.570
7	33.062	30.575	35.656	31.689
8	34.299	31.988	36.191	34.143
9	35.580	33.269	37.069	36.339
10	36.993	34.882	38.127	38.570
11	38.394	36.319	39.244	40.569
12	39.507	37.576	40.301	42.345
13	40.948	39.017	41.339	44.316
14	42.062	40.170	42.401	46.136
15	43.219	42.065	43.454	47.973
16	44.261	44.121	45.813	50.207
17	44.815	45.163	48.104	52.243
18	46.132	46.277	50.538	55.077
19	48.392	47.873	52.115	55.436
20	50.383	49.988	52.598	57.032
21	52.418	52.083	54.389	60.121
22	55.012	55.321	56.663	62.440
23	58.804	58.011	59.382	64.311
24	59.681	62.122	60.993	66.247
25	60.385	63.609	64.825	68.069
26	60.560	66.931	66.467	69.805
27	63.618	67.510	70.997	72.074
28	64.531	69.505	73.051	73.231
29	64.890	70.623	74.947	
30	65.429	71.561	75.347	
31	67.764			

Appendix I: HP steam pressure at ST

Time /(min)	HP Steam Pressure at ST 07-Jan-2021/(bar)	HP Steam Pressure at ST 12-Jan-2021/(bar)	HP Steam Pressure at ST 27-Jan-2021/(bar)	HP Steam Pressure at ST 25-Feb-2021/(bar)
0	33.106	29.864	35.998	23.325
1	32.171	28.929	35.094	23.506
2	31.703	27.994	34.633	23.874
3	30.774	27.527	34.284	24.784
4	29.864	26.654	34.408	25.713
5	29.559	26.467	34.228	27.09
6	30.425	27.402	33.76	28.493
7	30.893	28.306	33.698	30.357
8	31.827	29.678	34.165	32.638
9	33.224	31.08	34.633	34.508
10	34.602	32.451	35.568	36.846
11	35.98	33.829	36.97	38.685
12	36.908	35.201	37.874	40.555
13	38.311	36.597	38.81	42.417
14	39.714	37.507	40.181	44.264
15	40.648	39.838	41.116	46.134
16	42.051	42.176	43.952	48.472
17	41.584	42.176	46.29	50.342
18	42.986	44.077	49.095	52.805
19	45.854	45.012	49.118	52.337
20	47.755	47.38	49.625	54.456
21	50.093	49.749	51.518	58.134
22	53.49	53.521	54.331	60.503
23	57.314	56.295	57.168	62.403
24	57.76	60.596	58.602	64.304
25	58.228	62.164	63.371	66.228
26	58.321	64.991	64.732	67.671
27	61.625	65.552	69.915	70.071
28	62.091	67.401	70.881	71.006
29	62.435	68.325	72.752	
30	62.684	69.77	73.126	
31	66.487			

Appendix J: HP steam temperature at ST

Time /(min)	HP Steam temp at ST 07-Jan-2021/(°C)	HP Steam temp at ST 12-Jan-2021/(°C)	HP Steam temp at ST 27-Jan-2021/(°C)	HP Steam temp at ST 25-Feb-2021/(°C)
0	284.994	279.71	290.781	268.016
1	286.203	281.032	292.099	271.022
2	287.59	282.539	292.383	272.528
3	290.616	285.576	292.7	275.535
4	293.651	288.6	295.731	278.558
5	298.217	294.678	300.259	283.174
6	304.352	300.846	304.844	289.263
7	313.528	308.557	309.424	295.354
8	322.709	317.797	317.072	304.621
9	331.894	327.003	324.787	313.931
10	341.253	336.387	334.047	326.306
11	350.597	347.265	344.934	335.588
12	359.909	356.585	354.213	344.804
13	369.26	365.745	363.473	355.62
14	376.905	373.565	371.253	366.46
15	386.146	382.727	380.48	375.64
16	392.334	390.385	388.092	384.932
17	413.196	412.759	395.848	394.367
18	428.874	428.574	403.641	409.981
19	439.756	437.875	423.585	437.676
20	447.434	445.473	437.705	450.1
21	451.992	451.624	445.509	456.212
22	456.518	456.202	451.589	457.723
23	458.025	457.716	456.238	458.297
24	458.345	459.229	459.297	458.15
25	458.797	462.26	462.325	457.589
26	459.605	465.283	463.582	456.916
27	460.656	466.785	464.679	456.382
28	461.335	468.288	465.553	455.679
29	462.167	471.3	467.054	
30	462.737	472.661	470.061	
31	463.203			

Appendix K: HP steam flow rate

Time /(min)	HP Steam flow 07-Jan-2021/ (TPH)	HP Steam flow 12-Jan-2021/ (TPH)	HP Steam flow 27-Jan-2021/ (TPH)	HP Steam flow 25-Feb-2021/ (TPH)
0	45.013	45.562	44.372	32.269
1	44.154	50.374	43.664	32.494
2	52.685	62.051	43.304	32.964
3	54.16	60.75	43.041	33.651
4	68.953	73.286	53.684	34.712
5	69.555	72.208	56.208	35.873
6	69.261	72.567	72.129	42.633
7	77.24	73.982	71.315	44.979
8	78.432	75.982	82.281	47.316
9	80.326	78.284	83.078	61.498
10	82.634	80.63	83.948	63.829
11	84.983	85.261	85.341	73.331
12	87.33	87.57	87.015	75.649
13	88.776	89.227	88.34	77.949
14	91.089	91.561	89.837	80.272
15	92.992	81.238	91.456	81.507
16	91.133	74.754	72.606	78.108
17	104.263	102.093	74.94	78.019
18	90.247	70.462	60.373	88.616
19	80.234	94.193	96.919	97.44
20	80.121	103.105	86.439	82.017
21	82.436	77.279	86.637	73.488
22	63.634	63.363	75.43	73.851
23	77.346	83.417	79.888	81.224
24	84.744	64.417	81.508	79.745
25	97.59	78.099	58.912	79.825
26	98.184	81.97	83.555	82.005
27	78.256	76.859	39.477	77.589
28	92.296	86.539	86.328	87.311
29	97.124	94.747	90.031	
30	97.143	84.895	90.12	
31	53.768			

Appendix L: HP start-up vent open percentage

Time /(min)	HP Start-Up vent Open % (7-Jan-2021)	HP Start-Up vent Open % (2-Mar-2021)	HP Start-Up vent Open % (4-Mar-2021)	HP Start-Up vent Open % (9-Mar-2021)
0	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
6	0.000	13.650	0.000	0.000
7	0.000	13.646	11.996	0.000
8	8.387	17.761	11.896	12.823
9	10.492	17.886	11.967	12.773
10	10.567	17.882	11.921	12.773
11	10.567	19.712	11.921	12.773
12	10.567	24.504	11.942	12.773
13	10.567	28.915	15.004	21.571
14	10.567	29.040	26.083	21.616
15	10.567	29.034	34.348	21.616
16	10.567	29.040	34.529	21.621
17	10.567	32.594	34.554	21.621
18	10.567	32.649	34.529	21.621
19	20.794	32.644	34.529	21.646
20	20.794	46.235	34.554	21.646
21	39.725	46.360	34.529	21.646
22	39.793	49.644	34.548	36.861
23	41.623	49.912	34.529	37.061
24	47.864	49.944	39.893	44.122
25	48.015	49.937	39.893	44.173
26	48.015	49.944	57.314	61.349
27	48.015	33.852	61.098	61.449
28	48.015	22.122	61.273	61.441
29	48.015	0.316	61.273	61.449
30	48.015	0.000	61.273	61.449
31	48.015	0.000	61.290	61.424
32	48.015	0.000	61.273	48.934
33	30.394	0.000	61.273	45.074
34	17.460	0.000	46.285	18.388
35	4.953	0.000	31.171	5.279
36	0.000	0.000	14.753	20.719
37	0.000	0.000	15.104	24.178
38	0.000	0.000	11.996	1.193
39	0.000	0.000	0.000	0.000

Appendix M: HP Drum pressure

Time /(min)	HP Drum Pressure (7-Jan-2021) /(bar)	HP Drum Pressure (2-Mar-2021) /(bar)	HP Drum Pressure (4-Mar-2021/(bar)	HP Drum Pressure (9-Mar-2021) /(bar)
0	60.221	65.973	64.591	52.403
1	59.163	65.414	63.892	51.864
2	58.644	64.516	63.040	51.006
3	58.085	63.818	62.710	50.667
4	57.203	62.780	62.191	50.502
5	56.090	61.728	61.478	49.988
6	55.511	59.527	60.260	49.130
7	53.536	55.511	59.163	47.913
8	51.799	51.725	55.252	46.156
9	48.966	47.753	50.822	42.920
10	45.494	44.101	47.210	39.942
11	42.580	40.844	43.858	37.332
12	40.046	37.995	40.944	34.962
13	37.811	35.560	38.310	32.563
14	36.015	33.720	35.493	30.581
15	35.118	32.647	33.421	28.931
16	34.419	31.768	31.821	28.017
17	33.721	30.894	30.544	27.152
18	33.202	30.168	29.454	26.799
19	32.643	29.809	28.193	26.277
20	31.705	29.633	27.315	25.938
21	31.326	29.873	26.357	25.775
22	31.386	30.970	25.635	25.622
23	32.304	32.228	24.924	25.473
24	33.062	33.644	24.781	25.938
25	34.299	35.061	24.781	26.633
26	35.580	36.542	25.439	27.335
27	36.993	38.015	26.357	28.589
28	38.394	40.449	27.611	30.033
29	39.507	45.159	29.131	31.306
30	40.948	50.527	30.628	32.763
31	42.062	54.797	32.124	34.143
32	43.219	56.953	33.381	35.556
33	44.261	58.175	34.814	37.548
34	44.815	59.701	36.638	40.298
35	46.132	61.683	39.049	44.057
36	48.392	63.613	42.680	48.248
37	50.383	65.275	46.731	50.777
38	52.418	66.951	47.844	52.778
39	55.012	68.667	49.684	53.471
40	58.804	70.557	52.134	54.374
41	59.681	72.154	54.533	56.992
42	60.385	73.915	57.686	60.146

Appendix N: HP steam pressure at ST

Time /(min)	HP Steam Pressure at ST (7-Jan-2021) /(bar)	HP Steam Pressure at ST (2-Mar-2021) /(bar)	HP Steam Pressure at ST (4-Mar-2021)/(bar)	HP Steam Pressure at ST (9-Mar-2021) /(bar)
0	10.384	6.27	10.789	4.182
1	11.787	12.098	12.628	10.575
2	11.885	11.163	14.587	11.043
3	10.504	9.293	11.818	11.381
4	9.574	9.542	12.13	11.261
5	8.643	9.075	12.593	10.816
6	8.576	58.009	11.221	9.917
7	52.711	54.238	12.753	8.545
8	50.841	50.217	53.949	43.415
9	48.004	46.477	49.781	41.622
10	44.264	42.744	46.158	38.903
11	41.459	39.464	42.456	36.104
12	39.121	36.659	39.714	33.785
13	36.814	34.352	37.002	31.485
14	34.976	32.482	34.228	29.646
15	34.04	31.547	31.946	27.839
16	33.574	30.643	30.082	26.935
17	33.106	29.708	29.173	26
18	32.171	28.773	27.801	25.656
19	31.703	28.431	26.897	25.257
20	30.774	27.963	25.968	24.841
21	29.864	27.813	25.064	24.597
22	29.559	28.742	24.161	24.129
23	30.425	30.145	23.719	24.124
24	30.893	31.547	23.469	24.529
25	31.827	32.925	23.314	24.841
26	33.224	34.29	23.755	25.283
27	34.602	36.129	24.316	26.181
28	35.98	38.903	25.251	27.994
29	36.908	44.14	26.623	28.898
30	38.311	49.749	28.462	30.27
31	39.714	53.988	29.827	31.666
32	40.648	54.924	30.737	33.511
33	42.051	55.765	32.102	35.374
34	41.584	57.239	34.446	39.09
35	42.986	59.599	37.213	43.298
36	45.854	61.531	41.428	46.625
37	47.755	62.934	45.659	49.367
38	50.093	65.365	45.191	50.748
39	53.49	66.766	47.497	50.28
40	57.314	68.668	49.898	51.682
41	57.76	70.518	52.679	55.017
42	58.228	71.879	56.264	58.228

Appendix O: HP SH – 2 outlet temperature

Time /(min)	HP SH - 2 Out Temperature (7-Jan-2021) /(°C)	HP SH - 2 Out Temperature (2-Mar-2021) /(°C)	HP SH - 2 Out Temperature (4-Mar-2021) /(°C)	HP SH - 2 Out Temperature (9-Mar-2021) /(°C)
0	294.087	307.38	292.369	287.895
1	300.942	309.389	294.814	289.108
2	312.565	318.611	303.066	297.812
3	329.152	333.616	316.56	311.21
4	347.828	351.322	334.939	327.591
5	368.932	371.287	355.904	345.656
6	390.164	393.494	378.802	365.95
7	406.57	411.853	403.041	391.282
8	419.93	424.752	418.671	409.573
9	429.313	434.519	430.217	423.065
10	436.439	441.729	437.979	432.469
11	442.178	446.828	444.604	439.148
12	446.081	450.627	449.689	444.816
13	449.936	453.767	454.075	448.633
14	453.707	458.165	457.802	452.336
15	456.166			456.027

Appendix P: HP SH steam temperature at ST

Time /(min)	HP Steam temp at ST (7-Jan-2021) /(°C)	HP Steam temp at ST (2-Mar-2021) /(°C)	HP Steam temp at ST (4-Mar-2021) /(°C)	HP Steam temp at ST (9-Mar-2021) /(°C)
0	244.793	288.449	273.218	239.606
1	260.662	297.536	289.527	239.002
2	245.977	305.312	294.101	229.717
3	228.252	306.508	289.57	215.818
4	217.343	306.505	284.989	209.661
5	209.703	303.426	274.171	203.572
6	203.591	290.191	264.769	200.553
7	253.018	276.595	258.723	199.567
8	269.08	273.572	270.795	204.234
9	268.284	270.505	269.466	256.366
10	265.211	267.483	264.9	254.835
11	264.268	268.003	263.398	250.276
12	265.278	271.045	263.861	247.237
13	269.804	274.105	266.903	248.707
14	272.831	278.693	271.431	251.714
15	278.933	283.237	276.042	254.749
16	281.97	287.808	280.578	259.286
17	284.994	289.326	283.661	263.873
18	286.203	290.835	286.669	266.88
19	287.59	292.348	287.988	268.403
20	290.616	295.377	288.8	269.904
21	293.651	299.909	289.361	271.133
22	298.217	306.059	289.727	272.595
23	304.352	313.726	290.008	275.644
24	313.528	322.817	290.995	280.211
25	322.709	330.69	292.511	284.824
26	331.894	339.996	295.54	290.908
27	341.253	349.216	300.152	298.497
28	350.597	359.923	306.219	306.192
29	359.909	369.206	315.474	315.463
30	369.26	379.911	323.12	324.693
31	376.905	389.147	332.416	333.945
32	386.146	404.776	341.725	343.227
33	392.334	427.61	351.063	352.534
34	413.196	440.42	358.758	363.333
35	428.874	448.102	363.311	372.609
36	439.756	454.184	369.5	383.472
37	447.434	455.693	375.633	392.732
38	451.992	457.188	398.204	406.752
39	456.518	457.268	422.975	430.711
40	458.025	456.882	436.999	443.38
41	458.345	456.344	446.262	450.967
42	458.797	455.826	452.399	454.01

Appendix Q: New Vent Open percentage

Time /(min)	New Vent Open % (16-Jul-2020)	New Vent Open % (4-Mar-2021)	New Vent Open % (20-Mar-2021)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	25.51
7	0	1.558	53.046
8	0	36.761	72.363
9	0	60.187	87.584
10	0	77.951	101.05
11	0	92.195	104.233
12	0	104.446	104.37
13	0	104.572	104.559
14	0	104.645	104.596
15	0	104.721	104.608
16	0	104.785	104.745
17	0	104.822	104.758
18	0	104.846	104.758
19	0	104.895	104.785
20	0	104.91	104.81
21	0	104.935	104.834
22	0	104.947	104.834
23	0	104.959	104.874
24	0	104.971	104.858
25	0	105.02	104.883
26	0	105.02	104.922
27	0	105.06	104.922
28	0	105.072	104.91
29	0	105.109	104.947
30	0	105.096	104.959
31	0	105.121	104.959
32	0	105.148	104.984
33	0	105.161	105.011
34	0	105.148	105.011
35	0	105.161	105.035
36	0	105.121	105.035
37	0	105.161	103.482
38	0	87.497	57.054
39	0	59.677	0
40	0	0	0

Appendix R: HP SH – 2 outlet temperature

Time /(min)	HP SH - 2 Outlet temperature (16-Jul-2020) /(°C)	HP SH - 2 Outlet temperature (4-Mar-2021) /(°C)	HP SH - 2 Outlet temperature (20-Mar-2021) /(°C)
0	274.263	292.369	280.649
1	273.631	294.814	279.503
2	277.921	303.066	278.931
3	286.668	316.56	278.396
4	305.033	334.939	277.774
5	327.535	355.904	276.547
6	353.558	378.802	273.466
7	383.268	403.041	269.115
8	405.37	418.671	263.981
9	419.222	430.217	262.128
10	429.997	437.979	266.738
11	438.374	444.604	278.1
12	444.706	449.689	291.458
13	449.766	454.075	305.286
14	453.465	457.802	316.999
15	456.579		318.891
16			310.996

Appendix S: HP Steam temperature at ST

Time /(min)	HP steam Temp at ST (16-Jul-2020) /(°C)	HP steam Temp at ST (04-Mar-2021) /(°C)	HP steam Temp at ST (20-Mar-2021) /(°C)
0	267.493	269.466	299.469
1	266.755	264.9	316.856
2	265.983	263.398	321.405
3	265.587	263.861	322.165
4	265.307	266.903	319.126
5	264.469	271.431	316.067
6	265.073	276.042	284.91
7	269.596	280.578	270.703
8	271.11	283.661	269.724
9	272.62	286.669	268.235
10	274.13	287.988	268.361
11	275.329	288.8	269.875
12	276.354	289.361	271.395
13	276.943	289.727	276.005
14	279.348	290.008	280.571
15	282.375	290.995	285.095
16	285.419	292.511	286.601
17	291.497	295.54	288.104
18	299.176	300.152	289.37
19	306.932	306.219	289.903
20	316.184	315.474	290.505
21	325.476	323.12	293.441
22	334.782	332.416	296.494
23	345.524	341.725	301.021
24	354.704	351.063	308.662
25	364.167	358.758	316.302
26	373.439	363.311	324.069
27	382.591	369.5	333.315
28	390.312	375.633	344.1
29	398.018	398.204	353.364