Base Load Power Hub (BLPH)

Process Control, Operation, Start-up and Shutdown philosophy

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1 INTRODUCTION

1.1 PROJECT OVERVIEW

Crosswind, a Shell and Eneco joint venture, was awarded the tender to develop the offshore Hollandse Kust Noord (HKN) wind farm, located 18.5km off the coast of Netherlands near the town of Egmond aan Zee. The consortium plans to have HKN operational in 2023 with an installed capacity of 759MW generating at least 3.3TWh per year. This is sufficient renewable power to supply more than 1 million Dutch households with green electricity.

Offshore wind farms produce intermittent electricity and balancing these dips and peaks and integrating this electricity into the national energy system requires new technologies. For this reason, the offshore wind farm will include several new technologies that could be implemented at full-scale in the future. The new technologies being explored include a floating solar park, a short-duration battery storage as well as long-term storage via green hydrogen produced by water electrolysis and subsequently consumed in a fuel cell. The combination of these individual measures, herein referred to as the Base Load Power Hub (BLPH) will ensure a continuous power supply regardless of the wind situation.

Project Location

The Hollandse Kust Noord (HKN) wind farm is located 18.5km off the coast of the Netherlands near the town of Egmond aan Zee.

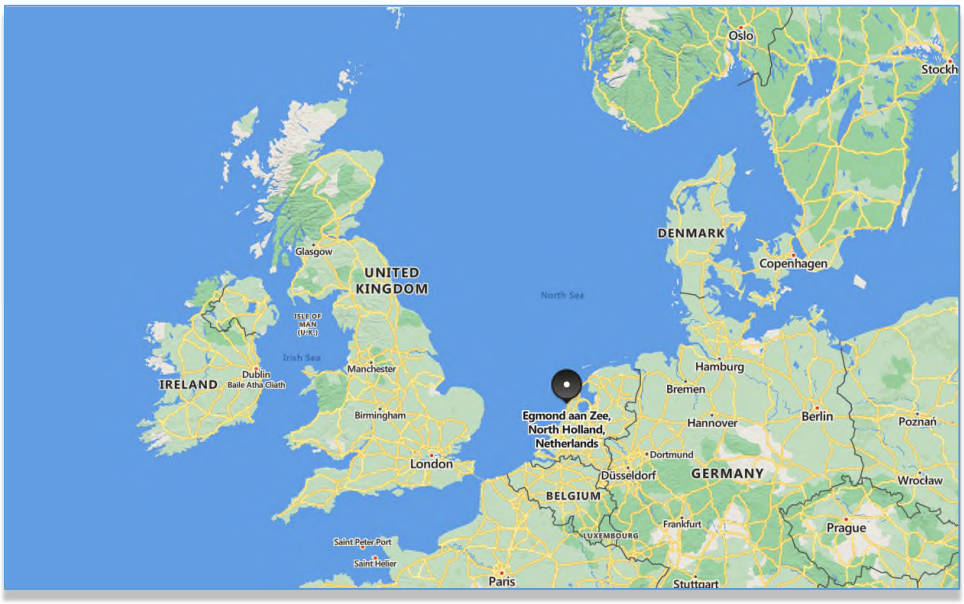


Figure 1 HOLLANDSE KUST NOORD WIND PARK Location Map

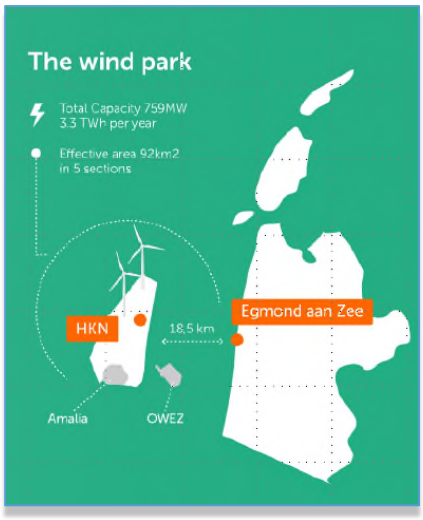


Figure 2 - Wind Park Details

The wind farm will consist of No. 69 x 11.5MW wind turbine generators each to be installed on a dedicated monopile structure. A 70th monopile located on coordinates E 590719.1, N 5841602.3 is reserved for installing the platform accommodating the BLPH. The monopile structure was designed and installed by Van Oord Offshore Wind (VooW) and therefore not part of the BLPH scope.

Project Concept

All components included in the BLPH will be integrated onshore on a topsides and installed in an offshore location within the boundaries of the HKN wind farm. At its simplest, the BLPH will store energy during periods of high electricity generation from renewable sources (a wind turbine generator and the floating solar PV farm) and release it during periods of low generation. In practice. It is expected that the energy stored will supplement generation from renewable sources to ensure that at least 1.0MW of power is exported to the electrical grid regardless of wind/solar availability.

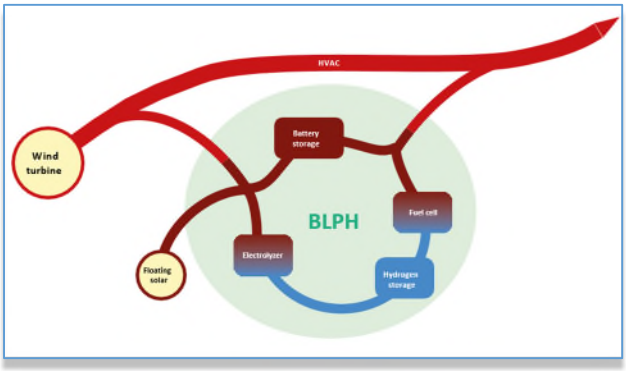


Figure 3 – BLPH Concept

Electricity in the BLPH will be stored in the form of electrons in a battery energy storage system (BESS) as well as converted into green hydrogen via water electrolysis. When the power output from the connecting wind turbine drops to below 1 MWe, the BLPH will return its stored energy to supplement the remaining power output. This will be by discharging the BESS, while stored hydrogen will be converted back into electricity using a fuel cell to extend the discharge duration.

The purpose of the BLPH is to function as a testbed for the integration of energy storage technologies with renewable generation. It is expected that equipment installed on the BLPH will operate as Normally Unmanned Installation for at least two (2) years with no or minimal maintenance and it will have its own independent control room with the ability to communicate with Crosswind's control room.

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2 DOCUMENT SCOPE

The scope of this document is intended to provide a description of the Process Control, Operation, Start-up and Shutdown philosophy to be adopted within the BLPH project.

Moreover, the main objectives of the present document are:

- To define the process control functional requirements to achieve safe and efficient control of process systems along the BLPH project
- To provide a logical explanation for each control and its function in controlling (and safeguarding, if any) of the equipment/system
- To provide an overall guideline for preparing, at later stages, the control narratives and schemes for process instrumentation.

This document should be read in conjunction with the "Process Flow Diagrams" (Ref. [5] to Ref. [10]) and the H&MB (Ref. [2]).

2.1 REFERENCES

Project Documents

Ref. [1] Basic Design Engineering Package_Rev2 - Doc. No: K559-2254-PM-PLN-003
Ref. [2] Heat And Mass Balance - Doc. No: 123A90-DDL-PR-BL-80002
Ref. [3] Equipment Sizing Philosophy and Calculations – Doc. No: 123A90-DDL-PR-CA-80033
Ref. [4] PSFS - Doc. No: 123A90-DDL-PR-DG-80038
Ref. [5] BLPH PROCESS FLOW SCHEME ELECTROLYSER AND HYDROGEN DRYING PACKAGE – Doc. No: 123A90-DDL-PR-DG-80003
Ref. [6] BLPH PROCESS FLOW SCHEME HYDROGEN STORAGE – Doc. No: 123A90-DDL-PR-DG-80004
Ref. [7] BLPH PROCESS FLOW SCHEME FUEL CELL PACKAGE – Doc. No: 123A90-DDL-PR-DG-80005
Ref. [8] BLPH UTILITY FLOW DIAGRAM WATER TREATMENT PLANT – Doc. No: 123A90-DDL-PR-UFD-80006
Ref. [9] BLPH UTILITY FLOW DIAGRAM INSTRUMENT AIR AND NITROGEN SYSTEMS – Doc. No: 123A90-DDL-PR-UFD-80007
Ref. [10] BLPH UTILITY FLOW DIAGRAM VENT SYSTEMS – Doc. No: 123A90-DDL-PR-UFD-80008
Ref. [11] Set of P&ID from 123A90-DDL-PR-PID-80009 to 80029 and 80041, 80042, Rev01
Ref. [12] Process Safety Cause & Effect Block Diagram – Doc. No: 123A90-DDL-PR-DG-80000_01
Ref. [13] Control System Philosophy – Doc. No: 123A90-DDL-IN-RE-40093
Ref. [14] Electrical System Description & Design Philosophy – Doc. No: 123A90-DDL-EL-SP-20141
Ref. [15] Design of Hydrogen Supply Pressure Control Valves : 25-PV-055 A/BCW-ROS-TQ-0016
Ref. [16] Utilities, Chemicals, Consumables, Lubricants Consumption List – Doc. N. 1724000448-MAC-LIS-00020
Ref. [17] Water Treatment Package P&iDs – Doc. N. 1724000448-PR-PID-00013
Ref. [18] Process Control Logics Description - 123A90-DDL-IN-RE-40095

International Codes and Standards

For a list of external, Industry and/or Vendor Standards as well as for a list of Shell DEPs that shall be applied to the project, reference shall be made to Section 10 of Ref. [1].

2.2 DEFINITIONS AND ABBREVIATIONS

DEFINITIONS

COMPANY or Client (CPY):	Crosswind
CONTRACTOR (CTR):	ROSETTI MARINO S.p.A.
PROJECT:	HOLLANDSE KUST NOORD WIND PARK Project

Table 1 - Definitions

ABBREVIATIONS

AMB	Ambient (Often Referred To Ambient Temperature)
BDV	Blowdown Valve
BESS	Battery Energy Storage System
BLPH	Base Load Power Hub
CIP	Cleaning In Place
DCS	Distributed Control System
DEP	Design Engineering Practice
D/S	Downstream
ESD	Emergency Shut Down
FC	Fuel Cell
FEED	Front-End Engineering Design
H&MB	Heat And Material Balance
LLLL	Low Low Liquid Level
MCC	Motor Control Center
PAH	Pressure Alarm High
PAL	Pressure Alarm Low
P&ID	Piping & Instrumentation Diagram
PSD	Process Shutdown
PSFS	Process Safeguarding Flow Schemes
PSV	Pressure Safety Relief Valve
PT	Pressure Transmitter
SCADA	Supervisory Control And Data Acquisition
SDV	Shut Down Valve
SoC	State Of Charge
SWRO	Seawater Reverse Osmosis
UCP	Unit Control Panel
UF	Ultra Filtration
UFD	Utility Flow Diagram
U/S	Upstream

Table 2 - Abbreviations

3 PROCESS CONTROL, OPERATION, START-UP AND SHUTDOWN PHILOSOPHY

3.1 GENERAL

Power is imported into the BLPH facility from the WTG CW57 and the floating solar Photovoltaic (PV) array (when the power output / export is in excess of 1 MW). This power is used to produce green hydrogen via water electrolysis and charge the BESS. When power output of the linked WTG (CW57) drops below 1 MW, the power export will be supplemented by discharging the BESS and converting the green hydrogen back into electricity using a fuel cell (FC).

The topside processes are summarized in the *Figure 4 – Process Flow Diagram simplified*.

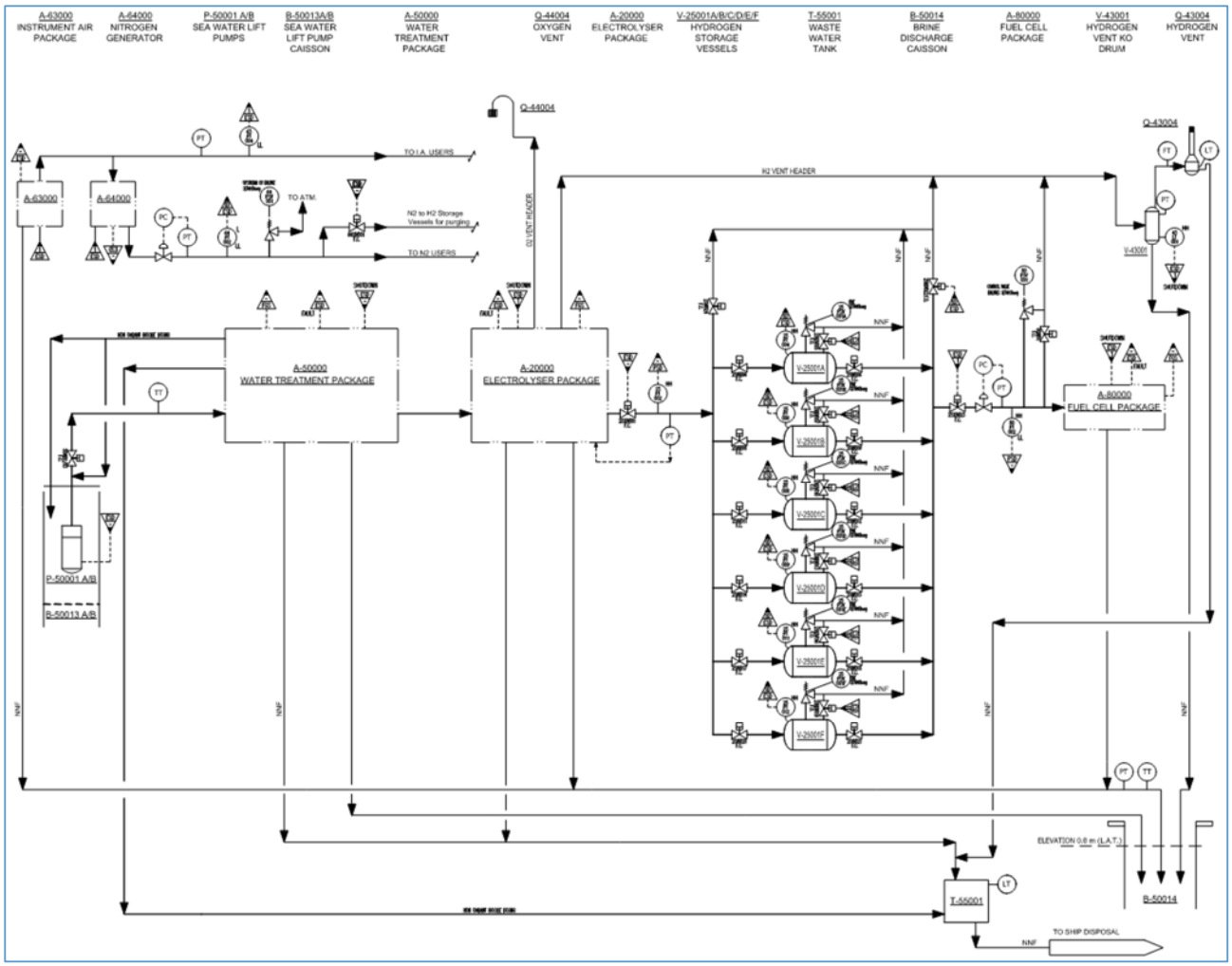


Figure 4 – Process Flow Diagram simplified

Monitoring and control of BLPH will be remote (shore-based control room) and the solar farm, battery and fuel-cell shall act cooperatively so that power from all sources will be combined to export power regardless of the prevailing weather. NOTE: Energy stored as hydrogen will leave only in the form of electricity through the Inter-Array Cable (IAC) connecting BLPH indirectly to a grid sub-station.

Whenever possible the fuel-cell will consume the platform's stored hydrogen prior to discharging the battery to ensure SoC is maintained high for it to react instantly to each demand for power.

From electrically point of view, following operation modes shall be applicable (Ref. [14]):

- Mode 0 = IDLE (power import only)
- Mode 1 = POWER IMPORT (charging)
- Mode 2 = HOT STANBY (power import no export required)
- Mode 3 = POWER EXPORT (Discharging)
- Mode 4 = COLD STANDBY (power import no export possible)
- Mode 4A = EMERGENCY (Island)
- Mode 5 = POWER OUT (black-out)
- Mode 6 = MAINTENANCE
- Mode 7 = RESEARCH
- Mode 8 = NONE MODE

For details of how above mode of operation for the Fuel Cell and Electrolyser will run, reference shall be made to (Ref. [14]).

3.2 SEA WATER LIFT PUMPS P-50001A/B

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80021)

3.2.1.1 Main Operating data

The seawater lift pumps are characterized by the following main operating data:

- Normal Operating mass flowrate ~2500 kg/h
- Normal Operating volumetric flowrate ~2.5 m^3/h
- Normal Discharge pressure (min./max) ~4.0 / 5.0 barg
- Normal Discharge temperature ~ 22.4 °C

3.2.1.2 Process Operation and Control Philosophy

Seawater is the raw water to be treated and then electrochemically converted into hydrogen (for energy accumulation purposes) and oxygen (to be continuously vented when the plant runs); thus seawater is lifted by means of 2 x 100% submersible centrifugal pumps P–50001A/B (one running and the other in stand-by mode), and then fed through the water treatment plant to remove the biological and inorganic "pollutants" that shall be eliminated prior to be served to the electrolyser package.

A logic control will be provided to prevent simultaneous running of both pumps A and B.

Downstream the sea water lift pumps, in order to monitor the temperature of brine going back to the brine discharge caisson B-50014, a temperature measurement (50-TI-001) is required just at inlet of water treatment system, to compare it with the one of the return-stream (50-TI-002) via differential function 50-TDI-002. By measuring the temperature difference between these two streams, one can ensure that the discharged water will not be too warm back into the sea, which could potentially harm the marine ecosystem.

This process is crucial for environmental conservation as it helps us maintain the temperature balance in the marine environment. By controlling the temperature of the discharged water, we mitigate any adverse effects on marine life and ecosystem.

Moreover, each pump can be put into operation by means of the remote MCC control system and the remote opening/closing of the (on/off) isolation valves 50-XV-001 and 50-XV-003 respectively.

The following signals will inform about each pump status:

- RUNNING/STOPPED
- AUTO START READY
- FAULT/TRIPPED
- SHUTDOWN ALARM
- START/STOP manual remote activation

All signals for motor control (start/stop) and monitoring are exchanged between MCC and DCS.

Moreover, a software interlock is provided to prevent pump from starting in case the relevant XV valve is closed:

1) should the valve 50-XV-001 be closed, the software interlock prevents pump "A" from starting;
2) should the valve 50-XV-003 be closed, the software interlock prevents pump "B" from starting.

A by-pass line on each Sea Water Lift Pump discharge side is provide, in order to dose with treated seawater (which already contains biocide) the sea water pump that is not running. Therefore the dosing is intermittent. The scope of this dosing is to disinfect the seawater lift pump discharge tube of the pump that is not running, to avoid biological growth.

Assume that the sea water pump that is running is the pump "A", the discharge tube of the pump "B" (stand-by pump) is dosed with treated sea water coming from pump "A" as follows:

- on/off valve 50 -XV-001 is open, installed on the pump A discharge side;
- on/off valve 50 -XV-003 is closed, installed on the pump "B" discharge side;
- on/off valve 50 -XV-002, on the by-pass discharge side of the pump "A" is closed;
- on/off valve 50 -XV-004 on the by-pass discharge side of the pump "B" will be open, to allow treated sea water coming from pump "A", which already contains biocide, passing through the by-pass line of the pump "B".

Moreover, a biocide inlet stream to the Seawater Lift Pumps Caissons B-50013A/B is provided, in order to also disinfect the seawater in the suction side of each Seawater Lift Pumps.

3.2.1.3 Start-up and Shut-Down philosophy

Air is very often present in column of a vertical pump for this specific application, thus, if air collects at the high point, a restriction occurs, which may cause head-loss and potentially lead to surges when the pocket of air moves from one location to another. Thus, an air/vacuum valve is mounted at pump discharge in order to vent the air before the downstream check valve is pushed open and allow to discharge water. Instead, when the pump stops, the air/vacuum valve, thanks to its internal float, will reopen and admit air into the pump column to prevent the formation of a vacuum as the water column drains. Usually when the valve is closed the float is guided and held upward tight against the resilient seat.

The activation of ESD-1 (and in cascade from ESD-1D and ASD) stops the running pump in the unlikely emergency event (Ref. [12]). The pump is also stopped for the PSD activation in case of:

1) fault signal from Electrolyser Package A-20000;
2) fault signal from Water Treatment System.

As this document serves as a philosophy, the following sequences for starting and stopping the vertical progressive cavity pumps, which draw seawater to supply a seawater treatment plant ultimately delivering filtered water to the electrolyser, are indicative only. It's important to note that the following sequences are preliminary at this stage and may need to be adapted based on manufacturer's manuals.

Startup Sequence:

- Pre-Startup Checks: Before initiating the pump, ensure all relevant valves in the seawater discharge line to the treatment plant are open.
- Engage Power Supply: Activate the power supply to the pump motor.
- Check Operational Status: Verify that the pump is in a standby mode and all safety measures are functional.
- Initiate Pump: Start the pump avoiding as far as possible sudden pressure surges and ensuring smooth operation.
- Monitor Performance: Keep a close eye on the pump's performance parameters such as flow rate (by reading the first available downstream flowmeters), pressure, and temperature.
- Stabilization: Allow the pump to stabilize at the required operating conditions.

Shutdown Sequence:

- Monitor Parameters: Continuously monitor the pump's performance parameters during the reduction in flow.
- Safety Checks: Ensure all safety protocols are followed according to manufacturer's operating manual, and no abnormalities are observed during the shutdown process.
- Cease Operation: Fully stop the pump motor.

- **Post-Operation Checks:** After shutdown, inspect the parameters and remote signals for any signs of abnormalities.
- **Record Keeping:** Maintain a log of the shutdown procedure, including any noteworthy observations or incidents.

3.2.1.4 Overpressure protection

It is noted that the discharge pipe of the Sea Water Lift Pumps P-50001A/B cannot withstand the maximum operating pressure that can be generated by the pumps (shutoff pressure of the pumps) in case of blocked discharge. There is then a risk to overpressure the discharge piping of the Sea Water Lift Pumps P-50001A/B. Therefore, on each Seawater Lift Pump discharge side a PSV is installed to protect the downstream system. PSVs are designed for blocked outlet.

On the discharge line of the Sea Water Lift Pump P-50001A (B) a pressure transmitter 50-PT-001 (002) is provided, with a high and low alarm to alert the operator in case of high pressure.

Moreover, since the inlet system of the Water Treatment Package A-50000 has a design pressure of 6 barg, a PSV (50-PSV-011) is installed at inlet of the package A-50000, in order to protect the water treatment package from overpressure, in case of blocked outlet within the package.

3.3 WATER TREATMENT PLANT

(Reference P&ID: Doc. N. 1724000448-PR-PID-00013)

The water treatment system in a standalone containerized unit containing all major components. It receives seawater from lift pumps and the scope of the system is to produce a provide pure water to the downstream Electrolyser Package. The water treatment system operating conditions and configuration are vendor specific. For control philosophy, start-up, shut-down operations and operating conditions reference shall be taken from original vendor's documentation.

Seawater is the raw water to be treated and then electrochemically converted into hydrogen (for energy accumulation purposes) and oxygen (to be continuously vented when the plant runs); thus seawater is lifted by means of 2 x 100% submersible pumps P–50001A/B (one running and the other in stand-by mode), and then fed through the water treatment plant to remove the biological and inorganic "pollutants" that shall be eliminated prior to be served to the electrolyser package.

The water treatment package will contain some water analyzers such as conductivity and hardness of water. The water treatment package will provide the signals on pH, temperature, hardness, and conductivity of feed water for the Electrolyser Package. Such signals will be sent from control system to Electrolyser UCP. Moreover, during the test, however, sampling will be carried out at regular intervals.
In case of a fault signal from the water treatment plant, the system is automatically stopped. The water treatment system also occurs in case of ESD-1 (and in cascade from ASD and ESD-1D), as per Ref. [12].

A non-oxidizing biocide system is provided (within the water treatment plant) to avoid (or remove) the biological content from seawater, or rather to discourage the growth of marine organisms within seawater systems.

The biocide injections are fed to the following items (Ref. [16]):

- Sea water lift pumps caissons B-50013A/B (discontinuous dosage);
- On the common manifold on the discharge line of the Seawater Lift Pumps (discontinuous dosage);
- Wastewater tank T-55001 (discontinuous dosage).

The discontinuous dosage of the discharge pipe of the seawater lift pump that is not running will be carried out when the mail seawater lift pump runs. Assuming that the pump "A" is running: at time is required to dose the discharge pipe of the pump "B", the valve 50-XV-004 will be open. It is noted that just upstream of such XV valve, an orifice is provided to guarantee a fine dosage of pump "B". A flow rate of just few liters per hour is required during this dosage (and the dosage will last few minutes), therefore the inlet flow rate of the seawater that is fed to the water treatment package will not be impacted considering that the order of magnitude between the two flow rates is more than a thousand.

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3.4 WASTEWATER TANK T-55001

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80026)

3.4.1.1 Main Operating Data

This accumulation tank is characterized by the following main operating data:

- Normal Operating inlet flowrate — gathering of the whole BLHP plant
- Normal Operating Pressure — slightly above the atmospheric
- Normal Operating Temperature — AMB
- Capacity — 16.0 m^3

3.4.1.2 Process Operation and Control Philosophy

The tank has the scope to accumulate all the wastewaters gathered intermittently from each wastewater stream installed at BLPH plant:

- Liquid from Seal Drum;
- Liquid from the Electrolyser Package;
- Liquid from the Water Treatment Package.

A level transmitter (55-LIT-001) send the signal of liquid level inside the tank to DCS following two level thresholds respectively high and low, to alert the operator.

An inlet stream of biocide is provided for the Wastewater Tank T-55001. The dosing will be intermittent. For frequency of dosage, flow rate and consumption of the biocide see Ref. [16].

3.4.1.3 Start-up and Shut-Down philosophy

No particular start-up or shutdown requirements are needed for this tank. The liquid is accumulated inside the large volume and then shipped to disposal when the level is reached.

3.5 PROCESS PLANT

Electrolyser package A-20000

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80011)

The electrolyser package in a standalone containerized unit containing all major components required for the production of hydrogen. The electrolyser operating conditions and configuration are vendor specific. When not in use for the production of Hydrogen the electrolyser can be in either a (hot) standby or an idle state. In hot standby, there is no hydrogen production but the temperature and pressure within the electrolyser is maintained for quick restarts. In Idle, the electrolyser is turned off and depressurized, with minimal power requirements, for systems such as control and winterization.

For control philosophy, start-up and shut-down operations reference shall be taken from original vendor's documentation and basis of design as reference too (Ref. [1]).

Hydrogen storage vessels V-25001A to F

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80015 to 80020)

The hydrogen storage system is constituted by six horizontal pressure vessels that will store the hydrogen production.

3.5.1.1 Main Operating Data

This hydrogen accumulation system is characterized by the following main operating data:

- Normal Operating overall inlet flowrate 106 kg/h of hydrogen
- Normal Operating overall Vol. Flow 500 Nm^3/hr of hydrogen
- Normal Operating Pressure NOP is a range; from ~4.5 barg to 30.0 barg
- Normal Operating Temperature AMB
- Capacity ~96.0 m^3/each vessel excluding heads volumes

3.5.1.2 Process Operation and Control Philosophy

Routing valves (XVs) are installed upstream and downstream at the hydrogen storage vessel manifolds to direct the flow of hydrogen during charging and discharging activities.

In case of charging activity, the system allows the possibility to charge one vessel at time by selecting the related upstream and downstream XVs valves.

During charging activity all XVs valves that are installed on the outlet of each vessel is closed, while only the XV valve installed on the inlet line of the vessel to be filled will be open. When the desired pressure inside the vessel is reached (say 30barg), the logic will close the XVs valve at the inlet of the vessel and at same time the XV valve installed on the inlet line of the next vessel to be filled will be open.

Let assume the sequence of the vessel to be filled is the following: V-25001A, V-25001B, V-25001C, V-25001D, V-25001E, V-25001F, then the logic will do the following:

1) Close all XVs valve that are installed on the outlet lines of each H2 Storage Vessel: 25-XV-006/009/012/015/018/021;
2) Open the valve 25-XV-004, installed on the inlet line of the V-25001A;
3) Wait until the pressure inside the vessel V-25001A is at 30 barg (pressure indication can be taken from 25-PT-035, installed on the vessel V-25001A);
4) When 25-PT-035 indicates 30 barg, then close the 25-XV-004 and at same time;
5) Open 25-XV-008, installed on the inlet line of the V-25001B;
6) Wait until the pressure inside the vessel V-25001B is at 30 barg (pressure indication can be taken from 25-PT-037, installed on the vessel V-25001B);
7) When 25-PT-037 indicates 30 barg, then close the 25-XV-008 and at same time;
8) Open 25-XV-011, installed on the inlet line of the V-25001C;
9) Wait until the pressure inside the vessel V-25001C is at 30 barg (pressure indication can be taken from 25-PT-040, installed on the vessel V-25001C);
10) When 25-PT-040 indicates 30 barg, then close the 25-XV-011 and at same time;
11) Open 25-XV-014, installed on the inlet line of the V-25001D;
12) Wait until the pressure inside the vessel V-25001D is at 30 barg (pressure indication can be taken from 25-PT-043, installed on the vessel V-25001D);
13) When 25-PT-043 indicates 30 barg, then close the 25-XV-014 and at same time;
14) Open 25-XV-017, installed on the inlet line of the V-25001E;
15) Wait until the pressure inside the vessel V-25001E is at 30 barg (pressure indication can be taken from 25-PT-046, installed on the vessel V-25001E);
16) When 25-PT-046 indicates 30 barg, then close the 25-XV-017 and at same time;
17) Open 25-XV-020, installed on the inlet line of the V-25001F;
18) Wait until the pressure inside the vessel V-25001F is at 30 barg (pressure indication can be taken from 25-PT-049, installed on the vessel V-25001F);
19) When 25-PT-049 indicates 30 barg, then close the 25-XV-020.

At this point all six vessels are full of hydrogen at operating pressure of 30 barg.

In addition, isolation valves (XVs) are installed on the inlet and outlet of each individual hydrogen storage vessel. The Fuel Cell pressure control valve(s) control(s) the hydrogen supply to the Fuel Cell by means of the control loop identified with pressure controllers 25-PIC-055A/B both with a high pressure threshold; moreover, the pressure control valves 25-PV-055A/B are one working and the other in stand-by mode and a hand selector 25-HS-025 allows for interchanging from a valve to another.

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When the vessels have reached maximum operating pressure, the electrolyser is turned off and put on Hot Standby.

Moreover, at inlet manifold of the vessels, there is a pressure transmitter (25-PT-001) that indicates the pressure value to the DCS with a high alarm threshold. This signal is replicated via software/serial link to the electrolyser package A-20000 in order to communicate the pressure level established inside the whole buffer volume.

Finally, an XV valve located at inlet hydrogen manifold allows for nitrogen purging during maintenance campaign.

3.5.1.3 Start-up and Shut-Down philosophy

No particular start-up or shutdown requirements are provided or needed for these vessels. Except that a dedicated pressure transmitter (25-PT-004/006/008/009/011/012) that handles the plant ESD in case of system overpressure. The emergency high-high level pressure signal is replicated to DCS. Moreover, no liquid is expected inside the large volumes as feed stream Hydrogen is completely dry, thanks to the gas treatment installed inside the electrolyser package A-20000.

PURGING OPERATION WITH HYDROGEN (FOR NITROGEN DISPLACEMENT)

Once the electrolyser package diverts the pure hydrogen stream towards the buffers, the startup sequence begins with purging each hydrogen buffer tank. The sweep purging method is applied to displaced under a constant pressure all residual gases or contaminants from the vessels.

During first vessel filling operation it is important to displace the nitrogen that is present within the vessel, in order to ensure a pure hydrogen feed stream to the downstream Fuel Cell Package.

It is assumed that:

1) the vessel V-25001A to be purged is already at a pressure at which the previous purging operation (for air displacement by mean of nitrogen) has been performed. Therefore, let assume the previous purging operation has been carried out at 2 barg* (see below section for "PURGING OPERATION WITH NITROGEN (FOR AIR DISPLACEMENT)");
2) the upstream Electrolyser Package is capable to deliver towards the vessel "A" a constant hydrogen flow rate of 500 Nm3/hr.

*Different values can be set, depending on the available time to carry out the purging operation. It is noted here that the higher the pressure at which sweep-through purging operation is carried out, the longer it will last. With a set point of 2 barg, the time required to finalize the sweep-trough purging operation is roughly 28 hours (for one vessel).

On the inlet line of the vessel "A" the XV valve 25-XV-004 shall be open, in order to let hydrogen entering to the vessel to be purged.

On the vent line of each H2 Storage Vessel a pressure control loop in provided, in order to control the pressure inside the vessel during purging operation. The pressure control loop is identified with:

1) Pressure controller: 25-PIC-035;
2) Pressure transmitter: 25-PT-035 (Process Variable, PV);
3) final element: 25-PV-035;
4) SP value: ~2 barg *;
5) Sub-Controller(s) action: DIRECT (pressure increase, valve open);
6) Failure direction: FC.

Should be the operating pressure (PV) fall under the PID regulator SP, the controller drives the control valve to decrease opening (Cv); vice versa, should the operating pressure (PV) rise above the PID regulator SP, the controller drives the control valve to increase its opening (Cv).
The purging operation with hydrogen (for nitrogen displacement) described above for the vessel V-25001A is also applicable to the other five vessels.

Safety Concentration Target: The purging process continues for a specific duration, ensuring theoretically safe levels of hydrogen concentration within the vessels. These levels are theoretically well below the explosivity limits, prioritizing safety during the startup phase.

Verification of Safe Conditions: Once the startup sequence is complete, thorough verification processes are conducted to ensure that the hydrogen concentration within the buffer tanks remains within safe limits. This verification step should include rigorous analysis to confirm the absence of any safety risks.

Readiness for Operation: Upon successful completion of the startup sequence and verification of safe conditions, the hydrogen buffer vessels are deemed ready for operation. They are then integrated into the hydrogen storage and distribution system, contributing to the overall functionality and reliability of the setup.

By following this startup sequence, the safety of hydrogen storage facilities is ensured but also the consistent and reliable operation of the buffer vessels throughout their service life.

PURGING OPERATION WITH NITROGEN (FOR HYDROGEN DISPLACEMENT)

Each vessel V-25001A to F is equipped with nitrogen inlet and outlet dedicated nozzles for purging. Each of such a system shall work in case of maintenance by feeding nitrogen under flow control.

During maintenance procedures, it's crucial to ensure that the hydrogen buffer vessel is thoroughly cleaned and free of any contaminants or residual gas. Purging with nitrogen serves this purpose effectively. Nitrogen, being inert, displaces any remaining hydrogen or other gases present in the vessel, creating a clean and safe environment for maintenance activities. By purging each buffer tank individually with nitrogen, maintenance technicians can ensure that each vessel receives proper attention and cleaning tailored to its specific requirements.

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Nitrogen is supplied under flow control (25-FIC-031/032/033/034/038/036 and the relevant flow control valves) in order to ensure a constant N2 flow rate during the time to pressurize the vessel under purging operation. It is important to note here that the status of the vessel is assumed to be at ATM pressure and containing air. Being the inlet N2 flow rate constant, it is possible to calculate and establish a time that is required to pressurise the vessel from 0 barg up to the chosen pressure at which sweep-through purging is performed (this will be the set point of the 25-PIC-035).

The nitrogen flow rate control valve controls the nitrogen supply to each H2 Storage Vessel during purging operation by means of the control loop identified with:

1) Flow rate controller: 25-FIC-031;
2) Flow rate transmitter: 25-FT-031 (Process Variable, PV);
3) final element: 25-FV-031;
4) SP value: ~42 Nm3/hr;
5) Sub-Controller(s) action: REVERSE (flow rate increase, valve close);
6) Failure direction: FC

Should be the operating flow rate (PV) fall under the PID regulator SP, the controller drives the control valve to increase its opening (Cv); vice versa, should the operating flow rate (PV) rise above the PID regulator SP, the controller drives the control valve to decrease its opening (Cv).

The above-described control loop is relevant to H2 Storage Vessel V-25001A. The same applies to the others five H2 Storage Vessel V-25001B/C/D/E/F.

At the time the 25-PV-035 set pressure is reached, the pressure control loop (below described) is used to keep constant the pressure at which the sweep-through purging operation is carried out. Thus, once the desired pressure is reached (set point of 25-PIC-035), the flow control loop will be deactivated, and the pressure will be kept constant by mean of the pressure control loop. It is important to note here that at the time the pressure set point is reached, the flow control valve 25-FV-031 will be commanded to remain in the last open position, this is to guarantee a nitrogen flow rate to the vessel under sweep-trough purging operation.

At the beginning of the purging operation (more specifically during pressurisation of the vessel to be purged) a timer alarm, in the control logic, will be implemented to determine if 25-PIC-035 failure opening the valve 25-PV-035. It is expected that, according to:

1) the constant flow rate of N2 entering to the vessel under purging operation;
2) the above indicated pressure set point of 2 barg,

the pressure set point of the 25-PIC-035 will be reached in roughly 4.5 hours. Therefore, after such time, should the 25-PT-035 indicate a pressure less than the above indicate set point, a time alarm will alert the operator that the vessel has not reach the pressure within the desired time. Once the pressure has been reached, then the time alarm shall be deactivated.

On the vent line of each H2 Storage Vessel a pressure control loop in provided, in order to control the pressure inside the vessel during purging operation. The pressure control loop is identified with:

7) Pressure controller: 25-PIC-035;
8) Pressure transmitter: 25-PT-035 (Process Variable, PV);
9) final element: 25-PV-035;
10) SP value: ~2 barg *;
11) Sub-Controller(s) action: DIRECT (pressure increase, valve open);
12) Failure direction: FC.

Should be the operating pressure (PV) fall under the PID regulator SP, the controller drives the control valve to decrease opening (Cv); vice versa, should the operating pressure (PV) rise above the PID regulator SP, the controller drives the control valve to increase its opening (Cv).
* Different values can be set, depending on the available time to carry out the purging operation. It is noted here that the higher the pressure at which sweep-through purging operation is carried out, the longer it will last. With a set point of 2 barg, the time required to finalize the sweep-trough purging operation is roughly 92 hours (for one vessel and excluding the pressurization time).

The control valve 25-PV-035 is used only in case of vessel purging. Therefore, a software interlock is provided to prevent 25-PV-035 being opened outside of a purge cycle operation. Another software interlock prevents the opening of the control valve 25-FV-031 outside of a purge cycle operation.

Moreover, once the desired pressure of 2 barg has been reached, should the pressure inside the vessel under purging operation fall below the set point of 2 barg, a low pressure alarm on the pressure transmitter 25-PT-035 is provided, to alert the operator. This low pressure alarm will be deactivated at beginning of the purging operation (during the pressurization phase), when the desired pressure is not yet reached. This is to prevent the low pressure alarm is triggered unnecessarily.

The above-described control loop is relevant to H2 Storage Vessel V-25001A under purging operation. The same applies to the others five H2 Storage Vessel V-25001B/C/D/E/F.

PURGING OPERATION WITH NITROGEN (FOR AIR DISPLACEMENT)

This purging operation is used when, after maintenance activities, displacement of air is required, before to reinsert H2 inside the vessel. The purpose of displacing the air from the vessel is to create an inert atmosphere inside the vessel before starting the hydrogen loading phase.

The above control loops described within the section "PURGING OPERATION WITH NITROGEN (FOR HYDROGEN DISPLACEMENT)" is also valid during the purging operation for air displacement.

It is noted that both N2 flow rate (during pressurization phase) and set point of the 25-PIC-035 (pressure at which purging for air displacement is performed) can be the same as the ones considered during purging for H2 displacement.

The only differences is the time required to finalize the sweep-trough purging operation, which will be roughly 51 hours (for one vessel and excluding the pressurization time), with a pressure set point of 2 barg.

3.5.1.4 Overpressure protection

The mechanical design pressure of the storage vessels is safeguarded by dedicated spring-loaded pressure control valve(s) (25-PSV-001A to F) whose set pressure is fixed at 40 barg. Moreover, each vessel is connected to the hydrogen vent system to allow depressurization during emergencies (25-BDV-005/007/010/013/016/019) and, as said above, prior to planned maintenance. The inlet and outlet hydrogen streams across the hydrogen storage vessels are sectioned thanks to the shutdown valves (25-SDV-001 and 25-SDV-023) and the 25-BDV-022 allows for depressurization of the outlet manifold as well.

Moreover, an additional level of safeguard is provided by the high pressure transmitter (25-PT-004/006/008/009/011/012); in the event of any abnormal increase in pressure beyond safe operating limits, the transmitter immediately communicates this information to the ESD system.

Fuel Cell package A-80000

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80012)

This package is a standalone fully prefabricated and assembled unit containing all major components required for the consumption of hydrogen. The operating conditions and configuration are vendor specific. For control philosophy, start-up and shut-down operations reference shall be taken from original vendor's documentation and basis of design as reference too (Ref. [1]).

Upstream the fuel cell package the following control and safeguarding devices are provided:

- 80-PT-002 to generate and ESD signal in case of the unlikely event of high-high pressure level (the signal is replicated to the DCS via software link)
- 80-PSV-001 to protect the downstream FC package from any failure of the upstream 25-PV-055A/B (or in case of blocked discharge)
- 80-XV-001 to allow for nitrogen purging prior to maintenance campaign

The Fuel Cell pressure control valve(s) control(s) the hydrogen supply to the Fuel Cell by means of the control loop identified with (Ref. [15]):

1) pressure controllers: 25-PIC-055A/B;
2) pressure transmitters: 25-PT-055A/B (Process Variable, PV);
3) final elements: 25-PV-055A/B;
4) SP value: normal 6 barg;
5) Sub-Controller(s) action: REVERSE (pressure increase, valve close);
6) Failure direction: FC

Should be the operating pressure (PV) fall under the PID regulator SP, the controller drives the relevant control valve to increase its opening (Cv); vice versa, should the operating pressure (PV) rise above the PID regulator SP, the controller drives the relevant control valve to decrease its opening (Cv).

Control valves 25-PV-055A/B work under split range. According to operating condition of the Fuel Cell Package in terms of minimum and maximum pressure as well as minimum and maximum flow rate, a wide range of operating CV is required. Therefore, two control valves in parallel will be used, one valve operates with high CV (valve "A", above a CV of 0,31) while the valve "B" will operate when lower operating CV is required (below a CV of 0,31).
In order to provide a fine pressure control, the software interlock prevents valve 25-PV-055B (A) to open if control valve 25-PV-055A (B) is working within the required valve opening range. This is to allow both valves operating within the optimum valve opening range, as designed.
Moreover, software interlock prevents opening of the control valves 25-PV-055A/B in case Fuel Cell package (A-80000) is not running.

AUTOMATIC SWITCHING FROM ONE VESSEL TO ANOTHER DURING FUEL CELL OPERATION

During Fuel Cell operation switching from one H2 vessel to another one is required, is case inlet pressure to the 25-PV-055A/B valves decreases. This happens since the H2 inventory inside one vessel is limited.

CASE of switching from H2 Storage Vessel V-25001A to V-25001B (switching logic from different vessels is similar):

Assuming that vessel A is the one used, the following description provides the operating mode of how switching from vessel A to vessel B. It is assumed that vessel "B" is ready to be used. This can be verified by mean of the pressure transmitter installed on the vessel "B" (25-PT-037).

On the vessel "A", a pressure transmitter is provided (25-PT-035). Should the operating value of 25-PT-035 reach a minimum value of 4.5 barg, the logic will control if there is enough pressure inside vessel "B" by mean of pressure transmitter 25-PT-037. In case there is enough pressure inside vessel "B", then the valve 25-XV-009 installed on the outlet line of the vessel "B" will be open, while the valve 25-XV-006 installed on the outlet line of the vessel "A" will be closed.

Should the pressure inside the vessel "B" be already at 4.5 barg, then the logic automatically performs a check over the remaining four vessels "C", "D", "E" and "F" checking the one with enough pressure inside (above 4.5 barg).

The above described logic will continue to perform this check and therefore consume hydrogen unless it is manually stopped by the operator (if permitted by the control logic).

At the time there is no enough pressure inside all six H2 Storage Vessels, both control valves 25-PV-055A/B will receive a signal to close.

As Fuel Cell stops, the control logic will force the operating control valve 25-PV-055A (or B) to fully close.

As the Fuel Cell starts, the 25-PIC-055A/B controller will command the opening of the control valve 25-PV-055A (or B) such that the downstream pressure will slowly increase to the point where 25-PIC-055A (or B) can be given automatic control, by fixing a control valve opening lower than the required operating point for a period that allows the fuel cells to run at full load.

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3.6 UTILITIES OTHER THAN WATER TREATMENT

Vent system and hydrogen vent KO Drum V-43001

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80029)

The Hydrogen Vent will be comprised of:

- A gathering network of hydrogen gas emergency discharges or maintenance discharges
- A Hydrogen Knock-Out Drum V-43001
- A Hydrogen Vent Stack Q-43004 equipped with a Liquid seal at its bottom

The hydrogen vent will be required for all emergency relief and blowdown scenarios and to vent the H2 off-spec from the Electrolyser package (A-20000). Furthermore, the blowdown network is continuously purged with nitrogen in order to keep it slightly pressurized and inert.

3.6.1.1 Process Operation and Control Philosophy

The hydrogen KO drum V-43001 is equipped with the following transmitters:

- 43-PT-001 as remote pressure indicator to DCS
- 43-LT-001 as remote level indicator, providing high and low level alarm and High-High trip (connected to ESD) to DCS

Moreover, at the exit of the V-43001 a flow transmitter (43-FT-001 with High alarm threshold) is provided to monitor the flowrate towards the stack.

The Hydrogen Vent stack Q-43004, is simply equipped with a level transmitter 43-LT-003 as remote level indicator that allows to monitor the liquid level inside the bottom, providing a low level alarm to DCS. The gas line must be kept submerged in a hydraulic seal to prevent the ingress of air into the system. Overall, ensuring that the gas line remains submerged in a hydraulic seal is essential for the reliable and safe operation of the equipment.

3.6.1.2 Overpressure protection

No need for overpressure protection. The sole and only overpressure protection is established by the proper design of the network.

Instrument air package A-63000

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80027)

The unit is fully prefabricated and self-standing package; thus in general, being a vendor specific item, for any further information and details the vendor's documentation shall be necessarily seen.

3.6.1.3 Process Operation and Control Philosophy

However, the instrument air package A-63000 will have the following main sensors installed at distribution header:

- 63-PT-003 to monitor the pressure value at the distribution header (signal to DCS). 63-PT-003 pressure transmitter also provides a low pressure alarm, to alert the operator
- 63-PT-004 to procure shutdown effects in case of low-low pressure value at the distribution header (the signal is replicated to DCS via software link)

3.6.1.4 Start-up and Shut-Down philosophy

The following signals will inform about the package A-63000 status:

- SUCTION
- DISCHARGE
- COMMON ALARM
- MCC DEVICE COMMS FAIL
- AVAILABLE STATUS
- RUN/STOP STATUS
- SHUTDOWN STATUS
- SHUTDOWN ALARM

All signals are exchanged between the UCP and the DCS.

The ESD signal trip and stop the package in an unlikely emergency event.

3.6.1.5 Overpressure protection

Overpressure protection will be provided inside the package with appropriate PSV where required by design codes (by vendor).

Nitrogen system A-64000

(Reference P&ID: Doc. N.123A90-DDL-PR-PID-80027)

The unit is fully prefabricated and self-standing package; thus in general, being a vendor specific item, for any further information and details the vendor's documentation shall be necessarily seen.

3.6.1.6 Process Operation and Control Philosophy

However, the air stream is derived from the discharge outlet of the instrument air package A-63000 (say as an additional air consumer). The system through molecular sieves separation units will generate pure nitrogen as required. It operates by separating nitrogen gas from compressed air through a process called

pressure swing adsorption. In this process, compressed air is passed through a adsorption material that selectively removes oxygen and other impurities, leaving behind a stream of pure nitrogen gas.

The oxygen rich stream is vented locally to safe location.

On the outlet line of the Nitrogen system (A-64000) a pressure control is provided, in order to guarantee a and maintain a pressure of 7 barg on the nitrogen distribution header, which is a suitable pressure to feed all nitrogen users. The control loop is identified with:

1) pressure controllers: 64-PIC-031A/B;
2) pressure transmitters: 264-PT-031A/B (Process Variable, PV);
3) final elements: 64-PV-031A/B;
4) SP value: 7 barg;
5) Sub-Controller(s) action: REVERSE (pressure increase, valve close);
6) Failure direction: FC

Should be the operating pressure (PV) fall under the PID regulator SP, the controller drives the relevant control valve to increase its opening (Cv); vice versa, should the operating pressure (PV) rise above the PID regulator SP, the controller drives the relevant control valve to decrease its opening (Cv).

Moreover, a hand selector 64-HS-031 will allow the operator (remotely) for selecting the valve that shall be put in service.

The pressure transmitters 64-PT-0031A/B give a low and high pressure alarm, to alert the operator.

On the main manifold of the nitrogen outlet line, a sub-header is derived, to divert nitrogen to six H2 Storage Vessels for purging operations. On such sub-header a shutdown valve (64-SDV-001) is provided, and it is normally left close. Valve 64-SDV-001 can also be operated from DCS system. In fact in case purging operation is required, then the valve is driven to open to allow sending nitrogen to the selected H2 Storage Vessel.

During purging operation (the 64-SDV-001 is fully open to allow nitrogen to be sent to the H2 Storage Vessel under purging operation) a low pressure alarm on pressure transmitter 64-PT-002 will be activated. Should the 64-PT-002 reach the low pressure alarm set point, the valve 64-SDV-001 will be closed, in order to give priority to other nitrogen users.

On the same pressure transmitter, 64-PT-002, a low-low pressure trip is provided, to detect if very low pressure is reached on the N2 Package discharge line. If this happens then the low-low pressure trip will perform ESD1D.

On the discharge side of the nitrogen system a connection to the vent system is provided, in order to continuously purge the vent system with nitrogen. On this line a needle valve and a flow meter (which is visible from the needle valve) is provided. The opening of the valve will be set at a value such that the flow meter indicates the desired flow. This is to have a fixed flow via a manually set valve.

3.6.1.7 Start-up and Shut-Down philosophy

The following signals shall inform about the package A-64000 status:

- SUCTION
- DISCHARGE
- COMMON ALARM
- MCC DEVICE COMMS FAIL
- AVAILABLE STATUS
- RUN/STOP STATUS
- SHUTDOWN STATUS
- SHUTDOWN ALARM

All signals are exchanged between the UCP and the DCS.

The ESD-1 (and the ASD and ESD-1D in cascade) signal trip and stop the package in an unlikely emergency event. The Nitrogen system is also stopped in case of a fault signal from the package itself (as per Ref. [12]).

Downstream of control loop, a pressure transmitter 64-PT-002 is provided, that gives ESD-1D in case of low-low pressure value inside the nitrogen header (signal is replicated to DCS via software link).

3.6.1.8 Overpressure protection

Overpressure protection will be provided inside the package with appropriate PSV where required by design codes (by vendor). In addition, at nitrogen header a PSV is provided and set directly to 10 barg in order:

1) to protect the downstream systems that may have a lower design pressure and/or;
2) to protect the upstream system in case of blocked discharge and/or;
3) to protect the nitrogen system from any backflow of 30 barg H2 from storage vessels V25001A-F.

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