Triton–C
Detailed Design Report: Power Take Off

DE-FOA-0001418: Demonstration of an Advanced Multi-Mode Point Absorber for Wave Energy Conversion
Award Number: DE-EE0007819.0000
Principle Investigator: Tim Mundon. Ph.D.
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Following drawings provided (see Index in Reference for more detail):
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182893901_Detailed Hydraulic_Schematic
1000-05,06 Electrical Block Diagrams

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Review

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Summary

This document describes the detailed design of Power Take Off (PTO) system and its supporting systems within the Triton-C wave energy device. The PTO system includes mechanical, hydraulic, electrical, and auxiliary cooling systems. The PTO system's relationship between major systems are outlined at a high level in Figure 1. The PTO is housed within the surface float and is connected to the reaction ring via the three tendons.

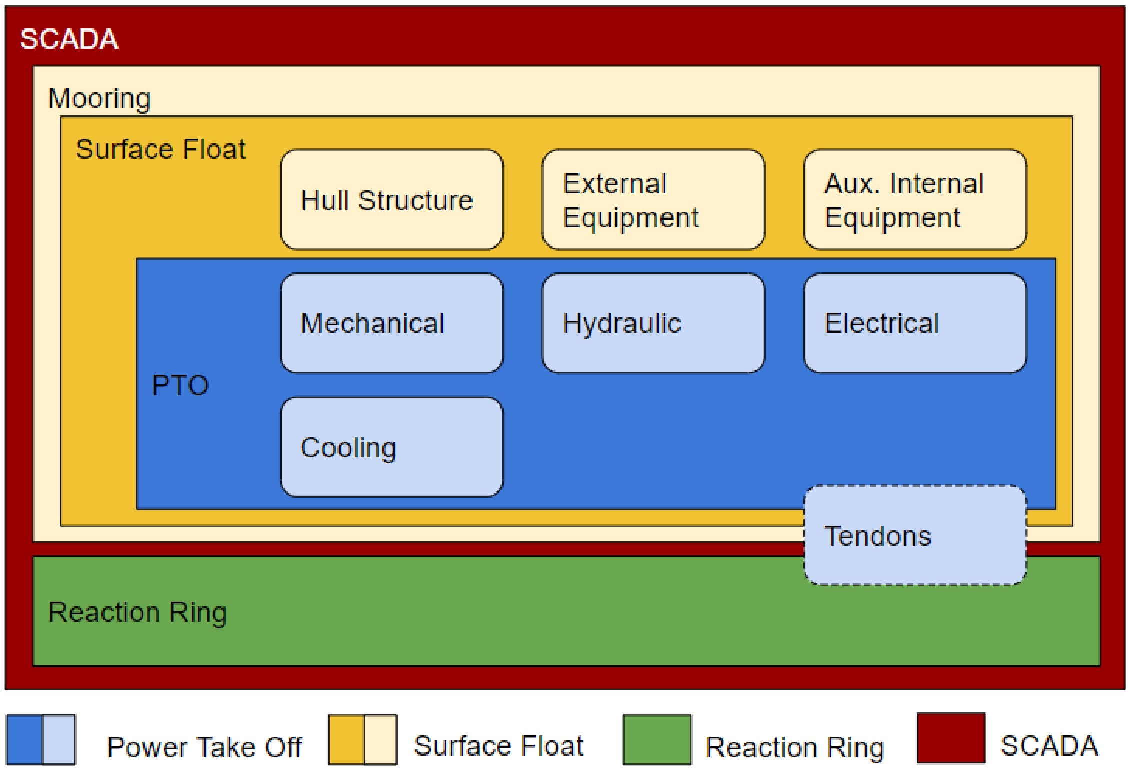

Figure 1. Triton-C system diagram

Drivetrain

The drivetrain assembly is the main power production component within the wave energy device. The drivetrain bears the loads from the reactions between the two bodies of the Triton-C, by transferring this linear motion into rotational motion for electrical power export. The power generation equipment is made up of compact mechanical components connected to the hydraulics, electrical, structural, and related cooling systems as shown in Figure 2.

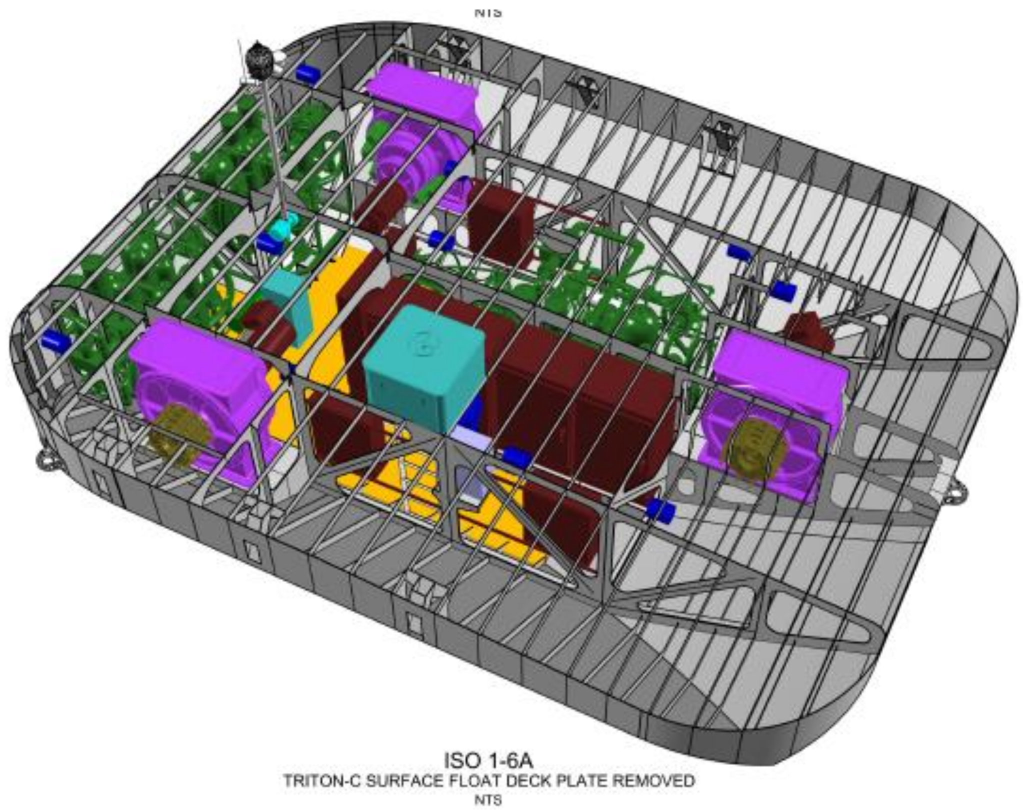

Figure 2. Hull assembly with drivetrains

Figure 3 is an energy flow diagram of the PTO system. Drivetrain forces flows through the sheave and gearbox and is converted into electrical energy at generator. To help control the motion of the drivetrain and generate a return force to balance the static mass of the reaction ring, the Triton-C uses a hydraulic system attached to the gearbox. A series of hydraulic motors attached to a ring gear, these hydraulic units work both as motors and pumps, as well as having the ability to apply a parking brake. The hydraulic system can apply different spring rates for operational conditions and sea states.

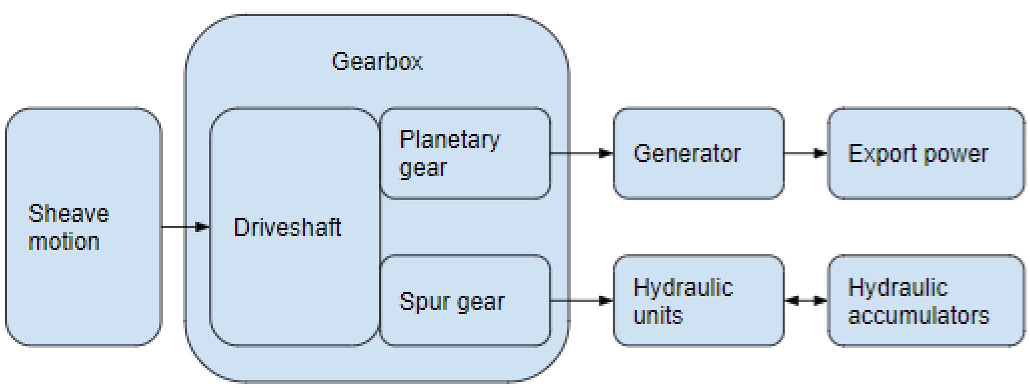

Figure 3. Drivetrain power flow block diagram

Mechanical

The primary mechanical systems within the PTO house and transfer load from the tendons to hull and allow power to be captured at the generator. The mechanical drivetrain comprises of sub-assemblies as seen in Figure 4. This breakdown can be further described by each mechanical component within these assemblies.

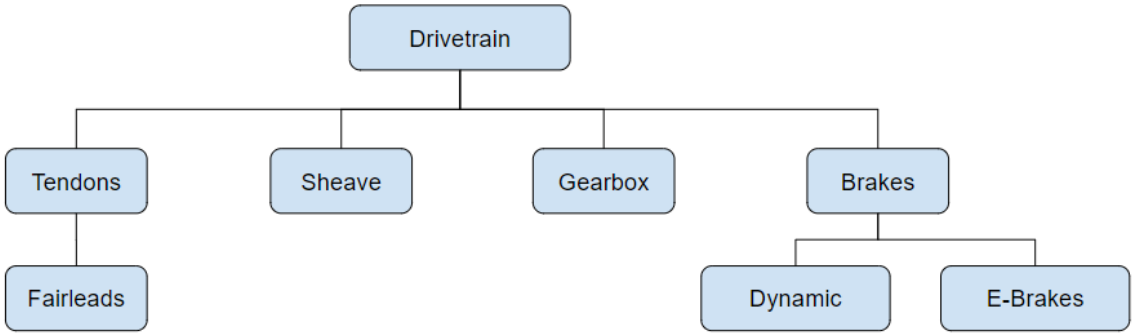

Figure 4. Mechanical system components

The hydraulic units and generator components are assembled into the gearbox and sheave assembly. Figure 4 shows the final detailed assembly CAD model. Each mechanical component will be further described in this section.

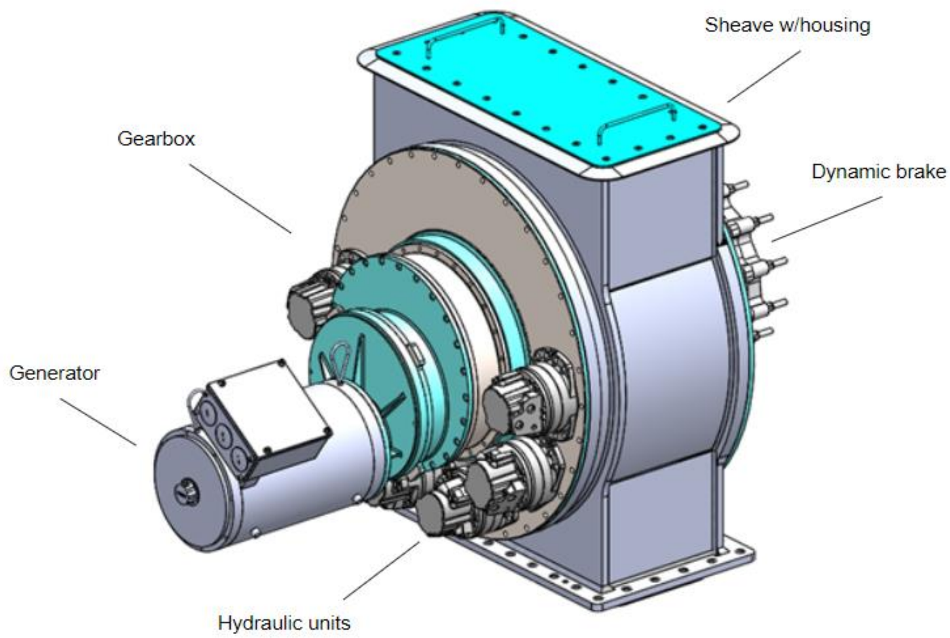

Figure 5. Complete drivetrain assembly 3D model (generator view)

Tendons and Fairlead

The reaction ring is connected to the surface float by three pairs of taut tendons each of which are approximately 22 meters in length, as measured from the stopper within the sheave to the socket connection at the reaction ring. Figure 6 shows the horizontal spacing between each of these three pairs of tendons: spanning five meters between the port and starboard tendons, and seven meters between either port or starboard tendon and the bow tendon. In operation, the wave action moves the float such that the tendons wind into and out of the drivetrains, and thus the relative spacing between the reaction ring and the float can vary between 15 to 25 meters.

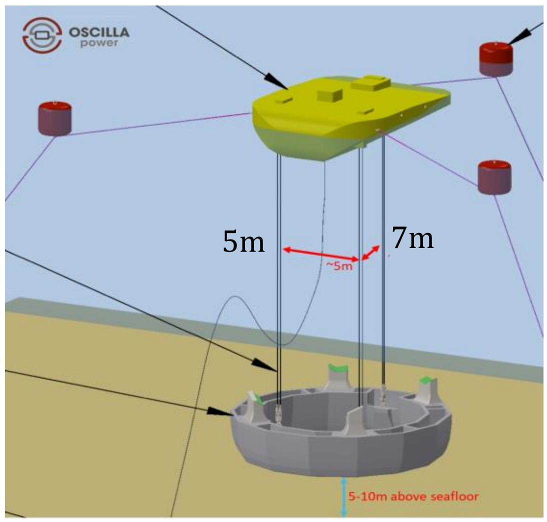

Figure 6. Hull tendon spacing dimensions

Each tendon comprises of two 1.5-inch ropes with a custom construction as shown in Figure 7. This consists of a core of parallel strands of *Technora* in a wire-lay construction for strength and extended fatigue life. Each bundle of strands has a polyester sheath and the overall rope has an outer *Spectra* braded sheath for extended abrasion resistance,

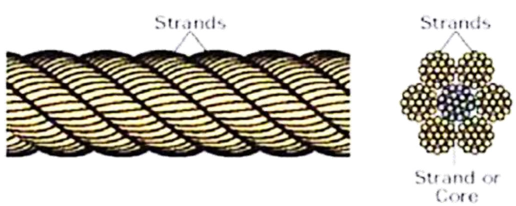

Figure 7. Inner Technora rope core assembly, outer sheath not shown [1]

The two ropes that comprise each tendon pair are maintained in parallel and kept at 10 centimeters separation. Extensive modelling confirms that the tendon tension will vary around a mean tension of 150 kN (~ 15MT) ensuring the ropes will behave as if rigid. In extreme conditions, a minimum tension of at least 10 kilonewtons (~ 1 MT) is maintained, ensuring that there will never be any slack in the line. Absolute maximum tension in extreme conditions will reach 390 kilonewtons (~39 MT) which is approximately five times lower than an individual rope breaking limit ~200,000lb. Figure 8 shows the configuration of how the tendons connect to the reaction ring. More detailed assembly can be found in assembly drawings in the Appendix.

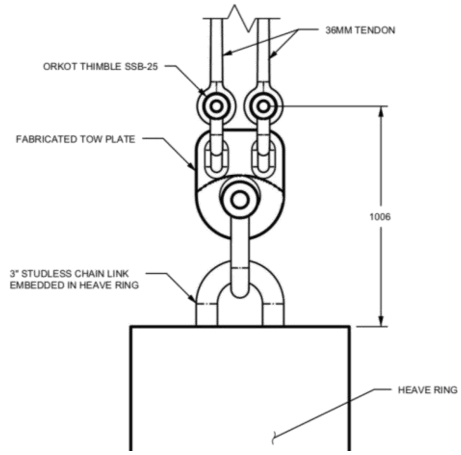

Figure 8. Tendon connections at lower termination to the reaction ring.

The tendon entrance to the surface float is through two fixed bell-mouth fairleads as shown in Figure 9. The structure around the fairleads has an opening and is exposed to the sea. This opening provides a pathway for tendons from the drum to the ring; it is sized at approximately 106 millimeters by 395 millimeters. The drivetrain enclosure is internally sealed to prevent water from penetrating the float. The fairlead structure supports the housing of the drivetrain within the hull structure.

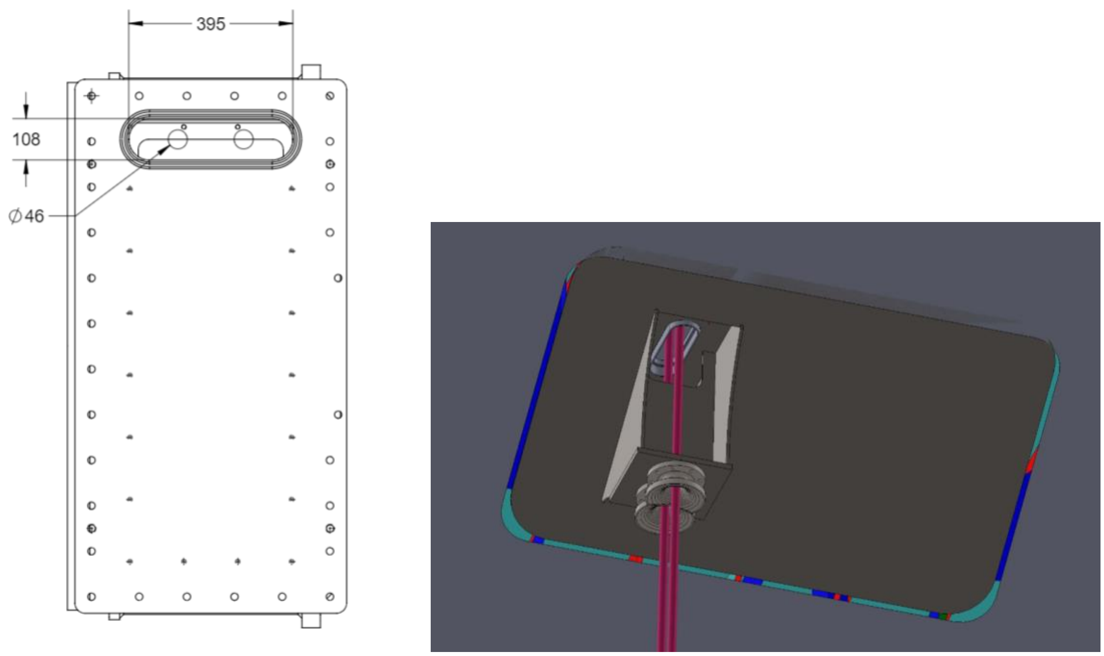

Figure 9. Hull opening dimension. Left: Bottom view of fairlead drawing (measurements in mm). Right: Perspective view of fairlead assembly looking from the bottom of hull.

Figure 10 shows the 3D geometry and shape of the inner and outer surfaces of the fairlead bell-mount. These mounts are fixed to the hull and drivetrain foundation as seen in Figure 9. Note that this part is captive to the tendon and therefore installed with the rope and the complete tendon assembly.

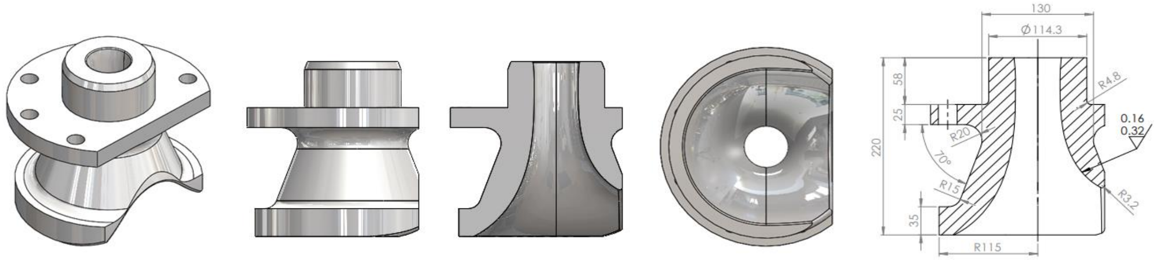

Figure 10. Fairlead bell-mouth geometry

Sheave

The sheave carries the dynamic mechanical load of the reaction ring to the surface float by converting the tendon loads to shaft torque. The tendons terminate inside the sheave with a socketed stopper connection.

The sheave acts as a drum, storing the tendon and allowing the drivetrain to travel during operation. During installation and recovery, the sheave winds the tendon and enables mating of the surface float and reaction ring. The sheave assembly can accommodate 9.4 meters of travel on the base layer of the sheave. An additional 12.1 meters of tendon can be stored during installation and recovery operations by raising up the reaction ring towards the surface float. The taper bore of the sheave hub is press fit to the driveshaft of the gearbox; the rear face of the hub is keyed for additional torque transfer and receives a face seal. The tendon stopper sockets terminate at a block inside of the drum as seen the two views of the sheave in Figure 11 and Figure 12.

Figure 11. Sheave model – showing stopper insert termination point on the indside of the drum

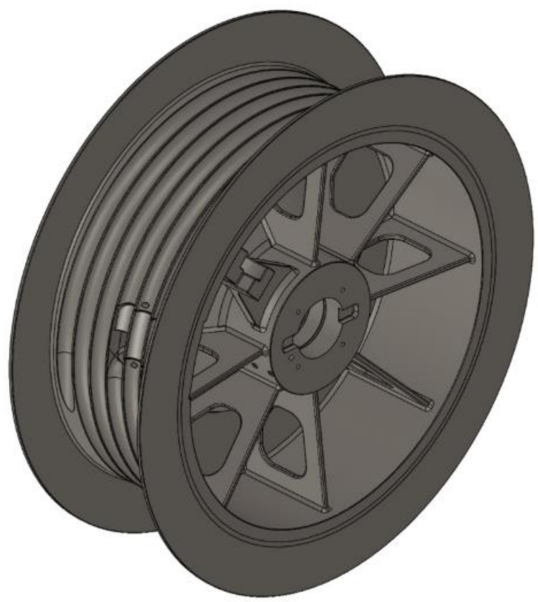

Figure 12. Sheave model – showing stopper insert termination point from the outside of the drum

The sheave is located within the drivetrain assembly shown in Figure 13. The driveshaft that passes through the sheave is isolated using a shaft seal, isolating the oil bath on the inside of the gearbox from the sea water surrounding the sheave. The housing has a removable access cover which allows personnel to access the tendon terminations on the sheave. A deck cover plate can also be removed for visual inspection and to provide access from the deck of the surface float. Provisions are made for the mounting of SCADA components for monitoring the health and performance of the drivetrain which are described in more detail within the SCADA System Report.

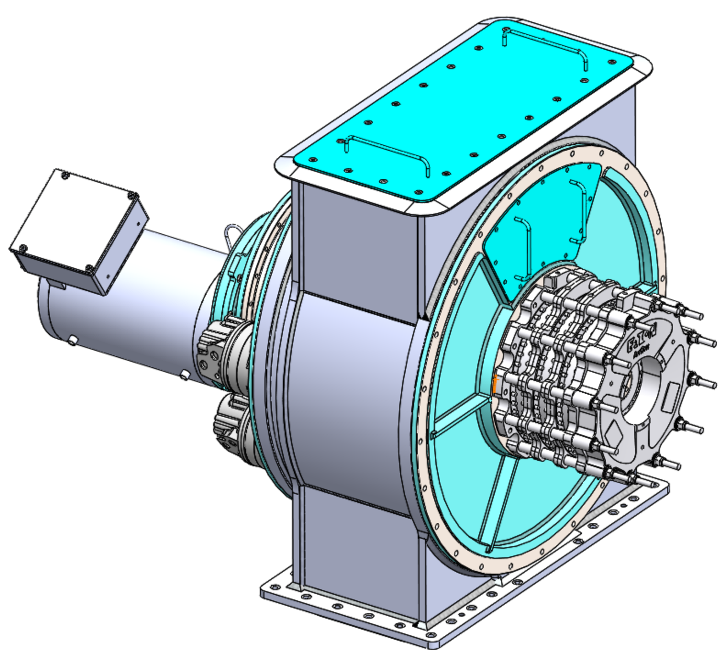

Figure 13. Complete drivetrain assembly 3D model (dynamic brake view). Note: sheave access hatches (in blue with handles) top access from outside the surface float and side access from within the float.

Gearbox

The gearbox increases shaft speeds to the drivetrain components. The drivetrain gearbox consists of two sub-systems: a planetary speed increaser connected to the generator, and a ring gear connected to the hydraulic system. The stages of the gearbox can be seen in Figure 14: the bull, planetary and spur gears.

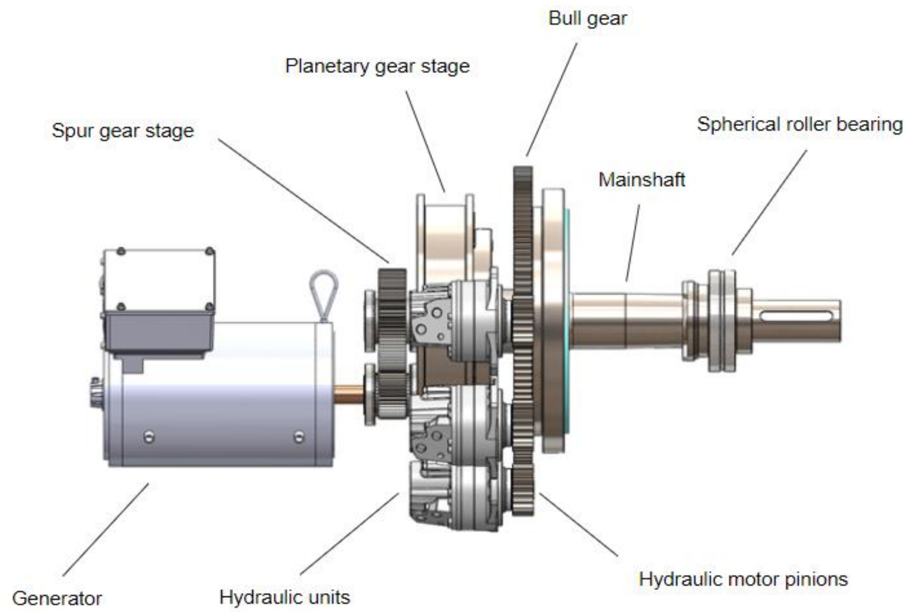

Figure 14. Drivetrain assembly with generator, gearbox and hydraulic drives (housing and sheave removed to show connection points)

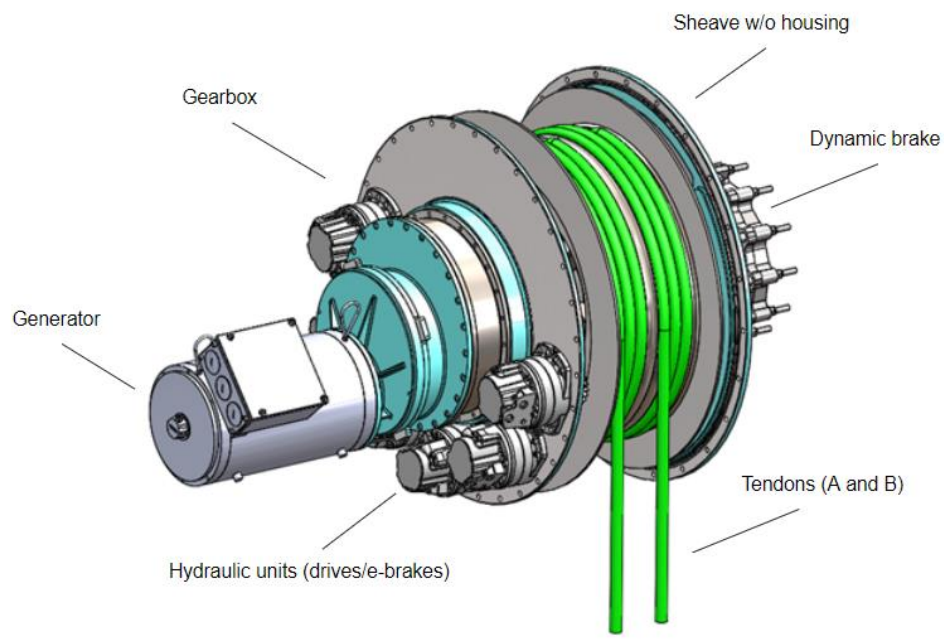

Figure 15. Complete drivetrain assembly with sheave housing removed to show tendon wrap

A large ring gear provides a speed increasing ratio of 6.57 to 1 to six hydraulic units. The hydraulic units are arranged in a compact circular pattern and mounted to the drivetrain housing. This is shown in Figure 15 and Figure 16 which shows the detail of the connection to the gearbox pinions.

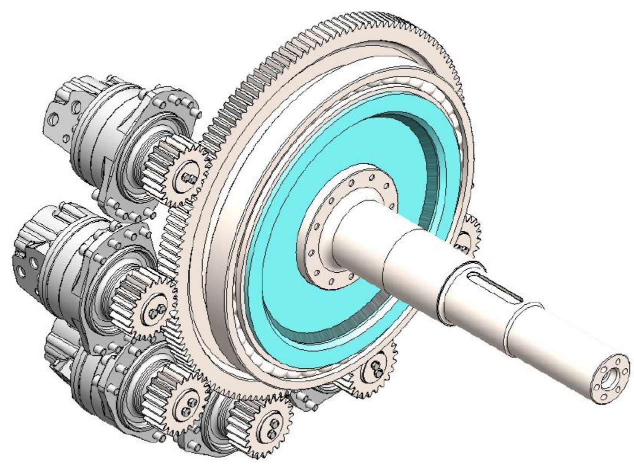

Figure 16. E-brakes or hydraulic units attached to the gearbox and low speed shaft pinions

The generator connects to the driveshaft via a two-stage gearbox with a speed increasing overall ratio of 19:1. Stage one is a planetary stage with ratio of 8.4:1. Stage two is a spur gear stage with ratio of 2.26:1.

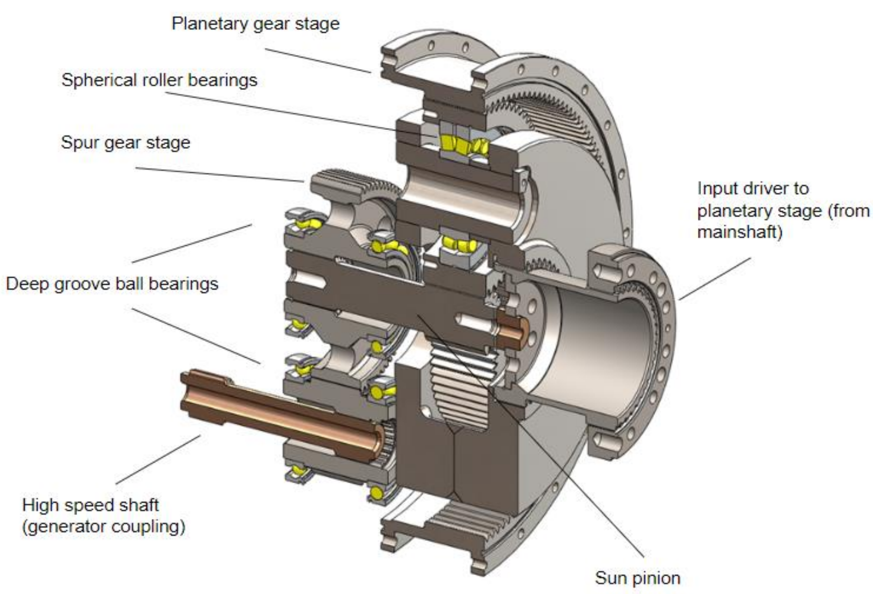

Figure 17. Cross section of multi-stage gearbox

Dynamic Brake

The function of the dynamic brake is to provide additional damping to the system when needed. The selected brake is a three discs, hydraulic actuated unit with liquid cooling, and is rated for continuous slip service. There are two scenarios where the brake is utilized: when the generator is normally operating in extremely high seas, and when the generator is in a fault condition. In extreme seas, the damping torque that is provided by the generator reduces as the speed approaches the maximum rated speed. For this scenario, the brake is used to supplement generator torque in these high velocity conditions. In a generator fault case, the brake is wholly relied on to damp the system and prevent overspeed events because the generator damping is no longer available.

The brake gear is press fit and keyed to the driveshaft of the gearbox; the mounting flange of the brake is bolted to the drivetrain housing. Above in Figure 13, the brake is shown mounted to the drivetrain assembly. Figure 18 shows a section view of the dynamic brake mounted in the sheave assembly.

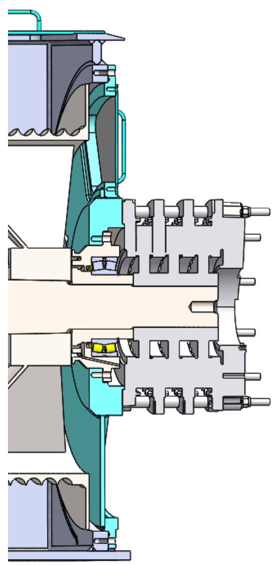

Figure 18. Eaton Airflex dyanmic brake attached to the sheave assembly

The emergency or parking brakes known as the E-Brakes for the drivetrain are part of the hydraulic unit assemblies will be described in the hydraulic system following this section.

Hydraulics

The hydraulic system provides the spring force to the drivetrain of the Triton-C. This force is applied through the hydraulic motors attached to the gearbox.

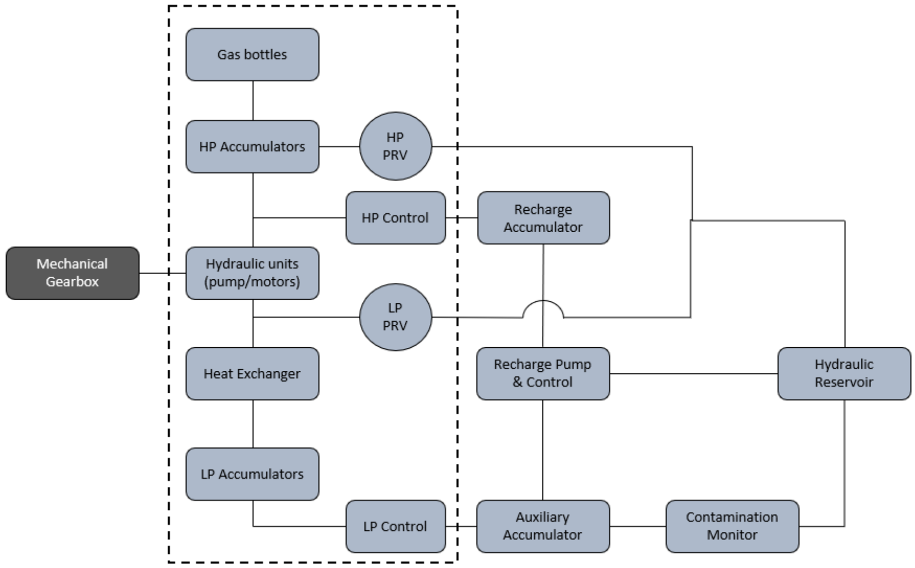

Figure 19. Hydraulic system components

Figure 19 shows a high-level block diagram of the hydraulic system on the surface float. The dotted line box within the diagram is the hydraulic system for a single drivetrain. This is replicated three times, one per drivetrain, with the appropriate connections going to the common system, which is shown outside the dotted line box. The shaded block entitled "Mechanical Gearbox" represents the connection of the hydraulic system to the mechanical system of the sheave via the ring gear.

Within the hydraulic system, there is a low-pressure (LP) and high-pressure (HP) supply, as well as an auxiliary supply to maintain pressure and flow rate during extreme operation. Where appropriate, some of the main components within the blocks are highlighted. The full hydraulic schematic with detailed component layout can be found in within the hydraulics schematics within the Appendix.

The hydraulic equipment is mounted within the surface float attached to the drivetrain manifolds and supporting structures within the drivetrain skids and common (recharge) skid mounted to the frame of the hull. This is shown in Figure 20 and further detailed within the Hull General Arrangement drawings.

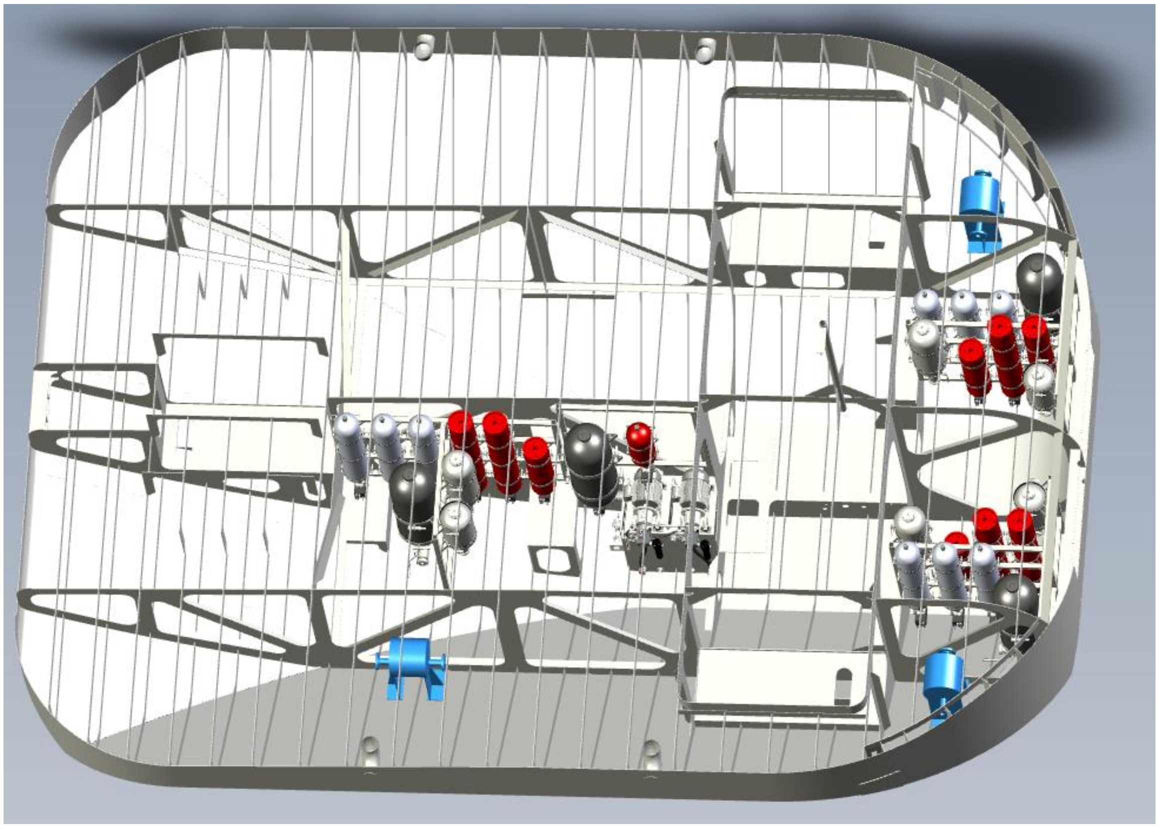

Figure 20. Hydraulics equipment within in the hull. Heat exchangers (blue) have been replaced by smaller units. Location of these units should be disregarded

Hydraulic Units (pump/motors)

There are six Poclain hydraulic units per drivetrain. They are the components linking the mechanical to the hydraulic system. These units act as pumps when the tendon extends, pumping oil from the low-pressure accumulator to the high-pressure accumulator. The units act as motors when the tendon retracts, driven by oil flowing from high to low pressure. When the system is at equilibrium, the units provide the torque that supports the weight of the reaction ring which equates to ~1.6 kNm force load per pump. The displacement of each pump is 625cc and therefore the pressure-drop over the pumps required to support the reaction ring is ~ 161 bar.

Figure 21. Poclain hydraulic units [2]

The Poclain units are fitted with brakes that are designed to hold the units stationary when the system is not operational. These E-Brakes are multidisc brakes that are activated by a lack of pressure and operate as parking/emergency brakes only. An internal spring exerts a force on a piston, which presses on the fixed and mobile discs and immobilizes the shaft. The braking torque decreases in linear proportion to the brake release pressure.

The hydraulic pumps within these units have some internal leakage due to clearances required for running them. The ratio between the oil that is pumped into the system, relative to the displacement of the pump, is called the volumetric efficiency. The oil that is not pumped into the system is returned to the hydraulic reservoir.

Low-pressure Accumulators

A set of five accumulators with a combined volume of 95 liters keep a pressure of approximately 15 bar. This is required to ensure the pumps are always supplied with enough oil on the extension stroke, while providing enough volume for oil on the retraction stroke without reaching excessive pressures. The accumulators are piston type, which is required due to the range of pressures that can be achieved, (5 to 40 bar), This pressure ratio exceeds that allowed for other types of accumulators.

Heat Exchanger

Losses in the hydraulic pumps heats the oil within the hydraulic system. A Printed Circuit (microchannel) type heat exchanger (Hx) is used to dissipate the heat. The Hx is designed to keep the oil temperature to below 75℃, to prevent oil and seals from degrading

As the flow through the Hx increases the pressure drop imparted to the oil increases. When the pressure-drop increases to more than 2 bar, a check valve is used to divert additional flow around the heat exchanger. This limits the power lost to the induced pressure drop.

The oil that flows through the check valves does not pass through the exchanger, and therefore only part of the oil is cooled. However, the oil mixes downstream of the exchanger and check valve, resulting in cooler oil downstream than upstream. A thermal model of the

HP and LP system was constructed to check that the oil is cooled enough to prevent the temperature from rising in the worst-case conditions.

High Pressure Accumulators

The high-pressure side of the system consists of three accumulators in parallel with a combined volume of 104-liter. When in equilibrium, each accumulator is half filled with oil at a pressure of 176-bar, which is equal to the low pressure drop and the pressure drop over the pumps combined. The accumulators are Piston Type in order to ensure that the port on the gas side that connects to three external gas bottles, can be sufficiently large.

Gas Bottles

The gas bottles have volumes of 19, 38, and 133 liters and can be individually and remotely opened and closed to provide a variable gas volume to the HP accumulators. Changing the gas volume, changes the rate of pressure increase/decrease for a given oil flow into/out of the accumulator, which effectively translates to a different spring rate experienced by the tendon.

Pressure relief valves

High-pressure pressure relief valves (PRV)
The pressure relief valve connected to the high-pressure side of the system prevents damage when/if pressure spikes occur. The PRV is set to open when pressure exceeds 350 bar.

Low pressure PRV
The pressure relief valve connected to the low-pressure side of the system is set to open when pressure exceeds 40 bar.

Pressure Control

High pressure control
The hydraulic system is a closed circuit, and as such any oil losses through leakage in the pumps and potentially through opening of the HP PRV needs to be replaced to maintain a correct equilibrium position (i.e. pressure needs to remain at 161 bar to support the ring weight) . The oil is replenished by a recharge pump (see common hydraulics section), with the volume monitored using the tendon mean position as a proxy. If this drifts beyond a set point, a signal is sent to the recharge control valve to open until the mean position is back to where its setpoint.

The recharge control valve is an isolation valve, that is either open or closed for this purpose of maintaining oil pressure and flow. When open, oil from the recharge accumulator (see common hydraulics section) flows into the high-pressure side of the system when the pressure in the HP side is below that in the recharge system. Any flow in the opposite direction is prevented by a check valve.

Low pressure control
The low-pressure part of the system can lose oil when the PRV opens. Similar to the high-pressure control, any lost oil from the LP side will need to be replenished. The oil level in the low-pressure side of the system is monitored through the average pressure. If this pressure

is lower than 15 bar, then oil is supplied from a 20 to 30 bar manifold. The valve closes when this set point pressure is reached again.

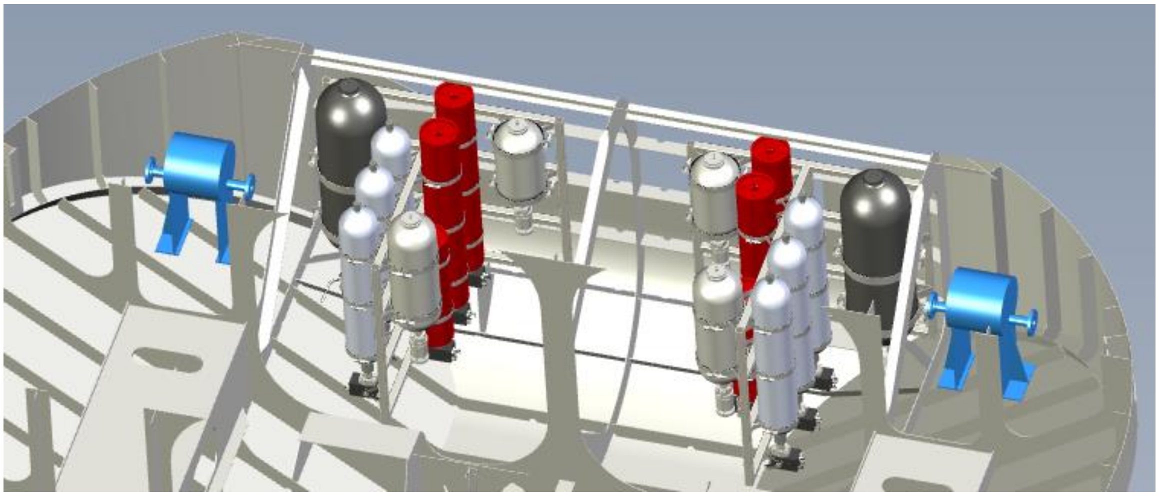

Figure 22. Aft drivetrain hydraulic skids (with HP and LP volumes)

Hydraulic Reservoir

The hydraulics reservoir holds a sufficient amount of oil to supply all parts of the system during operation. All the oil that is leaked from other parts of the system is returned here. The reservoir is fitted with baffle plates to minimize sloshing when the float is in motion. The locations of the return lines into the reservoir and the suction lines out of the reservoir, are on opposite sides of the reservoir so that oil returned to the reservoir has time to settle before it is pumped out again. This provides the opportunity for any air trapped in the oil to be released and any dirt to settle on the reservoir floor. There is an air breather located at the top of the reservoir to allow exchange of air to the reservoir when the oil level changes. The breather prevents contaminants and moisture from entering the reservoir.

Recharge Pump

This pump draws oil from the reservoir, filling the recharge and auxiliary accumulators. There are two identical pumps that are redundant in function. One pump runs continuously, and the second pump can be switched on to provide additional flow when required. The pumps are pressure compensated to ensure power usage is minimal when no flow is required.

The motors that drive the recharge pumps can operate at variable speed to match the oil delivery to the total leakage in the system. A 5-micron pressure filter is located downstream of the pump to ensure the hydraulic oil is kept clean.

The recharge pumps supply oil to both the recharge and the auxiliary accumulators and is connected to the control SCADA system. The majority of the time in normal operation, oil will be pumped into the recharge accumulator to replenish the oil leaked in the Poclain pumps. However, when the pressure in the auxiliary system drops below a controller setpoint at 20 bar, the pump flow is redirected to refill the auxiliary accumulator.

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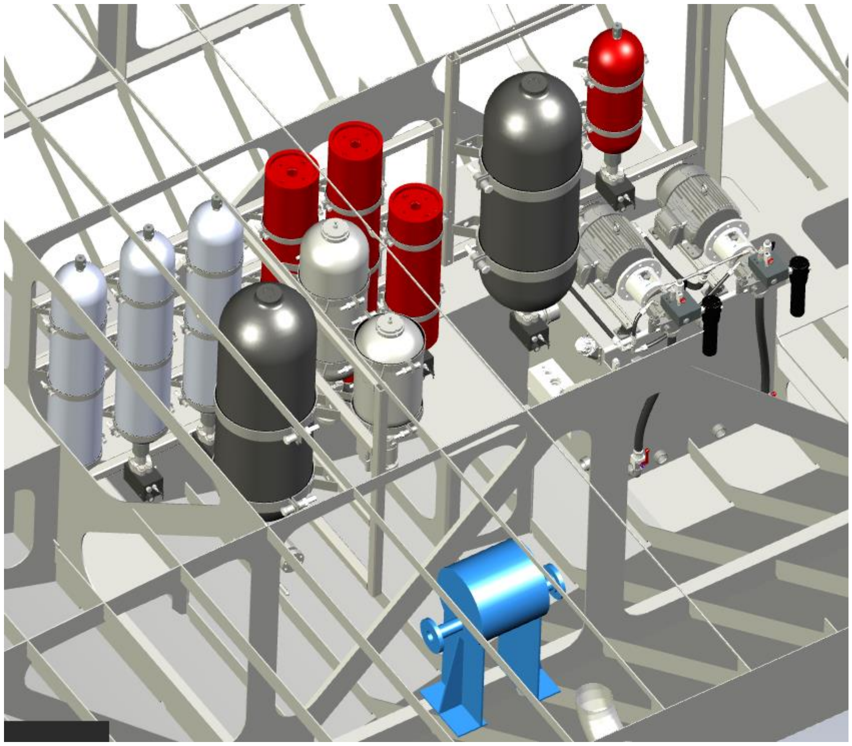


Figure 23. Bow drivetrain hydraulic and common skid

Recharge Accumulator

This is an 11-liter bladder accumulator held at a pressure that is close to the pressure in the high-pressure part of the system (~176 bar). The pressure is set by the compensator on the pumps. When the pressure in the high-pressure accumulators falls below the pressure in the recharge accumulator, oil flows from the recharge accumulator to the high-pressure accumulators, replenishing the lost oil.

Auxiliary Accumulator

This is a 53-liter bladder accumulator at a pressure of 20 to 30 bar. There is continuous leakage from the auxiliary system to the reservoir through the contamination monitor. This means that the pressure also drops continuously. When this drops below 20 bar, the recharge control switched the pump flow to fill this accumulator until the pressure reaches 30 bar, at which point it switches off. This accumulator is relatively large, because it also stores oil that is supplied to the low-pressure side of the system if the LP PRVs open. Since the flow rates can be high when this happens, a lot of oil will be replenished quickly. The auxiliary accumulator provides a buffer for these cases.

Contamination monitor

In order to provide all hydraulic components with sufficiently clean oil for their optimal operation, an ISO cleanliness of 16/14/11 will aim to be maintained. To monitor the cleanliness and the moisture content of the oil, a contamination monitor is installed. For correct operation, the monitor requires a small continuous flow of around 0.4 LPM. Placing it between the auxiliary system and the hydraulic reservoir ensures there is a constant supply of oil at a relatively low pressure, which minimizes power loss.

Electrical

The primary function of the Triton C power electronics and electric machines is to convert the mechanical shaft power at the output the Triton C gearboxes into electrical power for provision to a load (ideally a 3 phase, 60Hz utility connection).

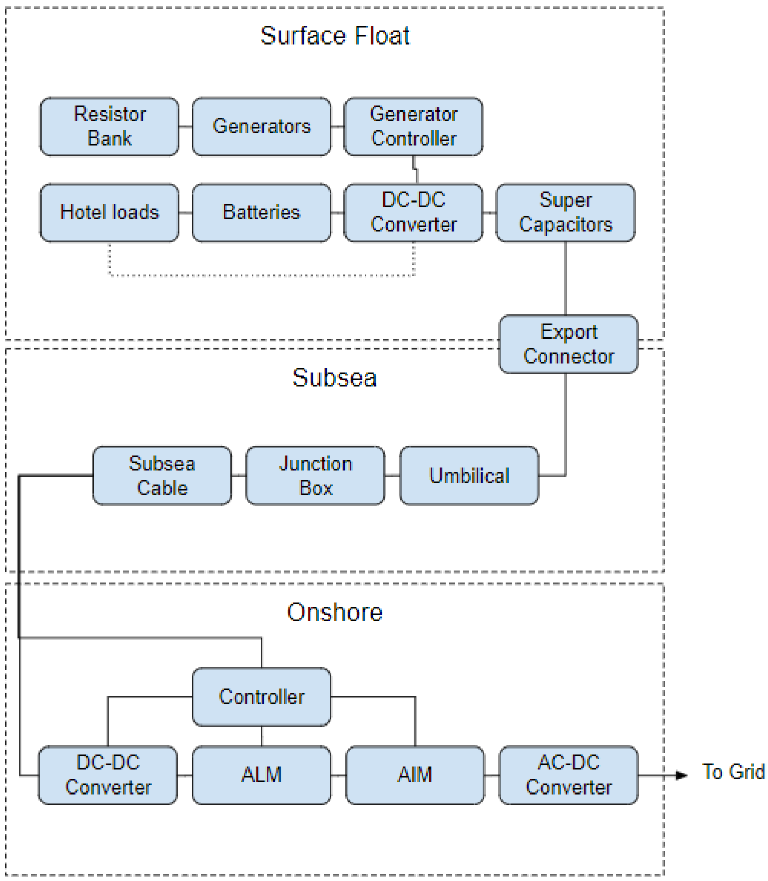


Figure 24. Electrical Power Configuration

Figure 25 **s**hows a block diagram of the power electronics in the surface float. The Triton-C has three permanent magnet synchronous machines. These machines can operate as either generators or motors, and the complete power conversion system is capable of full four-quadrant operation. The machines are driven as generators by the gearboxes in both directions of rotation. The stochastic nature of the waves results in a variable voltage, variable frequency, 3-phase output from the generators.

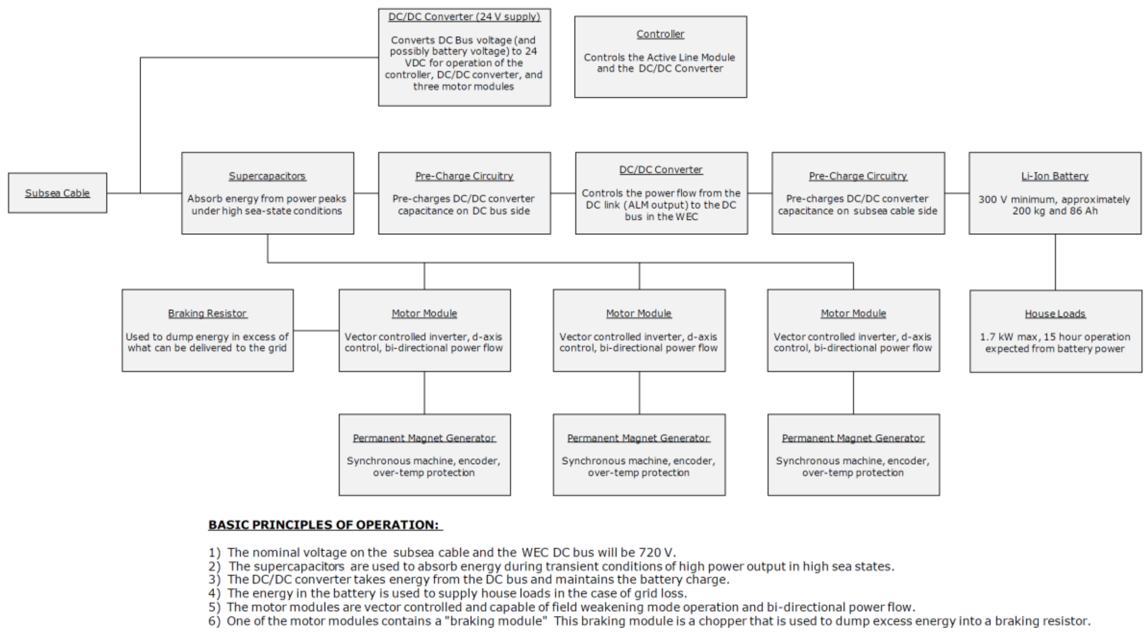


Figure 25: Block Diagram - Float Power Electronics

The AC output from the generators is converted to DC and combined onto a common DC bus by three vector-controlled inverters. The inverters are capable of field-weakening operation, allowing the generators to be operated in a constant power mode at speeds above rated speed. The control strategy is zero d-axis current in order to maximize machine torque/current. A contactor between each generator and inverter is there to disconnect the generators from the inverters in the event of generator speeds that would produce voltages that would damage the inverters and other power system components.

A braking resistor is connected to one of the inverters and can be used to dump any energy generated that is in excess of what can be delivered to the shore. Power delivered to shore is limited by the ampacity of the subsea cable and the export voltage level.

In energetic sea states, the generators will intermittently produce power far in excess of what can be put into the grid or dissipated as heat by the braking resistor. A supercapacitor array is used to absorb some of the instantaneous power peaks by providing some level of power smoothing. A manually controlled discharge switch allows the voltage on the supercapacitor to be safely bled off through a resistor when required.

A DC/DC converter is connected to the DC bus and maintains the charge on a Lithium-ion battery array that is used to power the house loads. House loads are powered in this way such that in the event of simultaneous grid loss and low energy production they can be powered from the batteries. The pre-charge circuitry on the DC bus and battery sides of the DC/DC converter is used to pre-charge the DC/DC converter's internal capacitances to the level of the DC bus and battery prior to making power connection.

A second DC/DC converter provides 24 VDC to various components in the system and can take its input power from either the DC bus or the battery.

A dedicated controller provides coordinated control of the entire system.

The DC bus is connected though a fused disconnect to the umbilical cable, which is connected to the subsea cable, and allows bi-directional power flow between the Triton C and the power electronics system onshore.

Generators

The generator inverters are bidirectional and are capable of four-quadrant operation of the generators at maximum torque. Operation of the generators as motors will be implement using advanced controls for improving system efficiency. The inverters are sized to be able to operate the generators intermittently at their maximum torque limits, in order to meet the damping requirements of the highest sea-state conditions. The inverters will monitor the generator thermistors to protect against over-temperature.

Figure 26. Solid shaft Siemens torque motor [3]

Figure 33 below shows the generator inverters, braking resistor, and generators schematic.

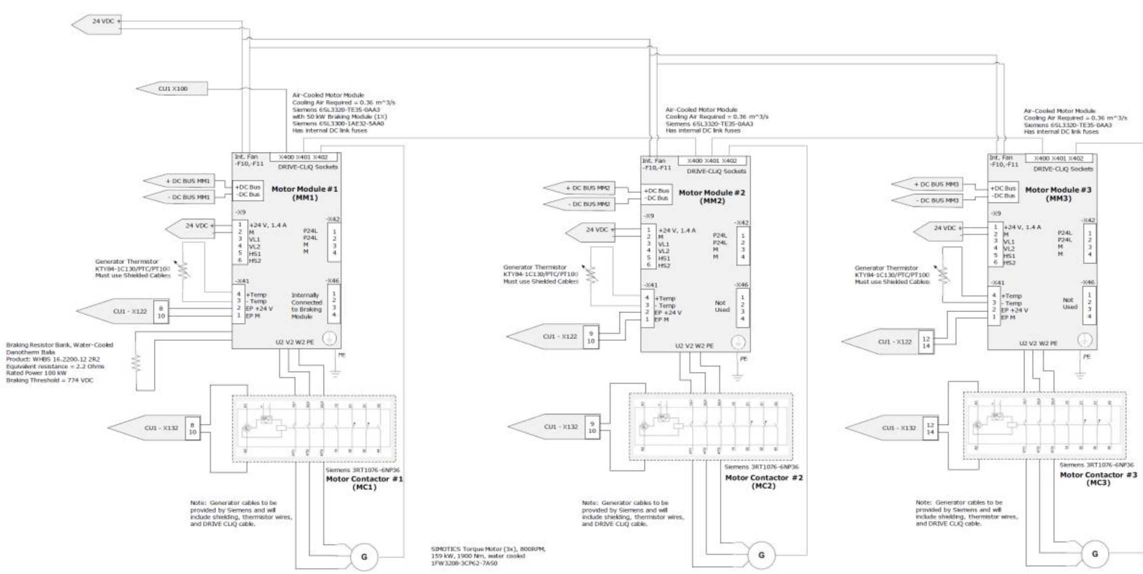


Figure 27: Generator Inverters, Braking Resistor, and Generators

The generators are rated at 800 RPM, 159 kW, and 1,900 Nm, with upper limits of 1,800 RPM, and 3,300 Nm. They have an absolute multi-turn encoder for position and three built-in thermistors for thermal protection. Figure 28 below shows the speed-torque curves for the selected machine. The dark black solid and dashed lines indicate the machine's maximum torque capabilities at speeds above rated with field weakening operation.

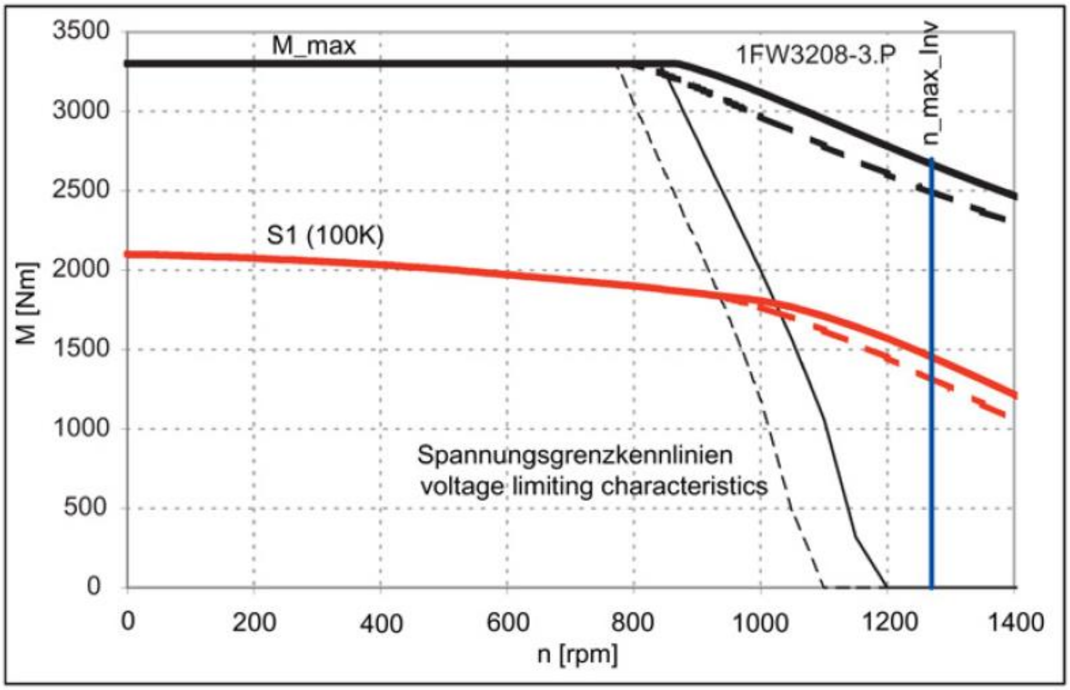


Figure 28: Speed/Torque Curves for the Siemens 1FW3208-3P Torque Motor

Generator Inverters (& Braking Resistor)

The generator inverters are bidirectional and are capable of four-quadrant operation of the generators at maximum torque. Operation of the generators as motors will be implemented if a suitable strategy for *advanced controls* can be developed. The inverters are sized to be able to operate the generators intermittently at their maximum torque limits, in order to meet the damping requirements of the highest sea-state conditions. The inverters will monitor the generator thermistors to protect against over-temperature.

One of the three inverters will contain a braking module that will activate if the DC bus voltage should exceed 774 volts. The braking module is capable of continuous operation at 50 kW, and intermittent operation at up to 250 kW.

The braking module has a large water-cooled resistor that is used to dump any (or all) excess energy. In energetic sea states, or when there is no grid connection, the braking resistor will be used.

Inverter Controller

Figure 29 below shows the grid inverter, control unit (CU 1), battery charger (DC/DC Converter), and 24 VDC power supply schematic. These components are all located in the float.

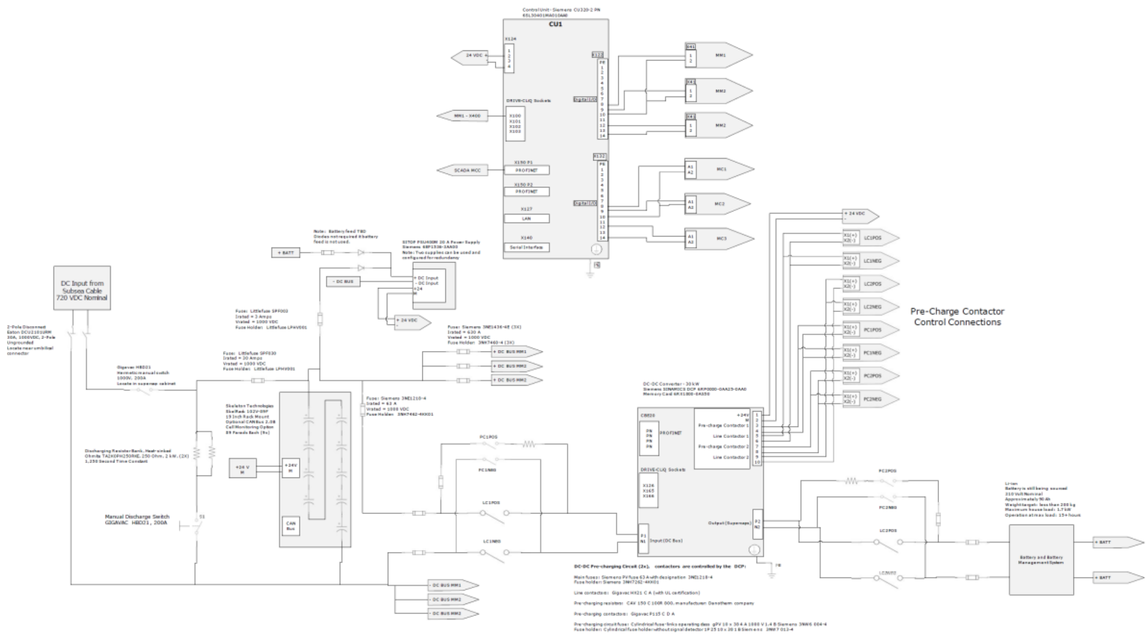


Figure 29: Inverter Controller, Supercapacitors, and Battery Charger

The onboard control unit (CU2) will control the three generator inverters and interface with the master PLC, allowing dynamic modification of the system parameters as needed. It will be capable of providing the high-bandwidth, velocity dependent closed-loop, field-oriented torque control that is required by the Triton-C.

The control unit will interface with top top-level PLC control via PROFINET bus and will be programmed to meet the grid support requirements of UL1741 SA for:

- Low/high voltage ride through
- Low/high frequency ride through
- Soft start ramp rate
- Specified power factor
- Normal and soft start ramp rate control
- Volt/VAR mode
- Volt-Watt mode
- Frequency-Watt mode
- Anti-islanding protection

Battery Storage

The battery storage system supplies power to the internal system loads (house loads) in cases of grid loss or any other event where power cannot be supplied from grid or passed through the DC bus during power generation.

The house load schematic is shown in Figure 30. House loads consist of:

- (2) 15 HP variable frequency drives (VFDs) for the hydraulic pumps
- (1) 3 HP VFD for the primary freshwater cooling pump
- (1) 1.5 HP VFD for the secondary freshwater cooling pump
- (2) 0.75 HP VFDs for the seawater cooling pump and the bilge pump
- (1) 24 VDC with 1200-watt maximum power draw for the SCADA system (as detailed in Triton-C Detailed Design Report: SCADA)

Each load has its own switch and fuse to allow its disconnection without interruption of the other loads.

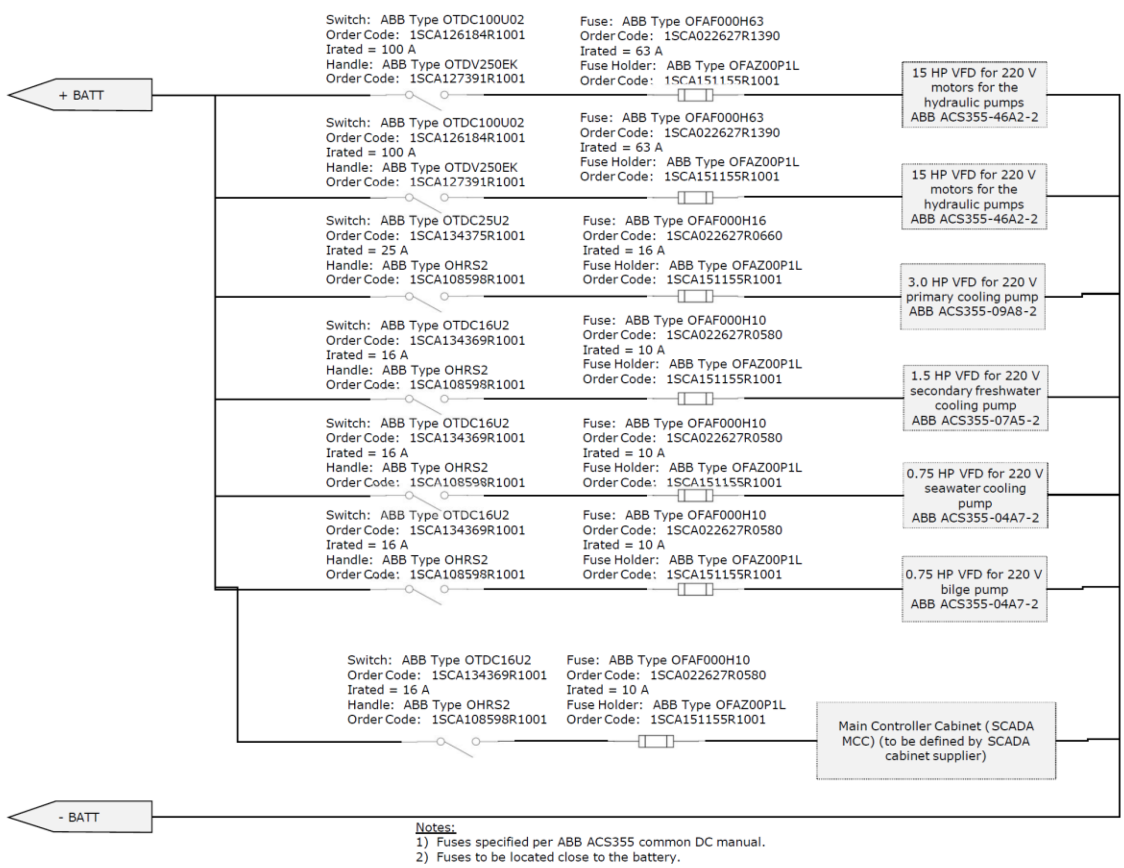


Figure 30: House Loads, Switches, and Fuses

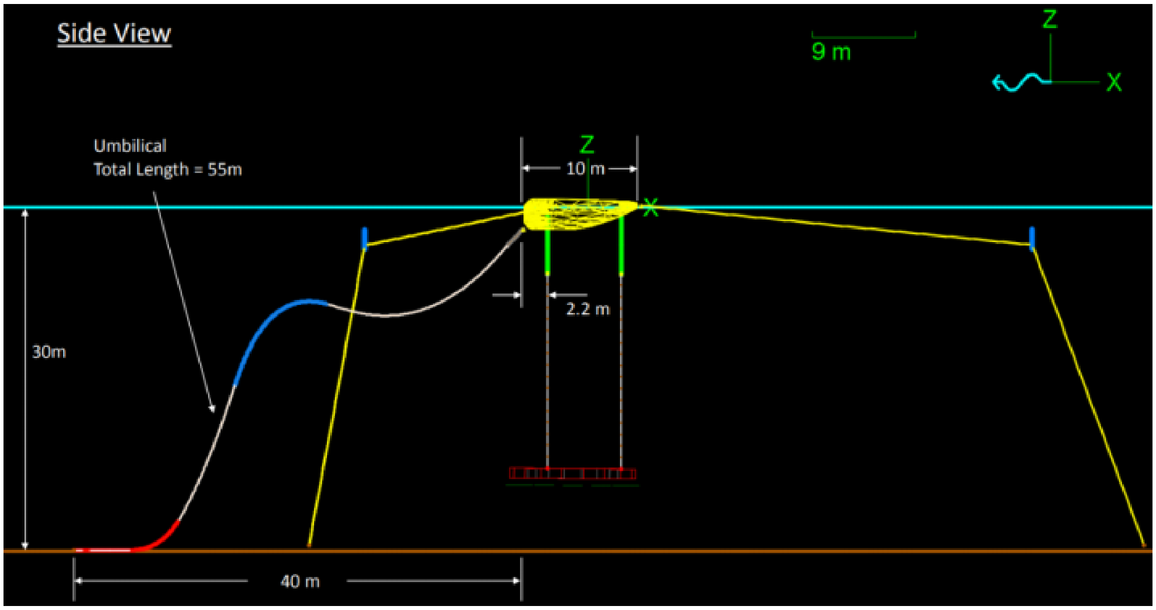
The battery system has a nominal voltage of 310 VDC with 86 amp-hr in charge. The expected mass is approximately 200 kg based on information received on cells and supporting battery management system. Battery voltage was selected to accommodate six different pump drives for the hydraulic, cooling and other auxiliary systems supporting the PTO. The minimum grid loss load is 1.7 kW to keep the SCADA monitoring system online and have the system ready for startup once connection to the grid is regained. This load will keep the system operating for up to 15.2 hours of continuous operation without grid power. The module chemistry is expected to be either Lithium Iron Phosphate (LFP) or Lithium Nickel Manganese Cobalt Oxide (NMC).

Figure 31. Example load cell for this battery application [4]

The battery charger is a DC/DC converter that is identical to the DC/DC converter onshore that is used to connect the DC Link onshore to the DC Bus in the float. The battery charger takes energy from the DC Bus to charge the Li-ion battery.

Umbilical

The power export cable from the Triton-C must be designed to run safely from the WEC to the seafloor junction box. The umbilical is a dynamic cable installed in a typical lazy-S arrangement with bend stiffeners, restrictors, and flotation.



Bill of Materials

Component	Description
Connector	Ditrel Konekta2 (see Konnector_Installation_dwg)
Umbilical	JDR Cable (see DWG 109944A). 2-core + Fiber. Length = 55m total including 2m bend restrictor
Arch section	Distributed syntactic foam collars. Length = 12 m, specific gravity = 0.89
Sag section	ABCO X150 Vertebrae bend restrictor. Length = 10m

Note: Components are listed in order from the hull to the seafloor junction box

Figure 32. Umbilical diagram and bill of materials

The cable will be made slightly heavier than seawater so that a lazy-S arrangement can be formed without any additional weight distributed on the cable. By using a light cable, the equipment needed is likely to be less and the load imparted to the WEC is reduced. Using OrcaFlex, a cable with 1 kg/m net weight in sea water was found to provide ideal cable dynamics. This cable design and connector is shown in Figure 33.

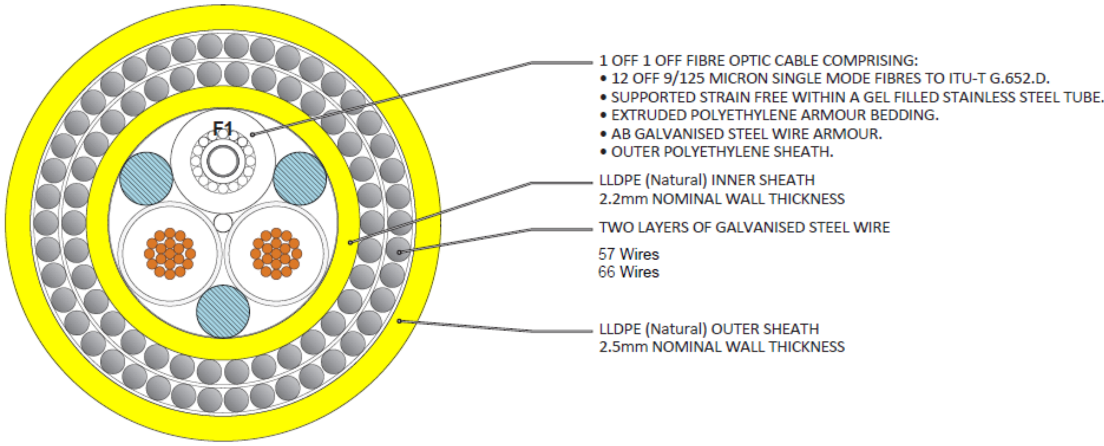


Figure 33. Umbilical cable core design [5]

The umbilical design is designed to meet the following requirements:

- Minimize loads imparted on the Triton-C
- Avoid clashes with the tendons, reaction ring and moorings
- Maximum loads within the working limit of 20 kN (80kN max)
- Minimum dynamic bend radius above 5850-mm.

The seafloor junction box will be located behind the hull and can be positioned at any distance away from the WEC. Since the Triton-C has a maximum surge displacement of approximately 20 m, we will place the junction box >40 m behind the WEC. This will avoid collision between the ring and the lower section of the umbilical. The junction box will be installed on the seafloor at a point half-way between the rear anchors (MC and AB) to minimize potential interference between the umbilical and the tendons/moorings. A lazy-wave configuration is selected to route the cable from the device to the junction box and accommodate Triton-C survival motions. In this configuration, the umbilical connects to the junction box horizontally.

The interface between the cable and the surface float is shown is Figure 32. Here, the umbilical connects at a 45° angle to the lower-rear corner of the hull. Moving the connector behind the tendons eliminates clashing altogether. Connector assembly is shown in Figure 34.

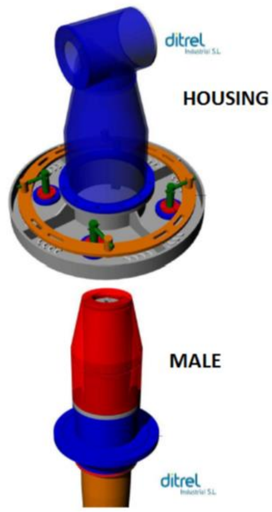


Figure 34. Connector assembly: female and male connectors [6]

An overall linear bending stiffness was assumed to be 0.1 kN*m^2. This is an order-of-magnitude estimate at the moment until the Nexans provides a more exact value. Vertebrae bend restrictors (VBR) will be placed onto line segments where there may be risk for overbending. One option that meets the Nexans cable diameter and minimum bend radius requirements is the ABCO X150, which has a 762 mm locked bend radius, shown in Figure 35.

The umbilical is 55 m long and comprises five segments.

1. At the connector, a 2-m long bend stiffener (grey) is used with the bend stiffness varying from 1 kNm^2 to 0.1 kNm^2 (these values are also approximate).
2. 18-m of cable (white) forms a sagging catenary.
3. A 12 m "arch" section (blue) holds the power cable up and forms an inverse-catenary. This section represents bend restrictors that limit the bending radius to 700mm but have a positive buoyancy. These were modelled as ABCO X150 units with specific gravity of 0.89, which in practice would be implemented with distributed syntactic foam collars around the restrictors to provide the correct buoyancy.
4. 13 m of cable (white).
5. 10 m of cable with ABCO X150 VBR.

This configuration was simulated in OrcaFlex. In the design wave conditions, the maximum axial load on the connector is 2.4 kN, which is within the working load limit of 20 kN.

POLYURETHANE VERTEBRAE BEND RESTRICTORS Technical Data

* All data below applies to polyurethane vertebrae bend restrictors.
ABCO Subsea also manufactures steel VBR assemblies.

Material Specs:

Material Designation	70 D or 85 D, Ether-based Polyurethane
Manufacturing Process	Atmospheric Cast
Specific Gravity	1.16 – 1.20
Standard Color	Yellow

Design Parameters for X-Series Vertebrae Bend Restrictor (VBR)

	X150	X300	X4000	X6000
Segment Weight in Air Range:	1 lbf [4.4 N]	~1.5 lbf [~7 N]	5 - 8 lbf [22 - 36 N]	10 - 14 lbf [44 - 62 N]
Maximum ID:	1.6 in. [40.6 mm]	3.13 in. [79.5 mm]	4.25 in. [108 mm]	6.25 in. [159 mm]
Segment OD:	5 in. [127 mm]	6.5 in. [217 mm]	8.9 in. [226 mm]	11.5 in. [292 mm]
Segment Pitch Length Range:	3.7 in. [94 mm]	3.8 in. [97 mm]	7.7 in. [196 mm] 11.6 in. [295 mm] 15.4 in. [391 mm]	9.2 in. [234 mm] 11.1 in. [282 mm] 15.4 in. [291 mm]
Flange Interface Options:	2 in. CL 150	4 in. CL 300	4 in. CL 150 4 in. CL 300 6 in. CL 300	6 in. CL 150 6 in. CL 300 8 in. CL 300
LBR Options:	30 in. [762 mm] 35 in. [889 mm]	58 in. [1.5 m] 90 in. [2.3 m] 120 in. [3.0 m] 162 in. [4.1 m]	40 in. [1 m] 60 in. [1.5 m] 80 in. [2.0 m]	48 in. [1.2 m] 58 in. [1.5 m] 80 in. [2.0 m]
Typical Maximum Static Moment:	355 ft*lbf [0.48 kN*m]	1.67 kip*ft [2.26 kN*m]	1.2 kip*ft [1.6 kN*m]	1.3 kip*ft [1.8 kN*m]
Typical Maximum Dynamic Moment:	500 ft*lbf [0.68 kN*m]	2.33 kip*ft [3.17 kN*m]	1.7 kip*ft [2.3 kN*m]	1.8 kip*ft [2.5 kN*m]
Typical Ultimate Moment:	875 ft*lbf [1.19 kN*m]	4.1 kip*ft [5.55 kN*m]	3 kip*ft [4 kN*m]	3.2 kip*ft [4.4 kN*m]

Figure 35. ABCO bend restrictors [7]

Onshore Grid Conversion

Due to challenges with the size of the existing submarine cable, we will be extending the system DC bus onto the submarine cable and thus to shore. The grid conversion will then be performed onshore.

The subsea cable is connected to a 30kW onshore DC/DC converter with pre-charge circuitry similar to the one in the Triton C that maintains the charge on the Li-ion battery. The DC/DC converter onshore is programmed to maintain a constant voltage on the subsea cable, and thus maintain the DC Bus voltage in the Triton C.

The DC/DC converter is then connected to a DC bus that is created by a Siemens Active Line Module (ALM) that is capable of bi-directional power flow and converts 3-phase AC to a regulated DC output, and vice-versa. A Siemens Active Interface Module (AIM) filters the out the switching noise on the 3-phase output from the ALM and delivers utility quality power to the grid through a fused disconnect switch. Grid connection equipment (transformer, protective relays, etc.) are still to be defined and will provide the interface between the grid and the fused disconnect switch based on HECO agreement.

Document References

Refer to Triton-C D11_Detailed Design Index_R0 for document indexing.

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Drivetrain_Combined_FEED_R1-0
FEED Report – Mechanical R1-0
Electrical System FEED R1-0
Triton-C BP1-_2 Continuation Report R1-6
Triton-C Detailed Design Summary_R1
Triton-C Detailed Design Report: Surface Float_R1
Triton-C Detailed Design Report: Reaction Ring_R1
Triton-C Detailed Design Report: SCADA System_R1

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