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The Hybrid Tug Reality – The Business Case for Green Technology in the Tugboat Industry

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SYNOPSIS

As detailed in a paper presented at the 2008 *International Tug & Salvage Convention*, Aspin Kemp & Associates (AKA) has collaborated with Foss Maritime to develop and build the world's first hybrid-powered tug. Now that ***Carolyn Dorothy*** is a reality, we are able to provide a comprehensive update to last year's paper, including lessons learned from the construction and commissioning process.

This paper presents the business case for hybrid propulsion in tug operations. The hybrid system and its application in harbour assist work are explained, illustrating how the award-winning hybrid propulsion technology delivers real benefits in harbour tug operations through improved fuel economy, decreased maintenance costs and reduced emissions and noise.

INTRODUCTION

The recent entry to service of Foss's ***Carolyn Dorothy,*** the world's first hybrid tug, marks the introduction of a new kind of environmentally sound, cost-effective technology designed specifically for the maritime industry. The innovative tug design was jointly developed by Foss Maritime and Aspin Kemp and Associates (AKA); the two companies are now jointly seeking patent protection for the system. It has received high praise from industry analysts and environmental officials alike, winning the Environmental Protection Agency's 2007 Clean Air Excellence Award for Clean Air Technology.

Having collaborated to shift hybrid tug propulsion technology from concept to reality, Foss and AKA are now working to confirm the expected benefits in emissions reduction, cost savings and workplace health. Specifically, the Foss-AKA hybrid team is validating:

- Emissions reduction performance – hybrid technology enables engines to run at or near best efficiency and only when needed. It is expected that lower fuel usage and cleaner combustion will contribute to reducing harmful emissions of CO, CO_2, SO_X, NO_X, hydrocarbons and particulate matter;
- Fuel economy performance – because the technology includes propulsion load sharing between diesel and electrical sources, it effectively eliminates unnecessary idling of the main propulsion engines. The incorporation of storage batteries also allows hotel and station-keeping electrical loads to be met without running diesels. Finally, the use of small, energy-efficient auxiliary engines for propulsion is expected to improve transit-speed efficiency. All of these factors contribute to reducing actual fuel consumption;
- Maintenance savings potential – lower maintenance costs are expected to be a collateral benefit of minimised main and auxiliary engine usage. Running engines less frequently extends the time between engine overhauls and oil and filter changes;
- Workplace health improvements – hybrid technology allows engines to be shut down at sea, without sacrificing operational readiness because the vessel is fully operable on battery power alone at low power levels. Reduced engine running is expected to cut workplace noise, helping to create a healthier workplace for crews.

BACKGROUND

Aspin Kemp and Associates (AKA)

From its headquarters in Owen Sound, Ontario, Canada, the AKA Group of Companies provides electrical, mechanical and marine engineering solutions to a global marine and offshore market. With core competencies in marine and offshore operations and a history of marine technology development, AKA has successfully refined technologies originally designed to support offshore oil exploration drilling rigs.

Foss Maritime

Seattle-based Foss Maritime offers a complete range of maritime services to customers across the Pacific Rim, Europe, South America and around the globe. The company has harbour services and transportation operations in all major US West Coast ports, including the Columbia and Snake River system. With one of the largest fleets of tugs and barges on the American West Coast, Foss also operates two shipyards and offers worldwide marine transportation.

THE RATIONALE FOR HYBRID HARBOUR TUGS

Hybrid propulsion makes sense for harbour tugs; it gains leverage from the inherent variability in tug operations. A hybrid plant's high level of configuration flexibility – reflected in the large number of permutations of engines, motors, generators and batteries available to operators – permits multiple points of optimum plant efficiency.

By comparison, conventional plants can be optimised only at a single point: near full power. For diesel engines, specific fuel consumption (SFC) is lowest at high engine loads. Above 50 per cent of full power, the SFC curve is typically quite flat; below that threshold, the range of SFC values is dramatic. A model combining Foss's operational statistics with engine manufacturer's data shows that, for marine diesel engines installed in conventional Dolphin tugs, SFC at the 15 per cent load level is 48 per cent higher than at 50 per cent load.

Tugboats are required to perform a wide variety of tasks across the entire power spectrum, from very low power (eg standing by, waiting for pilot's orders) to very high power (arresting the momentum of a large ship) and all points in between (in transit, during ship berthing, barge towing, and so on). They are rarely, if ever, assured of continued operations at or near the high power levels required for optimum engine performance. In actual fact, they operate at low engine load most of the time. Operational data reveals that Dolphin tugs operating in the Los Angeles-Long Beach area spent up to 60 per cent of their time at less than 20 per cent power, and 95 per cent of their time at less than 67 per cent power. The average main engine load (expressed as a percentage of full power) over the monitoring period was just 16 per cent. There were, of course, times when the tugs required full, or almost full, power; however, those episodes tended to be infrequent and of very short duration.

Often, a tugboat's main and auxiliary engines carry extremely low loads, where SFC performance is at its worst. Operational realities require tugs to be able to move at any moment without the delay of starting a main engine. Boats on duty must also always have electrical power available to meet hotel loads, navigation lights and electronics. Consequently, both main engines plus at least one diesel generator run constantly – usually, at idle – when a boat is away from the pier.

Hybrid systems take advantage of duty cycle variability to provide a significant increase in plant efficiency. On the ***Carolyn Dorothy***, the hybrid system exploits the SFC differences between low and high engine loads to generate emissions reduction and fuel economy. Collaterally, maintenance costs and workplace noise are also reduced.

A NEW REALITY: BUILDING THE WORLD'S FIRST HYBRID TUG

With experience providing high-reliability energy management solutions to the offshore oil and gas industry, AKA understood the need for redundancy and fail-safe operations in a marine hybrid plant. To meet Foss's requirements, the company proposed a system based on its proprietary XeroPoint hybrid technology, initially developed for a much smaller vessel, but highly scalable. Together, Foss and AKA incorporated their knowledge of operational tug realities to develop the system for use in a hybrid tug.

The system combines smaller main engines (compared to a conventional vessel of equal capability) with electric propulsion motors. It allows engines to shut down when not required, keeps engines at or near their design points when running, and engages its electric motors to provide the difference between available engine power and required power across the speed range. Energy stored in batteries is used to meet low-end power requirements and bridge transient periods when power is required, but engines are not yet at speed. The boat has the flexibility to operate in direct-diesel, diesel-electric and electric configurations, and delivers the same high power and bollard pull as a conventional Dolphin. To integrate these capabilities, the conventional design was modified to incorporate smaller main engines and larger diesel-generators. Room was made for motor/generators, fitted coaxially to main engines; storage batteries and new cabinets containing the power conversion and control equipment were also added.

Although the system is designed to be fully adaptable for existing vessels, Foss decided to produce a new hybrid version of its existing Dolphin class design, primarily to take advantage of the design flexibility inherent in a new-build. Having successfully delivered nine Dolphin class tugboats, the company was well prepared to build the hybrid vessel at its own shipyard in Rainier, Oregon.

Figure 1: The hybrid tug under construction (view looking aft).

INTRODUCING: *CAROLYN DOROTHY*

Foss's hybrid-powered tug, ***Carolyn Dorothy***, is based on the Dolphin class, designed by Robert Allan Limited specifically to provide optimal power and positioning in confined waterways. The vessel, less than 24m long, develops nearly 3,800kW of power and 58 tonnes of bollard pull (ahead).

Figure 2: The world's first hybrid-powered harbour tug, Foss's **Carolyn Dorothy** *at launch.*

Main propulsion engines	2 x Cummins QSK50 Tier 2 1342 kW @ 1,800 rpm
Main propulsion motor-generators	2 x Siemens type 1LA8, 690vAC 3Φ 900 kW @ 1,800 rpm
Auxiliary generator sets	2 x Cummins QSM 11 310 kW
Storage battery	126 x SBS 12GFT225 12v 223 A-hr (C8)
Z-drives	2 x Rolls Royce US205 FP
Length	23.77m
Beam	10.36m
Draft	4.27m
Bollard pull (ahead)	58 tonnes
Bollard pull (astern)	56 tonnes

Table 1 - ***Carolyn Dorothy*** *specifications.*

PROPULSION AND POWER PLANT ARRANGEMENT

The hybrid tug has two main diesel engines, shafted to Azimuthing Stern Drives (ASDs). Propulsion motor/generators (M/Gs) are fitted between the main engines and the ASDs, as illustrated in Figure *3*. The M/Gs are AC machines which function both as motors, when required to provide mechanical power to the ASDs, and as generators, when needed to provide electrical power machines which function both as motors, when required to provide mechanical power to the ASDs, and as generators, when needed to provide electrical power back to the system (eg to charge batteries).

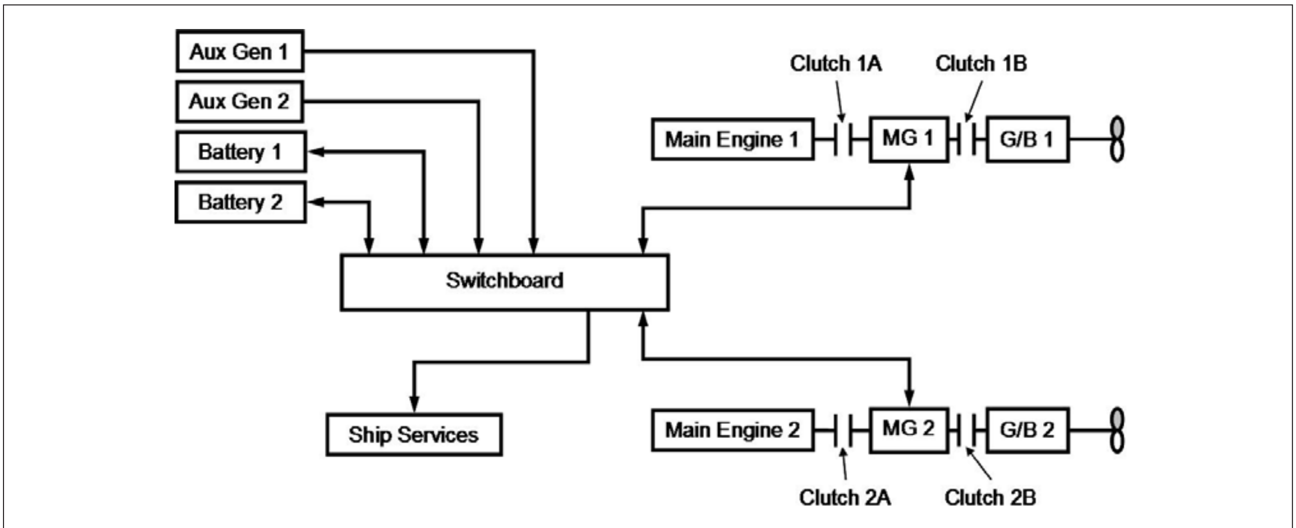

Figure 3: XeroPoint hybrid system – general arrangement.

The system also incorporates two auxiliary diesel generator sets (Aux Gen) to supply electrical power for propulsion, hotel services and battery charging. One or both auxiliary generators can provide propulsive power; the number of generators in operation is determined by the demands of the propulsion system, hotel and miscellaneous other loads (eg the deck winch). The electrical configuration is shown in *Figure 4* (see end of paper).

When the load on the plant changes enough to warrant a configuration change, the Energy Management System (EMS) takes automatic action, within the constraints set by the operational model. For example: the vessel is underway on a single auxiliary generator set and the sum of all propulsion, hotel and other loads exceeds the capacity of the on-line generator. Following a predetermined 'buffer' time limit, the system will automatically start and bring on-line an additional auxiliary generator set to deliver the required power. Starting a diesel and bringing a generator on-line takes a finite amount of time; during the buffer and through the interim period between the start command and the actual delivery of power, 'ride-through' energy s provided by the storage battery system.

Figure 5: Main switchboard/hybrid control system showing engine room console.

OPERATIONAL DESIGN

The hybrid tug uses auxiliary generators and batteries to augment main engines as sources of propulsion power; compared to a conventional boat, it therefore has vastly increased flexibility in machinery configuration. A hybrid can, for example, cruise on a single auxiliary generator or allocate power from one main engine to both propellers equally. There are 32 possible combinations of battery, auxiliary generators and/or main engines[1]. From an operational point of view, an increase in flexibility on this scale presents a challenge: how to provide operators sufficient control over plant configuration without overlaying a huge array of choices onto an already saturated information environment.

Foss and AKA used qualitative and quantitative data collected from Dolphin-class tug operations in San Pedro Bay to create a model optimised for operators' needs, operational requirements and machinery capability. Vessel performance data collected by Foss in 2006 provided important clues as to how the conventional Dolphins were actually operated during and between jobs. This data, together with information from a review of vessel operations, boat activity logs and discussions with captains, boat engineers, deck crew and port engineers was analysed for patterns that characterised typical operations. Combining computer simulations with observations of actual ship assist and escort operations and discussions with crews, the design team isolated the fundamentally important operating modes for the propulsion and power plant. We used this knowledge to create a conceptual model that provides a simple way for the crew to understand and operate the system.

Operating modes

The propulsion system is designed to work in either of two distinct modes of operation: hybrid or conventional. In normal operation the vessel will remain in hybrid mode. The conventional mode is available for emergencies, for example in the unlikely case of coincident failures of redundant hybrid control system components. When the vessel is in hybrid mode, a green 'Hybrid in Control' light is illuminated on the control panel.

Conventional mode

Switching from hybrid to conventional is done automatically under certain failure conditions. A manual change-over switch is also available to the operator.

In conventional mode, propulsion power is limited to the power developed by main engines only. Motor-generators, associated auxiliaries and controls are disabled. Steering units and clutches can be powered from the DC bus or the AC bus, depending on the nature of the event that instigated selection of the mode. (See *Figure 6* at end of paper).

Hybrid mode

In hybrid mode, full propulsion power is available to the operator, under four separate readiness levels. The motor-generators, certain auxiliary equipment, steering units and the towing winch are all powered from the DC bus. The AC bus is supported by the auxiliary generator(s) or by the DC bus, depending on plant configuration.

Readiness levels

The hybrid system is designed around four specific readiness levels, chosen to take advantage of the full range of plant configuration options without introducing excessive complexity. Established from operations reviews, engine operating data and history, boat activity logs and discussions with crew members and shore-side personnel, the power settings for each level reflect relevant operational scenarios.

Figure 7: Hybrid system control panel.

The vessel operator enables the hybrid system to operate the plant within pre-defined sets of configuration options by selecting between four readiness levels at the hybrid control panel –

- **Stop**
- **Idle**
- **Transit**
- **Assist**

Stop is the lowest level of plant readiness; Assist is the highest. The function and description of each level below:

Stop

The Stop level is used when the vessel is secured alongside. Choosing Stop will disable motor-generators and remove the throttle reference from the hybrid control system. This selection will also shut down the main engines if they are running. (See *Figure 8* at end of paper).

At this level, power for hotel loads and battery charging is provided by shore power. If shore power is not connected, power is supplied by the batteries. When the batteries have discharged to a pre-set State of Charge (SOC), a generator set will start up to replenish them.

Power Flow

At Stop, when shore power is connected, energy flows through the shore power contactor directly onto the Vessel Service Bus, providing power for hotel loads.

Idle

The Idle level is used when the vessel is stopped at sea. The name reflects the vessel's state, not the main engines' – typically, no engines are running at Idle, and the boat is producing zero emissions. The batteries provide power for hotel loads and minimal station keeping. A generator will automatically start up and come online to recharge batteries when they have declined to a pre-set SOC level. Pushing the throttles above a threshold will cue both main engines and both auxiliary generator sets to start, engine clutches to close and power to rise to meet throttle setting. (See *Figure 9* at end of paper).

Choosing Idle from a higher readiness level will cause rotating machinery to come offline as the throttle demand is reduced to within the Idle threshold.

Power Flow

Power at Idle is supplied primarily by the batteries. Current flows from the batteries onto the DC bus. Propulsion motor-generators are powered from the DC bus. AC power feeds the vessel service bus via the transformer. (See *Figure 10* at end of paper).

Transit

This level ensures that the vessel's power resources are used efficiently underway. Switching to Transit from Idle sends a command to the EMS to start one auxiliary generator set, if none is currently online. Switching to Transit from Assist causes the main engines to declutch and shut down when the throttle demand is reduced to within the Transit threshold. (See *Figure 11* at end of paper).

A single auxiliary generator provides power for hotel and 'harbour-speed' propulsion. The first throttle detent corresponds to an amount of power sufficient to propel the vessel at approximately 6 knots. Advancing the throttle beyond this setting will immediately start a second generator. Batteries will provide 'ride-through' power until the second generator is online.

At this level of readiness the generator(s) will stay online even if the power demand does not require it. If the vessel's power demand stays below the available online capacity for more than five minutes, an audible and visible signal indicates that the vessel is not operating efficiently. The operator can choose to silence the notification, switch to the Idle level or shut down one generator.

Power Flow

Power is supplied by one or two generators and the batteries. The generator supply feeds the vessel service bus and the DC bus. The EMS monitors and manages battery bank voltage via the DC/DC converters. For propulsion, the motor-generators are powered from the DC bus.

Assist

The Assist level is intended for most ship-assist work. Selecting Assist causes both main engines and both auxiliary generators to start. If the shaft speed is below engine idle speed, the clutch will close. Otherwise, the engine will accelerate to match shaft speed before it is engaged. The M/Gs and engines share load to provide full power. All rotating machinery will stay online until the operator de-selects the readiness level. (See *Figure 12* at end of paper).

Power Flow

Power is supplied by generators and batteries. The generator supply feeds the vessel service bus and the DC bus. Propulsion M/Gs are powered from the DC Bus.

MACHINERY CONFIGURATIONS

Each of the hybrid mode levels of readiness (plus the conventional mode) has a specific machinery/equipment configuration selected by the Energy Management System.

Device	Operating Mode/Readiness Level				
	Hybrid				Conventional
	Stop	Idle	Transit	Assist	
ME 1	Off	Off	Off	On	On
ME 2	Off	Off	Off	On	On
Eng Clutch	Open	Open	Open	Closed	Closed
Eng Clutch	Open	Open	Open	Closed	Closed
M/G 1	Off	On/Off	On	On	Off
M/G 2	Off	On/Off	On	On	Off
Gen 1	Off/On	Off/On	Off/On	On	Off/On
Gen 2	Off/On	Off/On	Off/On	On	Off/On
DC Bus	Hot	Hot	Hot	Hot	Cold

Table 2 – Machinery Configuration.

OPERATING RESULTS

At the time of writing, ***Carolyn Dorothy*** has been in service only a few weeks. We are still gathering data on plant performance, fuel economy and emissions reduction. Maintenance cost-saving data will be gathered over a longer term. However, there are already some very promising results to report.

- Preliminary fuel economy measurements show that, in transit while powered on a single auxiliary engine, the vessel can make 6 knots using far less fuel than experience suggests for a conventional sister boat on the same waterway;
- Bollard pull requirements can be amply met;
- The vessel can easily transit at the harbour speed limit using one or two auxiliary diesels – main engines are required only for ship assist duties;
- “Zero-emissions” operation – at sea, fully operational for station-keeping and low-speed manoeuvring, with no engines running – is realistic to expect in ordinary operations, for periods up to several hours in length, without significant impact on battery state of charge.

COST – BENEFIT ANALYSIS

The primary motivation behind the project is emission reduction. Diesel engines exhibit lower-efficiency combustion at the power levels where tugboats actually operate, most of the time. And, because the hybrid system delivers low-power efficiency improvements, the emissions benefits are expected to be greater than the fuel savings alone, especially for NOx and Particulate Matter (PM). Other combustion-related pollutants, such as CO_2 and SOx, should reduce proportional to consumption. The possibility of using shore power to supply hotel loads and recharge batteries while alongside creates the potential for even further emissions reduction, especially if shore power is from non-polluting sources. Currently, our analysis does not affix a financial value to emissions reductions.

The economic benefits of operating a hybrid harbour tug are realised through fuel savings and reduced maintenance costs (primarily overhauls and lube oil usage) for the major equipment. Reduced idling and improved efficiency are the main sources of fuel economy. Maintenance cost savings are expected to accrue from the fact that, with main engines shut down most of the time, the elapsed time between engine overhauls is increased significantly. Early results show that fuel savings may exceed initial design estimates of 20-30 per cent across all operations.

A discounted cash flow analysis provides a project valuation estimate for a 3800 kW tugboat, over a 20-year operational study period[2]. The results of the analysis are very positive. The project, which is defined as the addition of a hybrid system to an otherwise conventional new-build, is expected to be worth over US$900,000 in Net Present Value (NPV) terms. That is, the value of the project exceeds the cost of doing it by almost US$1m.

This analysis, using current market rates for the risk-free cost of capital and fuel price, is conservative; it estimates fuel economy cautiously and does not assign any financial value to emissions reduction. Sensitivity analyses on fuel price, cost of capital and inflation indicate that the project retains positive NPV at current fuel prices[3] with capital cost or inflation increased up to 5 percentage points above study levels. At currently projected capital costs and inflation rates, the project also makes clear financial sense for diesel prices well below US$1.00 per US gallon – a price not seen since before 2004.

CONCLUSIONS

Hybrid tugboat propulsion is now a reality. Although these are still early days in its development, the patent-pending technology shows considerable promise for delivering benefits to owners, operators, and society in general:

- Improve fuel economy: because hybrid technology shares the propulsion load between diesel and electrical sources, it means no unnecessary idling;
- Lower maintenance costs: hybrid technology means minimising engine use. Running engines less frequently means more time between engine overhauls and oil and filter changes;
- Reduce emissions: with hybrid technology, engines run at or near best efficiency – and only when needed. Less fuel usage and cleaner combustion both contribute to reducing harmful emissions, enabling operators to easily meet regulatory requirements and public expectations;
- Reduce noise: hybrid technology allows engines to be shut down at sea or alongside, without sacrificing operational readiness. Reduced engine running drastically cuts workplace noise, helping to create a healthier workplace for crews.

REFERENCES

[1] Including the configuration with *no* machinery running; a realistic option for a vessel which can respond instantaneously on battery power.

[2] The actual study period used is 21 years; it is assumed that Year 1 is spent on construction and that the vessel goes into operation at the start of Year 2.

[3] Specifically, using statistics from the US Government's Energy Information Administration, spot price for No 2 low-sulphur diesel at Los Angeles, average for period 13–23 February 2009 (US$1.2091 per US gallon).

Figure 4: XeroPoint hybrid system – electrical arrangement.

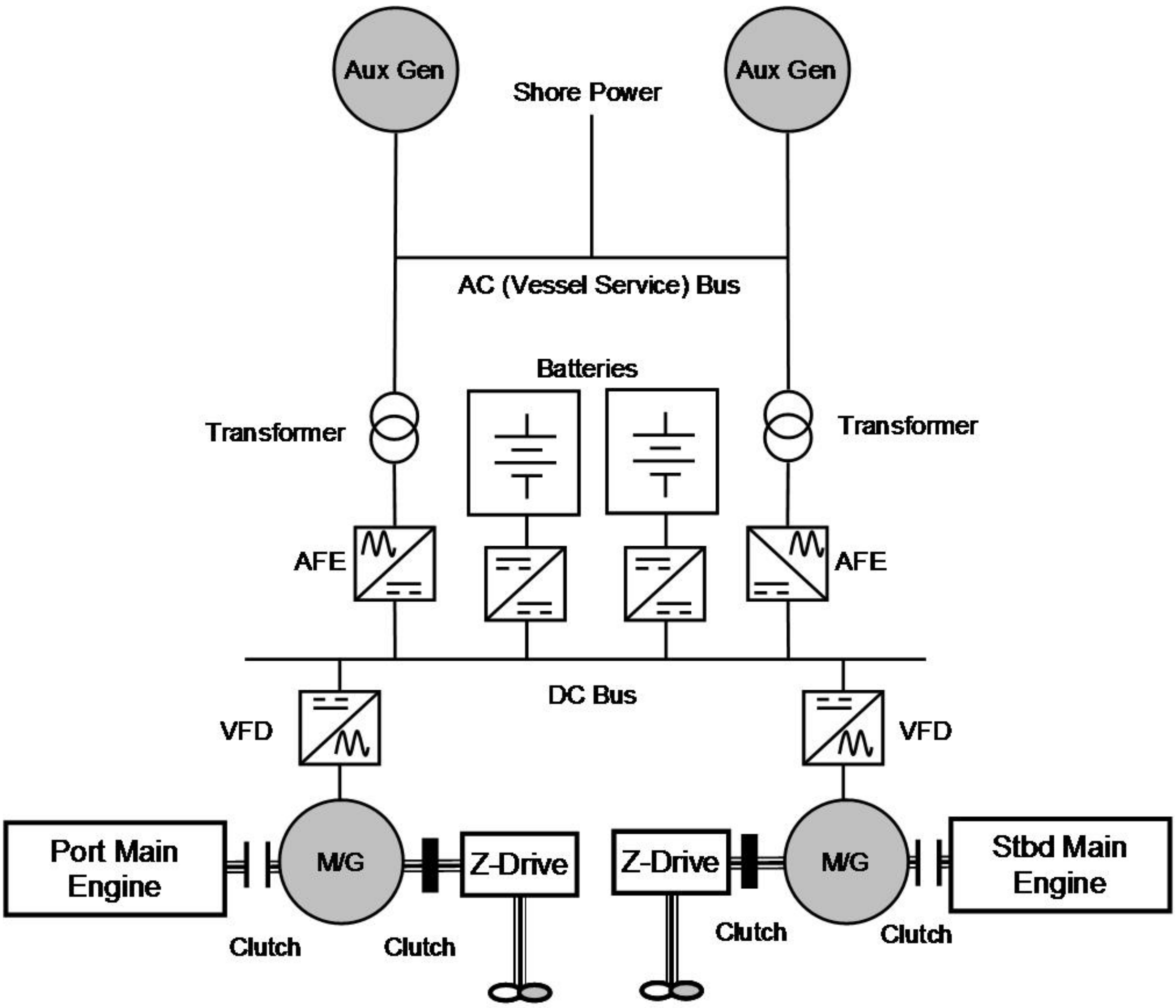

Figure 6: Conventional mode (DC bus disabled).

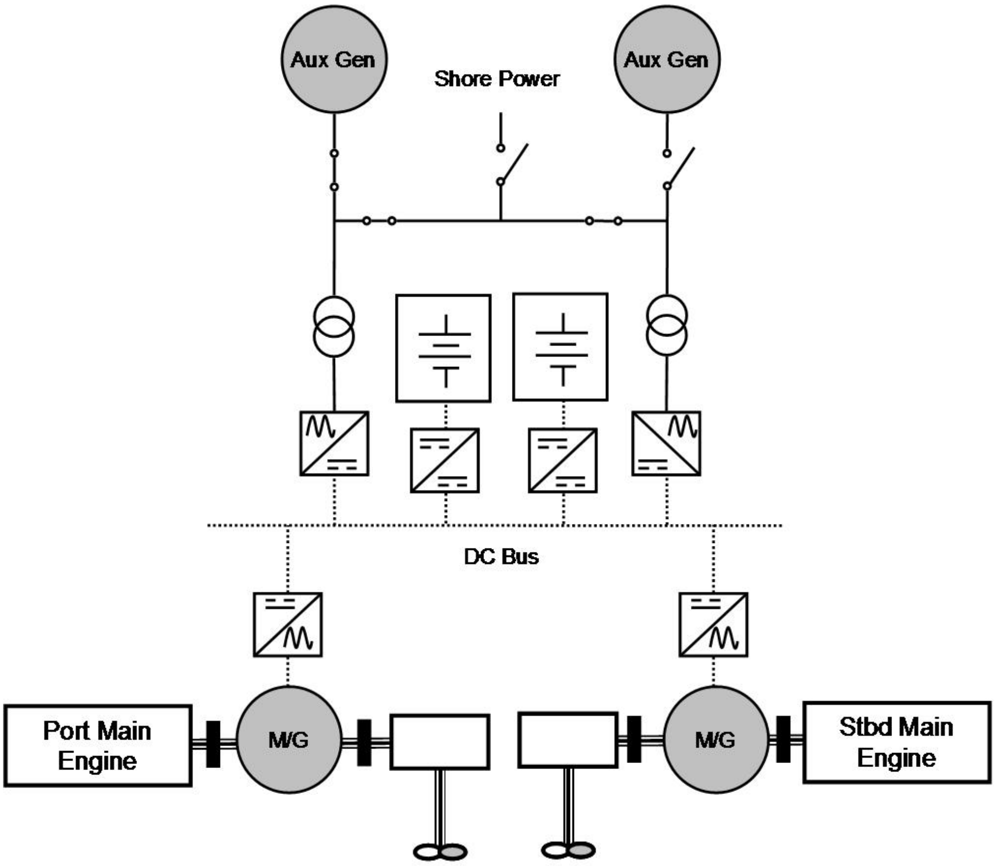

Figure 8: Readiness level 'Stop'.

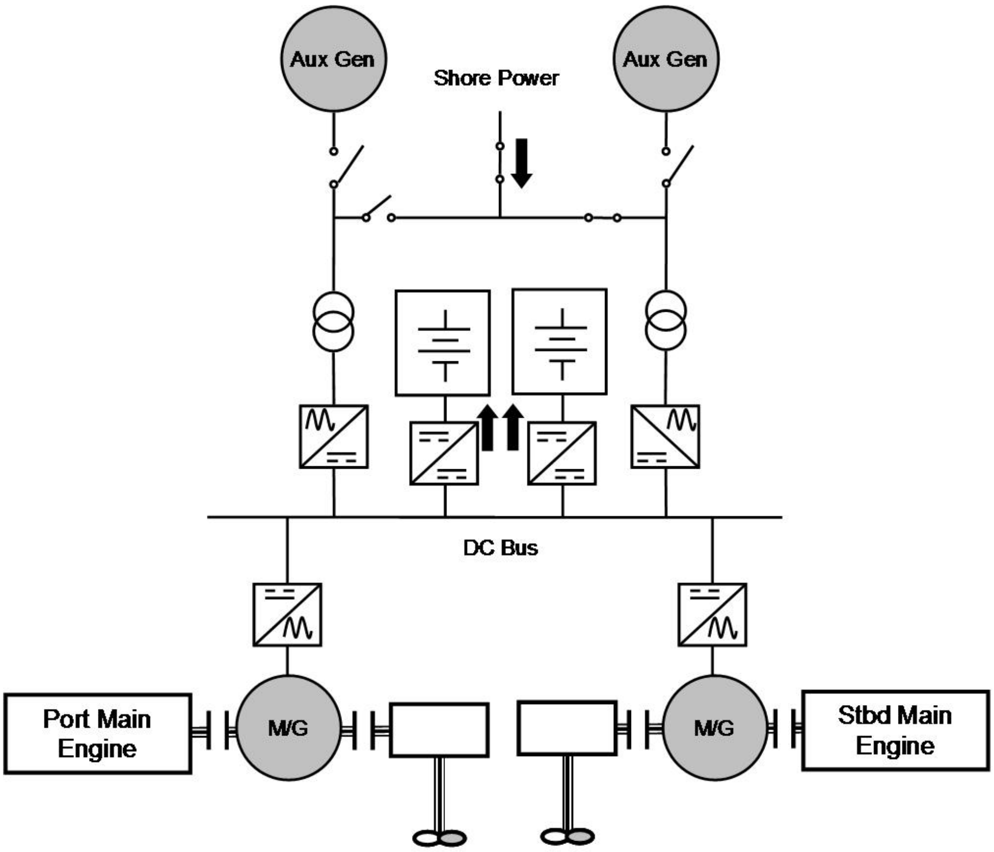

Figure 9: Readiness level 'Idle'.

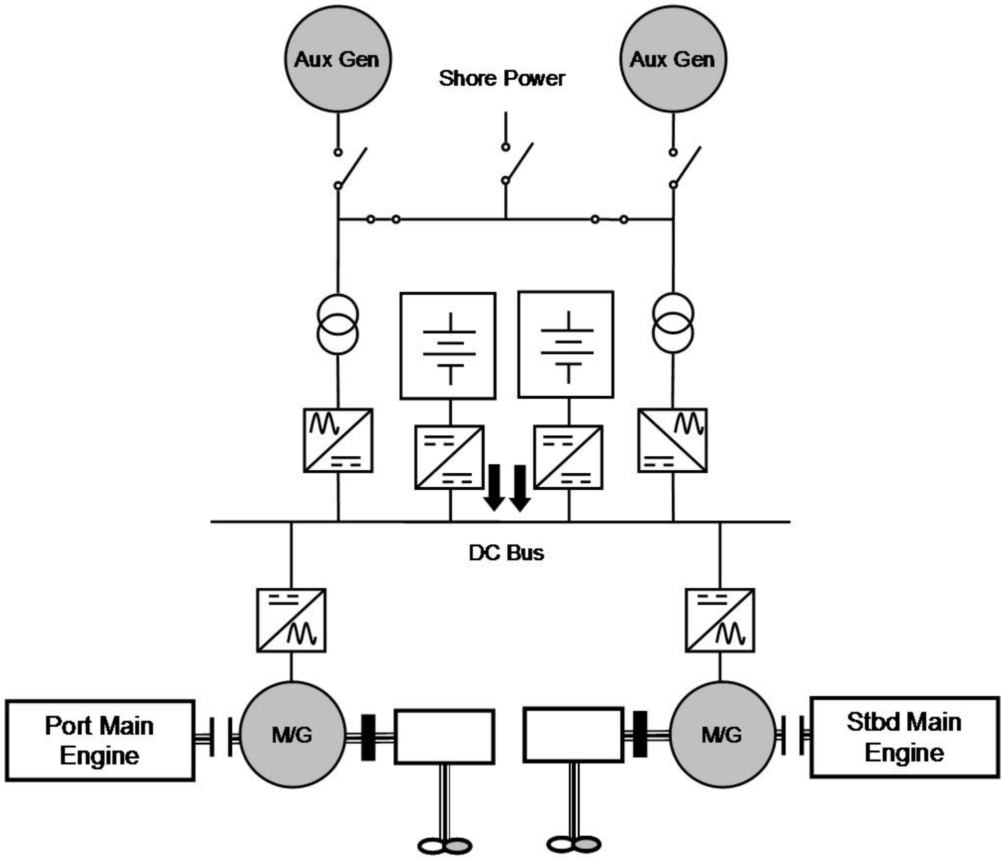

Figure 10: Readiness level 'Idle' or 'Transit' (one auxiliary generator).

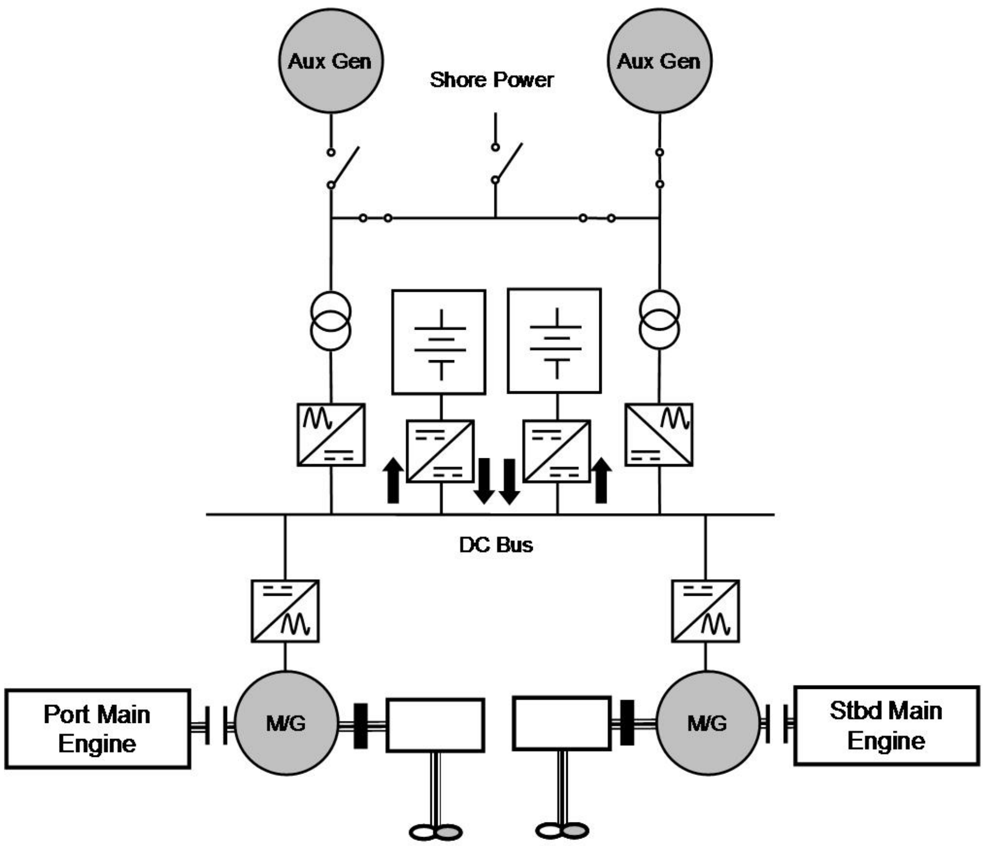

Figure 11: Readiness level 'Transit' (two auxiliary generators).

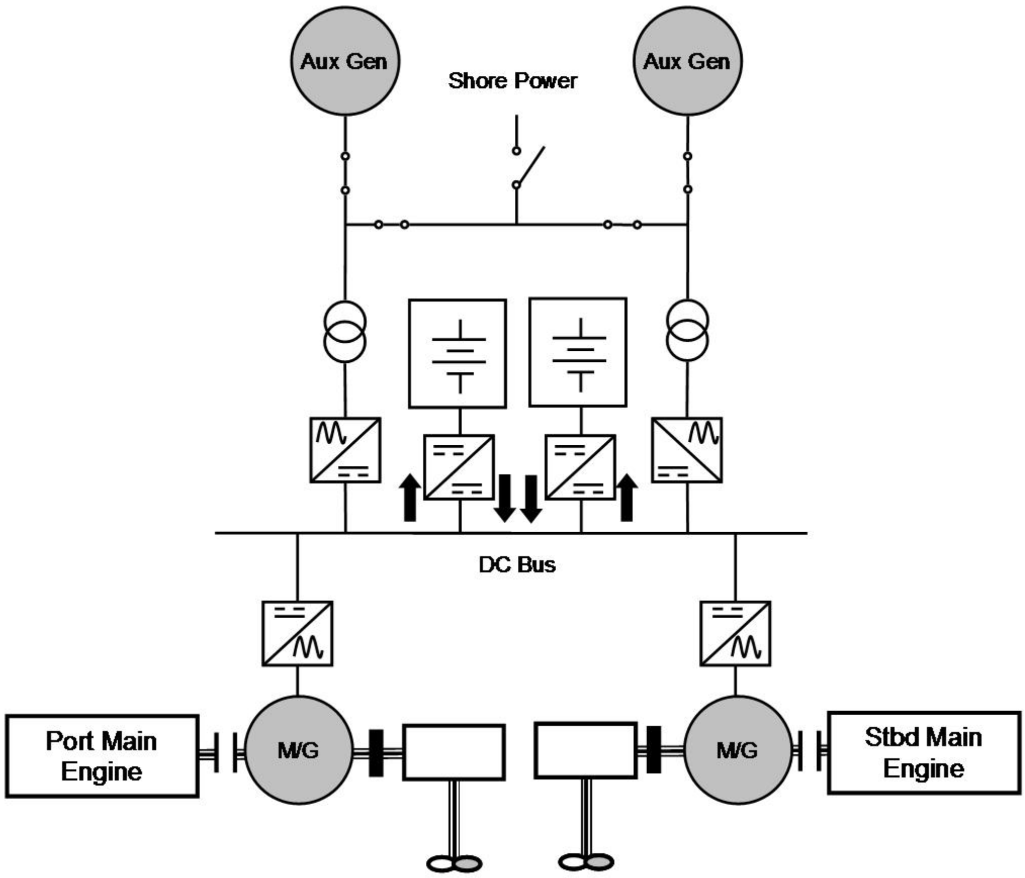

Figure 12: Readiness level 'Assist'.