A Hybrid Power System Laboratory for Testing of Electric and Hybrid Propulsion

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I. INTRODUCTION

International shipping contributes to a major portion of global emissions. This is expected to grow at a faster pace due to economic and population growth. The total shipping emissions during 2007-2012 are 3.1% of global CO_2 emissions, 2.8% of global CO_2 emissions, 13% of global SO_X emissions and 15% of global NO_X emissions, according to the third greenhouse gas (GHG) study'2014 of the International Maritime Organization (IMO). Further details are given in Table 1.

Table 1 TOTAL SHIPPING EMISSIONS (AVERAGE VALUE PER ANNUM DURING 2007-2012)

Parameter	CO_2 emissions	CO_2e emissions	SO_X emissions	NO_X emissions
Quantity (million tons)	1015	1036	11.3	20.9
% of global emissions	3.1	2.8	13	15

The IMO is implementing strategies to reduce the emissions from international shipping through standards, imposing restrictions and providing incentives. The initial strategy envisages a reduction in total GHG emissions from international shipping by at least 50% by 2050 compared to 2008, consistent with the Paris Agreement. IMO's global standard for SO_X emission is 3.5% m/m (mass by mass). IMO has set a new limit of 0.5% m/m by 2020 (MARPOL Annex VI). Similarly, the emission limit for nitrogen oxides (NO_X) from the engines is dependent on the type of the engine and the nominal engine speed. The global limit has been set to 14.4 g/kWh for engines with speed less than 130 rpm and 7.7 g/kWh for engines with speed greater than 2000 rpm as shown in Figure 1(right).

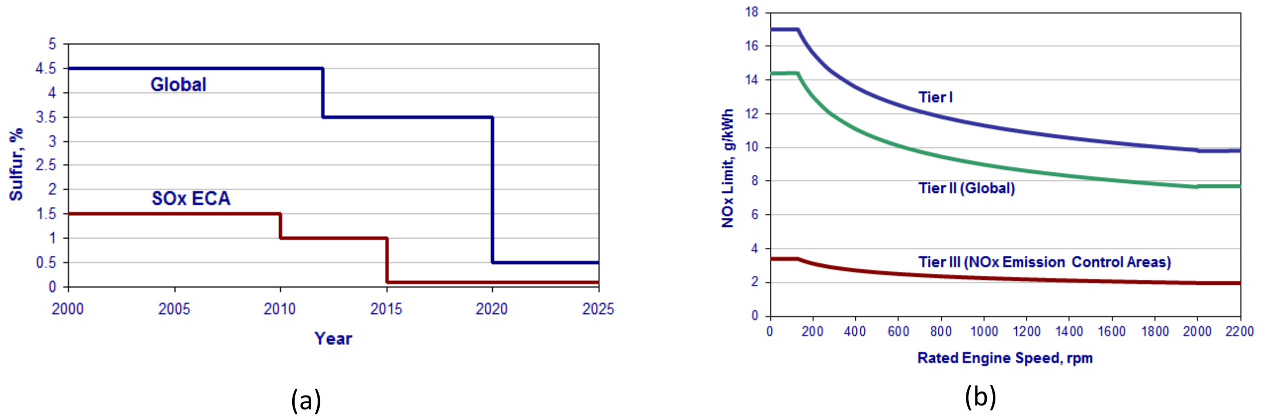


Figure 1 MARPOL Annex VI emission limits for global and Emission Controlled Areas (ECAs) perspective (a) SOX and (b) NOX (Courtesy DieselNet, www.dieselnet.com)

To comply with the standards and emission reduction goals set by IMO, the maritime industry is looking for reduced- and zero-emission technologies and approaches. The transition from traditional fossil fuel engines to zero-emission technologies are challenging in a competitive market, where manufacturers are struggling to increase revenue and reduce production cost. The incentives to reduce emissions and improve the efficiency of equipment are motivating ship manufacturers to adopt zero-emission technologies. Fuel cells and energy storages, such as battery and supercapacitor, reduce the greenhouse gas emissions and are key enablers for the realization of low-emission operation of marine vessels.

Both academic institutions and the maritime industries are working hand in hand to innovate cleaner, efficient and effective solutions. Recently, China has launched the fully electric cargo ship driven by the combination of supercapacitors and lithium batteries of the total energy capacity of 2.4 MWh. Small route ferries are being converted from the fossil fuel-driven engines to the hybrid type or fully electric vessels, for example, car and passenger ferry MF Ampere in Norway, Sweden's HH Ferries Group. Hurtigruten in Norway is building cruise ships driven by the hybrid power plant using a battery system that reduces the fuel consumption and CO_2 emission by 20%. Kongsberg Group, being one of the matured players in the maritime industry is working side by side with the academic institutions to innovate the new ideas. Kongsberg Group has recently been involved along with Yara in the development of zero-emission and autonomous container feeder Yara Birkeland which will be fully autonomous as well as full battery-powered and reduces the emissions by 40000 truck journeys per year.

The research infrastructure and facilities are a critical requirement to test new solutions and technologies that enable reduced- and zero-emission marine transportation. The Hybrid Power Systems (HPS) Laboratory at the Department of Marine Technology of Norwegian University of Science and Technology (NTNU), is an infrastructure for research and testing of marine electric power and propulsion based on DC electric power system. In this lab, the electric power required by the propulsion loads is supplied by a hybrid power system including generator sets as well as fuel cells, batteries, and supercapacitors. The propulsion loads are connected to the main DC power system through converter interfaces. This enables testing of the paradigm shift of ship propulsion from traditional mechanical propulsion to electric propulsion as well as the change of onboard energy scenarios from traditional diesel engines to reduced- and zero-emission energy solutions through hybrid power systems.

II. HYBRID POWER SYSTEM LABORATORY ARCHITECTURE

The layout diagram of the HPS lab at NTNU is shown in Figure 2. It has two variable speed diesel engine-generator sets with different capacities connected to a DC distribution system through rectifiers. The DC grid is also supplied by a fuel cell stack. Furthermore, the DC grid is connected to energy storage devices (ESDs), such as battery bank and supercapacitors bank, through DC-DC converters. Propulsion loads of the vessel are emulated via two electric consumers, each comprised of a variable speed electric motor driving an eddy current brake. These electric consumers can be dynamically loaded through a load controller where it is possible to select different setpoints, both for the speed and torque. The setpoints can be a fixed value or can be some functions like pulse, ramp, sinusoidal, etc.

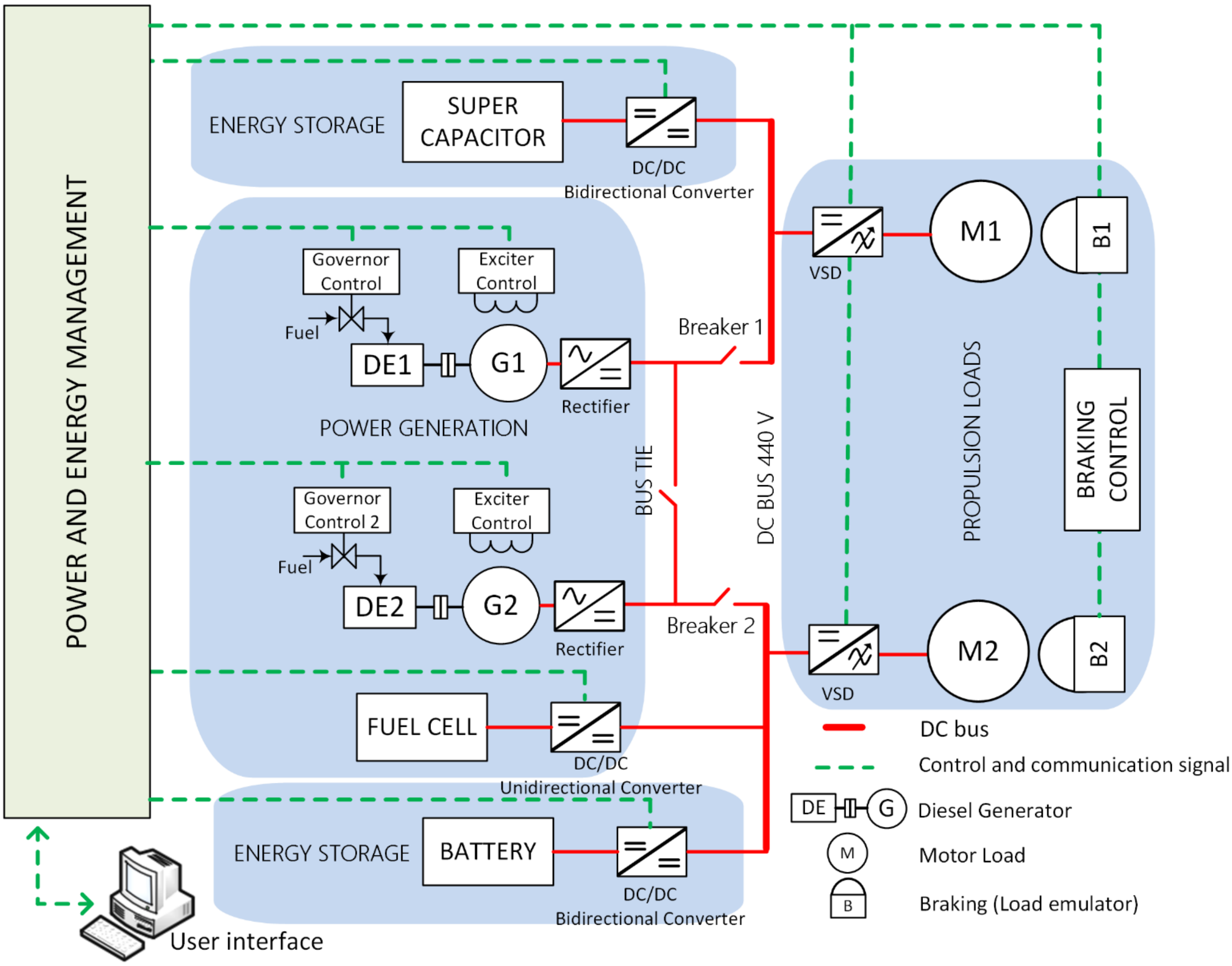


Figure 2 Single Line Diagram of the Hybrid Power Lab based on onboard DC power system.

Traditionally, the AC power grid has been dominating the marine power plants because of the complexity in the development of safety components and systems in the DC power grid. However, with the advances in the power electronics and solid-state safety systems for the DC power grids are being developed and are becoming more popular. The general benefits and the driving factors for adopting DC power grid include improved prime mover's efficiency; reduction in average fuel consumption; low overall transmission losses; faster and simpler parallel connection of generators; simpler implementation of ESDs.

Fuel cells, combustion engines, batteries, and supercapacitors are the most common energy carrier solutions that are in discussion for the hybrid power system. Selection of an energy carrier solution for a marine vessel depends on the mission of the vessel as well as the characteristics of the energy carriers. Energy density and power density are a few of the major characteristics that are necessary to be considered. A simplified Ragone plot in Figure 3 shows the range of the power density versus energy density in a log-log scale for different energy solutions. It shows that the capacitors have the highest power density, but the least energy density. At the same time, fuel cells have the highest energy density, but the least power density. Battery lies somewhere in between them. This signifies that capacitor, in general, can output very high power per mass, but its energy content per mass is very less. Fuel cells can output the least power per mass; however, its energy content per mass is the highest. On the other hand, the battery can deliver higher power per mass than the fuel cell and contains higher energy per mass than the capacitors. Range of energy and power density for energy storage solutions is one of the criteria used for deciding their functionality.

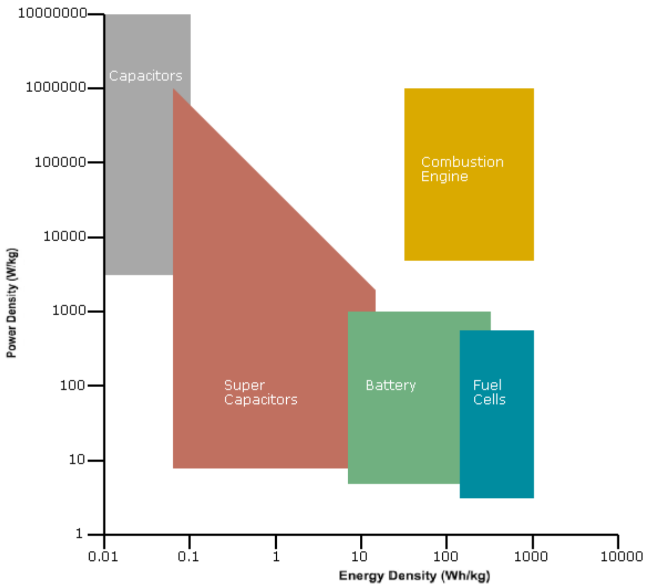


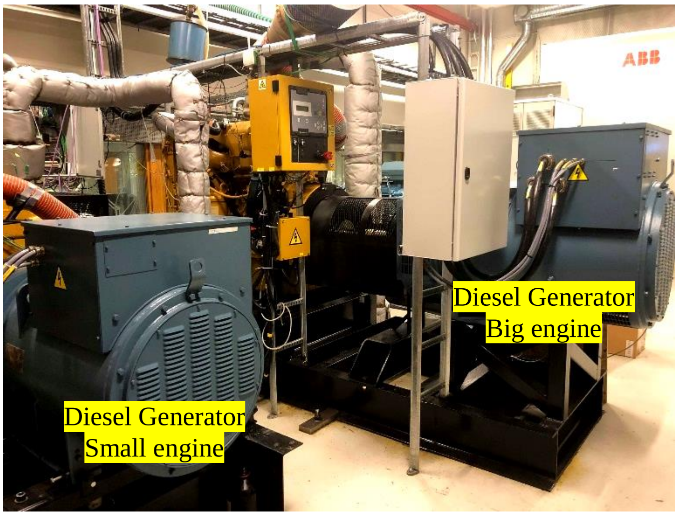
Figure 3 Simplified Ragone plot showing a range of power density versus energy densities for different energy carriers such as sources and storages.

ESDs in a marine vessel enhance the optimal operation of the conventional engines and hence reduce the emission and fuel consumptions. The major roles or functionalities of ESDs in a marine power plant are spinning reserve, peak shaving, enhanced dynamic performance, enhanced ride through, strategic loading and zero-emission.

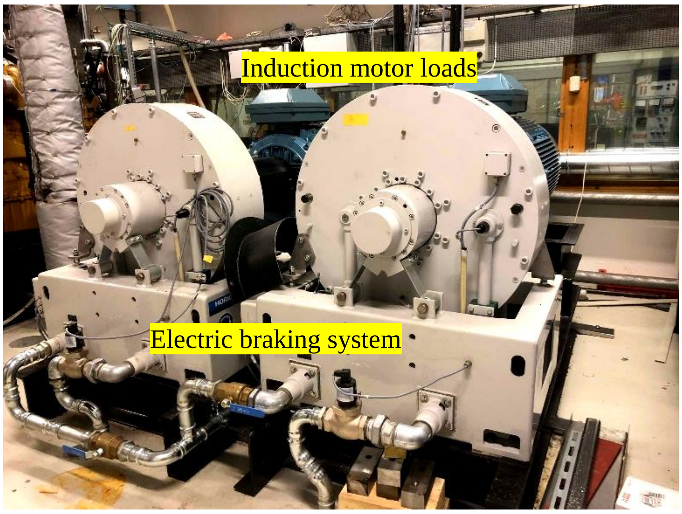
The specifications of some major equipment and energy carriers in the Hybrid Power lab are listed in Table 2. The infrastructures of the HPS laboratory are distributed between a lab machinery room, a dedicated control room, battery bank compartment along with an external compartment for the fuel cell. The power generated by two 30 kW modules of proton exchange membrane (PEM) fuel cell is connected to the hybrid lab, which is considered as a most suitable type of fuel cells for marine transportation due to low operating temperature, high power density and modularity (or scalability). Figure 4 shows some pictures from the HPS lab machinery room. The top left figure shows a variable speed engine along with the generator. Similarly, the top right figure shows the eddy current brakes along with the driving variable speed motors for emulating the marine loads. The hybrid power lab is fully equipped to monitor and operate it from the control room. Several sensors in the equipment are harvesting the real-time data that are available for research and studies in control and monitoring computers.

Table 2 Specifications of components

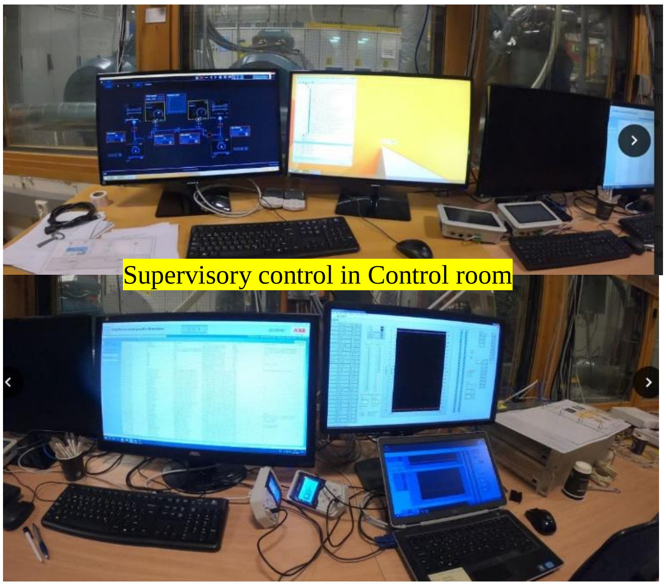
Equipment	Specifications
Big engine (Perkins 2506C-E15TAG1)	400 kVA, 900 – 1800 rpm
Small engine (Perkins 1306C)	230 kVA, 900 – 1800 rpm
Engine controller (governor)	CAT C15
Fuel cell stack	60 kW
Battery bank	Li-Ion, 159 Ah/45 kWh, 346 V
Capacitors bank	1 MWs, (3 kF x 200 pcs)
Electric motor loads – induction motor	160 kW, 1015 Nm at 1500 rpm
DC bus voltage	560 V DC
Electric braking (eddy current)	1000 Nm max braking
Data acquisition system	10 Hz, Labview NI cRIO
NOx emission sensor	Horiba Mexa-720



(a)



(b)



(c)

(d)

Figure 4 (a) Variable Speed Diesel Engine – Generator Sets, (b) Electric loads, (c) control room and (d) battery bank.

III. RESEARCH INFRASTRUCTURE IN THE HYBRID POWER SYSTEM LABORATORY

The main objective of the HPS lab is to enhance the research and research-based education in the field of marine power systems and marine electrification. The lab is used by researchers to verify the theoretical methods and controllers. On the other hand, the lab is used in the graduate courses related to marine electric power and propulsion. HPS lab offers several types of test experiment ranging from new control strategies to control the entire power plant. The load emulator generates load fluctuations similar to the real propulsion load by applying the real case of the ship load-profile. The control algorithms are developed for the hybrid energy system to reduce the fuel and emission through so-called energy and emission management system. By applying a control algorithm via the user interface to the central controller or supervisory controller of the power management system (PMS), experiments can be conducted such as:

1) ***Load sharing*** –to share the total load power between two generators connected in parallel. The load sharing may be implemented based on two control approaches such as isochronous and droop approach. Also, load sharing between generators and battery can be done. This will further be discussed in section III.A.

2) ***Peak shaving/power smoothing*** - Generator sets are connected to the load with the battery and the supercapacitor for peak shaving/ power smoothing. The power smoothing by the battery and supercapacitor is to provide the instantaneous power for the peak power during load fluctuation, which generator unable to serve due to delay from mechanical system dynamic. Thus, the diesel generators (DGs) will generate the constant average power and the rest will be supplied by battery and supercapacitor. Due to the high power density characteristic of the supercapacitor, it can provide instant high power with a short time to the load for high power smoothed, while the battery will provide the rest. It also used to compensate for

high-frequency load fluctuations. However, to provide the power smoothing larger than 1 minute, other devices with higher energy content and longer duration response such as the battery, can be activated.

3) **Strategic loading** – Testing the new control strategy or algorithm to optimize the operating point of the DG with and without the ESD. For example, to avoid being operated in a low load factor, DGs could charge the battery (in addition to serving the load) so as to reach optimal efficiency point based on the specific fuel consumption curve (SFC) of the engine. This study can also demonstrate the charging and discharging role of the onboard batteries while satisfying the operating point of the DG.

4) ***Zero-Emission propulsion* -** Running the load by only using ESD (battery) or fuel cell to demonstrate zero-emission operation where the diesel generators are not dispatched.

A. Load sharing scenario:

In a multi-source system, load sharing among parallel generators/sources based on droop concept mode is has been well established. Based on hierarchical control scheme in power systems, load sharing can be done at a primary level using local controllers. For example, in the AC distribution system, active and reactive power sharing are done by regulating the frequency and voltage, respectively which performed by the local control. Nevertheless, due to no frequency in DC distribution as well as reactive power, voltage is the only variable that can be controlled to realize the load sharing based on droop control. Therefore, frequency does not bring any effect to the power-sharing in the DC system. Voltage control in DC can be realized by using AVR or active rectifier (controlled rectifier). Voltage regulation using AVR is more cost-effective as compared to the active rectifier. However, it could not perform the decoupling control as in the active rectifier. Thus, any transient happens in AC generation side can bring effect to the DC side. In this laboratory facility, the voltage control for the DC bus is performed by the generator excitation or AVR. Figure 5 shows the equal load sharing between two generators. The droop coefficient is the variable to control the DG in order to have equal or unequal load sharing. Furthermore, the droop coefficient could be adjusted to have better fuel efficiency based on DG’s SFC map. Figure 6 shows the example of unequal load sharing between DG’s and the battery. The left side, which is denoted as “–ve” represents the charging region of the battery.

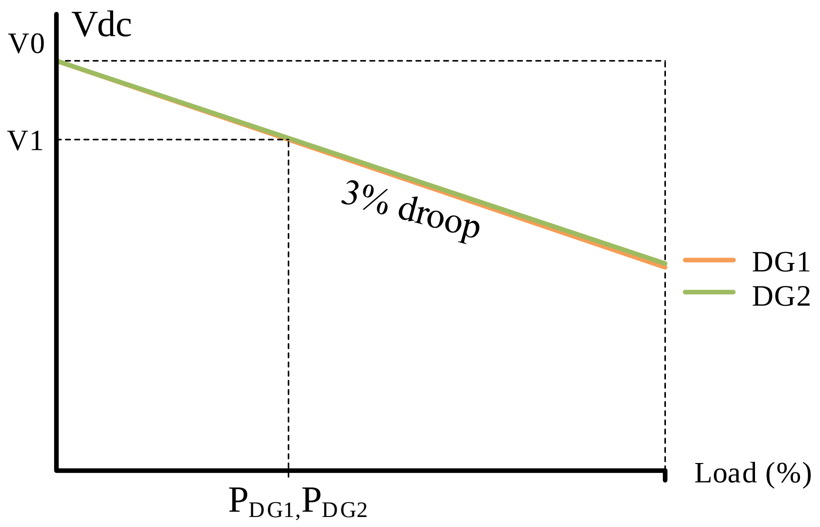


Figure 5 Equal droop power-sharing with two generator

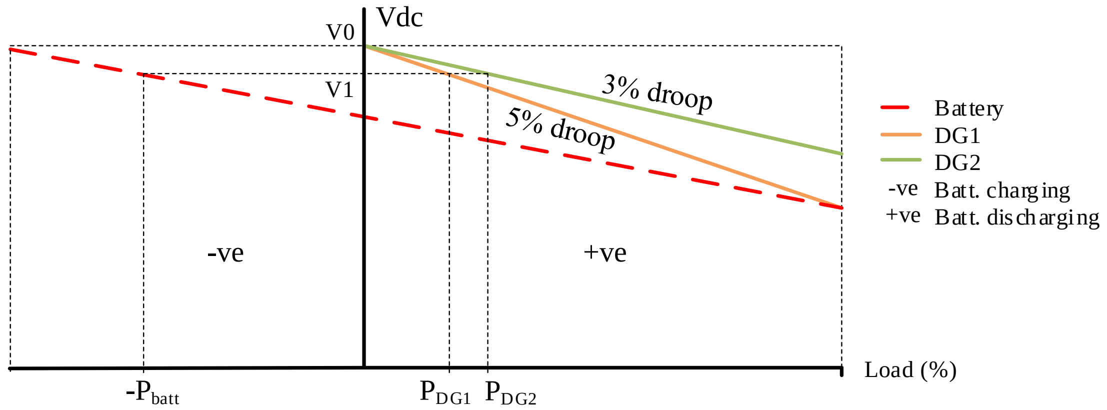


Figure 6 Unequal droop power-sharing with two DG and battery

B. Fuel consumption

Fuel consumption is estimated based on the engine's SFC map, which is provided by the engine manufacturers. Figure 7 shows the curve fitting of Perkins 2506C with a rated capacity of 460 kW which has been taken from the experimental data. Unlike AC system, variable speed of DG in the DC system is proven to have better fuel consumption based on the SFC curve. Due to the absence of frequency in the DC system, the engine speed can be varied. Therefore, the minimum SFC can be achieved by varying the engine speed to the optimal point. Moreover, DGs are built in such a way to have high efficiency when connected to 70 – 90% load factor.

Lower fuel consumption can be achieved by using strategic loading to the DG. As for example during low load condition, the battery can be discharged while DG is OFF. When the load is high, the battery can share the load with the DG to avoid another DG to be dispatched with a low load factor. Furthermore, during low load condition and battery with a low state of charge (SOC), DG can serve the load and charge the battery. To shift the DG's operating point to the lowest SFC, excess power from the generator can charge the battery.

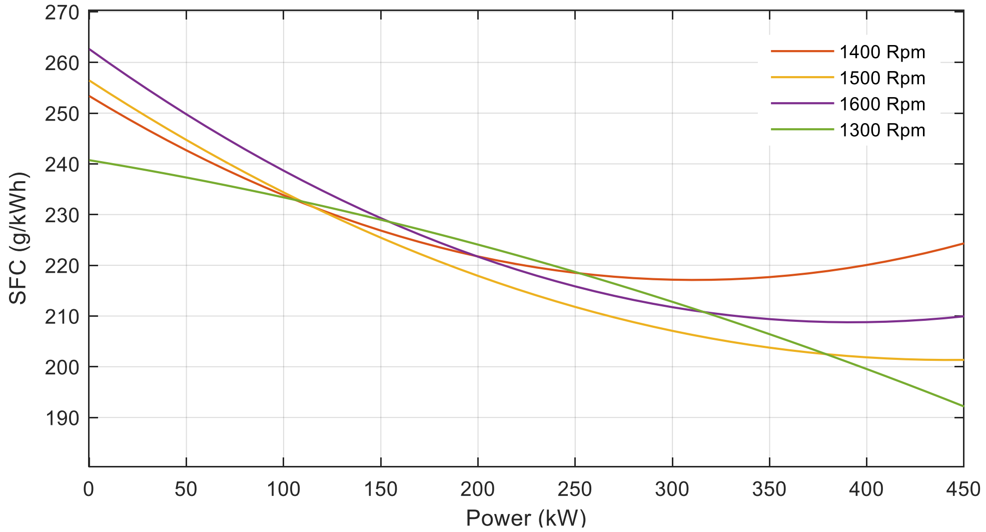


Figure 7 SFC curve fitting of different speed plotted based on real test case of DG - Perkins 2506C

Power and Energy Management in Figure 8 shows the classification of the control strategy of the HPS lab. Due to the similarity of a shipboard power system and a stand-alone microgrid, similar hierarchical control scheme can be implemented. The lowest control level called primary control will perform a local control such as voltage deviation, load power-sharing (e.g., droop, isochronous mode). The secondary control (power management system) perform the voltage restoration introduced by primary control and perform control action for ensuring the security of the system in meeting the load demand. The highest control level called tertiary control concerning more responsibilities to provide the power reference based on optimal strategy or power scheduling such as ruled-based, Equivalent Consumption Minimization Strategy (ECMS), optimization algorithm, etc. At this level, the control strategy can be done by including specific optimization objectives (e.g., minimize the fuel cost, emission) and considering several technical constraints (e.g., battery SOC limit, generator ramp-rate limit, start-up shut-down limit and so on). All individual control level is connected to the secondary and tertiary control by the communication signal, which carries all the measurement from the sensors.

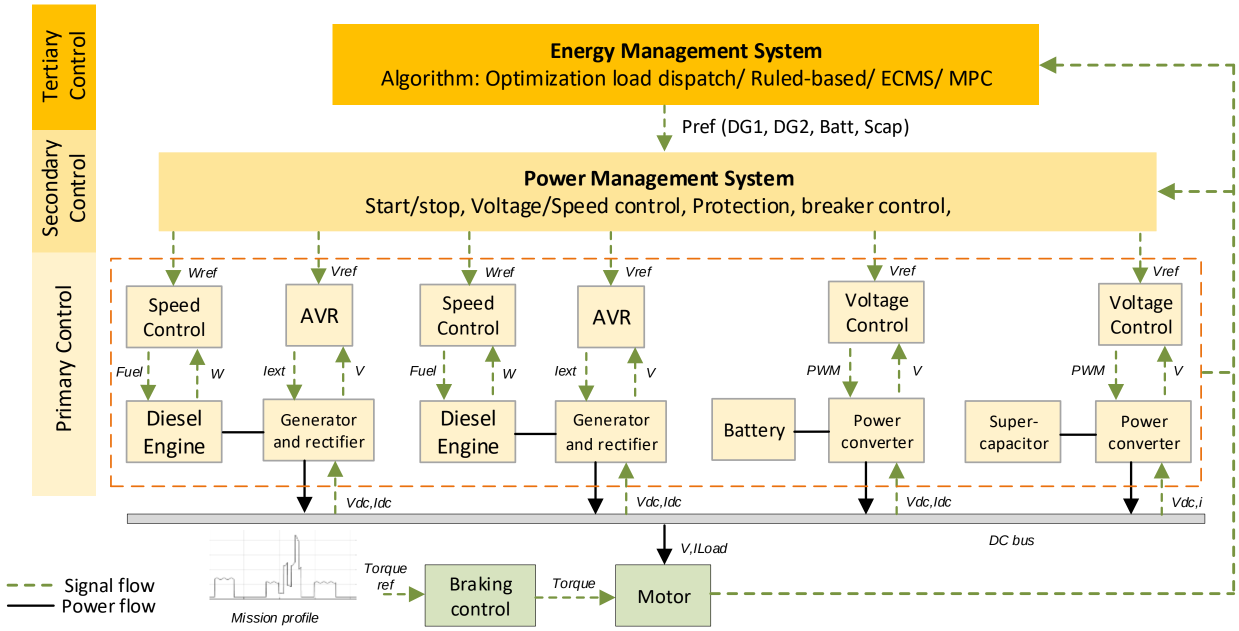
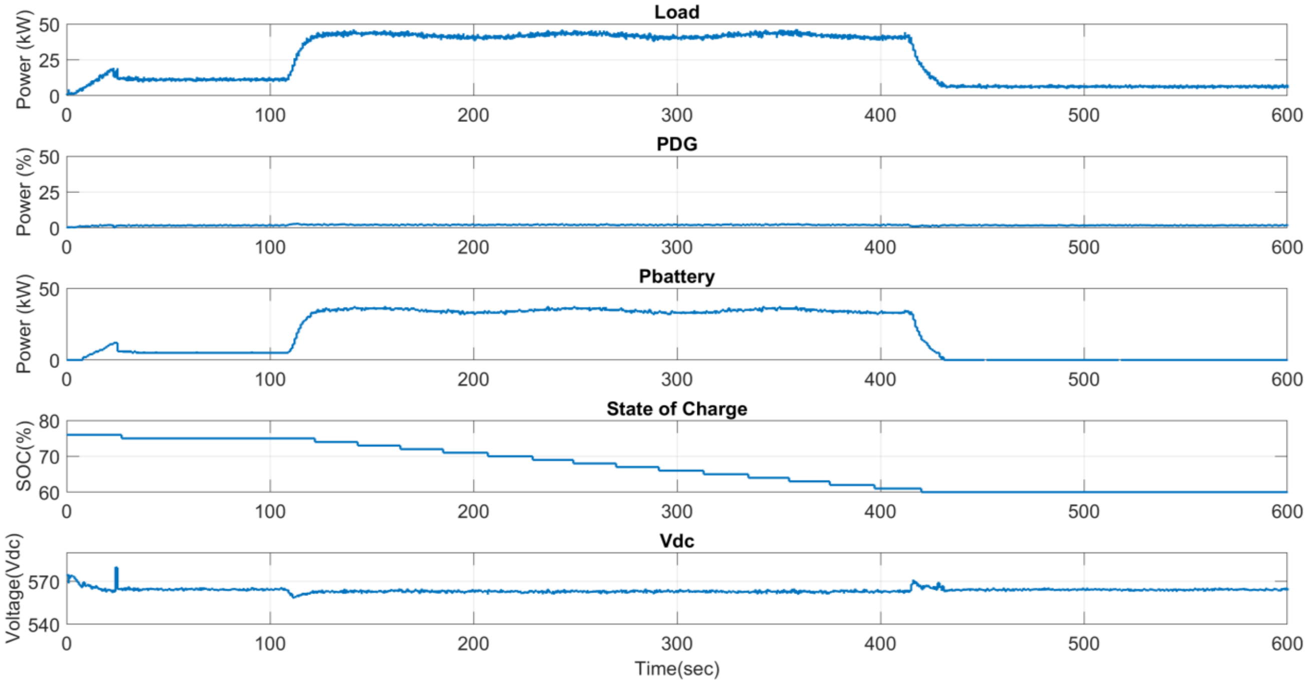


Figure 8 Simplified layout of a control system in a hybrid shipboard power system laboratory.

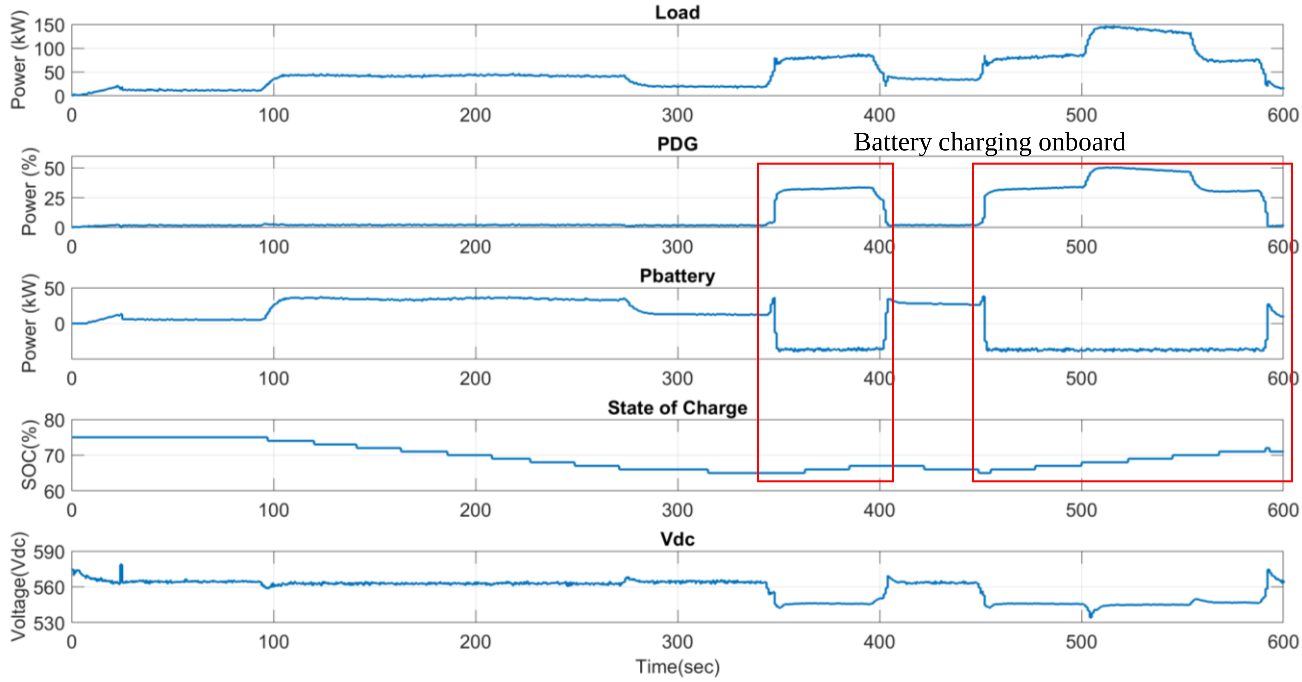
IV. EXPERIMENTAL VERIFICATION

Figure 9 shows the sample of experimental result which conducted in HPS lab for the testing of the ship power management with a predefined rule-based strategy in the supervisory controller. In this experiment, the real load-profile based on a tugboat operation is emulated by the eddy current brake loads and is used as a case study to test the power and energy management system. Figure 9(a) shows the battery used to serve the load while maintaining the DC bus voltage. Based on figure 9(b), there is a change of power dispatch between DG and battery to serve the load. At lower load demand, the battery will be used to serve the load. The onboard battery charging by DG is also demonstrated. At this point, the battery will be charged so that the load on the generator can be increased to prevent the generator from operating under low load conditions. DG can be adjusted to the optimal operating point by adjusting the charging power of the battery. Figure 9(c) shows the power-sharing between DG and battery to serve the load. In this case, droop mode power-sharing is demonstrated where DC voltage drops within 6% and the voltage of DC bus are maintained at 550 to 570 VDC.



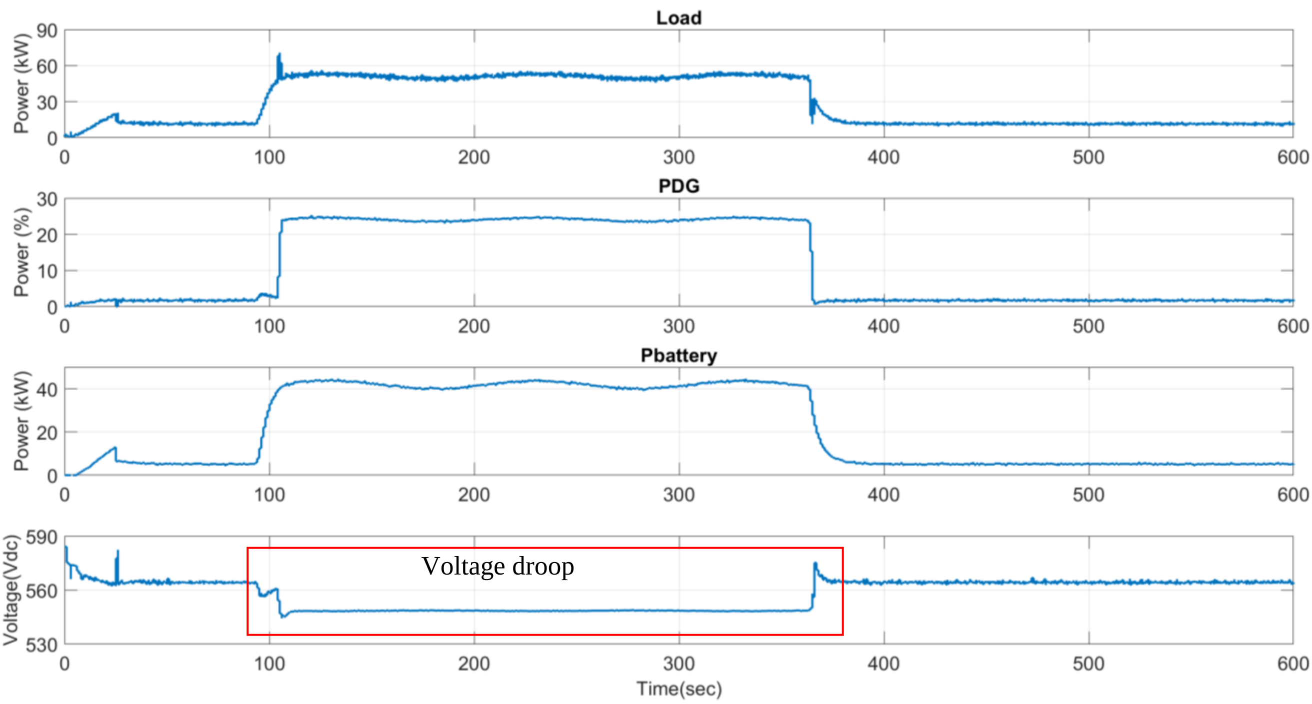
Load
Power (kW)
PDG
Power (%)
Pbattery
Power (kW)
State of Charge
SOC(%)
Vdc
Voltage(Vdc)
Time(sec)

(a)



Load
Power (kW)
Battery charging onboard
PDG
Power (%)
Pbattery
Power (kW)
State of Charge
SOC(%)
Vdc
Voltage(Vdc)
Time(sec)

(b)



(c)

Figure 9 Experimental verification of the energy management system with real ship load-profile: (a) Zero-emission mode with the battery during berthing (b) Hybrid propulsion mode with the diesel generator and battery (demonstrate battery charging/discharging) (c) Voltage droop power-sharing DG and battery.

V. CONCLUSIONS

The onboard hybrid power systems with low-emission energy carriers are a promising solution for green shipping, replacing conventional diesel engine-based energy systems. However, there are several existing challenges related to these new low-emission energy solutions that need to be investigated. A full-scale infrastructure for testing and verification of such systems is one of the important stepping stones while developing a reliable system. In this paper, hybrid power systems for ships and the related controllers have been discussed with a focus on the Hybrid Power System Laboratory at NTNU as an infrastructure for the testing and verification of shipboard DC power systems. A hierarchical control architecture for the power and energy management of the hybrid power system has been discussed. The experimental verification of the energy management system for both the zero-emission and hybrid propulsion mode along with voltage droop power-sharing using the real ship load-profile has been presented.

The Hybrid Power System laboratory can effectively contribute to the research and developments of zero-emission shipping solutions through the development of energy and emission management systems for hybrid power systems and technology development of shipboard microgrids. Moreover, the lab infrastructure could accommodate the development of new control strategies and performing hardware-in-the-loop (HIL) testing under the operating conditions of the actual ship operation. Various real field tests can also be conducted on the laboratory setup based on the real case mission profile, including the battery systems, supercapacitors, and fuel cells.

VI. FURTHER READING

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