HIPPO-2: The new Hybrid Integrated Propulsion Powertrain testbed at the Laboratory of Marine Engineering, NTUA

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Abstract

In 2013 the first hybrid diesel electric powertrain testbed HIPPO-1 was installed at LME/NTUA. It provided valuable insight into hybrid powerplant operation and control. The design of HIPPO-2, now being erected at LME, was based on the experience gathered from this first installation. The HIPPO-2 comprises of state-of-art components. A Caterpillar 9.3, 261 kW diesel engine has Tier 4 emission capability, incorporating EGR and a Particulate filter, a Selective Catalytic Reduction unit, an Oxidation Catalyst as well as an Ammonia trap, all controlled from a central unit using a multitude of sensing elements and actuators. The testbed dynamometer is an ABB 315 kW AC induction motor. The electric motor/generator is an ABB 90 kW AC induction motor. All three machines are based on a common bedplate, the whole drivetrain rotating in unison. The monitoring and control (overseeing control) of the HIPPO-2 testbed is based on the dSPACE Microautobox II platform. The LME HIPPO-2 testbed shall provide a unique state-of-art full-scale experimental facility in a very important area of marine propulsion.

Keywords: hybrid electric powertrains, ship propulsion diesel engines, aftertreatment systems, electrical drives.

1. Introduction

A hybrid vehicle uses several types of power sources. Although the term “hybrid” is quite fashionable nowadays, the combination of powerplants and energy sources has a long history in ship propulsion. In that respect the first ships with sails and steam engines were hybrid!

Developments in batteries in the early 1900’s allowed submarines to use air-breathing engines for propulsion and power generation during surface operation and battery

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powered electric motors for propulsion underwater. By 1914 the diesel-electric propulsion became standard for submarines.

Conventional diesel propulsion with direct or geared drive exhibits lower efficiency outside its nominal operating region (although some mitigation is achieved using the capabilities of the modern electronically controlled diesel engine). Hybrid Diesel-electric propulsion may be a promising technology for both emission reduction and fuel efficiency enhancement. Hybrid propulsion systems can be beneficial in several ship applications requiring a varying speed profile such as supply vessels, ferries, floating production vessels, drill ships, shuttle tankers, ice breakers, naval ships, cruise liners. Some recent interest of hybrid propulsion for the so called ECO ships has been from the implications of installing smaller engines and the resulting issues of acceleration as well as heavy sea propulsion.

It is stated [1] that upcoming hybrid propulsion systems will offer a wide range of opportunities for increases of propulsion efficiency. For some years, ships have been equipped with direct-driven diesel machinery occasionally combined with a shaft generator system, known as Power Take Out (PTO), generating power for some of the electrical demands of ship. Current designs consider the usage of electric auxiliary power to assist the main engine in some load situations, such as high bollard pull, sailing in icy conditions, harbor maneuvering or ”take-home” power, thus reversing the role to Power Take In (PTI) operation through powertrain hybridization. As a result, the size of main engine could be optimized to the propulsion power needed under normal conditions, while additional power boost can be taken from auxiliary generators as required [2].

Depending on their architecture, Hybrid Electric Powertrains (HEP) fall mainly into two categories: a) parallel or b) series. In the parallel scheme, both the (thermal) engine and the (electric) motor are connected to the transmission, and thus, they can power the vehicle either separately or in combination. In series hybrids, the electric motor is the only means of providing the demanded torque [3]. The major development which allows the wider use of hybrid propulsion solutions, has been the advancement in the electronics of drives for the electric motors.

2. HIPPO-1 Experimental Facility at LME/NTUA

One important issue in the operation of multi-prime mover system is the optimization of the load sharing between units and the load acceptance/shedding during transients.

The performance of a hybrid powertrain in terms of reducing both fuel consumption and exhaust emissions critically depends on the Energy Management System (EMS). An EMS is the supervising control algorithm that determines how the total power demand is shared between the power sources [4].

The LME/NTUA has a long legacy in detailed mathematical modelling of marine engines and ship propulsion systems. However, even very detailed models have shortcomings in predicting the behavior of complex interacting systems. The building of an experimental facility in full scale, allows measurements of the performance of components and systems under real conditions. This not only provides data for model improvement and validation, but allows for the development and testing of control algorithms, with rapid application and verification on the experimental powertrain system. With that in mind, LME started with the design of a hybrid powertrain experimental facility in 2010.

The Hybrid Integrated Propulsion POwertrain (HIPPO-1) testbed at LME [5] was built in the period 2010-2013 and consists of a marine diesel engine in parallel connection to an electric machine (see Fig. 1).

The prime mover in HIPPO-1 is a, Caterpillar 3176B, 6-cylinder, 10.3-liter marine diesel engine, with a rated power output of 425 kW at 2300 rpm. The electric machine is a VEM 315-s4 AC asynchronous-induction 3-phase motor, with a rated power of 112 kW. In this setup, the thermal and electric engine provide mechanical power simultaneously, with identical rotational speeds. A frequency inverter unit enables the torque output regulation of the electric motor under closed loop control. A water brake AVL-Zoellner with a load capacity of 1200 kW and maximum speed of 4000 rpm, applies the desired torque demand, which is regulated by a separate controller developed at LME. The water brake can be configured so as to simulate a ship's propeller/waterjet variable speed and torque demand, or a generator's load demand with constant speed.

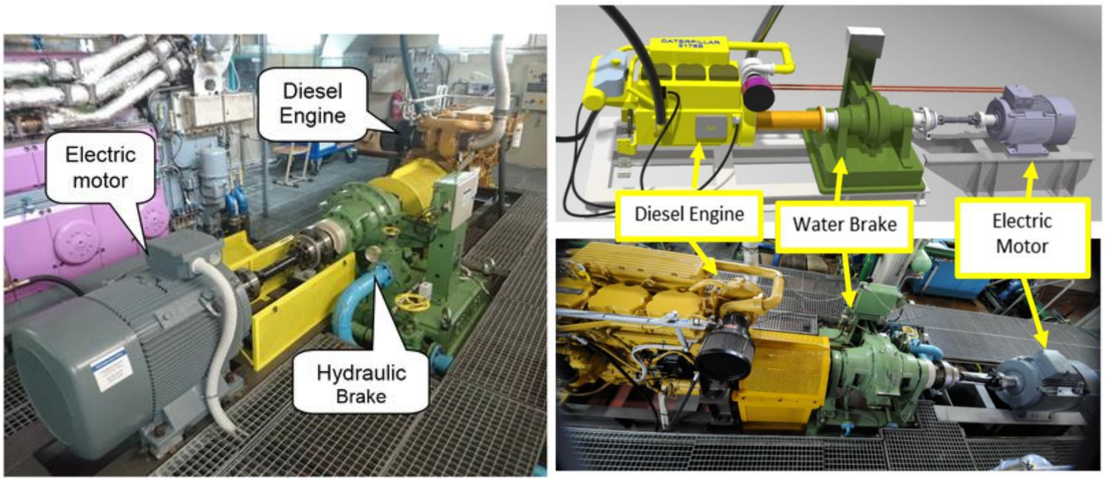

Fig. 1. The hybrid diesel-electric testbed HIPPO-1 at LME.

Apart from the overall monitoring and control, various additional sensors were installed in the testbed: for NO$_x$/oxygen (NGK, UniNO$_x$ 24V), for exhaust gas opacity (Green Instruments, G1000), for fuel mass flow (ABB Coriolis), for turbocharger speed (micro-epsilon), for intake manifold pressure, for the torque and speed of electric motor (HBM). The whole testbed is controlled and monitored by a dSPACE DS1103 controller board, programmed in the MATLAB/Simulink environment.

The concept of hybridization of a marine propulsion plant is presented schematically in Fig. 2. At low-load operation, where the internal combustion engine produces low torque, the electric motor assists the diesel engine, so as to meet the torque demand faster. With this setup the initially small margin (i.e. torque that the propulsion system has available for acceleration during transient operation) can be significantly increased.

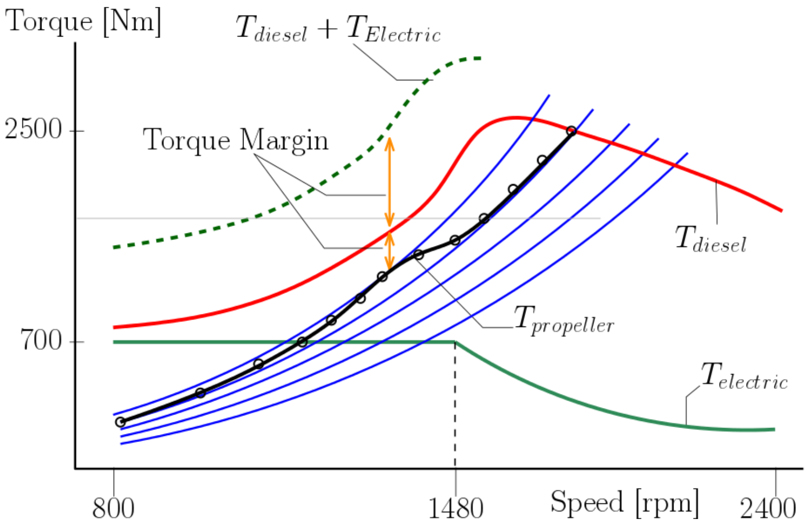

Fig. 2. Effect of hybridization of a marine propulsion plant during transient operation.

3. Results from research work on hybrid propulsion with HIPPO-1

A large spectrum of experiments were conducted on HIPPO-1 testbed. Some examples are presented here from experiments to evaluate the performance of the power split strategy. The control method in the HIPPO-1 testbed incorporates feedback control of λ (air to fuel-ratio). This engine parameter was proven suitable in the particular setup, as it is a close indicator of PM emissions and it directly relates to combustion temperature, which determines NO_x. Although the closed loop control of λ in internal combustion engines (ICE) has been a mature research field for more than fifteen years, in this work λ-manipulation is achieved only with the additional degree of freedom stemming from the hybridization of the powertrain [6]. The robust controller was synthesized based on the experimental modelling of the combined system of diesel engine and electric motor. These experiments can be divided in two main sections, as follows. The first set of experiments was conducted with a set lambda reference value and the engine operating at constant speed, with alternating load. This loading profile resembles a generator. In the second set of experiments the engine was operated with varying speed and demand torque, simulating a propeller loading profile.

CONSTANT SPEED

An experiment with load steps from 300 to 500 Nm at 1600 rpm is shown in Fig. 3. The static λ reference is set at $\lambda_{ref} = 3.1$ which was selected after repetitive experiments of the same loading cycle. It can be noted that the proposed controller provides good tracking performance during changes in the load. In the last subplot, the impact of the hybrid powertrain on the produced NO_x, as compared to the conventional setup, can be seen.

The λ set point represents the only parameter needed for tuning the strategy for a specific loading profile. The HIPPO-1 controller uses the deviation between the λ-set point and actual λ as input and engages the EM, producing torque. The total torque demand is still met, but the electric motor assists the ICE while it is accelerating, so as to reduce smoke and NO_x.

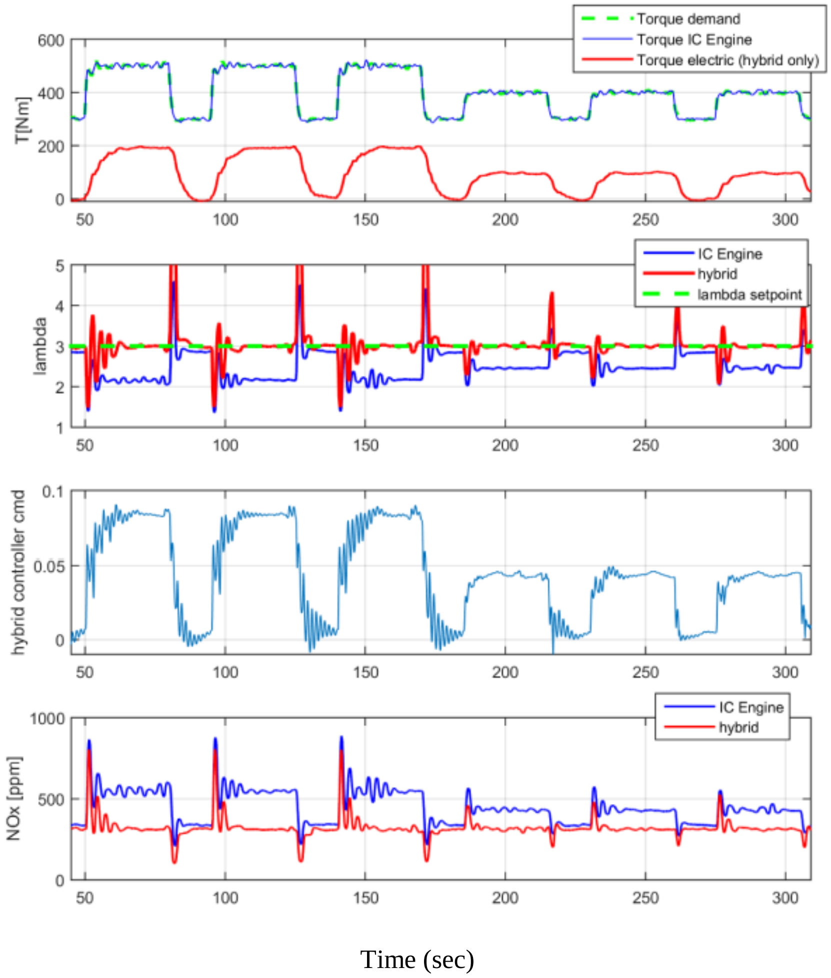

Fig. 3. Effect of the hybrid powetrain on λ and NO_x during constant speed operation.

PROPELLER LOADING

A set of ship-board measurements were conducted, in order to assess the proposed power split methodology against realistic loading profiles data from ships. Appropriate mobile equipment (emissions analyzers, shaft strain gauges and piezoelectric sensors) was installed on-board a high-speed ferry, as to gather actual engine performance and emissions data during normal service. This data was utilized as reference for the design and evaluation of candidate loading profiles, as seen in Fig. 4.

A varying λ set point based on these profiles was used as a reference to the power split controller. The main idea of dynamic λ reference points, is to shift the IC engine at more efficient operating points during transient loading, where, by engaging the Electric Motor the measured λ drops rapidly.

The designed controller leads to reduction of fuel consumption, NO_x emissions and exhaust gas opacity, with respect to the conventional (non-hybrid) powertrain, during acceleration.

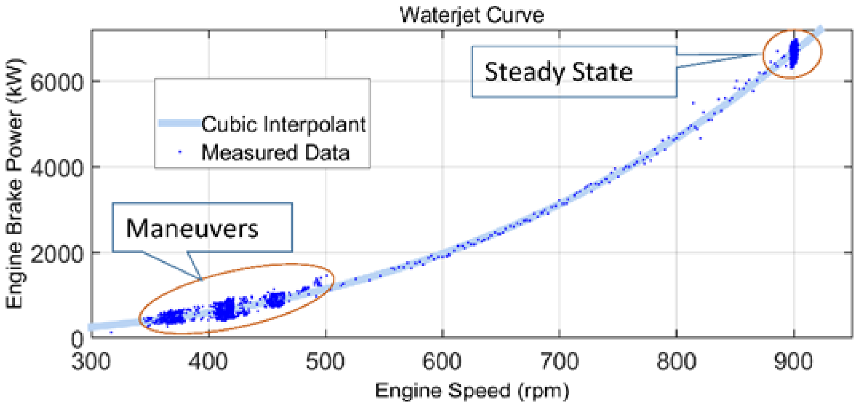

Fig. 4. Data from on-board measurements of a high-speed vessel.

The propeller power curves, measured λ values and the corresponding controller output are presented in Fig. 5. The propeller loading starts from 350 Nm to 800 Nm and the engine speed changes from 1100 rpm to 1850 rpm. The recorded λ values are higher using the hybrid setup (leaner combustion) than using the conventional one (i.e. without EM assistance), due to the HIPPO controller tracking the reference λ values in lookup tables.

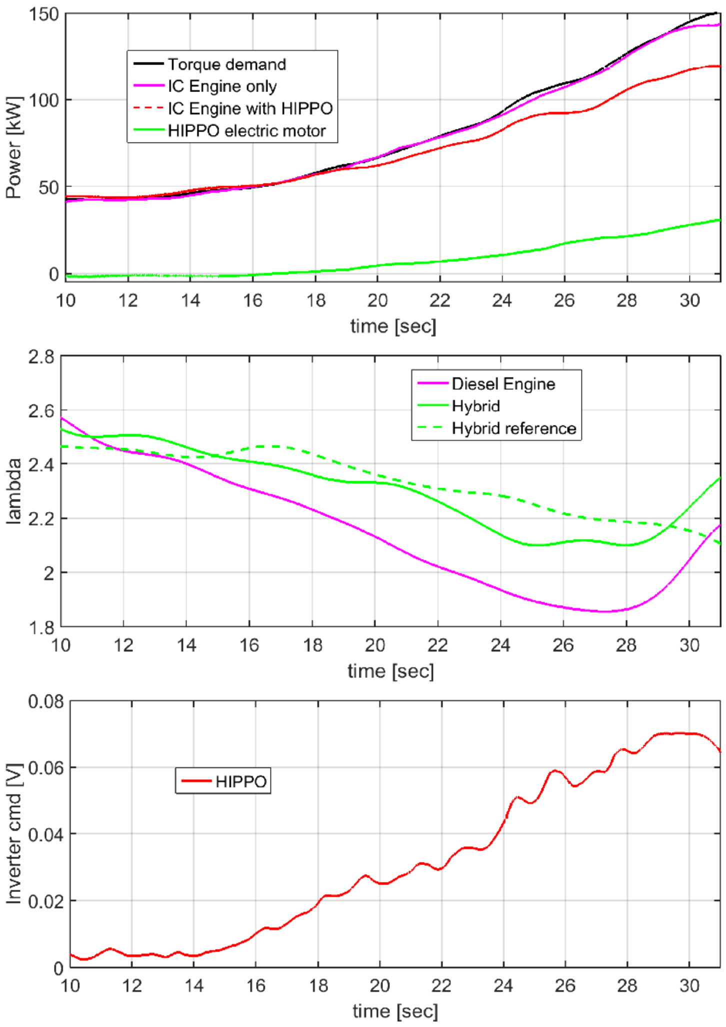

Fig. 5. Propeller loading power curves on the HIPPO-1 powertrain, λ values and controller output.

4. Design of a New Hybrid Testbed: HIPPO-2

The operation of HIPPO-1 testbed provided valuable insight on hybrid power plants and produced a wealth of experimental data.

At the same time some of the shortcomings of the facility emerged:

a. The existing ZOELNER hydraulic dynamometer 1.2 MW was too large for the total 0.5 MW maximum combined input of the HIPPO-1 CAT 3176B thermal engine (425 kW) and the electric motor (112 kW). As a result the dynamometer (water-brake) was operating at the lower end of its envelope. This resulted in unstable operation and “hunting” in some loading scenarios. Further, the transient loading capacity was limited due to the large size.
b. The CAT 3176B engine proved very reliable and easy to operate. However the ability for intervention in the engine control was very limited, thus the spectrum of possible experimental operation scenarios was narrow.

Based on the large experience gained in the development of the monitoring, control and data acquisition systems of HIPPO-1, a next generation testbed was designed, named HIPPO-2. The aim was increased flexibility in operation and more accurate control and measurement capability. The HIPPO-2 testbed was built-up from scratch following the tradition at LME to design and develop the major test facilities in-house, to secure the related knowledge, but also to reduce the initial cost. This new testbed uses the same layout i.e. the thermal engine, the dynamometer and the electric motor/generator are coupled rotating at the same speed.

HIPPO-2 comprises of state-of-art components and upgrades significantly the experimental capacity: The thermal engine is a Tier 4 technology Caterpillar CAT 9.3. The dynamometer is an ABB induction motor with an electronic drive unit, for very precise loading. The motor/generator is an ABB induction motor also equipped with an electronic drive unit.

All the 3 units (engine, dynamometer, motor) are placed on a common very stiff bedplate and are connected to one another with cardan-shafts (See Figs 6 and 7).

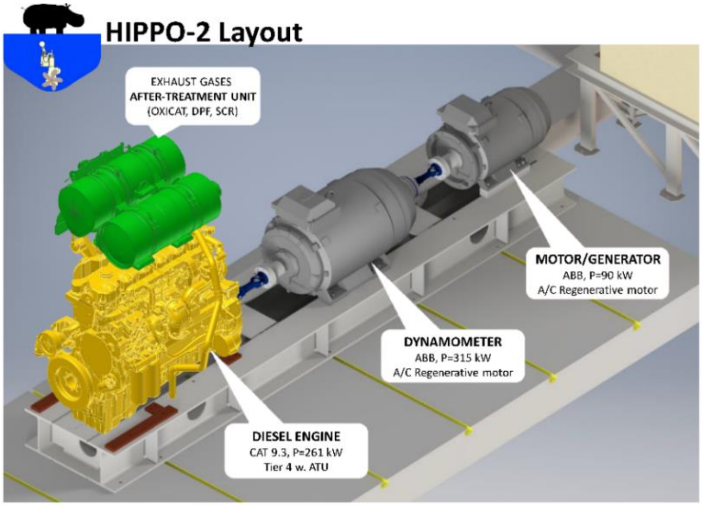

Fig. 6. 3-D representation of the units of the hybrid testbed placed on the bedplate.

Fig. 7. All units as placed on the common bedplate.

The Caterpillar 9.3 diesel engine provides 261 kW at 2200 rpm. It meets U.S. EPA Tier 4 Final and EU Stage IV emission standards. It uses a High-Pressure Common Rail Fuel System with full electronic injection. The engine also uses an internal exhaust gas recirculation (EGR) system which captures and cools a small quantity of exhaust gas, then routes it back into combustion chamber where it drives down combustion temperatures and reduces NO_x emissions. Installed are aftertreatment units of Particulate Filter, Selective Catalytic Reduction, Oxidation Catalyst as well as an Ammonia trap. A central electronic unit using a multitude of sensing elements and actuators controls the engine and the aftertreatment systems.The selected engine was configured in close collaboration with ELTRAK-Caterpillar who will be also involved in the engine startup and control integration to the Laboratory infrastructure.

The Diesel Oxidation Catalyst (DOC) uses a chemical oxidation process to reduce hydrocarbons and carbon monoxide in the exhaust stream.

The Diesel Particulate Filter (DPF) traps particulate matter that's carried in the exhaust stream, preventing it from being released into atmosphere. Inside the DPF, particulate matter, sometimes referred to as "soot", is trapped until it is oxidized during regeneration.

The Selective Catalytic Reduction (SCR) system consists of a SCR catalyst, AMOX and the Pump Electronics Tank Unit (PETU). This system uses a small amount of Diesel Exhaust Fluid (DEF) to convert NO_x emissions in the exhaust into nitrogen and water. The Pump Electronic Tank Unit (PETU) is responsible for storing, controlling and supplying the appropriate quantity of Diesel Exhaust Fluid from the DEF tank to the DEF injector. DEF is a solution of urea dissolved in deionized water to produce a concentration that is about 1/3 urea and 2/3 water.

The DEF (diesel exhaust fluid), is injected into the exhaust air stream containing NO_x, where it evaporates into ammonia (NH_3) due to a physical reaction triggered by the energy contained in hot exhaust gas. Once the exhaust gas and ammonia mixture contacts the SCR catalyst surface, a reduction reaction occurs, breaking down the NO_x (NO and NO_2) and NH_3 into nitrogen gas (N_2) and water vapor (H_20).

In order to ensure sufficient NO_x reduction, a small amount of excess Diesel Exhaust Fluid (DEF) is injected into the exhaust stream. This excess DEF may pass through the

Selective Catalytic Reduction (SCR) catalyst as ammonia. To prevent excess ammonia from entering the atmosphere, the exhaust gas flows through an Ammonia Oxidation Catalyst (AMOX) where the ammonia reacts with oxygen in the presence of this catalyst to form nitrogen and water.

The sizing and the selection of the testbed dynamometer, the electric motor generator and the respective drives was carried out in close collaboration with ABB SA, Greece. ABB is also responsible for the commissioning tests of the electrical units during the startup phase.

The dynamometer is an ABB 315 kW AC induction motor. It is controlled by an ABB ACS800 series four-quadrant drive of 390 kW capacity, based on the Direct Torque Control (DTC) method. DTC allows the motor's torque and stator flux to be used as primary control variables, both of which are obtained directly from the motor itself. Therefore, with DTC, there is no need for a separate voltage and frequency controlled Pulse Width Modulation (PWM) drive. Traditional PWM drives use output voltage and output frequency as the primary control variables, but these need to be pulse width modulated before being applied to the motor. This modulator stage adds to the signal processing time and therefore limits the level of torque and speed response possible from the PWM drive. Typically, DTC is 10 times faster than PWM modulator to respond to actual change, therefore the response of the dynamometer to load demand transients is much improved.

The regenerative drive also offers significant energy savings compared with other braking methods such as mechanical and resistor braking, as energy is fed back to the supply network. No external brake resistor is needed, which translates into simplified installation and no wasted heat.

The electric motor/generator is also an ABB 90 kW AC induction motor controlled by an ABB ACS800 series drive of 100 kW capacity respectively.

The drives and related electronic are housed in 2 large cabinets mounted separately in the test room, as seen in Fig. 8.

Fig. 8. The cabinets that host the electrical drives for the dynamometer and motor/generator.

The monitoring and control room is overviewing the installation, as shown in Fig. 9. The monitoring and high-level control of thermal engine and electric motors of the HIPPO-2 testbed will be implemented based on the dSPACE MicroAutobox II platform, in real time operation with MATLAB/Simulink, using industrial Ethernet and CAN-bus networks.

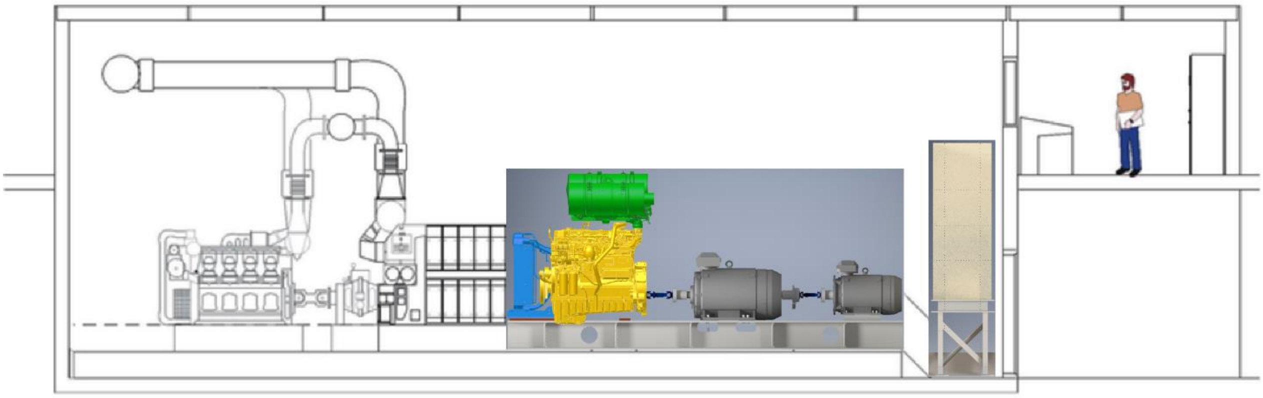

Fig. 9. Location of the new hybrid testbed in the existing infrastructure at LME.

The facility is in the buildup stage and is expected to be ready for individual startup tests in mid 2017. After all the sensors and data-acquisition system are installed, the full operation is expected to take place in end 2017. Due to the size of the facility, extreme experiments of load application and load shedding must be done with caution and well into 2018.

5. Acknowledgments

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