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Modelling and simulation of a zero-emission hybrid power plant for a domestic ferry

Lorenzo Balestra [*], *Ingrid Schjølberg*

Department of Marine Technology, Norwegian University of Science and Technology, NO-7491, Trondheim, Norway

HIGHLIGHTS

- Modelling of marine hybrid power-plant with PEM fuel cells and batteries.
- Energy management strategy for hybrid power-plant.
- Validation of the model using real world data for the double ended ferry.
- Analysis on the simulation result and optimization of the power-plant.

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ABSTRACT

This paper presents a simulation tool for marine hybrid power-plants equipped with polymer exchange membrane fuel cells and batteries. The virtual model, through the combination of operational data and dynamically modelled subsystems, can simulate power-plants of different sizes and configurations, in order to analyze the response of different energy management strategies. The model aims to replicate the realistic behavior of the components included in the vessel's grid, to asses if the hardware selected by the user is capable of delivering the power set-point requested by the energy management system. The model can then be used to optimize key factors such as hydrogen consumption. The case study presented in the paper demonstrates how the model can be used for the evaluation of a retrofitting operation, replacing a diesel electric power-plant with fuel cells and batteries. The vessel taken into consideration is a domestic ferry, operating car and passenger transport in Denmark. The vessel is outfitted with a diesel electric plant and an alternative hybrid power-plant is proposed. The hybrid configuration is tested using the model in a discrete time-domain.

Introduction

In recent years, the number of vessels transitioning from a conventional fossil fuel propulsion system to a hybrid or fully-electric system is increasing. The recent developments in battery technology and the cell's increase in energy density has encouraged the transition to hybrid power-plants, with batteries now included in a number of hybrid transport systems for energy storage purposes [1–4]. Such systems can reduce fuel consumption [5,6], reduce emissions from 10 to 35% up to 100%, and improve noise, vibration, maintainability, manoeuvrability and comfort [7]. The possibility to store

* *Corresponding author*. Otto Nielsens veg 10, Marine Technology Centre, Trondheim.
E-mail addresses: lorenzo.balestra@ntnu.no (L. Balestra), ingrid.schjolberg@ntnu.no (I. Schjølberg).

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excess power and release it on-demand, allows a more efficient use of a ships prime mover, enabling load leveling and peak shaving strategies [8].

While hybrid systems are able to reduce the level of emissions and fuel consumed, the next step for the maritime industry is the development of zero-emission vessels. Studies on zero-emission power generation systems for marine applications have been largely motivated by environmental goals aiming at to reduce pollution and greenhouse gas emissions. The United Nations and the International Maritime Organizations have both ratified documents planning a reduction in harmful emissions by 2050 [9,10], with local governments pledging to complement these commitments with national or regional environmentally friendly policies.

Currently, the majority of operational zero-emission vessels are equipped with battery systems. In Scandinavia, double-ended ferries such as the Aurora Af Helsingborg, the FinFerries' Elektra and MF Ampere are currently in operation facilitating the transportation of passengers and cars between coastal towns using large battery packs.

The fully electric configuration provides considerable environmental benefits, with a reduction of CO_2 emissions, for a vessel the size of the Aurora Af Helsingborg, estimated to be around 14 thousand tons per year. The vessel's power grid is also simplified when exclusively using batteries for energy storage, allowing for fewer maintanence operations. Nevertheless the full-electric configuration also presents drawbacks [11], mainly from an energy density and price perspective, that makes the transition to zero-emission challenging when considering to fully replace conventional fuel plants with battery packs for medium to long range applications. The limited amount of power stored in the pack relative to the weight and concerns regarding degradation of the battery cells, leads to a need for frequent dock recharging. To ensure low degradation of the battery pack and the highest capacity retention over the highest number of cycles, the ferry needs to discharge at a low C-Rate, if possible, and maintain a recommended value of state of charge (SOC) between 45% and 75%, depending on the specifications of the battery producer [12]. Battery systems also use a considerable amount of time to recharge, especially when considering megawatt scale applications. A ferry fast-charging during Roll on - Roll off (Ro-Ro) operations requires a dedicated infrastructure, with high voltage capabilities and values in the range of 10.000 V and 600 Amp when considering a 4 MW battery pack onboard [13]. The installation of this kind of infrastructure may be limited by financial considerations or by an inadequate and/or unstable electrical grid in remote location that still require zero-emission operations, such as remote locations in the fjord of Norway following 2026 regulation [14].

Given the limitations of batteries, not all routes that require zero-emission vessels can be operated by fully electric units. A hybrid power-plant using polymer exchange membrane fuel cell (PEMFC) technology, in conjunction with battery energy storage, can be considered as a zero-emission solution when greater range or flexibility is required [15]. The use of hydrogen, as an energy carrier, allows zero-emission operations in protected natural habitats, world heritage sites, CO_2 neutral ports and emission control areas, while maintaining an operational flexibility similar to a diesel vessel. The capability to charge batteries at sea during navigation eliminates the need for frequent dock recharging, furthermore the higher energy density of hydrogen compared to batteries, even it its pure compressed form, enables the storage of more energy on-board the vessel with considerable weight savings (Table 1).

Fuel cell technology is, in the maritime industry, at a lower technology readiness level (TRL) compared to battery technology, however the positive results with PEMFC in heavy duty transport applications, such as busses and trains, can be transferred to the maritime sector. PEMFC modules specifically designed and certified for marine use [16], have been presented in 2020, following the interest of ship operators such as Norled, in building a hydrogen vessel for passenger and car transport [17]. PEMFC have been tested aboard vessels, for example, on the FCS Alsterwasser in the EU project "zero emission ship" [18], and on a larger scale on the Viking Lady supply vessel.

The integration of fuel cells and batteries in hybrid powerplants is a non trivial task, as the operational profile and power requirements needs to be collected or data-mined, and because the operation is usually affected by the energy management system (EMS) [19]. The sizing of the powerplant decides the potential of powertrain system and affects the efficiency of the EMS. In other words, the selection of component size affects the design of the energy management strategy and vice versa.

The evaluation of the component's size and power rating should therefore be performed in a combined package with the creation of the EMS. The hybrid power-plant has to ensure a high levels of efficiency, satisfying the power demand of the vessel during operations taking into account the fuel cell and battery dynamics.

It is to aid the design process and observe the dynamic behavior of components such as battery and PEMFC in relation to the selected EMS strategy that, in this paper, is presented a model of a hybrid zero-emission power-plant. The model is developed to replicate the power-plant operation in a simulated environment, with a good degree of approximation, allowing the study of the components dynamic response to real world data inputs.

Several research approaches have been studied, considering that some limit their analysis to a predefined system and only focus on EMS [18], while others tend to ignore the EMS and focus on the optimal sizing problem [20].

This paper proposes a model that can be used to observe the effects of sizing on the EMS and vice versa, in a single software platform. This is necessary as the EMS may choose, with a smart algorithm, the optimal operational point for the power-plant and load sharing strategy, but if the hardware selected cannot realize the given strategy, different components or a different control should be chosen. The model can be adapted to different kinds of ships, and is scalable to

Table 1 – Energy density comparison.

Energy density	Pure H_2 (@700 Bar)	Li-Ion Battery
MJ/kg	120	1008
MJ/L	4.7	0.90 to 2.43

simulate power-plants up to 10 MW. The model includes converters and other power electronic components such as DC-Bus and switchboards.

To initialize the simulation the user can select or create an EMS strategy and input a series of parameters regarding the fuel cell and battery system considered. The results obtained at the end of the simulation include hydrogen consumption, which heavily impacts the vessel operating costs, as well as fuel cell degradation and battery usage. Results from different power-plants layouts and EMS strategies can be compared to choose the optimal solution for the vessel power delivery.

The model is tested using a hydrogen-hybrid configuration for a domestic double ended ferry operating in Danish national waters, currently equipped with a multi-megawatt diesel electric power-plant (see Fig. 1). The operational profile used for the initial configuration of the model was chosen to emulate a typical winter day in 2019 on the route of interest. This operational profile was one of many collected during a six month period in cooperation with the company. The case study demonstrates how the model can be used for the technical evaluation of a retrofitting operation, replacing the diesel electric power-plant with PEMFC and batteries. The power delivery values are observed and compared to the power demand in input. The power-plant sizing is validated only if the mean square error between the expected value and the produced value is below a certain threshold defined by the user, and, in general, there should be no sign of power shortages or blackouts. The technical evaluation allows further studies on the economical feasibility of the system. The data produced by the model provides figures that can be used to compare the ideal behavior of the hybrid system, the realistic behavior of the system under stress and highlight the differences with the diesel electric plant.

The study does not go into detail with respect to the changes in ship design when integrating a hydrogen system or hydrogen storage solutions such as metal amines [21,22], liquid hydrogen organic carries (LOHC) [23] or hydrides [24] that may be required to operate such power-plant. The imposed boundary condition is to assume that if a certain amount of pure hydrogen is required by the fuel cell stack, the demand can always be fulfilled by the storage.

Fig. 1 – The double ended ferry considered in the study case.

On-board power-plant

In this section is described the original diesel-electric configuration of the ferry and the new hybrid solution proposed by the authors.

Conventional system

The ferry taken into consideration during the case-study is a double ended ferry of approximately 100 m length, with capacity for 600 passengers ans 122 cars. The route is a crossing over a 7.7 nautical miles distance with voyage time averaging 45 min and voyage interval of 1 h (Fig. 2).

The prime movers of the ferry are 5 diesel generators rated at 800 kW, powering 4 Azimuth thrusters and additional auxiliaries. The diesel generators also provide all the power for service and hotel load. No energy storage technology is installed. The system is designed to comply with class regulations and is designed with passive redundancy in mind, considering that only three generators are switched on during the crossing, out of the five installed. This is to allow maintanence activities and ensure there is always a power reserve. The single line diagram of the diesel electric configuration is represented in Fig. 3.

With the double-ended design there is no requirement to turn around in ports, directly translating to less power pulses during docking procedures compared to the single-ended counterpart. The vessel crosses a busy shipping route and often has to give way to larger commercial vessels [26]; this influences the power demand during the crossings, as the ferry deviates from the optimal route to avoid traffic. The change in meteorological condition is also a factor influencing the power demand. The variation of wind and sea current strength happens yearly, with the summer being the easiest period to operate, but also daily, with variation between the first crossing 5.15 a.m. and the last at 22.15 p.m.

The ferry operates 18 crossings in a day (see Fig. 4). The values show that once the vessel is disconnected from the

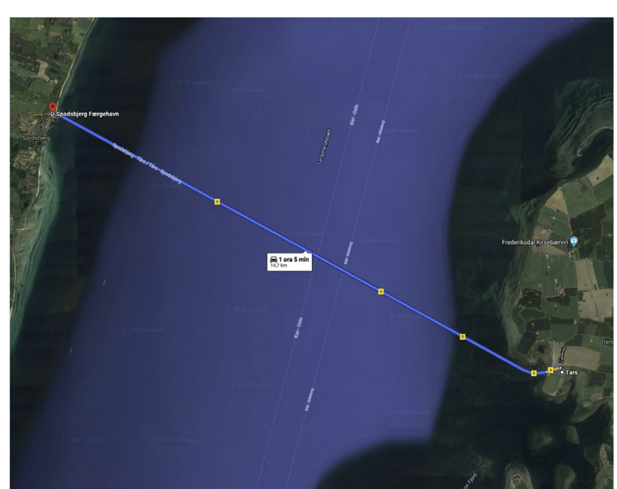

Fig. 2 – Ferry route [25].

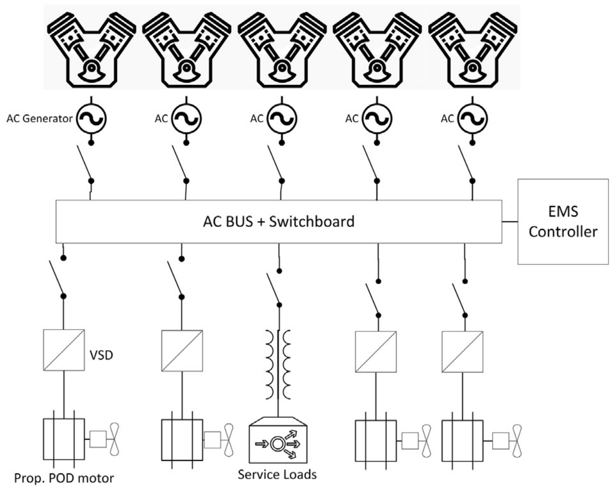

Fig. 3 – Simplified single line diagram for the diesel electric configuration.

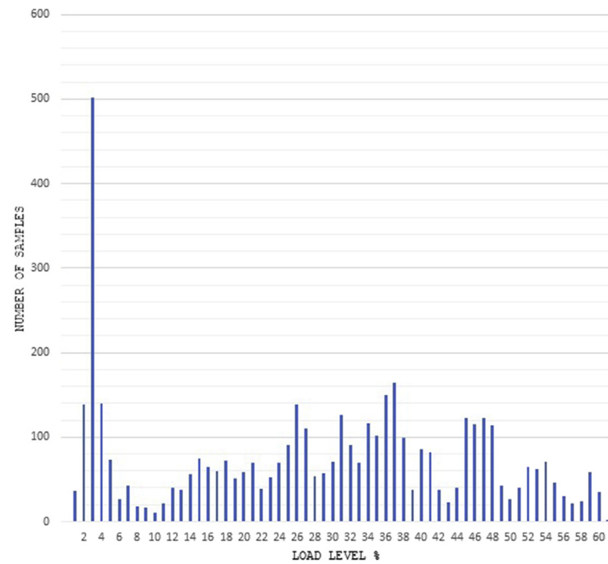

Fig. 5 – Load level distribution over one day of operations.

shore power supply, Ro-Ro operations are carried out using between 1% and 7% of the total power installed. The data collected during the crossings show that the power used for the crossing from Spodsbjerg is around 38% of the total power, while the one from Tårs is slightly higher around 48% (Fig. 5).

The observation of the power levels in Fig. 5 shows how an hybrid power-plant comprised of PEM fuel cells and batteries can eliminate pollution and greenhouse gas emissions, and also increase the overall efficiency through peak shaving or load leveling strategies.

During Ro-Ro operation for example, the load on the diesel generators is quite low (between 1% and 7% total power), forcing the units to operate at a point far from the optimal thermal efficiency [27]. This leads to a high specific fuel consumption, but cannot be prevented as the generators needs to be kept on to be ready for maneuvering.

During this phase, a hybrid propulsion plant equipped with PEM fuel cells and batteries could supply the power using some PEMFC stacks at a low load level, where the stack efficiency is higher (60%) than at rated load. This would also eliminate harmful emissions in the coastal area and the harbor [28].

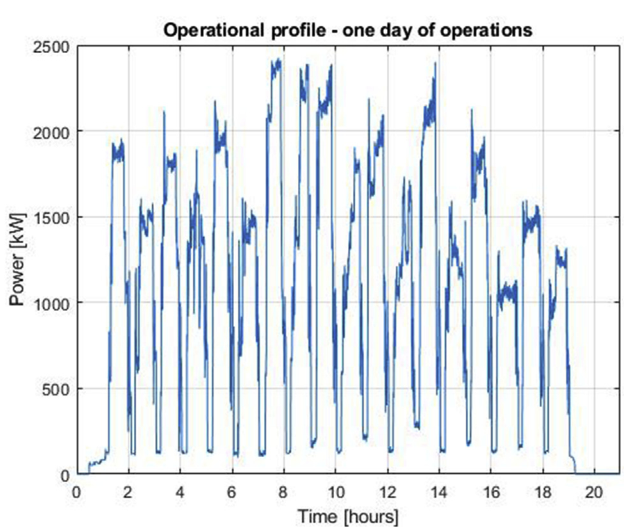

Fig. 4 – Measured power demand of the ferry over a full day of operations.

Hybrid propulsion system

The alternative, zero-emission power-plant presented for the ferry includes polymer exchange membrane fuel cells (PEMFC) and a Lithium-Ion (Li-Ion) battery packs for energy storage. Polymer exchange membrane technology has been selected for the fuel cells, in this case, after considerations on the operational requirements and good performance at relatively low temperatures [29,30]. The Lithium Ion battery pack has been selected for the high energy density and fast charging and discharging capabilities at multiple C-Ratings. The presented hybrid solution size and rating does not take into consideration vessel safety regulation for active or passive redundancy and is simply based on supplying the required power-demand. Compliance with class regulation can be achieved by increasing the number of PEMFC or batteries, but the study of the requirements was considered out of the scope of the paper. The additional PEMFCs and batteries required by the safety regulations do not impact the results obtained in this paper as they are considered switched off and disconnected from the system, only activated in case of emergency.

In Fig. 6, it is possible to observe a simplified single line diagram for the hybrid system proposed. The diagram represents the fuel cell unit unit as a single block, for the sake of clarity, with the notion that the fuel cell system is comprised of multiple stacks to reach the required rated load. The definition of the power rating for the battery and

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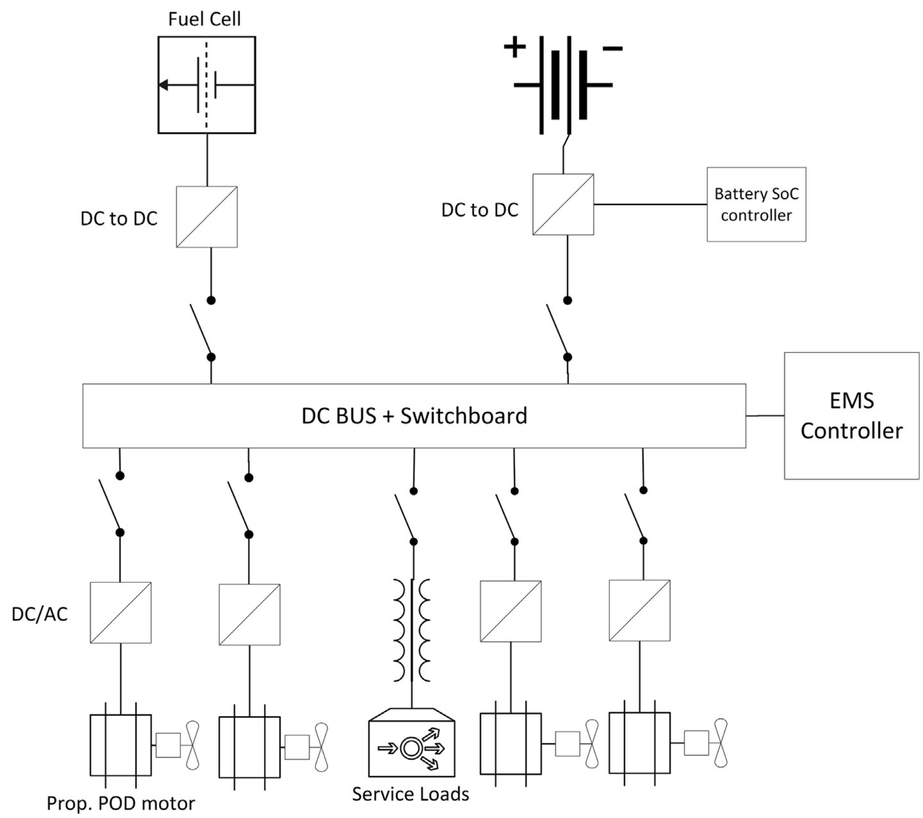

Fig. 6 – Simplified single line diagram for the hybrid configuration.

fuel cell stacks is non trivial, as the sizing defines the potential of the powertrain, influencing the energy management system, and vice versa [31,32]. In this case, both the fuel cell and the battery are intended as modular systems, meaning that a series of units can be combined in series or parallel to achieve different layout solutions and power ratings.

The first step in the sizing process is the identification of a first attempt configuration through the observation of the operational data. This configuration is, after the simulations with the digital model, either modified or validated if the results are satisfactory for the user.

The first factor that helps to define the total power rating of the battery and PEMFC system is the observation of the average power requirements during the crossing phase (Fig. 5). The power delivery capabilities of the proposed hybrid power-plant should be able to satisfy the average power demand during crossings while operating at their rated load, and be able to compensate for extra power demand if necessary.

The maximum power recorded during a crossing with the diesel electric configuration is equal to 2425 kW out of the 4 MW installed. The maximum recorded power is lower than the total installed power (4 MW) as only three out of the five diesel gen-sets are on during the crossing and the other two are considered as a power reserve. This reference value of 2425 kW provides a starting point for the dimensioning procedure of the hybrid power-plant active during the crossing. The combined output of battery and PEMFC cannot be lower than this value. To generate additional guidelines for this calculation, a power-plant design software developed by the authors has been used [33]. The hybrid configuration with batteries and PEMFC allows more flexibility when choosing power ratings compared to the selection of diesel generators. It is possible to consider that battery packs can compensate peaks in power demand with a fast response time and operating at C-Rates higher than 1, effectively allowing the increase of power delivered on demand at the expenses of a faster reduction in state of charge. Batteries also can be operated continuously and do not have to be switched off, unlike diesel generator, to perform extensive maintanence.

For the first attempt solution, the PEMFC's rating has been selected in relation to the battery size and characteristics, with the goal to provide enough power to avoid high depth of discharge cycles. The ratings are set, for the first attempt solution, to 15 PEMFC for a total of 1500 kWh and 2 batteries of 1000 kWh of batteries. The sum of the two values results a powerplant able to produce 3500 kWh at full load. Setting the rating higher limits the depth of discharge and therefore degradation. According to DC-Grid guidelines, a level of 690 V is suggested for the ship's grid in vessels with installed power up to 10 MW.

As both fuel cells and battery have a direct current (DC) output, the grid uses DC for the transfer of power, with inverters for the motors and service loads.

Model description

The model is the virtual representation of the systems illustrated in Fig. 6. The components such as fuel cell, battery and converters represented in the diagram, have been modelled to have a dynamic behavior similar to the real-world counterpart, allowing the study of their response to realistic input data. Propulsion loads and service loads are considered combined in this study, as the values sampled during operation represent the total power consumption of the vessel.

The working principle is illustrated in Fig. 7 The process starts by selecting a time interval from the database where the data are logged. The interval considered can be of variable length and can include multiple crossings, depending on the computational resources and time that the user wants to allocate for calculations. It is recommended to use a time interval between two docking operations or between two night layovers for better results. The time interval selected identifies, on the database, a list of power values in kilowatt representing the total power generated by the diesel-electric plant in the ferry's current configuration (Reference Fig. 4 for a time interval of 22 h). These power values, known as operational profile, are used as the vessel's power demand that needs to be satisfied by the new hybrid plant. The EMS contains the load sharing strategy and splits, according to the coded instructions, the total load between battery and fuel cells. Two converters control the power output of fuel cell and battery to the DC Bus, much like in the real system. The voltage is maintained constant on the DC Bus and at the recommended level using two feedback loops. A Recharging circuit is also included for the battery, giving the possibility of on-the-go recharging.

The power generated by the plant ("Produced power" in Fig. 7) is, in the end, compared with the operational profile given as input, to observe the efficiency of the EMS, and the selected components, in following the load profile. The capacity to generate the required amount of power using the hybrid plant can be seen as a validation of the components power rating and load sharing strategy.

Using as input the load profile of the diesel electric configuration for the hybrid power-plant allows for a direct comparison between the two solution. It is possible to calculate the equivalent amount of hydrogen required to carry out the same crossing and also estimate the degradation of both battery and PEMFC.

Table 2 – Fuel cell characteristics.

Rated power (net)	100 kW
Gross output at rated power	320 V/350 A
Peak power EOL...OCV BOL	250...500 V
System efficiency (Peak, BOL)	62%
System efficiency (BOL)	50%
Max waste heat	120 kW
Coolant outlet temperature	80C
Fuel inlet pressure	8–12 bar(g)
System pressure	1.6 bar(g)
Ambient temperature	−20 to +50C
Ambient relative humidity	5–95%, non-condensing
Installation environment Outdoor	Pollution degree 3
Weight	120–150 kg
Volume	300 l
Fuel quality	ISO 14687-2, SAE J2719
IP classification	IP54

Fuel cell

The fuel cell considered for this model is a polymer exchange membrane fuel cell with commercial characteristics. The reference values used in the model are reported in Table 2. The fuel cell model is a generic model parameterized to represent polymer exchange membrane fuel cells supplied with pure hydrogen and air (Fig. 8). The model is based on the work of Njoya et al. [34].

A boundary conditions of the model is set on the delivery of hydrogen and air to the fuel cell. In the model the supply of both hydrogen and air is carried out by ideal components

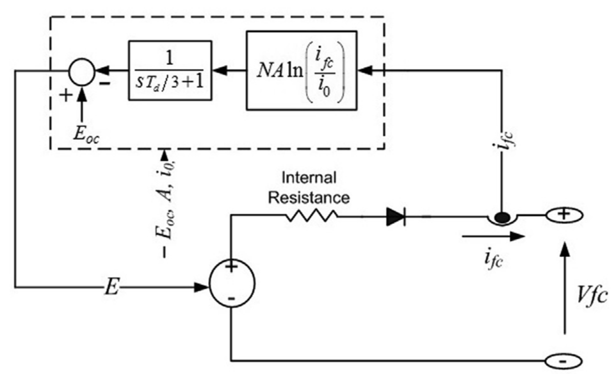

Fig. 8 – Equivalent circuit of the fuel cell included in the model [34].

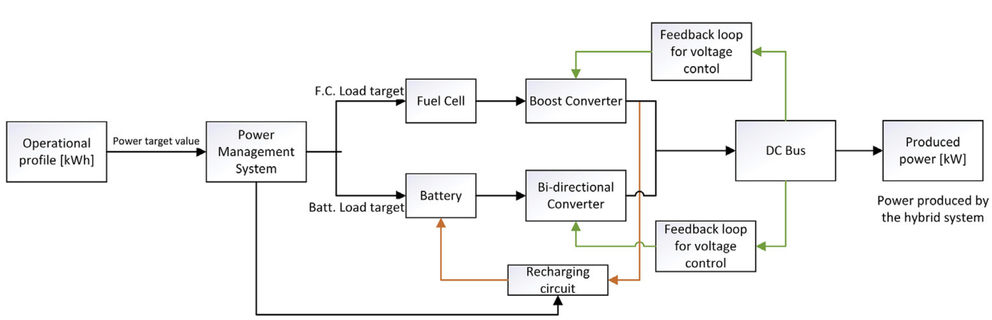

Fig. 7 – Model schematics.

(compressor and valves), eliminating problem of fuel and air starvation during dynamic loading. The assumption is made as the EMS is supposed to avoid high frequency transients on the fuel cells, limiting possible cases where air and hydrogen starvation may appear. In the model, the airflow value ($V_{lpm(air)nom}$) and the hydrogen flow value ($V_{lpm(fuel)nom}$) are calculated indirectly, based on the load power requirement (Fig. 9). This approach allows the user to quantify the hydrogen consumption at each timestep and calculate the total consumption at the end of the simulation in standard liters per minute. The degradation of the PEM fuel cell is a key aspect considered. A separate block is created to evaluate the degradation of the fuel cell over the operational time. In this case, the degradation values are based on the studies of Fletcher et al. [35] and listed in Table 3.

The equation to calculate the degradation is made up of two terms, one quantifying the degradation during constant power output periods and one for transient operations. These two values are summed to find the total value at the end of a simulation over a defined time interval.

$$Deg = \frac{Lpo}{3600}*t + \frac{Hpo}{3600}*t + \sum_{t=1}^{n} \frac{Tl*10^3}{P(t) - P(t-1)} \quad (1)$$

- Lpo = low power operation value [μV/h]
- Hpo = High power operation value [μV/h]
- τ = time sample duration [s]
- Tl = Transient loading value [μV/Δkw]
- P = Electric power μV/Δw
- Deg = degradation in μV
- t = time; n = last sim. timestamp

The calculation of the total degradation value allows the users to estimate the interval between maintenance activities and estimate the operational life of the fuel cell in relation to the implemented EMS.

Battery

The battery pack is included in the model to compensate for the slower dynamic response of the PEMFC and compensate occasional spikes in power demand during transient loading conditions. The installation of a battery also allows to include, in the energy management strategy, a peak shaving solution, reducing the overall usage of the fuel cell during high frequency transients and high power operations, therefore lowering its degradation and hydrogen consumption.

The model used for the battery is a parametric dynamic model adapted to simulate a lithium ion battery pack. The circuit is based off the work of Zhu et al. [37]. and Tremblay et al. [36] (see Fig. 10). The internal resistance is assumed to be constant during the charge and discharge cycles and does not vary with the amplitude of the current. The parameters of the model are derived from the discharge characteristics. The discharging and charging characteristics are assumed to be the same. The capacity of the battery does not change with the amplitude of the current (there is no Peukert effect).

The battery size has been calculated in relation to the 1500 kW of fuel cell capacity installed. Considering that the highest registered power demand value in the ferry's database is equal to 2425 kW, it was determined that two 1000 kWh battery packs were fitting the applications requirement maintaining the depth of discharge low. This value was calculated taking into account an efficiency of the power line of 90%. The battery selected is rated at 400 V. The nominal discharge current for one battery pack is equal to 1087 Ah and it is assumed that the battery can operate at an up to 2C. Additional characterization of the battery packs used can be observed in Fig. 11.

Converter connecting PEMFC and DC-Bus

The converter connecting the fuel cell, rated at 320 V, to the 690 V DC-bus is modelled as a conventional boost converter (see Fig. 13). The boost converter allows the increase of voltage using a IGBT, switching at 5 kHz, controlled using a PWM signal generator. The duty ratio of the PWM signal is adjusted between 0.1 and 0.9 according to the input voltage, to maintain the output voltage stable at 690 V. The duty ratio is controlled through a feedback loop with a PID controller. The values for inductance and capacitance used in the boost converter model are tuned to get a quick and non-oscillatory voltage rise with an acceptable level of voltage ripples [38].

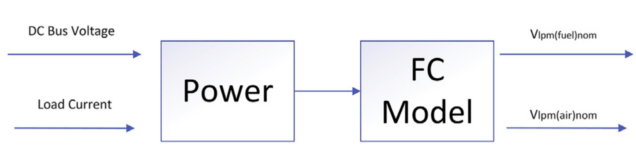

Fig. 9 – Input/output given to the fuel cell model from Njoya [34].

Table 3 – Degradation from Fletcher et al. [35].

Operating Conditions	Degradation Rate
Low power operation (<80%)	10.17 μV/h
High power operation	11.74 μV/h
Transient loading	0.0441 μV/Δkw
Start/stop	23.91 μV/cycle

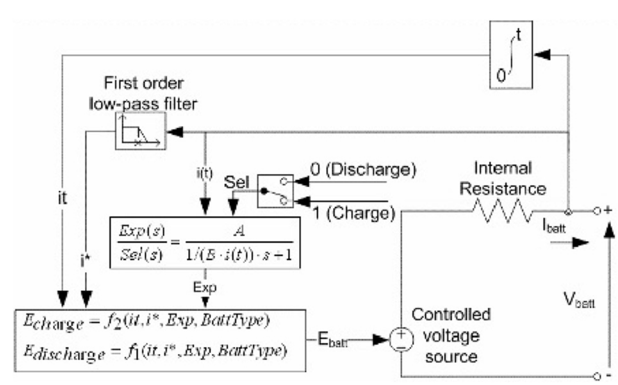

Fig. 10 – Equivalent circuit of the battery included in the model [36].

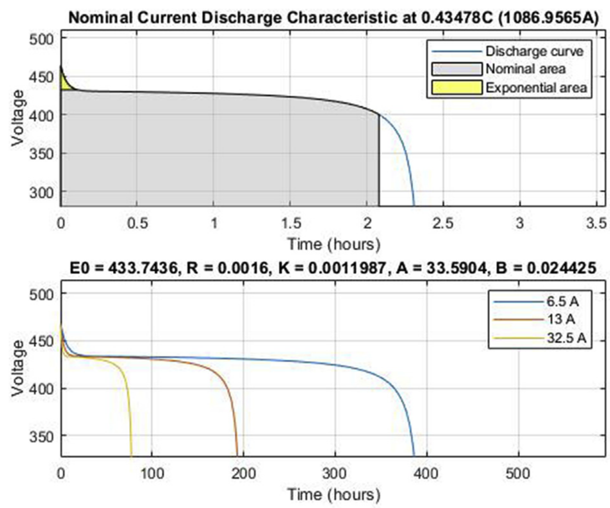

Fig. 11 – Graph representing the characteristics of the battery pack used in the model.

When tested, the model ensured a stable response well within the class limits of ±5% voltage variation during steady load and ±10% during transients. The EMS also ensures that components producing excessive or too low voltage can be disconnected from the switchboard to avoid damages to the whole system.

It has to be noted that with a switching frequency of 5 kHz and a simulation timestep in the order of the microsecond the model takes into consideration the switching dynamics and not an average model for the converter response.

Converter connecting the battery and DC-Bus

The battery is connected to the DC-Bus using a bi-directional DC/DC converter. This type of converter allows the flow of electric power in both direction (Fig. 14), allowing the discharge and recharge of the battery alternatively. The converter also provides voltage regulation, as the battery and the DC-Bus operate at different voltage levels.

The values for the inductance and capacitance of the converter have been tuned to get a non-oscillatory response with an acceptable level of voltage ripples.

The converter can operate in two distinct modes: a boost mode, used during discharge, and a buck mode used during recharge. The boost mode is used to bring the voltage on the battery side, rated at 400 V, to the level defined for the DC Bus of 690 V. The buck mode allows to lower the voltage from 690 V

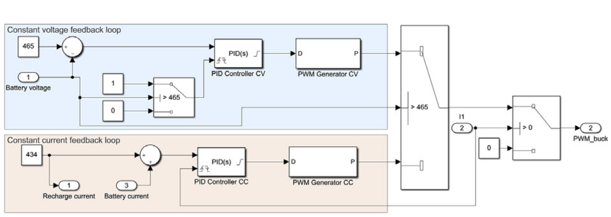

Fig. 12 – Buck mode circuit: battery recharge controller.

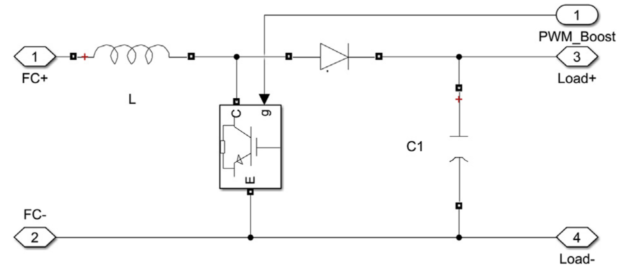

Fig. 13 – Boost converter connecting DC-Bus and PEMFC.

to a voltage level acceptable for the recharge of the battery. This voltage level is variable, according to the battery polarization curve, but higher than the rated battery voltage to allow for recharge.

The switches (IGBTs) in the bi-directional converter are controlled using a PWM source, similarly to the application in the fuel cell boost converter, with a switching frequency of 5 kHz. Also in this case the switching dynamics can be observed thanks to the simulation timestep of 1 μs. The PWM signal is generated, in both modes, using the feedback signal from a PID controller (Fig. 12 for the circuit relative to buck mode, Fig. 16 for boost mode). The PIDs are installed on feedback loops in charge of maintaining the voltage level at the desired value on the bus side during boost mode, and on the battery side during buck mode.

The buck-mode PWM signal generator can be controlled in different ways, using the EMS, to have different recharge strategies. In this study, it is considered that the battery pack is recharged at constant current at 1C when the fuel cell is able to generate the excess power needed. Once the fully charged voltage is reached, the value controlled becomes the battery voltage, kept at a constant value, using a second feedback loop, until the SOC of the battery reaches the specified upper limit (in this case 90% SOC) (see Fig. 15).

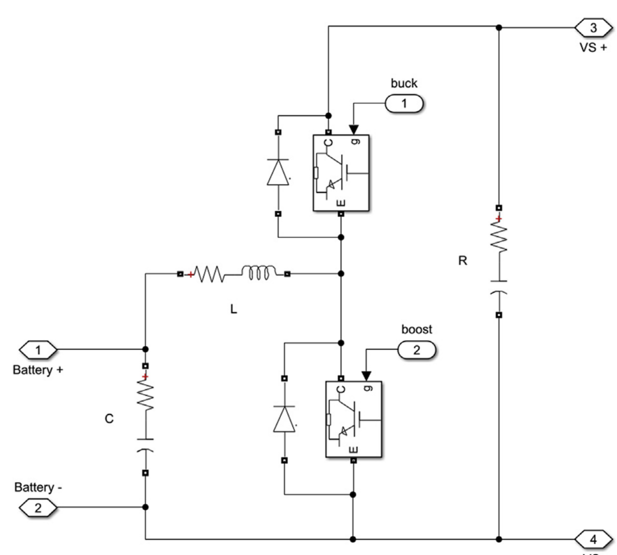

Fig. 14 – Bi-directional converter connecting the battery to the DC Bus.

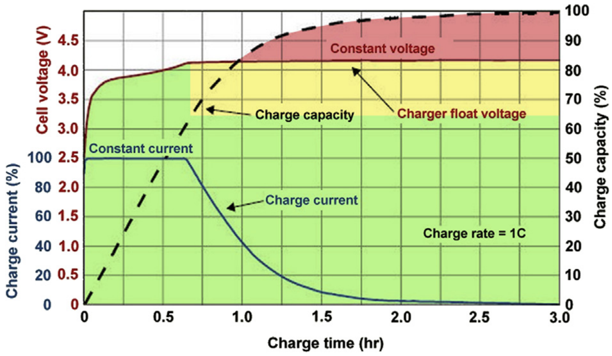

Fig. 15 – Graph representing the characteristics of the battery pack recharging.

Both PID controllers are connected to a reset switch as the battery, following the strategy of energy management system, is not permanently connected to the load. This reset switch is in charge of avoiding overshoots in the correction from the integral term of the PID.

Switchboard

The switchboard is modelled with ideal switches with a high snubber resistance (see Fig. 17). The connections realized are the one represented in the single line diagram of Fig. 6.

The connection between the bi-directional converter is modelled with two ideal switches, one dedicated to the discharge circuit and one to the recharge circuit. This differs from the single line diagram where only one switch is represented.

As the load, in this case, is modelled as a single block to include both propulsion loads and service loads, the connection between the switchboard and the load is operated by a single ideal switch.

All the switches are controlled using inputs from the energy management system.

Electrical load

The electrical load subsystem is tasked with simulating the variable power demand of the vessel over time. Once the time period that needs to be analyzed is selected, a series of power

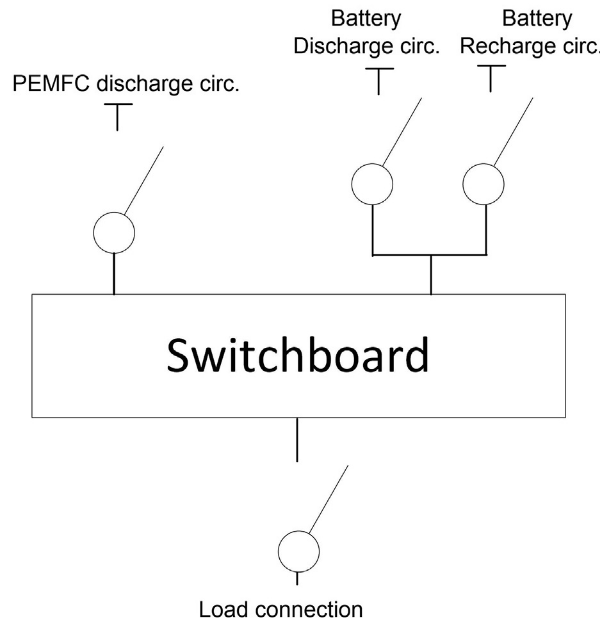

Fig. 17 – Switchboard simplified schematics.

values are extracted from the database and used as input of a interpolated sequence block to create a virtual operational profile. The power values used in this study are the combination of propulsion load, auxiliaries and hotel load.

The power demand defined by the operational profile need to be fulfilled by the combination of fuel cell output (P_{fc}) and battery (P_{batt}) output, both multiplied by the relative number of units installed in the system (n_{fc},n_{batt}).

$$P_{tot} = n_{batt} * P_{batt} + n_{fc} * P_{fc} \tag{2}$$

A complex representation for the load, including induction motors for the propulsion system, is considered out of the scope of the paper. The load is therefore modelled as a variable resistive load connected to the DC-Bus (Switchboard). This approach does not allow the observation of the effects of current and voltage waves, once the DC current is converted to AC current for the motors, but still allows to control the current flowing from the power source (PEMFC and battery) to the power sink (load sub-model). The load sub-model is based

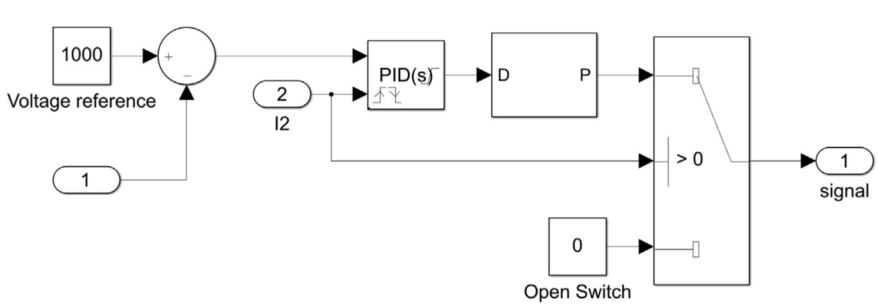

Fig. 16 – Boost mode circuit: battery discharge control.

on Ohm's law and electric power formulation. This is allowed as the components in the software environment do not have any limitations regarding the current that can flow through the controlled resistive load, in addition to no limitation on the power rating and operational temperature.

$$R_{fc} = \frac{V_{bus}^2}{P_{fc}} \quad (3)$$

$$R_{batt} = \frac{V_{bus}^2}{P_{batt}} \quad (4)$$

The resistive value used as input by the load sub-model is calculated, for the fuel cell stacks and batteries, using the formulation of Eqs. (3) and (4). V_{bus} is the same for both battery and fuel cells, equal to the value set by the DC-Grid guidelines for the proposed power-plant, 690 V. The voltage level is kept constant around the defined level by the feedback loop presented in Fig. 16. The value for the power output of the fuel cell (P_{fc}) and the power output of the battery (P_{batt}) is defined by the load sharing strategy coded in the energy management system.

The modelling of the load as a simple resistive electrical load allows also for lower computational complexity in the simulation reducing considerably the computational time compared to the solution including library models of induction motors and variable speed drives.

Energy management system

Targets and strategies

The energy management strategy defines how the load sharing between fuel cells and battery is carried out. A series of inputs, such as total power demand, fuel cell utilization level and battery state of charge is fed to the EMS that evaluates what actions to take according to a series of coded instructions if the system is rule based, or through some optimization algorithm, like for the equivalent fuel consumption minimization strategy.

Once the strategy for the specific operational point is defined, the control on the power delivered is carried out by giving an input to the switches included in the switchboard, connecting the necessary power sources to the load, and setting a target value for the power delivery of each component (P_{batt}, P_{fc}).

The sum of the fuel cell and battery power output should be equal to the value of the operational profile for each considered instant (Eq. (2)). Slight oscillations in the power output value may be present due to the PID way of operating, but the stability of the system is measured on the fact that only minor oscillation can be accepted. The presence of major differences between the power output and the requested power exposes errors in the power rating calculation or in the way the load in delivered.

The energy management system enables the optimization of one or more parameters. Some of these factors are, for example, the minimization of hydrogen consumption or degradation of the PEMFC membrane. For the battery, the main factor is the reduction of high depth of discharge cycles leading to premature degradation [12].

Different control strategies can be implemented to define the load sharing solutions. Some examples include [18]:

1. State based (or rule based)
2. Charge-depleting charge-sustaining (CDCS)
3. Classical PI
4. Equivalent fuel consumption minimization strategy

Rule based EMS

For the model presented in this study, a rule-based strategy has been developed. A rule based strategy consists in a series of coded instructions defining what actions to take and what target values for power delivery are for each possible operational mode (Table 4). The rule-based strategy created for this case study aims at the minimization of fuel cell degradation through load leveling. Load leveling can be implemented taking full advantage of the battery system by storing excess power when possible and deliver it once it is needed. In this case, the time where the fuel cell has to provide power at a high degradation rate is greatly reduced.

In this case, the main variables taken into consideration when coding the rule based strategy are the battery state of charge and the power output level of the fuel cell.

The fuel cell output is limited at 80% of the rated load for the considered 100 kW PEMFC unit for degradation reasons (Table 3). When considering the first attempt solution configuration presented in the hybrid power plant description, this is equal to 1200 kW of available fuel cell power during normal operation. Loads above this value are supplied using the battery pack, that is recharged once the power is available. The power dedicated to the recharge of the battery is indicated as P_{rec}.

$$P_{rec} = V_{batt-rec} * I_{nom} * C_{rate} * \eta_{conv} \quad (5)$$

When controlling the recharge of the 1000 kWh 400 V battery, at 1C, the battery can accept roughly 1086 Ah at 437 V during constant recharge mode. These two factors in addition to the efficiency rating for the bi-directional converter defines the value of P_{rec}. The power to recharge the battery is a quantity that has to be compensated by and increase in fuel cell power delivery. The battery optimal recharge point is when $P_{vessel} + P_{recharge}$ is equal to the maximum efficiency operational point of the PEMFC. This condition can be achieved during Ro-Ro operations. The maximum SoC value for the battery is set to 80%. This means that the battery is never charged using the constant voltage loop during navigation with the current EMS, but the system maintains the possibility to fully charge the battery to 100% from shore power (simulated in an independent voltage source) and by alternative future EMS strategies. The minimum value for the SOC of the battery is limited to 20%. This reduces the degradation of the battery limiting the number of cycles with high discharge rate.

Table 4 – Rule based energy management system instructions.

Power Available	SOC Level	Action Battery	Action FC
$P_{vessel} + P_{rec} \leq P_{fc\text{-}lim}$	$SOC \leq 80\%$	Battery Recharge	$FC_{target} = \frac{P_{vessel}}{n_{fc}} + \frac{P_{rec}}{n_{fc}}$
$P_{vessel} + P_{rec} \leq P_{fc\text{-}lim}$	$SOC > 80\%$	No Battery Recharge/Discharge	$FC_{target} = \frac{P_{vessel}}{n_{fc}}$
$P_{vessel} + P_{rec} > P_{fc\text{-}lim}$; $P_{vessel} \leq P_{fc\text{-}lim}$	$20 \leq SOC < 100\%$	No Battery Recharge/Discharge	$FC_{target} = \frac{P_{vessel}}{n_{fc}}$
$P_{vessel} > P_{fc\text{-}lim}$	$20 \leq SOC < 100\%$	Battery Discharge	$FC_{target} = P_{fc\text{-}lim}$
$P_{vessel} > P_{fc\text{-}lim}$	$SOC < 20\%$	No Battery Recharge/Discharge	$FC_{target} = P_{fc\text{-}lim}$

Simulation results and discussion

Simulation setup

The simulation with the proposed zero-emission hybrid power-plant for the ferry is carried out using the parameters listed in Table 5 and the power data relative to a single ferry crossing from Spodsbjerg to Tårs. A discrete time domain with fixed timestep in the order of the microsecond has been used. The selection of a discrete time domain allows for faster computation and the fixed timestep for the production of data with a consistent timestamp for the final comparison. The timestep selected is 1 μs, to minimize numerical errors and allow good precision in the feedback loops controlling the bus voltage and the battery recharge. A timestep of 1 μs also allows the observation of switching effects in the modelled converters. The solver used is ode3.

Simulation results

One crossing of the duration of 45 min, including an additional 15 min for the Ro-Ro operations, is taken into consideration for the simulation in the case-study. This crossing is one of eighteen carried out during a full day of operation. Once the simulation is completed it is possible to analyze the behavior of the digital system and compare it to the real-world power demand.

In Fig. 18 is represented the power demand of the vessel (blue line), and the power delivered by the hybrid power-plant (orange line). An analysis of the power values highlights how, the mean square error between the demand and the power delivered in kW is equal to 5.7601e+03. This means that for 72% of the analyzed operations, the difference between power requested and power delivered is below 100 kW.

Table 5 – Power-plant configuration for the first simulation.

Total power installed	3500 kW
Bus voltage	690 V
Battery units	2
Battery nom. voltage	400 V
Battery rated capacity	2500 Ah
Initial SOC	50%
Number of fuel cells	15
Rated power PEMFC	100 kW
Response time PEMFC	15s
Response time Battery	2s

The power provided by the powerplant is also lower than the power demand for just 1.47% of the power values, meaning that the power delivery is ensured for 98.5% of the considered time. In this first configuration, the focus of the EMS was to avoid a lack of available power and consequent blackout rather than optimize the power delivery to match the operational profile 100% of the time. The components selected in Table 5 can take care of the power requirements of the vessel for this specific crossing.

Spikes in the power output are visible around 600 s and 3200 s when the battery recharge loop is disconnected and reconnected to the system in rapid succession due to the power demand value oscillating between the two EMS conditions $P_{vessel} + P_{rec} > P_{fc\text{-}lim}$ and $P_{vessel} + P_{rec} < P_{fc\text{-}lim}$. This behavior shows one of the limitations of a simple rule based EMS, that applies coded instructions without knowing the conditions of the system in present or past states. It shows also that the power electronics components such as the converters and the DC-Bus capacitor should be rated to withstand this condition or re-tuned to reduce the intensity of this phenomenon.

It is possible to observe how, during the crossing phase, the system is outputting an excess of power between around 80 kW even if the EMS is providing the correct target value. This shows how the battery, during high load sequences, has a slightly different behavior than expected, and the set point for the battery current during discharge needs to be adjusted to account for this behavior. Alternatively it is possible to modify the load sharing strategy to reduce the stress on the battery or improve the efficiency of the bi-directional converter.

During the time interval analyzed, it is possible to observe how the feedback loop controlling the voltage output of the fuel cell is keeping the voltage level at the defined level for the DC Bus, with small spikes due to the aforementioned oscillations of power between two PEMFC target values (Fig. 19). The battery is influenced too by this power demand oscillation and it is possible to notice around 500 s, how the rapid connection and disconnection of the battery to the system does not allow the correct control of the output voltage on the battery side and creates a spike to 1255 V. These spikes show that both battery and fuel cells need to be able to quickly disconnect from the DC Bus if over-voltage or over-current conditions are present. The battery discharge controller operates well during the crossing phase (designed conditions), where the connection of the discharge circuit to the bus is stable and the output is kept around the 690 V value.

Fig. 20 shows the variation in the state of charge of the two installed batteries during the interval analyzed. The two Li-Ion

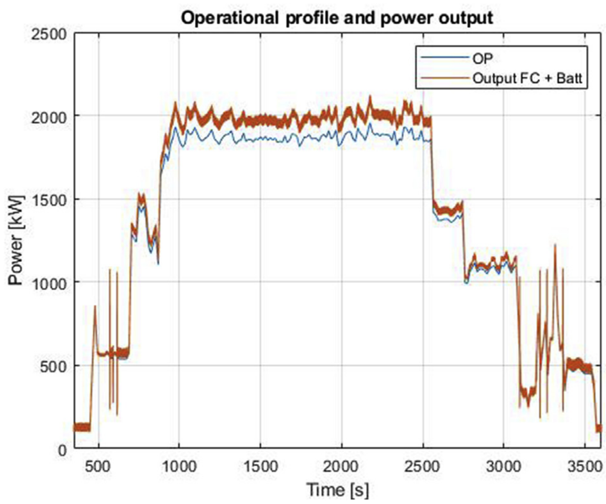

Fig. 18 – Total power output and operational profile comparison.

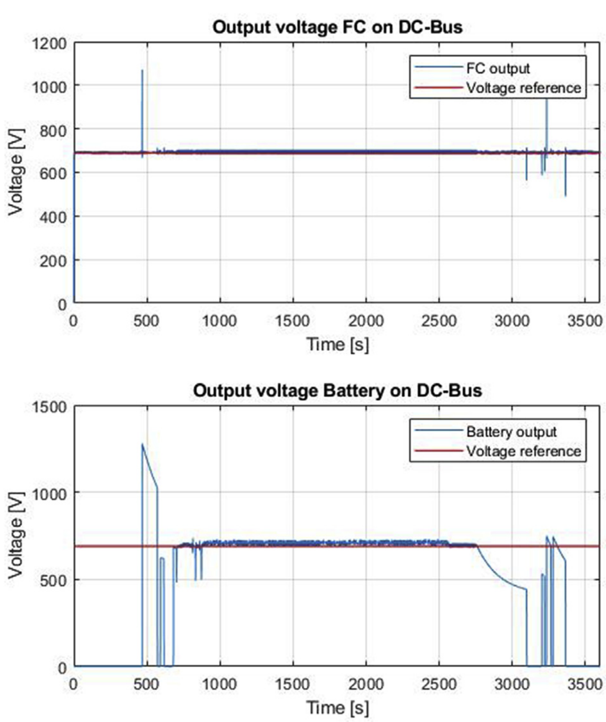

Fig. 19 – Output of battery and fuel cell to the DC-Bus.

packs are assumed identical and with the same dynamic behavior. It is possible to notice that around the last part of the crossing the SOC reaches the lower limit of 20%, but the impact of this condition causes no power deficit as once the battery reaches its lower limit, the ferry enters the maneuvering phase at the dock of destination, using mainly PEMFC power. This indicates that the battery size calculated for the plant is the smallest size that can be installed without experiencing power shortages in these specific conditions, with the given components and EMS.

The adoption of a battery pack of the size indicated in Table 5, operating with the presented components and EMS, allows to occupy a relatively small amount of space on the vessel while providing enough power for the crossing. The flexibility though is heavily impacted. Increasing the overall efficiency of the system reducing the wasted energy in the converters and improving the power delivery of the fuel cells to stabilize the baseline power supply would benefit the battery usage and allow to carry out the complete crossing retaining a power reserve.

Fig. 21 represents the consumption in liters per minute of air and hydrogen for the single fuel cell. The total hydrogen consumption for the crossing with the considered configuration and EMS strategy is equal to 1.4164e+04 standard liters per minute (SLPM), equivalent to around 1.26 kg for the single PEMFC (considering hydrogen density at STP equal to 0.089). By multiplying for the number of fuel cells we find that around 19 kg of hydrogen are required for the single crossing. The possibility to calculate the consumption in SLPM allows the ship operator to quantify the volume required for hydrogen storage on-board according to the storage technique (GH2 or LH2), and the costs of fuel per day.

The degradation of the single fuel cell, with the current setup and EMS strategy, is equivalent to 3.1050e+04 μV for the considered crossing. This value can help quantify the number of cycles that can be carried out by the fuel cell before maintenance is required.

With the system being powered entirely by PEMFC and batteries, the produced greenhouse gasses emission are equal to zero.

The obtained results seem to satisfy the power demand and validate the initial sizing in relation to the selected energy management strategy. These results can be taken as reference to improve the system efficiency, reduce the mean square error between the operational profile and the power produced and reduce the fuel consumption.

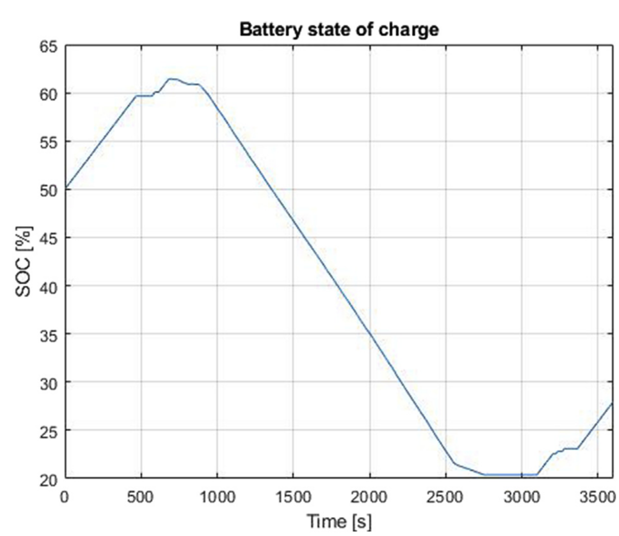

Fig. 20 – State of Charge of the battery.

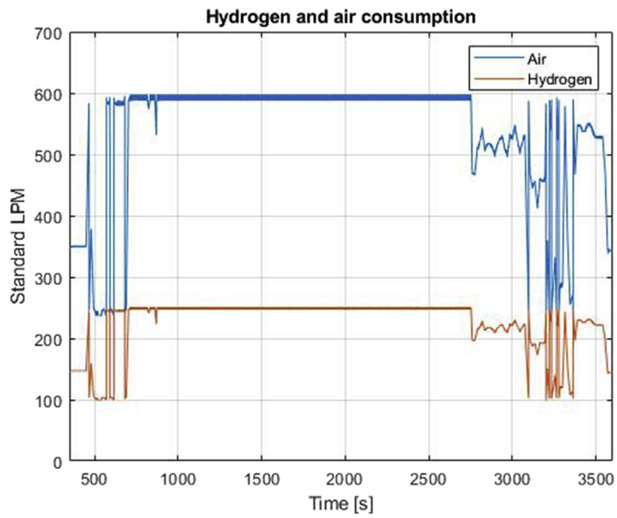

Fig. 21 – Hydrogen and Air consumption for a single PEMFC.

Some improvements that need to be addressed in a future version of the model can be listed below.

First, the oscillation of the power demand around the limit value: $P_{vessel} + P_{rec} < or > P_{fc\text{-}lim}$, used as a condition in Table 4, produces instability due to the rapid connection and disconnection of the recharge circuit multiple times. This leads to unstable voltage regulation, for a limited amount of time, on the battery side, and spikes in the value FC_{target}, that the system tries to follow, producing excess degradation on the PEMFC. This issue can be addressed by improving the rule based EMS including specific boundary conditions on the connection and disconnection of the recharge and discharge system or providing the system with a EMS using a different strategy based on feedback values (classical PI) or a different approach (charge depleting-charge sustaining). The condition can be further improved by improving the tuning of the power electronics components to fit this specific marine application.

Second, the state of charge of the battery reaching the lower limit of 20% is an indicator that the capacity of the battery should be increased or the battery power used in a more efficient way. Increasing the number of fuel cells or allow them to work in high degradation area, is also possible to ensure a certain amount of extra power in case there is a variation in the meteorological conditions or a change in route due to maritime traffic on the crossing route. The increase of the initial battery state of charge is also a possibility that can be considered if it is possible to recharge the ferry at the departure dock. Effects on the initial SOC on the entire day of operation can be carried out using the model and extending the time interval analyzed.

It is also possible to continue the fine-tuning process of the control system and the EMS to reduce the mean square error and eliminate the delivery of excess battery power, during the crossing phase.

All these improvements are a base for further development of the model, towards the optimal power-plant configuration that ensures flexibility and stable power output.

Discussion

The model

The development of a mathematical model, in digital form, representing a hybrid power-plant operating using PEMFC and batteries, serves multiple purposes during both research activity and during the design of new zero-emission maritime vessels.

To research the effects of component sizing in relation to the energy management system and vice versa, for a fuel cell driven ship, it is required to have a fuel cell model, a battery model, a DC grid, and an EMS block all in the same digital environment. This allows the components to interact with each other, simulating the behavior or the powerplant when real-world data is given as input.

Using the model presented in this paper, it is possible to study the behavior of different power-plant configurations and control strategies in relation to factors such as power demand, route length, and hydrogen consumption. The goal of such a model is to further develop the system optimization process through computational resources.

The results produced by the model are not only useful to evaluate to the power system performances, but also enable the calculation of key indicators not directly related to power generation. By calculating the number of components required and their rating, it is possible for maritime design researchers to estimate the size of the engine room, housing the hybrid system, and the relative weight of this configuration. The hydrogen consumption value can be used to calculate the size of the hydrogen tanks and the space required for storage in relation to the route length.

In the industry, a tool to quickly evaluate the behavior of a certain size fuel cell or battery when introduced into the system can allow for a faster design phase. Engineers tasked with the dimensioning problem can test different configuration and their response to energy management strategies to better satisfy their clients.

The model is built to be flexible, adapting to different marine power-plant configurations between 1 and 10 MW. Flexibility is a key attribute for such a model, as fuel cell propulsion in the maritime industry is not a mature technology therefore a tool to quickly evaluate the technical feasibility of the solution is most effective if it can be adapted to multiple vessel classes and sizes.

The presented case study can be considered a demonstration of the capabilities of such a model with future developments being considered in the areas of the energy management and control. Optimization of the computational resources is also a priority, as a faster simulation allows for more configuration and strategies to be tested, or longer operational intervals to be considered.

Last, it is also possible to use this model as a basis to include more specific fuel cell or battery models, which contain aging or temperature effects, in order to get a complete picture over the operational life of the fuel cell, battery or power electronics components.

The zero-emission solution for the ferry

The transition to hybrid systems allows companies and ship operators to meet the goals set by the UN and IMO for emissions and greenhouse gas control.

The configurations presented for the ferry, while merely being a first attempt solution which can be further optimized both from a sizing perspective and an energy management perspective, would allow for a significant reduction of NO_x, HC and CO emitted in the proximity of the two ports of departure and arrival. There are also benefits on the global scale, give a reduction of CO_2 levels introduced into the atmosphere. The elimination of diesel gen-sets operating at low thermal efficiency during Roll-on/Roll-off operations introduces an area where fuel savings become relevant if considering that the operation is carried out 18 times a day, every day of the year. With the technical feasibility of the solution evaluated via the case study, it is possible to assess the economical feasibility with the ship operator, taking into consideration the average cost of ownership and the possible return on investment for the new hybrid solution.

Conclusion

The creation of a digital representation of a maritime hybrid power-plant equipped with PEM fuel cells and battery can aid in the design process of new, zero-emission hydrogen vessels or the retrofitting operation for diesel electric ships.

In this paper, a diesel-electric ferry was used for reference. The power output of the diesel-electric plant becomes, in this model, the power demand for the hybrid system. Using a series of real-time data, in conjunction with a set of dynamic models representing the physical components of the hybrid system in the software environment, it is possible to output a series of data that can help analyze the behavior of the hybrid system. The comparison between the operational profile and the power demand helps validate the size and power rating of the components chosen for the power-plant. The behavior is to be considered satisfactory if the mean square error between the power provided and the power demand is below a certain threshold set by the user. The mean square error also provides a reference for future improvements of the hybrid system or the energy management strategy.

The model also produces a graph representing the state of charge of the battery over time. This graph can aid in the evaluation of the battery capacity and let the user observe the behavior of the energy storage.

An estimated hydrogen consumption value is produced according to the model by Njoya et al. [34]. This enables the evaluation of important factors such as running costs for the ferry. Maintenance can also be planned according to the degradation value calculated taking into consideration the operation of the PEM fuel cell.

The model has been created as a design tool, but also as a platform for future development. Testing of different energy management strategies for the optimization of factors such as hydrogen consumption, fuel cell or battery degradation can be carried out on this digital model with just a few changes. The ultimate goal is to promote the development of zero emission energy solution for the maritime environment. Such solution aids in the reduction of greenhouse gas emissions and pollutants to help mitigate the impact of maritime traffic and coastal communities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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