Simulation and Energy Management Strategy Development for a Fuel Cell Hybrid Electric Powertrain of a Zero-Emission Boat

Multi Disciplinary Optimization for Hybridization

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This research explores the potential of a fuel cell hybrid electric powertrain deployment for a zero emission low-power boat application in terms of technological and economical merits. A backward looking powertrain architecture consisting a 500 W fuel cell, a 5 kW Li-ion battery, a boost converter and an electric motor has been built in MatLAB-Simulink environment with various levels of modelling abstraction to acquire a high level of coherence. A low level and a supervisory energy management strategies have been developed to exploit the advantages of the hybridisation for range extension, high efficiency and longevity and to undermine the drawbacks of the power supplies as individuals. To demonstrate the capabilities of the developed approach in terms of the dynamic performance and energy distribution, the powertrain undertook an in-land cruise drive cycle and transient load stimuli. The powertrain has shown agile and precise responses to the loads with maximum ∓ 0.15 V bus voltage ripple and 74.6% overall powertrain efficiency. The load balancing could reach optimal fuel cell operation and the hydrogen expenditure was 0.24 nmi/g on the chosen cruise cycle. Finally, a multi-objective genetic algorithm has been developed to investigate cost effective and lean hybridisation solutions for the two main challenges in front this technology. A pareto-optimal set hosting 40 individuals has shown that an intuitive optimization study based on backward modelling prior to the design of the powertrain can yield up to 10% cost reduction and 70% leaner powertrain whilst performance constraints are satisfied.

Key Words: *fuel cell, electric powertrain, simulation, power management, fuel efficiency, genetic algorithm*

1 Introduction

There are numerous observable and predicted consequences of climate change, yet in a nutshell, the extreme weather conditions affected more than 5.5 million people and caused direct economic losses of more than €90 billion within past 20 years [1]. A commonly cited goal is to stabilize GHG concentrations around 450-550 ppm at which the most damaging impacts of climate change can be avoided. Technology of the zero emission fuel cell hybrid powertrain for maritime transport can be powerful tool whose impact falls on multiple wedges for climate action. Such that, whilst energy efficiency of the electric propulsion is much higher in comparison to conventional alternatives, hybridisation enables a higher fuel economy. Moreover, using hydrogen as a fuel is emission free and empowers utilization of renewable energy through solving the intermittency and storage issues.

Waterborne transport is the backbone of the global trade of $8.1 billion market with 80% trade volume and relies solely on high pollutant fuels [2]. Maritime transport is a relatively benign option in terms of CO_2 emission with approximately 3% contribution to global GHG emissions, yet is responsible of the global contaminations in combustion-born SOx by 8%, NOx by 15% and particulate matter by 15%. The air quality on coastal regions has been severely affected by the concentrated emissions of the maritime traffic, since about 70% of ship emissions occur within 400 km range of land. Air pollution caused by boat emissions of SOx, NOx and particulate matter accounts approximately for 50,000 premature deaths per year in Europe to which adds on an annual cost to society of more than €58 billion [3]. In April 2018, 170 member countries of IMO have reached to a revolutionary consensus to de-carbonize the maritime industry.

"***Shipping emissions will be halved by 2050, compared to 2008.***" (IMO, 2018a).

While 2050 may seem like a long way, most of the new ships built in the 2030s will have to run on zero carbon renewable fuels which requires compelling technological changes in the global industry with a fleet of over 50,000 ships trading internationally. Moreover, IMO has taken two short-term decisions regarding Emission Control Area **(ECA)** and Energy Efficiency Design Index **(EEDI)**. The maritime transportation is under growing pressure to comply with emission regulations which are stringent in ECA, as shown in Figure 1. Furthermore, IMO has empowered mandatory energy efficiency measures, EEDI, which will support the reduction of CO_2 emissions by limiting the emissions of each individual design for a multitude of boats and ships [4]. Mentioned developments are forcing a revolution in the industry. Although LNG hybridisation is raising attention for the heavy duty applications with opportunity for dual set-up to comply with ECAs, significant CO emissions will lock-out this technology. Hence, all-electric and hybrid-electric propulsion technologies have taken attention of the research and development affairs in the field.

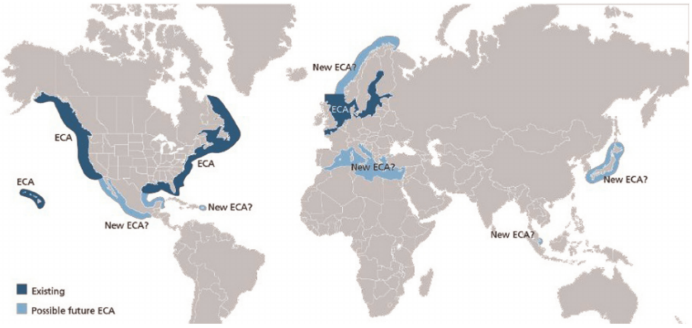

Figure 1: *Existing and potential ECAs around the world*

Electric propulsion for marine applications is attractive for many reasons; fuel saving, lower maintenance cost, environmental regulations and improved manoeuvrability are some to be mentioned. Despite a few applications in specific niches such as ice breakers, there is limited acceptance and immature market for the electric propulsion technology. On the other hand, the interest of recreational boat industry has already arisen and the early adopters of the technology will likely drive further developments in integrated system controlling which can significantly increase market acceptance and viability of the wider applications. Powerboat of the year 2010 in Germany was the 33 ft Greenline Hybrid by Segway and the recent 39 ft model has been nominated as Powerboat of the year 2018.

There are approximately 50 producers of zero-emission boats in the vessels smaller than 90 ft segment, and only producing battery electric propulsion systems, thus there is not a commercial attempt for a long range recreational boat production [5]. Since, battery powered applications are relatively restrained due to technological incompatibility for the range. There are few successful projects in which fuel cells empowered electric drive trains of marine applications for pleasure crafts and passenger vessels, yet none of them has achieved mass commercialization and remained rather as proof of concept.

There is a noticeable knowledge gap in hybrid and electric powertrain applications for maritime vehicles which performs under high fluctuations in voltage and frequency that occur in transient conditions of frequent and large amount of load changes. Although this problem has been widely investigated for mechanically driven systems, the hybrid systems can provide a more complex and flexible solution with the addition of one another energy source adding an extra degree of freedom to manage the load. The load distribution is supervised by an Energy Management Strategy **(EMS)**, henceforth determines the overall operating efficiency of the system as well. Although EMS has not any direct effect on component costs when coupled with the optimization, downsizing and longevity of the components can be controlled. For example, avoidance of transient load on the fuel cell can be possible with battery coupling, which might both down-size the fuel cell stack and reduce the maintenance and investment costs.

This research aims to investigate the feasibility of the zero-emission fuel cell powered hybrid electric boats in terms of technological and economic conditions. The goals of this research are listed as below:

1^{st} Analyse of the competence of a Fuel Cell Hybrid Electric Powertrain **(FCHEP)** for a low-power pleasure boat under an in-land cruise drive cycle and transient load stimuli

2^{nd} Development of an EMS providing safe and efficient load distribution

3^{rd} Investigation of power supply hybridisation options through multidisciplinary optimization to realize optimal solution across engineering and business fields

2 State of the Art

Literature review aims to provide a broad understanding of the technology. The feasibility of FCHEP has been analysed and the developed powertrain architectures have been introduced. The developments and challenges of the energy management strategies of the interested architecture have been explained. Finally, hybrid powertrain optimization methodologies and the respective studies were provided.

2.1 Feasibility of the FCHEP

Internal combustion engines **(ICE)** can only reach 40% efficiency at best which corresponds to very limited range of rpm and within usual performance range with drive-line inefficiencies, it reduces to 25%. Whereas, the fuel cell utilization of hydrogen is much more efficient than combustion of it. A fuel cell powered electric drive line is reaching to 60%, twice as hydrogen powered ICE drive-line [6].

Battery technology is integral for decarbonization of the transportation, yet battery powered powertrains are hindered by range and refuel timing. In a usual scenario, a single phase charger with maximum 3680 W (260V*16A) takes more than 8 h to recharge 30.5 kWh battery. For instance, 740 Mirage; a frontrunner battery powered boat, provides a 55 km range at 5 knots and can only run 35 minutes at full speed of 15 knots with a fully charged battery [7]. Moreover, the battery mass already constitutes significant portion of the over-all weight. As a result, increasing the size of battery cancels out the results as return of range. Using the batteries as only source of energy does not answer the need for longer cruises. Hybridization creates an opportunity window to benefit the specific power (W/kg) and fast response of the battery and the high specific energy (Wh/kg) of the fuel cell which suffers significant performance loss if not operated in the efficient region. Through hybridization the comfort of conventional refuel timing and range is met, whilst preserving all the benefits of an electric powertrain.

Fuel cells have no moving parts which reduces maintenance need and noise which improves the cruise comfort. Besides all the inherent advantageous of fuel cell systems and hydrogen as a strong alternative for transportation industry, the technology suffers from few economical and scientific challenges.

Cost: The theoretical price of a system in 2017 was an average of 46.9$/kW under mass production which is almost the double amount of US DoE feasibility limits. In July 2017, Honda and General Motors initiated a joint venture to mass produce fuel cells at the same cost of ICE systems [8].

Degradation: Degradation is measured as reduction in the performance with respect to certain time of use. Transport applications needs to meet 5000 hours based on a 250,000 km lifetime with 60% efficiency, whereas the lifetime of a well performing PEMFC is about 2500h [6]. The solution of cost and degradation issues are interdependent and counter forcing. The capital cost of the fuel cell can be reduced with lowered amount of Platinum in the catalyst or smaller stacks running at higher relative powers which affect the long term performance and reduce the lifetime and outweigh the gain from the manufacture costs.

Storage: The volumetric density of hydrogen needs to be increased with pressurizing, liquefaction or capturing into solid state storage. In practical terms, when conventional 3600 psi natural gas storage technology for vehicular applications has been utilized for hydrogen, there will be a 20 fold energy density penalty in comparison to gasoline [9]. High pressure storage needs to be accompanied with high insulation and safety mechanisms, whereas a solid state storage might cause lag in the powertrain due to slow rate of reaction limiting the hydrogen release.

Infrastructure: Lack of infrastructure for re-fuelling hinders mass production and use of hydrogen and locks the relation to a chicken and egg scenario. Development of entirely new propulsion system requiring a new fuel choice needs to balance off the societal costs in terms of financial and environmental sustainability.

2.2 FCHEP Architectures

As explained in 2.1, a fuel cell is not capable of responding abrupt changes in the power load. Thus, slow speed and relatively monotonous power delivering applications such as forklifts, trams and submarines utilize Fuel Cell Powertrain **(FCP)**. In order for a fuel cell to deliver high speed under varying load conditions, modifications need to be made to the basic powertrain which leads to new configurations of FCHEP. Basic powertrain architectures of FCP and FCHEP are shown in Figure 2. FCHEP adopts another Energy Storage System **(ESS)**, which can be a battery or an ultra-capacitor **(UC)**, to be charged or discharged based on power demand and supply. Deployment of power converters are varying according to the design and power control schemes, thus flexibility has been indicated with dashed lines in the drawing.

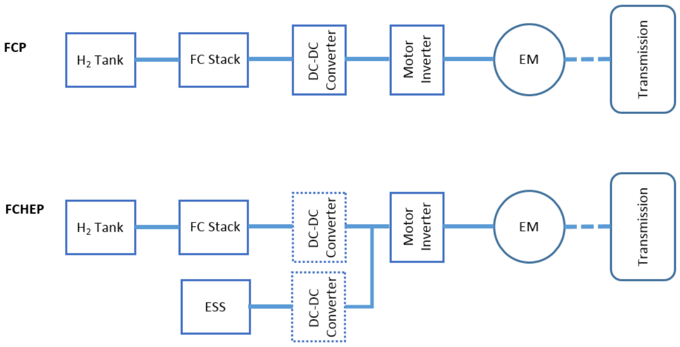

Figure 2: *Basic FCP and FCHEP configurations*

To benefit ESSs for managing with abrupt load changes in the bus and acquire efficient system performance, fuel cells are commonly hybridized in parallel configurations [10]. On contrary to the classical hybrid powertrain classification according to parallel or series arrangement, it is more intuitive to define the FCHEP architectures depending on the power conversion stages. [11].

Power conversion in a FCHEP usually takes place in multiple stages; initially low DC voltage from power sources is converted into high voltage DC and then inverted into AC to run the electric motor. The developed FCHEP hybridization schemes based on MPSC have been shown in Figure 3.

T2 is a preferred topology with power split control between sources via controlled FC with floating ESS [12], [13], [14]. The greatest benefits of fuel cell powertrains are realized when hybridised with batteries and the system capital cost, hydrogen cost and electricity cost are determinants of the feasibility [15]. The fuel cell serves as a range extender and allows for the downsize of the batteries in comparison to same range BEP and FCP [16]. *Hosseinzedah* utilized battery and UCs to downsize fuel cell stack and reduce the transient load on the stack which lead to a lower capital cost and volume savings, as well as longer operational life and simpler system control [6]. T2 is a promising architecture for cost conscious solutions and will be under investigation for this research.

2.3 Energy Management Strategies

Literature survey on EMS has been devoted particularly for the interested powertrain architecture, T2.

The optimal running points of individual components do not necessarily coincide with one another, meaning that a global compromise is required to avoid undesired operating points within the system. Most of the EMS related research aims to go beyond just delivering the required performance. Cost,

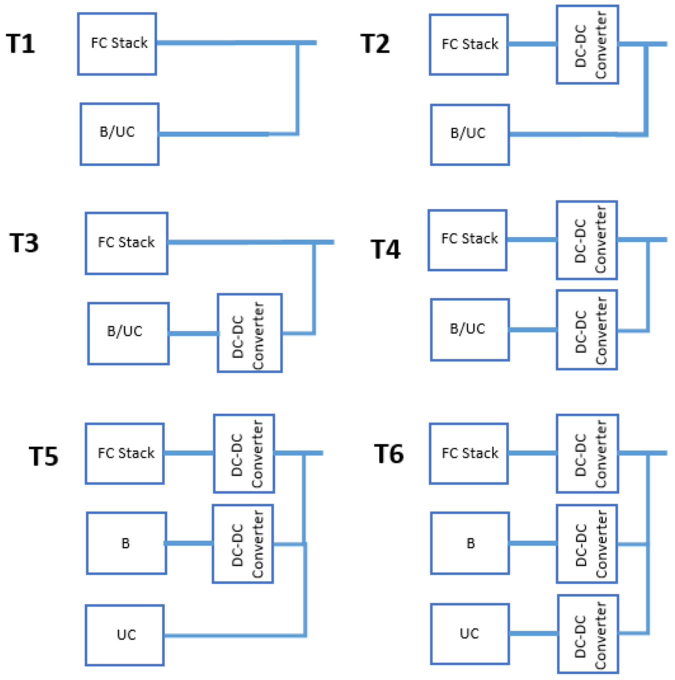

Figure 3: *FCHEP Hybridisation Topologies*

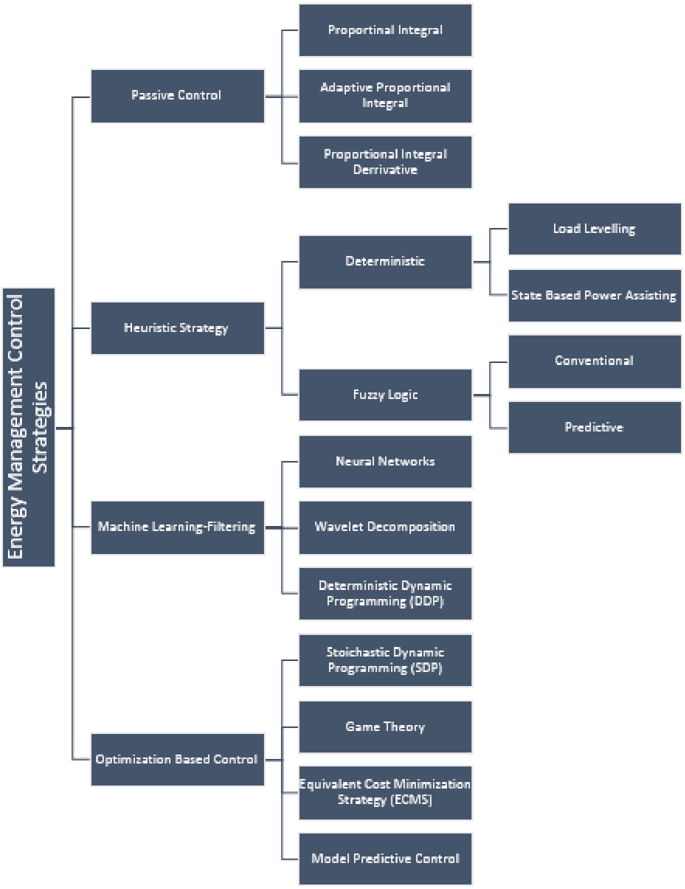

Figure 4: *EMS for MSPC FCHEP*

degradation and storage of hydrogen are the three main challenge areas of FCHEPs and can be improved with successfully designed EMS. Initial cost saving through battery hybridization can be boosted with effective usage of the battery. Load distribution enabling the battery for the transient loads and operation of the fuel cell within its optimum region will limit its degradation. In addition, EMS can contribute to the lifetime of the battery by controlling the state of charge and the current loading of the battery which have direct effect on degradation mechanisms. The fuel economy can be significantly improved by EMS easing the job of storage system.

Applied control approaches on multiple stage conversion deploying hybrid electric powertrains in the literature have been classified as shown in Figure 4. Few strategies are much sophisticated and complex to develop, yet the complexity does not necessarily offer the best solution. The most commonly investigated EMS are heuristic based strategies inspired by the expected behaviour of the propulsion system and uses predetermined sets of "rules" to determine operation states of the system. The simplicity and real time operation made this approach popular. The performance of the simulated powertrain in ADVISOR has been validated with experimentally measured values and the predicted fuel economy only deviated by 1% [17]. On the other hand, equivalent cost minimization strategy is a developing strategy based on creating a local optimum instantaneously by considering the total energy consumption, while maintaining a certain level of state of charge **(SOC)**. A study has stated that the greatest fuel economy in comparison to the fuzzy logic and predictive control are relatively more complex systems to design [18].

2.4 Multi-disciplinary Design Optimization

Determination of a powertrain architecture is the initiation step for the design of a powertrain capable of delivering the desired performance. Besides EMS optimization, the optimization of the components needs to be investigated to understand the cost-performance trade-off. As a result of literature survey, it was apparent that FCHEP architecture optimization literature has not developed yet. One study has optimized T4 topology for cost minimization with a basic and inefficient passive EMS by using particle swarm optimization [19]. However, it does not contribute to neither fuel economy nor durability. A research conducted con-current gradient based optimization of the EMS and powertrain simultaneously for maximizing the fuel economy and reached 17% extra fuel saving [20]. However, the gradient based optimizations are incapable of obtaining global optimization and objective function needs to be continuous, which may not be always the case for powertrain optimization. In addition, for multi-disciplinary optimizations, calculation of derivatives for each point is required which is computationally quite expensive. Genetic algorithms are global optimization focused, derivative free and efficient to solve the design optimization. There are few studies for multi-disciplinary optimization of hybrid powertrains for various objectives, such as fuel economy, emission reduction and cost minimization [21], [22].

3 System Modelling

3.1 Generic System Structure

The generic vehicle structure can be used to simulate any possible combination of power-sources and electronics in the powertrain and any desired FCHEP configurations can be created. In this study, a backward-facing structure, as represented in Figure 5 was used to reduce computational effort and complexity, since powertrain optimization study is desired to be conducted in addition to heuristic EMS based powertrain simulation. Therefore, a boat model including transmission system is performed to calculate the load on the powertrain.

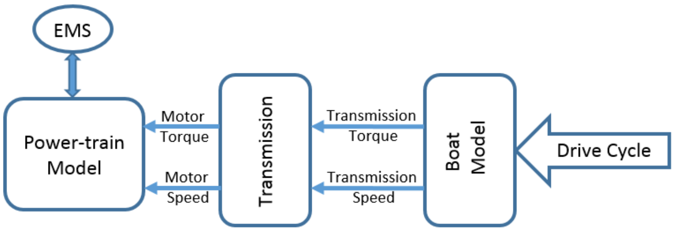

Figure 5: *Backward looking generic system structure*

The model begins with determining the required vehicle power using a known drive cycle and the power-demand from the sources is computed in consideration of respective efficiencies and performances.

3.1.1 Power Map Generation

In order to acquire a realistic drive cycle for this application, the maritime data-bank Marine Traffic data has been exploited for a vessel of interest displaying similar performance and activity characteristics of a boat in the target market. The power map of the drive cycle, shown in Figure 6 has been exploited after conducting the computations for the boat dynamics and the transmission system. It should be noted that negative acceleration denotes slowing down, namely 'braking' and subsequently 'negative power' demand has been produced for regenerative energy storage. Since the power-boat does not have the system to store this energy, those intervals are taken as zero load on the powertrain. The created power map is used as dynamic mechanic load of the powertrain for simulations and optimization.

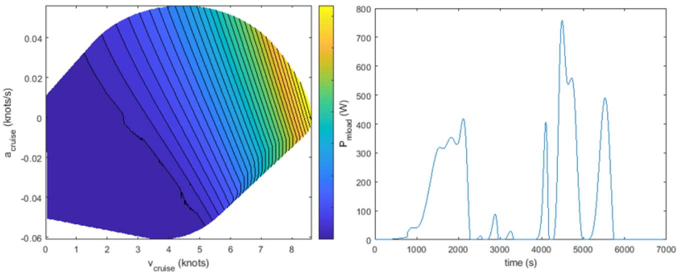

Figure 6: *Map of the mechanical power load on the powertrain*

3.2 Modelling of Powertrain Components

The performance, lifetime and cost of fuel cells and batteries are demonstrating a complex and interactive behaviour, this research aimed to capture the interface between the system level analysis of a T2 topology FCHEP and components modelled on different levels of mathematical framework for coherence.

3.2.1 PEMFC

Fuel cell stack has been simulated based on a complex nonlinear model reflecting the dynamic behaviour of the system utilizing Nernst relation and Tafel slope. SuSy500 PEMFC was deployed in the powertrain. The performance curve of the component shared by the manufacturer successfully matches with the polarization curve generated through simulation of the fuel cell, as shown in Figure 7.

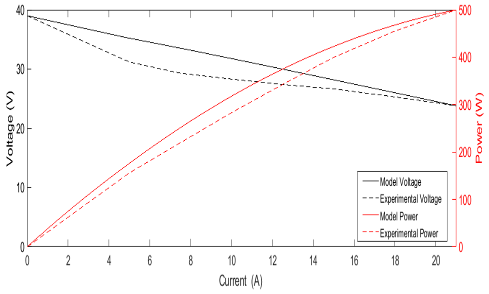

Figure 7: *Experimental polarization curve of the PEMFC (left), Model driven polarization curves of the PEMFC (right)*

The peak power of the PEMFC is 500 W, whereas the rated power is 465 W as indicated above. The fuel cell has advantage of operation in between [-10,50]^{o}C interval.

Fuel Delivery System

The fuel flow to the fuel cell stack has been controlled to achieve management decisions for current production. The fuel delivery has been modelled, as described in 1 with assumption of constant utilization ratio of Hydrogen, which is indicated as 4.5 slpm at 500W production in the data-sheet, corresponding to 0.8 utilization ratio for 2 bar fuel supply.

$$V_{lpmf} = \frac{60000RTNi_{fc}}{2Fx\%P_{fuel}U_{f_{H_2}}} \tag{1}$$

3.2.2 DC-DC Converter

The output voltage of the fuel cell system needs to be brought to the designed bus voltage level. Hence, the converter is essential for implementation of the fuel cell to the powertrain and also protecting the fuel cell from the voltage and current ripples due to transient loads.

The converter is always operated at first quadrant with a low average load profile according to the analysed drive cycle which can be plausibly modelled as a boost converter. For this research, a fully elaborated boost converter and it's closed loop dynamic control have been designed. The converter

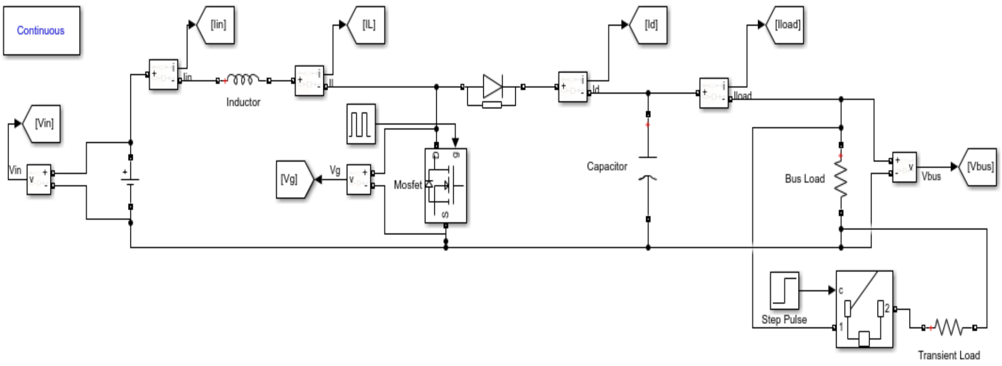

Figure 8: *Configuration of the boost converter under transient load*

should be able to provide a stable voltage in the range of 48 ∓ 9.6 V with a floating DC source of PEMFC to a bus under dynamic load. Too low and too high frequency current ripples limit the operational life and the general efficiency of the fuel cell, hence sizing of the components of the converter and efficient control is essential.

Control of DC-DC Converter

The competence of the system should be proven for sudden and strong load changes. For that purpose transient load simulation with step pulse has been implemented to the load with a circuit breaker, as shown in Figure 8, suddenly doubles the load on the converter and reaches peak load with adding parallel resistance.
Design of a closed loop control with varying duty cycle is compulsory for pertaining the desired performance under extreme conditions causing over-voltages and over-currents. Since the powertrain has an EMS regulating the FC current, the control of the converter only regulates the output voltage. For PI control design, system identification was made to obtain the transfer function of the closed loop system. The system has been identified with an under-damped pair of complex conjugate poles. As a result, the mean system voltage under transient load simulation has been detected as 47.8 V which is significantly precise.

3.2.3 Li-ion Battery

Li-ion battery has 10 times more power generation capacity in comparison to the fuel cell to secure performance delivery, to obtain more flexibility with a powerful floating energy supply. Table 1 lists the specifications.

Table 1: *Battery specifications*

Nominal Power	5 kW
Nominal Voltage	48 V
Maximum Power	16.5 kW
Voltage Operation Limits	37.8 V-58.8 V
Nominal Capacity	106 Ah
Response Time	1 s
Operation Temperature	0-40 ^{o}C

The battery has been modelled as a controlled voltage source with a constant internal resistance. The voltage control is based on the charge and discharge dynamics of the pack. In order to prevent algebraic loops in the model, delay simulation has been made with low pass filter for output voltage calculation.

3.2.4 Electric Motor

Brushless DC motor was chosen specifically to benefit the reduced size and silent operation. The electric motor of the powertrain is a 3 kW with nominal 4000 rpm. The motor performance data has been mapped with the complementary assumptions according to the experimental data. The motor model serves for two purposes; calculates the available torque that the motor can deliver based on transmission system load and subsequently finds the efficiency for the mechanical load on the motor to calculate the electrical load on the energy supply system.
The torque of the motor and the end of the propeller shaft should be the same, yet both of these components have their own torque-rotational speed characteristics. The information of the required shaft rotation for the mechanical load is necessary for determining the motor performance. The power needed to turn the propeller at a certain angular speed for a low-power boat has been modelled by Crouch speed [23].

$$P_{mload} = \gamma N^3 \qquad (2)$$

γ is a specific constant for a specific hull and propeller combination. To derive the propeller curve, modelled by 2, the propeller and motor have been coupled for an optimal zone of the motor efficiency map.

4 Energy Management Strategy

The fuel cell has been placed for range extension, in other words the battery is the main energy source, the fuel cell generally is not capable of delivering the average load. Therefore, the fuel cell serves the purpose of providing power and energy to be stored to maintain the confident operation limits of the battery to deliver the load. The target power of the fuel cell is determined with respect to the power requirement of the load and state of charge of the battery. The control of the fuel via fuel delivery system based on the reference fuel cell current, controls the actual power output of the fuel cell. The battery makes up for the power difference between the load and delivered power by the fuel cell system and consequently power distribution is attained.

The developed EMS has four objectives listed priority-wise as follows:

1. Safe operation of the power supplies: the maximum and minimum current limits of the components should be respected under all operating conditions
2. Performance delivery: the load should be met
3. Efficient fuel cell operation: minimization of fuel consumption
4. Longevity of the fuel cell: smooth power allocation to the fuel cell to avoid switch on and off or frequent load changes

The load distribution of the powertrain under supervision of the EMS is given in Figure 9.

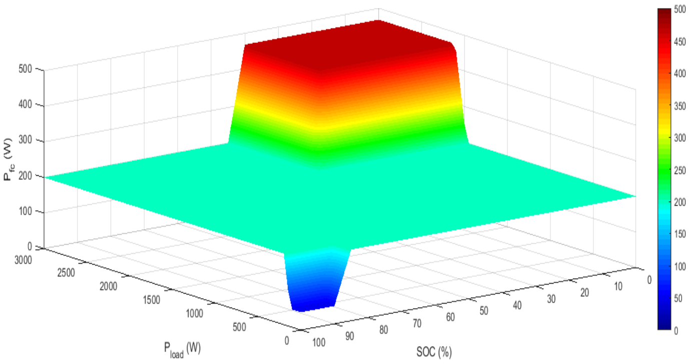

Figure 9: *Energy Management Strategy*

The EMS needs to monitor several dynamic parameters of the powertrain and know how the system is behaving in its entirety. It uses a single degree of freedom, the fuel cell current to achieve the desired powertrain performance. At the low level control, the closed loop controller focuses on its own subtask of voltage boost without any direct correlation with the overall supervision.

The algorithm seeks for the most efficient point of operation and the operation point reference is given after evaluation of the compatibility of that point with respect to the availability of the battery for safe operation. If the operation point is not eligible, the reference is incrementally increased or decreased until it fulfils the criteria. The power distribution reference always ensures safe operation and maximization of the efficiency for the required performance.

5 Performance Analysis

In the first section, the powertrain has been subjected to transient load stimuli under extreme conditions. The second section presents the response of the powertrain under the dynamic load modelled through the drive cycle.

5.1 FCHEP under Strong Transient Load

High and low load transients have been applied when the battery was operating at the extreme conditions of 5% and 95% states of charges, respectively. In Figure 10, response to a sudden load minimization when initial battery charge was 5%, has been shown. The reference current of the fuel cell depends on the available discharge capacity of the powertrain. Discharge safety of the battery was controlled with respect to the load and candidate fuel cell reference power.

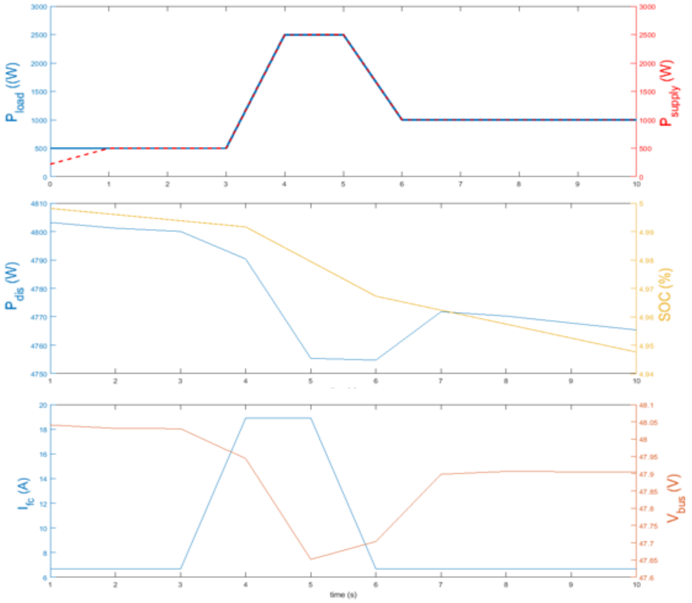

Figure 10: *Powertrain performance with high load transient*

Since, $P_{fc} < P_{load} \quad and \quad P_{dis} > P_{load} - P_{fc}$, fuel cell power has been deployed in its efficient working region. Under the high load of 2500 W, fuel cell performed at 465 W, whereas in the other regions, the fuel cell was contributing with 200 W at its most efficient operating point since, the battery is capable of balancing the load. Trend decrease in the high load region of the $SOC(\%)$ indicates the high contribution of the fuel cell. Moreover, the bus voltage has been successfully balanced with only 0.2% error with respect to the nominal bus voltage by the low-level control system of the closed loop PI control.

5.2 FCHEP under In-Land Cruise Drive Cycle

Due to high computational effort, the drive cycle has been decided to down-sample by 1/10 which allows to preserve the load changes in a tighter time interval. The simulation has been initiated with 50% SOC. In Figure 11, the variation of the voltage of the fuel cell and battery have been demonstrated in the upper figure. When the load of the electric motor and balancing currents of the fuel cell and battery shown in the figure below are considered, both battery and fuel cell changes their voltages to level the power. The ripple of the fuel cell voltage has been successfully limited by 2V, whereas the battery voltage fluctuates much less due to powerful charge and discharge capacity. The fluctuation of the

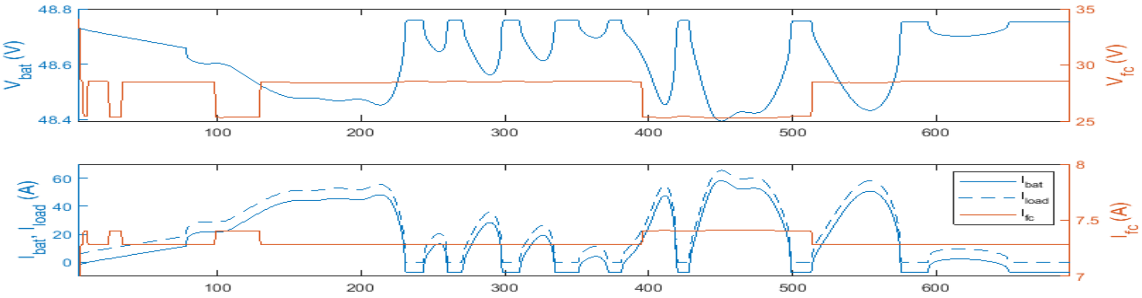

Figure 11: *Voltage and current fluctuation of the powertrain*

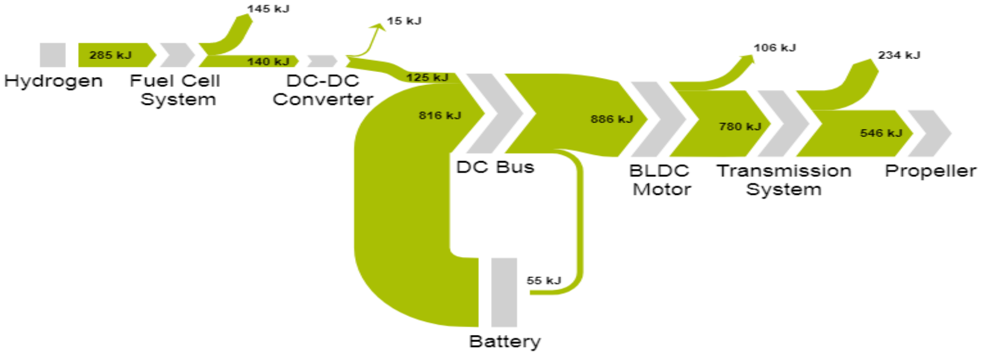

Figure 12: *Sankey energy diagram of the drive-train*

bus voltage was restrained with $\pm 0.15V$ and the bus voltage average is 48.7 V. The fuel cell generally operates at stable output other than a few disturbances whereas the battery floats to meet the load and store the excess power. The fuel cell current deviates slightly from the ideal due to the internal dynamic mechanisms of the fuel cell and voltage ripple by the DC-DC converter to maintain the outlet voltage.

From Figure 12, it can be observed that the discharging energy is much higher than the charging energy of the battery, since the fuel cell integration in this particular FCHEP is for range extension. Nearly all of the energy for the cruise has been provided by the battery. Average fuel cell efficiency is 49.3% which indicates a highly efficient performance. The energy provided by the fuel cell has been calculated using the Lower Heating Value of hydrogen, 33.3 kWh/kg in consideration of the hydrogen consumption of 2.37 g corresponding to 284 kJ. The powertrain hydrogen expenditure for the reduced drive cycle is 0.24 nmiles/g.

Designed DC-DC converter reaches 89% efficiency, which can be improved with high technology power electronics. And it should be noted that the design of the DC-DC converter is totally based on theoretical calculations which contain an error margin. 86% of the energy is provided by the battery which receives a small amount of energy from the fuel cell. The electric motor performs with 88% efficiency, which is significantly higher than any other conventional motor for maritime application. Finally the transmission system losses have assumed to be 30% to find out the mechanical energy on the propellers for creating the thrust. The over-all powertrain efficiency is 74.6%, whereas the drive-train efficiency is 52.3%.

6 Genetic Algorithm Based Multi-Disciplinary Optimization

Developed multi-objective genetic algorithm aims to minimize the cost of the power-supplies of the powertrain and achieve lean hybridization while ensuring the delivery of the performance for the desired drive cycle of interest, in-land cruise cycle. The main target is to find the trade-off solutions, known as Pareto-optimal set which presents solutions not dominated by any other with respect to all objectives involved.

The optimization problem is formulated as following:

$$\begin{aligned}
Minimize \quad & J(X_D, U(X_D)) \quad w.r.t. \quad X_D \\
& where \quad variables \quad X_D = [x_1, x_2] \\
& x_1 \in [250, 3000], x_2 \in [250, 3000] \\
& where \quad objectives \quad U_1(X_D) = \alpha_1 x_1 + \alpha_2 x_2 \\
& U_2(X_D) = \beta_1 x_1 + \beta_2 x_2 \\
& Subjected \quad to \quad c(X_D) \\
& c_1(X_D) : P_{peak} < x_1 + x_2 \\
& c_2(X_D) : 1.1(E_{cycle}) < Q_{b,sc} V_{b,sc} + \phi_{fc} x_2 \Delta t_{cycle}
\end{aligned}$$

The variables are the rated power of the battery and the fuel cell, respectively. The objective function $U_1(X_D)$ minimizes the cost of the powertrain, with the constants α_1 and α_2 standing for unit cost of the supplies per W. The second objective function seeks for minimization of the weight of the power supplies which is the main reason for hybridization, since the battery systems are much heavier than the fuel cell systems despite being significantly cheaper. The unit weight constants

Table 2: *Optimization problem constants*

Unit battery cost, α_1	0.814 / €W
Unit fuel cell cost, α_2	3.8 / €W
Unit battery weight, β_1	0.012 kg/W
Unit fuel cell weight, β_2	0.006 kg/W
Scaled nominal battery capacity, $Q_{b,sc}$	0.019 Ah/W
Scaled nominal battery voltage, $V_{b,sc}$	0.009 V/W
Load factor of fuel cell, ϕ_{fc}	0.4

β_1 and β_2 are given with in Table 2. The constraints of the optimization are delivery of peak power and ensuring that the range of the boat is capable of delivering 10% more than required. Instead of a con-current optimization embodying the detailed physical modelling of the components, system level modelling abstraction is applied to get an outline for the performance criteria in terms of the transient load and range. The fuel cell is assumed to operate at high efficiency region, which corresponds to load factor, ϕ_{fc} of 0.4. Hence, this optimization can only be an initial design optimization to be supported with third discipline of energy management system directly relating with dynamic operation of the powertrain. The flow of the optimization is described in Figure 13. The backward model of the boat firstly assesses the load profile on the hybrid power-supply indicating the peak power demand to set the first constrain. Algorithm starts execution to find fit candidates fulfilling both objectives. The constrain of the optimization is determined through energy mapping for desired performance of the power-supply. The second non-linear constrain ensures the range of the boat. The fittest individuals take place in the Pareto-optima set if they can satisfy range and peak power delivery criteria. In essence, the cross-over exploits the potential of the local search region, whereas random mutations explore the global space. The population of parents are then replaced with the off-spring population to be evaluated for the objective functions. This process is repeated until the fittest candidates are obtained. The cost minimization objective converged with the fittest individuals in between the €5,334 - €11,052 interval, whereas the weight of the power-supply has been minimized in the 20.5 kg - 40.3 kg range. Many of the Pareto-optimal solutions are above €10,000, since after this point, a significantly lean powertrain can be achieved.

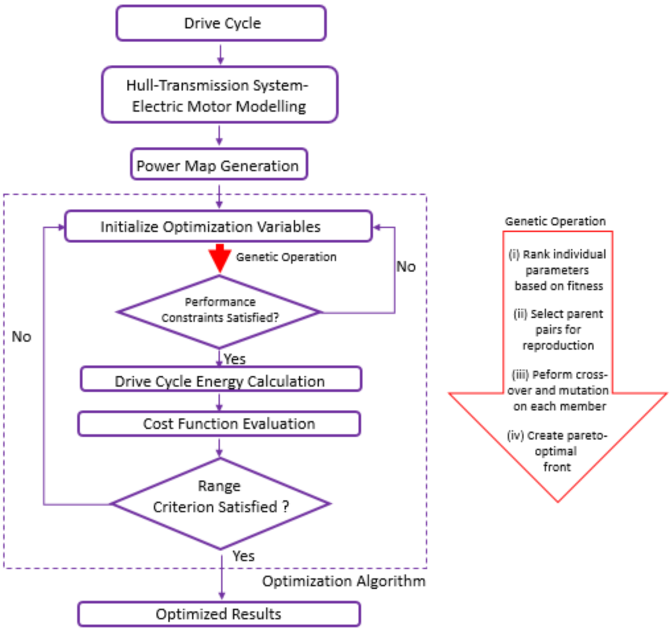

Figure 13: *Optimization flowchart*

Optimization results have been analysed based on hybridization ratio of the power-supply as well, as shown in Figure 14. Hybridization ratio is the ratio of the fuel cell rated power to the power-supply grant rated power, since the analysed FCHEP is a range extender. Current design of the powertrain deploys 500 W fuel cell and 5000 W battery, corresponding to 0.1 hybridization ratio which met the load. However, the fitness value of the design is € 5970 for 63 kg, which clearly could not take place in the Pareto-set due to over-sizing, hence suggests poor accelerative performance due to bulky design. Ideal hybridization ratios have been optimized in between 0.2 - 0.9, although the variable constraints were enabling much higher and lower results.

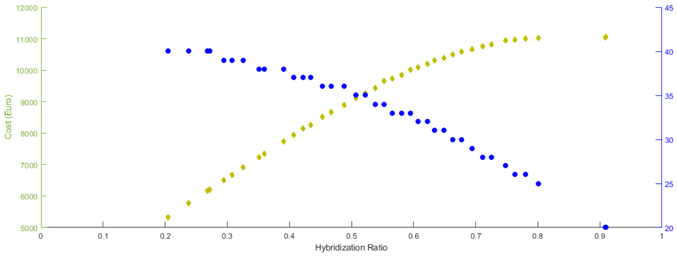

Figure 14: *Effect of degree of hybridization on cost and down-sizing*

From both scientific and commercial points of view, the multi-objective optimization of the powertrain design is promising. Nowadays, it is quite easy to develop a driving profile of a user and customizing the design yields much efficient designs as proved with the optimization results. For the required drive cycle, the powertrain could have been produced with 35% reduced weight for 90% of the cost. Backward modelling utilizing an estimated drive cycle offers a one step ahead intuition for the design of a powertrain and provides an overall understanding of its performance.

7 Conclusions and Future Work

Different levels of abstraction have been applied for modelling of the components to acquire a powertrain simulation with high fidelity to real life performance. The EMS managed the battery to follow the load whilst the fuel cell operated at optimal efficiency. The current loads on the components were optimized and a safe performance was ensured.

Hybridization of a battery electric powertrain with a fuel cell for range extension purposes for a zero-emission boat has proved to be a powerful alternative to substitute the pollutant internal combustion deployed low-power boats in the same segment. The developed powertrain has a highly agile and efficient performance under usual and extreme cruise conditions. The simulations of the boost converter implemented powertrain and optimization studies have shown that there is still plenty of room for cost reduction and performance improvement. Still, the diffusion of the technology in the market is weighed down in the short-term by the classic chicken and egg problem of the infrastructure. Hopefully, the possibilities deployed in this thesis will provide strategic advantages and innovation for the zero-emission maritime transportation in the future.

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