

# Integrating Modular Hydrogen Fuel Cell Drives for Ship Propulsion: Prospectus and Challenges

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**ABSTRACT:** This paper proposes a new drive system for the ship propulsion. The drive power for propelling ship varies from few MW in a small cruise ship to hundreds of MW for large cargo ships. A typical cruise ship has a 6 MW drive whereas a cargo ship has 80 MW drive. Combustion drives are not sustainable and environment friendly. An idea of electric drive system using hydrogen fuel cell and necessary storage has been proposed. The hydrogen reformer develops hydrogen fuel cell using off-shore renewables like Wind, Wave and Solar power but the power handling capability of this fuel cell system (100 kW) restricts the application to the propulsion drives of several MW. The detail drive scheme describing; how multiple modular hydrogen fuel cell drives are integrated to develop variable power. The different options available for the propulsion system and factors affecting the choice are discussed in detail. Also, how such modular drives are helpful in controlling torque and power requirements is discussed. Replacement of electric drive reduces volume and weight of the ship and the available volume can be utilized for the storage and reform systems. The proposed paper will give a remarkable concept to overcome the challenges of utilizing hydrogen fuel cell to the larger scale and in future it can be extended to all other applications.

## 1 INTRODUCTION

The shipping industry has come a long way using combustion engines in transporting goods between continents, but in general the transportation sector accounts for a large fraction of air pollutant emissions. Health and environmental effects of air pollutants such as NO<sub>x</sub>, CO, VOCs, and particulates are leading to stricter tailpipe emissions regulations worldwide. [1, 2]. Virtually all transportation fuels today are derived from oil. Oil production is projected to peak worldwide within a decade and there no guarantee that oil will be enough for worldwide increase in consumption.

New frontiers have opened in the application of hydrogen as fuel for ships. A hybrid research ship [3], this research ship turns silent when scientists start recording whale songs. A 42-m long slick, hydrogen yacht with sufficient power was reported in [4].

This paper is a step toward resolving the integration of three main components required to design and discuss the concept of a large power hydrogen powered ship; the hydrogen fuel cell, the electronic drive and a uniquely designed motor. The uniqueness of the design is in integration 100kW, 250kW and the latest 4MW solid oxide fuel cells [5] to energize each pole of a sixty pole induction motor, assuming the drive system provides sixty Hz.

There is no doubt that there is much work to be done in order to establish a hydrogen based shipping industry, but the technology to initiate the transformation is in place.

The fact that the process and the technology is in place will require a resolution on how the new industry should be developed. The overall idea of a shipping economy based on hydrogen is discussed in [6,7].

## 2 HYDROGEN FUEL CELL

Energy can be stored in variety of forms, but clean energy production from natural sources such as wind, tidal, waves and sun are abundant, but need storage to be utilized when needed. The electric power produced by all means is used to split water into hydrogen and oxygen. Hydrogen could be stored in high pressure tanks, these tanks are getting smaller to a degree that it could be utilized in ship design. The DOE hydrogen program reports, tube trailer delivery capacity of 700kg by 2010 and 1,100kg by 2015 at 8300psi. Note that heating energy in hydrogen is 33.33kWh/kg, for methane it is 13.9-kWh/kg and for petroleum 12.4kWh/kg. To travel 400km, a modern combustion vehicle needs 24-kg of gas, 8-kg of hydrogen in hydrogen combustion engine and 4-kg of hydrogen in a fuel cell, electric drive vehicle.

A hydrogen fuel cell is a device that converts hydrogen to electricity. The device exhausts pure water and heat in the process of this transformation. Fuel cell technology has improved to a degree that many car companies are introducing new models of commercially available hydrogen cars. DOE projection of hydrogen fuel cell prices have been achieved, as this market expands the fuel cell prices will be much lower than DOE projection. Figure 1 depicts price trends for hydrogen fuel cell.

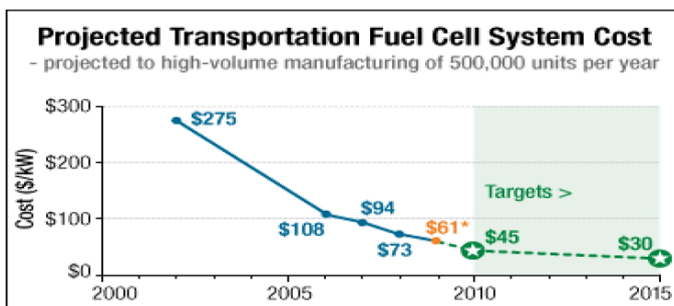


Fig. 1 Price Trend for Hydrogen Fuel Cell

To completely demonstrate the feasibility of the hydrogen based economy a model cargo ship, sixteen to twenty two mega watts should be constructed using hydrogen fuel cells with possibility of on board hydrogen reforming, production and storage.

To supplement hydrogen, we propose an aerodynamic cargo model ship with retrieving solar panels and small onboard wind turbines to produce power needed for in house hydrogen reformers.

Hydrogen production and dispensing is done by creating small scale hydrogen producing platforms, containing solar, wind, and wave energy conversion mechanisms. The electric energy produced is used to

split water into hydrogen and oxygen. These platforms also house a fueling station and limited storage for hydrogen. A typical MERP- Marine Energy and Refueling Ports is depicted in fig.2.

Using technology developed for automobile hydrogen refueling stations and applying it to Marine Energy and Refueling Port (MERP) is feasible, however, more studies need to be conducted to relate the two systems. Here are a few proposed models:

- 1 The first model is suitable to coastal areas where a hydrogen pipeline is part of an existing infrastructure to bring energy to urban and coastal areas. The MERP's can be integrated into this system and could simply contain small storage and fueling stations.
- 2 The second model is based on a distributed, small scale local supply for hydrogen shipping. This model encourages complete reliance on renewable energy resources such as tidal, wind, solar and, where available, wave energy.
- 3 Designing and utilizing mobile hydrogen producing ships equipped with wind turbines and hydrogen reformers. These mobile vessels could catch high winds and produce hydrogen and could also serve as on the way mobile refueling stations.

Marine Energy & Refueling Ports are envisioned as non-intrusive, small islands attached to coasts or in off-coastal areas where maximum energy yields can be harvested from wind, wave and tidal currents. Such an MERP will house a compatible hydrogen reformer, low pressure hydrogen storage and a fueling station. In addition, these structures should house a vertical axis wind turbine, a vertical axis tidal turbine, photo voltaic panels and the appropriate electronics necessary for the control and conversion.

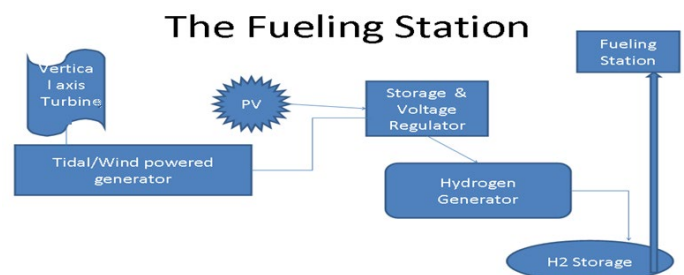


Fig. 2 Marine Energy & Refueling Port

Electric drives for ships are well developed and require little change when coupled to hydrogen fuel cells. The design proposed in this paper is an attempt to show how the technology developed for cars could be transferred to ship design.

### 3 ALL-ELECTRIC SHIP CONCEPT

Combustion drives will not be sustainable over the future and are not environmentally friendly. The electric drive system for the ship propulsion proposed in this paper has the advantages of [8]:

- Efficient and Improved life cycle cost
- High Power/volume and Power/weight ratio i.e. high payload of vessel
- Less propulsion noise and vibrations
- Ease of speed control
- Flexibility in thruster device locations

All-electric ships using fossil fuels are a present day reality. This concept leads to designs which can use on-board electric power for effective and efficient propulsion, while auxiliary systems usually powered by steam, hydraulic, or pneumatic energy are converted to electrical power. This “single bus” ship can thus allocate power as needed according to the mission profile of the vessel. Electric propulsion has been applied to different types of ships, such as cruise vessels, ferries, dynamically-positioned drilling vessels, thruster assisted moored floating production facilities, shuttle tankers, cable layers, pipe layers, icebreakers, supply vessels, and naval vessels. There are many different configurations available for the propulsion systems.

In conventional all-electric ship design configurations, sets of engine-generators produce electric power that is distributed for all auxiliary and main propulsion systems as shown in fig. 3. The system is approximately about as efficient as conventional non-electric drives, but the costs of generators, motors and static drives can make this solution expensive [9]. The operational benefits and the advantages of design flexibility justify such additional costs.

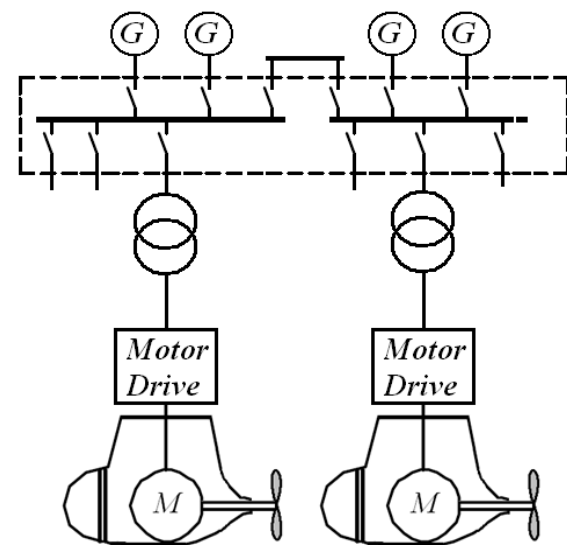


Fig.3 On-ship Power generation distribution and Propulsion Motor Controls

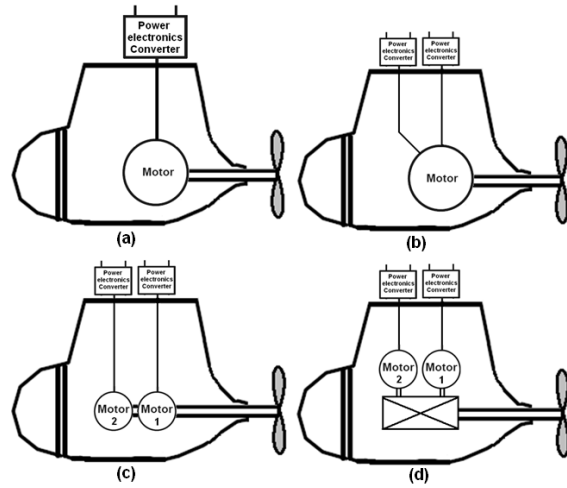


Fig.4 Different Propulsion drive configurations

In these configurations, the power developed by all generators is supplied to a common bus. Then the ship propeller is supplied power through transformers and converters as shown in fig.3.

Typically, for twin-screw ships, each propeller is controlled by a single motor drive as shown in fig. 4(a). Other common schemes used for E-Ship propulsion are shown in fig.4. A two winding motor with redundant converters is shown in fig. 4(b), in which the redundant winding is supplied through another power electronic converter. Fig.4 (c) shows Tandem motor with redundant converters, and fig.4 (d) shows a geared dual shaft propulsion drives in which, two motors are coupled to the propeller through a gear [10]. The application of these configurations depends on size and type of the ship.

### 4 HYDROGEN FUEL CELL BASED DRIVE

As discussed in section-1, the limitation of hydrogen fuel cell is to supply power at the level of 100 kW. For conventional diesel-generators and fuel based generators, one of the configurations discussed in section 3 can be used. Also, for boats and small ships, it is easier to handle propulsion power through one of the schemes shown in fig. 4. For cargo ships having power requirements much greater than 5 MW, it is difficult to address the challenge of making the ship all electric-ship utilizing hydrogen fuel cells. Two configurations are proposed in this paper namely (a) distributed modular generators, and (b) modular drive operation. Following section discusses each of the schemes in detail.

#### 4.1 Distributed modular generators

A distributed modular generation configuration is shown in fig. 5. It is possible to mount the hydrogen fuel cell (FC) modules in a distributed form in the ship. An AC bus can run through the ship and all

power is generated by fuel cells (FC) and controlled by a power electronic (PE) converter is supplied to this bus. A transformer provides the higher voltage required for the propulsion motor. The auxiliary supply can be met by either the similar fuel cell or using diesel-generator set. This configuration is advantageous when the fuel cells are located as distributed form. Control of each individual fuel cell power generator module is a challenge if they are located as distributed manner.

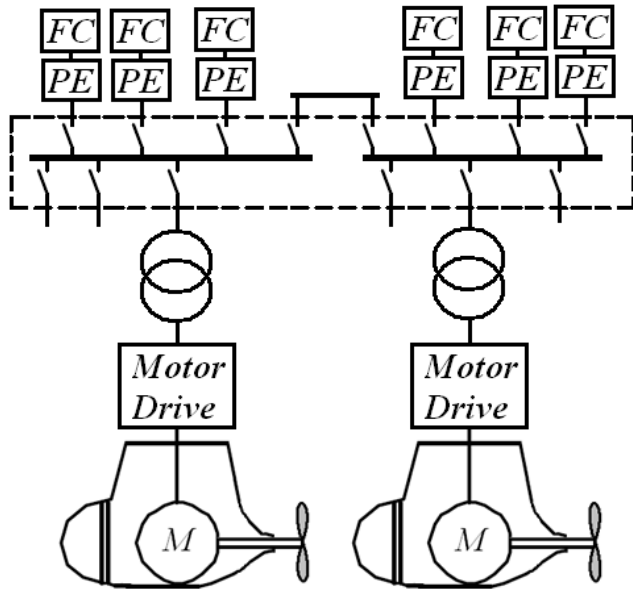


Fig. 5 Distributed Hydrogen Fuel Cell Power generations and Propulsion Motor Controls

#### 4.2 Modular drive operation.

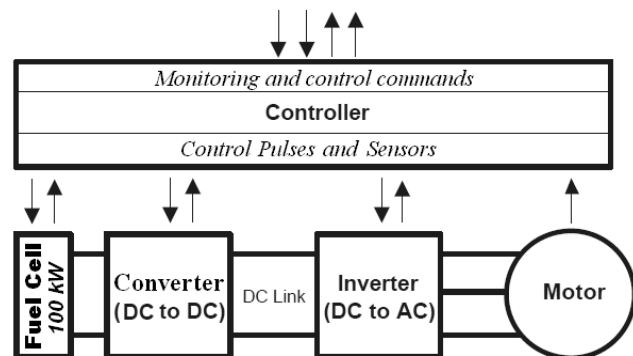


Fig. 6 100 kW Hydrogen FC power module

Another scheme is to place all hydrogen fuel cells centrally. Each of FC produces power in order of 100 kW. The PE module designed to work at low power rating of 100 kW, can control power flowing to the stator of the main motor as shown in fig. 6.

The sensors measure speed, position, load current and all necessary control parameters. The controller senses all these signals and send signals to centrally located control station for monitoring and control action. The controller also develops control pulses

for the FCs, PE converters, and inverters. All these modules are synchronized with motor parameters. Due to low power and voltage ratings, the cost of this module is low as compared to developing large rating PE converters discussed in section 4.a, and a transformer is not required to boost the ac voltage.

A typical small ship may have a 6 MW drive whereas a large cargo ship has an 80 MW drive [5]. To control 6 MW propulsion power, sixty such modules are placed as shown in fig.5. All these modules are integrated through a centralized distributed control system. For higher power applications, Permanent Magnet Synchronous Motors (PM SMs) could be employed. The advantages of PMSMs include high efficiency, ease of control, and high torque/weight ratio. Due to reductions in the cost of rare-earth magnets, these machines have lower payback periods. Thus, designers may select among alternative configurations depending upon the size and type of application for ship propulsion.

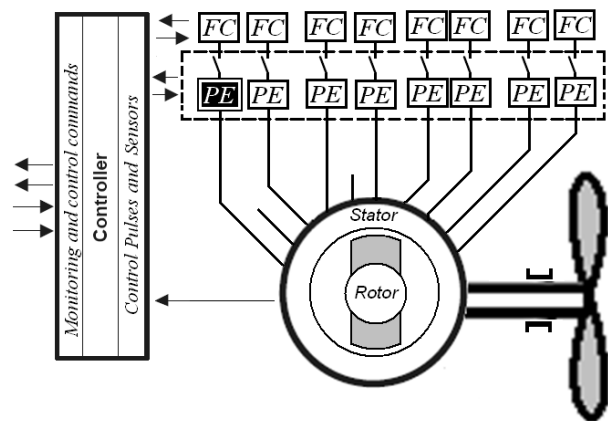


Fig. 6 Integrating Modular Hydrogen Fuel Cell Drives for ship Propulsion

## 5 SIZING EQUATION FOR PERMANENT MAGNET PROPULSION MOTOR

The output equation for the radial-flux PM BLDC motor is derived based on the expressions for the torque and back emf [11];

$$P_r = T\omega_m = \eta N_c E_{ph} I_{ph} \quad (1)$$

$$T = \frac{P_r}{\omega_m} = \frac{\eta N_c E_{ph} I_{ph}}{\omega_m} \quad (2)$$

By substituting the values of induced emf in the above equation, the torque is given as;

$$T = \frac{\eta N_c (N_m N_{spp} K_w B_g LD_{ro} n_s \omega_m / 2) I_{ph}}{\omega_m}$$

$$= \frac{\eta N_c N_m N_{spp} K_w B_g LD_{ro} I_s}{2} \quad (3)$$

$$LD_{ro} = \frac{2T}{\eta N_c N_m N_{spp} K_w B_g I_s} \quad (4)$$

The rated power output is the product of efficiency, phase voltage, phase current and the number of coil conducting simultaneously. The output is also given by the product of developed torque and the motor speed in rad/sec. Comparing the two and simplifying the equation the output equation for the radial-flux PM BLDC motor can be obtained. A specific slot loading  $I_s$  can be considered for the output equation. The  $LD_{ro}$  product depends on the torque developed by the motor, specific magnetic loading, specific slot loading, and the efficiency as shown below;

$$LD_{ro} = \frac{2}{\eta N_c N_m N_{spp} K_w B_g I_s} \left( \frac{P_r}{\omega_m} \right) \quad (5)$$

Output equation relates the physical dimensions of the radial-flux PM BLDC motor with the power output, speed, assumed efficiency, number of phases conducting simultaneously, number of magnet poles, slots per pole per phase, winding factor, assumed magnetic loading and assumed electric loading [11].

For the rated power of 6 MW, 100 rpm, 1000 V per drive module, 60 poles, 3 slots/poles/phase and Average airgap flux density of 0.6 T, following overall machine dimensions are obtained;

*Core Length of machine* = 0.95 m

*Rotor inner diameter* = 0.95 m

*Outer diameter of stator* = 1.57 m

*Efficiency of the machine* = 0.96

Usually, the shaft diameter for 6 MW propeller is 0.9 m. This parameter matches with the rotor inner diameter. The machine can accommodate 60 coils for each power electronics module. An idea of electric drive system using hydrogen fuel cell and necessary storage has been proposed [2]. The hydrogen reformer develops Hydrogen fuel cell using off-shore renewables like Wind, Wave and Solar power but the power handling capability of this fuel cell system (100 kW) restricts the application to the propulsion drives of several MW. The detail drive scheme describing; how multiple

modular hydrogen fuel cell drives are integrated to develop variable power is shown in fig. 6.

## 6 ECONOMIC CONSIDERATIONS

The economic advantages of hydrogen-based ship propulsion remain uncertain at present, but may become more apparent as hydrogen production and consumption becomes widespread. The factors that must be considered for an economic analysis of hydrogen ship propulsion include:

- The weight, volume, and cost of shipboard hydrogen fuel storage compared to traditional storage of fuel oil.
- The weight, volume, and cost of electric generating equipment and main propulsion motors compared with traditional diesel or steam main propulsion machinery and associated ship's service generators.
- The cost of obtaining hydrogen fuel as compared to obtaining hydrocarbon fuels that will satisfy environmental requirements in the future, on an energy-equivalence basis.
- The cost of periodic maintenance of hydrogen-electric machinery compared to traditional marine power plants.

This assumes that the availability and reliability of hydrogen-electric machinery will be equivalent to traditional plants. This is a fair assumption with respect to the electrical machinery, but remains to be proven for fuels cells and related equipment. Also, one must assume that adequate supplies of hydrogen will be available.

Given a twenty year life for a ship, an incremental analysis of equivalent ships having alternative propulsion modes would rely upon a net present value expression such as:

$$NPV(\Delta Cost) = \Delta Cost_{MACH} + \Delta Cost_{FUELSYS} + (P|A, i\%, 20) [\Delta AnnCost_{FUEL} + \Delta AnnCost_{MAINT}] \quad (6)$$

where the change in costs of machinery and fuel systems are capital expenditures in the present, and the sum of annual differences in the costs of fuel and maintenance are reduced to a single present value by the application of the Series Present Worth Factor over the life of the ship at a cost of capital of  $i\%$ .

For a cargo ship, the Minimum Required Freight rate (MRFR) is often used as a figure of merit is assessing a ship design. This is simply a ratio of the annualized cost of the acquisition and operation of the ship over the life of the ship, divided by the annual tonnage of cargo carried (i.e., the ATC), and the owner seeks to have a vessel with the minimal MRFR to be more competitive. Assuming that the

cargo carrying capacity of a hydrogen-powered vessel is the same as a conventionally powered ship, the change in Minimum required Freight rate would be

$$\Delta MRFR = \frac{(A|P, i\%, 20)NPV(\Delta Cost)}{ATC} \quad (7)$$

A singular advantage that could accrue to a hydrogen-powered vessel could be a reduction in weight and volume of the machinery and fuel storage, which would allow for additional cargo to be carried in a ship of equivalent displacement.

## 7 CONCLUSIONS

Replacement of electric drive reduces volume and weight of the ship and the available volume can be utilized for the storage and reform systems. The proposed modular drive scheme will give a remarkable concept to overcome the challenges of utilizing hydrogen fuel cell to the larger scale and in future it can be extended to all other type of marine applications.

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