Simulating the Engine Room of a Hydrogen Powered Cargo Ship

Yaqub M. Amani, PhD
Professor of Electrical Engineering, SUNY Maritime College,

Catherine K. Strez
Professor of Marine Engineering, SUNY Maritime College,

Abstract: The main objective of this paper is to present a basic model for simulating a hydrogen-powered cargo ship engine room and monitor the dynamic parameters related to operation of the engine using suitable simulation techniques. The modeling of a hydrogen powered ship engine room is important and will open a new direction in comparative studies of this new technology and combustion type engine room. The knowledge obtained from hydrogen cars shows interesting results in two particular aspects; the efficiency improves drastically and hydrogen powered cars have about 74% less parts. This in turn will drastically reduce the weight of a vehicle. Since hydrogen has half the energy density of gasoline and heavy oil used in shipping, hydrogen powered ships will require more storage space for long distance journeys. Hydrogen storage technology research shows promising alternatives for safe and compact storage. Onsite, on- demand hydrogen generators are available and could be utilized for future ship design. The results of the simulation are compared to a combustion engine room and also we look at the number of parameters monitored in a typical combustion engine. An attempt is made to estimate the size of a hydrogen powered engine room based on latest commercially available fuel cell, other electronic components and electric motors. The outcome of simulation will be analyzed for the operation simplicity and environmental impact. In our first attempt to demonstrate the virtual operation of a hydrogen powered ship, we will build a model based on input-output characteristics of each component and will include the monitoring of some basic physical functions, such as temperature, hydrogen intake pressure, volts and amperes delivered to load. The torque –speed characteristics of the electric motor used in our model will be integrated into simulation

Keywords: Hydrogen powered ship, cargo ship, maritime, marine environment, hydrogen ship simulation, LNG

1. Introduction

There is no doubt that electric propulsion for ships has many advantages, which include low pollution, low noise, less space and maneuverability. A typical electric propulsion system consists of a number of subsystems shown in Fig. 1. This scheme requires a number of components that have been designed for DC ships and the latest class of electric AC ships [1[i], [ii]2, [iii]3]. Due to weight, size and maintenance, DC ship designs were abandoned for AC powered ships. A great number of warships employ electric propulsion where maneuverability is a factor and electric propulsion is desirable for cruise ships because of low noise.

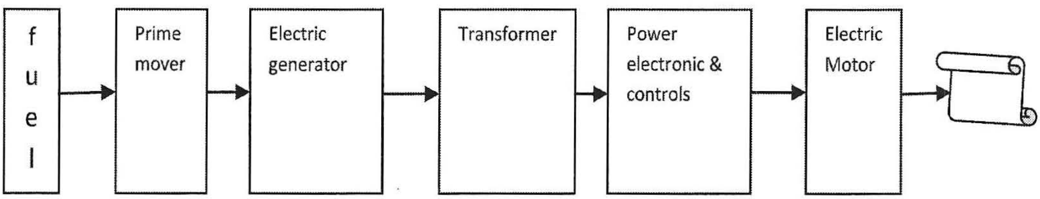

Figure 1 Typical Electric Propulsion

DC propulsion is common in submarines where the power source is a hydrogen fuel cell or nuclear power. The latest developments in hydrogen fuel cell technology, hydrogen generation technology and power electronics make hydrogen fueled electric propulsion system an attractive alternative for commercial ships. The idea of hydrogen propulsion should be coupled with hydrogen economy proposed at IAMU AGA11 and AGA12, [4, 5, and 6] which details the issue of hydrogen economy and comparative analysis of combustion cargo ship verses hydrogen powered cargo ships. To demonstrate the operational characteristics of a hydrogen powered ship, we have used Math-Lab, Power-Sim program. The basic assumption for our design is that hydrogen powered ships can be built by using a modular design concept. The idea is to deliver power to the main shaft by integrating a number of low powered motors synchronized and controlled by a central computer. This scheme can be implemented by a variety of designs and has many advantages, such as reliability and use of modular low power fuel cells and hydrogen generators or storage for hydrogen supply. The use of mobile Marine Energy producing and Refueling Platforms (MERPs) will make implementation of this approach for future ship design possible, since these ships will require minimal storage capacity.

Mathematical Model of for Hydrogen Fuel Cell

The mathematical model for Proton Exchange Membrane (PEM) hydrogen fuel cell is based on diffusion of hydrogen gas in the electrodes. There are a number of assumptions for (PEM) type fuel cell, listed in [7]. In this paper we outline the parameters we have included in our simulation model of fuel cell. The output voltage for a single fuel cell is obtained from:

$$\mathbf{E_{cell} = E_{0Cell} - K_E\,(T - 289)}$$

Where, K_E is an empirical constant when calculating Eo in volts/Kelvin at 289 degrees and one atmosphere.

Stacks are formed by layers of individual cells and the detailed model for a particular cell stack is constructed when a number of parameters such as pressure, fuel composition and hydrogen air flow rates vary. The open circuit voltage, current and Tafel slope are expressed as:

$$E_{oc} = K_c E_{cell}$$

$$I = [ZFk\,(P_{H2} + P_{o2})\, e^{-\Delta G/RT}]/Rh$$

$$A = RT/Z\alpha F$$

C is stack voltage constant, Z- number of electrons, F= 96845 is Faraday's potential, k – Boltzmann's constant, P_{H2} and P_{o2} are partial pressures of hydrogen and oxygen inside the stack, ΔG activation barrier size, R -8.3145 J/ mol-Kelvin , T – operating temperature, h- Plank's constant and α- charge transfer coefficient.

The hydrogen and oxygen utilization are given by:

$$U_{H2} = \frac{60000RTNI}{ZFP1\,V\,(x\%)}\ ;$$

P_1- fuel pressure, x% percentage of hydrogen in fuel

$$U_{O2} = \frac{60000RTNI}{2ZFP2OV(y\%)}\ ;$$

P_2 - absolute supply air pressure, y% - percentage of oxygen in the oxidant.

The hydrogen fuel cell and induction motor basic models are used from the components of Sim-Power but the entire auxiliary circuits and subsystems are designed in order to achieve the desired results for the simulation of hydrogen powered ship engine room. We have limited the scope of this paper to an introductory level simulation just to demonstrate the idea.

The Simulation Process

The block diagram of the simulation circuit is depicted in Fig.2. There are three main blocks in the circuit. The first block is the hydrogen fuel cell. In our simulation we have selected only hydrogen as input to the system. The model does not represent system temperature variation, air flow pressure, fuel pressure and many other parameters that will give us a detailed view of the engine room monitoring system. The motor block measurement circuit contains a number of subsystems for conversion of motor complex variables to real and also subsystems to measure motor RPM and other related parameters. The intermediate block is an inverter circuit using IGBT type transistors and is driven by pulse width modulator.

To see a drastic change in the values of simulation parameters, we have chosen to vary the mechanical torque as input to the drive system. Hydrogen supply regulator was designed to take the power demand by reading current delivered by fuel cell to the induction motor, the per phase rms value of the stator current which is representative current delivered by fuel cell was programmed to simulate hydrogen flow rate and utilization. The result of simulations must be considered to be the case for an ideal system, since we have assumed forward voltages of IGBTs to zero and also all losses incurred in induction motor are not represented in this model.

To simulate a more realistic engine room, one must take all the losses, temperature dependence of hydrogen fuel cell and hydrogen supply pressure which we will present in the future.

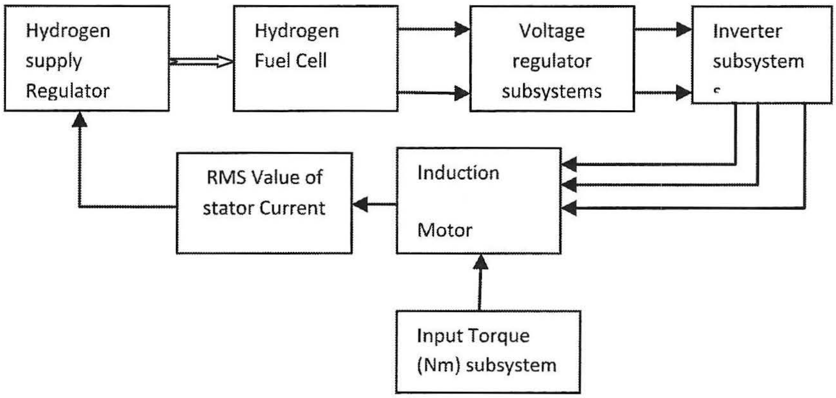

Figure 2 Block Diagram of Simulation

The Math-lab simulation model is complex, it requires many sub systems each containing secondary and sublevel systems. A simple first level component and subsystems is presented in fig. 3. There are a number of monitoring screens which can incorporate detailed monitoring of a large number of variables. We have limited ourselves to four monitors. Figure 3 from left to right the first top monitor display gas flow and utilization of HFC, the second displays electric output parameters of HFC, the third monitor displays inverter input and output variables and the last on the right displays the motor electric and mechanical characteristics.

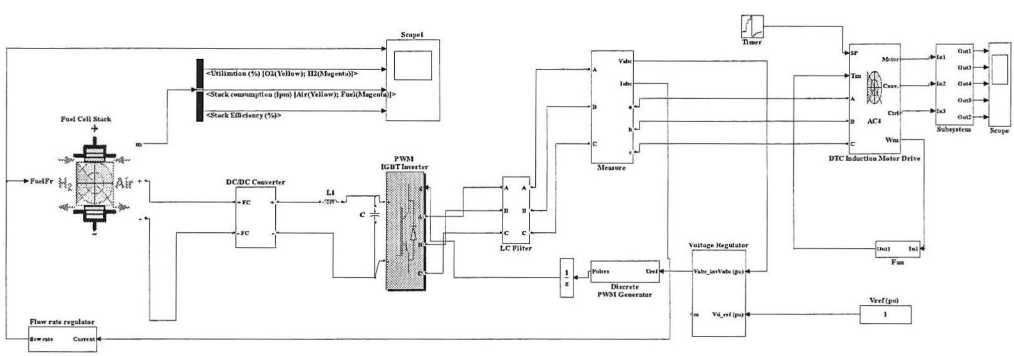

Figure 3 Actual Power-Sim Simulation Block Diagram

To present a complete picture of simulation analysis is out of the scope of this paper; therefore, only a few parameters are presented to emphasize the importance of this type of research in maritime related industries. The first graph in Fig.4 displays volt-ampere characteristic of the fuel cell employed in simulation. The result of simulation is within the range of these characteristics. It is important to point that the reason for selecting a low power fuel cell and motor is because the drive is considered to be a modular drive system. The preference would be a 300KW fuel cell driving 300KW motors running at 60Hz and sixty poles and producing 120

RPM max. Sixty motors integrated into a modular drive system will for our simulation result in a 3MW drive and for300KW HFC to 18MW power needed for this purpose.

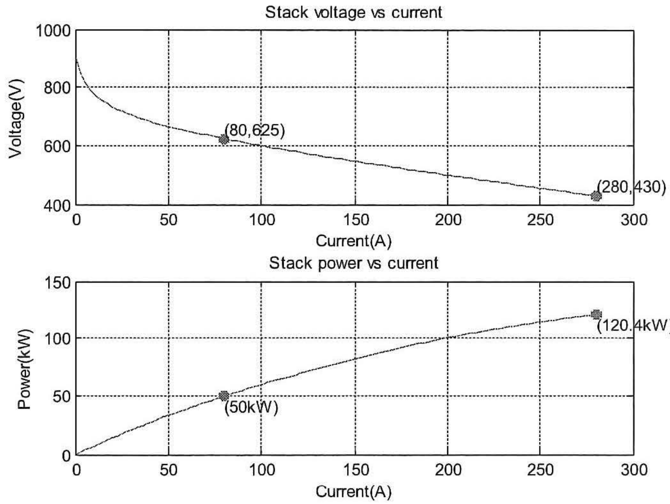

Figure 4 HFC Characteristics

The operating characteristics of the hydrogen fuel cell in Fig. 5, shows that it responds to power demand by the motor. The nominal characteristics of the fuel cell we have used for this simulation are;

Stack Power: 50,000W max 120.4KW
Resistance =0.66404 ohms
Nearest cell voltage = 1.1342 V
Utilization H_2; 99.25% $O_{2;}$ 70.4%
Consumption $H_{2;}$ 501.8 slpm, air 1194 slpm
Fuel composition %x = 99.95 % %y = 21%
Hydrogen flow rate 417.4 lpm max 1460 lpm
Air flow rate 2100 lpm max 7350 lpm

Fig. 5 shows the result of simulation for some these parameters. The nearest volts goes to zero once a large torque is applied to the motor, the fuel cell current jumps to a very high value exceeding the operating maximum of 280A because of large starting current of induction motor but stays around and below 280 A.

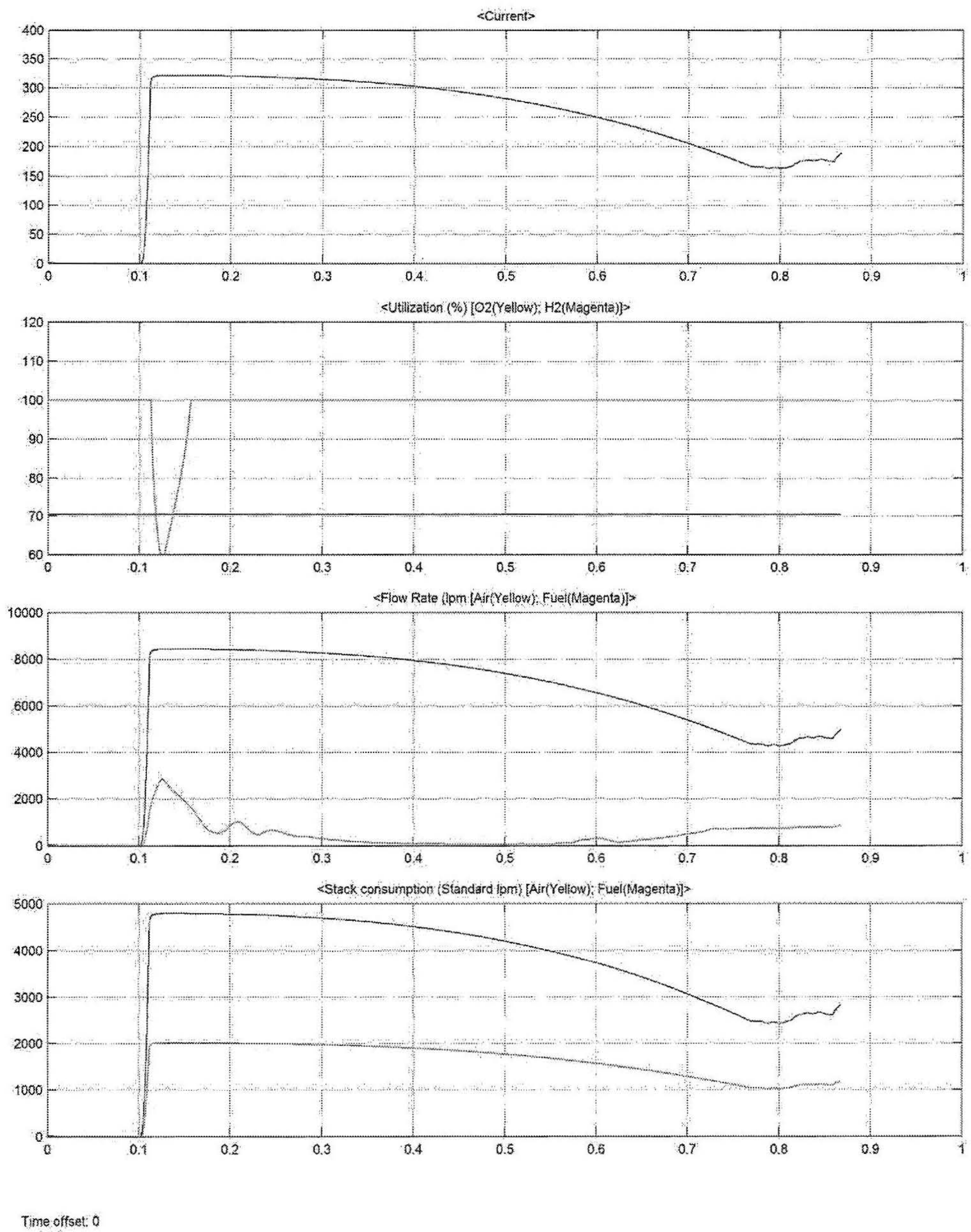

Figure 5 Fuel Cell Response

The flow rate for fuel and air stays within range after the induction motor transition period ends and reaches steady state.

Fig.6 is the response of the induction motor powered by fuel cell. The output of HFC is connected to the input of an inverter, which produces sixty Hertz sinusoidal three phase voltages and currents. The RMS value of the motor current is defining the behavior of the fuel cell

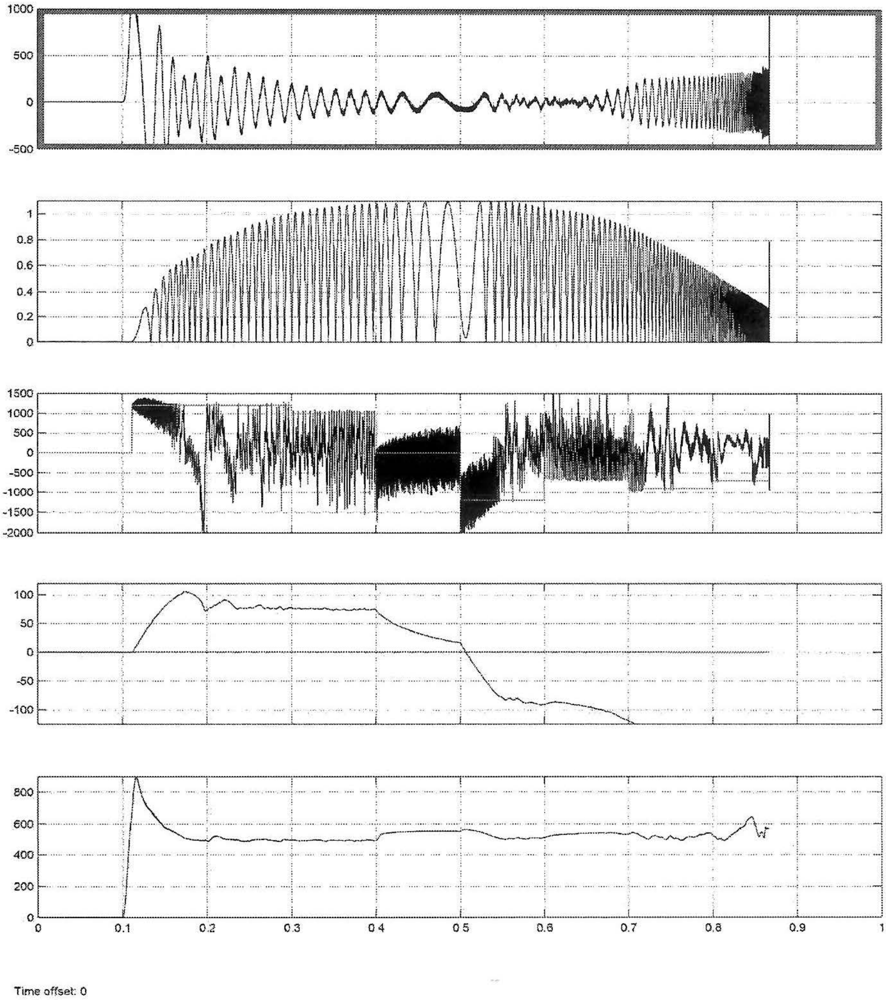

Figure 6 Induction Motor Response

1. Stator Phase Current (A)
2. Magnetic Flux (Wb)
3. Input torque (N-m)
4. Motor RPM
5. RMS value of bus voltage

2. Discussions Conclusions

This simulation is a model calculation for further development of the modular hydrogen powered ships. There are many reasons to think about modular drive system which first time was introduced at AGA11 in Pusan South Korea.

First it is more reliable design since the failure of one module will not compromise the integrity of the total drive system.

Second requires low power electronic components leading to lower prices for construction.

Third it allows the employment of small size Methane Steam Reformer modules for onsite on-demand hydrogen production, thus reducing criteria emission.

Fourth it will use LNG as fuel to produce hydrogen and the technology for transporting and storing LNG is already developed.

Fifth the sensors and powerful electronic compact mechanisms pave the way for synchronization of all modules and therefore creating possibilities for a number of ways to apply the concept of modular drive system.

Here we presented the simulation for only one module. To integrate a number of modules, the computing facilities must be large and requires the collaboration of at least five field of engineering which we hope to achieve for complete demonstration of this idea. The electrical engineers, to oversee the design of realistic modules presented here and to see the integration of these modules through a complex control system, marine engineers, naval architects and, mechanical engineers and computer engineers.

The perfect model ship for future will be a hydrogen powered ship with the use of renewable resources integrated in the design and having auxiliary LNG and Steam Methane Reformers on board. This will eliminate one of disadvantage of hydrogen for ships which is low energy density, a quarter of HFO. LNG having a higher energy density will reduce relative storage needed for hydrogen powered ships.

References

1. J.M. Prousalidis, N.D. Hatziargyriou, B.C. Papaddias "On Studying Ship Electric Propulsion Motor Driving Scheme" National Technical University of Athens
2. Alf Kare Adanes, Maritime electric propulsion and Diesel Electric propulsion, ABB AS Marine
3. Chee Mun Ong " Dynamic Simulation of Electric Machinery Using Mathlab Simulink, Prentice Hall, 1998
4. Y.M. Amani. 2010.Hydrogen Based Shipping Industry, AG11 Presentation, Pusan South Korea.
5. Y.M. Amani .2011, A Pioneering Hydrogen Fueled Cargo Ship. The First Global Conference on Innovation in Marine Technology and the Future of Maritime Transportation
6. Y.M. Amani, C. Strez, and C.Munsch. 2011.Comparative Analysis of Combustion verses Hydrogen Fueled Cargo Ship" IAMU, Gdynia Poland