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Modeling of Fuel Cell Electrical Supply Management System for Onboard Marine Application

K. Mercy Rosalina, K. Nirmala Kumari, N. Prema Kumar

***Abstract*— This paper presents the design of A dynamic model of the PROTON EXCHANGE FUEL CELL (PEMFC) developed in MATLAB for the marine applications of renewable power generation in on board ships or commercial vessels.. A three phase inverter has been modeled and connected between the PEMFC-DC-AC system on the one side and the utility grid on the other side through an ideal transformer. Modeling and simulation study of a PEMFC power system is investigated in this paper. A validated PEMFC dynamic model is used to model the fuel cell system. A three phase inverter has been modeled and connected between the PEMFC power system on one side and the utility grid on the other side through an ideal transformer. A MPPT system is also included in the system to improve the maximum power conditions of the PEMFC. Hence a fuel cell system suitable for the marine application is developed.**

***Index Terms*— Onboard Vessel, Fuel Cell, MPTT, Power management system, Simulations.**

I. Introduction

In present day of transportation sector which is considered to be as one of the most influential development index of the countries striving for the growth , research work is well concentrated in the field of the minimizing the emission of pollutants which is driving towards the need for development of the zero emission vehicles for the transportation sector, the research towards the development of such vehicles has laid routes for the development of the hybrid vehicles as well as the electric powered vehicles i.e. battery powered cars and buses.

Today about 90% of the world transportation been done through the marine sector, being the oldest and cheapest means of transportation the growth of the sector is very high compared to other forms of transport. At present the marine sector is solely depended on the conventional from of energy i.e. Diesel; as fuel mainly for its propulsion (Marine Diesel Engine) as well as for the prime movers of the alternators on board vessel (Diesel Generator). In regard of the above the marine sector too has to be viewed as a source of huge emissions. Now a days the marine sector is focused towards the use electrical propulsion over the conventional propulsion i.e. use of the electrical motor as the prime mover for the propeller instead of the diesel marine engine due to various operational advantages. But for the generation of the electrical power on board again the use of diesel engine as prime mover for the alternator is necessary. Currently, the use of the non conventional energies onboard a vessel to meet the required electrical demand completely is not feasible as the advanced technologies are still in research and development stages such as the use of Bio Fuel for the container vessels . So as an objective to reduce the emissions the use of fuel cell and its technologies are recommended on board vessel to share the electrical load requirements thus decreasing the demand on the conventional fuel for power generation. The fuel cell and its technologies could be developed to a state such that use of conventional diesel engines in the electrical propulsion vessel could be completely eliminated thus making the vessel completely a zero emission vehicle.

K. Mercy Rosalina, *Dept. of EEE, St. Martin's Engineering College Hyderabad, India.*
K. Nirmala Kumari*, Guest Faculty, AUCE(W), Andhra University, Visakhapatnam, India.*
Dr. N. Prema Kumar, *Dept. of Electrical Engineering, Andhra University, Visakhapatnam, India.*

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Initially the electrical supply, network, load, control and safety systems and requirements of the vessel during the various operating conditions of the vessel such as Sea going, Harbor Maneuvering and cargo handling etc. are studied. The various forms of ocean energy and their conversion technologies has been studied and the possibility of the generating the hydrogen fuel on board in abundant has lead to the choice of the fuel cell then various types of fuel cells are studied and the suitable i.e. PEMFC (Proton Exchange Membrane Fuel cell) due to its viability for the onboard applications. Then the PEMFC is synchronized with the existing alternators on board the vessel and also in the PMS (power management system) aspect the use of MPT (Maximum Power Tracking) is used in order to stabilize the fuel cell output voltage at the times of delivering maximum power to the load. The whole Fuel cell based power system is simulated and the desired performance is achieved with the use of the MATLAB Tool.

II. VESSEL ELECTRICAL SYSTEM

A ship is like a floating city with all the privileges enjoyed by any normal land city. Just like a conventional city, the ship also requires all the basic amenities to sustain life on board; the chief among them is power or electricity.

Power generation On board

Shipboard power is generated using a prime mover and an alternator working together. For this an alternating current generator is used on board. The generator works on the principle that when a magnetic field around a conductor varies, a current is induced in the conductor. Block Diagram of ship electrical power circuit is shown in figure 1 and On board ship electrical system power circuit is shown in figure 2.

The generator consists of a stationary set of conductors wound in coils on an iron core. This is known as the stator. A rotating magnet called the rotor turns inside this stator producing magnetic field. This field cuts across the conductor, generating an induced EMF or electro-magnetic force as the mechanical input causes the rotor to turn. The magnetic field is generated by induction (in a brushless alternator) and by a rotor winding energized by DC current through slip rings and brushes.

Power Distribution on board

The Power Distributed on board a ship needs to be supplied efficiently throughout the ship. For this the power distribution system of the ship is used. A shipboard distribution system consists of different component for distribution and safe operation of the system. They are: Ship Generator consisting of prime mover and alternator, ain switch board which is a metal enclosure taking power from the diesel generator and supplying it to different machinery, Bus Bars , Circuit breakers, Transformers. In a power distribution system, the voltage at which the system works is usually 440v and there are some large installations where the voltage is as high as 6600v.

Emergency Power

In case of the failure of the main power generation system on the ship, an emergency power system or a standby system is also present. The emergency power supply ensures that the essential machinery and system continues to operate the ship. Emergency power can be supplied by batteries or an emergency generator or even both systems can be used.

POWER MANAGEMENT SYSTEMS

A vessel may have a number of generating sets, a split bus bar and a variable load. The modern ship electrical system for PMS classification, automatic control has become common to ensure continuity of service and an efficient management of both generating and load equipment. Power management systems (PMS) have in the past been relay based, but a programmable electronic system (PES) using a programmable logic controller (PLC) is now more commonly used. This can also be integrated into a distributed control system (DCS) for supplying information to the bridge.

III. MODELING OF POLYMER ELECTROLYTE MEMBRANE FUEL CELL SYSTEMS

Validated mathematical models provide powerful tools for the development and improvement of fuel cell-based systems. Mathematical models can be used to describe the fundamental phenomena that take place in the system to predict the behavior under different operating conditions and to design and optimize the control of the system.

The models can be divided into two groups: empirical models and mechanistic models. Most of the empirical models are focused on the prediction of the polarization curve, which is used to characterize the electrical operation of the FC, by means of empirical equations. The empirical equation is used to calculate the voltage (E) at different current densities (J), fitting experimental data at several temperatures, pressures, and oxygen compositions in the cathode gas mixture:

$$E = E_0 - b \log J - RJm\, exp^{(nJ)} \quad (1)$$

where E0 is the thermodynamic open-circuit voltage. The exponential term characterizes the mass-transport region of the polarization curve, the zone where the increase in slope of the pseudo-linear region and the subsequent rapid fall-off of the cell potential. The parameter n has more pronounced effects than the parameter m in this region. The terms E0 and b yield the electrode kinetic parameters for oxygen reduction in the cell. R represents the resistance, predominantly ohmic, and, slightly, the charge-transfer resistance of the electro-oxidation of hydrogen.

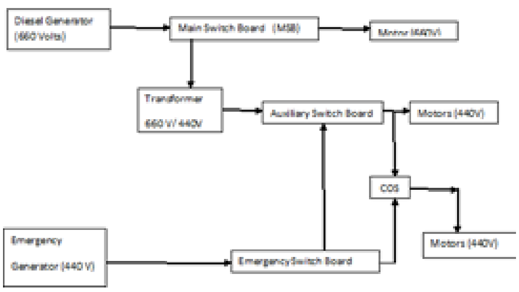

Fig.1 Block diagram of ship electrical circuit

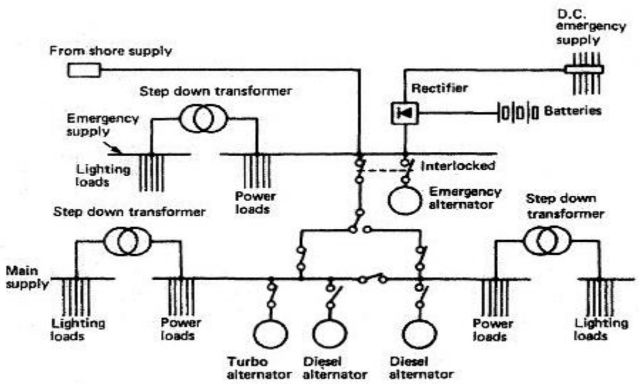

Fig. 2 On board ship electrical system power circuit

On the other hand, the mechanistic model considers the fundamental phenomena in detail such as, heat and mass transport, forces, and electrochemical processes. Mechanistic modeling (single and multi-domain) has been utilized to study a wide range of phenomena including polarization effects (activation, ohmic and concentration over potentials),water management, thermal management, CO kinetics, catalyst utilization and flow field geometry. All these models are parametric in the sense that they account for the cell performance of various input parameters, typically temperature, pressure and humidity.

Another approach to fuel cell modeling is the use of equivalent circuits to represent the system behavior. In fact, one of the most attractive aspects of the Electrochemical Impedance Spectroscopy as a tool for investigating the electrical and electrochemical properties of materials and systems, is the direct connection that often exists between the behavior of a real system and that of an idealized model circuit consisting of discrete electrical components. The procedure typically consist in the comparison or fitting the impedance data to an equivalent circuit, which is representative of the physical processes taking place in the system under investigation. There are analogies between the circuit elements and the electrochemical processes, so that the results of data fitting can be more easily converted into physical understanding.

Fuel Cell System Model

The model described has the following governing equations where the mass of air in the supply manifold, the masses of oxygen, nitrogen and water in the cathode and the masses of hydrogen and water in the anode are defined using the principle of mass conservation :

$$\frac{dm_{sm}}{dt} = W_{CP} - W_{sm,out}, \quad (2)$$

$$\frac{dm_{o2,ca}}{dt} = W_{O2,ca,in} - W_{O2,ca,out} - W_{O2,rct} \quad (3)$$

$$\frac{dm_{N2,ca}}{dt} = W_{N2,ca,in} - W_{N2,ca,out} \quad (4)$$

$$\frac{dm_{w,ca}}{dt} = W_{v,ca,in} - W_{v,ca,out} - W_{v,ca,gen} + W_{v,m} \quad (5)$$

$$\frac{dm_{H2}}{dt} = W_{H2,an,in} - W_{H2,an,out} - W_{H2,rct} \quad (6)$$

$$\frac{dm_{w,an}}{dt} = W_{v,an,in} - W_{v,an,out} - W_{l,an,out} - W_{v,m} \quad (7)$$

Where W_{cp} is the compressor flow, $W_{sm,out}$ is the outlet mass flow, $W_{O_2,ca,in}$ is the mass flow rate of oxygen gas entering the cathode, $W_{O_2,ca,out}$ is the mass flow rate of oxygen leaving the cathode, $W_{O_2,rct}$ is the mass flow rate of oxygen reacted, $W_{N_2,ca,in}$ is the mass flow rate of nitrogen gas entering the cathode, $W_{N_2,ca,out}$ is the mass flow rate of nitrogen gas leaving the cathode, $W_{v,ca,in}$ is the mass flow rate of vapor entering the cathode, $W_{v,ca,out}$ is the mass flow rate of vapor leaving the cathode, $W_{v,ca,gen}$ is the rate of vapor generated in the fuel cell reaction, $W_{v,menbr}$ is the mass flow rate of water across the fuel cell membrane, $W_{l,ca,out}$ is the mass flow rate of liquid water leaving the cathode, $W_{H_2,an,in}$ is the mass flow rate of hydrogen gas entering the anode, $W_{H_2,an,out}$ is the mass flow rate of hydrogen gas leaving the anode, $W_{H_2,rct}$ is the rate of hydrogen reacted, $W_{v,an,in}$ is the mass flow rate of vapor entering the anode, $W_{v,an,out}$ is the mass flow rate of vapor leaving the anode, $W_{v,m}$ is the mass flow rate of water transfer across the fuel cell membrane, and $W_{l,an,out}$ is the rate of liquid water leaving the anode.

The voltage of a fuel cell stack consisting of n fuel cells is given as

$$\boldsymbol{v}_{st} = ? \, \boldsymbol{v}_{FC} \quad (8)$$

where the voltage of a single fuel cell is defined as:

$$\boldsymbol{v}_{FC} = \boldsymbol{E} - \boldsymbol{v}_{act} - \boldsymbol{v}_{ohm} - \boldsymbol{v}_{conc} \quad (\mathbf{9})$$

with E being the open circuit voltage and v_{act} , v_{ohm} and v_{conc} being the activation, ohmic and concentration overpotentials, respectively. By fitting experimental data to the phenomenological model equations, the open circuit voltage and the three over potentials are respectively defined as:

$$E = \{1.229 - 0.85 * 10^{-3}(T_{fc} - T_{amb}) + 4.3085 * 10^{-5}T_{fc} * [ln(1.01325P_{H2}) + 1/2\, ln(1.01325P_{o2})]\} \quad (10)$$

The activation voltage is: $v_{act} = v_o + v_a(1 - e^{c1i})$ (11)

With $v_o = 0.279 - 8.5 * 10^{-4}(T_{fc} - T_{amb}) + 4.308 * 10^{-5}T_{fc} * \frac{[ln[(P_{ca} - P_{sat}(T_{fc})]}{1.0132} + 12\, ln\left\{\frac{[0.1173(P_{ca} - P_{sat}T_{fc})]]}{1.01325}\right\}$ (12)

$$v_a = (-1.618 * 10^{-5}T_{fc} + 1.1618 * 10^{-2}) * [\left(\frac{P_{o2}}{0.1173}\right) + P_{sat}(T_{fc})]^2 + (1.8 * 10^{-4}T_{fc} - 0.166)\left[\left(\frac{P_{o2}}{0.1173}\right) + P_{sat}(T_{fc})\right] * (-5.8 * 10^{-4}T_{fc} \;\; 0.5736) \quad (13)$$

And $c_1 = 10$ (14)

The ohmic Voltage $v_{ohm} = i * R_{ohm}$ with the fuel cell electrical resistance $R_{ohm} = \frac{t_m}{\sigma_m}$

the membrane conductivity:

$$\sigma_m = (b_{11}\mu_m - b_{12})\, exp\left[b_2\left(\frac{1}{303} - \frac{1}{T_{fc}}\right)\right] b_{11} = 5.139 * 10^{-3}, b_{12} = 3.26 * 10^{-3}, b_{13} = 350 \quad (15)$$

And $v_{conc} = i\,(c_2 * i/i_{max})^{c3}$ (16)

With $c_2 = (7.16 * 10^{-4}T_{fc} - 0.622)\left[\left(\frac{P_{o2}}{0.1173}\right) + P_{sat}T_{fc}\right] + (-1.45 * 10^{-3}T_{fc} + 1.68\; for\left[\left(\frac{P_{o2}}{0.1173}\right) + P_{sat}T_{fc}\right] < 2_{atm}\; \&\; c_2 = (8.66 * 10^{-5}T_{fc} - 0.068)\left[\left(\frac{P_{o2}}{0.1173}\right) + PsatTfc + (-1.6*10-4Tfc + 0.54\; for\left[\left(\frac{P_{o2}}{0.1173}\right) + P_{sat}T_{fc}\right] \geq 2_{atm}$ (17)

And $i_{max} = 2.2;\; C_3 = 2$ (18)

The governing equations for the supply manifold pressure and the return manifold pressure are respectively defined using the energy conservation principle and the standard thermodynamics relationships as follows:

$\frac{dP_{sm}}{dt} = [\frac{(\gamma * R_a) * (W_{cp}T_{cp} - W_{sm,out}T_{sm})}{V_{sm}}]$ and

$\frac{dP_{rm}}{dt} = \left[\frac{(T_{rm} * R_a) * (W_{ca,out} - W_{rm,out})}{V_{rm}}\right]$ (19)

where V_{sm} is the supply manifold volume, V_{rm} is the return manifold volume, T_{sm} is the supply manifold air temperature, T_{rm} is the return manifold air temperature, T_{cp} is the temperature of the air leaving the compressor, R_a is the air gas constant, and γ is the air specific heat ratio.

IV. SIMULATION & RESULTS

SIMULATION block diagram of FCPS developed in MATLAB simulink tool box for on board marine system is shown in figure. The simulation results are presented here for the on board marine ship electric power supply with the fuel cell. The MPPT algorithm has been developed for maximum utilization of the fuel cell output. Simulations are presented in the form of a isolated single machine system with the modeled equations for the fuel cell.

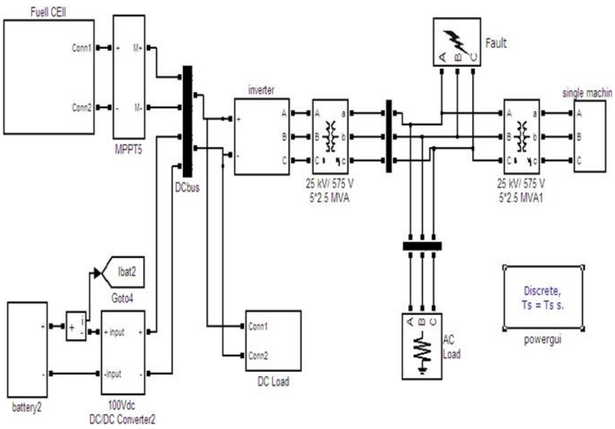

Fig.3 Simulation diagram of FCPS

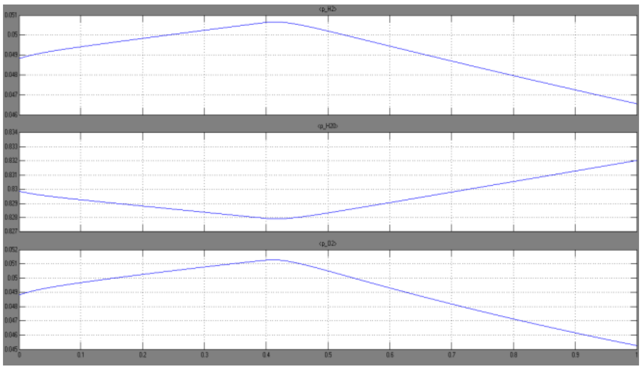

Fig. 4 FUEL CELL POWER, VOLTAGE AND CURRENT

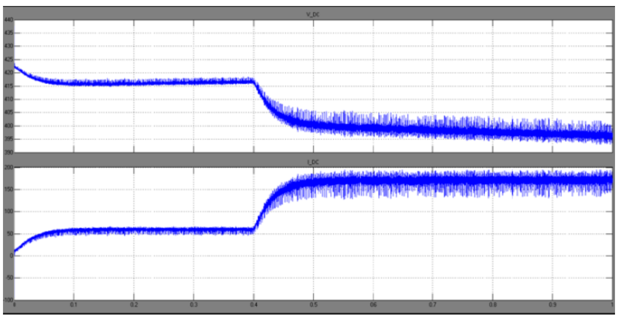

Fig. 5 FUEL CELL DC VOLTAGE AND DC CURRENT

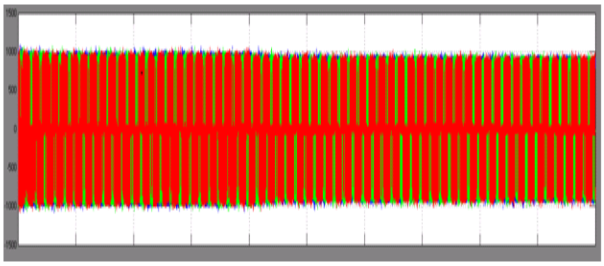

Fig.6 FUEL CELL AC VOLTAGE

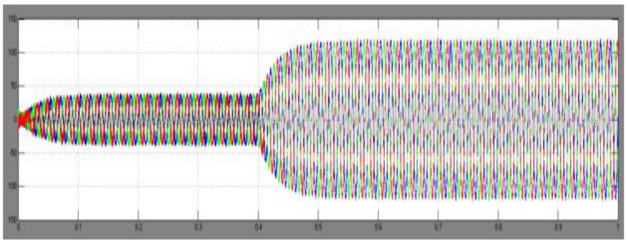

Fig. 7 FUEL CELL AC CURRENT

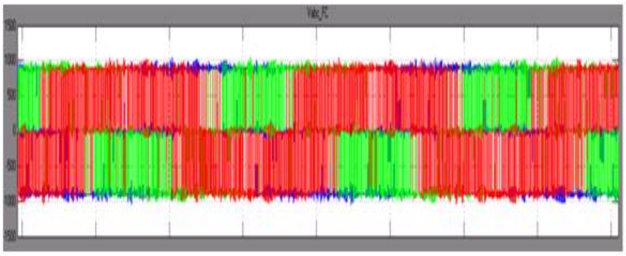

Fig.8 FUEL CELL AC VOLTAGE

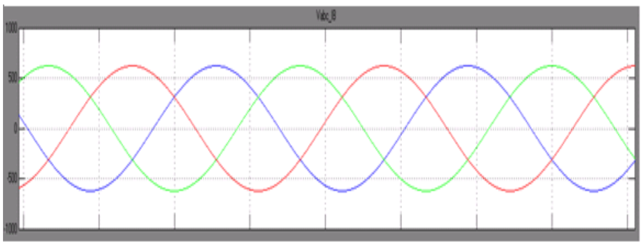

Fig.9 GRID VOLTAGE

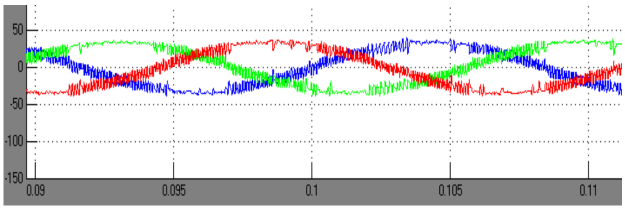

Fig.10 GRID CURRENT

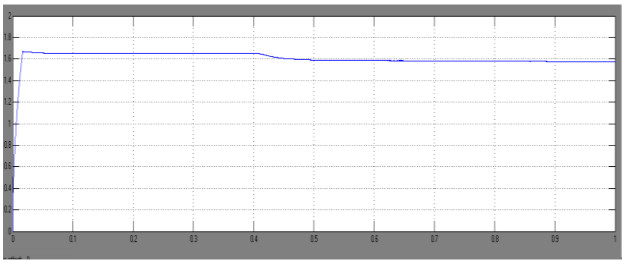

Fig.11 FUEL CELL TERMINAL VOLTAGE:

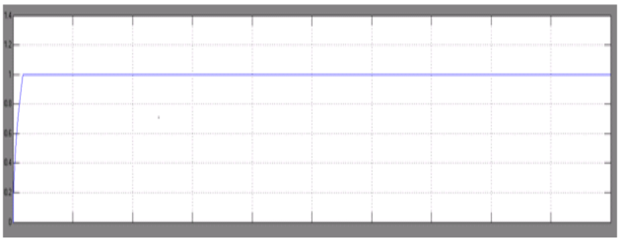

Fig.12 GRID TERMINAL VOLTAGE

At t = 0s, an active power reference (Pref) of 0.3pu is commanded. Observe that the reference is captured within 0.2s. At t = 0.4s, Pref = 1pu is commanded. Again, the reference is captured within 0.2s. The inverter uses hysteresis switching and controls active power by manipulation of direct-axis current while holding reactive power at 0VAr. The measurement blocks are rated at 50kW. Therefore, an active power reference of 1pu = 50kW.

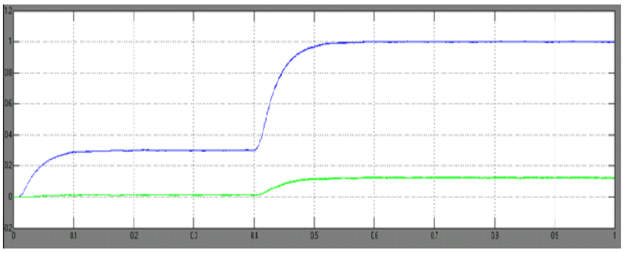

Fig.13 FUEL CELL ACTIVE AND REACTIVE POWER

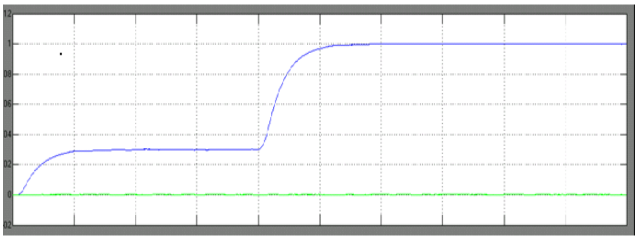

Fig.14 GRID ACTIVE AND REACTIVE POWER

V. CONCLUSION

A dynamic model of the PROTON EXCHANGE FUEL CELL (PEMFC) was developed in MATLAB. A three phase inverter has been modeled and connected between the PEMFC-DC-AC system on the one side and the utility grid on the other side through an ideal transformer. A control strategy for the inverter switching signals has been discussed and modeled successfully. The inverter control scheme uses a decoupled PQ control strategy to control the phase angle of the inverter and the voltage across the transformer. The characteristics for the system have been obtained. The transformer and inverter voltage waveforms have been plotted

In an industrial power generation, fuel cell is one of most important sources of distributed energy in the future. Modeling and simulation study of a PEMFC power system is investigated in this project. A validated PEMFC dynamic model is used to model the fuel cell system. A three phase inverter has been modeled and connected between the PEMFC power system on one side and the utility grid on the other side through an ideal transformer. A MPPT system is also included in the system to improve the maximum power conditions of the PEMFC. Hence a fuel cell system suitable for the marine application is developed.

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K. Mercy Rosalina had her M.Tech. in Power Systems from National Institute of Engineering, Mysore, Karnataka and presently pursuing her Ph.D. in Electrical Engineering from Andhra University. She is associated with St. Martin's Engineering College, Hyderabad as Assistant Professor of Electrical & Electronics Engineering. Her present research interests include distributed power generation, modeling of power system components and signal processing techniques.

K. Nirmala Kumari pursued her M.Sc.in Microbiology and M.Tech in Biotechnology from Acharya Nagarjuna University, Guntur, Andhra P radesh in 2005 and 2008 respectively. Presently she is persuing her M.Sc. in Organic Chemistry for School of Distance Education, Andhra University, Visakhapatnam. Her research interests include the areas in Microbiology, Biotechnology, Molecular structure designs and Bioinformatics.

Dr. N. Prema Kumar had M.E in Power Systems form Regional Engineering College (Now, National Institute of Technology), Tiruchirappalli, Tamilnadu and Ph.D. in Electrical Engineering from JNTU, Hyderabad. He is presently associated with Andhra University as Associate Professor in the department of Electrical Engineering, AUCE (A). His current research interests include Power Systems, Distributed and deregulated power systems, Renewable energy source and bioinformatics.