Floating Power Platforms for Mobile Cold-ironing

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***Abstract*—The colloquial term 'cold-ironing' refers to the shore power connection when a ship is at berth. Even though, cold-ironing is not new to the shipping industry only recently it received more attention, mainly due to strict emission regulations. When a ship receives shore power, its emissions can be eliminated and thus cold-ironing is becoming a popular service sought by ships that berth at emission controlled ports. Generally, the shore power connection is available only at berth and thus emissions from the ships that are anchored in and around the port is still a significant issue. This paper proposes a floating power platform for 'Mobile Cold-ironing' of anchored ships. In the proposed system, a fuel cell – battery hybrid system is used as the source. Efficacy of the proposed system in supplying dynamic loads is verified with simulation results.**

Keywords—Battery, cold ironing, fuel cell, LNG engine, power management, shore power.

I. INTRODUCTION

Shipping is the linchpin of the global economy accounting for more than 90% of the goods transported locally as well as internationally [1]. Therefore, with growth of economies and global population, shipping industry requires more ships which in turn results in an increase in the use of fossil fuel and associated emissions. As these emissions significantly contribute mortalities, climate change and other environmental issues many countries and regions have imposed strict emission regulations and defined emission control areas (ECAs) around their coasts [2]-[5]. When a ship come to an emission controlled port or sails in an ECA, it has to take measures to comply with the emission regulations [6]. Cold-ironing is one such measure where ships at berth shut down their relatively high emission engines and receive power from the shore connections [7, 8]. One can see cold-ironing as a process of shifting emissions from ship to the shore if the shore power is generated by burning fossil fuels such as coal or diesel. Nevertheless, power generation at shore can be done in a more controlled environment and in the end, there can be a net reduction in emissions [9]. Thus, the use of shore power is increasing in popularity in comparison to running on-board engines.

At present, shore power is available only when the ship is at berth during cargo operations or passenger transfer. Many ships that are anchored in and around the ports waiting for their turn do not have access to shore power. One possible way of connecting anchored ships to shore power is to use submerged cables [10]. Nevertheless, it is expensive to manage such a cable system and the serviceable range is limited and thus this has not drawn much attention. Therefore, currently, there is no an efficient and effective way for cold-ironing anchored ships and thus they have to run their main and/or auxiliary engines to supply essential loads. The associated emissions and their effects can be serious issues as the waiting time can vary from days to weeks.

As a solution, this paper proposes to use a mobile power platform for cold-ironing anchored ships. An overview of the proposed system, consisting of a fuel cell stack and a battery bank, is shown in Fig. 1. Schematic diagram of the corresponding power conversion system is shown in Fig. 2. The combined system can be installed in a platform such as a barge and moored closer to the anchored ships to supply the required electrical power. As reported in [11], installing a fuel cell power system in a floating platform, e.g. barge, is feasible.

Compared to the traditional shore power that may be generated from fossil fuel, the only by-product of fuel cells is water. Therefore, the proposed solution is the greenest approach for cold-ironing. Nevertheless, the slow response of fuel cells to rapidly changing loads, such as propulsion loads, requires them to be supported with a fast acting energy storage element [12]. Therefore, the proposed system uses a battery bank to support the fuel cell to cope with fast changing loads.

Various control and power management schemes are proposed in relevant literature for similar hybrid power systems. These techniques can be broadly classified as traditional PID based controls [13-16], model reference based controls [17-19], and learning based controls [20, 21]. Out of these three categories, the traditional PID based controls are the simplest and thus the most widely used. Nevertheless, model reference based control schemes render fast transient response while learning based controls are generally immune to parameter changes. In order to show that the proposed floating hybrid power system is capable of supplying dynamic loads without triggering blackouts, a simulation study was carried out with simple PI controllers and a straightforward power management strategy. The results show that the proposed fuel cell –battery hybrid system is capable of supplying fast changing loads without going into instabilities or resultant blackouts.

The paper is organised as follows. Modelling of the fuel cell stack and the battery bank is given in section II. Control techniques and the power management strategy used in this study are presented in section III. Results of the simulation study are presented in Section IV to demonstrate the capability of the proposed system in supplying fast changing loads that occur in a ship power system. Finally, conclusions drawn from the results of this study are given in Section V.

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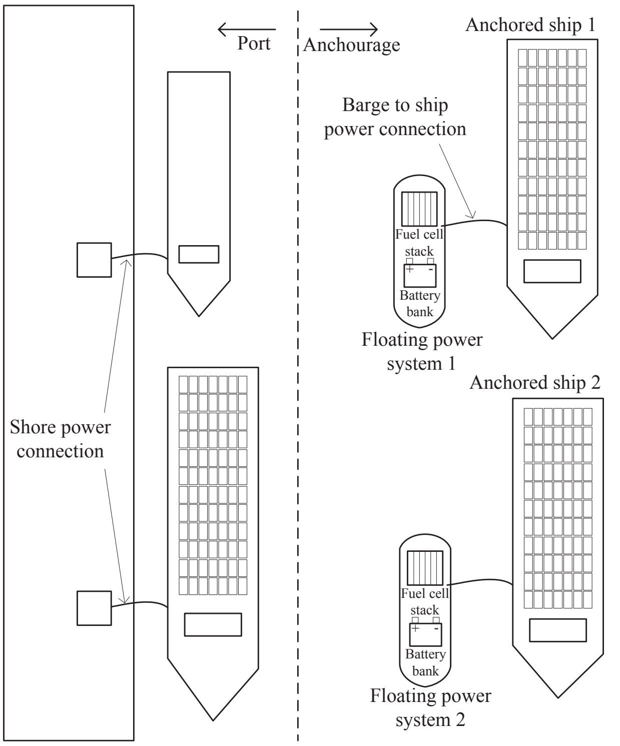


Fig. 1. An overview of the proposed system

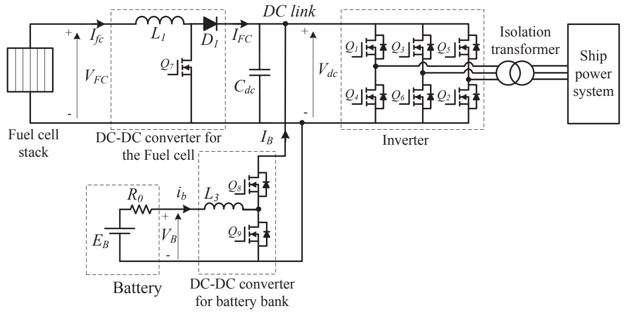


Fig. 2. Schematic diagram of the proposed 'mobile cold-ironing' system.

II. SYSTEM MODELING

A. Fuel Cell Model

Schematic diagram of the fuel cell model used in this study is shown in Fig. 3. In this model, the open circuit voltage (E_{oc}), exchange current (i_0) and the Tafel slope (A) are calculated using equations (1), (2) and (3) respectively [22, 23].

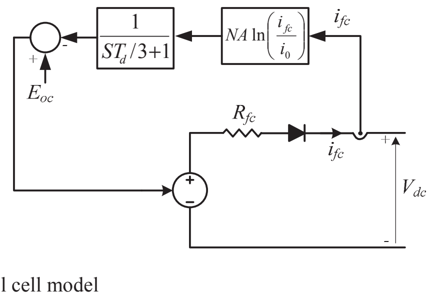


Fig. 3 Fuel cell model

$$E_{oc} = K_c E_n \tag{1}$$

$$i_o = \frac{zFk\left(P_{H_2} + P_{O_2}\right)}{Rh} e^{\frac{-\Delta G}{RT}} \tag{2}$$

$$A = \frac{RT}{z\alpha F} \tag{3}$$

where N is the number of cells in the fuel cell stack, R is the universal gas constant (8.3145 J/mol K), F is Faraday's constant (96485 C/mol), z is the number of moving electrons, E_n is the Nernst voltage which is the thermodynamics voltage of the cells that depends on the temperatures and partial pressures of reactants and products inside the stack (V), α is the charge transfer coefficient which depends on the type of electrodes and catalysts used, P_{H2} is the partial pressure of hydrogen inside the stack (atm), P_{O2} is the partial pressure of oxygen inside the stack (atm), k is the Boltzmann's constant (1.38×10^{-23} J/K), h is the Planck's constant (6.626×10^{-34} Js), ΔG is the size of the activation barrier which depends on the type of electrode and catalyst used, T is the temperature of operation (K), K_c is the voltage constant at nominal condition of operation, R_{fc} is the internal resistance of the fuel cell stack, S is the Laplace variable and T_d is the response time (s).

B. Battery Model

As mentioned in the introduction, the proposed system use a lithium-ion battery as the energy storage element. Lithium-ion battery models are generally complex and includes RC networks, environmental conditions and complex dynamics. Nevertheless, in order to simplify the model, the RC networks are neglected and the effect of the change of temperature is also neglected. The corresponding battery model used in this study, together with the equations for charging and discharging is given in Fig. 4 where, E_B is the nonlinear voltage of the battery (V), E_0 is the constant voltage (V), K is the polarization resistance (Ohms), i_b is the battery current, i_b^* is the battery current passed through a low pass filtered (A), Q is the maximum battery capacity (Ah), A is the exponential voltage (V) and B is the exponential capacity $(\mathrm{Ah})^{-1}$. The battery charge is given by:

$$q = \int_0^t i_b dt \tag{4}$$

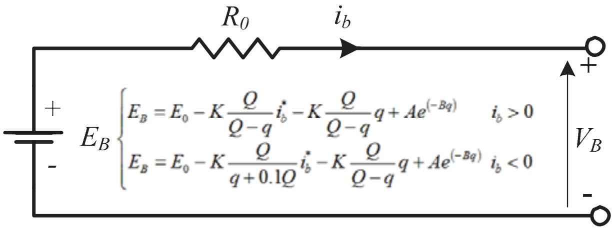


Fig. 4. Lithium-ion battery model

III. CONTROL AND POWER MANAGEMENT

A. Fuel Cell Power Controller

As shown in Fig. 2, the fuel cell is connected to the dc-link through a simple dc-dc buck converter. Power delivered by the fuel cell can be controlled by controlling its current. In order to control the fuel cell current duty cycle of the switching device Q7 has to be controlled. Therefore, the entire fuel cell power controller has two steps which are depicted in Fig. 5. The first step is to find out the required current to meet the power reference. This is done by dividing the fuel cell power reference, P_{fc}^*, by the voltage of the fuel cell stack, V_{FC}. Once the current reference, I_{FC}^*, is known it is compared with the actual current, I_{FC}. The error is passed through a PI controller to generate the duty cycle, D_{fc}. The duty cycle, which varies between 0 and 1, is then compared with a triangular carrier signal in the pulse width modulation (PWM) unit to generate gate pulse for the transistor *Q7*.

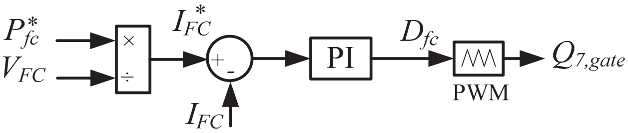


Fig. 5. Fuel cell power controller.

B. Battery Power Controller

Due to the slow dynamics of the fuel cell, the dc-link voltage tend to deviate from the set point under fast changing loads which can lead to instabilities and eventually cause a blackout. Therefore, the objective of the battery bank is to respond to fast changing loads and exchange power with the dc-link to maintain the voltage within an acceptable range. The corresponding battery power controller used achieve this objective is shown in Fig. 6. As shown in Fig. 6, the battery power controller senses the deviations in the dc-link voltage, V_{dc}, by comparing it against the set value, V_{dc}^*. The error is passed to a PI controller to generate the duty cycle, D_{Bat}, for the corresponding dc-dc converter. As described above, the PWM unit generate gate pulses for Transistors Q_8 and Q_9 based on the duty cycle. This controller attempts to restore the dc-link voltage. As a result of this voltage restoration effort, battery power varies. This controller is simple and easy to implement as it automatically takes care of both charging and discharging of the battery bank.

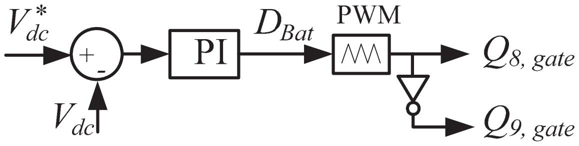


Fig. 6. Battery power controller.

C. Power Management Strategy

In this study, a simple power management strategy is used to manage the fuel cell power and the state of the charge (SoC) of the battery. In the proposed strategy the load power demand is passed through a low pass filter to remove its high frequency components and thereby obtain a smooth power reference for the fuel cell. The low pass filtered power demand is then added with an additional power reference which comes through the SoC controller to manage the battery SoC to be within a safe range. According to this strategy, if the battery SoC falls below the lower threshold, fuel cell power is increased by a certain amount to bring the SoC up to the nominal range. Similarly, if the SoC exceeds the upper threshold fuel cell power is reduced by a certain amount to bring the SoC down to the nominal range. The corresponding controller is shown in Fig. 7.

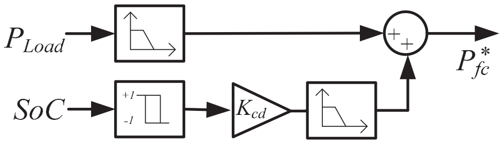


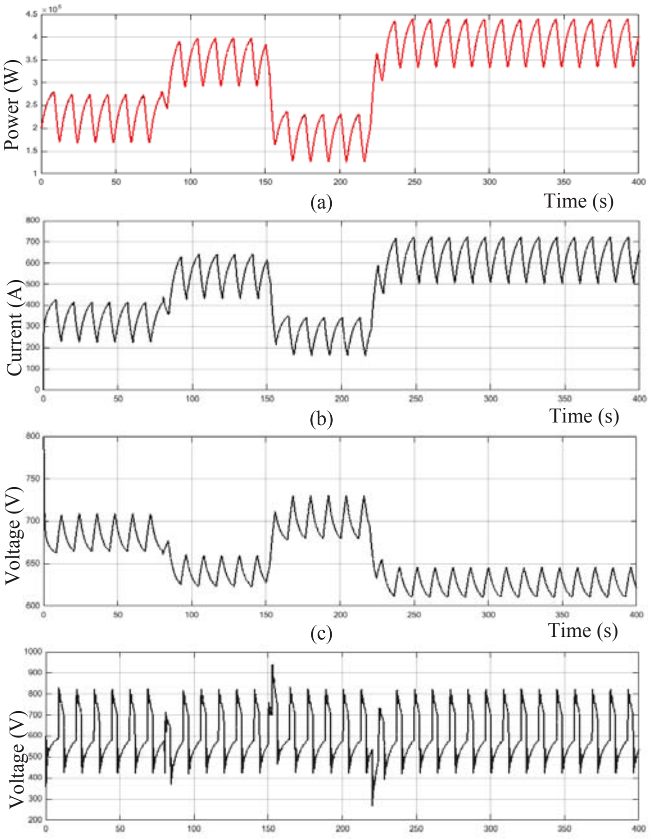
Fig. 7. Power management strategy.

IV. SIMULATION RESULTS

The proposed hybrid power system was modelled and simulated using the MATLAB/Simulink software to test its performance at dynamic loading conditions. System parameters of the simulation setup are given in Table I. Note that a small battery capacity is used to show the SoC changes and corresponding responses of the power management systems within a short period. In order to demonstrate the need of a battery energy storage system to support the fuel cell, two scenarios are simulated, namely without a battery and with a battery. Results of the first scenario are shown in Fig. 8. Load power variations used in this study are shown in Fig. 8(a) by the trace marked ‘Load power’ [22]. Since the fuel cell is the only source in this particular situation, it tries hard to supply the demand and thus both load power and fuel cell power curves overlap as seen in Fig. 8(a). Nevertheless, as the fuel cell tries hard to supply the fast changing demand, the fluctuations present in the load appear at the output current of the fuel cell as well as in its output voltage as shown in Figures 8(b) and 8(c) respectively. Even though the fuel cell seem to follow the demand such rapid changes degrade the performance of the fuel cell and reduce the life time. Moreover, the dc-link voltage fluctuates in a large range as shown in Fig. 8(d), which may result in an under voltage or an over voltage tripping in practical applications. Therefore, these results indicate that the fuel cell alone is not suitable of supplying fast changing loads.

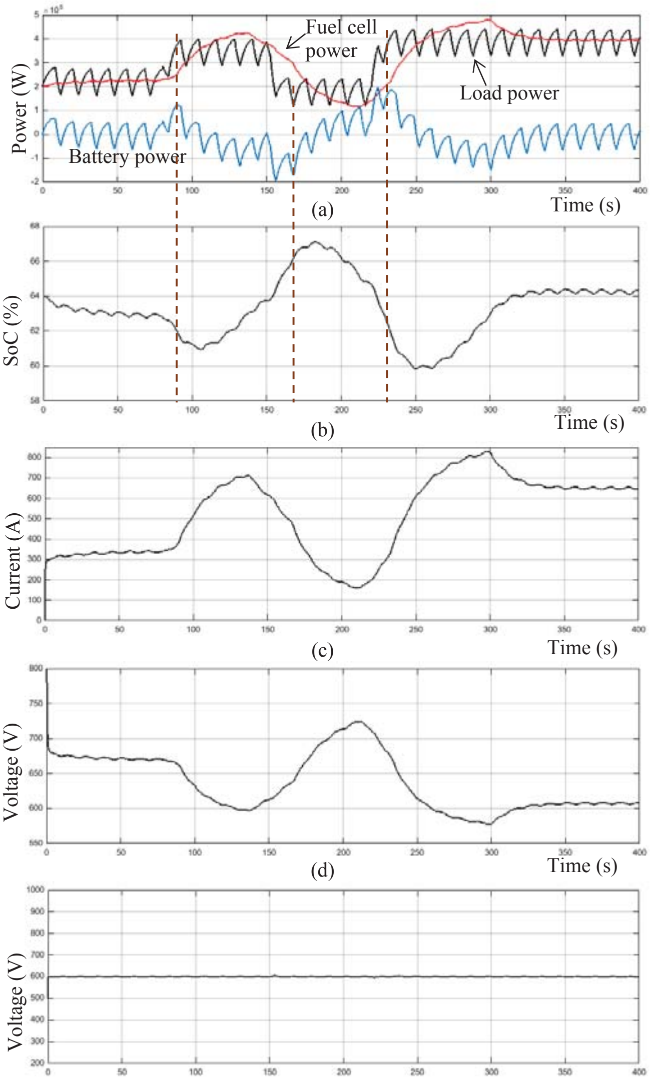
The second scenario uses a battery bank to supply fast changing loads. The corresponding results are shown in Fig. 9. The same load power profile was applied in the second scenario as well as shown in Fig. 9(a) by the trace marked ‘Load power’. Fuel cell power and battery power are also marked in the same figure with the corresponding names written closer to the relevant traces. As evident by the smooth curve of ‘Fuel cell power’ and rapidly changing ‘Battery power’ curve, the battery supplies fast changes in the load while the fuel cell supples the average power. As mentioned Section III, fuel cell changes its power to bring the battery SoC back to the nominal range in addition to supplying the average power. In order to illustrate this feature, in this simulation the lower threshold and upper threshold of the battery SoC have been set to 62% and 66% respectively. Practical values of these thresholds can be significantly different to these values depending on the application environment. The points at which the battery state of charge meets these thresholds are marked by vertical dashed lines in Fig. 9(b). When the battery SoC drops below 62%, the fuel cell delivers more power to increase the SoC. Similarly, when the battery SoC exceeds 66%, fuel cell power is reduced so that the battery SoC can return to the nominal range as shown in Fig. 9(b).

As mentioned above, the primary objective of having a battery bank is to absorb the high frequency fluctuations of the load and thereby smoothen fuel cell current, fuel cell voltage and the dc-link voltage. As evident in Figures 9(c), 9(d) and 9(e), all three variables are literally free from the high frequency fluctuations. Compared to the corresponding waveforms of scenario 1, it can be observed that the battery bank has prevented the propagation of high frequency fluctuation to the fuel cell. Therefore, these results verify that the proposed fuel cell – battery hybrid power system is capable of supplying dynamic loads while ensuring smooth operation of the fuel cell stack through appropriate control and power management.



(a) (b) (c) (d)

Fig. 8. Simulation results of the scenario 1, fuel cell only system, (a) load power and fuel cell power, (b) output current of the fuel cell, (c) output voltage of the fuel cell, (d) dc-link voltage.



(a) (b) (c) (d) (e)

Fig. 9. Simulation results of the scenario 2, fuel cell-battery hybrid system, (a) load power, fuel cell power and battery power, (b) battery SoC, (c) output current of the fuel cell, (d) output voltage of the fuel cell, (e) dc-link voltage.

Table I System parameters of the simulation setup

Rated power of the fuel cell stack	500kW
No load voltage of the fuel cell stack	900V
DC-Link voltage reference	600V
Nominal voltage of the battery bank	480V
Maximum capacity of the battery bank	40Ah
Output line voltage (V_{LL-rms})	440V
Output frequency	60Hz

V. CONCLUSIONS

This paper proposes a fuel cell-battery hybrid power system for mobile cold-ironing of ships that are anchored in and around ports. The feasibility of the proposed systems in terms of control and power management have been investigated in this study. A simple average power scheme with SoC restoration effort is used as part of the power management strategy. A simple PI controller dc-link voltage regulator is used to control battery power. Simulation results show that the fuel cell and battery combination is able to supply fast changing loads without going in to instabilities that may result in tripping of the system. Based on the results, it can be concluded that the proposed hybrid power system is capable of supplying dynamic loads while ensuring smooth operation of the fuel cell stack. Therefore, it can be concluded that this is a viable option to provide efficient, effective and low emission power to a large fleet of vessels anchored in and around congested ports across the world.

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