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Hybrid Power Management System Using Fuel Cells and Batteries

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Abstract

In the future, hybrid power management systems using fuel cells (FCs) and batteries will be used as the driving power systems of ships. These systems consist of an FC, a converter, an inverter, and a battery. In general, an FC provides steady-state energy; a battery provides the dynamic energy in the start state of a ship for enabling a smooth operation, and provides or absorbs the peak or dynamic power when the load varies and the FC cannot respond immediately. The FC voltage range is very wide and depends on the load; Therefore, the FC cannot directly connect to the inverter. In this paper, we propose a power management strategy and design process involving a unidirectional converter, a bidirectional converter, and an inverter, considering the ship's operating conditions and the power conditions of the FC and the battery. The presented experimental results were verified through a simulation.

Index Terms: Battery, Bidirectional converter (BDC), Converter, Energy, Fuel cell, Power, Unidirectional converter (UDC)

I. INTRODUCTION

In this paper, we propose a power management scheme for a hybrid power system using a fuel cell (FC) and a battery. The hybrid power system consists of an FC, converters, an inverter, and a battery for driving the propulsion system of small ships. In general, an FC has limitations in terms of the energy storage, response capability, cold start, and voltage fluctuation with a peak load. To address these issues, FC-based power systems have to be combined with auxiliary energy systems such as a battery or an ultra-capacitor for improving dynamic (response) characteristics. Battery systems cannot control their charging and discharging current. In order to control the charging/discharging current, a converter needs to be installed between a DC bus and a battery.

The proposed hybrid power system has two power sources: an FC and a battery system as an auxiliary source. The battery system is connected directly in parallel to the DC bus; its function is to enhance the peak power capacity and power the load during a cold start. The FC and the battery system are connected to the same DC bus through an appropriate unidirectional converter (UDC) and bidirectional converter (BDC), respectively.

The hybrid power system operates well under various load conditions (e.g., steady, cold start, and overload). The operation of the battery system can be controlled by the battery voltage and the DC bus. The battery system is connected to the DC bus through the BDC, which can be controlled according to the voltage level. The voltage level of the battery is categorized into three types: over-discharge, normal, and over-charged. The battery system is connected

to the DC bus, which is operated in either the buck mode, the boost mode, or the stop mode [1].

In this paper, we propose a hybrid power management scheme for the propulsion system of a small leisure ship, which is operated with a load variation according to the state of the sea. When the pulse load is generated, the power source supplies a considerably higher peak current than that in the case of a constant load. Once the peak load is generated, the battery is damaged by the rush current. Therefore, the power flow of the proposed hybrid power system is controlled with a BDC. Finally, the simulator for the hybrid power system was developed for analyzing the operating characteristics according to the load.

II. HYBRID POWER SYSTEM DESIGN

In this paper, we present a hybrid power system design for small ships (e.g., leisure ships and fishing boats). FCs are a promising technology used for electric power generation in ships because of their high efficiency and low carbon emission.

In general, the ship's main power system is a stand-alone system where most of the power is used for propulsion. Fig. 1 shows the power system used in small ships for electric propulsion. It is composed of several parts: the generator, storage, converter, filter, and the propulsion part [2-4].

The output voltage range of an FC is very wide and depends on the load; therefore, the FC cannot directly connect to the inverter. The output voltage of an FC is selected according to the rating power.

For peak power applications, a battery is used in modules in which many submodules are connected in series and in parallel in order to obtain acceptable voltage and power. The battery terminal voltage V_b determines the number of battery submodules that must be connected in series to form a module.

A. Fuel Cell

In FC cell of power generation system, the FC cell potential voltage E_f is defined as follows:
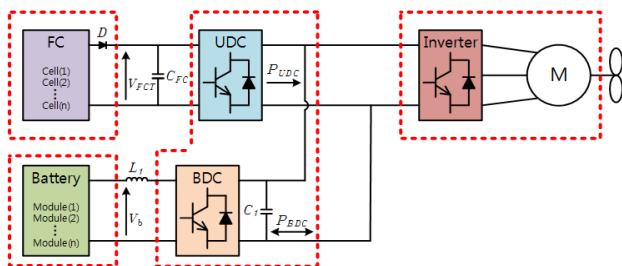

Fig. 1. Proposed hybrid power system for ships.

$$E_{fc} = E_{T,P} - \frac{RT_f}{\alpha F} \ln \left(\frac{i + i_{lo}}{i_c} \right) - \frac{RT_f}{\alpha F} \ln \left(\frac{i_L}{i_L - i} \right) - iR_i \quad . \quad (1)$$

Here, E_{fc} denotes the polarization voltage; $E_{T,P}$, the ideal cell voltage of the temperature and pressure functions; R, the gas constant; T_f, the chemical reaction temperature; α, the transfer coefficient; F, the Faraday constant; i_{lo}, the current loss; i_c, the exchange current density; i_L, the limiting current density; and R_i, the internal resistance.

B. DC/DC Converter

The hybrid power system has a UDC and a BDC. Normally, a UDC is required for obtaining a constant output voltage, which is the input voltage of the inverter. The input and the output currents and the voltage ripple of the UDC are small and ensure the safe operation of the FC module. The UDC has to control and condition the output power of the FC, and its electric characteristics have to match those provided by the FC and demanded by the load.

The UDC is designed with the full-bridge converter that is widely used in an FC power system. UDC can operate under a constant voltage condition and a limited current condition. Fig. 2 shows the main circuit of the power management system [5-7].

In general, the output of the UDC is connected to the DC bus, which is followed by the inverter with the output of the propulsion motor (220 VAC/60 Hz). The UDC output V_{UDCO} voltage can be calculated as follows:

$$V_{UDCO} = 2 \frac{N_2 D}{N_1} V_i - V_{TVD} \quad . \quad (2)$$

Here, V_i denotes the input voltage of the converter; N_2, the number of turns on the secondary side of the transformer; N_1, the number of turns on the primary side of the transformer; D, the duty ratio of the converter; and V_{TVD},
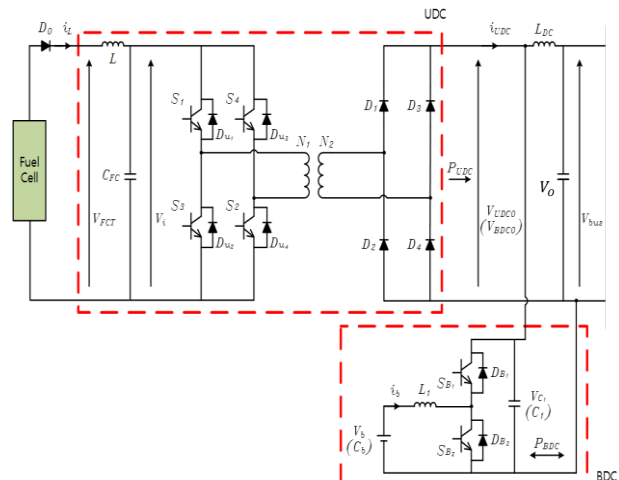

Fig. 2. Main circuit of power management system.

the total voltage drop.

The BDC allows both directional power flows for the discharge and recharge of the energy storage. Its response needs to be sufficiently fast to compensate for the slow dynamics of the FC during startup or sudden load changes. The battery is connected in parallel to the high-voltage DC bus through the BDC, which should be controlled in a suitable mode according to the condition of the battery and the FC. The BDC connects the DC bus and the battery, and can transmit the energy in both directions. In general, a buck–boost converter is widely used as the BDC, which can work in the buck mode to charge the battery and in the boost mode to discharge the battery. The output voltage V_{BDCO} can be calculated as follows:

$$V_{BDCO} = \frac{D}{1-D} V_b \ . \tag{3}$$

If $D < 0.5$, the BDC is in the buck mode ($V_{BDCO} < V_b$). If $D > 0.5$, the BDC is in the boost mode ($V_{BDCO} > V_b$), and if $D = 0.5$, V_{BDCO} is equal to V_b [8].

In the buck mode, the output voltage of the BDC is the battery voltage V_b, and the limited current is the inductor current. In the boost mode, the output voltage of BDC is the DC bus voltage V_{bus}, and the limited current is the inductor current, which is in the reverse direction of the inductor current in the buck mode.

During the start period, first, the battery powers the load and the BDC works in constant voltage mode, where $V_{bus} = V_{BDCO}$ [9]. The transient state in the BDC is generated with a mode change, which switches from the charge mode to the discharge mode, or vice versa. The transient time is given as follows:

$$\Delta t_{ctd} = \frac{L_1}{V_b} (I_{ch} + I'_{ds}) \ , \tag{4}$$

$$\Delta t_{dtc} = \frac{L_1}{V_{C_1} - V_b} (I'_{ch} + I_{ds}) \ . \tag{5}$$

Here, Δt_{ctd} denotes the transient time from the charge mode to the discharge mode; Δt_{dtc}, the transient time from the discharge mode to the charge mode. I_{ch} represents the charge current to the battery; I_{ds}, the discharge current from the battery; I'_{ds}, the discharge order current; I'_{ch}, the charge order current; and V_{C_1}, the capacitor voltage.

In order to ensure the continuous-condition current mode, the inductor L_1 is operated in the buck and the boost converter modes as follows [10]:

$$L_{1(bu)} > \frac{DT_s}{2I_{ch}} (V_{C_1} - V_b) \ , \tag{6}$$

$$L_{1(bo)} > \frac{T_s D(1-D)}{2I_{ds}} V_{C_1} \ . \tag{7}$$

Further, the capacitor C_1 is designed according to the delay time t_d, the voltage drop ΔV_{C_1}, and the inverter

maximum current I_{im} as follows:

$$C_1 = I_{im} \cdot \frac{t_d}{\Delta V_{C_1}} \ . \tag{8}$$

C. Battery

A battery can be employed in the power system as an auxiliary energy source. The choice of battery is related to the selection of the BDC. The capacity of the battery C_b is defined on the basis of the power flow at the system start period. The start duration of the FC is tens of seconds. In this study, $0.7 C_b$ is chosen as the maximum discharge current. Further, the minimum voltage of each single battery cell is 2 V, and the voltage of the battery package is 24 V.

$$V_b = V_{oc} - \left(\frac{K}{B_{soc}}\right) i_b - R_b i_b \ . \tag{9}$$

Here, V_b denotes the battery terminal voltage; V_{oc}, the open-circuit voltage; K, the polarization constant; B_{soc}, the battery state of charge (SOC); R_b, the internal resistance; and i_b, the output current.

Among the many modeling methods, the internal resistance model is used. This model can estimate the SOC using power.

Further, B_{soc} is proportional to the charging current i_{ch}.

$$B_{soc} = \frac{1}{C_b V_b} \int i_{ch} \, dt \ . \tag{10}$$

The battery SOC in the steady-state B_{ssoc} can be expressed as follows:

$$B_{ssoc} = \frac{V_{C_1} \cdot e_{ce}}{C_b V_{bm} V_b} \int (i_{bus} - i_{UDC}) \, dt \ , \tag{11}$$

where i_{UDC} denotes the UDC output current; i_{bus}, the load current into the inverter; and e_{ce}, the converter efficiency, which is fixed at 0.95.

An inverter and a motor chosen for many industrial applications are employed in this system.

III. DC/DC CONVERTER OPERATION

In the UDC, all switches are closed at $t = t_0$. V_{FCT} magnetizes the inductor L, and its maximum current i_{Lm} is given as follows:

$$i_{Lm} = \frac{1}{L} V_{FCT} \cdot t_1 \ , \tag{12}$$

where L denotes the inductor on the FC side and t_1 represents the open time of S_3 and S_4 shown in Fig. 2.

The difference between the inductor current i_L and the switch ($S_1 - S_4$) current i_s charges the capacitor C_{FC}, until

both currents reach the same value i_T at t_{1s} [11].

$$V_i - V_{bus} = L_{DC} \cdot \frac{i_T}{t_{1s}-t_1} \ , \qquad (13)$$

$$V_{FCT} - V_i = L_{DC} \cdot \frac{i_T - i_{Lm}}{t_{1s}-t_1} \ . \qquad (14)$$

The operation of the proposed UDC shown in Fig. 2 is simplified, and all devices and components are assumed to be ideal. Fig. 3 shows the operation mode diagrams of the UDC, and one operating cycle can be divided into four modes.

Fig. 4 shows the corresponding waveforms for each mode. T_s denotes the switching period, and $t_1 - t'_2$ represents the operating period of each mode. Modes 1 and 3 are the same and Modes 2 and 4 are different in the dynamic equations [9].

1) Mode 1 ($t_1 = \frac{1}{2}DT$, $S_1 - S_4$ turn on); Mode 3 ($t_3 = DT + \frac{1}{2}(1-D)T_s$, $S_1 - S_4$ turn on)

$$V_{FCT} = L\frac{di_L}{dt} + \frac{1}{C_{FC}}\int i_L dt \ , \qquad (15)$$

$$\frac{1}{C}\int i_{bus} dt = V_{bus} \ . \qquad (16)$$

2) Mode 2 ($t_2 = \frac{1}{2}DT_s + \frac{1}{2}(1-D)T_s$, $S_1 - S_2$ turn off); Mode 4 ($t_4 = DT_s + (1-D)T_s$, $S_3 - S_4$ turn off)

$$V_{UDCO} = \frac{N_2}{N_1}(V_{FCT} - L\frac{di_L}{dt}) \ , \qquad (17)$$

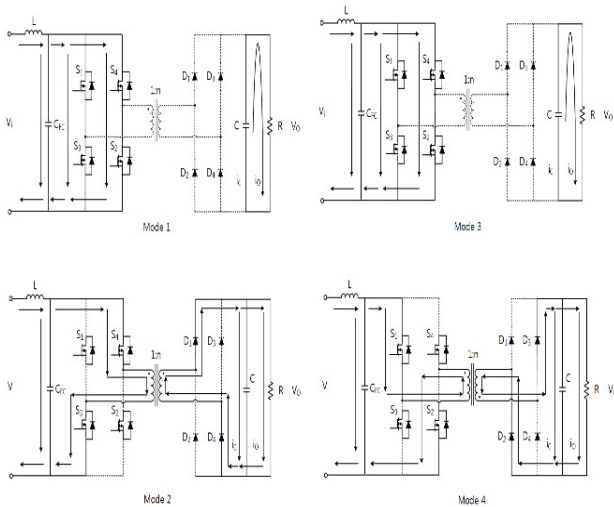$$i_{D1}(Mode\ 4) = i_{D3}(Mode\ 2) = i_{UDC} = C\frac{dV_C}{dt} + \frac{V_{bus}}{R} \ . \qquad (18)$$
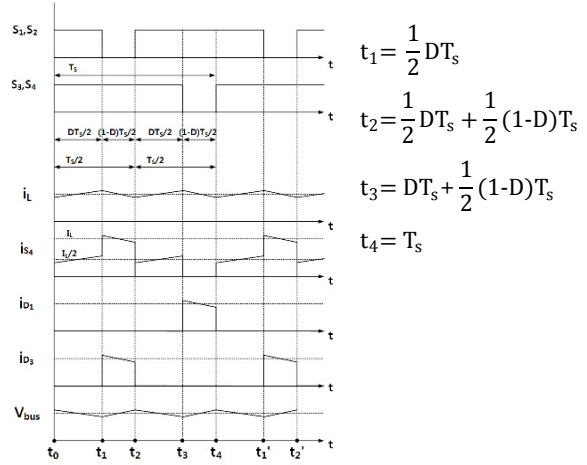

Fig. 3. Operation mode diagrams of UDC.

Fig. 4. Waveforms for each mode.

$$t_1 = \frac{1}{2}DT_s$$

$$t_2 = \frac{1}{2}DT_s + \frac{1}{2}(1-D)T_s$$

$$t_3 = DT_s + \frac{1}{2}(1-D)T_s$$

$$t_4 = T_s$$

The current flows through the DC bus are shown in Fig. 5 can be expressed as follows:

$$i_{bus} = i_{UDC} + i_{BDC} \ . \qquad (19)$$

The output voltages V_{UDCO} and V_{BDCO} in the DC bus can be expressed as follows:

$$V_{UDCO} = V_b(1 + \frac{D}{1-D}) \ , \qquad (20)$$

$$V_{BDCO(boost)} = V_b\frac{D}{1-D} \ . \qquad (21)$$

IV. SIMULATION AND EXPERIMENTAL RESULTS

The FC is connected to the DC bus through the UDC, and the battery is connected to the DC bus through the BDC. The UDC and the BDC should operate under a suitable control according to the conditions of the FC and the battery. Table 1 shows the hybrid system operation condition.

The DC bus is changed by the operation condition of the FC. The working condition of the FC is defined by the FC limited power point voltage V_{FCLP}. For the simulation, the operation condition of the FC can be defined using the DC bus voltage as follows:

1) $V_{bus} < V_{FCLP}$: Battery needs to supply energy to the load.
2) $V_{bus} > V_{UDCO}$: There is a surplus power transfer to the battery.
3) $V_{FCLP} \leq V_{bus} \leq V_{UDCO}$: This is the FC normal state.

We have to select the FC limit-power point voltage V_{FCLP}, which has two control points, namely the slip-in point V_{SLIP} and the slip-out point V_{SLOP}. Further, V_{bus} is sensed for the control process of the hybrid power system [12, 13].

Table 1. Hybrid system operation situation

	FC	Battery	UDC	BDC
Cold start mode				
Step 1	Warm up	Supply	No operation	Boost (increase i_{BDC})
Step 2	Warm up	Supply	No operation	Boost (constant voltage) [$V_{bus} = V_{BDCO}$]
Step 3	Standby (supply)	Supply	Soft start	Boost (decrease i_{BDC})
Step 4	Supply	Slip out	$V_{bus} = V_{UDCO}$ (constant voltage)	No (i_{BDC} reach to Zero)
Overload mode				
Step 1	Supply (cold start)	No supply	Operation ($V_{bus} = V_{UDCO}$)	No operation
Step 2	Supply (FC output limit)	No supply	Operation (with capacitor)	No operation
Step 3	Supply	Supply	Operation	Boost (start)
Step 4	Supply (increasing)	Supply (decreasing)	Operation	Boost (constant voltage)
Step 5	Supply (rated power)	Supply (inadequate power)	Operation (limited current) [$i_{UCD} = I_{UDC}$]	Boost ($V_{bus} = V_{UDCO}$)
Step 6	Supply	Slip out	Operation ($V_{bus} = V_{UDCO}$)	No (i_{BDC} reach to zero)

During the overload condition, the battery needs to slip into the system, and the BDC should begin to work in the boost constant-voltage mode. Further, V_{SLIP} can be determined under the overload condition. It should be less than $V_{BCDO-Boost}$ but close to $V_{BDCO-Boost}$. V_{SLOP} is determined according to the battery's slip-out time and the FC's self-start finish time. When the FC finishes its self-start and powers up to the load, the UDC operates under a constant-voltage condition and $V_{bus} = V_{UDCO}$. In this study, V_{SLOP} is determined as $V_{BDCO-Boost} < V_{SLOP} < V_{UDCO}$.

The FC response time is tens of seconds during the cold-start state, and hundreds of milliseconds in the standby (warm up) condition. The UDC response time is tens of microseconds. Therefore, the UDC response performance is not a serious issue in the hybrid system.

Models of the 1.5-kW fuel cell system using the BDC are

obtained for each part of this study. To research the UDC, the BDC power is changed by varying the load, and the simulation is performed using LabVIEW. In the simulation, the BDC reaction rate is considered to be the maximum [14].

The UDC control algorithm regulates the DC bus voltage and adjusts the UDC output voltage. The fuel cell has a limitation with respect to the increase or decrease in the power. When the load increases sharply, the UDC power increases at a constant rate. Consequently, the UDC power handles the entire load. Further, the UDC power shows a similar trend for a decreasing load.

The BDC control algorithm is different for the two modes. The current travels from the battery to the DC bus in the boost mode, and from the DC bus to the battery in the buck mode. The boost mode algorithm regulates the DC bus voltage and adjusts the BDC output voltage. When the load increases sharply, the BDC power increases rapidly. If the increase in the load is greater than that in the BDC power, the BDC is switched to the boost mode, as shown in Figs. 5 and 6.
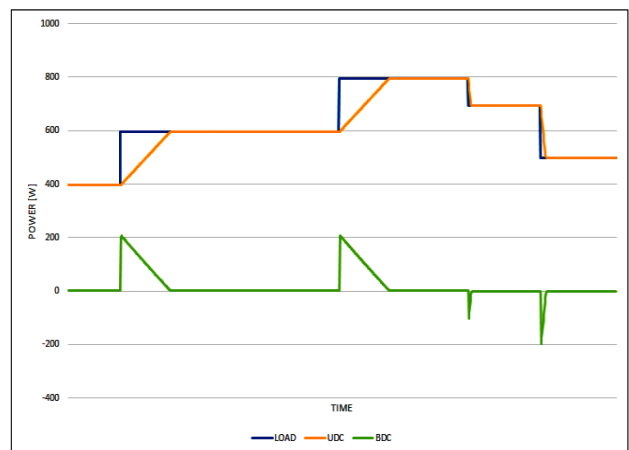

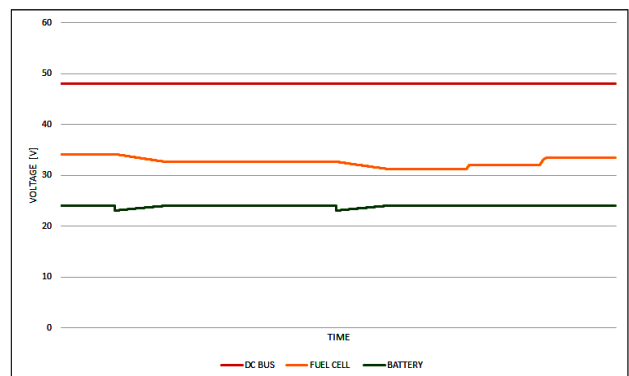**Fig. 5.** UDC and BDC power response during a load change in the BDC boost mode.

Fig. 6. DC bus, FC, and battery voltage response during a load change in the BDC boost mode.
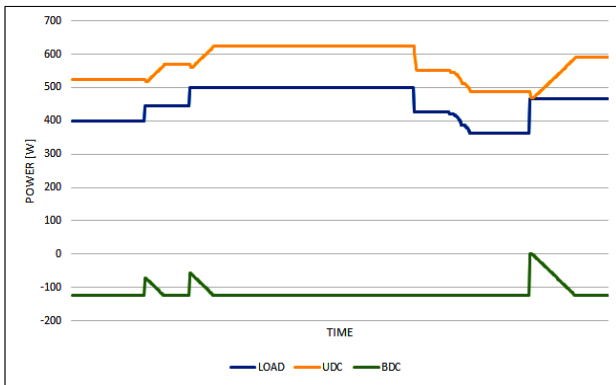
Fig. 7. UDC and BDC power response during a load change in the BDC buck mode.
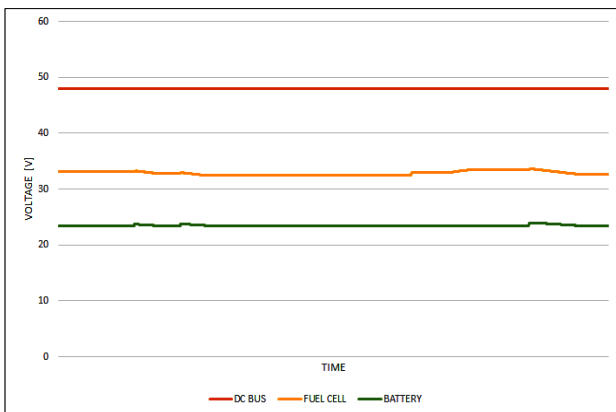

Fig. 8. DC bus, FC, and battery voltage response during a load change in the BDC buck mode.

The buck mode algorithm is used when there are no sudden increases in the load. If the load increases sharply in the buck mode, the BDC output voltage decreases, leading to a drop in the battery charging current. In the event of a regenerative current, the BDC mode switches to the buck mode, as shown in Figs. 7 and 8 and returns to the boost mode shortly.

V. CONCLUSION

The use of the BDC system has many advantages. First, the battery charging current can be selected. Second, the volume of the battery pack can be optimized by adjusting the battery charging or discharging current. Third, frequent charging and discharging of the battery is prevented by adjusting the BDC switching time. This can be expected to increase the battery life. However, switching devices improvement in high power system is need to use BDC with safety operation. This problem can be solved with technological advances in the near future.

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