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A variable DC approach to minimize drivetrain losses in fuel cell marine power systems

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Abstract—This paper presents a method of operating a zero-emission power system in marine vessels. The main goal of the proposed method is to reduce losses of drivetrain devices. The power sources considered in this work are proton exchange membrane fuel cell and lithium-ion battery while the main power consumers are induction motors. Both sources and consumers are connected to a common DC bus through power conversion devices. In the proposed method, the DC bus voltage level is controlled according to the loading of the fuel cells. By controlling the DC bus voltage, it allows operation of fuel cell DC/DC converter in Freewheeling mode which significantly reduces the converter losses. In addition, this approach is also expected to reduce the motor and battery drive losses. Feasibility of the proposed operation method and loss calculations are presented on a real-time hardware-in-loop simulator consisting of real control units and virtual power device models.

I. INTRODUCTION

International Maritime Organization has recently taken a decision to halve greenhouse gas emissions by year 2050 and limit Sulphur content from ship fuel to 0.5% starting from year 2020. To avoid possible carbon fee penalties, vessel operators are searching for alternative methods for low emission propulsion. Hydrogen fuel cells (FC) and batteries are suggested to have large potential as green power sources for the shipping industry [1]. However, high cost of fuel cells and hydrogen is strongly slowing down their adoption in marine vessels. Therefore, designing power systems to maximize their efficiencies is an important step to accelerate the adoption of FCs in marine systems.

FCs and batteries are both DC power sources with characteristics of variable terminal voltages as a function of load and state of charge (SOC), respectively. In a modern DC distribution system, the DC voltage is commonly set at a predefined level, e.g. 1000 VDC, with slight droop for load sharing among the power sources. For this reason, DC/DC converters are usually needed to regulate the output voltage. Electric propulsion motors are connected to the same DC bus through a voltage source inverter (VSI). In typical marine vessels, hotel loads such as lighting, HVAC, and navigation still require AC power and therefore off-grid converters are typically used to generate the AC network. A generic single line diagram of a marine vessel with FCs and batteries as power sources is illustrated in Figure 1. The DC voltage level is typically designed to enable the VSI to operate at maximum power. However, some marine vessels typically operate at lower loads

than dimensioning or design set points. For example, vessel types such as dynamic positioning vessels or offshore vessels have been known to spend 90% of total energy consumption when operating at partial loads, less than 60-70% of full power [2-3].

However, controlling the voltage level to reduce losses has been known technique, for example in electric vehicles. Therein, varying the voltage based on propulsion motor load is found to reduce losses, especially at low loads [4-6]. At lower loads, propulsion motor is operated at voltage level lower than nominal. Therefore, reducing the DC bus voltage also reduces the voltage stress and current ripple (caused by VSI) which reduce the VSI and electric motor losses.

Contrary to [4-6], where DC voltage level is proposed to be adjusted based on propulsion drive operation point, this paper proposes to control the DC bus voltage based on the FC operation point. In particular during partial loads, the FC converter (a buck-boost type) is proposed to be operated in Freewheeling mode, where current is left to freely flow to the DC bus and the converter is operating with zero switching losses. In this scenario, a maximum $\pm 10\%$ DC bus voltage variation from nominal value is allowed. This small voltage variation will have a minor reducing effect in propulsion drive and battery drive losses but significantly reduce the FC DC/DC converter losses.

Figure 1: Generic single line diagram of a fuel cell powered marine vessel system with DC distribution.

This paper is organized as follows. The proposed DC bus voltage control method, which is key to keeping the system

stable during different dynamic conditions, is set forth in Section II. Advantages of variable DC bus voltage control method in a FC and battery hybrid system will be studied using a hardware-in-loop (HIL) setup consisting of a mix of real power converter control units and virtual models as discussed in Section III. HIL equipment used in this work are Typhoon HIL 604 devices. The simulation results are presented in Section IV. The paper concludes with discussion and recommendations of future research in Section IV.

II. VARIABLE DC BUS VOLTAGE CONTROL METHOD

A general voltage polarization curve of an FC (150 kW nominal power) is illustrated in Figure 2. FC voltage, V_{fc} , has a significant nonlinear relation to the FC load. In conventional power systems, a power converter is used to constantly convert the varying FC voltage to a fixed DC voltage at the common DC bus. In aim of improving system efficiency, the variable DC bus voltage control method takes advantage of the FC voltage variation by also varying the DC bus voltage accordingly. By controlling the DC bus voltage to equal the FC voltage, the power conversion between FC and DC bus can be bypassed, which reduces power conversion losses. The DC bus voltage is constantly controlled by battery power sources with quick dynamic characteristics.

Figure 2: Fuel cell polarization curve. V_{dc_min} and V_{dc_max} are minimum and maximum DC bus operation voltages used in the control method of this paper.

The operation of DC bus voltage control method is illustrated in block diagrams in Figure 3. For simplicity, these block diagrams contain only one FC and one battery as power sources. In case more FCs (with same operating voltages) are simultaneously connected to the DC bus, the voltage measurement of each FC needs to be considered for mode selection. FCs are loaded symmetrically, meaning that each FC converter is given the same current reference, I_{ref} . Symmetrical load sharing is preferred because, excluding operation in activation region, the lower the load seen by FC is, the higher the efficiency of the FC [7]. In case more batteries are simultaneously connected to the DC bus, each battery converter is given the same voltage reference, V_{ref} . Also, instead of using current measurement of one battery, I_{bat} , the sum of current measurements from all batteries is used as feedback for PI controllers. Load power is equally shared between batteries through voltage droop control. The operation points of load

drives do not affect this control method. Therefore, load drives are omitted from Figure 3.

In this control method, three different operation modes exist. The operation mode to be used is chosen based on the FC operation voltage. The DC bus voltage is controlled based on the active operation mode:

$$V_{dc} = \begin{cases} V_{dc_max}, & V_{fc} > V_{dc_max} \\ V_{fc}, & V_{dc_min} \leq V_{fc} \leq V_{dc_max} \\ V_{dc_nom}, & V_{fc} < V_{dc_min}, \end{cases} \quad (1)$$

where V_{nom} , is nominal FC voltage, V_{dc_min} is minimum DC bus voltage and V_{dc_max} is maximum DC bus voltage. The DC bus voltage is always kept inside the operation limits, $[V_{dc_min}, V_{dc_max}]$ to ensure safe operation conditions for other vessel equipment (e.g. hotel load converters) connected to the DC bus.

When $V_{fc} > V_{dc_max}$, power conversion between FCs and DC bus is required. The FC DC/DC converter is used as a buck converter to step down the FC voltage to V_{dc_max} . This operation mode is called Buck mode (Figure 3a). In the Buck mode, voltage reference, V_{ref} , given to the battery converter is fixed at V_{dc_max} . The FC converter is operated in current control mode. FC current reference, I_{ref} , is obtained from a PI controller which is tuned to control the battery current, I_{bat} , to zero. By controlling I_{bat} to be zero, it is ensured that FC supplies base load to the DC bus and battery is not overly charged or discharged. The PI controller is tuned to be slow enough for the batteries to always react first on load dynamics. Positive value for I_{bat} refers to charge current and negative value refers to discharge current.

When $V_{dc_min} \leq V_{fc} \leq V_{dc_max}$, FC voltage is inside DC bus voltage operation area, and thus the DC bus voltage can be controlled (by battery converter) to be equal to FC voltage. Therefore, voltage conversion between FC and DC bus is not required, meaning that the the power conversion of FC converter can be bypassed. This mode is called Freewheeling mode because FC current is allowed to freely flow through the DC/DC converter unit to the DC bus. In the Freewheeling mode (Figure 3b), the V_{ref} is obtained from a PI controller which, as PI controller in Buck mode, is tuned to control the I_{bat} to zero. Lowering the DC bus voltage also lowers FC voltage which, as shown in Figure 2, leads to increased FC power towards the DC bus. Contrarily, increasing the DC bus voltage leads to a lowered FC voltage towards the DC bus. Therefore, even in the Freewheeling mode, FC current is indirectly controlled through control of DC bus voltage by battery converter.

When $V_{fc} < V_{dc_min}$, FC voltage is again outside DC bus operating area and power conversion is needed between FC and DC bus. The FC converter is used as a boost converter to step up the FC voltage to V_{dc_nom} . This operation mode is called Boost mode (Figure 3a). In Boost mode, the FC converter and the battery converter are operated similarly to in Buck mode. The I_{ref} is obtained from a PI controller which is tuned to slowly control I_{bat} to zero. The V_{ref} to battery converter is set to V_{nom} . The reason for using V_{nom} instead of V_{dc_min} is to ensure high enough input voltage margin for propulsion motor inverters when operating at higher powers.

Figure 3: Operation modes of DC bus voltage control scheme: a) Buck mode, b) Freewheeling mode and c) Boost mode. Modes are named based on operation mode of the FC DC/DC converter.

Since changing between the operation modes is managed solely by comparing V_{fc} to the voltage limits (V_{dc_min} and V_{dc_max}), operation of FCs close to the voltage limits may cause unwanted oscillation between the operation modes. One way to avoid this is to set a minimum amount of time that the system must spend in one operation mode before moving to another. E.g., if system is operating in Freewheeling mode and suddenly changes to Buck mode, it will spend a prespecified time, t_m , in Buck mode before moving back to Freewheeling mode. This way frequent swaps between operation modes are avoided.

III. HYBRID POWER SYSTEM MODEL FOR HIL TESTING

A. Proton exchange membrane fuel cell

Proton exchange membrane (PEM) FCs are low temperature FCs and used often in transport applications (i.e. electric cars, trains, busses, etc.). For dynamic and steady state modelling of a PEM FC, an equivalent circuit model presented in [8] and illustrated in Figure 4 is used in this work. The FC voltage is given by

$$V_{fc} = N_{FC}(E_{rv} - V_{act} - V_{con} - V_{res}), \quad (2)$$

where N_{FC} is the number of cells in series, E_{rv} is the reversible open circuit voltage, V_{act} is the activation voltage drop, V_{con} is

the concentration voltage drop and V_{res} is the resistive voltage drop of an FC.

The reversible open circuit voltage is a theoretical maximum FC voltage given by Nernst equation [9]. However, in practice, even the voltage is slightly lower due to irreversible voltage loss which occurs inside the FC. The resistive losses occur mostly when hydrogen ions pass through the membrane and electrons pass through the electrodes and the bipolar plates. Resistive losses are given by

$$V_{res} = R_{res}i_{res}, \quad (3)$$

where i_{fc} is FC current. The activation voltage drop occurs on the electrode surface and is due to slowness in reactions of reactants with the electrode catalysts. The activation voltage drop is obtained using Tafel equation,

$$V_{act} = A_t \ln\left(\frac{i_{fc}}{i_0}\right), \quad (4)$$

where A is a Tafel constant and i_0 is the amount of exchange current which indicates the electrode activity. Concentration losses become more significant at higher current densities and are due to difficulty in supplying enough reactants through the flow channels to satisfy fuel demand, while at the same time removing the product water from the cathode. The following empirical equation is commonly used to obtain concentration voltage drop [9]:

$$V_{con} = m_c e^{n_c i_{fc}}, \quad (5)$$

where m_c and n_c are parameters obtained by curve fitting with actual measured results.

Figure 4: Electrical equivalent model of a PEM fuel cell.

B. Lithium-ion battery

Lithium ion (Li-ion) batteries are common battery types used in transportation applications due to their high energy and power density. A dual polarization (DP) electrical equivalent circuit model for a Li-ion battery is found to offer good dynamic performance and is therefore suitable for hybrid system design [10]. The DP model is illustrated in Figure 5. Model describes both the electrochemical polarization and the concentration polarization characteristics of a Li-ion battery.

Figure 5: Electrical equivalent model of a Li-ion battery.

C. Drivetrain devices

The propulsion motor type used in this work is a three-phase induction motor controlled by an ABB HES880 control unit [11]. The induction motor is a virtual model from Typhoon HIL library [12]. The battery DC/DC converter is an interleaved three-phase bidirectional DC/DC converter. The power unit of the battery converter is a virtual model from Typhoon HIL library which is controlled by a real ABB HES880 control unit with a DC/DC conversion control software.

The FC converter is a unidirectional buck-boost type DC/DC converter. Basically, it consists of two generic buck and boost converters combined as shown in Figure 6. It can operate in Buck mode (Figure 6a), Freewheeling mode (Figure 6b) or Boost mode (Figure 6c). In Freewheeling mode, switch S_1 is constantly on ($S_2 - S_4$ are off) which allows the FC current to freely flow towards the DC bus. The reason for using a single-phase topology (instead of three-phase) for buck conversion is because Buck mode is used only during low FC loads (i.e. start-up, shutdown and protection from faults). During freewheeling or Boost mode, S_1 is always closed and therefore lightly stressed compared to when switching at a high frequency.

Figure 6: Main circuit of FC converter and its operation modes: a) Buck mode (S_1 in PWM, S_2-4 off), b) Freewheeling mode (S_1 constantly on, S_2-4 off) and c) Boost mode (S_1 constantly on, S_2-4 in PWM)

D. Loss models for energy efficiency calculations

To analyze drivetrain efficiency in different operation modes, proper loss equations are needed. For drivetrain devices used in this work, losses can be divided to IGBT, diode, inductor and capacitor losses. Conduction and switching losses of IGBT and diode are obtained from [13]. Switching losses are given by

$$P_{sw}(t) = \frac{u_{dc}(t)i_L(t)}{U_r I_r} f_{sw}(t)(E_{sw}), \quad (6)$$

where i_L is inductor current and E_{sw} (obtained from manufacturer datasheet) is the sum of IGBT and diode switching energy losses per cycle given at voltage U_r and current I_r . The conduction losses are obtained from

$$P_{IGBT_con}(t) = U_{ce0}i_L(t) + R_{ce0}i_L(t)^2, \quad (7)$$

$$P_{diode_con}(t) = (U_{fw0}i_F(t) + R_{fw0}i_F(t)^2), \quad (8)$$

where, i_F is diode forward current, u_{ce0} and u_{fw0} are IGBT and diode threshold voltages respectively and R_{ce0} and R_{fw0} are IGBT and diode on-state resistances respectively. In this

work, FF600R12IP4 IGBT pack from Infineon is used for reference [14].

Inductor winding losses and capacitor losses are calculated using equivalent series resistances (ESRs) of the inductor and capacitor respectively. Inductor and capacitor losses are given by

$$P_{L_win}(t) = i_L(t)^2 ESR_L, \quad (9)$$

$$P_C(t) = i_C(t)^2 ESR_C, \quad (10)$$

where i_C is capacitor current. Inductor core losses are calculated using Steinmetz equation [15] which gives core losses per unit volume

$$P_{core/V_c} = k f_{sw}^a B_m^b, \quad (11)$$

where B_m is peak flux density and constants a , b and k are Steinmetz coefficients which are obtained by curve fitting from a B-H curve of used core material. V_c is the volume of the inductor core. Coefficients a , b and k used in this work are obtained from [15]. Peak flux density is obtained from

$$B_m = \frac{L_{fc} i_p}{N_L A_c}, \quad (12)$$

where i_p is peak inductor current, L_{fc} is inductor inductance, N_L is number of turns and A_c is core area [16].

IV. HIL RESULTS AND DISCUSSION

To verify the functionality of the variable DC bus voltage control method and estimate the effect the control method has on drivetrain losses, a real-time HIL simulation setup is built. The setup contains virtual models of one FC and one battery with their respective DC/DC converters and one induction motor with a DC/AC converter. The parameters used in the models for the HIL tests are presented in **Virhe. Viitteen lähde**.

Table 1: Parameters used in HIL simulations

PEM FC		Converters	
N_{FC}	849	U_r	600 V
E_{rv}	1.1 V	I_r	60 A
R_{res}	366 $\mu\Omega$	f_{sw}	5000 kHz
A_t	52.5 * mV	L_{fc}	250 μ H
i_0	3.33 A	C_{in}, C_{out}	3.0 mF
m_c	0.77 * μ V	E_{sw}	49 mJ
n_c	33.3 * mA ⁻¹	U_{ce0}	0.81 V
C_{cdl}	0.4 F	R_{ce0}	1.92 * 10 ⁻³ Ω
Li-ion Battery		U_{fw0}	1.05 V
E_{OCV}	511 V	R_{fw0}	1.07 * 10 ⁻³ Ω
R_{ohm}	24 m Ω	ESR_C	30 * 10 ⁻³ Ω
R_{ep}	0.65 * m Ω	ESR_L	20 * 10 ⁻³ Ω
C_{ep}	5700 F	k	1.873
R_{cp}	8.39 * m Ω	a	1.727
C_{cp}	53817 F	b	1.865
System		V_c	8.3 * 10 ⁻⁴ m ³
V_{nom}	720 V	N_L	23
V_{dc_min}	660 V	A_c	3108 mm ²
V_{dc_max}	770 V		
t_m	5.0 s		

The operation of the hybrid FC - battery powered DC system with variable DC bus voltage at different loads is illustrated in Figure 7. The transition between different operation modes is highlighted with dashed vertical lines. Figure 7a illustrates how battery and FC react to different load dynamics. Even with quick load dynamics, load changes seen by FC are relatively slow which ensures that fuel starvation is avoided. By observing the power waveforms in Figure 7a, no difference can be seen whether the system operates in Buck, Freewheeling or Boost mode. This indicates that from a system perspective, controlling DC bus voltage to maximize system efficiency does not undermine system reliability when comparing to conventional systems with a fixed DC bus voltage. Figure 7b illustrates the voltage levels at different loading levels. Figure 7c illustrates the total power conversion losses between FC output terminals and propulsion motor input terminals. When operating in Freewheeling mode, losses are significantly decreased compared to operation in the two other modes. The main loss reduction factor in Freewheeling mode is absence of high frequency switching which eliminates the switching losses of semiconductors in of the FC converter and reduces core losses in the passive components of the FC converter.

Figure 7: a) Power, b) voltage and c) losses of drivetrain components when operated with variable DC bus control method.

In order to evaluate impacts that the variable DC bus voltage control method has on a system operating with FCs and batteries, efficiency of such a system is compared to a similar system operating constantly with a fixed DC bus voltage. The drivetrain power losses at six different operation points for both types of systems are presented in Table 2. The values are HIL simulated for both FC converter and the propulsion load converter. In the system with a fixed DC bus voltage, the DC bus voltage is constantly kept at nominal value (720 V). At 25 kW FC power, the system in variable DC bus voltage mode operates in Buck mode and the DC bus voltage is 770 V. At 188 kW FC power, the system operates in Boost mode and the DC bus voltage is 720 V. In the rest of the operating points of Table 2, the system operates in Freewheeling mode.

The values in Table 2 show that implementation of variable DC bus voltage control method can reduce drivetrain losses by up to 28 %. In Freewheeling mode, the reduction in losses occurs mainly due to omission of switching losses of the FC converter. Additionally, since the load converter losses are also proportional to DC bus voltage, they also behave such that when DC bus voltage is lower than nominal voltage, the load converter losses are lower in variable DC bus voltage-

controlled system than in conventional fixed DC bus voltage-controlled system. However, the drawback is that at lower loads, when DC bus voltage is higher than the nominal voltage, the load converter losses are slightly increased in variable DC voltage-controlled system. In Buck mode, the increased load converter losses are compensated by reduced FC converter losses. The reason is that due to the DC bus voltage being higher than nominal voltage, the voltage conversion requirement from FC to DC bus is lower. This decreases the energy needed to store in the FC converter choke and the voltage stress over the FC converter semiconductors. In Boost mode, the operation in variable DC bus voltage-controlled system is identical to that in the system with a fixed DC bus voltage. Therefore, the power losses are also not affected.

Table 2: Converter losses in a conventional system with fixed DC bus voltage and corresponding loss values with a variable voltage-controlled system. FC converter losses include the choke, semiconductor and capacitor losses. The load converter losses include semiconductor and capacitor losses.

FC Power	Losses in fixed DC mode		Losses in variable DC mode		change-%
	FC conv.	Load Conv.	FC conv.	Load Conv.	
25 kw	870 W	1050 W	403 W	1147 W	-19 %
55 kw	965 W	1550 W	199 W	1613 W	-28 %
102 kw	1460 W	2390 W	460 W	2385 W	-26 %
133 kw	1660 W	2712 W	699 W	2684 W	-23 %
161 kw	2630 W	3420 W	1000 W	3333 W	-28 %
188 kw	4050 W	3900 W	4050 W	3900 W	0 %

FCs are known to be sensitive to current ripples, especially those with low frequency ($\sim 100\text{Hz}$) ripple [17-18]. In order to compare FC current waveforms in freewheeling mode to currents in Buck and Boost modes, the FC currents during the three operating modes are illustrated in Figure 8. The current waveforms in freewheeling mode appear thinner than currents in Buck or Boost mode. The reason is that without the switching of FC converter, the FC voltage follows the voltage on the DC bus. Therefore, the more accurate the voltage control of the battery converter the less ripple appear in the FC current. From the HIL simulations (Figure 8), the medium FC peak-to-peak current ripple in freewheeling modes is found to be less than 1 A. This compares with the medium peak-to-peak current ripples of 12 A and 6.7 A in Buck and Boost modes. Therefore, operation in freewheeling mode, could slightly improve the lifetime and efficiency of the FC.

Figure 8: FC current waveforms during different operation modes.

V. CONCLUSION

This work has proposed a varying DC bus operation method for FC and battery hybrid power systems for marine vessels with DC distribution. The DC bus voltage control method enables system operation in Freewheeling mode during partial loads, which significantly decreases losses in electric drivetrain equipment. The stability tests performed in this work using HIL simulation prove the feasibility of the variable voltage control method. Based on the FC current waveforms from HIL simulations, connecting FCs directly to common DC bus can potentially improve FC efficiency and lifetime due to decreased amount of current ripple. Possibility to operate in Freewheeling mode is highly beneficial for marine vessels which mainly operate at partial loads, especially during docking or maneuvering.

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