Haxhiu, Arber; Kyyrä, Jorma; Chan, Ricky; Kanerva, Sami

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Modified Variable DC Approach Applicable to Fuel Cells and DOL Batteries in Shipboard Power Systems

Arber Haxhiu
Electric Solutions
ABB Marine and Ports
Helsinki, Finland
arber.haxhiu@fi.abb.com

Jorma Kyyrä
Electrical Engineering and Automation
Aalto University
Espoo, Finland
jorma.kyyra@aalto.fi

Ricky Chan
Electric Solutions
ABB Marine and Ports
Helsinki, Finland
ricky.chan@fi.abb.com

Sami Kanerva
Electric Solutions
ABB Marine and Ports
Helsinki, Finland
sami.kanerva@fi.abb.com

***Abstract* – Previously, a Variable DC approach has been proposed for hybrid fuel cell and battery shipboard systems. The approach was shown to reduce system powertrain losses, and hence cost of operation. However, in addition to cost, some vessel types are quite sensible to system weight and footprint. For such vessels, use of batteries without power converters is an attractive solution. However, the Variable DC approach is not applicable to batteries integrated without power converters. This paper proposes modifications on the previously presented Variable DC approach. The new approach enables reductions in system weight and footprint, while also achieving improvements in powertrain efficiency. The validation of the proposed method is carried out using a real-time hardware in loop test setup.**

Index Terms – Powertrain, Fuel cell, DOL battery, Control, Marine, Variable DC Voltage.

I. Introduction

In recent years, the maritime industry has faced major scrutiny over harmful emissions released from carbon-based power sources that are used for shipboard power production. Hence, a transformation towards greener power sources is occurring. To reduce emissions in shipboard power production, proton exchange membrane (PEM) fuel cells (FCs) and lithium-ion (li-ion) batteries are often considered as potential power sources. To date, li-ion batteries have already been adopted in dozens of vessels. However, adoption of PEM FCs is still at its infancy. To accelerate adoption of FCs and batteries in marine vessels, innovative power system concepts are needed to achieve highest efficiency and lowest cost of operation.

In the past decade, hybrid operation of FCs and batteries for various applications has been widely studied. For marine vessels, a lot of effort has been placed into finding energy management strategies (EMS's) that optimize FC efficiency. For example, an EMS aiming at FC efficiency optimization via coordinated load sharing between FCs and batteries has been proposed in [1]. A fuzzy logic-based EMS targeting maximum FC performance is proposed in [2]. A states-based EMS which also targets FC efficiency improvements via controlled load sharing, has been proposed in [3]. Other relevant works can be found in [4]-[6]. However, while many studies on optimal EMS's exist, methods to reduce total powertrain losses are rare.

In applications similar to marine applications (i.e., vehicle applications), variation of DC bus voltage has been found to reduce losses in power conversion devices and electric motors [7]-[10]. At low loads, where motor input voltage is low, the DC bus voltage is reduced. Reduction of DC bus voltage results in reduced voltage stress over power conversion devices and reduced flux density ripple in motor magnetic circuits, and hence reduced losses in mentioned components. In vehicles, such an approach is feasible because the motor is typically the only component that requires high voltage for operation. However, in marine vessels, there exists several different load types that require high voltage for operation. Such loads, typically called hotel loads, are e.g., heating, air conditioning and lighting. Thus, large variations in DC bus voltage are typically not allowed in a marine vessel.

In aim of overcoming the abovementioned challenge for marine vessels, a novel Variable DC approach was proposed in [11]. In the approach, the system is designed to sustain small voltage variations (±10 %) around the nominal DC bus voltage. Within the voltage range, the DC voltage is controlled equal to FC voltage and power conversion between the FC and DC bus is bypassed. Hence, switching losses are eliminated, resulting in lower cost of operation.

While cost of operation is obviously important for any vessel type, some vessel types (e.g., high-speed passenger vessels) are also very sensible to system weight and footprint [12]. For such vessel types, an attractive solution is connection of batteries direct on-line (DOL), instead of through DC/DC converters. Such a system is shown in Figure 1. Omission of battery converters is beneficial because in addition to reducing the total weight and footprint of the system, it also reduces the total cost of investment in such a system. However, since the Variable DC approach proposed in [11] is highly dependent on voltage control performed by battery converters, the approach is not applicable for a system with DOL batteries. In order to apply the Variable DC approach on systems with FCs and DOL batteries, this work proposes modifications to the original approach. The new modified approach enables reductions in system weight and footprint, while also maintaining the powertrain efficiency improvements provided by the original approach.

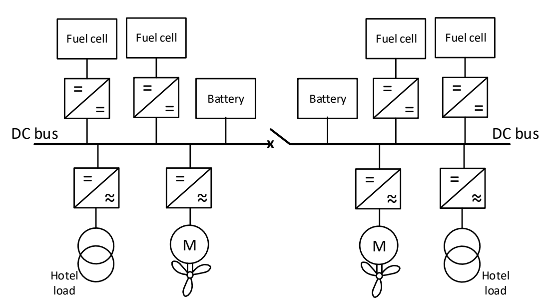

Figure 1: A Generic single line diagram of a fuel cell powered marine vessel system with DC distribution. Apart from propulsion, all other load (e.g., lighting and air conditioning) is considered hotel load.

The paper is organized as follows. Section II introduces voltage characteristics of PEM FCs and Li-ion batteries. The proposed modified Variable DC approach is set forth in Section III. The approach is validated in a real-time hardware in loop (HIL) test setup which will be described in Section IV. The test results of the proposed approach are presented in Section V. The paper concludes with discussion and recommendations of future research in Section VI.

II. PEM FUEL CELLS AND LI-ION BATTERIES

Applying of the Variable DC approach on systems with FCs and DOL batteries requires good understanding of voltage characteristics of the power sources. For both power source types, various models have been developed to describe their output voltages as function of current. One commonly used model for estimation of FC voltage is an empirical equation described in [13]. The voltage is described as follows:

$$V_f = N_f \left(E_{f0} - R_f i_f - A_f \ln\left(\frac{i_f}{i_0}\right) - m_f e^{n_f i_f} \right), \qquad (1)$$

where N_f is the number of cells connected in series, E_{f0} is thermodynamically estimated no-load voltage, R_f is ion and electron transfer resistance, A_f is an activation voltage drop coefficient, i_0 is exchange current value and m_f and n_f are empirically determined constants used for modeling of voltage drop due to reactant concentration. The activation voltage drop is usually dominant at low FC loading, while the voltage drop due to fuel concentration mainly becomes significant at high loadings. A voltage polarization curve of a 180 kW PEM FC used in this work is illustrated in Figure 2a. The dashed lines (V_{dc_min} and V_{dc_max}) in the figure highlight the minimum and maximum DC bus operation ranges. They will be further described in Section III. The FC model parameters used in this test are presented in Table 1.

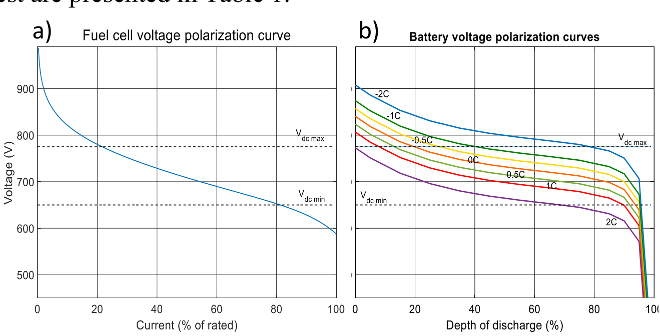

Figure 2: a) A fuel cell and b) battery voltage polarization curves where V_{dc_min} and V_{dc_max} are minimum and maximum DC bus operation voltages, respectively.

A dynamic model suitable for describing the battery voltage as a function of current and state of charge (SOC) has been presented in [14]. The battery voltage is described as follows:

$$V_b = N_b \left(E_{b0} - R_b i_b - K_b \frac{Q}{Q - Q_d} + A_b e^{-BQ_d} \right), \qquad (2)$$

where N_b is number of battery cells in series, E_{b0} is a voltage constant, R_b is series resistance, i_b is battery current, K_b polarization voltage, Q is full charge capacity, A_b and B are empirically determined constants describing the voltage drop over the exponential zone (see [14] for the definition of the exponential zone) and Q_d is a state of discharge. The state of discharge is given in Ah, and is calculated as follows:

$$Q_d = \int i_b \, dt. \qquad (3)$$

Voltage polarization curves of the Li-ion battery analysed in this work are illustrated in Figure 2b. The battery model parameters used in this test are presented in Table 1.

Table 1: Fuel cell and battery model parameters used in this work.

Parameter	Symbol	Value
Fuel cell no-load voltage	E_{f0}	1.1 V
Activation voltage drop coefficient	A_f	0.0525 V
Fuel cell exchange current	i_0	3.33 A
ion and electron transport resistivity	R_f	366 μΩ
Mass transport loss constant 1	m_f	0.77 μV
Mass transport loss constant 2	n_f	33.3 mA^{-1}
Number of fuel cells in series	N_f	849
Battery constant voltage	E_{b0}	3.62 V
Battery cell capacity	Q	25 Ah
Battery cell polarization voltage coeff.	K_b	21.8 mV
Battery cell Internal resistance	R_b	6.75 mΩ
Inverse exponential zone time constant	B	0.156
Battery voltage empiric constant	A_b	607.5 mV
Number of battery cells in series	N_b	200

III. THE VARIABLE DC APPROACH

A. The general philosofy of the approach

The concept of the Variable DC approach for hybrid FC and battery marine power systems has been presented in [11]. In the approach, FCs and batteries are connected to a common DC bus via DC/DC converters. The FC converter type is required to be a non-isolated converter with both buck and boost capabilities. One suitably FC converter topology is shown in [[11], Fig. 6]. The control of the FC converter is divided into three operation modes: Buck, Freewheel and Boost modes. The DC bus voltage is allowed to vary within a certain operation range $[V_{dc\_min}, V_{dc\_max}]$. When an FC is lightly loaded and its voltage is higher than V_{dc_max}, the FC converter is operated in Buck mode. When FC is highly loaded and its voltage is lower than V_{dc_min}, the FC converter is operated in Boost mode. However, when the FC voltage is within $[V_{dc\_min}, V_{dc\_max}]$, switches of the FC converter are controlled into a static state to allow free between FC and the DC bus. This mode is called Freewheel mode. In Freewheel mode, DC bus voltage is maintained at a wanted value by battery DC/DC converters. Since FC converter switches are static, switching losses of FC converters are eliminated, resulting in improved total powertrain efficiency.

In the original Variable DC approach, operation in Freewheel mode is completely dependent on voltage control performed by battery converters. The FC loading is controlled by adjusting the DC bus voltage to a suitable value. However, since DOL batteries cannot perform voltage control, control of FC loading via control of DC bus voltage is not possible. Therefore, a different kind of control approach is needed. The system must be designed such that the DC bus voltage and battery SOC stay within their allowed operation ranges. Additionally, since FCs are typically very sensible to quick power transients [15], the FCs must be prevented from experiencing quick power transients. A load power transient is considered quick if it leads to FC current increasing or decreasing faster than allowed by the FC requirements. In the following, we describe the modified Variable DC approach for operation of hybrid FC and DOL battery systems.

B. Modified Variable DC Approach for hybrid FC and DOL battery systems

In the original Variable DC Approach, FC converter operation modes are selected purely based on FC voltage. In Buck mode, the current reference to FC converter is adjusted such that battery current is controlled to zero. Hence, the batteries are typically charged or discharged only during occurrences of quick load transients. Following the transient, the FC current is controlled to bring battery power back to zero. The same operating principle is followed in the proposed modified Variable DC approach for FCs and DOL batteries. However, since a DOL battery cannot perform DC bus voltage regulation nor control its own SOC, the FC converter must also be tuned to limit the FC current if either DC bus voltage or battery SOC increase above their maximum allowed values. However, it should be noted that commercial FC products typically require certain amount of FC current to always be drawn out during operation. Typically, the minimum allowed FC current, i_{fc_min}, is between 5-15% of nominal FC current. If FC current drops below this value, the FC must be turned off. The proposed control method for Buck mode is illustrated in Figure 3.

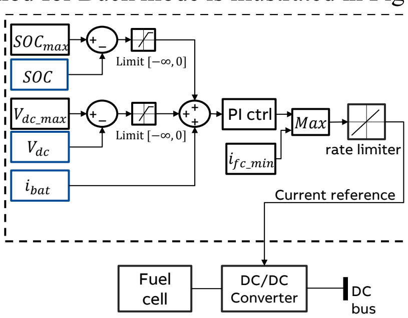

Figure 3: Current control diagram in Buck mode. Blue and black boxes represent measurement feedbacks and preset constants, respectively.

In the Boost mode, the current reference to FC converter is adjusted such that battery current is controlled to zero. If either DC bus voltage or battery SOC decrease below minimum allowed values, their further decrease must be prevented by increasing the FC current. Also, since the Boost mode is used at high loads, it must be ensured that the DC bus voltage is high enough for propulsion motor loads and the battery current does not exceed its maximum allowed value, I_{bat_max}. For a voltage source inverter, the minimum required DC input voltage is typically the motor AC input voltage multiplied by a square of two. Both the increase of DC bus voltage and the reduction of battery current are achieved by increasing the FC current. The proposed control method for Boost mode is shown in Figure 4.

In the Freewheel mode, both FCs and batteries are directly connected to the DC bus as illustrated in Figure 5. For simplicity, the total load seen by the two power sources is represented as an ideal current source. In the figure, the lower switches in the FC converter are dimmed because they are not used in Freewheel mode, and thus appear as open circuits. Since the FC is connected to the DC bus via static switches (S_1 and $D_{1\text{-}3}$), the DC bus voltage can be expressed in terms of FC voltage

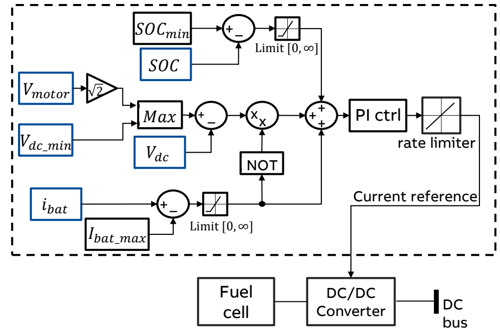

Figure 4: Current control diagram in Boost mode. Blue and black boxes represent measurement feedbacks and preset constants, respectively.

and voltage drop over the FC converter as follows:

$$V_{dc} = N_f\left(E_{f0} - R_f i_f - A_f \ln\left(\frac{i_f}{i_0}\right) - m_f e^{n_f i_f}\right) - V_{con}, \quad (4)$$

where V_{con} is the total on-state voltage drop over the FC converter switches. The voltage drop over FC converter switches can be calculated as follows [11], [16]:

$$V_{con} = U_{ce0} + R_{ce0} i_{fc} + \frac{1}{3} ESR_L i_{fc} + U_{fw0} + \frac{1}{3} R_{ce0} i_{fc}, \quad (5)$$

where U_{ce0} and U_{fw0} are transistor and forward diode threshold voltages, respectively, R_{ce0} and R_{fw0} are transistor and forward diode on-state resistances, respectively, and ESR_L is the equivalent series phase resistance of a converter choke. Since the inductor and diodes consist of three phases, the current flowing through one component is third of the total FC current.

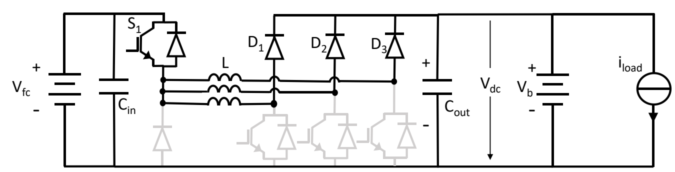

Figure 5: A simplified equivalent circuit for a fuel cell, a battery and a load. Some components in FC converter are dimmed because they are not active in Freewheel mode.

On the other hand, the battery is also directly connected to the DC bus and therefore, the DC bus voltage can also be expressed in terms of the battery voltage as follows:

$$V_{dc} = N_b\left(E_{b0} - R_b i_b - K_b \frac{Q}{Q - Q_d} + A_b e^{-BQ_d}\right). \quad (6)$$

Since both the battery and the FC are directly connected to the DC bus, the power flow between the power sources and load will always drift towards a steady state where all load power is supplied by the FC. Therefore, in steady state, $i_b = 0$. Recalling from Section II, the voltage over the exponential zone is typically significant only at high battery SOC levels which occur outside the operating range of Freewheel the mode. Therefore, the exponential term in (6) can be ignored. Hence, (6) can be simplified to describe steady state as follows:

$$V_{dc} = N_b\left(E_{b0} - K_b \frac{Q}{Q - Q_d}\right). \quad (7)$$

Since at steady state all load is supplied by the FC, the DC bus voltage can also be expressed in terms of load power, P_{load}, and FC current as follows:

$$V_{dc} = \frac{P_{load}}{i_f}. \quad (8)$$

Therefore, by inserting (8) into (7) and solving Q_d, the state of discharge at steady state as a function of load power can be calculated as follows:

$$Q_d = Q\left(1 - \frac{K_b}{E_{b0} - \frac{P_{load}}{N_b i_f}}\right). \quad (9)$$

During normal operation in the Freewheel mode, the battery SOC varies as a function of load power according to (9). The time it takes for the battery SOC to reach steady state value following a load transient is dependent on the energy capacity of the battery, as given by (3). If battery capacity is low, the SOC settles quickly to the steady state value, and hence FC power also ramps quickly. Therefore, a sought FC power ramp rate can be achieved by careful selection of the battery capacity.

However, in some events (e.g., a failure) a non-expected power transient may occur on the DC bus. In such events, part of the transient is absorbed by the battery and rest by the FC. Recalling that FCs are very sensible to quick load transients, FCs should be prevented from experiencing such transients. This is achieved by tuning the FC converter to perform current limitation if FC current rate of change exceeds limits set by FC requirements. To that end, a current limitation method based on hysteresis control is presented in Figure 6. In the method, a tolerance band is set for the FC current. When current is within the tolerance band. FC converter allows free flow towards DC bus. If the current exceeds the band, the current is limited. The tolerance band is allowed to increase or decrease via ramp rates that represent the maximum allowed FC current ramp rates. The functionality of the presented current controller will be illustrated in Section V.

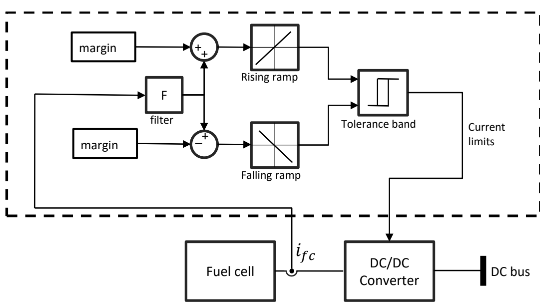

Figure 6: FC converter current limiting control in Freewheeling mode.

C. Control mode selection in the modified approach

In the original Variable DC approach, control modes were selected by comparing FC voltage to DC bus voltage. However, in the modified approach, more conditions are needed. In general, the FCs should be operated in Freewheel mode for highest efficiency. If the system is lightly loaded, the FC voltage and battery SOC tend to increase. If the DC bus voltage or battery SOC increase above V_{dc_max} and SOC_{max}, respectively, the converter must be set to Buck mode. Due to low FC loading in the Buck mode, FC voltage is higher than the DC bus voltage. If the system loading falls lower than required by the FCs, the battery SOC or DC bus voltage may exceed their respective maximum allowed values. In these cases, the FC must be turned off. The FC can be turned back on once both DC bus voltage and battery SOC are below their respective maximum values. In order to avoid frequent start-ups and shutdowns of an FC, some voltage and SOC margin should be used for starting condition. If both SOC and DC bus voltage are below their maximum allowed values and FC voltage is equal to the DC bus voltage, the FC converter is set to Freewheel mode. On the other hand, if the system is highly loaded, DC bus voltage and SOC tend to decrease. If the DC bus voltage or the battery SOC drop below their respective minimum values, the FC converter is set to Boost mode. Also, the Boost mode must be activated if battery current reaches its maximum value or DC bus voltage needs to be increased for propulsion motor loads. Once none of the conditions that led to Boost mode are valid, the FC converter is returned to Freewheel mode. A flow chart for determining the active FC converter mode is illustrated in Figure 7.

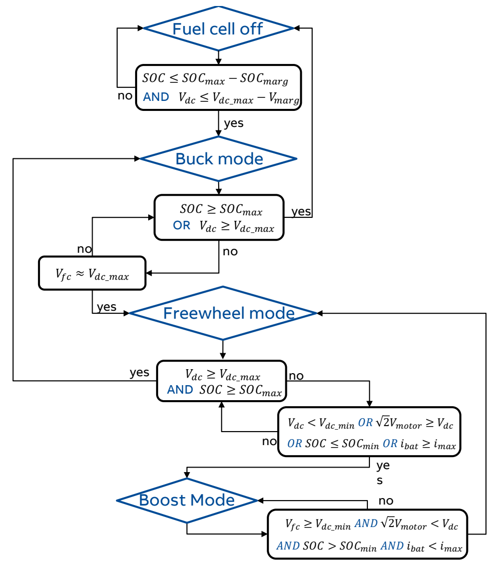

Figure 7: A control mode flowchart. Blue and black shapes represent control modes and conditions leading to mode changes, respectively.

IV. HIL SETUP FOR SYSTEM VALIDATION

The validation of the proposed method is carried out using a real-time HIL test setup illustrated in Figure 8. It consists of a real-time Typhoon HIL simulator and two real power converter controllers; one HES880 controller and one ACS880 controller [17], [18]. A virtual power system of one FC, one battery and one load is created in the HIL simulator using pre-validated models from Typhoon HIL library [19]. The control units are connected to the HIL setup via hardwired IO. The IO are used to transfer gate pulses and measurement feedbacks between the real controllers and the virtual models in HIL simulator. The HES880 and ACS880 controllers are used to control the boost part of the FC converter and the propulsion load converter, respectively. The simulator runs with a 1 µs simulation step.

V. RESULTS AND DISCUSSION

In this section, the proposed Variable DC approach is validated using the HIL setup. For simplicity, only an FC, a battery and a propulsion load is used. The V_{dc_min} and V_{dc_max} are 650 V and 775 V, respectively. First, it will be shown how the system behaves during normal operation conditions in Buck, Freewheel and Boost modes. Next, it will be presented how the FC converter behaves when an FC experiences a quick power transient. Last, the efficiency of the system is analyzed over the complete operation range.

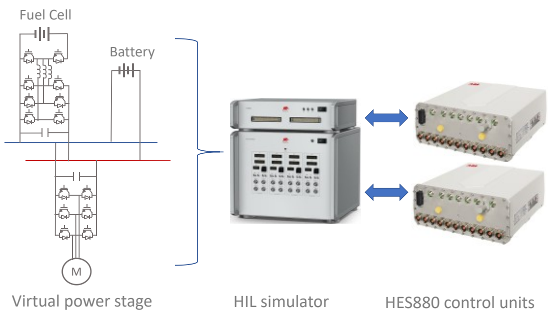

Figure 8: A HIL test setup used for validation of the proposed method.

The voltage, current and power waveforms in Buck and Freewheel modes are presented in Figure 9. First, the propulsion motor is lightly loaded, and the FC converter operates in Buck mode. The battery voltage (which is also the DC bus voltage) is controlled to V_{dc_max}. The propulsion load is increased and at ~8s, the FC voltage is equal to the DC bus voltage. Thus, Freewheel mode is activated. In the Freewheel mode, the load is increased to 125 kW, and followed by a decrease to 25 kW. Despite FC converter not being used, the FC power follows behavior of the load power. At ~23s, the FC voltage increases to V_{dc_max}, and the FC is set back to Buck mode. The DC bus voltage is again controlled to V_{dc_max}.

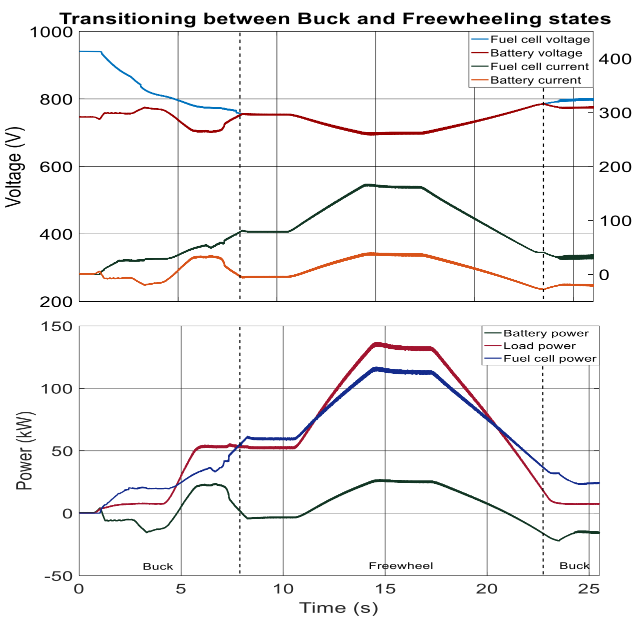

Figure 9: Normal operation in Buck and Freewheel modes. The vertical dashed lines highlight a mode transition.

The voltage, current and power waveforms in Freewheel and Boost modes are presented in Figure 10. The load power starts at 50 kW and the FC converter operates in Freewheel mode. The load is increased to 200 kW. At ~10s, the FC voltage drops below V_{dc_min}, and thus the Boost mode is activated. The DC bus voltage is controlled to V_{dc_min}. At ~15s, the load is decreased towards 50 kW. Hence, FC voltage increases and at ~16s reaches V_{dc_min}. Hence, the FC converter is returned to Freewheel mode.

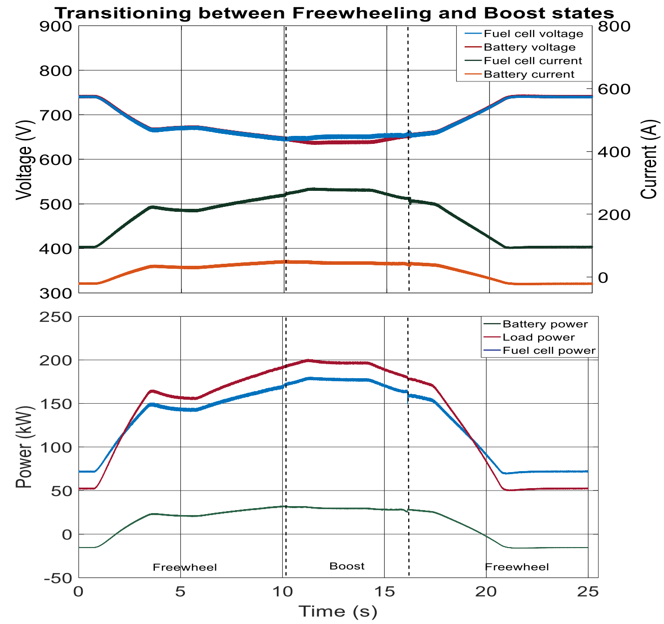

Figure 10: Normal operation in Boost and Freewheel modes. The vertical dashed lines highlight a mode transition.

The previous two figures illustrated the system performance during normal operation. It performed well without any issues. However, sometimes in marine systems, unexpected events (e.g., failure) may occur and cause quick power transients on the system. In Section III, a hysteresis controller was designed to prevent FCs from experiencing such power transients. To validate the functionality of the controller, the system is set to Freewheel mode, and then quick power transients are applied to it using the propulsion load. Current, voltage and power waveforms of the system are presented in Figure 11. At 2s, the propulsion load is quickly increased from 50 kW to 90 kW. The transient results in rapid increase in FC current. However, once the FC current exceeds the upper limit of the tolerance band, the converter starts to limit the current. The FC current is increased according to maximum allowed FC current ramp rate. At ~7s, the propulsion load causes a decreasing power transient. The FC current is again limited by the FC converter. Once the current settles, the FC converter is set back to Freewheel mode.

Originally, the Variable DC approach was designed to improve the total powertrain efficiency of a hybrid FC and battery power system. The efficiency improvements were presented in [11]. In general, the modified Variable DC approach is based on the same operating principles, and hence similar efficiency improvements can be expected. However, with DOL batteries, the system efficiency is also dependent on the battery SOC. This dependency is illustrated in Figure 12. The figure shows that the highest efficiency is achieved between 50-150 kW. This corresponds to operation in the Freewheel mode where switching losses in FC converter are eliminated. Hence, the highest efficiency. Moreover, the highest efficiency at each power level is obtained when battery current is zero. This occurs when the battery state of discharge is at a value obtained with (9). In such cases, all FC current flows directly to the load without going through the battery.

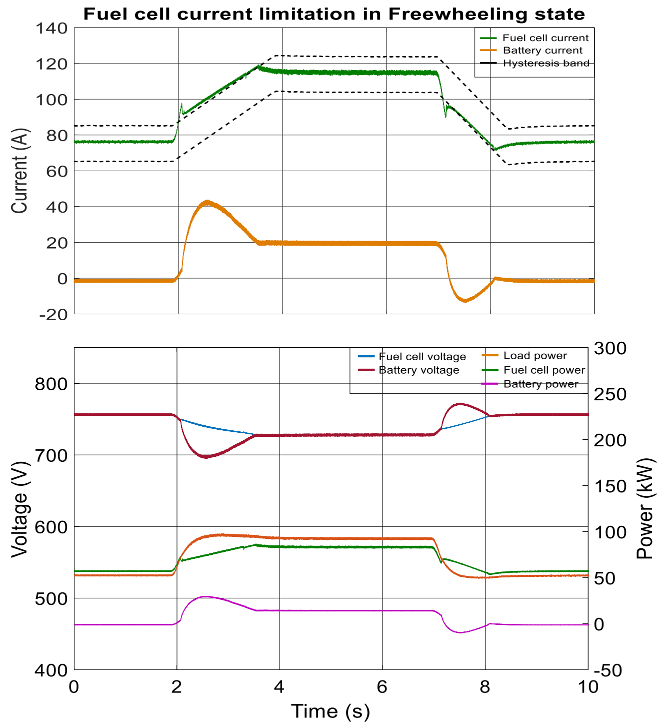

Figure 11: Activation of current limits due to sudden changes in load power. Black dashed lines illustrated the current tolerance band.

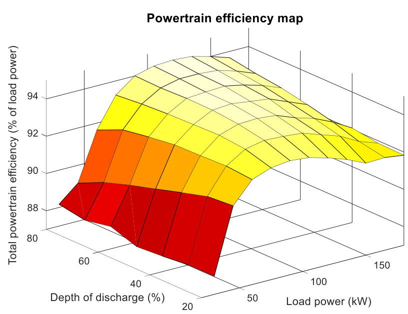

Figure 12: Total powertrain efficiency map as a function of battery depth of discharge and load power.

VI. Conclusion

This work has proposed modifications to the Variable DC approach for hybrid FC and battery power systems in marine vessels. Previously, the Variable DC approach has been shown to significantly reduce total powertrain losses. However, use of the approach was only feasible if batteries on the system were integrated via DC/DC converters. With the modifications on controls and mode selections proposed in this work, the Variable DC approach is now also applicable to systems powered by FCs and DOL batteries. Use of DOL batteries, instead of batteries with converters, reduces weight and footprint of a system due to omission of the battery converters. Therefore, with the modified approach, the efficiency improvements provided by the original Variable DC approach can be achieved while also obtaining reductions in cost, weight and footprint of the system. For future research and further improvement of the proposed approach, EMS's suitable for a system with DOL batteries and Variable DC approach can be further studied. The studies should target highest FC performance, while also optimizing total drivetrain efficiency.

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