The Variable DC Approach for Improved Powertrain Energy Efficiency in Fuel Cell-Fed Marine Vessels

Arbër Haxhiu
The Variable DC Approach for Improved Powertrain Energy Efficiency in Fuel Cell-Fed Marine Vessels

Arbër Haxhiu

A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS1 of the school on 09 December 2022 at 12 noon.

Aalto University
School of Electrical Engineering
Electrical Engineering and Automation (EEA)
Industrial electronics and electric drives
Supervising professor
Professor Jorma Kyrrä, Aalto University, Finland

Thesis advisor
Dr. Sami Kanerva, ABB Marine and Ports, Finland

Preliminary examiners
Professor Tegoeh Tjahjowidodo, KU Leuven, Belgium
Professor Aaron M. Cramer, University of Kentucky, USA

Opponent
Professor Frede Blaabjerg, Aalborg University, Denmark

Aalto University publication series
DOCTORAL THESES 160/2022

© 2022 Arbër Haxhiu

ISBN 978-952-64-1004-3 (printed)
ISBN 978-952-64-1005-0 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Unigrafia Oy
Helsinki 2022

Finland
Abstract

The maritime industry is undergoing a significant transition from carbon-based fuels towards less environmentally harmful fuels. This transition is primarily being driven by international regulations calling for significant limitations on maximum-allowed environmentally harmful emissions. Hydrogen and fuel cells are often touted as one potential means for the decarbonization of the maritime industry. However, their adoption on board marine vessels is still in its infancy; some of the main reasons for the slow adoption being both high investment and operating costs.

This dissertation proposes a new electric integration and operation concept for DC-based fuel cell-fed marine vessel power systems. The concept is designed to enable significant reductions in total powertrain energy losses, thereby reducing operating fuel consumption, which further leads to reduced vessel operating costs. The reduced cost of operation is highly beneficial in order to accelerate the adoption of fuel cells as main power sources for marine vessels, which in turn would also improve the environmental impact of the maritime shipping industry.

The proposed concept is entitled the Variable DC Approach and is based on the variable operation of a common DC bus voltage. In its simplicity, the Variable DC Approach omits one power conversion stage which typically exists between fuel cells and a common DC bus. The omission of the power conversion stage eliminates all energy losses associated with high-frequency switching in the said power conversion stage. This dissertation develops and presents advanced power and voltage control systems necessary for efficient utilization of the Variable DC Approach concept.

The feasibility of the Variable DC Approach is validated using a real-time hardware-in-loop test setup specifically designed for marine vessel power system testing. The performed validation tests show good performances during both normal and failure-containing operating conditions. Furthermore, the tests show the Variable DC Approach enables an improvement of as much as 28% in total powertrain energy efficiency compared to operating with conventional fixed DC bus voltage. In addition, another positive benefit of the Variable DC Approach is found in its elimination of the high-frequency fuel cell current ripple, which can lead to improved long-term operation of the fuel cell power sources.
Tekijä
Arbër Haxhiu

Väittöskirjan nimi
Vaihtuva tasavirtamenetelmä polttokennokäyttöisten merialusten voimansiirron energiatehokkuuden parantamiseksi

Julkaisija
Sähköteknikan korkeakoulu

Yksikkö
Sähköteknikan ja automaation laitos

Sarja
Aalto University publication series DOCTORAL THESES 160/2022

Tutkimusala
Teollisuuselektroniikka ja sähkökäytöt

Käsikirjoituksen pvm 06.06.2022
Väittöspäivä 09.12.2022

Väittelyluvan myöntämispäivä 27.09.2022
Kieli Englanti

Monografia Artikkeli/väittöskirja Eseseväittöskirja

Tiivistelmä

Tässä opinnäyttetystä kehitetään uutta sähköistä integroitinta- ja toimintakonseptia tasasähköön perustuva polttokennokäyttöisiin laivojen voimajärjestelmiin. Konsepti on suunniteltu merkittävästi vähentämään voimansiirron kokonaisenergiahäviöitä ja siten alentamaan polttoainetuen kulutusta, mikä edelleen johtaa alukseen käyttökustannusten alennemiseen. Käyttökustannusten aleneiminen on erittäin edullista polttokennonjun omaksumisen nopeuttamiseksi merialusten päävoimalanlähenteiksi, mikä puolestaan parantaisi myös merenkulun ympäristövaikutuksia.

Opinnäyttetyössä tutkittu konsepti on nimeltään Variable DC Approach, ja se perustuu operointiin muuttuvalla tasavirtajakeluläitedielle. Yksinkertaisuudessaan konsepti jättää pois yhden tehon muunnosvaiheen, joka on tyyplillisesti omassa polttokennonjoen ja yhteisen tasajännitekiskoston välillä. Tehnomuunnosvaiheen poisjättämineen eliminoi kaikki korkeataajuiseen kytkentään liittyvät energiahäviöitä mainitussa tehonomuuntovaiheessa. Tässä opinnäyttetyössä kehitetään ja esitellään kehitetyn tehon ja jännitteen ohjausjärjestelmää, joita tarvitaan Variable DC Approach - konseptin tehokkaaseen hyödyntämiseen.

Variable DC Approach - konseptin toteutettavuus validoidaan käyttämällä reaalialkaista hardware-in-loop testausjärjestelymää, joka on suunniteltu erityisesti merialusten tehjärjestelmän testaukseen. Suoritettujen testien perusteella konsepti toimii hyvin sekä normaalilla että vikoja sisältävällä käyttöolosuhteissa. Lisäksi testit osoittavat konseptin mahdollistavan jopa 28% pareman kokonaisvoimansiirron energiatehokkuuden verrattuna toimintaan tavanomaisella kiinteällä tasajännitteellä. Lisäksi konseptin toinen myönteinen etu on korkeataajuisen polttokennovirran aaltoilun eliminointi, mikä voidaan pitkällä aikavälillä johtaa polttokennojen tehokkaampaan toimintaan.

Avainsanat
Hybridi, hyötyyhteys, häviöt, merenkulku, polttokennot, sähköjärjestelmän ohjaus, vaihtuva dc-jännite, voimensiirto

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ISSN (painettu)</td>
<td>1799-4934</td>
<td>ISSN (pdf)</td>
<td>1799-4942</td>
</tr>
<tr>
<td>Julkaisupaikka</td>
<td>Helsinksi</td>
<td>Painopaikka</td>
<td>Helsinksi</td>
</tr>
<tr>
<td>Vuosi</td>
<td>2022</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Abstract

The maritime industry is undergoing a significant transition from carbon-based fuels towards less environmentally harmful fuels. This transition is primarily being driven by international regulations calling for significant limitations on maximum-allowed environmentally harmful emissions. Hydrogen and fuel cells are often touted as one potential means for the decarbonization of the maritime industry. However, their adoption on board marine vessels is still in its infancy; some of the main reasons for the slow adoption being both high investment and operating costs.

This dissertation proposes a new electric integration and operation concept for DC-based fuel cell-fed marine vessel power systems. The concept is designed to enable significant reductions in total powertrain energy losses, thereby reducing operating fuel consumption, which further leads to reduced vessel operating costs. The reduced cost of operation is highly beneficial in order to accelerate the adoption of fuel cells as main power sources for marine vessels, which in turn would also improve the environmental impact of the maritime shipping industry.

The proposed concept is entitled the Variable DC Approach and is based on the variable operation of a common DC bus voltage. In its simplicity, the Variable DC Approach omits one power conversion stage which typically exists between fuel cells and a common DC bus. The omission of the power conversion stage eliminates all energy losses associated with high-frequency switching in the said power conversion stage. This dissertation develops and presents advanced power and voltage control systems necessary for efficient utilization of the Variable DC Approach concept.

The feasibility of the Variable DC Approach is validated using a real-time hardware-in-loop test setup specifically designed for marine vessel power system testing. The performed validation tests show good performances during both normal and failure-containing operating conditions. Furthermore, the tests show the Variable DC Approach enables an improvement of as much as 28% in total powertrain energy efficiency compared to operating with conventional fixed DC bus voltage. In addition, another positive benefit of the Variable DC Approach is found in its elimination of the high-frequency fuel cell current ripple, which can lead to improved long-term operation of the fuel cell power sources.

Abstract

Meriteollisuudessa on meneillään merkittävä siirtymä hiilipohjaisista polttoaineista ympäristölle vähemmän haitallisiin polttoaineisiin. Siirtymä ohjaa ensisijaisesti kansainvälisten määräykset, jotka vaativat merkittäviä rajoituksia ympäristölle haitallisten päästöjen enimmäismäärälle.
Vetyä ja polttokennoja pidetään usein yhtenä tehokkaana keinoa meriteollisuuden hiilidioksidipäästöjen vähentämiseksi. Niiden käyttöönotto merialuksilla on kuitenkin vielä erittäin alku vaiheessa ja yksiä tärkeimmä syitä hitaalle käyttöönotolle on sekä korkeat investointi- että käyttökustannukset.

Tässä opinnäytetyössä kehitetään uutta sähköistä integrointi- ja toimintakonseptia tasasähköön perustuvaen polttokennokäyttöisiin laivojen voima järjestelmiin. Konsepti on suunniteltu merkittävästi vähentämään voiman stirron kokonaisenergia häviöitä ja siten alentamaan polttoa nineen kulutusta, mikä edelleen johtaa aluksen käyttökustannusten alenemiseen. Käyttökustannusten alenneminen on erittäin edullista polttokennojen omaksuminen nopeuttamiseksi merialusten päävoimanlähteiksi, mikä puolestaan parantaisi myös merenkulun ympäristö vaikutuksia.

Opinnäytetyössä tutkittu konsepti on nimeltään Variable DC Approach, ja se perustuu operointiin muuttuvalla tasavirtajakelujännitteellä. Yksinkertaisuudessaan ke nsepti jättää pois yhden tehon muunnos vaiheen, joka on tyyppillisesti olemassa polttokennojen ja yhteisen tasajännitekiskoston välillä. Tehonmuunnos vaiheen pois jättäminen eliminoi kaikki korkeataaju sein kaikkien tehokkaan voiman siirron energiahäviöt mainitussa tehonmuunn ovaiheessa. Tässä opinnäytetyössä kehitetään ja esitellään kehittyneitä tehon ja jännite ohjaus järjestelmiä, joita tarvitaan Variable DC Approach -konseptin tehokkaaseen hyödyntämiseen.

Variable DC Approach - konseptin toteutettavuus validoidaan käyttämällä reaaliaikaisista hardware-in-loop testausjärjestelymää, joka on suunniteltu erityisesti merialusten tehojärjestelmän testaukseen. Suoritettujen testien perusteella konsepti toimii hyvin sekä normaleissa että vikoja sisältävissä käyttökustannusiss. Lisäksi testit osoittavat konseptin mahdollistavan jopa 28% paremman kokonaisvoimansiirron energiatehokkuuden verrattuna toimintaan tavannonaisella kiinteällä tasajännitteellä. Lisäksi konseptin toinen myönteinen etu on korkeataajuisen polttokennovirran aaltoilun eliminointi, mikä voi pitkällä aikavälillä johtaa polttokennojen tehokkaampaan toimintaan.
Preface

This dissertation was carried out in the Power Electronics research group at the Department of Electrical Engineering and Automation, Aalto University, Finland. The work has been financed by ABB. At ABB, I would like to thank Dr. Ricky Chan, Dr. Juha Orivuori and Mrs. Aino Okkeri for kindly accepting to support this work.

My supervisor, Professor Jorma Kyyrä, deserves my utmost gratitude for all his guidance and support throughout the work. Our numerous discussions together provided me confidence to push forward with the dissertation work, especially at times when I might have felt insecure about my work. Also, similar gratitude deserves my dissertation advisor, Dr. Sami Kanerva, who was never too busy to encourage and support me via technical discussions on the various topics of the dissertation.

I wish to thank Dr. Ahmed Abdelhakim and Mr. Jostein Bogen for co-authoring one of the papers appended in this dissertation. Your insights in the topic were a valuable addition to this work. Additionally, I would also like to express my gratitude to the pre-examiners Professors Aaron Cramer and Tegoeh Tjahjowidodo. I found your feedback valuable and via it was able improve the quality of my dissertation. Moreover, I wish to also thank all my colleagues at both ABB and Aalto University for providing an amazing working environment.

Finally and most importantly, I want to express my warmest gratitude to my loving family and friends for the continuous support you have given me throughout this dissertation. Specifically, I want to give the highest gratitude to my loving parents, Jakup and Bahrije, and my dear sisters, Arlinda, Ardita and Ilirida. Your support throughout this dissertation and my life will always be appreciated and cherished.

Helsinki, October 31, 2022,

Arber Haxhiu
Contents

Preface 3
Contents 5
List of Publications 9
Author’s Contribution 11
List of Figures 15
List of Tables 19
Abbreviations 21
Symbols 23

1. Introduction 27
   1.1 Background 27
   1.2 Motivation and targets of the dissertation 29
   1.3 Scientific contributions 30
   1.4 Dissertation outline 31

2. Fuel cells and their electric integration into marine vessels 33
   2.1 Marine vessel types 33
   2.2 Fuel cell power sources 36
      2.2.1 The operation principle of a PEM fuel cell 36
      2.2.2 PEM fuel cell voltage 38
      2.2.3 Fuel cell considerations on marine power systems 40
   2.3 State-of-art electric integration concepts for fuel cell-fed
      marine power systems 44
      2.3.1 DC integration 44
      2.3.2 AC integration 48
      2.3.3 Hybrid AC and DC integration 50
      2.3.4 Comparison of the reviewed integration concepts 51
3. The Variable DC Approach concept
3.1 The general principle ........................................ 54
3.2 Control of DC bus voltage and fuel cell current reference . 57
3.3 Fuel cell voltage model-based control of the DC bus voltage 59
3.4 Control of fuel cell DC/DC converter .......................... 63
3.5 The Variable DC Approach with direct on-line batteries . 67
3.6 A dynamic performance estimation method for fuel cell-fed marine power systems .......................... 70

4. Method of concept validation .................................... 75
4.1 Hardware-in-loop simulation ................................. 75
4.2 Marine power system Implementation in the Hardware-in-loop setup .................................................. 76
4.2.1 Power sources .................................................. 77
4.2.2 Loads .......................................................... 78
4.2.3 Energy loss models for energy efficiency estimation 79
4.3 The HIL-based marine power system test setup ............ 80

5. Application and results ........................................... 83
5.1 System operation during normal operating conditions ..... 83
5.1.1 Operation with converter-controlled batteries ......... 83
5.1.2 Control of parallel operating fuel cell systems with differing voltage characteristics ...................... 85
5.1.3 Operation with DOL batteries ............................ 86
5.1.4 Estimation of DC bus voltage dips as function of system power transients ................................. 88
5.2 Advantages of the Variable DC Approach ................. 90
5.2.1 Powertrain efficiency ........................................ 91
5.2.2 Fuel cell current ripple ...................................... 93
5.3 System operation during fault conditions ................. 96
5.3.1 Sudden DC bus voltage transients .................... 96
5.3.2 Hotel AC network short circuit .......................... 98
5.3.3 Propulsion motor terminal short circuit ............... 99
5.3.4 Battery system failure ..................................... 101
5.3.5 Fuel cell system failure .................................... 102
5.3.6 DC bus overvoltage ........................................ 103
5.3.7 DC bus undervoltage ...................................... 105

6. Concluding remarks ............................................. 107
6.1 Future prospects .................................................. 109

References .................................................................. 111

Errata ........................................................................ 117
This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.


This paper presents a comprehensive overview on electric integration concepts for fuel cell and battery-powered marine vessels. The integration concepts are categorized based on used power distribution (i.e., AC or DC) technology. A proper description of each integration concept is provided, while simultaneously highlighting the merits and the seen challenges behind each concept. Additionally, the state-of-the-art power conversion devices are highlighted for each integration concept based on their relevance and potential. Furthermore, the paper includes a comparative assessment of the reviewed integration concepts in terms of operating voltage and power, integration complexity, energy efficiency, cost, size, and weight.

Arber Haxhiu performed the research on the electric integration concepts for marine vessels, including the comparative assessment of the integration concepts, the history of electric integration in marine vessels, and the impacts of fuel cell characteristics on marine vessels. Dr. Ahmed Abdelhakim performed the research on relevant power conversion devices as well as that on potential fuels for the fuel cell-powered marine vessels. Dr. Sami Kanerva performed the research on electric integration for shore connection. Mr. Jostein Bogen contributed through his discussions and comments on the paper. The paper was co-written by Arber and Ahmed.

Publication II: “A variable DC approach to minimize drivetrain losses in fuel cell marine power systems”

This paper presents the Variable DC approach for fuel cell-powered marine vessels. The method utilizes variable voltage on the DC distribution bus voltage to reduce the losses of powertrain devices. The DC bus voltage
level is controlled according to the loading of the fuel cells. Such control allows operation of the fuel cell DC/DC converter in the freewheeling mode, which significantly reduces the converter losses.

Arber Haxhiu invented the Variable DC Approach and performed the research involved. He designed the HIL test setup to validate the proposed control method and generated the presented results. Arber wrote the paper with support from Prof. Jorma Kyyrä, Dr. Ricky Chan, and Dr. Sami Kanerva who contributed by discussing and commenting on the paper.


This paper proposes a fuel cell model-based voltage controller for control of DC bus voltage via battery DC/DC converters in the Variable DC approach concept. The controller utilizes a non-linear fuel cell voltage model to allow simultaneous control of the battery and fuel cell powers. The proposed controller is shown to provide great control accuracy and reliability, which are verified by the HIL tests presented in the paper.

Arber Haxhiu designed the proposed voltage controller and generated the results to validate its functionality. Arber wrote the paper with support from prof. Jorma Kyyrä, Dr. Ricky Chan, and Dr. Sami Kanerva who contributed by discussing and commenting on the paper.


This paper proposes a fuel cell DC/DC converter control system to meet the control requirements of the Variable DC approach. The control system provides accurate control of the fuel cell current and seamless transitioning between the Variable DC approach operation modes. The functionality of the proposed converter controller is validated under normal operation conditions and various fault conditions.

Arber Haxhiu developed the proposed fuel cell DC/DC converter control system, designed the test cases for control validation, and generated the presented results. Arber wrote the paper with support from Prof. Jorma Kyyrä, Dr. Ricky Chan and Dr. Sami Kanerva who contributed by discussing and commenting on the paper.
Publication V: “Modified Variable DC Approach Applicable to Fuel Cells and DOL Batteries in Shipboard Power Systems”

This paper researches the Variable DC approach concept for application with direct on-line connected batteries. In such a system, batteries are connected to the DC bus without DC/DC conversion devices, thus providing the reduced weight and footprint of the system, while also maintaining the improved system efficiency provided by the Variable DC approach concept. Such power configurations are especially interesting for vessel types, such as high-speed passenger vessels, which are known to be sensitive to power system weight and footprint.

Arber Haxhiu developed the proposed modifications to the Variable DC approach concept and generated the results to validate its functionality. Arber wrote the paper with support from Prof. Jorma Kyyrä, Dr. Ricky Chan, and Dr. Sami Kanerva who contributed by discussing and commenting on the paper.


This paper proposes a system level method to estimate the maximum load steps that can be applied in fuel cell-powered marine DC distribution systems. The method utilizes a DC power system model to estimate DC voltage drops following sudden load changes applied to the system. The voltage drop is used as a metric to determine whether a system can sustain the applied load change. The proposed method is interesting especially for shipboard power management systems for coordination of load-dependent starting and stopping of fuel cells. Additionally, the method is useful for early-stage dimensioning of fuel cell power sources and selection of system configuration.

Arber Haxhiu developed the proposed estimation method and generated the results to validate its functionality. Arber wrote the paper with support from Prof. Jorma Kyyrä, Dr. Ricky Chan, and Dr. Sami Kanerva who contributed by discussing and commenting on the paper.
List of Figures

2.1 Generic illustrations of various vessel types: a) a cruise vessel, b) a passenger vessel, c) a Ro-pax vessel, d) a tanker vessel, e) a cargo vessel, f) an off-shore vessel, g) an ice-breaking vessel, h) a pushboat, i) a naval vessel and j) a yacht. ........................................ 34

2.2 Operational profiles of a) a bulk carrier in the Rhône river and two passenger vessels in b) the Rhine river and c) Danube river. The bars show load power distribution for a single trip, whereas the curve shows cumulative time. . . . 35

2.3 A generic illustration of a fuel cell system comprised of fuel cell stacks and balance of plant components. . . . . . 37

2.4 A 3D-visualization of a megawatt-scale PEM fuel cell system designed by ABB and Ballard Power Systems. The system is designed for 3-MW electrical output power in marine vessels. ........................................ 38

2.5 a) Illustration of fuel cell voltage/power characteristics and b) associated voltage losses. The blue, green and red background colors are used to indicate voltage loss regions where the activation, resistive and concentration losses, respectively, are most sensitive to current changes. . . . . . 40

2.6 a) Illustration of a state-of-art DC integration concept in which the output powers of both fuel cells and batteries are controlled by DC/DC converters. b) A DC/DC converter bypass circuit is utilized. ........................................ 45

2.7 a) Illustration of a state-of-art DC integration concept in which the output powers of fuel cells are controlled by DC/DC converters, whereas batteries are directly connected into the DC bus. ........................................ 46
2.8 a) Illustration of an integration concept in which a) super-capacitors are directly connected to the fuel cell output terminals and b) batteries are connected to the fuel cell output terminals via DC/DC converters. 47

2.9 Illustration of state-of-art AC integration concepts for a) low and b) medium voltage AC distribution systems. 49

2.10 a) Illustration of hybrid DC/AC integration concepts in which a) both fuel cells and batteries are converter-controlled and b) batteries are connected direct on-line into a distributed DC bus. 50

2.11 a) Illustration of hybrid DC/AC integration concept in which fuel cell power generation is distributed such that part of the fuel cell capacity supplies power directly to a common DC link of a propulsion drive with the rest supplying power towards the AC distribution grid. 51

3.1 Illustration of the Variable DC approach voltage limits compared to fuel cell output voltage. 56

3.2 A control flowchart for the Variable DC Approach concept. The red rhombuses and black rectangles represent control modes and mode transition conditions, respectively. 57

3.3 Control of fuel cell current and DC bus voltage references in Buck and Boost modes. The DC bus voltage reference is $V_{dc_{max}}$ and $V_{dc_{nom}}$ in Buck and Boost modes, respectively. 58

3.4 Control of fuel cell current and DC bus voltage references Freewheel mode. "Freewheel" block indicates fuel cell converter is controlled to allow free current flow towards the DC bus. 59

3.5 The high-level control diagram of the proposed fuel cell model-based DC bus voltage controller. 62

3.6 Illustration of a unidirectional buck-boost converter and its current flow in a) Buck mode, b) Freewheel mode and c) Boost mode. The red color highlights which components are in use in the respective modes. 64

3.7 A fuel cell DC/DC converter current control diagram for the Variable DC approach. The switch $S_1$ is controlled by the output $PWM_1$, whereas the switches $S_2$ and $S_4$ are controlled by the output $PWM_2$. In the figure, $D_1 \sim D_4$ refer to diodes, $C_1$ and $C_2$ refer to capacitors and $L$ refers to inductor. The $K_p$ and $K_i$ are proportional and integral gains of the current controller, whereas $H_1$ and $H_2$ are the hysteresis limits of the ramp rate controller. 65
3.8 A simplified equivalent circuit diagram of a fuel cell unit with a DC/DC converter, a DOL battery, and a load. Some components in the fuel cell converter are dimmed due to not being active in the Freewheel mode. .................. 68

3.9 A control flowchart for the Variable DC Approach with DOL batteries. The red rhombuses and black rectangles represent control modes and mode transition conditions, respectively. The green rectangle illustrates change to the flowchart from Figure 3.2. ...................... 69

4.1 A schematic diagram of the marine power system used in this research. ................................. 77

4.2 A battery and HESS80 DC/DC converter in loop. ......... 78

4.3 A fuel cell and DC/DC converter control system. ......... 78

4.4 A motor drive in the loop. ................................ 79

4.5 A grid converter in the loop. ............................ 79

4.6 The real-time HIL setup used for validation of the system control methods proposed in this work. ............... 80

4.7 a) The Typhoon HIL604 simulators used in this work, and b) the interior of a control cabinet comprising converter control units used in this work. The HIL lab comprises four identical control cabinets. ............................... 81

4.8 Illustration of the HIL SCADA system. The SCADA shown on the right is that of the Typhoon HIL simulator, whereas the one on the left is that of the ABB Power and Energy Management system (PEMS™). ............. 81

5.1 Illustration of power and voltage waveforms of the system operating in the Variable DC approach during normal operating conditions. Color-coding in the background is used to highlight the different operating modes: Buck (blue), Freewheel (green) and Boost (red). .................. 84

5.2 Illustration of power and voltage waveforms of a system which comprises two fuel cells with differing voltage characteristics. Color coding in the background is used to highlight the different operating modes; Buck (blue), Freewheel (green) and Boost (red). ...................... 86

5.3 Illustration of power and voltage waveforms of a system with DOL batteries operating in Variable DC approach, in which a) shows transitions between Buck and Freewheel modes (Battery SOC = 70%), and b) shows transitions between Freewheel and Boost modes (Battery SOC = 25%). Color-coding in the background is used to highlight the operating modes; Buck (blue), Freewheel (green) and Boost (red). ...................... 88
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>Estimated voltage dips during appliance of three different power transient steps: 6.67kW at 0.5s, 10kW at 3s, and 12.5 kW at 7s. Only one fuel cell unit is running.</td>
</tr>
<tr>
<td>5.5</td>
<td>Estimated voltage dips during appliance of three different power transient steps: 6.67kW at 0.5s, 10kW at 3s, and 125 kW at 7s. Two fuel cell units are running.</td>
</tr>
<tr>
<td>5.6</td>
<td>Illustration of system (a) Power, (b) voltage, and (c) loss waveforms during operation in the different operating modes of the Variable DC approach. The optimal efficiency is shown to be achieved in the Freewheel mode.</td>
</tr>
<tr>
<td>5.7</td>
<td>Total powertrain efficiency map as function of power and DC bus voltage.</td>
</tr>
<tr>
<td>5.8</td>
<td>Illustration of high-frequency ripple in fuel cell current on different Variable DC approach operating modes.</td>
</tr>
<tr>
<td>5.9</td>
<td>Illustration of low-frequency ripple in fuel cell current on different Variable DC approach operating modes. Peak-to-peak current ripple are approximately 7.5A, 5.5A, and 5.8A in Buck, Freewheel, and Boost modes, respectively.</td>
</tr>
<tr>
<td>5.10</td>
<td>Fuel cell current behavior during DC bus voltage transients in a system with converter-controlled batteries.</td>
</tr>
<tr>
<td>5.11</td>
<td>Fuel cell current behavior during DC bus voltage transients in a system with DOL batteries.</td>
</tr>
<tr>
<td>5.12</td>
<td>System current, power, and voltage waveforms during a phase-to-phase short circuit in the AC network. The short circuit occurs between Phases A and C.</td>
</tr>
<tr>
<td>5.13</td>
<td>System current, power and voltage waveforms during a phase-to-phase short circuit in the propulsion motor terminals.</td>
</tr>
<tr>
<td>5.14</td>
<td>System power and voltage waveforms during failure of the last connected battery system.</td>
</tr>
<tr>
<td>5.15</td>
<td>System power waveforms during failure of a parallel operating fuel cell system.</td>
</tr>
<tr>
<td>5.16</td>
<td>System power and voltage waveforms during DC bus overvoltage.</td>
</tr>
<tr>
<td>5.17</td>
<td>System power and voltage waveforms during DC bus undervoltage.</td>
</tr>
</tbody>
</table>
List of Tables

2.1 Comparison of main features between the presented integration concepts. In the table, FC refers to fuel cell, ES to energy storage (i.e., battery or supercapacitor) and PM to propulsion motor. .................................................. 52

5.1 Comparison of the estimate voltage dip values to those obtained via the HIL system. The difference between estimated and measured value (rightmost column) is given as a percentage of the nominal DC bus voltage. .................. 90

5.2 Comparison of Variable DC approach powertrain losses in steady-state to those of a conventional Fixed DC bus voltage system. FC denotes fuel cell, whereas conv. and diff. are short for converter and difference. ...................... 93
Abbreviations

AC  Alternating current
ACS880  A commercial industrial power converter device from ABB
BOL  Beginning of life
BOP  Balance of plant
DBSE  Document based system engineering
DC  Direct current
DOD  Depth of discharge
EMS  Energy management system
EOL  End of life
EU  European Union
FC  Fuel cell
FCH JU  Fuel Cells and Hydrogen Joint Undertaking
GHG  Greenhouse gas
HES880  A commercial harsh environment power converter device from ABB
HIL  Hardware-in-loop
IMO  International Maritime Organization
Li-ion  Lithium ion
MBSE  model-based system engineering
MV  Medium voltage
PEM  Proton exchange membrane
Abbreviations

**PWM**  Pulse width modulation

**SCADA**  Supervisory Control and Data Acquisition

**VMC**  Voltage model-based controller.

**VSI**  Voltage source inverter
Symbols

\( A_a \) Fuel cell activation voltage loss coefficient
\( A_b \) Empiric constant used in battery voltage model
\( a_j \) current value about which the activation voltage is linearized.
\( B_{fc,j} \) A constant used in voltage dip estimation model
\( C \) Capacitance
\( C_{bus} \) DC bus capacitance
\( C_{fc,j} \) A constant used in voltage dip estimation model
\( D_{fc,j} \) A constant used in voltage dip estimation model
\( DOD_a \) battery depth of discharge
\( DOD_{pu} \) battery depth of discharge in per unit
\( e^- \) electron
\( E_{act} \) Fuel cell activation voltage drop
\( E_{b0} \) voltage constant used in the battery voltage equation
\( E_{con} \) Fuel cell concentration voltage drop
\( E_{fc} \) Fuel cell stack voltage
\( E_{lin}^{fc,j} \) Linearized voltage of fuel cell sources \( j \).
\( E_{ocv} \) Open circuit voltage
\( E_{res} \) Fuel cell resistive voltage drop
\( G_x \) Gain constant used by fuel cell DC/DC converter
\( H^- \) Ionized hydrogen
Symbols

$H_2$ Hydrogen

$H_2O$ Water

$i_0$ Fuel cell exchange current

$i_b$ Battery current

$i_{b,act}$ Actual battery current

$i_{b,max}$ Maximum battery current

$i_{b,ref}$ Battery reference current

$i_f$ Fuel cell current

$i_{f,c}^{init}$ Fuel cell current at a first instant of a transient

$i_{f,c,DDC,max}$ Maximum fuel cell DC/DC converter current

$i_{f,c,DDC,min}$ Maximum fuel cell DC/DC converter current

$i_{f,c,DDC,ref}$ Fuel cell DC/DC converter current reference

$i_{f,c,new}$ New fuel cell current values used in the proposed voltage model-based controller

$J$ Total number of connected power sources.

$K_b$ Battery polarization voltage

$K_i$ Integrator gain

$K_p$ Proportional gain

$L$ Inductance

$M$ Total number of connected power loads

$m_c$ Empirically determined constant in fuel cell voltage

$N_b$ Number of battery cells connected in series

$n_c$ Empirically determined constant in fuel cell voltage

$N_{f,c}$ Number of fuel cells connected in series

$O^2$ Oxygen

$P$ Active power

$P_{bat}$ Battery power

$P_{f,c}$ Fuel cell power
Symbols

\( P_{fc_{\text{min}}} \) Minimum allowed fuel cell power

\( P_{fc_{\text{tot}}} \) Total fuel cell power at the end of a transient

\( P_{fc_{\text{init}}} \) Total fuel cell power at the beginning of a transient

\( P_{load} \) Load power

\( p_{i,m} \) Power of load m

\( p_{s,j} \) Power of power source j

\( R \) Resistance

\( R_b \) Internal battery resistance

\( R_c \) Fuel cell charge transfer resistance

\( SOC_f \) Battery full charge capacity

\( SOC_{max} \) Maximum allowed battery SOC

\( SOC_{min} \) Minimum allowed battery SOC

\( t \) Time

\( U_{dc_{\text{max}}} \) Maximum allowed DC voltage in the fuel cell DC/DC converter

\( U_{dc_{\text{min}}} \) Minimum allowed DC voltage in the fuel cell DC/DC converter

\( V_{bat} \) Battery unit voltage

\( V_{b_{\text{ref}}} \) Battery DC/DC converter voltage reference

\( V_{dc} \) DC bus voltage

\( V_{dc_{\text{max}}} \) Maximum DC bus voltage

\( V_{dc_{\text{min}}} \) Minimum DC bus voltage

\( V_{dc_{\text{nom}}} \) Nominal DC bus voltage

\( V_{fc} \) Fuel cell unit voltage

\( V_{\text{motor}} \) input RMS voltage of a propulsion motor

\( \Delta P_l \) Total change in load power

\( \Delta t \) Load transient time period

\( \Delta V \) Voltage difference term

\( \tau_L \) Power rise time
1. Introduction

1.1 Background

In the past century, ship propulsion systems were typically arranged by mechanically integrating the rotating shafts of combustion-based prime movers (typically diesel engines), directly or via a gear system, into ship propellers. For a rather lengthy period, such propulsion systems were extremely common, and the technology was highly developed. However, although the mechanical integration concepts as a technology are mature and simple, they have lacked energy efficiency when compared to more electric integration concepts. With the development of fast-switching semiconductor devices (i.e., AC and DC drives) at the end of the 20th century, electric integration concepts have started to gain greater popularity over mechanical integration concepts for marine propulsion [1].

Compared to the mechanical integration of combustion engines and propellers, electric integration has allowed operation of the propellers at different speeds compared to the combustion engines. This has meaningfully impacted total propulsion energy efficiency due to the following reasons. The optimum energy efficiency point for combustion engines is typically reached when operated at 80% - 90% of rated power. The efficiency drops significantly at lower loading points. With electric integration concepts, the mechanical energy of combustion engines is converted into electric energy via electric generators. The electric energy is then used to run electric motors, the shafts of which are connected to ship propellers. Via the use of electric drives, the speed of the propellers can be freely adjusted regardless of engine speeds. Furthermore, instead of using just one or two large combustion engines, as is typical in mechanical integration concepts, the electric integration concepts enable use of several smaller engines which can be switched on and off depending on the power-loading level. At lower powers, part of the power generation can be switched off, resulting in operation at more optimal operation points, and consequently
higher energy efficiencies. An electric propulsion system which is powered by several diesel engines is typically known as a diesel-electric propulsion system.

Due to the mentioned advantages, several ship types have currently adopted electric integration for vessel propulsion. Some of the first vessel types to utilize electric integration were ice-breakers due to their significantly varying power profiles. They were quickly followed by large cruise vessels and offshore drilling vessels [2]. In cruise vessels, the magnitude of onboard power consumption can reach up to 100 MW (e.g., "Allure of the Seas"). The cost of fuel for such vessels is typically very high, constituting a large part of the total operation costs. Therefore, even minor improvements on fuel efficiencies can have significant impacts on the total lifecycle costs of such vessels. On the other hand, offshore drilling vessels are known for their operation in dynamic positioning (DP). For DP-classed vessels, high levels of safety and redundancy are typically required. The electric integration concepts enable splitting of the power generation plant into several electric sections for improved redundancy. In addition, since DP vessels typically operate at low propulsion loads, the electric integration enables greater energy efficiencies than mechanical integration, especially for situations in which combustion engines can operate at variable speeds [3]. Currently, the latest vessel types undergoing a strong transitioning towards electrification are the various ferry type vessels [4].

In general, electrified vessels can be divided into two categories based on the way in which electric power is distributed on board; They are AC distribution systems and DC distribution systems. To date, diesel generators have been the dominant choice as power sources in electric propulsion systems. They produce AC power which is mostly consumed by AC-based loads, such as propulsion motors or other onboard hotel loads (e.g., control, lighting, navigation, heating, and ventilation systems). In the past, the dominance of AC-based loads, as well as the higher maturity of medium voltage AC (above 1 kV) devices compared to medium voltage DC devices, has led to AC being the voltage type of choice for onboard power distribution. However, in the last decade, DC distribution-based propulsion systems have also attracted a fair amount of attention [3, 5]. One compelling reason for this interest in DC distribution systems has been the opportunity to operate diesel engines at variable speeds, thus enabling higher engine energy efficiency at partial loads [5]. Another significant advantage favoring DC distribution systems has been the recently growing interest towards DC-based power sources (e.g., fuel cells and batteries).

To date, due to significant attention paid to environmental and climate related topics, hydrogen fuel cells and batteries have attracted great interest from the shipping industry. Both fuel cells and batteries are electric power sources, resulting in their integration for propulsion power production on board a ship always being via electric integration. However, although
batteries are quickly finding their way on board various vessel types, the adoption of fuel cells as power sources for marine propulsion is still in its infancy. In the past two decades, only a few fuel cell units have been integrated on board vessels, and they have mainly been for testing and technology demonstration purposes [6]. Nevertheless, especially in the last few years, interest towards fuel cell adoption in marine vessel applications has significantly increased. For example, in California, USA, a comprehensive feasibility study is being conducted on a zero-emission hydrogen fuel cells-fed high-speed passenger ferry [7]. In France and Norway, two zero-emission hybrid fuel cell and batteries-fed electric vessels are being designed [8, 9]. The vessels, both container carriers, are expected to be operational by 2023. With the ever-tightening regulation on harmful emissions, the interest towards zero-emission power sources, such as hydrogen fuel cells and batteries, is expected to grow further in the next 5-10 years. To accelerate the adoption of mentioned power sources for zero-emission shipping, efficient and reliable electrical integration concepts are needed.

The electrical integration of fuel cells and batteries into marine propulsion systems typically requires many electrical devices for power safe onboard power generation and distribution. For example, the varying voltages at fuel cell and battery terminals usually need to be converted to suitable levels for connection to the rest of the onboard power system. The power distribution is naturally managed as AC or DC. The voltage of the distributed power then needs to be further converted to suitable levels for controlled rotation of vessel propulsion motors and supply of different onboard hotel loads. All this requires several power conversion and protection devices, as well as advanced onboard power and energy management strategies. The way in which the fuel cells, batteries, and different power conversion devices are electrically integrated plays a significant role in total system efficiency and reliability.

1.2 Motivation and targets of the dissertation

In 2018, the total Greenhouse gas (GHG) emissions from the maritime shipping activities accounted for 2.9% of global GHG emissions [10]. In absolute terms, the GHG emissions from the shipping industry have grown by 10.1% between the period of 2012 - 2018. If the current trend of increasing emissions is allowed without any counter activities, the emissions could further increase by 50% by 2050. Hydrogen fuel cells and batteries have been proposed as a potential means for decarbonizing the shipping industry. However, whilst both fuel cell and battery technologies are well developed for various land-based vehicles, the use of fuel cells in commercial shipping is still in its infancy. Using traditional electrical integration methods originally designed for rotating machinery can lead to non-optimized energy
efficiency and, consequently, increased emissions and operation costs.

Thus, the aim of this work is to propose a new efficient electrical power system operation concept for hybrid fuel cell and battery-powered DC grid-based marine vessels. The concept, titled in this work as the Variable DC Approach, utilizes the variable nature of fuel cell voltage as a function of load power to control the DC power system in a manner which allows for significantly reduced powertrain losses. This work also proposes fuel cell and battery converter control systems applicable to the Variable DC Approach concept. Additionally, the work also proposes an algorithm for estimating maximum load steps that can be applied in fuel cell-powered marine DC systems. The Variable DC Approach concept is designed for DC grid-based power systems in which batteries are integrated either via DC/DC converters or directly online (DOL). The methods proposed in this work are verified using real-time hardware-in-loop (HIL) technology, which is a well-established technique used to verify complex control systems in various industries, such as aerospace and automotive.

1.3 Scientific contributions

The main contributions of this dissertation are summarized as follows:

- Main fuel cell electrical integration requirements are identified and their impacts on marine power systems are analyzed.

- The state of art electric power integration concepts for fuel cell and battery-fed marine systems are reviewed by analyzing their advantages and disadvantages. Additionally, a comparative assessment is performed on the reviewed integration concepts.

- A Comprehensive HIL-based test setup is created for marine vessel power systems. The setup includes real power converter control hardware and virtual models for fuel cells, batteries, machines and power converter control systems.

- A new system operation concept, the Variable DC approach, is proposed for hybrid fuel cell and battery-powered marine systems. The proposed concept is shown to significantly reduce total powertrain losses. Additionally, the concept enables elimination of high-frequency ripple components in fuel cell current, which, in the long term, can lead to improved fuel cell operation.

- A fuel cell voltage model-based control algorithm is proposed for control of DC bus voltage by battery DC/DC converters operating in the Variable DC approach concept. The controller utilizes a non-linear fuel cell voltage model to allow simultaneous control of the
battery and fuel cell powers. The proposed controller is shown to provide great control accuracy and reliability.

- A converter control system is proposed for fuel cell DC/DC converters operating in the Variable DC approach concept. The control system enables accurate control of fuel cell current and seamless transitioning between the Variable DC approach operating modes.

- A modified Variable DC approach concept is proposed to enable operation of direct on-line connected batteries in the Variable DC approach concept. In such a system, batteries are connected to the DC bus without DC/DC conversion devices, thus enabling reduced cost, weight, and footprint for a system, while also enjoying improved efficiency accustomed to the Variable DC approach concept. Such systems are especially interesting for smaller vessels, such as high-speed passenger vessels, which are known to be sensitive to power system weight and footprint.

- A system level algorithm is proposed to estimate dynamic performance of fuel cell powered marine DC distribution systems. The method utilizes a DC-based power system model to estimate DC voltage drops following sudden load changes applied to the system. The voltage drop is used as a metric to determine whether a system can sustain the applied load change. The proposed method is interesting especially for shipboard power management systems for coordinating the load dependent starting and stopping of fuel cells. Additionally, the method is useful for early-stage dimensioning of fuel cell power sources and selection of system configuration.

1.4 Dissertation outline

This dissertation is organized as follows. This chapter provides a brief introduction to the topic, motivation, targets, and scientific contributions of the dissertation. Chapter 2 reviews the most relevant prior works related to the topic of this dissertation. The proposed Variable DC Approach and control systems related to it are set forth in Chapter 3. Chapter 4 presents the HIL setup used to validate the proposed concept. The results from the HIL tests are provided in Chapter 5. Finally, Chapter 6 concludes with discussion and recommendations for future research.
2. Fuel cells and their electric integration into marine vessels

According to the International Maritime Organization (IMO), the shipping industry accounts for nearly 3% of total GHG emissions [10]. Furthermore, the shipping industry also accounts for about 90% of total world trade. To date, compared to different transportation means, shipping has the lowest environmental footprint, thus defining it as the most efficient means of transportation of both goods and people. However, due to its effectiveness as a means of transport, the shipping industry is estimated to significantly grow in the near future, thus resulting in a correspondingly significant growth of emissions. If left unchecked, the share of emissions from the shipping industry could rise to 17% of global GHG emissions by 2050 [11].

Hydrogen and fuel cells could play a significant role as means for decarbonization of the shipping industry. They are already proven technologies in other applications, such as heavy-duty automotive vehicles, and could also fit well into marine vessels. However, marine vessels as applications differ significantly from other types of vehicles, such as automotive vehicles. For example, marine vessels typically comprise numerous different types of power loads which are usually fed by more than one power source. The loads and sources are interconnected in a fashion which cause the marine vessel power systems to resemble isolated microgrids. Moreover, many different vessel types exist, each with different operation profiles and requirements. Therefore, to effectively utilize fuel cell power sources in marine vessel power systems, knowledge is needed of both fuel cells characteristics as power sources as well as vessel electric integration concepts and operating profiles.

2.1 Marine vessel types

Marine vessels are typically categorized into different vessel types based on their operating routes (e.g., river or sea) and the type of cargo they are designed to carry. Generic illustrations of various vessel types are provided in Figure 2.1. Cruise vessels are typically large ships designed to
function as floating leisure places for a large number of passengers while also transporting them overseas. Passenger ferries are similar to cruise vessels but typically smaller and operate for shorter distances. Similarly, Ro-pax vessels are a type of ferry vessel which have limited passenger facilities; instead the typically include long car-lanes for transport of light and heavy-duty vehicles. On the other hand, tanker and dry cargo vessels are designed for transport of goods and materials. The designation “tanker” is typically used when the cargo being transferred is liquid e.g., gas and oil. Ice-breaking vessels are designed for the special purpose of breaking thick ice built on sea in order to enable movement of other vessels during winter times. The Off-shore vessels are built for various support activities in the offshore energy industry. Push-boats are typical in rivers and their function is typically to push floating goods; this category would include vehicles such as barges. Naval vessels are another category of vessel types which are designed for various tasks in the field of warfare. Finally, yachts are a type of leisure vessel typically carrying passengers but in a much smaller capacity than, for example, ferries.

As shown in Figure 2.1 marine vessels differ significantly from each other in both appearance and the tasks carried out. From a power system perspective, the differences are typically visible in the form of operational power profile. The power profile is a key factor defining the power system requirements, thus also rendering it an important consideration when introducing fuel cells as power sources. Often, the characteristics of power source devices behave such that optimum efficiencies are reached at certain
Figure 2.2. Operational profiles of a) a bulk carrier in the Rhône river and two passenger vessels in b) the Rhine river and c) Danube river. The bars show load power distribution for a single trip, whereas the curve shows cumulative time.
power operating points. However, as illustrated in Figure 2.2, operational profiles differ notably between different vessel types and routes [12]. The figure illustrates the operational power profiles of three different vessels, a bulk carrier (a type of cargo vessel) and two passenger vessels. The bulk carrier is shown to mainly operate at power levels below 40%, whereas the passenger vessels in the Rhine and Danube are shown to mainly operate around 50% and 95%, respectively. Since different vessel types have very different operational power profiles, various means, such as power and energy management, are required to achieve high energy efficiencies across the whole marine vessel segment.

2.2 Fuel cell power sources

A fuel cell is an energy conversion device which, through a series of electrochemical reactions, converts chemical energy stored in fuels (e.g., hydrogen or hydrogen-rich fuels) into electrical energy to be used, for instance, as propulsion power for a marine vessel. The electrochemical operating principle of a fuel cell greatly depends on the fuel cell type and the fuel used.

Fuel cells have been in use for decades in various applications of which most notable are automotive, portable electronics, space, and stationary applications. However, the use of fuel cells in marine applications is still in its infancy, and to date their use has been mainly technology demonstrations as will be discussed in Section 2.3. Nevertheless, due to their indisputable potential in de-carbonization of marine transportation, they have received ample attention in the maritime industry in the past few years. This research focuses on proton exchange membrane (PEM) fuel cells, which are considered more techno-economically mature and viable than other fuel cell types considered for use in marine vessels.

2.2.1 The operation principle of a PEM fuel cell

A PEM fuel cell is a low temperature fuel cell with a solid electrolyte. Through a chemical reaction, the PEM fuel cell combines hydrogen ($H_2$) and Oxygen ($O_2$) reactants to produce electricity, heat and water. In its simplest form, a PEM fuel cell consists of two electrodes (usually platinum layers spread out on carbon powder) wrapped around a highly ion conductive polymer electrolyte [13]. During operation, one of the electrodes (negative anode) is fed with hydrogen and the other (positive cathode) is fed with oxygen. Once hydrogen atoms react with the catalyst in the anode, they become oxidized and split into electrons ($e^-$) and hydrogen ions ($H^-\)$. The hydrogen ions flow through the porous electrolyte to the cathode, then react with oxygen atoms to form water molecules ($H_2O$). Since the electrolyte is designed to prevent electrons from passing through (although, in practice,
Fuel cells and their electric integration into marine vessels

In commercial fuel cell products utilizing pure hydrogen as fuel, the voltage of a single fuel cell commonly ranges from \( \sim 0.5 \) V at maximum power to a maximum of \( 1.1 \) V at no load, depending on the fuel cell operating temperature. Higher voltages, and consequently operating powers, can be obtained by connecting several cells in series to form fuel cell stacks. This is usually achieved by wrapping two highly conductive bipolar plates around the cell and connecting them with other cell assemblies. The bipolar plates, typically made of metal or graphite, are designed with flow field channels, through which hydrogen and oxygen are supplied into the membrane electrode assembly [13].

A generic PEM fuel cell system is illustrated in Figure 2.3. The fuel cell system typically comprises the fuel cell stack, hydrogen, and oxygen (or commonly, air) delivery systems, a heat management system, as well as a safety and control system. Due to its abundance, air is typically used as reactant instead of pure oxygen. Together, these sub-systems are typically known as the balance of plant (BOP) for the fuel cell stack. Optimum control of the BOP is critical to achieving optimum fuel cell performance. The hydrogen delivery system typically comprises pressure control valves while the oxygen delivery system comprises an air compressor and air filters to control the pressure and purity of the supplied air. Often, one or both of these delivery systems also contain a humidifier to moisturize the supplied air and/or hydrogen and in that way, control the membrane hydration, the lack of which could result in significant fuel cell performance degradation [14]. On the other hand, the heat management system is
used to transfer the excess heat generated as a byproduct during fuel cell operation out of the fuel cell. The fuel cell exhaust (or more specifically, cathode exhaust) comprises of the water byproduct and depleted air from the electrochemical process. The electrical efficiency for the complete fuel cell system is typically between $50\% - 60\%$ depending on the power loading [15].

An example of a real-application design of a megawatt-scale PEM fuel cell system designed in collaboration by ABB and Ballard Power Systems for Marine vessels is illustrated in Figure 2.4 [16]. The shown fuel cell system is designed for 3-MW electrical output power. The process air is supplied from the side of the unit and the air supply system comprises an air-filter, compressor and air humidifier. On the other hand, pressurized hydrogen is supplied from the other side of the unit and the hydrogen supply system comprises pressure regulation and block valves (although, the valves are not visible in Figure 2.4). For safety reasons, the fuel cell stacks and all hydrogen containing assemblies are installed inside a hydrogen tight compartment to prevent hydrogen leaks outside the unit. The system components are monitored and controlled by an electronic control system.

### 2.2.2 PEM fuel cell voltage

The fuel cell voltage is generated as a result of series of electrochemical processes occurring in the fuel cell. From an electrical system integration perspective, the behavior of the produced fuel cell voltage is one of the key operating parameters to consider in marine system design. The efficiency
of a fuel cell is directly proportional to the fuel cell voltage; thus, its reliable estimation is often beneficial from the perspective of system operation and performance. To that end, numerous different fuel cell voltage estimation models have been proposed in the literature. One of the more commonly used voltage models is that described in \[13\] and \[17\]:

\[
E_{fc} = N_{fc}(E_{ocv} - E_{act} - E_{res} - E_{con}),
\]

where, \(N_{fc}\) is number of fuel cells connected in series, \(E_{ocv}\) is no-load voltage of a fuel cell, \(E_{act}\) is the activation voltage drop due reaction kinetics, \(E_{res}\) is the resistive loss due to ion and electro transport, and \(E_{con}\) is the concentration voltage drop due to mass transport limitations.

The fuel cell open circuit voltage depends on several factors, such as fuel cell operating temperature, reactant partial pressures and concentration of process gases. The activation losses occur on the surface of fuel cell electrodes on which energy is required as a driving force for the transport of electrons. The activation voltage behavior as function of fuel cell current is highly non-linear and can be effectively described by the Tafel equation:

\[
E_{act} = A_a \ln\left(\frac{i_{fc}}{i_0}\right),
\]

where \(i_{fc}\) is fuel cell current, \(A_a\) is activation loss coefficient, and \(i_0\) is fuel cell exchange current. The exchange current describes the current value at which the activation voltage losses start to occur. The activation voltage losses are dominant at low fuel cell loads. The resistive voltage drop, or ohmic voltage drop, can be described via Ohm’s law:

\[
E_{res} = R_c i_{fc},
\]

where \(R_c\) describes the resistivity of electrons travelling between electrodes via bipolar plates and ions travelling through the electrolytes. The ion transport resistivity typically dominates much more than the electron transport resistivity. Finally, the concentration voltage loss is due to the transport of very large masses through limited flow fields, resulting in decreased reactant partial pressures at the electrode surfaces and, consequently, in voltage losses, i.e., concentration losses. Obviously, concentration losses occur more dominantly at high fuel cell loading where transport of reactants is also high. A convenient way to estimate concentration losses as function of fuel cell current is by an empirical relationship as follows:

\[
E_{con} = m_c e^{n_c i_{fc}},
\]

where \(m_c\) and \(n_c\) are empirically determined constants, which can be obtained, e.g., via curve fitting to actual fuel cell voltage. A generic 150kW fuel cell voltage polarization curve, including its voltage loss components, obtained by (2.1) is illustrated in Figure 2.5.
2.2.3 Fuel cell considerations on marine power systems

For a long period of time, combustion engine-powered electric generators have been the power source of choice for marine power systems. Such power sources (most typically diesel engines) have certain operating characteristics which are well known and considered when designing marine power systems (i.e., load consumers, protection devices, operation methods, etc.). In contrast, fuel cells have only recently emerged as potential power sources for the marine industry. To certain extent, their characteristics as power sources notably differ from those of combustion engine powered generators, thus also requiring different design considerations in the rest of the power system. From a marine power system integration and operation perspective, the main differing considerations between fuel cells and electric generators are as follows:

- Voltage behavior as a function of load power.
- Dynamic power response
- Susceptibility to current ripples
- Protection requirements
• General operation considerations

The fuel cell voltage behavior was presented in Figure 2.5. The voltage at full load is significantly lower than open circuit voltage, often in the range of 50% lower. Typically, power conversion devices are used to convert the varying fuel cell voltage either into fixed DC voltage or AC voltage for power distribution on board a vessel. Therefore, depending on the vessel power system requirements, the fuel cell voltage variation must be considered when designing the power conversion device. Moreover, since the power conversion device connected to the fuel cell unit must be designed for both maximum voltage and maximum current, the power conversion devices often end up being rated for much higher power than available from the fuel cell unit.

Due to fuel cells being electrochemical power conversion devices, their dynamic power characteristics significantly differ from those of conventional combustion engine-based devices (i.e., diesel engines). In optimal conditions, it has been shown that a fuel cell unit can manage a power increase from 50% load to 94% within 0.1s without noticeable problems in fuel supply [18]. Nonetheless, in commercial products, the allowed ramp rates are more moderate. For example, a 200 kW marine fuel cell unit from Ballard Power Systems allows power ramp rates of 20kW/s (i.e., 10% per second) [8]. This compares very favorably against typical marine diesel engines in which power ramp up times are typically about 2% per second [19]. However, unlike diesel engines with electric generators, fuel cell units do not comprise rotation of large masses in their power conversion process. While that is typically seen as an advantage, e.g., from the perspective of noise, wear, and tear, it does also hold one disadvantage. For combustion engines, the large inertia functions as a small energy storage which plays an important role during step-like load transients. In case of a step-like increasing load transient, the load increases instantly, whereas adjustment of fuel supply occurs with a certain delay. During such an event, load power temporarily exceeds fuel supply leading to energy being spontaneously supplied from the inertia of the combustion engine and electric generator, which is typically seen in a reduction of combustion engine speed. Since fuel cells do not store inertial energy by nature, they are very susceptible to step-like load transients or any other event in which momentary energy consumption exceeds the energy content of supplied fuel. This phenomenon is more generally known as fuel starvation, and even very short periods of such incidents should be avoided, as starving a fuel cell from fuel can greatly damage the cell [20, 21]. In a ship environment, such an event could potentially lead to a system blackout which is always unwanted [22]. To avoid both damaging fuel cells and causing potential blackouts, energy storage devices, such as batteries, are usually operated in parallel with fuel cells, during which the energy storage devices are used to supply such
Fuel cells and their electric integration into marine vessels

The fuel cell current ripple is another factor known to impact fuel cell performance. It typically causes extra heating leading to losses in the fuel cells, which in the worst cases, impact the actual electrochemical reactions on the cell surface potentially resulting in accelerated degradation on the stacks. The magnitude and frequency of the current ripple is typically dependent on the design of the used power converter (e.g., topology, PWM concept and component dimensioning), type of load consumers, and the system power and energy control philosophy. The power electronic converters typically induce high-frequency current ripples (>1 kHz); although for some converter topologies, the fuel cell ripple content can be completely mitigated [23]. In contrast, low-frequency ripples (< 100 Hz) typically depend on the load types, selected system power, and energy control strategy. Of the two current ripple types, the high end of low-frequency ripple (i.e., 100 Hz) is generally believed to have some extent of impact on the fuel cell lifetime, whereas the high-frequency ripple does not, due to it being effectively filtered out by a charge double layer capacitance formed between fuel cell membranes and electrodes [24]. However, in some tests, even the high-frequency ripple is shown to cause up to 10% faster voltage degradation over a longer period of time [25]. Moreover, it should be noted that the magnitude of the charge double layer capacitance, which functions as the filtering mechanism for the high-frequency ripple, is typically directly proportional to catalyst loading on the fuel cell electrodes. For example, since a platinum catalyst is known to have a relatively high cost compared to the rest of the cell materials, a reduction of catalyst usage is generally wanted. Hence, reduced catalyst loadings could result in reduced charge double layer capacitances and further lead to reduced high-frequency current filtering. In any case, the fuel cell current ripple is an important consideration in the power system design.

Protection philosophy is a key consideration in the design of a marine power system. From the power system perspective, many protection considerations (e.g., grid overloads and overvoltages) can be similarly approached regardless of the power source used. However, since fuel cells have certain characteristics which differ from other energy sources, such as electrical generators and batteries, fuel cell protection functions typically require some extra attention. First, fuel starvation should always be avoided. Secondly, since most commercial marine fuel cell products currently function only as electrical power sources and cannot sustain any reverse power, any current flow towards the fuel cells must be avoided. A current flow towards fuel cells would result in a reverse reaction process in the fuel cells; and by them not being designed for such a reaction, they could become severely damaged. Due to fuel cells being typically integrated in a power system via power conversion devices, the mentioned protection functionality is usually implemented in the said power conversion devices. Another significantly
differing protection-related feature for fuel cells is their short-circuit current generation capacity. Adopting electric generators as an example, it is known that on a short-circuit, the peak current generation capacity is typically about 6-8 times their rated current and the peak current decays to a steady state value within seconds depending on their L/R ratio, where L refers to inductance and R to resistance. The relatively long decay time provides ample time for current-breaking by fuses or conventional circuit breakers. On the other hand, the generated short-circuit current peak for fuel cells can reach up to 10 times the rated fuel cell current value with it then decaying to its steady state value within about 50 ms [26]. The very fast decay time occurs due to a lack of reactant supply into the fuel cells, thus resulting in the fuel cell current settling to a value depending on the reactant flow. While fuses are often used for protection from short-circuit conditions, proper dimensioning of the said fuses can be challenging due to the very fast short-circuit current decay time. Nevertheless, current power converters are based on fast responding power electronic systems, therefore, rendering them capable of interrupting fault currents at fast rates. Therefore, it is common to also utilize the power conversion devices interruption of short-circuit currents, which further adds to the requirements of the power conversion device.

Finally, since general fuel cell operation behavior also differs significantly from conventional generators or batteries, these considerations must also be considered in the general power system design. For example, both generators and batteries can be indefinitely run idle (i.e., at zero load), whereas commercial marine fuel cell products typically require a minimum operating power to avoid operation in the region in which activation losses are dominant. If the fuel cells are run at lower loads than the minimum specified for a certain period of time (typically 10 seconds to minutes), the fuel cell unit will automatically shut down. Therefore, the marine power system must be designed such that it can always absorb the minimum required fuel cell power unless the fuel cell unit can be turned off. Typically, the said power absorption capacity is managed via hybridization with energy storage devices which can be charged should the power system load power fall below minimum fuel cell power. Another general operation consideration for fuel cells is their electrical efficiency behavior. The fuel cell system efficiency tends to be highest when operating at partial loads (typically ~20-30%) and then gradually decreases as the power reaches maximum rated power. This efficiency behavior is very different from, e.g., diesel engines which are known to reach their highest efficiency at near maximum power ratings, whereas efficiency is much lower at partial loads. Therefore, the power system must be designed such as to enable fuel cells operation at their highest efficiency points while naturally also considering the total system cost.
2.3 State-of-art electric integration concepts for fuel cell-fed marine power systems

2.3.1 DC integration

The simplest and most common fuel cell and battery integration concepts are based on DC distribution systems. In a DC distribution system, power sources and load consumers are typically coupled together on a DC switchboard. Since various power sources and load consumers have different types and levels of voltages, the coupling on the DC bus is typically managed through power converter devices. Compared to AC distribution systems, the DC distribution systems have several advantages. For example, if combustion engines are used as power sources, the speed of each combustion engine can be freely varied, allowing them to operate at their optimal efficiency points. Furthermore, since DC voltage has zero frequency, power control and load sharing techniques are easier compared to AC distribution systems in which both voltage and frequency must be considered. In addition, no reactive power is transmitted in DC systems, which is considered an advantage because the additional current required for the transport of reactive power generates additional heat losses, resulting in reduced system energy efficiency. For DC power sources (e.g., fuel cells and batteries) particularly, the DC distribution systems are attractive because their integration into a DC distribution system does not need to involve AC conversion.

The most basic DC integration concept for fuel cells and batteries is one where all power sources and loads are converter-controlled. Such systems are widely suggested in the literature as well, and even utilized in a few technology demonstration vessels [27–39]. An example of such a system is illustrated in Figure 2.6a in which fuel cells and batteries are integrated into a common DC bus via DC/DC converters, whereas propulsion motors and hotel loads are supplied via DC/AC converters. The hotel load supply typically involves a power transformer which provides galvanic isolation and voltage adjustment for the hotel loads. Typically, the benefits of this DC integration concept are simple integrability and good power controllability due to the high-speed power conversion devices. The powertrain between power sources and propulsion motors incorporates only two power conversion stages; therefore, the concept displays a good energy efficiency.

A variant of the concept shown in Figure 2.6a, is illustrated Figure 2.6b in which switches are used to bypass the fuel cell DC/DC converters [40]. In such a system, fuel cell DC/DC converter is bypassed whenever DC bus voltage is within the fuel cell output voltage range, whereas at other times the converter is used for voltage matching. Therefore, with the expense of
the extra switches, the system energy efficiency is improved whenever the converter can be bypassed. However, it should be noted that during times when a bypass circuit is closed, the fuel cell system is completely exposed to any potential system failure from the DC bus side. The switchover control between the DC/DC converter and the bypass circuit may be challenging, especially if very quick switchovers during failures are needed.

A known way to improve steady-state efficiency and power conversion system size of a DC distribution concept is to utilize direct to DC bus connected batteries, commonly known as direct on-line (DOL) batteries. A generic illustration of such an integration concept is presented in Figure 2.7. The omission of battery DC/DC converters reduces the total investment cost, weight, and size of the power system, as well as improves the battery system energy efficiency. However, while the system looks hardware-wise simpler than that of Figure 2.6a, it possesses some drawbacks. The common DC bus voltage is mainly determined by the battery system voltage which varies significantly as function of the battery state-of-charge (SOC) and current, as shown in [39]. The wide voltage variation range results in higher voltage rating requirements for the power components, thus also increasing their size and cost. For example, in a typical low voltage (LV) DC system, the propulsion motor nominal voltages are often 690 Vac [2]. To produce such voltages, e.g., by VSIs, the DC bus voltage needs to be about 1000 Vdc. Hence, to maintain the 1000 Vdc at all times, the batteries must be dimensioned such that their minimum voltage is above 1000 Vdc. An option would be to reduce the nominal voltage of the propulsion motors to allow for a lower DC bus voltage resulting from decreased battery SOCs. However, that would also lead to increased motor currents, resulting in increased motor drive and cabling requirements, and often higher energy losses. Additionally, depending on the type of fuel cell DC/DC converters used, significant reductions in DC bus voltage may also affect the dimen-

Figure 2.6. a) Illustration of a state-of-art DC integration concept in which the output powers of both fuel cells and batteries are controlled by DC/DC converters. b) A DC/DC converter bypass circuit is utilized.
Fuel cells and their electric integration into marine vessels

Figure 2.7. a) Illustration of a state-of-art DC integration concept in which the output powers of fuel cells are controlled by DC/DC converters, whereas batteries are directly connected into the DC bus.

sioning requirements of the fuel cells. Fuel cells often utilize boost type DC/DC converters which typically require a DC bus voltage higher than the fuel cell voltage. If the requirement is not met, uncontrolled current flow from fuel cells towards the DC bus will occur through the converter freewheel diodes. Nevertheless, for many simpler vessel types, the DC integration concept with DOL batteries can be the most optimal integration concept [41–46].

In the literature, the integration concepts presented in Figures 2.6a and 2.7 are by far the most commonly proposed and applied DC-based integration concepts. One more unconventional integration concept is proposed in [47], and conceptually illustrated in Figure 2.8a. In that integration concept, energy storage devices (typically supercapacitors) are proposed to be directly parallel coupled with the fuel cell unit outputs. The energy storage devices effectively function as low-pass filters for the fuel cell current. The low-pass functionality enables the DC/DC converter to be operated with quicker power responses without risking degradation of fuel cells which are known to be sensible to quick and frequent power variations [18]. The filter characteristics of the energy storage device are determined based on the energy storage type and dimensioning.

The main advantage of the integration concept in Figure 2.8a is reduced rating requirement for DC/DC converters and DC switches compared to those in Figures 2.6 and 2.7. However, the concept also possesses several disadvantages. For example, the fuel cells have a minimum allowed operation voltage which is typically about 50 – 60% of the fuel cell maximum voltage. Therefore, for supercapacitors, all energy capacity corresponding to operating voltages below the minimum fuel cell voltage cannot be used, thus leading to overdimensioning of the supercapacitors. Moreover, in addition to the overdimensioning challenges, operational challenges also exist. First, while the parallel coupled energy storage does provide
Fuel cells and their electric integration into marine vessels

filtering for quick power transients, it does not eliminate them, unless very bulky energy storage devices are used. Secondly, due to the direct parallel coupling of fuel cell and energy storage units, failure in one component (e.g., the DC/DC converter) will lead to unusability of both fuel cell and energy storage units.

To avoid the mentioned overdimensioning challenges, a similar integration concept, but with converter-controlled energy storage devices, is proposed in [47, 48], and conceptually illustrated in Figure 2.8b. The use of a DC/DC converter decouples the voltages between fuel cell and energy storage units, thus reducing the challenge of overdimensioning. Compared to the integration concept in Figure 2.8a, the concept provides better fuel cell current filtering due to typically very fast power responses of DC/DC converters. However, the requirement for an additional DC/DC converter increases cost and energy losses due to an extra power conversion stage. Moreover, the total power supply is limited by the rating of the fuel cell (main) DC/DC converter, and thus, simultaneous power supply from both batteries and fuel cells would require increased rating of the main DC/DC converter. Nevertheless, since fuel cell voltage is typically much lower than that of the common DC bus, the voltage rating of the energy storage DC/DC converter may be selected lower than, e.g., that in the basic integration concept from Figure 2.6a. Therefore, this solution might be cost-efficient for systems in which fuel cell units are rated for full-vessel load capacity with energy storage devices only being intended as dynamic performance enhancers for the fuel cells.

Figure 2.8. a) Illustration of an integration concept in which a) supercapacitors are directly connected to the fuel cell output terminals and b) batteries are connected to the fuel cell output terminals via DC/DC converters.
2.3.2 AC integration

Traditionally, due to the use of rotating combustion engines as main power sources, AC distribution systems have been the preferred integration concepts in marine vessels. In an AC distribution system, power sources and load consumers are typically coupled together on a main AC switchboard. The electric generators produce AC voltage with the same magnitude and frequency as the AC distribution voltage; thus, they are directly connected to the main AC switchboard. For power sources with voltage not matching that of the Main switchboards (e.g., fuel cells), the integration is arranged via DC/AC converters or AC/AC converters. The propulsion speed and power are controlled by AC/AC converters, whereas the hotel loads are typically supplied by distribution transformers.

The simplest AC-based integration concept for fuel cells is illustrated in Figure 2.9a. The integration concept highly resembles its DC-based counterpart from Figure 2.6a. Each power source and propulsion load are coupled at a common AC bus via power converters, whereas the power towards hotel loads is distributed via power transformers. Due to its similarities to the basic DC integration concept from Figure 2.6a, operation of the system can be handled quite similarly to the DC integration concept. Despite this, the AC integration concept has quite a few integration and operational disadvantages. Due to the characteristics of AC power, the AC-based integration concept also requires generation and distribution of re-active power, which typically increases system losses and requires a slightly higher power converter and cable current ratings. Moreover, the powertrain between the power sources and propulsion motors comprises three power conversions compared to two in the mentioned DC integration concept. The higher number of power conversions typically leads to significantly higher hardware investment costs and reduced total power system efficiency [49]. In addition, since both fuel cells and batteries generate DC voltage which significantly decreases as the load power increases, the dimensioning of the DC/AC converters can be challenging. For example, the fuel cell output voltage at high loads can be 50% lower than that at low loads. Therefore, the power rating of DC/AC converters is significantly derated, hence resulting in a higher investment cost.

Although AC distribution systems for fuel cells and batteries are typically less efficient than their DC counterparts, they currently still have one major advantage over the DC systems. Due to the current zero-crossings in AC systems, fault current interruption with traditional electromechanical switchgear is typically easier and quicker in AC systems. Although, with power electronic converters, efficient and quick current control and interruption can also be managed in DC systems. However, in medium voltage (MV) marine applications with DC distribution, reliable fault current interruption, and fault segregation still remains a challenge [50,51].
Therefore, MV DC integration concepts are yet to be adopted in marine vessels. The reason is mainly due to a lack of proper commercial components. Hence, current MV marine applications are almost invariably AC-based. Using MV AC distribution systems is typical in large vessels such as cruise lines [52]. An example of such an integration concept for a fuel cells and batteries-fed power system is presented in Figure 2.9b. The principle of the integration concept is the same as the one in Figure 2.9a, but the power sources are integrated into the main switchboard via step-up power transformers, whereas the propulsion loads are integrated via step-down power transformers.

The use of elevated voltage levels provides several system advantages, mainly due to reduced current levels. The current ratings of MV switchboard breakers, power converters, cables and propulsion motors decrease proportionally with the increase of operating voltage, thus typically resulting in lower system size, weight, cost, and energy losses in said devices. Additionally, due to the power transformers, each power source and load consumer are galvanically isolated from each other, resulting in higher system safety, e.g., in case of earth faults or short-circuits. However, for any vessel application in which the use of low voltage (i.e., less than 1500 $V_{dc}$ or 1000 $V_{ac}$) is feasible, the drawbacks in size, efficiency, and cost of bulky power transformers far outweigh the benefits. This holds especially true for fuel cell-powered systems in which the number of needed transformers is high. Therefore, AC integration concepts such as the one in Figure 2.9b are rarely proposed for fuel cell-fed marine vessels.
2.3.3 Hybrid AC and DC integration

Based on the above discussion, DC integration concepts are clearly more suitable and efficient for fuel cell integration than their AC counterparts. However, in MV applications, marine power systems are almost invariably AC-based, as discussed in Subsection 2.3.2. In order to achieve some of the benefits of DC integration concepts, while also utilizing the known and technologically mature AC systems, hybrid AC-DC integration concepts can be used. Two hybrid AC-DC integration concepts which combine the integration principles from Figures 2.6a, 2.7 and 2.9a, are presented in Figure 2.10. In Figure 2.10a, both fuel cells and batteries are converter-controlled, whereas in Figure 2.10b batteries are DOL-connected. All power consumers are interconnected on an AC switchboard. The common DC buses and the AC switchboard are interconnected via DC/AC converters. The benefits of such integration concepts stem from the integration of fuel cell and batteries which can be done as DC, hence rendering them simpler, as was discussed in Subsection 2.3.1. Figure 2.10b illustrates the same hybrid concept but with DOL batteries the advantages and disadvantages of which were already discussed in Subsection 2.3.1.

In both of the AC-DC integration concepts presented thus far, a major drawback is the reduced system efficiency due to a requirement for four power conversions between fuel cell outputs and propulsion motor inputs. To reduce the number of power conversions, the fuel cells and their DC/DC converters can be directly connected to the DC link of the propulsion frequency converters. A generic illustration of such an integration concept is presented in Figure 2.11 in which the number of power conversions between fuel cells and propulsion motors is reduced to two, resulting in
Figure 2.11. a) Illustration of hybrid DC/AC integration concept in which fuel cell power generation is distributed such that part of the fuel cell capacity supplies power directly to a common DC link of a propulsion drive with the rest supplying power towards the AC distribution grid.

the total system efficiency being significantly improved. Furthermore, since the cost of DC/DC converters is typically less than that of DC/AC converters, the total investment cost of the power systems is also reduced. In Figure 2.11, the fuel cell power capacity allocation between the AC grid supply and propulsion drive supply should be chosen depending on the load distribution between propulsion and hotel load. In that way, the powertrain efficiency can be optimized since unnecessary power supply from the AC grid supplying fuel cells to the propulsion motors is avoided. This hybrid DC-AC integration concept provides good flexibility towards different vessel types and power profiles.

2.3.4 Comparison of the reviewed integration concepts

This section has reviewed 10 different integration concepts. From the discussion in this section, DC-based distribution concepts are found to be the simplest and most effective of the concept types. The same conclusion can be drawn from the comparative assessment of the integration concepts presented in Table 2.1 [53]. The table presents for each integration concept the most typical performance parameters, such as cost, size, integration complexity, powertrain efficiencies, and number of components. Details of the presented comparison are found in [53].
Table 2.1. Comparison of main features between the presented integration concepts. In the table, FC refers to fuel cell, ES to energy storage (i.e., battery or supercapacitor) and PM to propulsion motor.

<table>
<thead>
<tr>
<th></th>
<th>AC concepts</th>
<th>DC concepts</th>
<th>Hybrid concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AC-1</td>
<td>AC-2</td>
<td>DC-1, 2</td>
</tr>
<tr>
<td>Schematic</td>
<td>Fig. 2.9a</td>
<td>Fig. 2.9b</td>
<td>Fig. 2.6</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>0.4–1 kV</td>
<td>3.3–11 kV</td>
<td>0.6–1 kV</td>
</tr>
<tr>
<td>Operating power</td>
<td>&lt; 15 MW</td>
<td>&gt; 20 MW</td>
<td>2 - 15 MW</td>
</tr>
<tr>
<td>System complexity</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Low/ Moderate</td>
</tr>
<tr>
<td>FC to PM efficiency</td>
<td>91 - 96.5%</td>
<td>89 - 95.5%</td>
<td>96 - 99.5%</td>
</tr>
<tr>
<td>FC to ES efficiency</td>
<td>95 - 97%</td>
<td>91 - 95%</td>
<td>95 - 98.5%</td>
</tr>
<tr>
<td>ES to PM efficiency</td>
<td>91 - 96.5%</td>
<td>89 - 95.5%</td>
<td>96 - 98%</td>
</tr>
<tr>
<td>System cost</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>System weight &amp; size</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>No. of power converters</td>
<td>8</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>No. of transformers</td>
<td>2</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>
3. The Variable DC Approach concept

For power conversion devices, such as power converters and electric motors, variation of DC bus voltage as a means to reduce energy losses is a well-known technique. Already in 1993, it was shown that magnetic materials supplied by PWM-controlled power sources tend to have lower losses when operated with a higher PWM modulation index compared to lower modulation index [54]. The modulation index has a direct impact on the converter current ripples and variation of magnetic flux density induced in the magnetic material. A lower modulation index typically results in higher current and flux density ripples, and consequently higher energy losses [55,56]. For VSI-type converters, the required modulation index is dependent on the magnitude ratio between DC bus voltage and output AC voltage. Therefore, dynamic adjustment of DC bus voltage as a means to optimize the modulation index results in improved energy efficiency. Such a technique has been widely studied, especially for land-based electric vehicle applications in which most typically a battery DC/DC converter is proposed to adjust the voltage of a DC bus supplying a motor drive [57–59]. In such applications, the DC bus voltage is proposed to be proportionally adjusted to the motor input voltage which in turn is proportionally controlled to the motor speed. In that way, significant efficiency boosts can be achieved when the vehicle operates at lower speeds than nominal [60].

Considering the operational power profiles shown in Figure 2.2, it is evident that marine vessels, especially those operating for long periods at loads much lower than nominal, would also benefit from the efficiency boost achieved by applying adjustable DC bus voltages. However, as was shown in Section 2.3, most DC grid-based marine power systems utilize common DC buses into which load consumers, such as propulsion drives and hotel load VSIs, are coupled. When a vessel is operating at low propulsion speeds, propulsion drives would efficiency-wise benefit from the reduction of DC voltage. However, the hotel load switchboards, which are typically AC switchboards, require fixed (or with minor droop applied) AC frequency and voltage, regardless of power consumption. Therefore, large DC voltage variations would not be feasible, unless the hotel load VSIs were dimen-
The Variable DC Approach concept

sioned for much lower DC operating voltages than the rated DC bus voltage. However, such a dimensioning would be counter-productive because while enabling improved efficiency in the propulsion drives, it would decrease the efficiency in the hotel load supplying drives. Moreover, reduced voltage rating in the hotel VSIs would lead to higher current supply requirements, and consequently lead to hardware component overdimensioning, resulting in a higher cost and size due to increased amount of hardware.

This work proposes a novel control technique based on minor variations in DC bus voltage and targeted for fuel cell-fed marine power systems. Like the variable DC voltage techniques suggested for electric vehicles, the proposed technique too targets improved power system efficiencies by varying the system DC bus voltage at different system operation points. However, the principle of the proposed variable DC approach is completely different from the ones previously proposed for land-going vehicles. In the proposed approach, it not recommended that the DC bus voltage be varied as a function of propulsion motor input voltage, but instead it is proposed to be varied as a function of fuel cell output voltage. To avoid compromising the hotel load supply, the DC bus variation is capped at ±5-10% around the nominal DC bus voltage, depending on the power system design and vessel type. For vessels in which hotel load power constitutes a major portion of total vessel power consumption, the DC bus voltage variation range should be tighter, whereas for vessels in which the propulsion load constitutes a major portion of total vessel power consumption, the said variation range could be wider. In this work, the proposed method is called the Variable DC approach. The operating philosophy of the Variable DC approach has been described in [38] and is presented in this chapter.

Section 3.1 describes the main principle of the Variable DC approach. Section 3.2 presents the basic control logic required for controlling fuel cell DC/DC converter current references and battery DC/DC converter DC bus voltage references. However, more advanced control systems proposed for DC bus voltage control and fuel cell DC/DC converter control are described in Sections 3.3 and 3.4, respectively. Section 3.5 describes the main considerations and required modifications for applying the Variable DC approach on DC-based integration concepts with DOL batteries. Finally, Section 3.6 describes an analytic method to estimate the maximum allowed load power steps that can be applied on a fuel cell-powered DC-based marine power system.

3.1 The general principle

As discussed in Section 2.2, fuel cells are DC power sources with varying output voltage characteristics as a function of produced current. The voltage variation is commonly considered to be too large for fuel cells to be
The Variable DC Approach concept directly connected to a common DC, and instead DC/DC converters are used. The use of fuel cell DC/DC converters provides significant advantages, such as robust control of fuel cell current/power and voltage step-up or step-down depending on the system need. However, similar to any other power component, the DC/DC converters generate energy losses through heat generation. As with batteries, the DOL connection of fuel cells into a common DC bus could provide improved system energy efficiency. However, as discussed in Subsection 2.2.2, the fuel cell voltage typically varies as much as 40-60% of its open circuit voltage value. Allowing such a voltage variation in a common DC bus would typically not be feasible for the reasons mentioned at the beginning of this chapter.

The Variable DC approach is a fuel cell power system-operating concept in which the fuel cell power sources are converter-controlled but partially operated as if they were DOL-connected into a common DC bus. In such a concept, power sources and system loads are designed to sustain a limited variation in the common DC bus voltage, typically ±5-10% around the nominal DC bus voltage. The fuel cell power sources are dimensioned such that the common DC bus voltage operating range is within the voltage range of the fuel cells. An illustration of such a voltage dimensioning is presented in Figure 3.1. In the figure, the minimum DC bus voltage, $V_{dc_{\min}}$, and maximum DC bus voltage, $V_{dc_{\max}}$, are selected as 650V and 780V, respectively, whereas the nominal DC bus voltage, $V_{dc_{\text{nom}}}$, is 720V.

Whenever the system power loading level is such that fuel cell voltage is within $[V_{dc_{\min}}, V_{dc_{\max}}]$, the fuel cell DC/DC converter is controlled into a static state which mimics the DOL connection of fuel cells into a common DC bus. In such a state, a free current flow between the fuel cells and common DC bus is allowed. Such an operation is highly beneficial because, due to the static operation of the DC/DC converter, energy losses affiliated with high-frequency switching of the DC/DC converter are completely eliminated. On the other hand, whenever the fuel cell voltage exceeds the allowed DC bus voltage operation range, fuel cell DC/DC conversion is used for the required voltage matching.

The Variable DC approach control principle comprises three operating modes: A buck mode, a Freewheel mode, and a Boost mode. The modes are named based on the operating principle of the fuel cell DC/DC converter. Buck mode is used to step-down fuel cell voltage whenever it is above $V_{dc_{\max}}$ which typically occurs at low system loads. On the other hand, Boost mode is used to step-up fuel cell voltage whenever it is below $V_{dc_{\min}}$. The Boost mode typically occurs at high system loads during which the load voltage requirements are also typically higher. Therefore, rather than controlling the DC bus voltage to $V_{dc_{\min}}$ in Boost mode, the DC bus voltage is controlled to $V_{dc_{\text{nom}}}$. Finally, whenever the fuel cell voltage is within the DC bus voltage operating range, the Freewheel mode is used. Therefore,
The Variable DC Approach concept

**FC voltage and Variable DC approach operation limits**

![Diagram of voltage limits](image)

**Figure 3.1.** Illustration of the Variable DC approach voltage limits compared to fuel cell output voltage.

the common DC bus voltage behavior can be described as follows:

\[
V_{dc} = \begin{cases} 
V_{dc,\text{max}}, & V_{fc} > V_{dc,\text{max}} \\
V_{fc}, & V_{dc,\text{min}} \leq V_{fc} \leq V_{dc,\text{max}} \\
V_{dc,\text{nom}}, & V_{fc} < V_{dc,\text{min}}
\end{cases} \quad (3.1)
\]

A system control flowchart illustrating the Variable DC approach modes and the transitioning conditions between modes is presented in Figure 3.2. As mentioned above, the Buck mode is used whenever the fuel cell voltage is higher than \(V_{dc,\text{max}}\). However, should the system load fall so low as to lead to fuel cell power decreasing below the minimum allowed fuel cell power, \(P_{fc,\text{min}}\), which was discussed in Subsection 2.2.3, the fuel cell unit must be switched off. The fuel cell unit is started and connected to the DC bus once the system load is sufficiently high to maintain the fuel cell power at \(P_{fc,\text{min}}\) plus a small margin, or in case the SOC of any parallel connected battery unit drops below the minimum allowed SOC value, \(SOC_{\text{min}}\). The small power margin is used to avoid potential events during which a fuel cell unit is started and stopped many times over a short period of time due to operation at the vicinity of \(V_{dc,\text{max}}\). Once total system load increases such that the fuel cell voltage decreases below \(V_{dc,\text{max}}\), the system moves into Freewheel mode. The Freewheel mode is the most preferred operation mode due to the improved system efficiency. It is exited for Boost mode only if one of the following conditions becomes true: \(V_{dc} < V_{dc,\text{min}}\), \(i_b \geq i_{b,\text{max}}\) or \(V_{dc} < \sqrt{2}V_{\text{motor}}\), where \(V_{\text{motor}}\) is the input root mean square (RMS) voltage of a propulsion motor and \(i_b\) is the battery current. The first condition
The Variable DC Approach concept

Buck mode

\[ P_{\text{out}} > P_{\text{fc}_{-\text{min}}} \]

\[ |V_{\text{dc}}| < V_{\text{dc}_{-\text{max}}} \]

\[ V_{\text{dc}} \geq V_{\text{dc}_{-\text{max}}} \]

Freewheel mode

\[ V_{\text{dc}} < V_{\text{dc}_{-\text{min}}} \]

\[ \sqrt{2}V_{\text{motor}} \geq V_{\text{dc}} \]

\[ i_{b} \geq i_{b_{-\text{max}}} \]

Boost mode

\[ V_{\text{fc}} \geq V_{\text{dc}_{-\text{min}}} \]

\[ \sqrt{2}V_{\text{motor}} < V_{\text{dc}_{-\text{min}}} \]

\[ i_{b} < i_{b_{-\text{max}}} \]

Fuel cell off

\[ P_{\text{out}} > P_{\text{fc}_{-\text{min}}} + P_{\text{marg}} \]

\[ \text{SOC} < \text{SOC}_{\text{min}} \]

\[ V_{\text{fc}} < V_{\text{dc}_{-\text{max}}} \]

\[ V_{\text{fc}} > V_{\text{dc}_{-\text{max}}} \]

\[ \text{SOC} > \text{SOC}_{\text{max}} \]

Figure 3.2. A control flowchart for the Variable DC Approach concept. The red rhombuses and black rectangles represent control modes and mode transition conditions, respectively.

is to prevent DC bus voltage from falling below the allowed operation limit, whereas the second is to prevent the overload of batteries. The third condition, on the other hand, is to ensure sufficient input voltage for the propulsion loads. In this work, the propulsion motors are assumed to be supplied by 2-level VSIs which typically require their DC supply voltage to be \( \sqrt{2} \) times higher than the input RMS voltage of the supplied motor. The system returns to Freewheel voltage only once none of the mentioned conditions are true anymore.

3.2 Control of DC bus voltage and fuel cell current reference

As discussed in Subsection 2.2.3, fuel cells are power sources with good power dynamic characteristics but are susceptible to step-like load power transients. For optimal lifetime of the fuel cells, they are often operated with a certain ramp rate (typically 2-10% of rated power per second). On the other hand, batteries are known for their very quick power dynamic characteristics and good endurance even towards step-like loads. However,
The energy density of batteries is lower than that of hydrogen storage; thus, the batteries require larger footprints of space and are also heavier than hydrogen storage. In order to take advantage of the benefits of both power source types, in this work, the fuel cells are operated as base power suppliers, whereas batteries are used to supply power transients with faster ramp rates than allowed for fuel cells. Therefore, during steady load power states, the battery powers are zero and all load power is supplied by fuel cells. In order to achieve the described power source load-sharing principle, the fuel cell units are primarily current/power-controlled power sources, whereas batteries are DC bus voltage-controlled power sources. Therefore, the battery power sources maintain a steady DC bus voltage which is gradually varied according to the power system-loading level.

In the Buck and Boost modes, the fuel cell voltage is unequal to the DC bus voltage; therefore, DC/DC power conversion is needed for voltage matching. In the Buck mode, battery DC/DC converter voltage reference is maintained steady at \( V_{dc,\text{max}} \), whereas in Boost mode, the voltage reference is \( V_{dc,\text{nom}} \). On the other hand, since the control target for the method is to maintain fuel cells as base load power suppliers, the fuel cell DC/DC converter current reference is controlled such that it would result in \( i_b = 0 \). This can be managed by a simple PI-controller in which the control input is the difference between actual battery current and a current reference. A control diagram for the Buck and Boost modes is illustrated in Figure 3.3.

In normal conditions during which \( i_b = 0 \) is wanted, the battery current Reference is set to zero. If a different loading strategy (e.g., during the charging of batteries) is needed, the reference can be freely selected. In Figure 3.3, positive \( i_b \) means discharging power, whereas negative \( i_b \) means charging power.

In the Freewheel mode, fuel cell DC/DC converters are controlled to a static state to mimic DOL connection of fuel cells into common DC bus i.e., to allow free current flow between fuel cells and DC bus. However, in spite of fuel cell DC/DC converters being uncontrolled in this mode, active

---

**Figure 3.3.** Control of fuel cell current and DC bus voltage references in Buck and Boost modes. The DC bus voltage reference is \( V_{dc,\text{max}} \) and \( V_{dc,\text{nom}} \) in Buck and Boost modes, respectively.
The Variable DC Approach concept

Freewheel

Vref

Battery converter

Fuel cell converter

Reference

PI-controller

$V_{ref}$

$i_b$

feedback

Figure 3.4. Control of fuel cell current and DC bus voltage references Freewheel mode. "Freewheel" block indicates fuel cell converter is controlled to allow free current flow towards the DC bus.

fuel cell power control is still performed by the system. The fuel cell power control is managed indirectly via control of DC bus voltage by battery DC/DC converters. Observing the fuel cell voltage polarization curve in Figure 2.5, it can be noticed that although the fuel cell voltage varies as a function of fuel cell load, the opposite is equally applicable, i.e., the fuel cell power can also be varied as a function of fuel cell voltage. Since fuel cell voltage in Freewheel mode is equal to common DC bus voltage, the DC bus voltage can be used as a control means for fuel cell power. A decrease of DC bus voltage results in an increase of fuel cell power, whereas an increase of DC bus voltage results in a decrease of fuel cell power. Again, since the control target for the method is to achieve $i_b = 0$, this can also be managed by a simple PI-controller where the control input is the difference between actual battery current and a current reference. A control diagram for the Freewheel mode is illustrated in Figure 3.4.

The PI-controllers thus far presented in Figures 3.3 and 3.4 can be used as simple control methods to achieve the proposed Variable DC approach concept. They are quick to design and easy to use. However, for more robust system control performance, more advanced control systems for both battery DC/DC converter voltage references and fuel cell DC/DC converter current references are described in Sections 3.3 and 3.4.

3.3 Fuel cell voltage model-based control of the DC bus voltage

In the Freewheel mode of the Variable DC approach, fuel cell power is controlled via adjustments of the DC bus voltage level using a battery DC/DC converter. Since the fuel cell output terminals are directly coupled to the DC bus, control of DC bus voltage practically also means control
of the fuel cell voltage. The control of DC bus voltage is implemented with a battery DC/DC converter; thus, control of the fuel cell power is accomplished by controlling a voltage reference of the battery DC/DC converter. In [38], the battery DC/DC converter control was managed via a PI-controller. PI-controllers are known to provide good results in control of linear systems. However, as was shown in Subsection 2.2.2, fuel cell power has a non-linear relationship to fuel cell voltage. Therefore, a non-linear control system would provide better control results. This work proposes a control system based on a non-linear fuel cell voltage model. The principle of the voltage model-based controller (VMC) is described in detail in [39].

In Subsection 2.2.2, the fuel cell voltage as a function of fuel cell current was described by (2.1) - (2.4). Assuming that the constants in the voltage equation are known, the fuel cell voltage can be estimated for any fuel cell current. However, for simplification of the voltage equation, it is recommended that the concentration voltage drop described by (2.4) be neglected. Ignoring concentration losses is acceptable because they mainly occur at high fuel cell loadings, which is not a typical operation point in Freewheel mode, as shown in Figure 3.1. Since fuel cell voltage, $V_{fc}$, equals DC bus voltage, $V_{dc}$, the DC bus voltage can described as follows:

$$V_{dc} = N \left( E_{ocv} - A_a \ln \left( \frac{i_{fc}}{i_0} \right) - R_c i_{fc} \right)$$

(3.2)

In a marine power system powered by fuel cells and batteries, the power balance equation, from which losses are excluded, goes as follows:

$$P_{load} + P_{fc} + P_{es} = 0,$$

(3.3)

where $P_{load}$ is the total power of all loads, $P_{fc}$ is the total power of all fuel cell power sources and $P_{bat}$ is the total power of all batteries. From a power system control perspective, it is evident that if it is desired to use fuel cells as base power loads, the $P_{es}$ should be controlled to zero. Whenever $P_{es}$, or the actual battery current, $i_{b_{act}}$, differs from zero, the DC bus voltage should be adjusted such that the $P_{es}$ (and $i_{b_{act}}$) is brought back to zero. Since DC voltage is controlled by the battery DC/DC converter, the battery DC/DC converter should be selected by adding a voltage difference term, $\Delta V$, to actual DC bus voltage as follows:

$$V_{b_{ref}} = V_{dc} + \Delta V.$$  

(3.4)

Since $V_{b_{ref}}$ will become the DC bus voltage value, and consequently fuel cell voltage value, it can also be written using the fuel cell voltage equation as follows:

$$V_{b_{ref}} = N \left( E_{ocv} - A_a \ln \left( \frac{i_{fc_{new}}}{i_0} \right) - R_c i_{fc_{new}} \right),$$

(3.5)

where $i_{fc_{new}}$ is the new fuel cell current after the voltage adjustment. Since $i_{fc_{new}}$ is the new fuel cell current obtained by controlling $i_{b_{act}}$ to
zero, the \( i_{fc,\text{new}} \) can be described as follows:

\[
i_{fc,\text{new}} = i_{b,\text{act}} + i_{fc}.
\] (3.6)

By inserting (3.2) and (3.5) into (3.4) and solving \( \Delta V \) yields

\[
\Delta V = N \left( -A_a \left( \ln \left( \frac{i_{fc,\text{new}}}{i_0} \right) - \ln \left( \frac{i_{fc}}{i_0} \right) \right) - R_c (i_{fc,\text{new}} - i_{fc}) \right).
\] (3.7)

Using (3.6), (3.7) can be simplified as follows:

\[
\Delta V = N \left( -A_a \left( \ln \left( \frac{i_{b,\text{act}}}{i_{fc}} \right) - 1 \right) - R_c i_{b,\text{act}} \right).
\] (3.8)

By further inserting (3.8) into (3.4), the battery voltage reference becomes as follows:

\[
V_{b,\text{ref}} = V_{dc} - N \left( A_a \left( \ln \left( \frac{i_{b,\text{act}}}{i_{fc}} \right) - 1 \right) + R_c i_{b,\text{act}} \right).
\] (3.9)

In a practical application, the DC bus voltage \( (V_{dc}) \) and battery current \( (i_{b,\text{act}}) \) used in (3.9), would be available from the battery DC/DC converter. The actual fuel cell current \( (i_{fc}) \) could be sent to the VMC via fieldbus or hardwired IO communication. However, in such cases, the controller could become prone to communication errors or failures. Alternatively, a fuel cell current estimator could be used, thus improving the reliability of the controller. One way to estimate the fuel cell is to apply Newton-Rhapson method on (3.2) as follows [61]:

\[
\hat{i}_{fc} = \hat{i}_{fc,\text{prev}} - \frac{N \left( E_{ocv} - R_c \hat{i}_{fc,\text{prev}} - A_a \ln \left( \frac{i_{fc,\text{prev}}}{i_0} \right) \right) - V_{dc}}{N \left( -R_c - \frac{A_a}{i_{fc,\text{prev}}} \right)}.
\] (3.10)

By replacing \( i_{fc} \) in (3.9) by \( \hat{i}_{fc} \) estimated with (3.10), the VMC can be utilized without communication requirements from the rest of the marine power system.

In this subsection above, the target of the VMC was mentioned as being controlling the battery current \( (i_{b,\text{act}}) \) to zero, the result of which would lead to fuel cell power sources supplying the base load of the power system, whereas batteries supplying the quick power transients occurring in the common DC bus. However, in real marine applications, there may be a desire to charge or discharge batteries, e.g., to maintain the SOC at a desired level. In such cases, it would be desirable to control the battery current to an arbitrary value enabling the wanted rate of charge or discharge. Therefore, instead of using \( i_{b,\text{act}} \) as control input in (3.9), it would be more convenient to replace it with the following:

\[
i_{bc,\text{err}} = i_{b,\text{ref}} - i_{b,\text{act}},
\] (3.11)
where \(i_{b,ref}\) is a reference representing the value at which the battery current is desired in a steady state. This reference value could be, e.g., the output of an SOC controller or zero when neither charging nor discharging is wanted but instead that fuel cell units would supply the all system load.

Finally, recalling the change of rate of fuel cell current as one of the critical fuel cell requirements from Subsection 2.2.3, it would be beneficial for the VMC controller to provide a fuel cell current ramp rate control feature as well. By examining (3.9), it can be noticed that the controller constantly adjusts the DC bus voltage by a voltage difference term proportional to the control input term (i.e., \(i_{bc, err}\) or \(i_{b, act}\)). Therefore, the ramp rate control functionality can be achieved via the VMC by limiting the magnitude of prior to feeding it into (3.9). Since, the difference term is added to the DC bus voltage during each control cycle, the relationship between the maximum fuel cell current ramp rate (A/s) and the \(i_{bc, err}\) is as follows:

\[
i_{fc, ramp} = f_{ctrl} * i_{bc, err},
\]

(3.12)

where \(f_{ctrl}\) is the rate at which the difference term is added to the DC bus voltage, or, in other words, the controller task frequency (in Hz). Therefore, to achieve the wanted fuel cell current ramp rate, the control input used in the VMC should be limited as follows:

\[
i_{b, lim} = MIN \left( \frac{-i_{fc, ramp}}{f_{ctrl}}, MAX \left( \frac{i_{fc, ramp}}{f_{ctrl}}, i_{bc, err} \right) \right),
\]

(3.13)

where min and max are maximum functions used to specify the maximum decreasing and increasing ramp rates, respectively. A high-level control diagram of the proposed VMC is illustrated in Figure 3.5. The FC voltage model, the FC current estimator and the current limit refer to (3.9), (3.10), and (3.13), respectively.
3.4 Control of fuel cell DC/DC converter

The key principle of the Variable DC approach is the operation of fuel cells DC/DC converters in three different operating modes: Buck, Freewheel, and Boost. Therefore, considering these operating mode requirements and the fuel cell application requirements from Subsection 2.2.3, the following is required from the fuel cell DC/DC converter:

1. to be galvanically non-isolating
2. to be controllable to a static state in which the converter's semiconductors allow a free non-controlled flow from fuel cell towards the common DC bus
3. to be able to perform voltage step-up and step-down functionality
4. to be able to provide increasing and decreasing fuel cell current ramp control
5. to be able to perform quick fuel cell current interruption.

Both the first and second requirements stem from the Freewheel mode during which the fuel cell current is expected to freely flow towards a DC bus. Galvanic isolation (e.g., via a transformer) blocks the DC current flow, thus preventing the converter from functioning in the Freewheel mode. On the other hand, some converter topologies might be galvanically non-isolating, yet still, due to their operating characteristics, not enable free fuel cell current flow towards a DC bus. An example of such a topology is the conventional buck-boost converter with which operation at 100% duty cycle is not allowed. Voltage step-down and step-up functionalities in turn are required for Buck and Boost modes, respectively. Finally, fuel cell current ramp rate control and possibility for current interruption is critical for fuel cells generally in order to avoid fuel starvations at any conditions.

A very suitable DC/DC converter topology for fuel cell applications in Variable DC Approach concept is the topology built from back-to-back connected buck and boost converters, the topology which is illustrated in Figure 3.6. From hardware perspective, this converter topology meets each of the specified requirement. Since Buck mode is only used at low fuel cell loadings, one converter phase is sufficient for buck conversion. On the other, Boost mode is used at high fuel cell loadings; thus, three interleaved phases are utilized. In Figure 3.6, the red color is used to highlight which components of the converter conduct current during the different operation modes.

The fuel cell DC/DC converter control principle is illustrated in Figure 3.7, whereas the details of the control are presented in [62]. The controller comprises six separate control features:
The Variable DC Approach concept

Figure 3.6. Illustration of a unidirectional buck-boost converter and its current flow in a) Buck mode, b) Freewheel mode and c) Boost mode. The red color highlights which components are in use in the respective modes.

- A mode selector
- A reference controller
- A current controller
- An anti-windup
- A current ramp rate controller
- An over- and undervoltage controller

The mode selector is used to determine the Variable DC approach operation mode for the converter controller. In practice, differences in individual marine vessel requirements could lead to variations in the design of the mode selector but in principle, the mode selector should comply with (3.1). The functionality of the mode selector used in this work has been previously described in Figure 3.2.

The reference controller determines the current reference to be followed when no limitations from ramp rate or over- and undervoltage controllers
Figure 3.7. A fuel cell DC/DC converter current control diagram for the Variable DC approach. The switch $S_1$ is controlled by the output $PWM_1$, whereas the switches $S_2$–$S_4$ are controlled by the output $PWM_2$. In the figure, $D_1$–$D_4$ refer to diodes, $C_1$ and $C_2$ refer to capacitors and $L$ refers to inductor. The $K_p$ and $K_i$ are proportional and integral gains of the current controller, whereas $H_1$ and $H_2$ are the hysteresis limits of the ramp rate controller.
The Variable DC Approach concept are active. The non-limited current reference is determined as follows:

\[
i_{fc_{-DDC}}^{ref} = \begin{cases} 
  i_{fc_{-ddc}}, & \text{Freewheel mode} \\
  i_{fc_{-ddc}} + i_b_{-act} - i_b_{-ref}, & \text{Buck and Boost modes}
\end{cases}
\]  

where \( i_{fc_{-ddc}} \) is actual fuel cell DC/DC converter current. In Freewheel mode, the converter is intended to not be controlled; thus using its actual current as a reference. In buck and boost modes, the current reference settles to a value which results in the desired battery current being selected by \( i_b_{-ref} \). Generally, \( i_b_{-ref} = 0 \) in order to achieve functionality where fuel cells supply the base load of the power system, whereas batteries only power transients quicker than allowed fuel cell power ramp rates. However, for cases for which intentional charging/discharging of batteries is needed, e.g., during low/high SOCs, \( i_b_{-ref} \) could be selected to something else.

The current controller is the heart of the DC/DC converter and its role is to maintain the actual DC/DC converter current at the final reference value, i.e., the reference after all limitations are applied. In this work, the well-known PI-controller is used.

The anti-windup performs two tasks. First, like all anti-windups, it prevents an integral windup in the PI-controller by maintaining the output of the PI-controller within [-1, 1]. Secondly, it allows smooth transitions between the Variable DC approach modes by dynamically changing the minimum and maximum values of its limiter. In Buck mode, the limits of the anti-windup are [-1,0], whereas for Freewheel and Boost modes the limits are [0, 0] and [0, 1], respectively. The output of the anti-windup block is the modulation index to the PWM-modulators.

In contrast, the ramp-rate controller is used to limit the rate of change of fuel cell current. It comprises both increasing and decreasing ramp rate limiters. Whenever the rate of change of fuel cell current is within the allowed limits, the current ramp rate controller is inactive and has no impact on the operation. However, if at any time the increasing or decreasing rate of current change exceeds the allowed limits, the ramp-rate controller activates and simultaneously forces the DC/DC converter in either Buck or Boost modes, depending on whether increasing or decreasing rate of change limitation is needed.

Finally, the over- and undervoltage controller is used to raise or reduce the fuel cell current in case of DC bus over- or undervoltage. The over- and undervoltage controller comprises a limit whose minimum and maximum values are dynamically adjusted as follows:

\[
i_{fc_{-DDC}}^{max} = (U_{dc_{-max}} - V_{DC}) \times G_1
\]

\[
i_{fc_{-DDC}}^{min} = MIN ((U_{dc_{-min}} - V_{DC}) \times G_2, i_{max_{-fc}}),
\]

where \( i_{max_{-fc}} \) is the maximum allowed fuel cell current, \( U_{dc_{-min}} \) and \( U_{dc_{-max}} \) are minimum and maximum DC bus voltage values, respectively, and \( G_1 \)
and $G_2$ are gain constants used to determine the rate of current change in case of an over- or undervoltage. Whenever the DC bus voltage is within the allowed limits, the over- and undervoltage controller is inactive and has no impact on the operation.

### 3.5 The Variable DC Approach with direct on-line batteries

The Variable DC approach proposed thus far has been primarily designed for the DC-based integration concept which was previously presented in Figure 2.6a. However, as discussed in Subsection 2.3.1, some vessel types, typically those simpler in design and operational profile, can be very sensitive to total system cost and size. Such vessel types include high-speed passenger vessels [7]. Thus, the DC-based integration concept from Figure 2.7 in which the batteries are DOL-connected into a common DC bus is often found to be very attractive due to its reduced cost and the size of the power system provided by omitting the battery DC/DC converter.

Although the Variable DC approach was primarily designed for DC-based concepts with converter-controlled batteries, it can also be applied to a DC system with DOL batteries, but with certain considerations as previously presented in [46]. In the Freewheel mode, the control of fuel cell power was based on the control of DC bus voltage level by battery DC/DC converters. Since DOL batteries do not utilize DC/DC converters, active control of DC bus voltage in Freewheel mode is not possible. Therefore, the battery units must be dimensioned such that their complete operating voltage range is within the fuel cell unit-operating voltage range which falls into the Freewheel mode. The load-sharing between fuel cell units and batteries occurs via a natural voltage droop based on the fuel cell unit and battery unit impedances, as well as battery state of charge. Therefore, power transients applied to the DC bus are also divided between fuel cell units and battery units with the power ratio similarly depending on their relative internal impedances. In many cases, the power transient portion on the fuel cell unit might result in higher power steps than allowed; thus, such power transients should be avoided. Nevertheless, that is well managed by the Current ramp rate controller of the fuel cell DC/DC converter previously described in Figure 3.7. On the other hand, since power flows of neither fuel cell unit nor battery unit are controlled in the freewheel mode, the battery SOC at steady state will continuously vary depending on the total load power. This section will derive a simplified equation to describe the battery depth of discharge (DOD) as a function of load. The DOD describes the discharge level of a battery i.e., $DOD = 1 - SOC(\%)$. Finally, since the control mode flowchart presented in Figure 3.2 was designed for systems with converter-controlled batteries, it also requires a minor modification due to the lack of control of battery SOC in Freewheel mode.
An updated flowchart will be presented in this section.

A simplified equivalent circuit diagram of a fuel cell unit with a DC/DC converter and a DOL battery connected to a common DC bus is illustrated in Figure 3.8. For the sake of simplicity, the rest of the power system is modeled as a simple load with load current, $i_{load}$. The fuel cell is connected to the DC bus via a DC/DC converter, whereas the battery is DOL-connected. The switches $S_{2-4}$ and $D_1$ are dimmed due to not being in use in the Freewheel mode.

Due to the DOL connection of battery, the common DC bus voltage can be described using the battery voltage equation described in [46]:

$$V_{dc} = N_b \left( E_{b0} - R_b i_b - K_b \frac{SOC_f}{SOC_f - DOD_a} + A_b e^{B_{bat} DOD_a} \right), \quad (3.17)$$

where $N_b$ is number of battery cells connected in series, $E_{b0}$ is a voltage constant used in the equation, $R_b$ is an internal battery resistance, $i_b$ is battery current, $K_b$ is battery polarization voltage, $DOD_a$ is the instantaneous battery depth of discharge, $SOC_f$ is battery full charge capacity, whereas $A_b$ and $B_{bat}$ are empirically determined constants used to describe the voltage drop over the exponential zone of the battery polarization curve.

In a steady state, during which the total system load is supplied by fuel cells, the battery is equal to zero. Moreover, noting that the right-most term in (3.17) is significant mainly at very high SOCs which are uncommon in Freewheel mode, it is reasonable to ignore the term. Thus, the (3.17) can be simplified as follows:

$$V_{dc} = N_b \left( E_{b0} - K_b \frac{SOC_f}{SOC_f - DOD_a} \right). \quad (3.18)$$

Furthermore, since in steady state all power to the DC bus is supplied by the fuel cell unit, the common DC bus voltage can also be described as follows:

$$V_{dc} = \frac{P_{load}}{i_{fc}}, \quad (3.19)$$

where $P_{load}$ is the vessel system load power. By inserting (3.19) into (3.18)
The Variable DC Approach concept

and solving the \( DOD_{pu} = \frac{DOD_a}{SOC_f} \) yields

\[
DOD_{pu} = 1 - \frac{K_f}{E_{60}} - \frac{P_{load}}{N_{60}f},
\]

where \( DOD_{pu} \) is the depth of discharge in per unit. In other words, the equation estimates the steady-state DOD based on the system load power. It can be useful, e.g., for a vessel power management system (PMS), which can use it for decision-making tasks, such as SOC-based operation mode changes or load power control.

From control sequence perspective, the principal operation method of the Variable DC approach with DOL batteries is very similar to the one with converter-controlled batteries. The only difference between the two systems is that the SOC of DOL batteries cannot be controlled in the Freewheel mode. Therefore, SOC-based mode changes are required as shown in the flowchart illustrated in Figure 3.9, the flowchart which describes mode transitions in the Variable DC approach for DOL batteries.

![Figure 3.9. A control flowchart for the Variable DC Approach with DOL batteries. The red rhombuses and black rectangles represent control modes and mode transition conditions, respectively. The green rectangle illustrates change to the flowchart from Figure 3.2.](image-url)
3.6 A dynamic performance estimation method for fuel cell-fed marine power systems

To date, marine fuel cell applications are typically proposed to always comprise some sort of energy storage devices (usually batteries) for enhanced dynamic performance. The dynamic performance of fuel cells alone is considered insufficient for marine power system applications. Nevertheless, many vessel types which are very sensitive to system size and weight, a purely fuel cell powered system could be an advantage. However, to reliably operate such a system would require methods to estimate the performance of the system. One such method has been presented in [22] which develops an analytic method to estimate DC bus voltage dips as a function of DC bus power transients. The voltage drop is used as a performance metric for the system performance during system load transients. The method bears two interesting use cases. First, it can be used to support the design of system loads connected to a fuel cell-powered marine power system. Secondly, it can be utilized to support certain decision-making by a vessel PMS. Such decisions could include

- coordination of starting and stopping of fuel cell units according to system load requirements,
- prevention of start-up of large load consumers during times when system performance is estimated as no sufficient for the added load,
- coordination of load shedding strategy due estimation of weakened system performance.

The estimation method is described in the following.

As has been shown in Subsection 2.3.1, fuel cell integration into DC-based distribution systems is typically managed by DC/DC converters. The common DC bus, into which the power sources couple, typically comprise capacitor banks in order to maintain a steady voltage for power distribution. Therefore, from the well-known capacitor voltage equation, the following equation can be written to describe the relationship between DC bus voltage, power source supply power, and load consumption power:

\[
C_{bus} \frac{dV_{dc}(t)}{dt} = \left( \sum_{j=1}^{J} p_{s,j}(t) - \sum_{m=1}^{M} p_{l,m}(t) \right) v_{dc}(t),
\]

where \( C_{bus} \) is total DC bus capacitance, \( t \) is time, \( J \) and \( M \) are total number of connected power sources and loads, respectively, \( p_{s,j} \) is instantaneous power of power source \( j \) and \( p_{l,m} \) is instantaneous power of load \( m \). By rearranging (3.21) and applying integration from the beginning of the power transient until the end of the transient, the following equation is
The Variable DC Approach concept obtained:

\[ C_{bus} \int_{v_i}^{v_f} v_{dc}(t) du(t) = \int_{t_i}^{t_f} \left( \sum_{j=1}^{J} p_{s,j}(t) - \sum_{m=1}^{M} p_{l,m}(t) \right) dt, \]  

(3.22)

where subscripts i and f refer to the instants at beginning and end of the power transient, respectively.

From (3.22), it can be observed that any change in DC bus voltage only occurs when the source power is unequal to the load power. During a power transient (e.g., a load increase), the system power balance is temporarily left unsatisfied, resulting in the variation of DC bus voltage. Therefore, instead of describing the DC bus voltage variation using absolute values, it is more convenient to describe it using the changes in power sources and load powers as follows:

\[ C_{bus} \int_{v_i}^{v_f} v_{dc}(t) du(t) = \int_{t_i}^{t_f} \left( \sum_{j=1}^{J} \Delta p_{s,j}(t) - \sum_{m=1}^{M} \Delta p_{l,m}(t) \right) dt \]  

(3.23)

where \( \Delta \) refers to a change in the powers. However, for the system to eventually recover from the transient, the total change in source power must eventually match the total change in load power; thus, the following power balance equation can be written:

\[ \sum_{j=1}^{J} \Delta p_{s,j}(t) - \sum_{m=1}^{M} \Delta p_{l,m}(t) = 0. \]  

(3.24)

Usually in marine applications, it is unknown which of the loads will be the cause of a power transient. Thus it is convenient to write the total power transient as follows:

\[ \Delta P_{l} = \sum_{m=1}^{M} \Delta p_{l,m}(t), \]  

(3.25)

where \( \Delta P_{l} \) is the total change in load power. Additionally, instead of projecting a time-dependent change in load power, it is convenient to assume a worst-case scenario during which a load power transient instantly occurs. Furthermore, recalling that this method is designed specifically for fuel cell power sources, it is convenient to replace the \( p_{s,j} \) in (3.24) by fuel cell voltage from (2.1) multiplied by fuel cell current. Thus, by inserting (3.25) into (3.24) and rearranging, the following is obtained:

\[ \sum_{j=1}^{J} \Delta (E_{fc,j} i_{fc,j}) = \Delta P_{l}. \]  

(3.26)

As was discussed in Subsection 2.2.2, the fuel cell voltage behavior as a function of current is highly non-linear owing to the voltage drops related
The Variable DC Approach concept to activation and concentration. The non-linearity is most visible at very low and very high current values, whereas for most of the operating range the trend becomes almost linear. As was established earlier in Section 3.3, operation at very high fuel cell current values is usually unwanted due to the significant decrease of fuel cell efficiency resulting from concentration losses. Thus, it is appropriate to neglect the concentration losses. On the other hand, due to activation losses being dominant mostly at very low current values, it is convenient to linearize the voltage drop, e.g., by using the first order Taylor polynomial as follows:

\[ E_{\text{lin}}^{i,j} = N_{f_{c,j}} \left( A_{a,j} \left( \ln \left( \frac{a_j}{i_{0,j}} \right) - 1 \right) - \left( \frac{A_{a,j}}{a_j} + R_{c,j} \right) i_{f_{c,j}} \right), \]  

(3.27)

where \( a_j \) is the current value about which the activation voltage is linearized. Compared to the non-linear voltage equation, the linearized equation is much simpler to use in estimation of the fuel cell power changes used in (3.26).

Observing (3.26), the fuel cell voltage and current are expressed as changes of voltage and current, instead of absolute values. Since fuel cell voltage varies as a function of current, the change of current will also determine the change of voltage. In Subsection 2.2.3, it was discussed that due to the fuel cell characteristics, their current is typically ramped up using a certain ramp rate which depends on the design of the complete fuel cell unit and is typically provided by fuel cell manufacturers in product datasheet. The compliance to the current ramp rates is typically ensured by the DC/DC converter connected to the fuel cell output terminals. Therefore, during fuel cell current transients, the fuel cell current can be expressed as a function of the duration of the transient as follows:

\[ i_{f_{c,j}}(\Delta t) = i_{f_{c,j}}^{\text{init}} + r_{c,j} \Delta t, \]  

(3.28)

where \( i_{f_{c,j}}^{\text{init}} \) is the fuel cell current at the first instant of the transient, \( r_{c,j} \) is the maximum allowed fuel cell current ramp rate and \( \Delta t = t_{f} - t_{i} \) is the duration of the transient. The \( r_{c,j} \) is selected positive for increasing current and negative for decreasing current. Therefore, using (3.27) and (3.28), the estimated fuel cell power at the end of the transient is

\[ \hat{P}_{f_{c,tot}}(\Delta t) = B_{f_{c,j}} \Delta (t)^2 + C_{f_{c,j}} \Delta (t) + D_{f_{c,j}}, \]  

(3.29)

where \( B_{f_{c,j}}, C_{f_{c,j}} \) and \( D_{f_{c,j}} \) are constants derived by fuel cell voltage model parameters as follows:

\[ B_{f_{c,j}} = - \sum_{j=1}^{J} \left( \frac{A_{a,j}}{a_j} + R_{c,j} \right) r_{c,j}^2, \]  

(3.30)

\[ C_{f_{c,j}} = \sum_{j=1}^{J} N_{f_{c,j}} \left( E_{ocv,j} - A_{a,j} \left( \ln \left( \frac{a_j}{i^{\text{init}}_{f_{c,j}}} \right) - 1 \right) - 2 \left( \frac{A_{a,j}}{a_j} + R_{c,j} \right) i_{f_{c,j}}^{\text{init}} \right) r_{c,j}, \]  

(3.31)
The Variable DC Approach concept

\[
D_{fc,j} = \sum_{j=1}^{J} N_{fc,j} \left( E_{ocv,j} - A_{a,j} \left( \frac{a_j}{b_{o,j}} \right) - 1 \right) - \left( \frac{A_{a,j}}{a_j} + R_{c,j} \right) \left( i_{fc,j}^\text{init} \right)^{i_{fc,j}^\text{init}}, \quad (3.32)
\]

Thus, to obtain the change in total fuel cell power during the power change, the initial fuel cell power at the start of the transient must be subtracted from the estimated fuel cell power at the end as follows:

\[
\sum_{j=1}^{J} \Delta p_{a,j}(t) = B_{fc,j} \Delta(t)^2 + C_{fc,j} \Delta(t) + D_{fc,j} - P_{fc_{\text{tot}}}^\text{init}, \quad (3.33)
\]

where \( P_{fc_{\text{tot}}}^\text{init} \) is the total initial fuel cell power at the start of the transient.

By inserting (3.33) and (3.25) into (3.24), the power balance equation becomes

\[
B_{fc,j} \Delta(t)^2 + C_{fc,j} \Delta(t) + D_{fc,j} - P_{fc_{\text{tot}}}^\text{init} = \Delta P_l \quad (3.34)
\]

from which the duration of the transient (i.e., \( \Delta t \)) can be solved. The equation has two solutions but the one which is positive and closer to zero should be selected due to it representing the first instance when the power supply meets demand after the transient. The solution to (3.34) is

\[
\Delta t = -C_{fc,j} + \sqrt{C_{fc,j}^2 - 4B_{fc,j} \left( D_{fc,j} - P_{fc_{\text{tot}}}^\text{init} - \Delta P_l \right)} \quad (3.35)
\]

Finally, with a solution to \( \Delta t \), it is possible to return to (3.22) and solve it as well. Hence, insertion of (3.25) and (3.33) into (3.23), followed by integration of both sides of (3.23) yields

\[
\frac{1}{2} C_{bus} \left( v_f^2 - v_i^2 \right) = \frac{B_{fc,j} \Delta t^3}{3} + \frac{C_{fc,j} \Delta t^3}{2} + \left( D_{fc,j} - P_{fc_{\text{tot}}}^\text{init} - \Delta P_l \right) \Delta t \quad (3.36)
\]

from which the voltage at the end of the transient can be solved as follows:

\[
v_f(\Delta P_l) = \sqrt{2 \left( \frac{B_{fc,j} \Delta t^3}{3} + \frac{C_{fc,j} \Delta t^3}{2} \right) + \left( D_{fc,j} - P_{fc_{\text{tot}}}^\text{init} - \Delta P_l \right) \Delta t} + u_i^2 \quad (3.37)
\]

However, it should be recalled during derivation of (3.37), the load transient was assumed to be step-like in nature which is a reasonable consideration since many system power transients can be unexpected, therefore, proving the worth in considering a worst-case scenario. On the other hand, as was mentioned in the beginning of this subsection, one interesting use case for this method is the support of decision-making by a vessel PMS. In such an application, a load transient may also be an expected event, e.g., due to the start-up or shut-down of a large power consumer. During such an event, the load transient might not be step-like in nature, but instead follow a certain rise time, \( \tau_L \), which is already known in advance. For such cases, it
The Variable DC Approach concept is more convenient to substitute $\Delta P_l$ (3.37) with $(1 - \tau_L) \Delta P_l$, which would yield

$$v_f(\Delta P_l) = \sqrt{2 \frac{B_{fc,j} \Delta t^3}{3} + \frac{C_{fc,j} \Delta t^3}{2} + \frac{D_{fc,j} P_{fc,init} - (1 - \tau_L) \Delta P_l}{C_{bus}} \Delta t} + u^2. \quad (3.38)$$

By using (3.38) together with (3.35), the level to which the DC bus voltage dips following a system power transient can be estimated. The voltage dip works as an important metric for evaluation of system performance against system load power transients. It can be noticed that aside from the fuel cell parameters and magnitude of the load power transient, other important variables impacting the DC voltage drop are initial fuel cell operating power, DC bus capacitance, fuel cell current ramp rate, and initial DC bus voltage.
4. Method of concept validation

4.1 Hardware-in-loop simulation

Chapter 3 laid forth the Variable DC approach concept which was proposed for improved powertrain efficiency of fuel cell-powered marine power systems. The chapter presented the basic principles of the concept and control systems required to operate a system utilizing the concept. However, after having presented the theoretical background of the proposed concept, the concept validation method must also be discussed. This section describes the marine power system test setup used for concept validation. The setup is based on real-time hardware-in-loop simulation technology.

A marine power system is a complex entity often referred to as a system of systems due to the vast amount of different systems integrated together to perform a wanted set of onboard functionalities; the most notable, of course, being the generation of vessel thrust. In the maritime sector, document-based systems engineering (DBSE) has historically been a common practice for system design. In such a design approach, documents are the main deliverable of the system analysis. They describe the functionality of the system and evaluate its feasibility. The reason for the earlier popularity of the DBSE has primarily been the infeasibility of using real systems for validation prior to the actual ship build. Naturally, the lack of real system testing has forced the actual system validation to occur after the ship-build during the first operational trials. As complementary to the DBSE, model-based systems engineering (MBSE) has been proposed [63]. In the MBSE approach, digital models, instead of the documents, are considered the main deliverable of the system analysis. By providing a good representation of the physical devices, the digital models, can be used for early-stage system validation via simulation long before the start of the ship build. In that way, potential design shortcomings can be identified and rectified early in the system design phase, thus enabling a more cost-efficient and reliable design process.
However, although a very necessary early-stage step in the ship power system design, pure simulation alone is rarely a sufficiently accurate representation of an actual physical system, resulting in it potentially being unable to provide the desired system validation results. On the other hand, as mentioned above, having a real marine power system test setup can be unreasonably challenging due to a very high investment cost. Therefore, a good compromise between pure simulation-based testing and real system testing, is found in the real-time HIL simulation technology [64]. The HIL simulation technology as means of control system validation is already a widely used method in the aerospace and automotive industries and can also be applied to marine power system control [63]. In this research, a HIL simulation-based marine testbed is implemented as a validation method for the proposed Variable DC Approach concept. In the HIL simulation applied in this work, the electrical and mechanical aspects of the studied marine power plant are virtually modelled using pre-validated power component models, whereas digital logic containing marine power system controllers are applied using real hardware. The combination of real hardware and detailed virtual models provides a credible validation environment for the proposed control systems of the Variable DC Approach concept.

4.2 Marine power system Implementation in the Hardware-in-loop setup

The schematic diagram of the real-time HIL-based test setup used in this research is presented in Figure 4.1. The system comprises two fuel cell units, a battery unit, a propulsion motor, and a generic hotel load. The fuel cell units are connected to a common DC bus via a DC/DC converter described in Section 3.4, whereas the battery is connected to the DC bus via a conventional three-phase interleaved boost converter. The propulsion motor and the hotel load are supplied from the common DC bus via three-phase VSIs.

In the test setup, the power stage (i.e., power carrying components) is simulated using two Typhoon HIL-604 simulators. The simulation step used in the simulation is $1\mu s$. Two HES880 and one ACS880 converter control units from ABB are connected to the HIL simulators for control of the virtually simulated power converter power stages. One HES880 converter control unit is used to control the battery DC/DC converter; therefore, it is equipped with a DC/DC converter control firmware. Another HES880 unit is used to control the motor supplying VSI resulting in it being equipped with an electrical machine control firmware. Finally, the ACS880 converter is used to control the hotel load supplying VSI; thus, it is equipped with a grid control firmware.
4.2.1 Power sources

A battery and a DC/DC converter are illustrated in Figure 4.2. The battery model and its parameters are described in [39]. The virtual DC/DC converter is controlled by a HES880 converter control unit equipped with a DC/DC converter control firmware. The control unit receives DC link voltage and battery side current measurements as $\pm10V$ analog signals. Based on the measurement feedbacks, the control unit sends six $\pm5V$ control signals to the HIL simulator for control of the converter switches. For simulations in which DOL batteries are used, the DC/DC converter and the HES880 control unit are excluded. Moreover, in this research DOL batteries have a higher DC voltage than converter-controlled batteries; thus, their parameters slightly differ from those used in converter-controlled batteries. The DOL battery parameters are described in [46].

A fuel cell and a DC/DC converter are illustrated in Figure 4.3. The fuel cell model and its parameters are described in [46]. The DC/DC converter is a back-to-back connected buck and interleaved boost converter. It is controlled by a digital control system implemented in the same HIL simulators in which the electrical models are also run. The sample time of the control system is 1 $\mu$s. The details of the control system have been described in Section 3.4.
Method of concept validation

Virtual HIL model

HES880 control unit

Real control hardware

Virtual HIL model

Current meas. ±10V

Gate pulses ±5V

Voltage meas. ±10V

Figure 4.2. A battery and HES880 DC/DC converter in loop.

Virtual HIL model

Fuel cell model

Control system from Section 3.4

Figure 4.3. A fuel cell and DC/DC converter control system.

4.2.2 Loads

A propulsion motor and a VSI are illustrated in Figure 4.4. The virtual motor model is an induction motor connected to a vessel propeller. The motor parameters and propeller characteristics are described in [39]. The virtual VSI is controlled by a HES880 converter control unit equipped with a motor inverter control firmware. The physical interface between the motor model and the HES880 converter control unit is the same as that described in Subsection 4.2.1.

A grid converter comprising an LCL-filter is illustrated in Figure 4.5. The virtual grid converter is controlled by an ACS880 converter control system equipped with an optimal grid control firmware. The ACS880 converter control system comprises a main control unit, an interface unit, and a measurement unit. The main control software runs in the main control unit, whereas the interface unit functions as a power stage interface between the main control unit and the converter switches. The physical interface between interface unit and the converter model is the same as that above described for HES880 converter control units. However, in addition to the DC link voltage measurements and output AC current measurements, the
4.2.3 Energy loss models for energy efficiency estimation

A key design target for the Variable DC Approach concept is the improvement of total power train energy efficiency compared to the state-of-art operating methods. Since the concept performance is validated using a real-time HIL setup, proper loss models are needed to evaluate the system energy efficiency. To that end, this work utilizes the energy loss models described in [38, 39]. The energy loss models are pre-validated models that utilize data, typically found in component manufacturer datasheets. Each energy loss model parameter used in this work is presented in [38].
Figure 4.6. The real-time HIL setup used for validation of the system control methods proposed in this work.

4.3 The HIL-based marine power system test setup

An overview of the HIL-based marine power system setup used in this research is illustrated in Figure 4.6. In general, the HIL setup comprises HIL simulation hardware, control equipment, as well as a supervisory control and data acquisition (SCADA) system. A more detailed view of the HIL simulators is presented in Figure 4.7a. The figure comprises three Typhoon HIL simulators and three HIL-Connect devices. The HIL-Connect devices function as signal conditioners between the simulators and the connected control hardware under test. Furthermore, the interiors of the control system cabinets are shown in Figure 4.7b. The control cabinet comprises various ABB hardware used for control of fuel cell, battery, generator and propulsion systems. However, as described in Section 4.2, this research only utilizes the ACS880 and HES880 converter control systems. Finally, a generic illustration of the SCADA system is presented in Figure 4.8. The SCADA system comprises an ABB PEMSTM on the left and the Typhoon HIL SCADA on the right. In this research, all high-sampled data was obtained using the Typhoon HIL SCADA, whereas the PEMS SCADA is only for high-level performance monitoring.
Method of concept validation

Figure 4.7. a) The Typhoon HIL604 simulators used in this work, and b) the interior of a control cabinet comprising converter control units used in this work. The HIL lab comprises four identical control cabinets.

Figure 4.8. Illustration of the HIL SCADA system. The SCADA shown on the right is that of the Typhoon HIL simulator, whereas the one on the left is that of the ABB Power and Energy Management system (PEMS™).
5. Application and results

This chapter presents results obtained using the real-time HIL setup described in Chapter 4. The results have been obtained from the operational tests performed in publication works compiled in this dissertation. The first section provides results on the Variable DC approach operation during normal conditions with both converter-controlled and DOL batteries. Additionally, the section provides results on the accuracy of the voltage DIP estimation method as a function of load power transients. The second section presents results on impacts the Variable DC approach concept has on total power system efficiency and fuel cell current ripple. Finally, the operating performance of the proposed system during fault conditions are presented in the third section. The results will mainly focus in the Free-wheel mode due to it being the unique mode characterizing the Variable DC approach concept, whereas the Buck and Boost modes are conventional modes well-known in the industry and literature.

5.1 System operation during normal operating conditions

The specialty in the Variable DC approach concept is the utilization of Freewheel mode in which fuel cells systems mimic DOL operation by keeping fuel cell DC/DC static to allow a free current flow between fuel cells and a common DC distribution bus. The power of fuel cells is controlled by varying the common DC bus voltage. This section presents the functionality of the Variable DC approach during normal operating conditions, i.e., situations in which no unexpected system failures have occurred.

5.1.1 Operation with converter-controlled batteries

In this subsection, the marine power system comprises a fuel cell unit with a DC/DC converter and a battery unit with a DC/DC converter and a VSI-fed propulsion motor and a VSI-fed hotel load. The power and voltage waveforms of the said system during normal operation are presented in
Application and results

Figure 5.1. Illustration of power and voltage waveforms of the system operating in the Variable DC approach during normal operating conditions. Color-coding in the background is used to highlight the different operating modes: Buck (blue), Freewheel (green) and Boost (red).

Figure 5.1. In the figure, color-coding in the background is used to highlight the different operating modes; Buck (blue), Freewheel (green) and Boost (red). In the examined operation case, the magnitude of the hotel load is kept at a constant 15kW, whereas the magnitude of the propulsion load is varied to alter the system operating condition.

At the beginning of the event presented in Figure 5.1, the propulsion load is zero and the total auxiliary load is supplied by the fuel cell unit. Due to the fuel cell voltage being above 775V, the system is in Buck mode. The fuel cell DC/DC converter is tuned to limit the fuel cell current ramp rate to 10%/s. At 5s, the propulsion load starts to increase; thus, an increase of fuel cell power is initiated as well. At 8s, fuel cell voltage drops below 775V and the system enters Freewheel mode. To maintain increasing fuel cell power, the DC bus voltage is decreased until at 14s, fuel cell voltage drops below 650V; thus propelling the system into Boost mode. During the period between 5s - 14s, the propulsion power ramp rate is higher than the maximum allowed ramp rate for the fuel cell unit, therefore creating a power mismatch between the total load power and fuel cell power. To preserve a balance in power generation and consumption, the said mismatch is compensated by the battery unit. At 22s, the decrease of propulsion load is initiated, simultaneously causing the fuel cell power to start to decrease, whereas the fuel cell voltage increases. At 25s, the fuel voltage exceeds 650V, thus returning the system to Freewheel mode. To maintain decreasing fuel cell power, the DC bus voltage is increased until
the system reaches a steady state at 27s. At 32.5s, another propulsion load decrease is initiated with the target to bring it to zero. The DC bus voltage is again increased to achieve decreasing fuel cell power until at 34s the fuel cell voltage exceeds 775V, thus returning the system to Buck mode.

Based on the examined operation, the Variable DC Approach is seen to perform well during normal operation conditions. The transitions between the different modes are seen to be smooth without causing any potentially harmful power transients on the fuel cell output. Furthermore, it is seen that although fuel cell power is not converter-controlled in Freewheel mode, the maximum allowed fuel cell ramp rates are also respected in that mode. This is managed by controlling the rate of change of the DC bus voltage.

5.1.2 Control of parallel operating fuel cell systems with differing voltage characteristics

The previous subsection presented the normal operation of a system with only one fuel cell system. In theory, in the case of more fuel cell systems with identical ratings and design parameters being connected in the power system, the behavior of the system would be the same but with the exception that the total fuel cell power would be equally shared between all the parallel operating fuel cell systems. However, in practical systems, the fuel cell systems might not always be identical, even if they were intended to be during their design phases. It is common that over time during operation, the fuel cells experience voltage degradation. The degradation rarely occurs at the same rate for all fuel cells, commonly and potentially resulting in the voltage polarization curves of different fuel cell units significantly differing from each other. In Freewheel mode, differing voltage characteristics between fuel cell units will result in uneven load-sharing between the units. In order to analyze the behavior of a system comprising more than one fuel cell unit, the setup from previous subsection is expanded with another fuel cell unit with a DC/DC converter. In addition, to mimic a degree of performance degradation, the voltage characteristics of the added fuel cell unit is reduced by 5%. The power and voltage waveforms of the system during normal operating conditions is illustrated in Figure 5.2. The event in the figure starts with both fuel cells being Freewheel mode, thus having equal output voltage in line with DC bus voltage. In the figure, Fuel cell 1 represents the degraded fuel cell unit with its output power being lower than that of Fuel cell 2. At ~2s, the total system load is reduced and the total fuel cell power is seen to also reduce to accommodate the new load. However, at 6s, the degraded fuel cell unit is forced to Boost mode, and the current reference of the its DC/DC converter is set equal to the actual current of Fuel cell 2. The voltage of Fuel cell 1 drops below that of Fuel cell 2 and DC bus voltage, in that way achieving an equal load-sharing between the fuel cell units. At 15s, the Fuel cell 1 is allowed
to return to Freewheel mode; thus settling its voltage to the same as that of Fuel cell 2 and the DC bus. Concurrently, the small difference returns between the powers of the two fuel cell units.

Based on the examined operation, it is clear that more than one fuel cell systems can be parallel-operated with the Variable DC approach, even in cases in which the fuel cells have differing voltage characteristics. Although differences in fuel cell voltage characteristics lead to uneven load-sharing in the Freewheel mode, they do not cause any disturbance in the system performance. Should, for any reason, equal load sharing be a necessity in the system, it can always be achieved by forcing the degraded fuel cell system into Boost mode, as shown in Figure 5.2.

### 5.1.3 Operation with DOL batteries

The Freewheel mode of the Variable DC approach concept relies heavily on converter-controlled energy storage systems to perform fuel cell power control via common DC bus voltage control. Since DOL-connected batteries do not comprise DC/DC conversion devices, they cannot actively control the DC bus voltage, resulting in active fuel cell power control in the Freewheel mode also not being possible. Instead, the common DC bus voltage is always determined by the DOL-connected batteries’ voltage which, in contrast, depends on the battery current, the SOC, and battery characteristics...
i.e., the number of series connected cells and internal impedance.

In order to analyze the behavior of a system comprising DOL batteries and operating in the Variable DC approach, the HIL setup was modified by removing the DC/DC converter between the battery unit and DC bus. The power, voltage, and current waveforms of the system during normal operating conditions is illustrated in Figure 5.3. Figure 5.3a illustrates operation in Buck and Freewheel modes, whereas Figure 5.3b illustrates operation in Freewheel and Boost modes. In Figure 5.3a, the system starts in Buck mode at zero load. Between 2s and 7.5s, the system load is first increased to 30kW and then decreased to 10kW. The fuel cell unit in Buck mode follows the load variation with the target of maintaining battery power at zero load. At 10s, the system load is increased to 80 kW, the increase which is also followed by the fuel cell unit. The fuel cell power increase leads to the fuel cell voltage decreasing to below $V_{dc\_max}$; thus, the fuel cell unit enters the Freewheel mode. In Freewheel mode, the fuel cell power is no longer controllable; hence, load-sharing between the fuel cell unit and battery unit is determined based on their voltage characteristics and the battery SOC. Therefore, when the load power increases, the powers of both fuel cell and battery similarly increase, whereas the opposite occurs when the load power decreases. However, it should be noted that since the battery SOC tends to decrease (increase) when discharging (charging), the battery power always eventually drifts to zero in the steady state. At 28s, the load power decreases back to 30 kW, which results in the fuel cell power increasing above $V_{dc\_max}$, thus returning the fuel cell unit to Buck mode.

In Figure 5.3b, the system starts in Freewheel mode and the load power is 150kW. At 3s, the load power is increased to 210kW. The power increase leads to the DC bus voltage dropping to $V_{dc\_min}$, thus propelling the fuel cell unit into Boost mode where the fuel cell power is again controllable. Therefore, the control target to maintain battery power at zero load is again manageable. At 23s, the load power is decreased back to 150kW. In an attempt to control the battery power to zero, the fuel cell voltage exceeds $V_{dc\_min}$ (at 28s), thus returning to Freewheel mode.

Based on the illustrated operation, it is apparent that DOL batteries can perform well in the Variable DC approach concept during normal operating conditions. The Buck and Boost modes function similarly to converter-controlled batteries, with the only difference being that the DC bus voltage varies according to the battery voltage. Therefore, instead of being fixed at $V_{dc\_max}$ and $V_{dc\_nom}$ in Buck and Boost modes, respectively, it can be anything within $V_{dc\_min}$ and $V_{dc\_max}$ depending on the battery SOC and power. In contrast, the Freewheel mode significantly differs from operation with converter-controlled batteries due to the lack of control of both fuel cell and battery power. Nevertheless, despite this lack of power control, the required system power balance is well managed.
5.1.4 Estimation of DC bus voltage dips as function system power transients

The proposed voltage dip estimation method was validated using the HIL setup with a marine power system comprising two fuel cell units and two different hotel loads: a DC/DC converter-supplied DC load hotel load and a DC/AC converter-supplied AC load. Results from two different tests are presented in this subsection. In the first test, only one fuel cell unit is used to power the system, whereas in the second test, the system is powered by two fuel cell units. The nominal power of the fuel cells is 150kW and their design parameters are presented in [22]. The nominal DC bus voltage is 750V, whereas the minimum allowed DC bus voltage is 600V. In both tests, three load power transients of different magnitude are applied to the system: 6.67kW, 10kW, and 12.5 kW. The power transients are created by quick increases in the DC load, whereas the AC load is maintained at constant. The voltage dips for each power transient is estimated using the proposed voltage dip estimation method and compared to those obtained using the real-time HIL system.

The test results of the first test are presented in Figure 5.4. In the figure, the measured DC bus voltage, fuel cell power, DC load, and AC load are illustrated in red, green, blue, and orange lines, respectively. For each power transient, the DC bus voltage dip level is estimated using
Application and results

Figure 5.4. Estimated voltage dips during appliance of three different power transient steps: 6.67 kW at 0.5 s, 10 kW at 3 s, and 12.5 kW at 7 s. Only one fuel cell unit is running.

The test results of the second test are presented in Figure 5.5. The graphs and marks in the figure are the same as in Figure 5.4 but with the addition of the second fuel cell power which is illustrated with a pink line. This time, with added power supply capacity, none of the power transients result in the voltage drop reaching the minimum allowed power limit. Instead, the voltage dip levels are estimated with a good accuracy (error within 1.1% of nominal voltage) during all three power transients. The results from
Table 5.1. Comparison of the estimate voltage dip values to those obtained via the HIL system. The difference between estimated and measured value (rightmost column) is given as a percentage of the nominal DC bus voltage.

<table>
<thead>
<tr>
<th>Test</th>
<th>Load transient</th>
<th>Voltage dip in HIL system</th>
<th>Estimated voltage dip</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.67 kW</td>
<td>698 V</td>
<td>707 V</td>
<td>1.2 %</td>
</tr>
<tr>
<td></td>
<td>10 kW</td>
<td>665 V</td>
<td>659 V</td>
<td>0.8 %</td>
</tr>
<tr>
<td></td>
<td>12.5 kW</td>
<td>600 V</td>
<td>570 V</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>6.67 kW</td>
<td>724 V</td>
<td>732 V</td>
<td>1.1%</td>
</tr>
<tr>
<td></td>
<td>10 kW</td>
<td>712 V</td>
<td>732 V</td>
<td>0.6 %</td>
</tr>
<tr>
<td></td>
<td>12.5 kW</td>
<td>665 V</td>
<td>665 V</td>
<td>0</td>
</tr>
</tbody>
</table>

both tests are summarized in Table 5.1. The table shows that the error between the values estimated with the proposed estimation method and the values obtained with the HIL system are less than 1.2%. For the third load step of first test, the difference between estimated value and value obtained from HIL setup is marked as not applicable (N/A) because of the mentioned interruption from the DC/AC converter.

5.2 Advantages of the Variable DC Approach

The Variable DC Approach concept was designed to improve powertrain energy efficiencies of fuel cell-powered marine LV DC power systems. The improved energy efficiency is achieved via operation in Freewheel mode during which semiconductor switches in fuel cell DC/DC converters are maintained static, thus eliminating the DC/DC converter switching losses.
This section presents results on the improving impact the Freewheel mode has on the total powertrain energy losses. Additionally, the section provides results on the reducing impact the Freewheel mode has on high-frequency ripple content on the fuel cell output current. The reduced high-frequency current ripple was not a main design target for the Variable DC Approach concept but is, nevertheless, a highly appreciated additional benefit of the concept.

5.2.1 Powertrain efficiency

The powertrain energy efficiency for the HIL system operating in Variable DC Approach is illustrated in Figure 5.6. The figure shows a single fuel cell unit and a battery unit powering a propulsion load at different loads, and consequently, in different Variable DC Approach operating modes. All sources and loads are converter-controlled. The top, middle, and bottom plots in the figure illustrate the power, voltage, and power loss waveforms of the system. The losses in the bottom graph comprise total power losses occurring in the powertrain devices between the power sources and the propulsion motor (i.e., fuel cell DC/DC converter, battery DC/DC converter and the propulsion motor inverter. Background color-coding is used to highlight the active Variable DC Approach operating mode.

The system operation in the figure starts at low power, hence, in Buck mode. The total powertrain losses are about 5.5% of system load power. At 2.5s, the propulsion load is increased, leading to an increase in fuel cell power and a consequent decrease in fuel cell voltage. At 5s, the fuel cell voltage drops to below $V_{dc_{-}max}$ (775V); thus, the system enters Freewheel mode. The mode transition leads to a significant drop in the power losses, the losses which settle to below 3% of load power. The delay between the time the mode transition occurs and the drop in power losses is due to the high-power battery discharging, which creates a temporary increase of power losses in the battery DC/DC converter. Between 10s and 30s, the load is increased further to illustrate losses behavior at higher loading but still in Freewheel mode. It can be observed that the low power losses level is maintained over the whole Freewheel mode operating range. At 31s, the total load has increased to such an extent that the fuel cell voltage has dropped below $V_{dc_{-}min}$ (650V); thus, the system enters Boost mode. At the time of the transition, a brief power spike is visible in the battery power, the spike which occurs due to the rapid increase of DC bus voltage to $V_{dc_{-}nom}$ (720V). Since the DC bus comprises capacitors, the voltage increase requires a brief power-spike to build up energy in the capacitors. In the Boost mode, the power losses increase to above 4% of load power. At 51s, the load is again decreased and, at 56s, the system returns in Freewheel mode where the power losses are again decreased to about 2.6% of load power.
Application and results

To further analyze the powertrain efficiency, the HIL system was operated at different loading points in both the Variable DC Approach and a fixed DC bus voltage. The fixed DC bus voltage was selected as $V_{dc,nom}$. The results are presented in Table 5.2. The rightmost column in the table shows the difference in power losses between the Variable DC Approach and the fixed DC approach. It can be observed that up to 28% improvement in total power train efficiency. The efficiency improvements are primarily due to operation in the Freewheel mode. Nevertheless, noticeable improvement can be observed in the Buck mode as well. The improved efficiency in Buck mode is mainly due to the reduced losses in the fuel cell DC/DC converter. With the Variable DC approach, the DC bus voltage in Buck mode is higher (775V) than that with the Fixed DC approach (720V); therefore, less voltage conversion is needed from the fuel cell DC/DC converter. The reduced voltage stress enables lower losses mainly in the DC/DC converter filter. On the other hand, the increased DC bus voltage with the Variable DC Approach leads to slightly higher voltage stress in the motor inverter, thus resulting in slightly higher load converter losses than if operating
Table 5.2. Comparison of Variable DC approach powertrain losses in steady-state to those of a conventional Fixed DC bus voltage system. FC denotes fuel cell, whereas conv. and diff. are short for converter and difference.

<table>
<thead>
<tr>
<th>FC power (kW)</th>
<th>Losses with the fixed DC approach</th>
<th>Losses with the Variable DC approach</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC conv. (kW)</td>
<td>Load conv. (kW)</td>
<td>Operation mode</td>
</tr>
<tr>
<td>25</td>
<td>0.87</td>
<td>1.05</td>
<td>Buck</td>
</tr>
<tr>
<td>55</td>
<td>0.97</td>
<td>1.55</td>
<td>Buck</td>
</tr>
<tr>
<td>102</td>
<td>1.46</td>
<td>2.39</td>
<td>Boost</td>
</tr>
<tr>
<td>133</td>
<td>1.66</td>
<td>2.71</td>
<td>Boost</td>
</tr>
<tr>
<td>161</td>
<td>2.63</td>
<td>3.42</td>
<td>Boost</td>
</tr>
<tr>
<td>188</td>
<td>4.05</td>
<td>3.90</td>
<td>Boost</td>
</tr>
</tbody>
</table>

with the Fixed DC bus voltage. Nevertheless, the reduction in fuel cell converter losses is higher than the increase in load converter losses, thus rendering the Variable DC Approach the more efficient of the two. Contrastively, in Boost mode, both concepts operate at nominal voltage, thus resulting in the behavior of losses being identical.

Based on the results presented thus far in Figure 5.6 and Table 5.2, it is clear that the Variable DC Approach enables significant improvement of total powertrain energy efficiency. The meaningful efficiency improvements occur mainly in the Freewheel mode in which the fuel cell DC/DC converter switching losses are eliminated. The same conclusion can be further observed in the powertrain efficiency map illustrated in Figure 5.7. The efficiency map is created by operating the HIL system at different operating points and calculating the powertrain efficiency at different operating points. In the efficiency map, the blue-colored area shows the operating points with the highest powertrain efficiency as a function of DC bus voltage and load power. The magenta line illustrates the Freewheel mode operating points which are well within the optimal operating area. The white area in the bottom right corner indicates operating points at which the DC bus voltage is insufficient to produce sufficiently high motor voltage for the required power, thus prohibiting operation in that area.

### 5.2.2 Fuel cell current ripple

Ideally, the magnitudes of fuel cell output current and voltage would be constant with a constant load. However, power conversion devices and uneven loads tend to induce current and, consequently, voltage ripples in the fuel cell output power. The frequency and the amplitude of the ripple content is dependent on the used power converter topology and
the characteristics of the supplied power system. The fuel cell power converter topology used in the HIL system (see Figure 3.6) is a back-to-back connected buck and boost converter. It inherently induces high-frequency ripple content into the fuel cell output current as illustrated in Figure 5.8. Due to the Boost mode utilizing three interleaved switches compared to one by Buck mode, the current ripple frequency in Boost mode is three times higher than that in Buck mode. Nevertheless, it is interesting to observe the complete lack of high-frequency current ripple in the Freewheel mode. The non-existence of the ripple is mainly due to the switching-free operation of the fuel cell converter. Furthermore, any high-frequency ripple content that would otherwise be induced from other power converters connected in the system (e.g., load inverters) are effectively filtered by the bulky DC bus capacitors and the fuel cell DC/DC converter inductor.

On the other hand, the low-frequency ripple content primarily depends on the system load variations, robustness of converter controllers as well as the magnitudes of the capacitances and inductances in the system. The low-frequency ripple content can be extracted from the actual current waveform by applying a low-pass filter to it. In this work, the low-pass filtering is applied to the actual current using an oversampling and averaging method which has been described in Subsection 3.3.2 of [65]. In this work, the switching frequency of the DC/DC converter is 5 kHz and between each switching period the actual current value is sampled ten times at equal intervals. The average of the sampled values is then calculated to obtain a current waveform without any current ripples above 5 kHz. The low-frequency ripple content obtained with the HIL system are presented in Figure 5.9. No meaningful difference can be observed in the ripples between the different operating modes. The average peak-to-peak
**Figure 5.8.** Illustration of high-frequency ripple in fuel cell current on different Variable DC approach operating modes.

**Figure 5.9.** Illustration of low-frequency ripple in fuel cell current on different Variable DC approach operating modes. Peak-to-peak current ripple are approximately 7.5A, 5.5A, and 5.8A in Buck, Freewheel, and Boost modes, respectively.
ripple values for the measured period are 7.5A, 5.5A, and 5.8A for Buck, Freewheel, and Boost modes, respectively. Therefore, it is safe to conclude that operation in the Variable DC approach has no meaningful impact on the low-frequency fuel cell current ripple content.

5.3 System operation during fault conditions

Systems are generally designed to operate during normal operating conditions, i.e., without faults present. However, system or product failures eventually always occur and must be protected against. Since marine vessels operate in seas, lakes, or rivers, their power systems are typically not accepted to be designed such that a single failure in the system can cause a complete blackout. Therefore, a certain amount of power system redundancy is always required. In Section 5.1, the Variable DC Approach concept was shown to perform well during normal operating conditions. This section will present the results of the system performance during fault conditions. The following failure cases will be analysed:

- DC bus voltage transients
- Hotel load short-circuit
- Propulsion load short-circuit
- Battery system failure
- Fuel cell system failure
- DC bus overvoltage
- DC bus undervoltage

Apart from the first case (i.e., DC bus voltage transients), the system behavior will be mainly demonstrated for systems with converter-controlled batteries due to the behavior not being dependent on whether converter-controlled or DOL batteries are used. Nonetheless, for the first case, the results will be showed for both converter-controlled and DOL-battery systems.

5.3.1 Sudden DC bus voltage transients

In the Freewheel mode, the fuel cell power is controlled via control of the DC bus voltage. A steady DC bus voltage results in a steady fuel cell power supply. On the other hand, sudden voltage transients result in fuel cell power transients. Therefore, to protect from such voltage transients, the fuel cell DC/DC converter was designed with a current-ramp rate controller described in Section 3.4.
Figure 5.10 illustrates the fuel cell current behavior in a system with converter-controlled batteries during sudden DC bus voltage transients. The top graph shows system voltages, whereas the bottom graph displays fuel cell current. The voltage transients are created by rapidly changing the voltage reference of the battery DC/DC converter. At $\sim 3s$, the DC bus voltage is step-like decreased from 750V to 650V. However, instead of fuel cell power increasing step-like as well, the fuel cell current is gradually increased according to its maximum allowed current ramp rate. The fuel cell voltage is also seen to gradually decrease according to the fuel cell current increase. The gradual current decrease is managed by the current-ramp rate controller such that the fuel cell unit is temporarily switched to Buck mode until the DC bus voltage has stabilized to a value which respects the defined fuel cell current rates and the unit is returned to Freewheel mode. The Buck mode is used because during the transient period, fuel cell voltage needs to be maintained above the DC bus voltage. During this transient period, the difference between fuel cell power and load power is supplied by the battery unit. At $\sim 13.5$, the DC voltage is step-like decreased. Again, instead of step-like behavior in fuel cell current and voltage, they are gradually controlled to the steady state values. Since, the fuel cell voltage is needed to be below DC bus voltage during the transient period, the current control is managed via temporarily using the fuel cell unit in Boost mode.

In marine systems with DOL-controlled batteries, the DC bus voltage is
inherently dependent on the battery voltage as described in Section 3.5. Since battery voltage is highly dependent on battery current, large current transients lead to significant voltage transients. Figure 5.11 illustrates the fuel cell current behavior in a system with DOL batteries during sudden DC bus voltage transients. The sudden DC bus voltage transients are created via rapid load power transitions; the load is illustrated in the top graph of the figure. The behavior of the system with a DOL battery is very similar to that with converter-controlled batteries. The current ramp rate controller of the fuel cell DC/DC converter notices the initialization of the unallowed fuel cell current transient and activates to prevent it by instead gradually controlling the fuel cell current according to defined current ramp rates.

5.3.2 Hotel AC network short circuit

Inherited from conventional AC-based distribution systems, hotel networks on board marine vessels are typically three-phase AC networks. Short-circuits are one of the most severe types of failures in the AC network. Typically, they may occur due to cable or component failures. In this subsection, the system performance during phase-to-phase short-circuit in the hotel AC network is analyzed.

System current, power and voltage waveforms during a phase-to-phase short circuit in the AC network are shown in 5.12. The top graph in the
5.3.3 Propulsion motor terminal short circuit

Similar to in hotel AC networks, short-circuits may occur in three-phase propulsion motors cables or in the motor windings. System current, power and voltage waveforms during a phase-to-phase short circuit in the propul-

**Figure 5.12.** System current, power, and voltage waveforms during a phase-to-phase short circuit in the AC network. The short circuit occurs between Phases A and C. The figure illustrates the three-phase current of the VSI supplying the hotel network. The middle graphs shows the power waveforms of the main components. The system voltage waveforms are shown in the bottom graph. At 0.17s, a short-circuit is applied between Phases A and C in the hotel network. The fault is cleared by a circuit breaker trip at 0.29s. During the fault period, only minor power oscillation is visible in fuel cell power. The power oscillation is caused by small voltage variations in the DC bus voltage which, in turn, is caused by the supply of high currents towards the short-circuit in the hotel network. The propulsion load stays uninterrupted for the whole fault period.
Figure 5.13. System current, power and voltage waveforms during a phase-to-phase short circuit in the propulsion motor terminals.

sion motor input terminals are shown in 5.13. The top graph in the figure shows motor currents, second graph shows main component powers, whereas the bottom graph presents system voltages. At 0.2s, a short-circuit is applied between Phases A and C supplying the propulsion motor. The following can be observed in the figure. The short circuit instantly leads to an overcurrent trip in the VSI supplying the motor, and naturally instant interruption of current supply to the motor. Therefore, following the short-circuit, the power supply from the DC bus towards the propulsion motor is cut to zero. The overcurrent prior to motor VSI trip leads to a short-term DC bus undervoltage which is quickly corrected by the battery drive. The fuel cell unit protects itself from rapid current changes via the fuel cell DC/DC converter current ramp rate controller. Therefore, in order for the fuel cell unit to uninterruptedly maintain its power supply, the battery drive fills in the load void left by the propulsion motor by adjusting the charging power to the same magnitude at which the propulsion load was
prior to the short-circuit. It is to be noted that the motor power experiences significant oscillations until settling to zero. The power oscillation occurs due to a torque oscillation which, in turn, occurs due to the phase-to-phase short-circuit in the motor input terminals. Therefore, this power oscillation does not transfer to the DC bus, thus having no impact on the operation of the rest of the system. Therefore, the rest of the system seamlessly continues operation immediately after the current is interrupted by the inverter.

5.3.4 Battery system failure

The Freewheel mode relies on battery systems for control of DC bus voltage. However, like other components, the battery systems may also experience failures, and if the batteries fail, the said voltage control is lost. Nevertheless, regardless of the loss of a battery system, the power system should be able to continue functioning without ending in a blackout. This subsection presents results on system performance during the failure of a battery unit during Freewheel mode. In the examined case, a fuel cell unit remains the sole power source following the trip of the battery system.

System power and voltage waveforms during the occurrence of a battery fault are illustrated in Figure 5.14. Initially, the fuel cell unit supplies the total load power and the battery power hovers around zero. At 0.5s, the battery system is tripped to mimic a failure case. Since, the battery power is zero at the time of the fault, the system powers continue unperturbed following the fault. Between 4s and 6.5s, the propulsion load is decreased to zero and disconnected; thus, the fuel cell system is left to supply only the hotel load power. Therefore, the system shows to perform well following a battery unit failure. However, the following are to be noted. The fuel cell dynamic power is limited based on the dynamic characteristics of the fuel supply systems as discussed in Subsection 2.2.3. Quick, and especially step-like, load power variations can lead to fuel starvation, and consequently a system blackout. Moreover, if the system is operated in Freewheel mode without batteries, the DC bus voltage will vary uncontrollably between minimum \((U_{DC,min})\) and maximum \((U_{DC,max})\) DC voltage values configured into the fuel cell DC/DC converter under- and overvoltage controllers. In this system, \(U_{DC,max} = 800V\), thus the DC bus voltage ends up at 800V in the figure. Therefore, for reliable system operation, it is recommended to design the power system with two or more battery units; in the event of one of them failing, another can be used to perform the desired DC bus voltage control.
5.3.5 Fuel cell system failure

As with batteries, a fuel cell system failure would lead to trip and disconnection of the faulty fuel cell unit. This subsection analyzes system behavior following a failure in a fuel cell system. The power system under test comprises two parallel operating fuel cell systems, a battery system, and a propulsion system. The results are presented in Figure 5.15. Initially, the two fuel cells supply the total propulsion power whereas battery power is zero. The load is equally shared between the fuel cell units. At 3s, an increase in propulsion load power is initiated. During the increase in fuel cell powers, one of the fuel cell units (fuel cell 2) fails, thus disconnecting from the system. The failure occurs at 5s. The power void left by the failing fuel cell unit is immediately filled in by the battery unit discharging. The healthy fuel cell unit continues increasing its power without any interruption and reaches a value equaling the total propulsion power, resulting in battery power returning to zero load. The results show that a failure in a fuel cell system has no noticeable impact on the operation of the rest of fuel cell units nor on the operation of the power system. However, in practice, the failure of a fuel cell system would of course be noticed by a reduced total power supply capacity. Nevertheless, reliable operation of the system is maintained.
5.3.6 DC bus overvoltage

DC bus overvoltage is another unwanted failure case that may occur in the system. Overvoltages may occur, e.g., during failure or quick shutdown of big load consumers which causes a temporary period in which power generation exceeds power consumption. In such cases, a rapid adjustment of power generation is essential. For systems equipped with batteries, managing overvoltage situations is typically straightforward due to the charging capabilities of batteries. If the voltage exceeds the desired level, the batteries function as loads (i.e., charge) in order to bring the voltage back to the required level. If the battery has sufficient charging power capacity to completely fill in the power void left by a disconnection of a load, no actions are needed from the rest of the system, e.g., in this case, fuel cells. However, in many cases, a single power load (e.g., main propulsion system) may be much larger than the available power capacity in the batteries, thus requiring action from the rest of the system.

To analyze the system behavior in Freewheel mode and during an overvoltage condition, the battery unit charging power capacity was limited to 50kW. Then, a 100kW load reduction was applied to the system to investigate its performance. The results are presented in Figure 5.16 which illustrates the power and voltage waveforms of the said system. Initially in the figure, the propulsion and hotel load are 20kW and 125kW, respectively, and are completely supplied by the fuel cell unit. At 0.6s, the hotel load is
Application and results

Figure 5.16. System power and voltage waveforms during DC bus overvoltage.

suddenly decreased by 100kW. With the aim of matching the reduction in load power, the battery charging power instantly increases to its maximum charging power capacity. However, since the battery charging capacity is not sufficient to completely replace the lost load power, the DC bus voltage starts to increase. When the DC bus voltage reaches $U_{DC_{max}} = 800$V, the overvoltage controller of the fuel cell DC/DC converter activates resulting in a rapid decrease of fuel cell voltage in order to prevent the DC bus voltage exceeding $U_{DC_{max}}$. The initial fuel cell power decrease is followed by a 1.9s period during which the DC bus voltage stays at $U_{DC_{max}}$ and the fuel cell power is locked to 100kW, and only after that does the fuel cell power gradually decrease to match the load demand and bring the battery to zero. The delay in the fuel cell power decrease is due to the fuel cell DC/DC converter current ramp rate controller. Upon overvoltage, the ramp rate controller is temporarily overridden by the overvoltage controller which decreases the fuel cell current, and consequently, power, to prevent voltage increase above the maximum limit. However, during this period, the fuel cell current is below the hysteresis band of the current ramp rate controller, thus preventing it from decreasing any more than required by the overvoltage controller. Since the increase/decrease rates of the hysteresis band are the same as the maximum allowed current ramp rates of the fuel cell unit, it requires the mentioned 1.9s for the fuel cell current to again be within the hysteresis band; therefore, the fuel cell decrease continues only at 2s. Nevertheless, the system performs well during the examined overvoltage event.
5.3.7 DC bus undervoltage

Undervoltages are opposite events to overvoltages. They typically occur during events in which power generation is less than power consumption. They can occur, e.g., due to failures in power sources or in the case of rapid increases in load consumption. Similarly to overvoltages, managing undervoltages is also straightforward when batteries are involved. However, in many cases, discharging the power capacity of batteries might not be sufficient to meet a load change, thus also requiring action from the rest of the system.

![Fuel cell, battery and load powers](image1)

![Fuel cell, battery and DC bus voltages](image2)

**Figure 5.17.** System power and voltage waveforms during DC bus undervoltage.

To analyze the system behavior in Freewheel mode and during an undervoltage condition, the battery unit discharging power capacity was limited to 30kW. Then, an 80kW load increase was applied to the system to investigate its performance. The results are presented in Figure 5.17 which illustrates the power and voltage waveforms of the said system. Initially in the figure, the propulsion and hotel load are 45kW and 25kW, respectively, and they are completely supplied by the fuel cell unit. At 1.5s, the hotel load is rapidly increased by 80kW. To match the increase in load power, the battery discharging power instantly increases to its maximum discharging power capacity. However, since the maximum battery discharging power is not sufficient to match the total load power increase, thus increasing the fuel cell power to a maximum temporary power level, the power level of which is limited by $i_{\text{max}_fc}$. Recalling Subsection 2.2.3, large step-like increases in fuel cell power are not allowed due to slowness in fuel cell supply.
Since the combined increase in fuel cell and battery power is inadequate to match the load power increase, the DC bus voltage starts to decrease. The initial step-like power increase of fuel cell power is followed by a gradual power increase in order to prevent potential fuel starvation. The gradual power increase is managed by operating the fuel cell unit in Buck mode. However, regardless of the increased fuel cell and battery power supply, the power generation is not sufficient to meet the load demand, and at 1.9s, the DC bus voltage drops to a value which activates the undervoltage protection functionality of the hotel load supply converter. The hotel load converter undervoltage protection function leads to a brief decrease in hotel load power which results in a rapid recovery of the DC bus voltage. The fuel cell power continues gradual increase according to its increasing power ramp rate until, at 3.4s, reaching a value equal to the total load consumption. At 3.4s, the fuel cell unit returns to Freewheel mode and the system resumes normal operation.
6. Concluding remarks

Hydrogen and fuel cells are considered a potent means for decarbonization of the maritime shipping industry. However, while power generation from hydrogen via fuel cells is a known technology, the application of fuel cell technology in marine vessels is still in its infancy. One important reason for that is typically considered to be the high cost of both fuel cells and hydrogen as fuel. Therefore, to accelerate the adoption of hydrogen fuel cells as the main power generation means that on board marine vessels, more efficient integration and operation methods are needed to render them economical.

The main contribution of this dissertation is the proposal of a new electric integration and operation concept called the Variable DC Approach for fuel cell-powered DC-based marine vessel power systems. The concept provides reduced total powertrain losses, resulting in reduced operating fuel costs for vessel operators. The results of this dissertation are important because, at the time of writing, the high cost of hydrogen fuel is still considered to be one of the major hindrances to adopting hydrogen fuel cell technology on board marine vessels. With the significantly improved operating efficiency, this concept reduces the total cost of ownership for vessel operators, thus increasing the attractiveness of hydrogen as a fuel for marine vessels. In a case study performed in Publication III, the concept is shown to provide up to 1.87%-p reduction in hydrogen fuel consumption, which would translate to very meaningful monetary savings for vessel operation.

The Variable DC Approach concept is designed for DC-based marine power systems in which fuel cells are used as primary power-generating devices. An integral part of the concept is the variation of the DC bus voltage as a function of the system operating power. However, the concept is completely different from any previously proposed variable DC voltage-based concepts. Existing concepts typically target reductions in propulsion motor iron losses, whereas the Variable DC approach targets reductions in fuel cell and DC/DC conversion losses. Therefore, due to the different design targets, the implementation between the concepts is also completely different. In this dissertation, the Variable DC Approach is shown to
provide up to 28% reduction on total powertrain losses when compared to the same system operating with fixed DC bus voltage.

The Variable DC Approach concept is applicable to both DC-based power systems with either converter-controlled or DOL-connected battery systems. The method for systems with converter-controlled batteries devices is comprehensively described in Publications II and III, whereas Publication V defines the method for systems with DOL batteries. The Variable DC approach is shown to improve the total powertrain efficiency of both types of systems. However, since with DOL batteries the powers of neither fuel cells nor batteries can be actively controlled, any application of power and energy management is impossible. Therefore, for practical applications, the converter-controlled batteries are preferred over DOL batteries. Nevertheless, for vessels in which weight and system footprint are key design factors, the DOL batteries with the Variable DC Approach can still be used.

In addition to the control methods associated with the Variable DC approach, this dissertation has also proposed a method to estimate maximum power steps that can be applied to systems primarily powered by fuel cells. The method is described in Publication VI. The method was designed to complement the Variable DC Approach concept and is very useful as a support tool in the early-stage design of fuel cell-powered marine systems. The system performance information provided by the method is useful because it allows for the design of more cost-efficient power systems. Furthermore, the tool can be utilized by an onboard PMS to support decision-making, e.g., coordinating the starting and stopping of power sources and loads. The method enables improved system operation reliability, thus greatly benefiting vessel operators.

The concept proposed in this dissertation has been validated using a real-time HIL simulation test platform. HIL simulation was selected as a validation means due to its good flexibility with power system configurations and high-level operation detail when operated with industrial power converter control equipment. The concept validation was divided into three parts. The first part focused on system performance during normal operating conditions (i.e., without applying failure events). The second part examined the achievement of the pre-set design objective, i.e., the efficiency improvement. Finally, the third part studied the performance of the system during typical fault conditions that may occur in real vessel power systems. The proposed concept was shown to perform well during both normal and fault conditions. In addition, as already discussed earlier, the achieved total powertrain efficiency boost was found to be substantial, thus validating the main benefit of the proposed concept.
6.1 Future prospects

This dissertation developed and researched the Variable DC Approach concept for fuel cell-fed marine power systems. Various aspects around the proposed concept were studied and validated. The dissertation finds the concept to be ready for implementation in a real marine vessel. However, for future research and further advancement of the Variable DC approach concept, some parts of it could be further improved.

The fuel cell DC/DC converter used in this work was a back-to-back connected buck and boost converter topology. However, new more efficient non-galvanic isolated DC/DC converter technologies should be explored. The emphasis in the converter research should be laid on reducing converter conduction losses when operating in Freewheel mode. As was shown in Figure 3.6, in the back-to-back connected buck and boost converter, current flow in Freewheel mode passes through three series of connected components (i.e., a switch, an inductor, and a diode). Each component generates energy losses, thus finding a topology which would reduce the number of series-connected devices in the current path of the Freewheel mode would lead to an improved total efficiency.

Another important research area is the optimal utilization of power and energy management strategies in conjunction with the Variable DC Approach. The fuel cell power systems, especially when operated with the Variable DC approach, have a very different efficiency behavior compared to conventional diesel power systems. Therefore, they should also be approached differently in terms of power and energy management. The optimization of power and energy management strategies in conjunction with the Variable DC Approach would significantly benefit the vessel operators in the form of reduced operating costs.

The Variable DC Approach was primarily developed to minimize total vessel powertrain losses. Nevertheless, another positive benefit of the concept is the elimination of high-frequency fuel cell current ripple. Several previous research works have studied the impacts of such current ripples on fuel cell lifetime. However, few works have studied how said current ripples could affect fuel cell energy losses. Typically, for many passive components, such as capacitors, current ripples result in additional heating, thus reducing operating efficiency. Therefore, it would be interesting to pinpoint if elimination of the high-frequency current ripple would also have any positively meaningful impact on the fuel cell efficiency.

Finally, further consideration could be given to developing design and dimensioning guidelines for systems utilizing the Variable DC Approach. The topics that could be covered by the guidelines are, e.g., optimal sizing of fuel cell and battery power sources based on system load types and tuning instructions for the fuel cell voltage model-based controller and the voltage dip estimator. Such guidelines would be beneficial as a means to
Concluding remarks

reducing the total cost of the power system.
References


[59] K. Prabhakar et al., “Loss minimization of electric drive systems using a dc/dc converter and an optimized battery voltage in automotive applications,” in Efficiency investigation for electric vehicle powertrain with variable DC-link bus voltage, 2016, pp. 1796–1801.


Errata

Publication VI

1. In Figure 8, the legend box mistakenly states that the blue graph is 30kW. Instead, it should be 45kW

2. Section 2.2 lacks a notion that constants B, C and D are specific for each fuel cell power source j.
Efficient electrical integration of new energy sources, such as fuel cells, into marine vessels requires advanced hardware and control concepts. In the past, diesel engines with rotating electrical machines have been the primary power sources used in ships. Therefore, development of the electric integration concepts and control systems has also focused on said power sources. However, with the recently emerged interest towards use of fuel cells in marine vessels, the traditional concepts can be considered outdated due to their focus having previously been mainly in diesel generators.

This dissertation proposes a new electric integration concept for marine power systems in which fuel cells are used as primary power generating devices. An integral part of the proposed concept is the variation of the DC bus voltage as a function of fuel cell power generation. The voltage variation enables switching-free operation of fuel cell power converters resulting in meaningful improvements in ship's fuel consumption, and thus can significantly reduce the operating costs of a ship operator. This dissertation develops hardware and control methods associated to the proposed electric integration concept and presents operating results of a system utilizing the said concept. The methods are verified using a marine power system hardware-in-loop test setup developed for the purpose of electric system testing.