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Zero-Emission Marine Vessels: Multidomain Modeling and Real-Time Hardware-in-the-Loop Emulation on Adaptive Compute Acceleration Platform

Zero-emission marine vessels: modeling and real-time emulation.

Digital Object Identifier 10.1109/MELE.2023.3320509
Date of current version: 28 November 2023

PROTON EXCHANGE MEMBRANE FUEL cells (PEMFCs) are becoming increasingly common in modern marine electric vessels, helping achieve the sustainable development objective of lowered emissions and zero-emission marine transportation. This article introduces a hierarchical hardware-in-the-loop (HIL) emulation scheme for the zero-emission marine vessel at the system

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level and device level. A comprehensive computational PEMFC model is presented in electrical, thermal, and fluid domains. Electromagnetic transient program models are utilized for batteries, power converters, and electric thrusters to describe their behavior and dynamic response and analyze the influence of system components on their performance. The real-time hardware emulation on the Xilinx Versal adaptive compute acceleration platform (ACAP) provides the ability to simulate the complete system at microsecond-level time intervals, which is essential for validating the marine vessel's dynamic behavior under various operating conditions. The results demonstrate that the multidomain PEMFC model effectively captures the complex electrical, fluid, and thermal behavior and the interaction with marine vessels. Additionally, the proposed hierarchical HIL emulation scheme is proven to be a valuable tool for the design and testing of zero-emission marine vessels, which enables comprehensive assessment and verification of vessel performance.

Introduction

In recent years, there has been an increase in demand for hydrogen as a fuel for the future due to its immense environmental benefits, particularly the reduction of carbon emissions. Hydrogen fuel is considered a zero-emission energy source, which means there is no net release of carbon dioxide or other greenhouse gas into the atmosphere during operations. The emission profile of hydrogen makes it environmentally friendly and contributes to reducing greenhouse gas emissions and addressing climate change concerns. It seems that it is only a matter of time before hydrogen permeates additional facets of society, such as marine transportation (Skjong et al. 2017).

In 2018, the initial greenhouse gas strategy was adopted by the Marine Environment Protection Committee of the International Marine Organization (IMO). Figure 1 demonstrates the planned actions from IMO to cut the greenhouse gas emissions from marine transport work. This strategy's urgent goal is to phase hydrogen-powered vessels in as quickly as feasible among the other short- and long-term candidate initiatives for this century. In particular, the energy efficiency design index for new

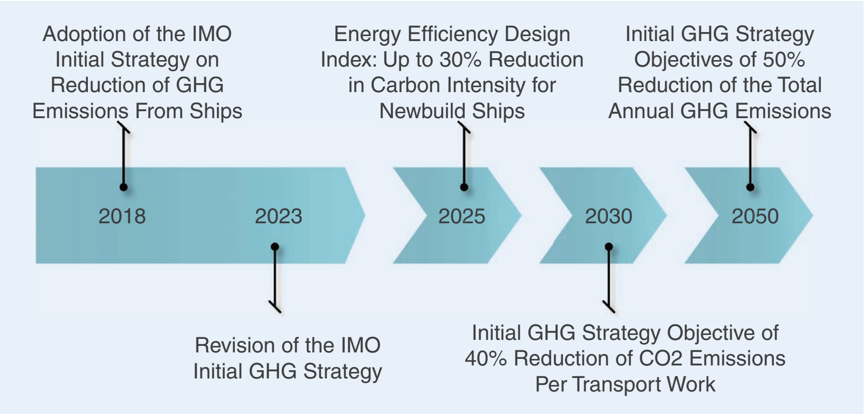

Figure 1. A decade of action for IMO to cut emissions from marine transport work. GHG: greenhouse gas.

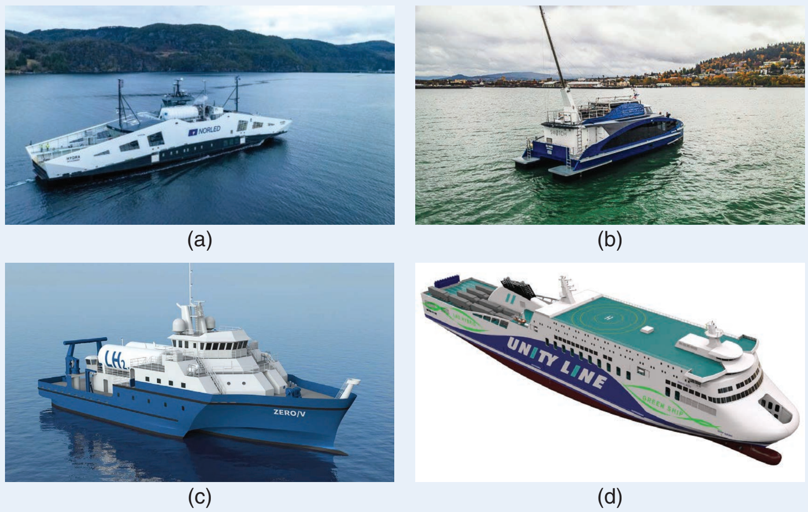

Figure 2. Hydrogen fuel cell-powered marine vessels: (a) the *MF Hydra* in Norway; (b) the *Switch* passenger ferry in the United States; (c) the *Zero-V* research vessel in the United States; and (d) the Polish ferry *Unity Line*, which will be operated in the Baltic Sea.

ships will be implemented in additional phases to reduce the carbon intensity from marine vessels. As shown in Figure 1, the goal is to decrease the carbon intensity of international shipping by reducing greenhouse gas emissions per unit of transport work. The target is to achieve a reduction of at least 40% by 2030 compared with the 2008 level. The ultimate objective is to reduce total annual emissions by at least 50% by 2050 compared with the 2008 levels (according to IMO). Efforts are being made to pursue a pathway toward zero-emission marine transport. This involves not only reducing emissions but also working toward phasing hydrogen-powered vessels out entirely. The vision is to move toward a future where marine transport operates with zero emissions.

Furthermore, according to the IMO policy, "the emissions estimates demonstrate that gains in efficiency are crucial in containing emissions growth, but even the most considerable improvements modeled do not result in a downward trend. If fossil fuels continue to predominate, changes in the fuel mix have a minimal effect on greenhouse gas emissions compared to regulatory or market-driven efficiency improvements."

To achieve this goal, liquid hydrogen (LH_2) fuel cell technology is widely implemented on short-ocean marine vessels and passenger ferries. Meanwhile, the manufacturers are accelerating the progress toward developing zero-emission marine vessels. Figure 2(a) shows the first LH_2-powered ferry in the world, which is operated in Norway, making history when it began using hydrogen fuel that emits no emissions. With its 80 cubic meter hydrogen storage tank, the ferry should be able to reduce its carbon emissions annually by up to 95%. Figure 2(b) demonstrates the *Switch* passenger ferry in America, which has a capacity of seventy-five passengers and a maximum cruise speed of twenty-one knots thanks to the 410 kW LH_2 PEMFCs and lithium-ion batteries on board. Table 1 summarizes the specifications of marine vessels and passenger ferries. The *Zero-V* research vessel is shown in Figure 2(c), and Figure 2(d) shows the Polish ferry *Unity Line*, which will be operated in the Baltic Sea in the future.

Among the rapidly developing large-scale modular technologies, PEMFCs have emerged as one of the most appealing power sources for marine vessels. This is primarily due to the following key advantages they offer:

1) *Environmentally friendly*: PEMFCs are environmentally friendly power sources as they only emit water and oxygen during their operation, which supports the achievement of sustainable and net-zero-emission marine transport. By utilizing PEMFCs, vessels can significantly reduce their carbon footprint and contribute to environmental conservation.
2) *Highly efficient*: PEMFCs exhibit high efficiency, offering an energy conversion efficiency of approximately 60%. When considering the overall fuel cell systems, their efficiency ranges from 45% to 55%.
3) *Long distance to empty (DOE)*: PEMFCs are particularly suitable for medium- and long-range marine transport due to their extended DOE capability. Unlike lithium-ion batteries, PEMFCs do not require additional charging processes after operations. This advantage

TABLE 1. The marine vessel and passenger ferry specifications.

Marine Vessel Name	Passenger Capacity	Length	Max. Speed	Energy Storage Type	Energy Storage
MF Hydra	300	82.4 m	9 knots	LH_2 PEMFC	24 MW
Switch	75	21.3 m	21 knots	LH_2 PEMFC and battery	410 KW
Zero-V	15	51.8 m	10 knots	LH_2 PEMFC	1.8 MW
Unity Line	400	195 m	10 knots	LH_2 PEMFC	15 MW

allows marine vessels equipped with PEMFCs to cover longer distances without interruptions for recharging, thereby improving operational efficiency.

4) *Stability*: PEMFCs have highly stable performance and a mature integrated liquid cooling system, which contribute to impressive thermal performance and reliable power generation and enhance the overall durability and longevity of the energy storage system.

There are three common models used for PEMFCs: equivalent-circuit-based models, physics-based models, and machine learning models. At the PEMFC layer level, various dynamic models have been developed to investigate the electrical behavior and thermal performance (Gao et al. 2012). The equivalent-circuit-based model has undergone improvements, particularly regarding the heat component for individual cells. To incorporate fuel cell degradation into the equivalent-circuit model, resistance and capacitance elements are combined. These models provide valuable tools for understanding and studying the performance and behavior of PEMFCs.

In medium- and high-voltage applications such as marine vessels, the device-level models play a critical role in the interconnection of power converters and energy systems. Hierarchical HIL emulation is more critical in operating a modular multilevel converter (MMC) (Dinavahi and Lin 2021), which facilitates the interaction between multiterminal energy and power and a high-power electric propulsion system. The increasing number of energy storage devices naturally brings new challenges for the HIL emulation scheme to maintain in real time.

Among the rapidly developing large-scale modular technologies, PEMFCs have emerged as one of the most appealing power sources for marine vessels.

The hierarchical real-time hardware emulation approach is now regarded as a useful tool for the power system of marine vessels during the initial design and testing phases. Comprehensive dynamic device-level models, composed of PEMFCs, batteries, and power switches, are built to describe behavioral transients during operation. The development of system-on-a-chip and multicore technologies has led to significant advancements in HIL and software-in-the-loop emulation over the past ten years. Enhancing multidomain modeling for devices in subsystems and putting in place a cutting-edge computing platform for real-time hardware emulation of zero-emission maritime vessels are crucial. The following is a list of the key expectations:

1) The multidomain models provide explicit representations of dynamic behavioral transients in PEMFCs through ordinary differential equations from the perspectives of electrical, fluid, and thermal domains. These ordinary differential equations mathematically couple the interactions among these domains during the solution process. In addition, device-level modeling of power switches is implemented for real-time emulation of power converters in control systems.
2) The hardware emulation scheme is improved for representing both device-level and system-level features of the energy storage and electric propulsion systems in marine vessels. The proposed hierarchical HIL scheme enables the development of detailed models for PEMFCs to explicitly present device-level steady-state and dynamic characteristics in real time; meanwhile, the system-level emulation is carried out at the same time.
3) Xilinx Versal ACAP offers exceptional compute performance with embedded artificial intelligence engines (AIEs) and programmable logic (PL) arrays. These platforms facilitate the mathematical separation and parallel solving of device-level and subsystem models.

In this article, the *Zero-V* marine research vessel is used as an example for HIL emulation. The comprehensive PEMFC model is validated with the empirical model from Simulink. The hardware emulation is performed on the Xilinx VCK190 board with the ACAP device XCVC1902. The results indicate that the proposed hierarchical hardware emulation effectively represents detailed information at the device and system levels during steady-state and transient conditions.

Marine Vessel Power Systems

Figure 3 shows an example of onboard power systems for marine transport, including power converters, electrical propulsion systems, and energy storage systems. The electrical propulsion system provides the main thrust and maintains the position of the ship, while the PEMFC and battery system is the only power supply and energy storage. In this section, these main subsystems are introduced and analyzed.

Electric Propulsion System

The marine vessel is equipped with stern thrusters in each outer hull and a retractable azimuth bow thruster to facilitate precise position-keeping during on-station science activities. To optimize the steering forces generated by the main propellers during station preservation, high-lift flap rudders are also incorporated. This propulsion system provides sufficient maneuverability and positioning capability for the ship under the required operating conditions, and the specific powertrain parameters can be found in Table 2. The 500-kW motors possess sufficient reserve power for safe operation in rough sea conditions, dynamic positioning, and meeting the diverse mission requirements. The permanent magnet motor

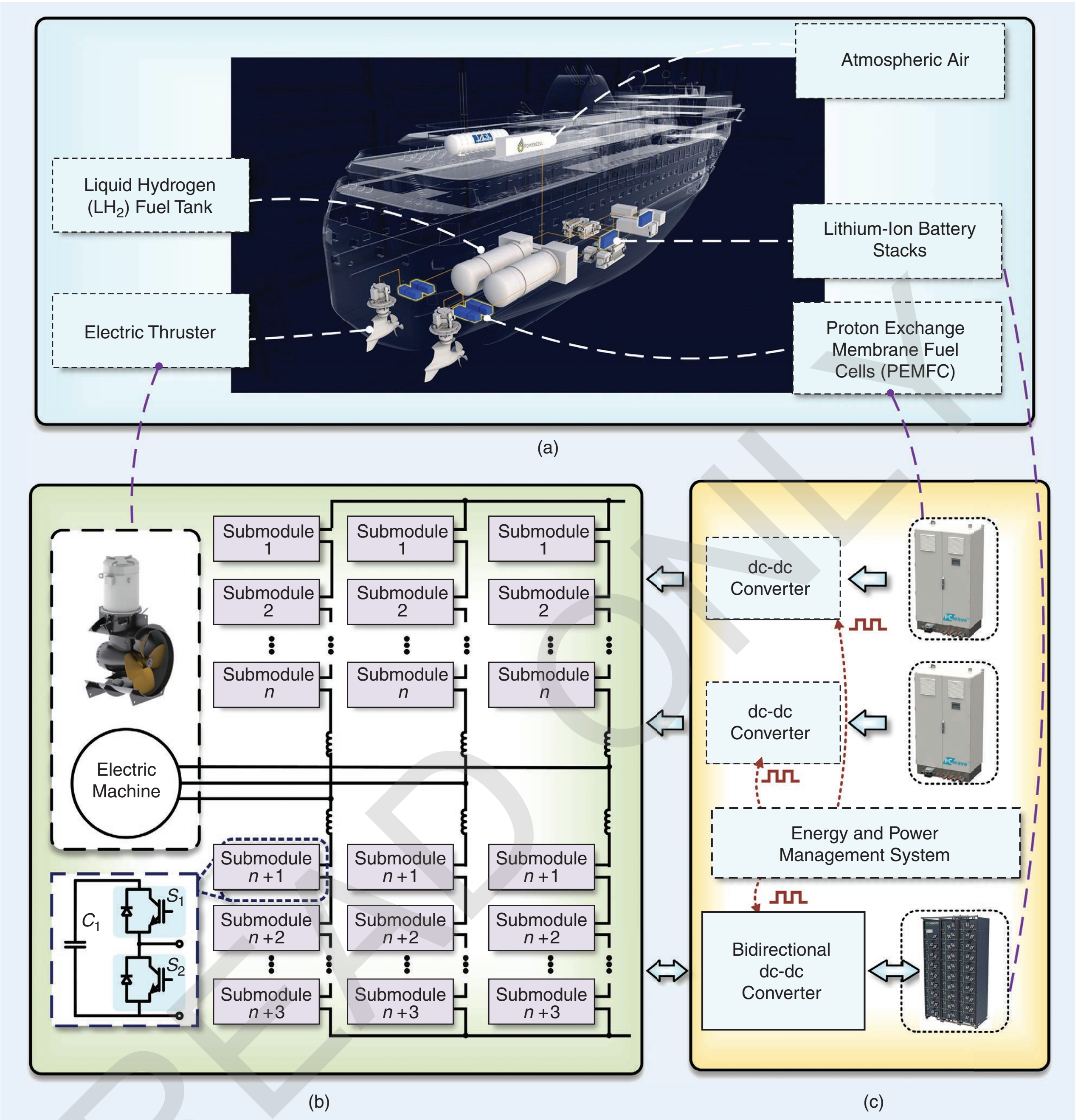

Figure 3. The diagram of hydrogen and battery hybrid marine vessel: (a) diagram for electrical systems of hybrid marine vessel, (b) power converter and electric propulsion system, and (c) onboard energy storage systems.

TABLE 2. The *Zero-V* marine research vessel powertrain.

Specifications	Value
PEMFC power	10 × 180 kW
LH_2 tanks	2 × 28,800 gallon
Propulsion	2 × 500 kW
Bow thruster	500 kW
Stern thrusters	2 × 500 kW

(PMSM) has been chosen for the electric propulsion system as it offers advantageous characteristics such as effective and quiet operation when directly connected to the propeller shaft.

In the case study, conventional tunnel thrusters, which are based on PMSMs, were utilized for the stern thrusters (Klebanoff et al. 2018).

The *Zero-V* marine vessel operates at a dc bus voltage of 900 V. Power converters are required for the energy storage devices to regulate the output voltage. Furthermore, considering that the efficiency of PEMFCs is dependent on the operating voltage and current, it will be more efficient

TABLE 3. Comparison of energy storage devices.

Devices	Type	Power Density	Rated Current	Operating Temperature	Peak Efficiency
PEMFC	FCwave	200 W/kg	550 A	−40–60 °C	53.5%
	FCvelocity	178 W/kg	400 A	−45–60 °C	56.5%
Lithium-ion battery (Chemali et al. 2016)	Lithium iron phosphate	204 W/kg	300 A	−30–55 °C	98.0%
	Nickel cobalt aluminum oxide	279 W/kg	350 A	−20–50 °C	98.0%

for the marine vessel to operate the PEMFC stack at its peak efficiency. Therefore, the controller is modified to consider the efficiency constraint, ensuring that the PEMFC stack operates at its optimal efficiency level.

The onboard power systems, which are made up of thousands of energy storage devices coupled with power converters, are the only energy sources for zero-emission vessels, while the electric propulsion systems are usually operated by electric machines such as induction and synchronous motors. Many models for energy storage devices only consider electrical properties. To offer electrical and thermal data for energy management techniques, it is crucial to build multidomain models for batteries and fuel cells.

Energy Storage System

Table 3 compares the PEMFC with lithium-ion batteries in terms of power density, rated current, operating temperature, and peak efficiency. The batteries have better power density, thermal performance, and peak efficiency, while a single PEMFC cell can deliver higher operating currents. In the marine vessel, the PEMFC plays the role of main energy storage, while batteries are energy buffering to improve the overall benefits of energy storage systems.

As shown in Figure 3(c), the energy storage system is based on the PEMFCs and batteries. PEMFCs are versatile and can be applied to both medium- and low-voltage ac and dc power systems. They can be explored in combination with batteries or other energy storage devices, allowing for various system configurations. The integration of PEMFCs into vessels can be done in different ways, including fully hydrogen-electric systems or as part of hybrid power systems. By incorporating the PEMFC power plant, marine vessels can significantly extend their running hours in zero-emission mode. Moreover, shore charging infrastructure provides even more flexibility and energy storage capabilities.

In this case study, batteries are introduced to the onboard energy storage system since batteries have better power density than PEMFC, as shown in Table 3. Batteries play an important role in energy buffering, improving the maximum output current capacity of the entire system. In addition, fuel cells have high recyclability, contributing to the overall sustainability of the onboard power system.

Thanks to the onboard fuel tank and LH_2 circulation systems, direct trailer refueling has been identified as the preferred strategy, where LH_2 trailers dock alongside the vessel and connect to a stationary fueling stanchion. This method allows for safe and efficient refueling without the need for the vessel to move during the process. While initially expensive, having a large and reliable customer for renewable hydrogen fuel would encourage suppliers to make renewable LH_2 more widely available nationwide. This demonstrates the potential for sustainable and renewable hydrogen as a fuel source for marine transportation applications.

Multidomain Modeling and Real-Time Emulation

In this section, the multidomain modeling for PEMFC and real-time HIL emulation are developed and implemented on a Versal ACAP. The main PEMFC modeling is introduced, and the hardware platform is also introduced.

Proton Exchange Membrane Modeling

As the main energy source in the marine vessel, the PEMFC stacks need to be precisely modeled in the electrical, fluid, and thermal domains to reveal detailed information for energy management systems. Figure 4 demonstrates the insight into a single PEMFC on the *Zero-V* marine vessel, where the hydrogen fuel goes through the anode channel to the cathode catalyst. Then H^+ ions can cross the proton exchange membrane to the cathode catalyst, where the chemical reaction occurred. The extra oxygen and water come out from the cathode channel.

Electrical Domain

In general, the output voltage of PEMFC (U_{FC}) can be calculated as follows:

$$U_{FC} = E_{FC} - U_{ohm} - U_{act} - U_{con}$$

where E_{FC} is the is the ideal potential, U_{ohm} is the ohmic loss, U_{act} is the activation loss, and U_{con} is the loss caused by convection and diffusion naturally caused by the electrical reaction.

Actually, the PEMFC model is a time-varying and nonlinear model that requires a nonlinear solver during the device-level emulation. To accelerate the HIL emulation and achieve real-time emulation, the advanced software architecture and hardware platform are implemented in this article.

Fluid Domain

The Maxwell–Stefan equations are widely used for description of the diffusion phenomenon, where diffusive fluxes, P_i, of species through a plane depend on all independent driving forces. The gas diffusion of the ith species in the layers is described by

$$\Delta P_i = \frac{\delta R T}{P_t S} \sum_{j \neq i} \frac{P_i \frac{q_j}{M_j} - P_j \frac{q_i}{M_i}}{D_{ij}}$$

where δ is the gas diffusion layer thickness, P_t is the total gas pressure, S is the gas diffusion layer, M_j is the gas molar mass, j stands for species other than the ith species, and D_{ij} is the binary diffusion coefficient between the ith and jth species.

Thermal Domain

Figure 5 illustrates a thermal network for PEMFC, which incorporates four heat sources and two resistance–capacitance couples to account for convection and radiation effects. In addition, the main thermal energy of a PEMFC cell is the difference between the chemical energy of hydrogen and oxygen and the electrical energy of the stack. This thermal energy is distributed as the sensible heat of the coolant and reactants, the latent heat during the phase change of the water, and heat loss to the surroundings by convection.

The main internal resistance of the PEMFC arises from the variable resistance of the membrane, which is noted as R_{mem}, which leads to an irreversible voltage drop. As power is generated through the electrochemical reactions in the PEMFC, heat is also produced. These phenomena can be quantitatively calculated using specific equations or mathematical models. The abovementioned phenomenon can be calculated by

$$Q_{FC} = I_{FC}^2 R_{mem} + I_{FC} \cdot \left(\Delta U_{act} - \frac{T_C \cdot \Delta S}{2F}\right) + \frac{\lambda_{mem} \cdot A_{mem} \cdot (T_{mem} - T_c)}{d_{mem}}$$

where R_{mem} is the equivalent resistance of the proton exchange membrane, ΔS is the entropy changes, λ_{mem} is the membrane's material thermal conductivity, A_{mem} is the contact area between the membrane and catalyst of the cathode side, and d_{mem} is the layer thickness. T_{mem} and T_c are the membrane and catalyst temperatures, respectively.

The electrical, fluid, and thermal domains are mathematically coupled with each other since the electrical behavior calculations require fluid and thermal information. In this case, it is important to advance the HIL scheme to achieve real-time device-level emulation.

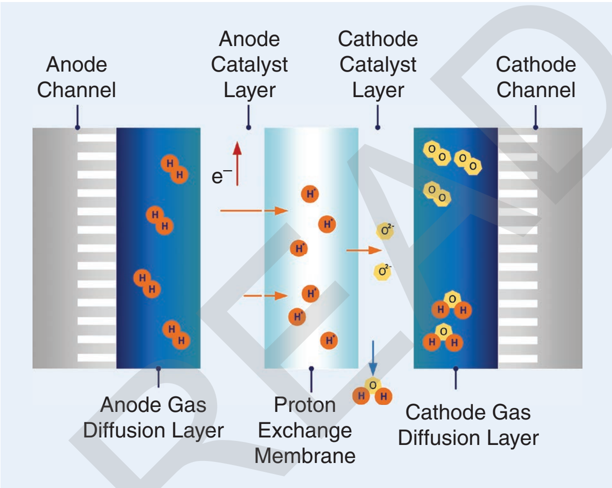

Figure 4. A diagram of a PEMFC.

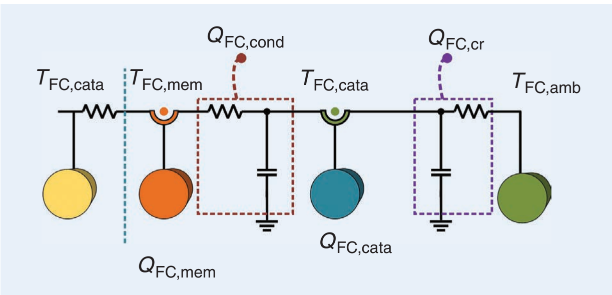

Figure 5. The thermal network model for a PEMFC.

Real-Time HIL Emulation

Figure 6 depicts the architecture of the Xilinx ACAP board, which comprises various components such as AIEs, PL, and an Advanced RISC Machine (ARM) core integrated into the chip. The AIE array serves as a higher-level hierarchy within the AIE architecture and consists of a two-dimensional array of AIE tiles. The AIE can establish connectivity with other parts of the device either through the network-on-chip or by directly interfacing with the PL via the AIE array interface.

Each AIE tile, as shown in Figure 6, includes an engine capable of accessing at most four memory modules, a dedicated memory module itself, and a tile interconnect module. The ACAP kit used in this article has a maximum capacity of four hundred AIE tiles. The AIE processor is highly optimized to support both fixed- and floating-point precision.

Programming the AIE involves a two-stage approach within the Vitis environment, which includes kernel programming and graph programming. The communication between the AIEs and other components of the device is represented as a graph, where kernels are instantiated and connected through buffers and streams. This approach facilitates efficient and scalable programming of the AIE for implementing complex algorithms and computations.

General-purpose computing is provided by the ARM processing unit, which is based on the ARM Cortex-A72 CPU core. It is suitable for solving the multidomain PEMFC model due to its capabilities and high clock frequency. OpenCL is adopted for software programming, enabling parallel execution of multiple kernels with an initialized command queue, resulting in improved speed. The PL is a flexible structure that allows for the creation of various hardware functionalities. It consists of adjustable logic blocks, configurable RAM, and digital signal processor engines. These components can be interconnected and combined to generate a wide range of functions, including processors, functional pipeline units, peripherals, and accelerators. The PL provides the flexibility to tailor the hardware configuration to specific requirements.

This connection is essential for effective memory management and enables the system to handle large datasets efficiently.

In the design of the energy storage system, the global memory input/output port plays a crucial role. This port serves as a connection point for external memory, which can be mapped to or from the main memory of the system. It enables efficient and seamless data transfer between the system and external memory sources. This connection is essential for effective memory management and enables the system to handle large datasets efficiently.

To set up and establish connections among the components within the PL and ARM cores, specialized software tools such as the Vivado design suite and the Vitis integrated software platform toolset are utilized. These tools provide a comprehensive environment for specifying the configuration, connectivity, and interoperation of the PL components. They offer features and functionalities that facilitate the design, development, and optimization of the PL and ARM cores.

By utilizing these software tools, designers can define and configure the PL components, specify their connectivity, and optimize their performance. The tools enable the creation of a programmable device image that can be loaded onto the hardware to implement the desired functionality. This image represents the configured PL components and their interconnections, allowing the hardware to execute the required operations as defined in the design.

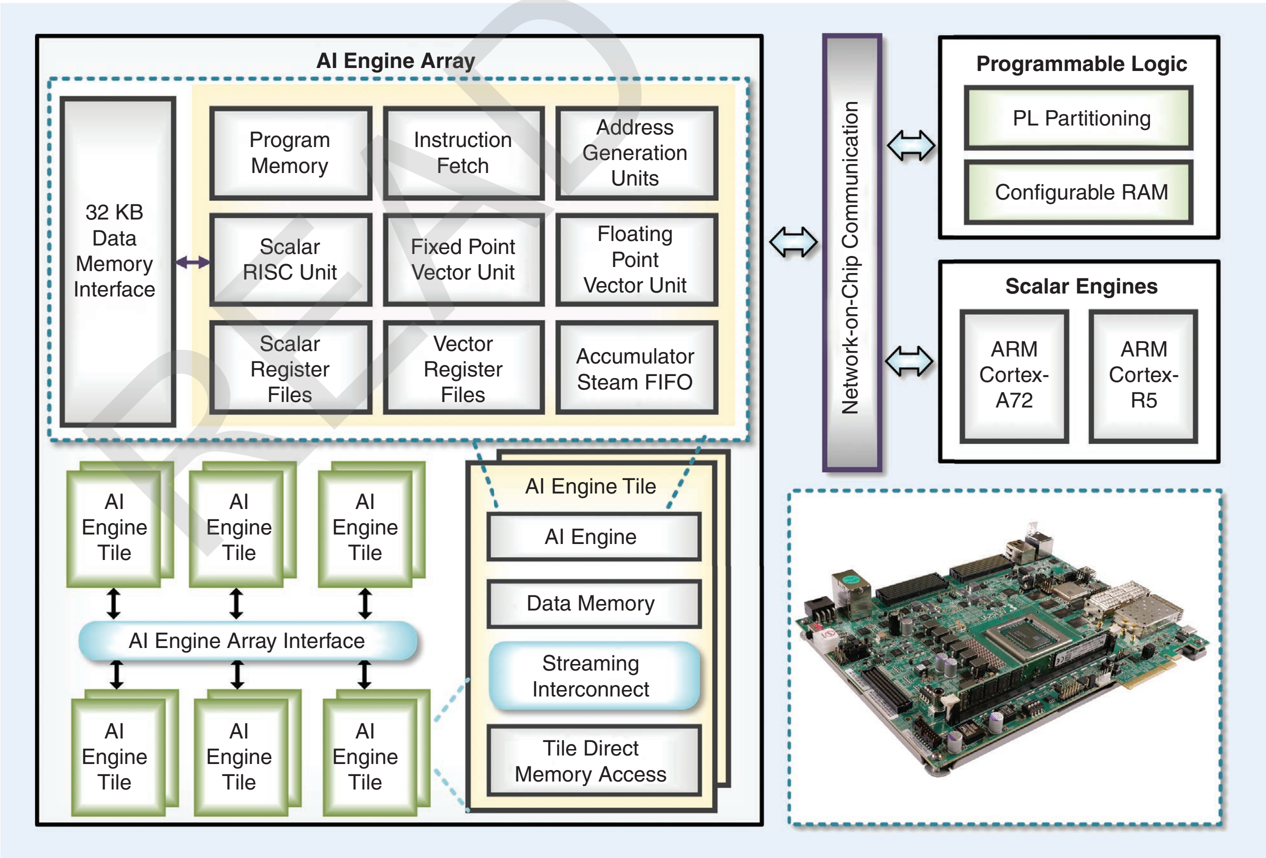

Figure 6. The architecture of the Xilinx Versal ACAP. PL: programmable logic, RISC: reduced instruction set computer.

Real-Time HIL Emulation Results and Discussion

In the case study, the configuration and specifications of the *Zero-V* marine vessel are adopted in this article. The propulsion switchboard receives electricity from each PEMFC and battery pack via a dc–dc converter, which changes the voltage to a constant nominal voltage of 900 V dc. The propulsion switchboard supplies power through dc–ac drives to the different heavy loads, including the propulsion, thruster, and winch motors. Moreover, redundant dc–ac power converters provide ship service electrical power to the 480 V ac ship service switchboard. The ship service switchboard supplies smaller loads like lights, fans, and pumps. The time step for the HIL emulation of PEMFCs and power converters is 0.5 μs.

Figure 7 illustrates the operations of power converters and multidomain modeling of the onboard PEMFC in the electrical and fluid domains. In Figure 7(a), the

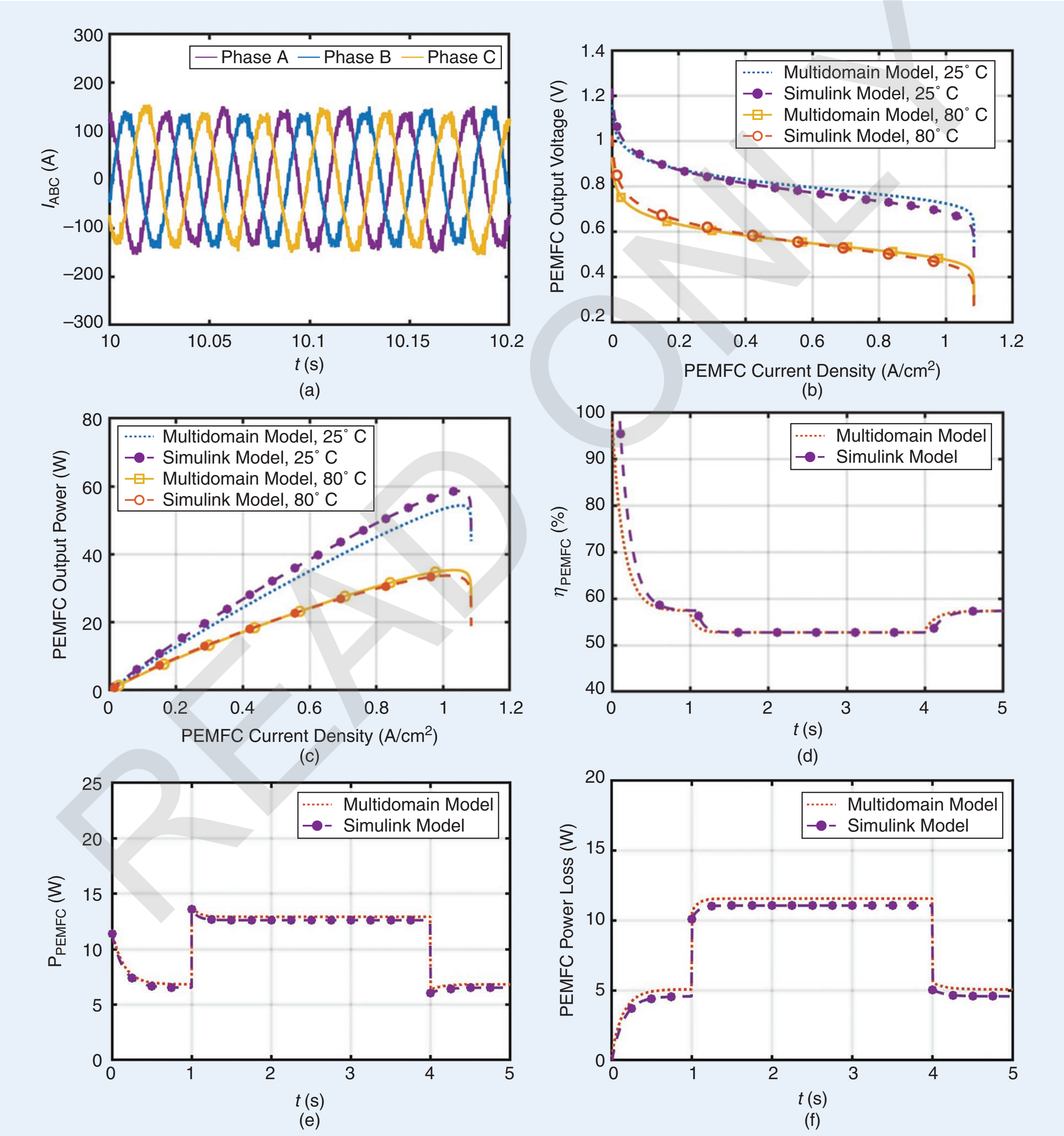

Figure 7. The PEMFC modeling and HIL emulation results: (a) the inverter current of the inverter between the PEMFC and the PMSM, (b) the PEMFC current density versus the output voltage, (c) the PEMFC current density versus the PEMFC output power, (d) the PEMFC efficiency, (e) the power consumption of the PEMFC during varying LH_2, and (f) the PEMFC power loss during varying LH_2.

three-phase output currents of the MMC are shown using an average model under preset operating conditions. The PMSM torque and speed are generated according to the preset operating conditions of the marine vessel. Then, these currents serve as inputs for device-level emulation.

Figure 7(b) presents the basic relationship between the current and the output, while Figure 7(c) depicts the current and output power curve in steady state during PEMFC operations. In Figure 7(b), the voltage output experiences a significant jump/drop when the current density falls below 0.18 or exceeds 1.03. Additionally, the output power increases with increasing current density but starts to decline when the current exceeds 1.03 times the rated current. In addition, the output power sharply decreases when the PEMFC is overloaded. This behavior is attributed to the negative effects of overcurrent on the electrical performance of PEMFCs.

Figure 7(d), (e), and (f) demonstrates the efficiency, power consumption, and power loss of the PEMFCs during varying LH_2 supply. In the presented scenario, the hydrogen fuel supply increases between 1 s and 4 s, leading to a decrease in efficiency and an increase in power consumption and power losses. This phenomenon occurs because the excessive supply of LH_2 cannot be sufficiently reacted with oxygen, resulting in increased power losses and overall power consumption. Despite the output power remaining relatively constant, the overall efficiency of the PEMFCs decreases throughout the process. Overall, the proposed HIL emulation scheme can reveal the insight into power converters and PEMFC from the electrical, fluid, and thermal domains in real time.

Furthermore, the hierarchical nature of HIL emulation allows for mathematical decoupling and separate solving in ACAP, thereby reducing the emulation time.

Conclusions

Significant innovations in zero-emission energy storage, such as lithium-ion batteries and hydrogen fuel cells, have been driving urgent research in zero-emission marine transportation. These innovations play a critical role in reducing emissions across all industry sectors. In this context, it is essential to advance device-level modeling to understand the intricacies of power systems and improve control and management objectives through real-time emulation. HIL emulation plays a crucial role in marine vessel design, and device-level modeling provides valuable information across the electrical, chemical, hydraulic, and thermal domains. The advanced computing platform, ACAP, represents the state of the art in parallel computation, offering significant potential for large-scale device-level emulation and improved computation speed for real-time emulation. Furthermore, the hierarchical nature of HIL emulation allows for mathematical decoupling and separate solving in ACAP, thereby reducing the emulation time. Future research will focus on developing multidomain models for various fuel cell types, including solid oxide fuel cells. Additionally, real-time HIL emulation will be developed for zero-emission transport sections with megawatt-level power consumption and hydrogen-based oceangoing marine vessels Furthermore, hybrid electromagnetic transient and machine learning methods will be investigated for device-level modeling, and parallel-in-time-and-space methods will be implemented for HIL emulation to improve efficiency and maintain accuracy.

For Further Reading

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