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Review on hardware-in-the-loop simulation of wave energy converters and power take-offs

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ABSTRACT

This paper reviews the state-of-the-art on Hardware-In-The-Loop simulation methodologies and technologies applied in the research field of wave energy converters. It reveals important issues, such as an unclear taxonomy and representations of these methodologies, which are critical for the success of the approach, mostly during the design of experiments and presentation of results. Moreover, a classification approach to these methodologies is not found in the literature. Thus, a generic taxonomical and classification framework is developed to support the review process. This framework is built based on three taxonomic subsystems that the review shows to be effective in organizing the reviewed methodologies: simulated, real and interface subsystems. In particular, the definition of the interface subsystem is key to overcoming the limitations found in the methodological representations. Furthermore, this review borrows the term actionability to this approach to better describe the nuances and gaps between the reviewed case studies. It is found that the different technical implementations are easily organized with the proposed framework, and the results cover a wide range of wave energy converter development phases. Likewise, this review shows opportunities for improvements in the methodology and application to a wider number of new case studies.

1. Introduction

In the Hardware-In-The-Loop (HIL) simulation, some virtual components in the numerical model of the system being simulated are replaced by real components, as explained in Refs. [1,2]. This mixed, hybrid, or co-simulation approach aims to simplify the simulation of complex physical components or phenomena that are difficult to accurately model or simulate in a reasonable timeframe. For instance, the flow of water around ship hulls and propellers, the complex electro-visco-elastic behavior of generators, and wind flow around wind turbines can be challenging to simulate accurately, while other components may be numerically simulated cost-effectively and with precision [3,4]. However, the real components may be under test to verify their compliance with the functional requirements, such as testing if a controller is operating as a final product in the simulated environment, with Technology Readiness Level (TRL) 4 and above [5,6].

The development of HIL simulations started in aeronautics (e.g., flight simulators) and then in the military, aerospace, and automotive industries [7]. It is currently considered a well-proven, widespread, and state-of-the-art method in many fields of activity [6,8]. It has been applied to car traction applications and electric drives, and recently proposed as a new and improved method for testing, verifying, and certifying modern machinery systems for marine vessels, specifically on control and monitoring systems [6,9]. This is particularly important for the marine industry as it allows for the simulation of various operating conditions, including extreme weather and sea conditions, which are difficult to replicate during physical testing. This need is related to the increased complexity of the marine systems and the verification of their quality, functionality, performance, and compliance with classification rules, which are intended to provide confidence to the vessel owners [6].

HIL has been increasingly applied in the development process of engineering systems in the renewable energy field, such as in the research and development of Wave Energy Converters (WECs) [10,11] and wind turbine systems [12,13]. WECs are specifically designed to extract low-frequency motions of ocean waves and utilize Power Take-Offs (PTOs) to convert the absorbed energy into useable electricity [14].

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List of abbreviations

AC	Alternating Current
A/D	Analog to Digital
ADC	Analog to Digital Converter
CD-DEG	Diaphragm Dielectric Elastomer Generator
cRIO	Target PLC
D/A	Digital to Analog
DAQ	Data Acquisition System
DC	Direct Current
D I/O	Digital Input/Output
DSP	Digital Signal Processing
DuT	Devices Under Test
EMDB	Electric Machine Drives Board
EMMC	Energy-Maximizing Moment-based optimal Control
FB	Pitch angle feedback
FPGA	Field Programmable Gate Array
GPU	Graphics Processing Unit
HAWT	Horizontal Axis Wind Turbine
HIL	Hardware-In-The-Loop
I/O	Input/Output
ISWEC	Inertial Sea Wave Energy Converter
LUT	Look Up Table
LVDT	Linear Variable Differential Transformer
MPC	Model-based Predictive Control
MPPT	Maximum Power Point Tracking
MTI	Inertial sensor
NMPC	Nonlinear Model Predictive Control
OWC	Oscillating Water Column
OWSC	Oscillating Wave Surge Converter
P	Proportional
PC	Personal Computer
PI	Proportional – Integrative
PID	Proportional – Integrative – Derivative
PLC	Programmable Logic Computer
PMSG	Permanent Magnet Synchronous Generator
PMSM	Permanent Magnet Synchronous Machine
PTO	Power Take Off
PWM	Pulse Width Modulation
PXI	Standalone Real-Time Simulator Machine
R–W2W	Wave to Wire Real Part
RT	Real Time
RTS	Real-Time Simulator
RTSM	Real-Time Simulator Machine
SOSM	Second Order Sliding Mode
S – R W2W	Wave to Wire Simulated and Real Part
S – W2W	Wave to Wire Simulated Part
TRL	Technology Readiness Level
VAWT	Vertical Axis Wind Turbine
W2W	Wave to Wire modelWEC Wave Energy Converter
xPC	Target Personal Computer

Although various studies have been published on HIL research related to WECs, a comprehensive review of the state-of-the-art has yet to be found in the literature. Additionally, no widely accepted and clear taxonomy or classification scheme for HIL methodologies has been established.

The main objective of this paper is to discuss the advantages and challenges associated with the application of HIL methodology, with a particular focus on WECs. These challenges include the lack of a standardized taxonomy and classification for the various HIL methodologies, as well as technical issues such as scaling effects on HIL simulations. This paper also aims to provide wave energy researchers, developers, and stakeholders with insights into potential HIL applications, as well as a well-established and widely accepted taxonomy.

This taxonomy will enhance communication and promote a more efficient development process among these groups, particularly in a global context where entities may be collaborating on joint projects but are located in different countries and regions. The development of this taxonomy will facilitate better communication and contribute to the establishment of HIL testing standards. Furthermore, the taxonomy is intended to promote the development of HIL testing in the research community, as research taxonomies are an important tool for the management and utilization of increasing knowledge and complex information produced in the scientific fields, thus making scientific knowledge and texts clearer and useable. This tool also helps researchers to find scientific solutions to their research questions and analyse scientific studies and observations [15].

To achieve these aims, the paper is structured into six sections. Section 2 presents the HIL operation principle and discusses the advantages and challenges of its implementation, including methodological and technical issues. It also discusses the taxonomic barriers that can hinder effective communication between developers, researchers, and stakeholders; Section 3 proposes the HIL taxonomy and classification framework; Section 4 applies this framework to the comparison of diverse HIL methodologies; Section 5 discusses the review results, which are then summarized in the conclusion.

2. HIL implementation methodology

2.1. Principle of operation and advantages

The HIL methodology simulates the operation of WECs and their interactions with the PTO. A generic representation of these relations is schematically shown in Fig. 1, which depicts the Wave-to-Wire (W2W) model [7].

For example, a heaving point floater is used as an absorber to capture the energy of the wave resource and convert it into mechanical energy in the form of oscillating motions. Then the transmission stage rectifies this oscillatory energy by converting the mechanical into oil-hydraulic energy and delivering it to the generation stage. In the generation stage, the oil-hydraulic energy is converted into electrical energy, which is then adapted to the grid in the conditioning stage. The system main parameters are $a = [F_{exc}\ \dot{x}\ T\ i\ P_{out}]$ and $r = [F_{\mathrm{PTO}}\ \omega\ v]$, where ($F_{exc}$) is the wave excitation force, ($\dot{x}$) the absorber speed, (T) the mechanical torque of the hydraulic motor, (i) the generator current, (P_{out}) the power delivered to the grid, (F_{PTO}) the PTO force, (ω) the generator shaft rotational speed and (v) the power converter voltage. The control inputs are used to control the WEC and optimize its efficiency [16]. The transmission stage, generation and conditioning stages have been experimentally validated, for constant and variable oil pressure PTO variations, [17,18].

In cases where the WEC is directly connected to the generator, as in the direct conversion stage using a linear generator [10,19], the transmission stage may be omitted.

The WECs may include different types of absorbers which are connected to different PTO technologies. This paper reviews WEC concepts where the HIL methodology has been used. For instance, in Fig. 2a, an absorber composed of two articulated rafts is attached to the interface of an oil hydraulic transmission PTO [20], while Fig. 2b displays a point absorber floater connected to a mechanical transmission PTO [21].

The WEC absorber can be indirectly powered by the motion of air displaced by sea waves, such as a chamber where the oscillations of the water column pressurize and depressurizes the trapped air. This air is

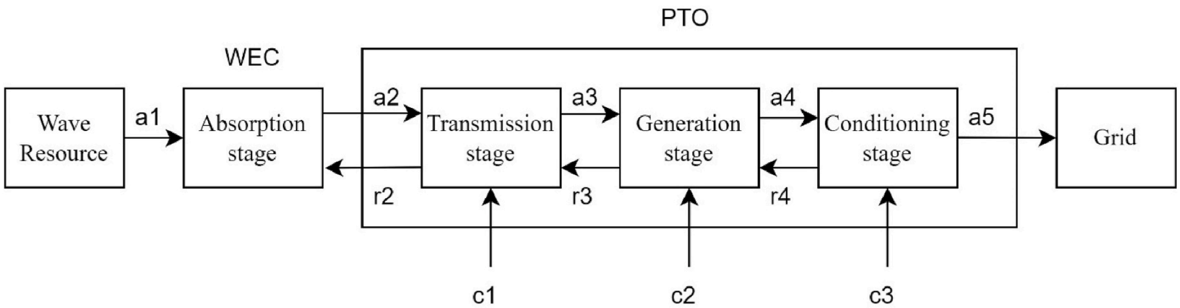
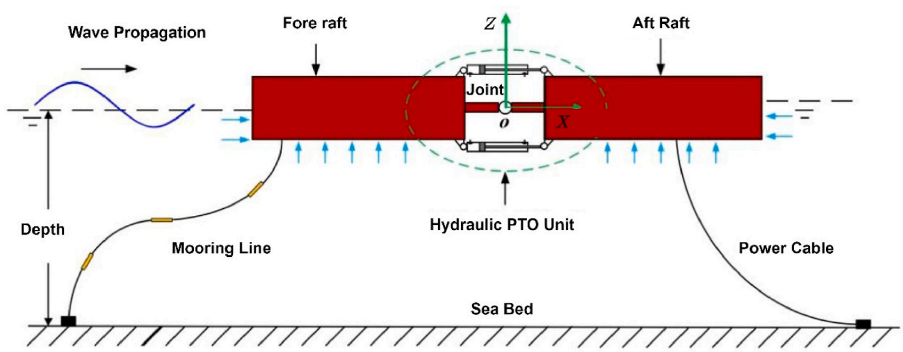
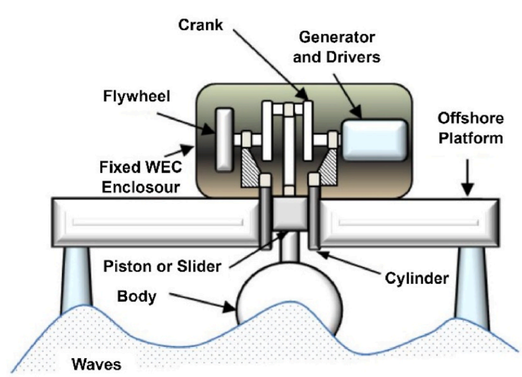


Fig. 1. W2W generic model. The wave resource absorption stage is performed by the WEC absorber while the transmission, generation, and conditioning stages are by the PTO. The flow of actions across the conversion chain, from wave resource until the grid, is represented by the system main parameters a_i ($i = 1$ to 5) while the flow of reactions with parameters r_i ($i = 2$ to 4). The control inputs of each PTO conversion stage are represented by parameters c_i ($i = 1$ to 3). Adapted from Ref. [10].



(a)



(b)

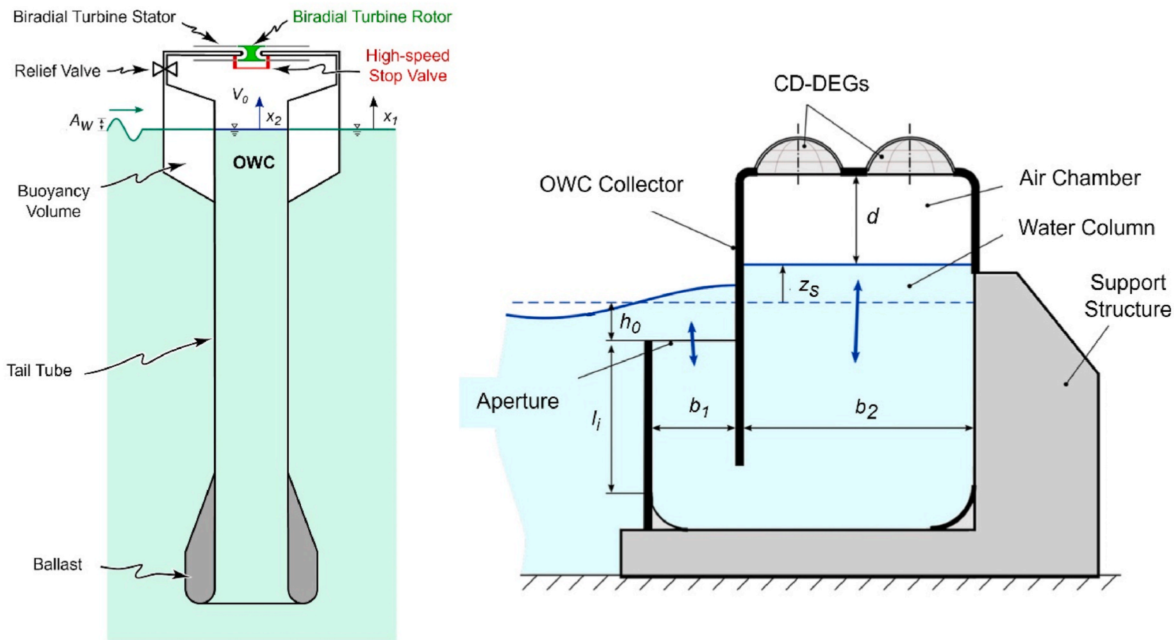
Fig. 2. WEC with hydraulic and mechanical PTO transmissions. (a) Two-raft-type with oil-hydraulic PTO, (b) point floater with slider-crank PTO. Adapted from Refs. [20,21].

then forced through the PTO pneumatic transmission. Fig. 3a illustrates one such device where the PTO is an air turbine [22]. Alternatively, as shown in Fig. 3b, elastic dielectric diaphragms may be used [23].

The HIL method involves partially or completely replacing one or more of the W2W stages with real ones. Fig. 4 demonstrates this approach in the context of the Inertial Sea WEC (ISWEC). It shows a setup made of a dry part, the WEC PTO (left side view) and a wet one, the WEC absorber (right side view). The pitching motions of the hull are absorbed by the PTO inertial spinning flywheel and then mechanically transmitted to the generator for electrical generation. The hull pitching motions, induced by the waves, are simulated with a rocking platform located below the PTO. This HIL simulation is validated by real tank tests with an error as small as 10 % [2].

Fig. 5 provides a detailed and logically structured representation of the HIL methodology applied to the ISWEC. It shows that wave force (wave resource stage) and hull dynamics (absorber stage) are numerically simulated while the test rig supports and interfaces between the simulated hull dynamics (absorber stage) and the real part of the ISWEC (transmission and generation stages). The PTO pitching reference setting is determined in real-time (RT) at the hull dynamics block based on the wave and gyro loads. This reference setting is then transmitted to the control hardware of the rocking platform.

Other high-level representations of the HIL method are presented in the research literature, such as architectures [20,24], layouts [25], configurations [22], overviews [26], block diagrams [23,27], system structure [28,29] and frameworks [12,30]. Some of these representations are related to the wind turbine research fields [12,27] as some of their HIL test rigs may also be applied to WECs [31]. This review defines



(a) (b)

Fig. 3. WEC with the pneumatic transmission. (a) Oscillating-Water-Column (OWC) with biradial turbine PTO (b) OWC with Circular Diaphragm Dielectric Elastomer Generator (CD-DEGs). Legend: (A_w) wave height, (V_0) initial chamber volume and (h_o, l_i, b_1, b_2, z_s and d) the WEC geometric parameters. Adapted from Refs. [22,23].

(a) (b)

Fig. 4. ISWEC HIL simulation. (a) test rig with PTO assembled on top of the rocking platform, (b) hull in the wave tank. Legend: (A) inertial flywheel; (B) Generator and (C) the rocking platform. Adapted from Ref. [2].

these representations as architectures and classifies them based on their actionable and abstracted information.

The term "actionability" or "actionable information" is derived from the definition that refers to the "ability of information to indicate specific actions to be taken to achieve the desired objective" [32,33]. This term is used in the product development process where the customer needs, which are often more abstract and subjective, are translated into product specifications (i.e., actionable information). Thus, the more actionable the information, the easier it is to provide a technical description of the product. Conversely, the more abstract information is, the less actionable for technical implementation. Moreover, the term "actionability" is associated with architecture granularity, which is an appropriate metaphor to consider when analyzing the level of technical detail of the HIL architecture.

For example, Fig. 6 presents a more detailed architecture (i.e., more granular) than the one shown in Fig. 5). It contains an inner feedback loop with the sum block (∑) that determines the error of the PTO relative position. This error is then sent to the simulator hardware, which is not shown in Fig. 5. The details go further to the Analogic to Digital Converters (ADC) and integrator (1/s), thus showing some actionability of this architecture.

Finally, the W2W stages that should be virtual or real are related to

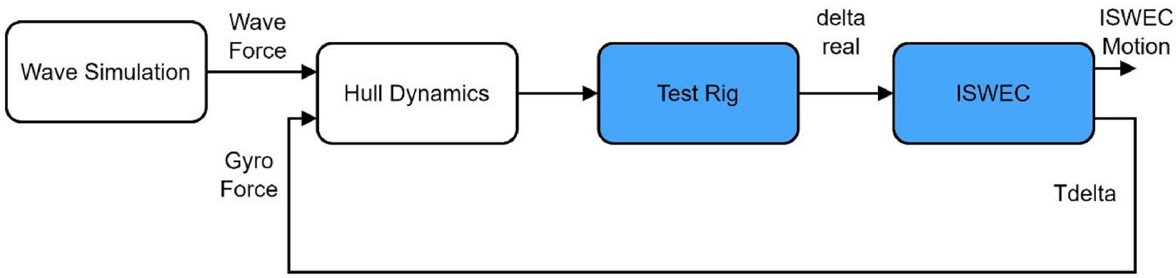


Fig. 5. ISWEC HIL simulation. Logic diagram with virtual and real parts of the WEC, identified with white and non-white colored blocks, respectively. Adapted from Ref. [2].

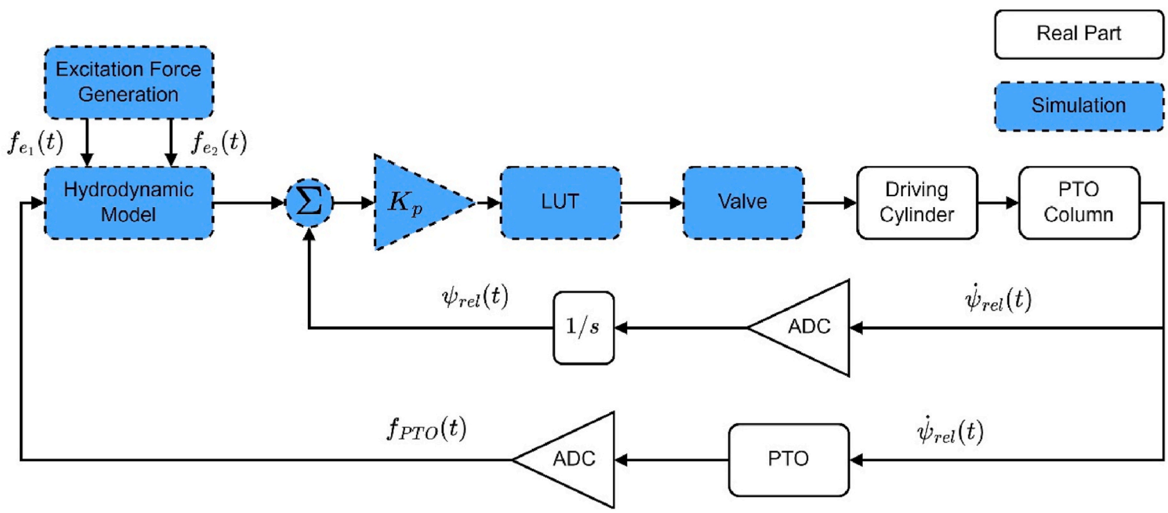


Fig. 6. Heaving point absorber WEC with simulated (grey-colored) and real (white-colored) components. Legend: (f_{e1}) excitation force acting on body-1, (f_{e2}) excitation force acting on body-2, (K_p) proportional gain, (f_{PTO}) PTO force, (ψ_{rel}) bodies relative position and (LTU) the Look Up Table. Adapted from Ref. [4].

the application requirements and the trade-off between expensive tests on real systems and approximated numerical simulations [4,34]. The complexity of the physical system and the level of fidelity required in the simulations are also important considerations. In some cases, it may be more practical and cost-effective to include only certain components in the HIL setup, while in other cases, a full-scale HIL simulation may be necessary to accurately represent the real system behavior. Ultimately, the decision should be made based on a careful evaluation of the benefits and limitations of each approach in the specific application context.

Regarding the advantages of HIL testing, it enables safe, controlled and repeatable testing in a test environment and significantly reduces operational risks, costs and execution time, compared to testing a real system operating in real conditions (e.g., sea or wave tank) [34]. It is also particularly suitable for the initial design stage and manufacturing process of the system, where failures and errors can be early found, investigated and solved, thus speeding up research and time-to-market of new technological solutions [12]. These advantages are especially important when moving directly from the simulation phase (TRL2) to the wave tank or open sea tests (TRL5), which are both time-consuming and very expensive [3,35]. Additionally, the availability of wave tank testing facilities with sufficient capability decreases as the size of the prototype being tested increases, thus leading to higher costs.

Other advantages are the ability to test various scenarios with different system geometries and dimensions that may be not presented in the physical prototype. This method also allows for the simulation of extreme conditions, such as high temperatures and accelerations, as well as performing additional experiments that cannot be conducted during field tests. Sensor and actuator characteristics, such as noise, dead band, hysteresis and backlash, can be included in the simulation. Moreover, the HIL method can investigate the behavior of the system under faulty conditions, such as faulty actuators, sensors, and control algorithms, as well examining their degradation over time, delays, sensor sensitivity errors, temperature effects, or peculiar working environments, as mentioned in Refs. [2,4,12].

Thus, the HIL method is considered an effective and efficient approach to designing, optimizing and testing WEC controllers and advanced PTO systems [35,36]. The HIL method has been utilized in the analysis and validation of PTO dynamics, control equipment, control algorithms, performance, efficiency and mathematical model calibration under typical operating conditions [13,36].

2.2. Methodological challenges

This section describes the methodological challenges that arise during the implementation of the HIL simulation. Fig. 7 reveals some of these issues.

Fig. 7 decomposes the “Simulated parts” subsystem into “Software model and controller” and “Hydraulic power pack system” sub-subsystems. The latter sub-subsystem does not belong to the WEC model as it only serves as an interface between simulated and real parts. Thus, the classification of the “Hydraulic power pack system” as part of the simulated subsystem is related to its functionality in the HIL architecture, which is to present the effects of the simulated WEC parts on the real ones. However, this classification may not be clear, as the power pack and controller are considered real in terms of their hardware and software components, but not real within the context of the WEC model.

Thus, it is important to note that distinctions between simulated and real parts of the model should not be confused with software and

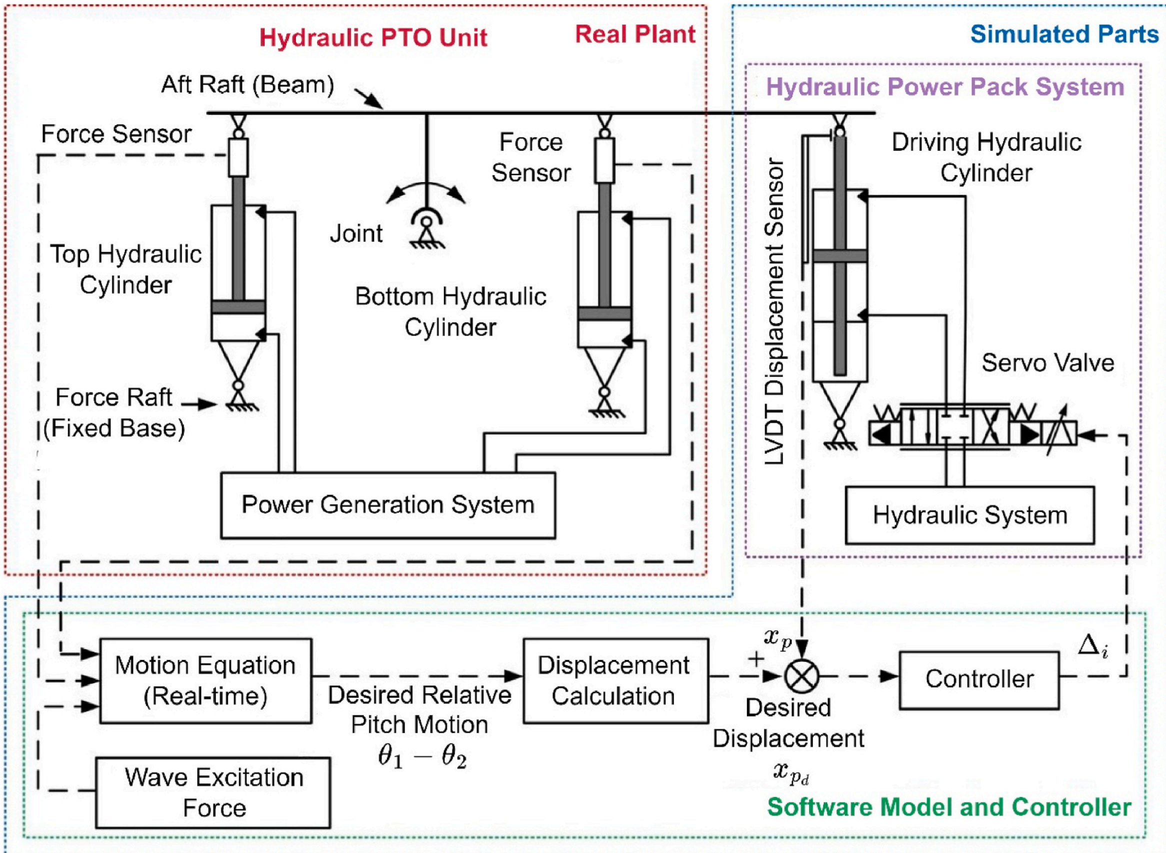


Fig. 7. Two-raft-type WEC with subsystems separating real from simulated parts. Legend: (x_p) cylinder rod displacement, (x_{p_d}) desired displacement, (θ_1) pitch displacement of the fore raft, (θ_2) pitch displacement of aft raft, (Δi) current delta and (LVDT) the Linear Variable Differential Transformer. Adapted from Ref. [20].

hardware distinctions [4]. Hardware can be used to simulate the effects of numerical into real parts (e.g., "Hydraulic power pack system") or may itself be a real part of the WEC model (e.g., "Hydraulic PTO unit"). Similarly, Fig. 8 shows that HIL testing is applied to software as well. The software can be used to simulate parts or be the object of the test itself (control law).

Fig. 8 shows a different decomposition of the HIL architecture. It consists of two distinct subsystems, the "HIL simulation and data logging (prototype scale)" and the "Tecnalia test rig (model scale)". Each subsystem is a combination of hardware and software. The test rig subsystem includes the simulator of the biradial turbine torque (Grid, Power converter and motor), the generation (Generator, PLC and control law), conditioning (Power converter) and grid stages. The turbine simulator is controlled to provide the RT desired torque, calculated from the WEC

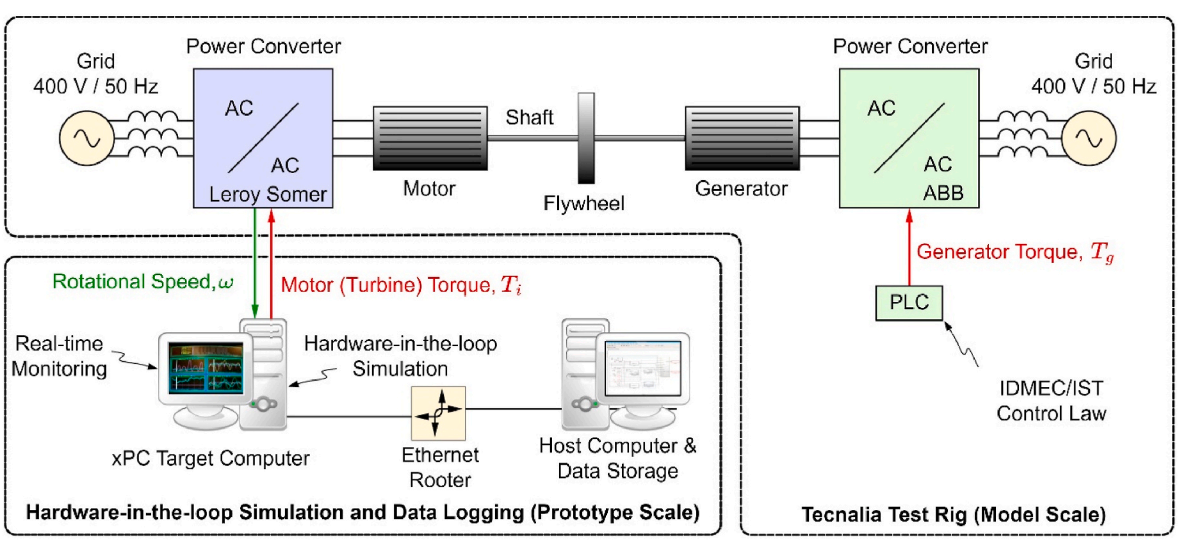


Fig. 8. Representation of the OWC WEC HIL architecture. The wave energy resource and WEC absorber stages are numerically simulated in the target Personal Computer (xPC) while the generator, Programable Logic Computer (PLC), control law, conditioning and grid stages are the real parts of the W2W model (Figs. 1 and 3a). Legend: (AC) Alternating Current. Adapted from Ref. [22].

and wave models simulated in the xPC target computer. Although, the simulator is not a simulated or real part of the WEC model, the generator, PLC, control law (software), power converter and the grid are real parts of the model.

In terms of actionability the architecture shown in Fig. 8 is comparatively located at a lower, more functional or actionable level than the previous architectures, shown in Figs. 5–7. On the other hand, the architecture in Fig. 7 occupies a position between the logical and technological architectures depicted in Figs. 6 and 8, respectively. Thus, it comprises both logical and technological components featuring the numerically simulated wave resource ("wave excitation force") and absorber ("motion equation") stages, and the real transmission ("Hydraulic PTO unit") and generator ("Power generation system") stages. The interface between the simulated absorber and real transmission stages is performed by the hardware and software controller of a real hydraulic power pack. The interface is regulated based on the error signal, which is derived from the difference between the desired and real displacements. The desired cylinder displacement is determined by the wave excitation forces and PTO forces acting on the hull (i.e., fore and aft rafts). Compared to the previous architectures, the HIL architecture presented in Fig. 7 provides a more detailed depiction of the PTO transmission and the interface between the simulator and real-world components. Thus, logical relations between conversion stages are less evident, but technological implementation is clearer.

Fig. 9 shows an architecture located between the more actionable ones in Figs. 7 and 8 and the less actionable ones shown in Fig. 5. It offers guidance on technical implementation, such as cylinder, piston, power electronics and CD-DEG voltage. The architecture is decomposed into three subsystems: "CD-DEG PTO", "Mechanical driver" and "Software". The "CD-DEG PTO" consists of physical parts, including CD-DEGs, power electronics, pressure sensors and air chambers. The "Mechanical driver" simulates the cyclical compression and expansion of the air inside the air chamber, induced by the water column oscillations. This simulation is performed by a piston that slides inside a cylinder attached to the air chamber. The "Software" subsystem contains the "Hydrodynamic model" and the "Control logics". The former is used to determine the water displacement (i.e., the piston position of the "Mechanical driver") and the latter to control the power electronics of the CD-DEG. The feedback from the CD-DEG ("measured pressure, p_H") is given back to the "Software" subsystem to update the piston position and control logic. Thus, the control logic and the power electronics are real parts of the WEC model, but they are software and hardware, respectively. Furthermore, the interface between simulated and real parts is clearer in comparison to the previous architectures.

Fig. 10 shows a HIL architecture with a similar actionability level to the one presented in Fig. 9. However, parts are classified into two subsystems: "Simulation" and "Hardware" [21,26].

As presented in Fig. 10, the "Simulation" subsystem includes the typical simulated parts of the WEC model, such as the wave resource and absorber stages, as well as the generator and motor control algorithms. However, the motor control algorithm is not a simulated part of the WEC model, because is included in the system that emulates the driving torques of the crank on the generator. On the other hand, the "Hardware" subsystem consists of a flywheel, generator, motor and power electronics ("Electric Machine Drives Board" (EMDB)). The power electronics receive control signals from algorithms to control the generator and motor, respectively. Thus, the authors establish an interface between simulation and hardware subsystems, where the former contains the simulated parts of the WEC model and control algorithms of the crank torque simulator, while the latter includes the real components of the model (i.e., power electronics, generator and inertia wheel) and the crank simulator (i.e., power electronics and motor) [26]. Thus, this architecture is intended to differentiate between software and hardware components, rather than to distinguish between simulated and real parts of the WEC.

Fig. 11 shows an architecture with a comparatively higher actionability level. However, the identification of the simulated and real parts is less evident. The system is designed to test one real and three simulated parts of the WEC model. The real part is the oil-hydraulic transmission stage, which begins with two one-rod-cylinders (4-1 and 4-2) and ends at the motor (#13). The first two simulated parts are the wave resource and absorber stages, which operate within the computer (#19). Their effects on the real parts are realized using a hydraulic power pack consisting of one pump (#1), flowrate valve (#2) and two-rod cylinders (#4). The third simulated part is the generator stage and its physical actuation on the hydraulic motor (#13) is simulated by a magnetic powder braking system (#15 and #16) that represents the generator resistance torque. The desired torque references are determined by an algorithm that runs in a PLC (not apparent in computer # 19), making the PLC and control algorithm the real parts of the WEC model. This architecture uses two interfaces between simulated and real parts, the power pack to emulate the effects of the absorber motions on the

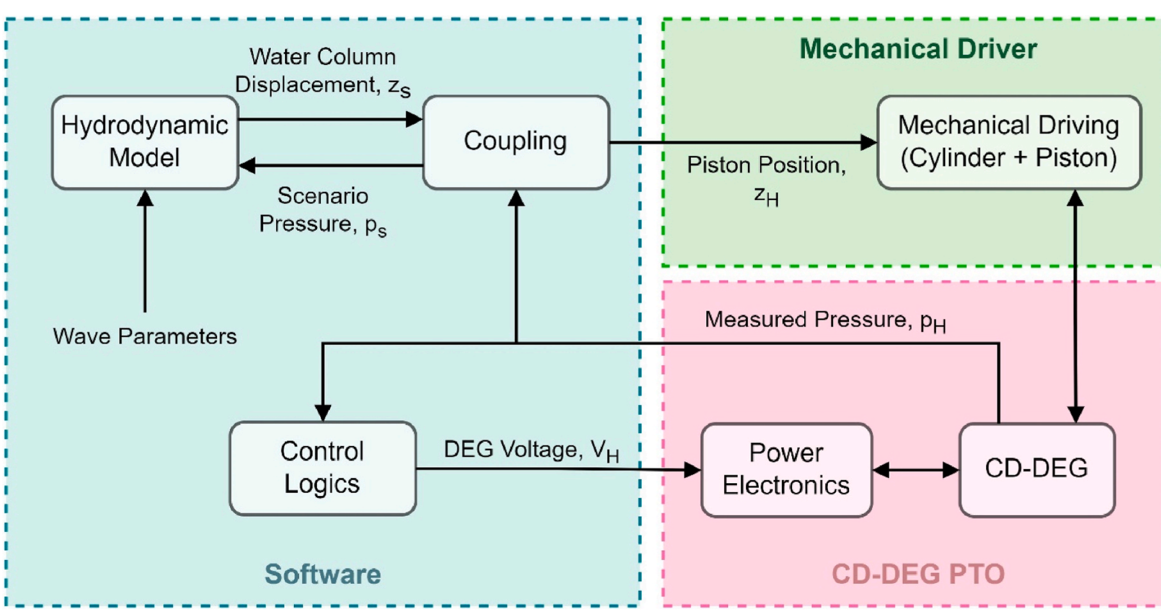


Fig. 9. HIL architecture of the OWC with CD-DEGs (Fig. 3b). Adapted from Ref. [23].

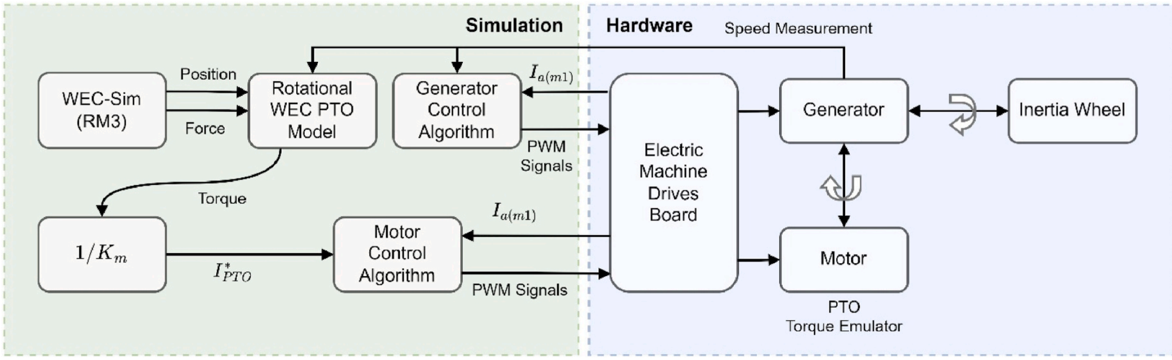


Fig. 10. HIL architecture of the slider-crank PTO at a more abstract level. Legend: ($I_{a(m1)}$) generator current sensor, ($I_{a(m2)}$) motor current sensor, (I_{PTO}) PTO current, (K_m) motor torque constant and (PWM) the Pulse Width Modulation. Adapted from Ref. [26].

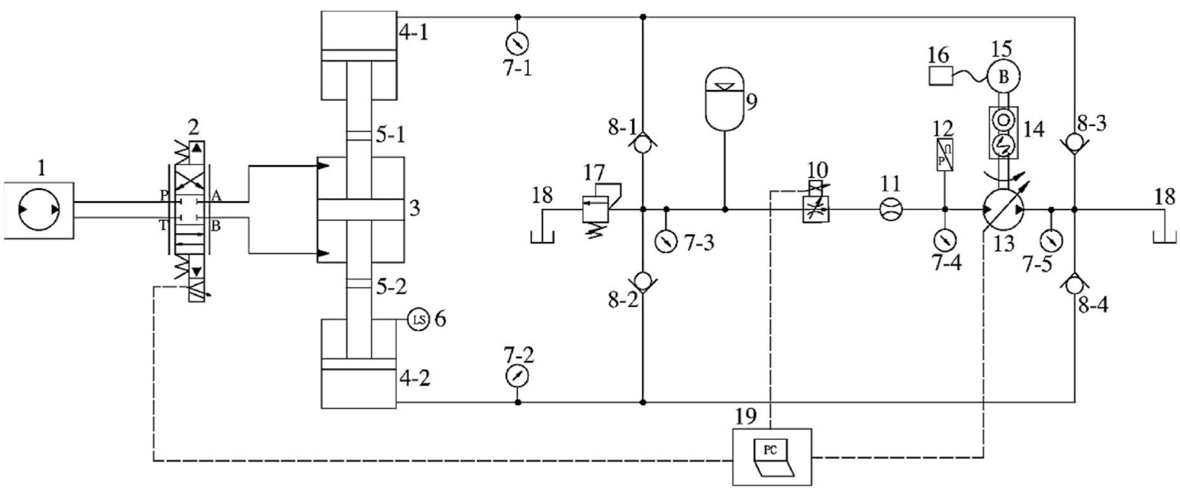


Fig. 11. HIL architecture of a floating-pendulum WEC. Legend: (1) pump station, (2) 3-position 4-way direction-control valve, (3) double-acting double-rod cylinder, (4) two single-acting single-rod cylinders, (5) two bidirectional force transducers, (6) displacement transducer, (7) five pressure gauges, (8) four check valves, (9) high-pressure accumulator, (10) flow control valve, (11) flow-rate transducer, (12) pressure transducer, (13) variable axial-piston motor, (14) torque-speed transducer, (15) magnetic powder brake, (16) current controller, (17) relief valve, (18) low-pressure reservoir and (19) the monitoring system consisting of a Portable Computer (PC) and a PLC. Adapted from Ref. [37].

hydraulic cylinder displacements and the motor braking system to emulate the resistance torque of the generator on the hydraulic motor.

The HIL architectures may be also presented with different actionability levels for the same experimental setup. The objective is to provide a better understating of the setup by exploring the complementarity of abstract and actionable representations. It also helps to have a top-to-bottom view of the methodology and vice-versa. For example, Fig. 12 shows a more actionable representation of the architecture than the one in Fig. 5. It shows two subsystems. In the first one, the wave simulation and hull hydrodynamic numerical models run in an RT Simulator Machine (PXI). The same board contains the algorithm that controls the electrical drive of the WEC pitch emulator by a power electronics unit (DS2000). The second subsystem is dedicated to real parts, which are the generator, gyroscope, controller and control algorithm. The control is performed by a PLC and power electronics unit (DM2020).

Fig. 13 shows another representation of the HIL setup that complements the representation presented in Fig. 10.

The real part, the PTO generator attached to a flywheel, is represented by a DC machine. It is attached to a second DC machine that emulates the crank torque produced by the floater heaving motions and is transmitted to the generator by the connecting shaft. The DC machines are powered by an EMDB which is attached to the I/O board by a terminal board. The interface control algorithm runs on the I/O board.

The same hardware, such as I/O, terminal and EMDBs, is used to control the generator resistance torque, in other words, to test the real parts (i.e., generator and control algorithm). The wave and WEC hydrodynamic RT models run inside the same I/O board. Hence, the I/O board, simulation and development software are located inside the same computer, in other words, the host computer is used to develop the control algorithm.

In summary, the methodological challenges are related to the unclear representation of the HIL method, which is often caused by blurred distinctions between real and virtual WEC parts, as well as parts that do not belong to the WEC. Moreover, the distinction between WEC parts is often misunderstood as being between which is software or hardware, when it should instead be between real parts that physically exist in the WEC and numerically simulated parts. Furthermore, the lack of consistency in taxonomical terms further compounds this issue, with different terms often being used interchangeably to refer to the same concept.

2.3. Technical challenges

2.3.1. Modeling and simulation

The technical challenges associated with implementing HIL testing in WEC development are multidimensional. One of the main challenges is the complexity of simulating and modeling the interactions between the WEC and its PTO. Additionally, there is difficulty in replicating the exact properties of a continuous system operation, such as hydraulic fluid

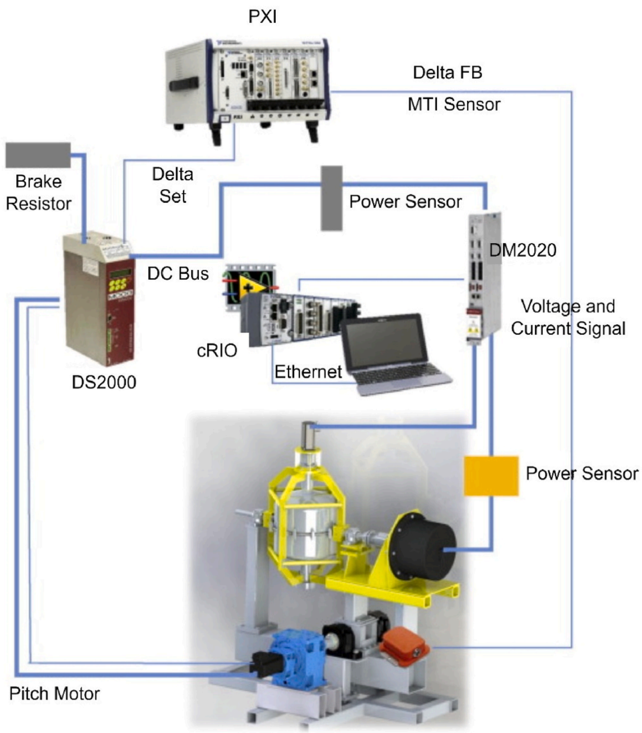


Fig. 12. ISWEC HIL setup. Legend: (DC) Direct Current, (FB) pitch angle feedback and (MTI) Inertial sensor. Adapted from Ref. [2].

degradation and system faults. Model inaccuracies also pose a challenge, as models are often oversimplified for the sake of computational efficiency and to enable the use of linear analysis techniques. This can result in important factors being omitted, such as cylinder friction, oil compressibility, force saturation, velocity and power, which can affect the accuracy of the results [4].

The simulation sample time is a critical aspect of HIL testing because affects the accuracy of the overall process. The number of samples in each irregular sea state is determined by the sample time, making it an important consideration when setting up the simulation. The sample time is influenced by various factors, such as the number of blocks and delays in the model (e.g., Simulink model) and the interface with physical components (e.g., the sampling period of control units) [21,28].

Another technical challenge in HIL testing is the interface between the numerical and physical components of the WEC, which can impact the stability and accuracy of the simulation. Many HIL simulations operate in a fast domain, while large-scale dynamics are slow, making it difficult to maintain accuracy. However, this issue can be mitigated with the use of an interface compensator. For example, Fig. 9 presents a coupling block in the ISWEC HIL to adjust the measured air pressure fed to the software solver, and the piston position calculated from the hydrodynamic model.

RT computing is one of the major challenges in the HIL testing process that imposes one of the main costs of WEC emulators. HIL testing requires high-speed computing and data processing capabilities to achieve accurate RT simulations of WEC behaviour. This can be challenging in the context of large and complex WEC models, which may require significant computational resources to simulate, RT computing platforms such as Field Programmable Gate Arrays (FPGAs) and Graphics Processing Units (GPUs) can be used to accelerate the simulation of WEC models and improve the accuracy of HIL testing [38].

2.3.2. Control

Nonlinearities in the physical system are also an important challenge in HIL testing. Many WECs exhibit nonlinear behavior, which can be difficult to accurately capture in a numerical model. Nonlinearities can arise from a variety of sources, including fluid-structure interactions, non-linear PTOs, and control systems. Neglecting these nonlinearities can result in inaccurate predictions of WEC behavior in real-world conditions. Techniques, such as Nonlinear Model Predictive Control (NMPC) can be used to address some of these issues [39].

Performing control system design within the HIL testing process is also challenging. The design of the control system for a WEC must ensure stable and efficient operation in the face of uncertain and variable input conditions. In HIL testing, the control system must be capable of accurately tracking the desired reference signals and responding to disturbances and other nonlinearities in the system. Advanced control techniques such as Model-based Predictive Control (MPC) and adaptive control can be used to improve the performance of WEC control systems [40].

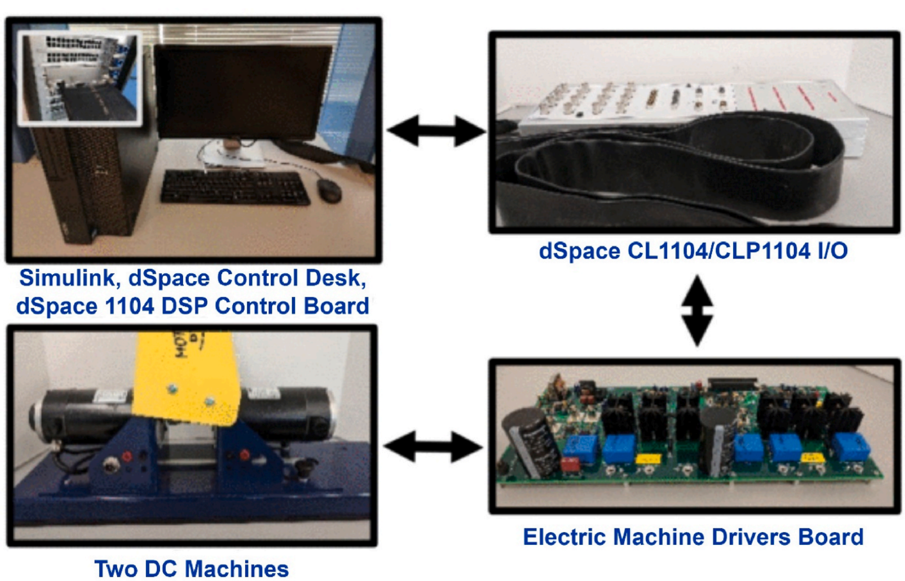


Fig. 13. HIL setup of the slider-crank PTO. Top-left side: host computer with simulation software (Simulink, dSPACE Control Desk) and I/O board (dSPACE 1104 Digital Signal Processing (DSP) control board). Top-right side: I/O terminal board (dSPACE CL1104/CLP1104 I/O). Bottom-right side: power electronics (EMDB). Bottom-left side: emulator drive and target hardware (two DC machines). Adapted from Ref. [26].

2.3.3. Model scaling

Scaled models are often used in testing due to cost and space constraints [41,42]. However, the use of scaled models can have a significant impact on test results, as scaling can affect the physical behavior of the system being tested. Some of the scaling effects are geometric, material, time and control type, and their impacts are observed in the dynamics, fluid dynamics, inertia, friction, and control, including systems instrumentation and actuation. These are explained here in detail.

When a physical system is scaled, its geometric dimensions, such as length, width and height, change in proportion to the scaling factor. As a result, the surface area, volume and mass of the system change by the square and cube of the scaling factor, respectively. The geometric scaling effects can affect the dynamics, kinematics and flow patterns of the system, resulting in changes in the system behavior. The system dynamics can be affected because, for example, it may have a higher natural frequency, which can lead to different dynamic behavior than the full-scale system. In systems involving fluids, scaling can have a significant impact on fluid dynamics and hydrodynamics [2].

For example, the Reynolds number, which is a measure of the ratio of inertial to viscous forces in a fluid, can be affected by scaling. This can lead to changes in flow line patterns and turbulence in the system. Froude's law is also used as a reference to recalculate system parameters. For example, in the case of WECs, the torque versus speed working range is first examined to find the appropriate Froude scale number. The sea state is the factor that causes a change in the magnitude of torque and speed for a given buoy geometry [43]. The wave behavior is dependent on gravity; for this reason, Froude's law is used, to keep the strong relationship between gravitational and inertial forces in the scaled model [34].

The physical properties of the materials used in the scaled model may differ from those of the full-scale system. For example, the stiffness, density and strength of the material may change with scale. These material scaling effects can affect the structural response, energy dissipation and overall behavior of the system. In scaled models, inertia is another important consideration [34]. The mass of components is reduced, which can affect the inertia of the system [43]. This can lead to changes in the response of the system to external forces and accelerations. Also, frictional forces can be affected by scaling. The contact areas between components may be smaller, which can lead to changes in the amount of friction between components [23]. This can affect the system behavior, particularly in systems that rely on friction for stability or control.

In some cases, it may be necessary to scale time in addition to the physical dimensions of the system. This is often the case in dynamic systems where the time scales of interest span several orders of magnitude. Time scaling can affect the transient response, stability and frequency response of the system. The time scaling problem is also important for the control of HIL systems. For example, control scaling effects are important in control algorithms used in the HIL testbed and may need to be scaled to match the dynamics of the scaled model [44]. This can affect the stability, response time and overall performance of the control system [45]. In addition, scaling can also affect the instrumentation (transducers) and actuation components of the HIL control system. For example, scaled sensors may have lower resolution or accuracy, while scaled actuators may have different response times or force capabilities [37].

Typically, testing of large-scale PTOs onshore is oversimplified and does not account for realistic sea conditions, which can hinder a full understanding of the system dynamics. Consequently, the design of the system is often overengineered, sub-optimal in terms of power harvesting performance, and subjected to increased risks [4]. Nonetheless, dedicated solutions can correct these effects and provide a consistent dynamic equivalence between simulated and hardware systems [23].

To compensate for the scaling effects, various methods can be used, such as scaling the control parameters or using a scale model of the surrounding environment. One approach is to use an interface compensator that provides a dynamic equivalence between the simulated and hardware systems [25,46]. The compensator can include adaptive filters and model-based control strategies that account for the scaling effects.

An example of a WEC HIL test with scaled parameters could involve a model of a point absorber WEC. The model would be scaled down to reduce the cost and size of the test rig. The scaled model would include a PTO system, which would be simulated numerically, and a scaled physical model of the point absorber. The scaling factor would affect the dynamic properties of the system, such as the natural frequency and damping. An interface compensator could be used to adjust the control parameters of the PTO system and the point absorber model to compensate for these effects. The compensator would also account for the hydrodynamic effects of the scaled model by using model-based control strategies that simulate the full-scale system.

Overall, scaling effects can be complex and interdependent, and scaling can have a significant impact on the accuracy of the results of HIL testing. The scaling of the model should be done in order not to modify the proportionality of the forces with those of the real prototype (inertial, gravitational, viscous, elastic, and pressure) [34]. It is therefore important to carefully consider the effects of scaling when designing and performing HIL tests and to ensure that the results of scaled tests are adequately validated against the full-scale system.

3. HIL taxonomy

The comparative analysis in Section 2 indicates that a coherent, well-defined and generic HIL architecture and taxonomy has not been established for HIL methodology.

In this study, the HIL system architecture is defined as one or a set of formal representations of the system organization, embodied in its subsystems, components and interrelations. These representations may describe a general, high-level functional organization of the components and/or a more detailed and concrete one, i.e., actionability levels. On the other hand, taxonomy provides a classification scheme and description language of the HIL system architecture. Thus, it provides a vocabulary in which all terms belong to a single hierarchical structure and have relations to other terms.

Thus, a second and more extensive examination of the literature is conducted by comparing terminologies, clustering terms with similar definitions, and organizing them hierarchically and horizontally.

Table 1 shows the review results, organized according to the proposed taxonomic framework. In the first two columns, the proposed taxonomic terms and their definitions are presented while the clustered terms and their utilizations in WECs are presented in the last two columns. The presented definitions are created by merging the definitions of the clustered terms. The latter have been used towards different objects. For example, the term "emulator" is used about the machine that executes the actions of the virtual on the real parts, that is, the interface emulator.

As presented in Table 1, the taxonomy decomposes the HIL system into three subsystems, classified as simulated (S – W2W), real (R–W2W) and interface (S – R W2W) type. Then each subsystem is decomposed into classifications regarding sub-subsystems and components.

The S – W2W subsystem pertains to the numerical simulation of the W2W stages, which encompasses hardware and control algorithms. These stages are numerically modeled and simulated using integrated software running on a host computer. The software comprises a compiler and drivers that convert the developed simulation model into an RT model. The RT model consists of code that can be executed on a dedicated RTSM. The RTSM (e.g., Input/Output board) is integrated into the host computer or a separate computer that interacts with the host computer (in the latter case, referred to as the Master computer). Alternatively, the RTSM may function as a standalone unit. The software also facilitates RT communication with the RTSM to collect data for visualization and tuning of the RT model parameters.

Table 1
HIL taxonomy framework. Legend: (HAWT) Horizontal Axis Wind Turbine, (RTSM) Real Time Simulator Machine, (RTS) Real-Time Simulator, (VAWT) Vertical Axis Wind Turbine, (DuT) Device under Test, (A/D) Analog to Digital, (D/A) Digital to Analog, (D I/O) the Digital I/O and (DAQ) the Data Acquisition System.

Term	Definition	Clustered terms	WEC type
S – W2W:			
Simulated part	Numerically simulated W2W subsystem or part (e.g., hardware, control algorithm).	Numeric, software, control algorithm or virtual component [47]. Simulated system [43], plant [24], part [26] or component [4], Simulated algorithm, Virtual system [25], plant [28], machine [48] or component [4].	CENTIPOD [47], COPPE Heaving point floater [43], Heaving two-body point absorber [4], HAWT [25], OWSC [7], Slider-Crank [26].
Simulation model	Numerical model of the simulated subsystems or/ and parts.	Simulation model [49] or W2W numerical model [31], Virtual model [50].	OWC [49], Wavestar [31].
Simulation software	Tools for the development of the simulation model and compilation into an RT model. User interface tools for online visualization of the RT model parameters and variables.	RT simulation software [24].	
RT model	RT version of the simulation model.	RT virtual rotor model [12].	HAWT [12], OWSC [7], WECfarm [51].
RT code	Executable code of the RT model that is loaded into the RTSM. A compiled control algorithm uses the “RT control code” term.	Real-time code [4], RT control code [24] or W2W code [31].	Heaving two-body point absorber [4], Wavestar [31].
Compiler	Software that automatically converts the simulation model into an RT model. Dedicated libraries of the RTSM may be required for the compilation process (I/O libraries).	RT code generator and compiler [24].	
RTS	Real-time simulation digitally performed in a high-speed processing machine.	RTS [52].	Power system networks [52], OWSC [7].
RTSM	RTS machine is available standalone or integrated into a host computer (I/O board).	RTSM [52], Controller board [9], Target RT machine [23], RT target machine [47].	CENTIPOD [47], HAWT [9], OWC [20], Power system network [52], Two-raft [23], WECfarm [51].

Table 1 (*continued*)

Term	Definition	Clustered terms	WEC type
Communication interface	Provides communication and data transfer between simulation software and RT model.	Interfaces and protocols [52], communication interface [24].	
I/O drivers	Set of pre-defined blocks (I/O library) representing functions implemented in the RTSM that allows the interaction between the RTSM and the RT model.	Library of I/O drivers [24].	Slider-Crank [26].
Host computer	Contains the simulation software, RT model and RTSM (e.g., I/O board). This functionality may be separated into two computers, the first as the RTSM while the second (master computer) is dedicated to the development of simulation models, conversion to RT models, RT code loading on the RTSM, and data storage.	Host PC [13] or machine [4].	Heaving two-body point absorber [4], Membrane-pump device [13], Power system networks [52], Wavestar [49], WECfarm [51].
R–W2W:			
Embedded part	W2W physical subsystem or part (e.g., hardware, controller and control algorithm).	Physical system, component [34], controller [52] or model [22], Physical or hardware component [47]. Real system [28]. hardware and software [7], part [1], component [2], controller [24] or model [1]. Embedded plant [53], component [31] or controller [53].	CENTIPOD [47], Floating OWC [34], Floating-pendulum [22], ISWEC [2], OWC [22], OWSC [7], Power system networks [52], Slider-Crank [26], VAWT [28], Wavestar [31].
Device under Test	Embedded part subjected to experimental testing.	DuT [43]	COPPE Heaving point floater [43]. OWSC [7]
Target hardware, controller or control algorithm	A term is more generic than DuT. It may be a primary or secondary type, if it is the primary target in the testing activity or is indirectly tested during the	Target PC [31], primary and secondary system [6], hardware or controller.	ISWEC [2], Wavestar [31].

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Table 1 (*continued*)

Term	Definition	Clustered terms	WEC type
	testing of a primary target, respectively.		
Development software	Software to develop, compile and load the control algorithm into the target hardware.	Tools for modeling and simulation, code generation software for automatic building of real-time models [24].	
Development computer	Contains the development software and interacts with the target controller.		
S - R W2W:			
Emulator interface	Emulates the physical action of the RT model on the target hardware or controller. The emulator is made of a controller, control algorithm, terminal board, power electronics and electrical drive.	System [43], device [31] or component emulator. The interface between software and hardware [28] or between real and simulated parts [34]. Electro-mechanical driving interface [23]. Actuation system interface [7].	COPPE Heaving point floater [43], Floating OWC [34], OWC [22], OWSC [7], Power system networks [52], Slider-Crank [26], VAWT [28], Wavestar [31].
Interface control algorithm	Control algorithm developed and compiled inside the host computer and loaded into the emulator controller (e.g., I/O board).		
Interface compensator	Ensures an accurate emulation of the physical actions on the target hardware by compensating the difference between the target and test rig specifications (e.g., inertia, rated generator speed, torque and inverter nominal power, scaling effects). The compensation may also add corrections on the emulator interface to guarantee a consistent coupled dynamic behavior between the RT model and target hardware.	Virtual-plant disturbance compensator [28].	VAWT [28].

Table 1 (*continued*)

Term	Definition	Clustered terms	WEC type
I/O board	Used to control the emulator interface, run the RT model and as a target controller with a target control algorithm loaded from the host computer. The I/O board includes the DSP, A/D, D/A and D I/Os and is wired to a terminal board. The connection between I/O, terminal boards and power electronics may be performed by an ethernet-based field-bus network and dedicated communication protocol to meet hard RT requirements (e.g., processing speed).	I/O [54], controller or DSP hardware [26] board. PC-based controller or microcontroller [24].	HAWT [12], Heaving point floater [35], Slider-Crank [54], Wavestar [31].
D/A module	Converts Digital to Analog signal (i.e., signals from RT model to target hardware).	D/A module [29].	HAWT [29].
A/D module	Converts Analog to Digital signal (i.e., signals from target hardware to RT model).	A/D module [29].	HAWT [29].
D I/O module	Input and Output Digital module.	I/O module [4].	Wavestar [55], Heaving two-body point absorber [4].
Terminal board	Allows quick, simple, protected and insulated wire and cable connections between the RTSM (e.g., I.O board) and hardware (e.g., sensors, power electronics).	I/O interface [26].	Slider-Crank [26].
Communication protocol	Used to build a network of interconnected devices, master and slave modules. For example, motor controller modules receive control and send sensor information from and to the target hardware, over a network protocol.	Interfaces and protocols [52].	HAWT [12].

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Table 1 (*continued*)

Term	Definition	Clustered terms	WEC type
DAQ	Data acquisition system.	DAQ [29].	Heaving point floater [35], HAWT [29], OWSC [56].
Power electronics	Used to drive electrical machines, such as a motor and generator, both connected in the same shaft. The motor may drive the emulator interface while the generator is the target hardware. Power electronics may be used for grid simulation.	Power electronics [28], driver [43] or EMDB [54].	COPPE heaving point floater [43], Slider-Crank [26], VAWT [28].
Electrical drive	Part of the emulator interface is in direct contact with the real W2W part.	Electric drive	HAWT [9]

The R–W2W subsystem pertains to the embedded subsystems or parts of the W2W stages (e.g., hardware, controller and control algorithms). These are the real physical parts of the W2W stages subjected to experimental testing, thus named DuT or target hardware, controllers or control algorithms. Development software, installed in a development computer, is used to develop the target control algorithm and compile and load it onto the target controller (e.g., PLC or I/O board).

The S – R W2W subsystem is related to the system that physically emulates the action of the numerically simulated parts on the embedded ones. This system is referred to as the emulator interface and comprises a controller (e.g., I/O board), an interface control algorithm, power electronics and an electrical drive. The controller receives signals from the RT model and implements them on the target hardware through power electronics and an electrical driver. The emulator's dedicated control algorithm performs the precise implementation of these control signals. However, a compensator may be incorporated to adjust the differences between the target and test rig hardware specifications and to mitigate the influence of the emulator dynamics on the simulation.

The RTS and control of the emulator interface are usually performed in the same controller hardware. However, this hardware may be also used as a target controller. Thus, different combinations may be achieved, depending on experimental complexity, specifications and testing costs.

Table 1 shows that the largest and most diverse groups of terms are clustered in the categories located at the top of each taxonomical subsystem, namely i.e., the *Simulated part*, *Embedded part* and *Emulator interface*. Moreover, these terms are found in the largest groups of case studies (fourth column). Thus, these results may indicate that the basic building blocks of the framework are ill–defined across the HIL developers and researchers, and so, affecting all the attempts to build up a concise clear and well–defined taxonomy, based on the hierarchical organization of unambiguous classification terms.

The HIL taxonomy is schematically represented in Fig. 15. The terms are presented in successive levels of classification (taxonomic categories) in decreasing order. This presentation is intended to complement Table 1 to provide a better understanding of the taxonomy and terminology.

The present taxonomy supports the construction of the HIL architecture represented with different actionability levels as presented in Fig. 16. From the point of view of experiment design, where HIL testing requirements are converted into specifications, the process is developed from left to right, by defining the target of the HIL test, then by a formal representation that clarifies which are the real parts of this target and the simulated ones, a clarification of the interface between them and finally, the technological implementation of the experiment. On the other hand, the right-to-left view may complement the implementation of the experiments and the presentation of results since it helps to have a broader view of the methodology.

As also presented in Fig. 16, the formalization of the HIL methodology may be performed by abstraction from the more technological representations, when for example, the researcher is not given higher level ones, and on the other hand, the implementation of the HIL methodology by successive levels of actionable information when the researcher is not provided with lower levels of representations. These translation processes are supported by the presented taxonomic framework.

4. Classification of HIL methodologies

A third literature review pass is conducted to classify HIL methodologies using the proposed taxonomical framework to facilitate comparative analysis. Accordingly, the classification is performed at the technical level, considering the WEC type, PTO technology, model scale, power and TRL. Since the TRL levels are not provided by the literature, they are inferred in each case by analyzing the model scale and HIL setup and using the TRL classification scale [57]. The review results are presented in Table 2.

Table 2 illustrates that although a considerable number of WEC concepts have been proposed worldwide, only approximately a dozen case studies have been published. However, these case studies encompass a wide range of possible WEC categories, based on classifications of their shape and orientation towards the incoming waves [61]. Accordingly, the covered PTO technologies including hydraulic, electrical, mechanical and pneumatics are all within the scope of current research.

Table 2 also shows that model scales that may be tested with the presented HIL test rigs are within 1:1 and 1:30 and power levels between 50 W and 320 kW. The model scales are given in some case studies, not given in others, and some are inferred by applying the power scaling law to given model and prototype powers, such as in the case study dedicated to the Floating pendulum WEC. Then the TRL levels are inferred by using these model scales in the TRL classification table. In particular, higher TRL levels, 7 and 8, are selected if the connection of the PTO device to the grid is emulated or real, respectively.

The TRL results indicate a range of TRL levels within 4 and 8. This means that HIL methodologies have been applied at PTO development stages 2, 3 and 4. Stage 2 (TRL 4) is dedicated to PTO design validation (Bench test PTO & generator). Stage 3 is focused on PTO systems validation and is decomposed in TRLs 5 (advanced PTO) and 6 (True PTO and electric generator). Stage 4 is also decomposed in TRLs 7 (grid emulator) and 8 (grid-connected).

As regards the methodology, the ocean waves and absorbers are, in most cases, numerically simulated (S–W2W), however, the simulation may include some parts of the PTO as well. This happens in the COPPE heaving point floater (pulley and speed multiplier), Floating OWC (turbine), Floating pendulum (gear and rack), OWC (biradial turbine) and Slider-Crank (slider and crank) WECs.

As regards embedded parts (R–W2W), these are mainly the generator and related control (driver, controller and control algorithm). In some cases, other parts may be attached to the generator, such as a gyroscope (ISWEC), turbine (Membrane pump device) and flywheel (Slider-Crank). The OWC with dielectric elastomer generator is a special case where a linear generator is attached to an elastic dome, but still with all the related control (power electronics and control logic). As regards oil-hydraulic technology, a complete hydrostatic transmission, with a hydraulic cylinder, cylinder controller and control algorithm, may be

Table 2
HIL case studies.

WEC	PTO	Scale	Power	TRL	S – W2W	R–W2W	S – R W2W
CENTIPOD [47]	Nonlinear PTO	NA	6 kW	NA	Waves, absorber	PMSG, sensors, instrumentation, power converter, controller and control algorithm.	Linear Testbed
COPPE heaving point floater [43].	Pulley, speed multiplier and generator.	1:5	3.7 kW	5–6	Waves, absorber, pulley, speed and multiplier.	Generator, driver, generator controller and control algorithm.	Electric motor, driver, motor controller and control algorithm.
Flap WEC (Oyster) [58]	Servo motor	1:30	NA	4	Waves	Absorber, servo motor, driver, controller and control algorithm.	Mechanical coupling, servo motor, driver, controller
Floating OWC [34].	Turbine and generator.	NA	11 kW	4	Waves, absorber and turbine.	Generator, power converter, generator controller and control algorithm.	Electric motor, optional flywheel, power converter and controller.
Floating pendulum [37].	Gear and rack, hydraulic cylinders, hydrostatic transmission and generator.	1:1–2	2 kW	7	Waves, absorber, gear and rack.	Hydraulic cylinders, hydrostatic transmission and controller. Generator.	Absorber motions emulator: hydraulic pump, proportional valve and controller Generator emulator: magnetic brake and controller.
Heaving point floater [35].	Carriage and electric actuators.	1:17	NA	4	Waves and absorber.	Electric actuators and drives.	Absorber motions emulator: electric actuators, spring and mass bricks.
Heaving two body point absorber [4].	Hydraulic cylinder, hydrostatic transmission and generator.	NA	NA	NA	Waves and absorber.	Hydraulic cylinder.	Absorber motions emulator: Driving hydraulic cylinder, power pack and controller PTO emulator: proportional valve and controller.
ISWEC [2].	Gyroscope and generator.	1:8	540 W	5–6	Waves and absorber.	Gyroscope, generator, generator controller and control algorithm.	Rocking platform, gearbox, electric motor and motor controller.
Membrane pump device [13].	Turbine and generator.	1:24	11 kW	4	Waves and absorber.	Turbine, generator, generator controller and control algorithm.	Centrifugal fan, electric motor, plenum chambers and duct system.
OWC [22].	Biradial turbine and generator.	1:4.7	11 kW	5–6	Waves, absorber and biradial turbine.	Generator, power converter, generator, controller and control algorithm.	Electric motor, flywheel, power converter and controller.
OWC [23].	Circular diaphragm and dielectric elastomer generator.	1:30 to 1:10	7.7 W	1–4	Waves and absorber.	Circular diaphragm, dielectric elastomer generator, power electronics and control logic.	Electric motor, linear stage and piston.
OWSC [7].	Electromechanical generator(s) with ballscrew(s) – single and parallel configurations	1:1	65 kW	4	Waves and absorber	Single PMSM generator configuration, power converter, controller and control algorithm. Parallel PMSMs generators configuration	Parallel PMSMs configuration, operating as motors. Single PMSM configuration, operating as a motor
Slider-Crank [54]	Slider, crank, flywheel, generator and drives.	1:25 1:15	50 W 250 W	4	Waves, absorber, slider and crank.	Generator, flywheel, EMDB and generator control algorithm.	Electric motor, EMDB and motor control algorithm.
Two-raft [20]	Hydraulic cylinders, hydrostatic transmission and generator.	NA	NA	NA	Waves and absorber.	Hydraulic cylinders, hydrostatic transmission, generator and controller.	Hydraulic cylinder, servo-valve, hydraulic system and controller.
Wavestar [49]	Hydraulic cylinder, hydrostatic transmission and generator.	1:1	11 kW	7	Waves and absorber.	Generator, generator controller and control algorithm.	Electric motor, power converter and controller.
Wavestar [55]	Multi-chambered cylinder, discrete control array, hydrostatic transmission, generator and power converter.	NA	320 kW	7–8	Waves and absorber.	Full PTO, multi-chambered cylinder controller and control algorithm, generator controller and control algorithm.	Hydraulic cylinder, servo-valve, hydraulic power pack and controller.
Wavestar [59]	Linear PTO	1:20	NA	NA	NA	Absorber, direct drive, controller and control algorithm	Wave tank paddles (generate on the tank water the actions of a wave numerical model
WEC array [60]	Linear PTO	NA	50 W	NA	Waves and absorber	Linear generator, AC/DC rectifier, electronic board	Simulator rotating motor, driver.
WECfarm [51]	Linear PTO	NA	NA	NA	NA	Absorber, PMSM generator, gearbox, rack and pinion system, controller and control algorithm	Wave tank paddles (generate on the tank water the actions of a wave numerical model)

NA stands for Not Available.

attached to the generator (Two-raft and Wavestar). This latter case is a full implementation of the PTO technology, but other cases may exclude the generator (Floating pendulum) or use only one fraction of the PTO like in the Heaving two body point absorber WEC (hydraulic cylinder).

The interface emulator (S–R W2W) predominantly comprises an electrical motor, with or without a flywheel, and related control (driver, controller and control algorithm). It may be connected to the embedded parts by a rotating shaft (e.g., COPPE), gearbox and rocking station (ISWEC), linear stage and piston (OWC) or by a bigger chain of interconnected parts, like a centrifugal fan, plenum chambers and duct system (Membrane pump). All these parts are included in the interface emulator.

Furthermore, connections to the embedded parts may be performed with interface emulators made of oil-hydraulics, which may include a few parts (Floating pendulum) to a complete system (Two-raft, Wavestar). Magnetic brakes and associated control are also connected to embedded parts (the PTO hydrostatic transmission generator in the Floating pendulum WEC).

The distinctions between these methodologies are furthermore analyzed regarding control algorithms, technologies and HIL representations. The review results are organized around the same case studies and per subsystem class, as presented in Table 3.

Table 3 shows that the simulated parameters, calculated by the simulation models and then sent to the interface emulator, are torque, force, displacement and pressure type. The physical concretization of these parameters is performed with interface conventional control algorithms, such as PI and PID type (some case studies don't reveal the control type). As regards the target control algorithms, they may be the conventional constant damping, linear damping and control law type or the more sophisticated reactive control (Slider-Crank, Wavestar). However, the range of tested control algorithms is comparatively lower than the large range proposed and studied for the PTO control, from reactive and latching to the MPC and more recent and novel control strategies [62].

The target control algorithms run inside industrial PLCs (Beckhoff) and research dedicated PLCs (cRIO) and I/O boards (dSPACE, National Instruments and Speedgoat). These are considered target controllers as well, supposing that have been selected according to the real operating conditions and not because of their availability for testing. The latter may be true, since the same controllers, except the industrial PLC, are

Table 3
HIL case studies (continuation). Legend: (MPPT) Maximum Power Point Tracking, (P) Proportional, (PI) Proportional – Integrative and (PID) the Proportional – Integrative – Derivative.

WEC	Control algorithm			Technologies		
	Simulated	Target	Interface	Target	Interface	Taxonomy
CENTIPOD [47]	PMSG force	PMSG force control (NMPC)	Linear testbed displacement control	Speedgoat (RTSM)	Speedgoat (RTSM)	Unclear separation between representation subsystems. HIL methodology is represented at logical and technological levels.
COPPE heaving point floater [43].	Pulley torque.	Constant damping control.	Torque control.	dSPACE I/O board (1st) Power inverter (1st).	dSPACE I/O board (2nd) Power inverter (2nd).	Clear separation of representation subsystems (S, R and S–R W2W). Representations are provided at a more technological level, however with different levels of actionability.
Flap WEC (Oyster) [58]	Generator torque	Generator torque control (SOSM)	Servo motor torque control	NI 6343 I/O board	NI 6343 I/O board	Unclear separation between representation subsystems. HIL methodology is represented at a logical level.
Floating OWC [34].	Turbine torque	Generator speed control (MPPT, PI).	Motor Torque control (PI).	Beckhoff (PLC)	dSPACE I/O board	Two subsystem representations (S and S–R subsystems are merged and separated from the R subsystem). Top-down description of the HIL methodology, from logical to technological representations.
Floating pendulum [37].	PTO cylinder applied force.	Linear damping.	Cylinder force control.	PLC	RTSM	Unclear separation between representation subsystems. HIL methodology is represented at a technological level.
Heaving point floater [35].	Actuator applied torque.	Actuator torque control (P, PI).	Motor torque control (PI).	Speedgoat (RTSM)	Speedgoat (RTSM)	HIL methodology is represented at a high technological level. S, R and S – R representations are hard to grasp from the provided representation.
Heaving two body point absorber [4].	PTO cylinder applied force	Linear damping force control	Driving cylinder force control.	cRIO (PLC).	cRIO (RTSM).	Two subsystem representations (S and S–R subsystems are merged and separated from the R subsystem). Top-down description of the HIL methodology, from logical to technological representations.
ISWEC [2].	Hull pitch angle.	NA	Pitch angle control (PID).	cRIO (PLC).	NI PXI (RTSM).	Two subsystem representations (S and S–R subsystems are merged and separated from the R subsystem). Top-down description of the HIL methodology, i.e., from abstract down to technological representations.
Membrane pump device [13].	Turbine available pressure head.	Generator control law.	NA	NI6221 I/O board (1st).	NI6221 I/O board (2nd).	HIL methodology is represented at a technological level. S, R and S – R representations are hard to grasp from the provided representation.
OWC [22].	Turbine torque.	Generator control law.	NA	Beckhoff (PLC).	dSPACE I/O board.	Two subsystem representations (R and S–R subsystems are merged and separated from the S subsystem).
OWC [23].	Air column pressure.	Dielectric voltage control.	Piston position control.	Speedgoat (RTSM).	Speedgoat (RTSM)	Three subsystems representation. No clear distinction between S and R subsystems. HIL methodology is represented at a logical and abstract level.
OWSC [7].	Generator Torque	PMSM torque control (passive and reactive)	PMSM torque control	PLC	PLC	HIL methodology is represented at a high technological level. S, R and S – R representations are hard to grasp from the provided representation.
Slider-Crank [30, 54]	Crankshaft torque.	Generator speed control (PI, PID). Reactive control	Motor torque control (PI, PID).	dSPACE I/O board.	dSPACE I/O board.	The S – R subsystem is merged with S and R subsystems. Top-down description of the HIL methodology, i.e., from abstract down to technological representations.
Two-raft [20]	PTO cylinder exerted force.	NA	Driving cylinder position.	NA	NA	The S–R subsystem is merged with the S subsystem. The R subsystem is well-defined.
Wavestar [49]	Hydraulic motor torque.	Generator speed control strategies.	Electrical motor torque control (PI).	Beckhoff (PLC).	dSPACE I/O board.	Two subsystem representations (S and S–R subsystems are merged and separated from the R subsystem).
Wavestar [55]	PTO cylinder exerted force.	PTO cylinder force control (reactive control).	Driving cylinder force control.	NA	NA	HIL methodology is represented at a high technological level. S, R and S – R representations are hard to grasp from the provided representation.
Wavestar [59]	PTO cylinder exerted force.	PTO cylinder force control (EMMC)	Wave tank paddles displacement	NI6221 I/O board (1st).	NA	Unclear separation between representation subsystems. HIL methodology is represented at a logical level.
WEC array [60]	PTO damping force	PTO damping force control (MPC)	Driving motor force control	RT-LAB (RTSM)	RT-LAB (RTSM)	Unclear separation between representation subsystems. HIL methodology is represented at a logical level.
WECfarm [51]	NA	Generator torque control (reactive control)	Wave tank paddles displacement	Speedgoat (RTSM)	NA	Unclear separation between representation subsystems. HIL methodology is represented at logical and technological levels.

NA stands for Not Available.

involved in the control of interface emulators and execution of simulation models (as RTSMs). Moreover, the target and interfacing functionalities may run in the same (Heaving point absorber, OWC and Slider-Crank), probably for economic reasons, or separated I/O boards (COPPE, Membrane pump device).

Table 3 shows that only the COPPE case provides a comprehensive HIL methodological description based on three distinct representation subsystems (S, R and S – R W2W). Although the OWC case also employs three subsystems, the S and R subsystems are not entirely separated. Thus, the methodologies are mostly described with two subsystems, the R and the one resulting from the merging of S and S–R subsystems (six case studies in total). In the remaining cases it is hard to grasp the taxonomic subsystems, mainly because are merged and the separations are unclear (eleven case studies in total).

Table 3 also shows that in six case studies, more than one representation is provided for the same methodology and with different actionability levels, from the top (more abstract) to the bottom (more technological). This approach gives a more in-depth understanding of the methodology. The remaining case studies are located in one of these extremes of actionability, some more abstract and others more technologically oriented, however the broader view of the methodology is lost. Even in these cases several representations are given for the same methodology, but not far from the extremes.

These results reinforce the need to have a well-defined taxonomy to describe and classify HIL methods. One of the benefits would be clear communication between developers and researchers. For example, Fig. 14 describes a methodology applied on the same test rig of the OWC WEC in Fig. 8.

The comparative analysis of these two case studies shows that the same HIL methodology is described with two different representations. The representation in Fig. 8 merges the S–R and R subsystems while the one in Fig. 14 merges the S–R with the S subsystem.

5. Discussion

The review results reveal that knowledge of HIL simulation has been developed in the research field focused on WECs and PTO testing. However, different terminologies and approaches for the representation of the HIL architectures have been identified, leading to challenges in clarifying the HIL simulation approach for a broader community of novice and experienced researchers.

Despite the variations in HIL architectures, certain important patterns are found. The level of architecture actionability and abstractness varies depending on the specific objective, with some setups providing a broader view of the test methodology (more abstract and less actionable) and others a narrower view of implementation details (less abstract and more actionable). In many case studies, one or more levels of actionability are used in conjunction. Another common trend is the presence of an interface between the simulated and real parts of the WEC, which can be challenging to define precisely the boundaries of the simulated and real components. Moreover, the terminology used for HIL simulation can be inconsistent, and it can be difficult to identify which software or hardware is being targeted for testing or interfacing between the simulated and real parts of the WEC. To address these challenges, a taxonomy has been proposed to promote a more systematic and transparent application of HIL simulation methodology in WEC research and other fields.

As regards the technical information, this review highlights significant potential for improvement and application of HIL in WEC research. Despite the limited number of case studies presented, they cover a broader range of WEC development stages, from TRL 4 until TRL 8, making them suitable for adaptation to the specific research needs of researchers and developers. However, this review goes further, by providing global and coherent technical information about typical control parameters and proven technologies in each simulated, emulated and interfacing subsystem of the HIL methodology. This information is crucial for the successful implementation of the methodology, as it plays a critical role in the early stages of experimental design, which can significantly impact the subsequent research activities in terms of time and effort. Therefore, this information should be particularly relevant for researchers, developers and stakeholders seeking to improve the productivity of their activities.

6. Conclusions

This review presents the main technical challenges for HIL implementation that should be addressed by researchers and also critical HIL methodological issues in the state of the art. The latter is an unclear representation of the HIL methodology, caused by blurred distinctions between real and virtual WEC parts as well as parts that do not belong to the WEC, a misunderstanding in the distinction of WEC parts based on software or hardware when it should instead be based between real parts that physically exist in the WEC and numerically simulated ones, and finally, the lack of consistency in taxonomical terms, with different

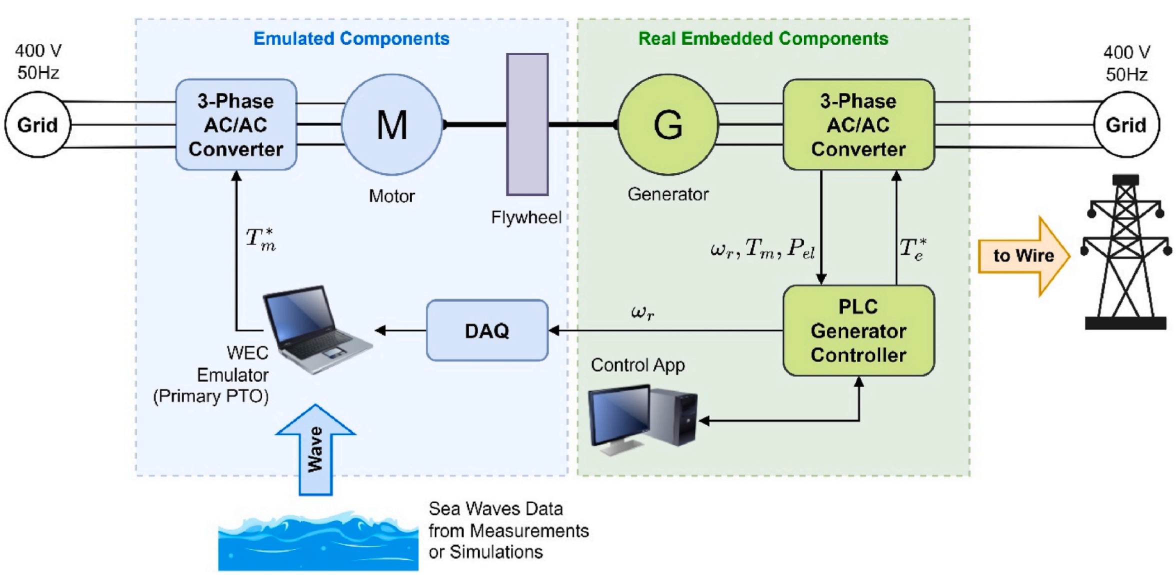

Fig. 14. Representation of the Floating OWC HIL architecture. Legend: (T_m) mechanical torque, (ω_r) rotational speed, (P_{el}) electrical power and (T_e) electrical torque. Adapted from Ref. [34].

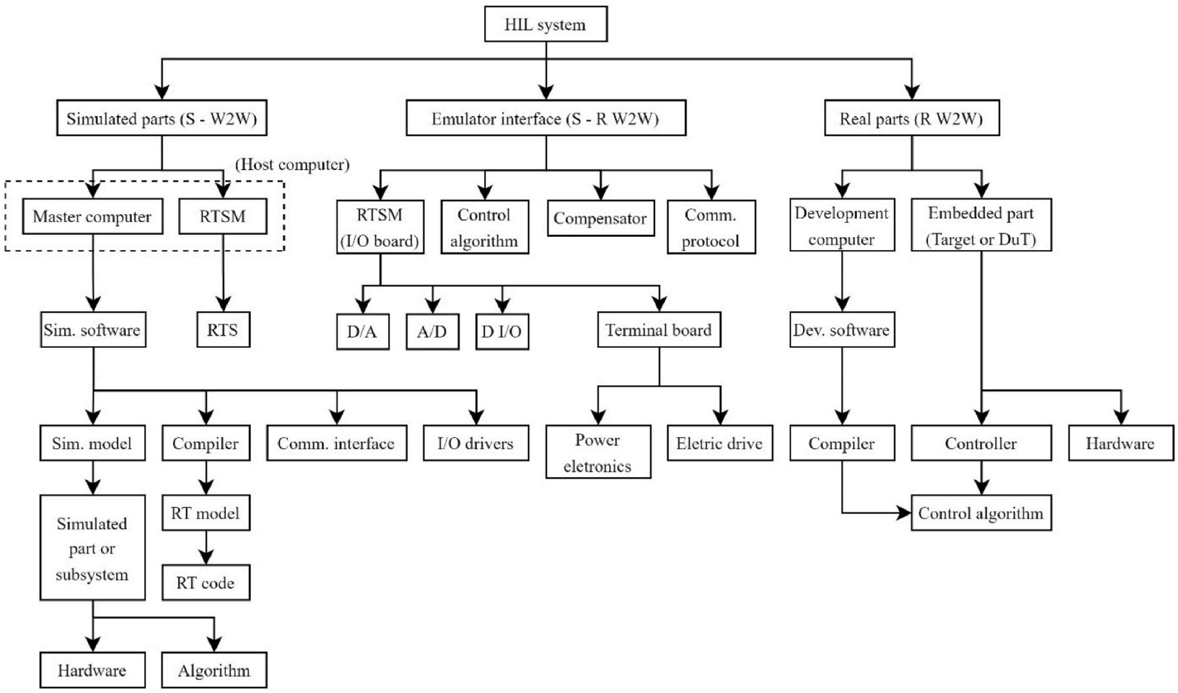

Fig. 15. HIL taxonomy.

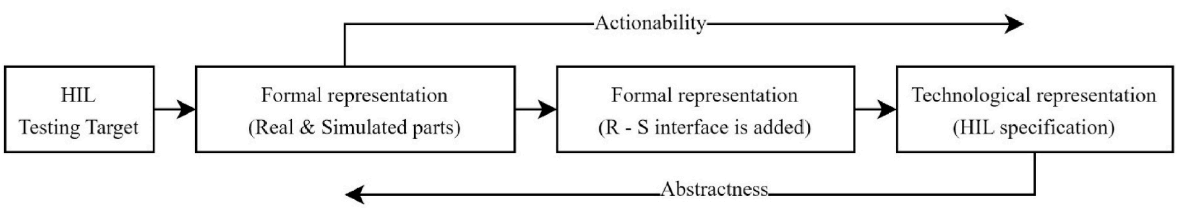

Fig. 16. Actionability and abstractness of HIL representations.

terms often being used interchangeably to refer to the same concept.

To enhance the effectiveness of research activities across all phases, such as experiment design, testing, and result presentation, it is crucial to address these methodological issues. Therefore, a taxonomy and framework to tackle these challenges are presented and recommended for researchers. The taxonomic framework classifies three HIL subsystems that clearly distinguish numerical simulations from physical testing, as well as the interface between them. The terminology is defined to clarify these distinctions and associated terms found in the literature are given to provide researchers with a better understating of case studies, in the light of this more generic and taxonomical framework.

The taxonomic framework also classifies these subsystems regarding the actionability of the provided information. It demonstrates that various representations of the HIL methodology can be employed with different levels of actionability, ranging from abstract and symbolic representations to more technical ones. By utilizing different representations of the same methodology, researchers can achieve a top-down and comprehensive view of the methodology, which can lead to a more effective approach. This approach may be especially relevant for joint research activities performed globally by different players in the research process, such as developers, stakeholders, and researchers. Furthermore, the proposed taxonomic framework is expected to have an important role in the development of the HIL technology, since researchers are the HIL front-end users and developers.

This study also provides technical information regarding HIL implementation and reveals that the reviewed case studies cover a wide range of development phases. Thus, a portfolio of solutions is provided which can be selected by researchers based on their needs. However, these are presented according to the proposed taxonomy to make clear the technical implementation. Moreover, it reveals opportunities for improvements in the methodology and application of more case studies, given that only about a dozen of them have been published.

It is important to note that this review has limitations, including a small number of case studies, and a comparative analysis based on observations and limited quantitative information. Future research should be focused on finding metrics for quantitative comparison between HIL methodologies, such as measuring the actionability level of each HIL representation. By doing so, more robust indications and better-informed decision-making in the research community may be provided.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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