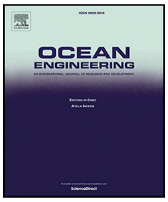
Ocean Engineering 316 (2025) 119794

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Review

Fault management in wave energy systems: Diagnosis, prognosis, and fault-tolerant control

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ARTICLE INFO

Keywords:
Fault components
Fault diagnosis
Fault detection and isolation
Fault estimation
Fault prognosis
Fault-tolerant control
Wave energy converters

ABSTRACT

Wave energy converters (WECs) are a promising technology to contribute to the mix of renewable energies in the pursuit of a cleaner energy future. However, the demanding environment in which WECs operate presents a challenge from reliability and economic perspectives. There is a high likelihood of fault occurrence on WEC components, especially in offshore locations. While the control technology field can enhance energy extraction from WECs, any fault compromises the performance of the system and, in the worst case, can halt energy production, directly impacting revenue generation. Dealing with unexpected faults leads to more frequent maintenance operations, resulting in higher operational expenses. Similarly, strengthening WEC components to withstand harsh conditions comes with increased capital costs. Thus, fault management becomes crucial, whether it involves avoiding operation and maintenance (O&M) entirely or transitioning O&M to planned activities through a fault management mechanism (condition monitoring, fault-tolerant control, etc.), whereby the WEC maintains a certain level of system performance (or prevents emergency shutdown), eliminating the necessity for immediate intervention while still generating energy. In this regard, this study explores WEC components that are most likely to fail, also comprehensively covering WEC fault diagnosis, prognosis, condition monitoring and fault-tolerant control methods covered in the literature. Additionally, unexplored possibilities are pointed out, and future directions are suggested.

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https://doi.org/10.1016/j.oceaneng.2024.119794
Received 3 April 2024; Received in revised form 24 September 2024; Accepted 13 November 2024

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1. Introduction

Ocean waves present an immense, yet largely untapped, reserve of renewable energy, estimated to range from 16 000 to 18 500 TWh/yr (Reguero et al., 2015). The potential of this resource could play a significant role in transitioning towards a more sustainable energy supply mix on a global scale. Moreover, wave power possesses some advantages when compared to other conventional renewable resources, such as solar and wind power: (a) Wave power has a high-energy density, over 10 times that of solar and wind power (McConnell and Prewett, 1983). (b) Wave power has a high availability, up to 90%, while the availability of wind and solar is generally in the range 20%–30% (López et al., 2013). (c) Wave power is relatively more predictable (Chozas et al., 2013; Sasaki, 2017), giving more flexibility for regional and national power management, and planning.

Unfortunately, wave energy has barely been exploited and WECs have yet to reach full commercialisation (Guo and Ringwood, 2021). There are several reasons for this, including the diversity of working principles (Drew et al., 2009; de O. Falcão, 2010; Guo et al., 2022; López et al., 2013) and the lack of convergence in technology. The generated electricity from wave power is, at present, more expensive than other renewables, and can only be economically viable if supported by subsidies (Astariz and Iglesias, 2015). This scenario mirrors the early days of wind turbines, where costs decreased significantly with scale-up to large production volumes.

The levelised cost of energy (LCoE) is the fundamental metric by which energy-generating technologies are assessed, defined as:

$$\text{LCoE} = \frac{\text{Capital Expenditure} + \text{Operational Expenditure}}{\text{Produced energy over the WEC lifetime}}. \tag{1}$$

Current wave energy technical challenges are largely responsible for the relatively poor levelised cost of wave energy. For example, high capital costs are present in the full-scale prototype, testing and deployment. In addition, high operational costs are associated with the harsh conditions in which WECs operate, especially for offshore devices, where maintenance and/or repair activities are limited to specific weather windows (Sørensen, 2009; Ambühl et al., 2015a), threatening to lower the total produced energy over the lifetime of the device.

Control technology can play a major role in the LCoE metric, by developing optimal controllers (Faedo et al., 2017; Garcia-Violini et al., 2020; Faedo, 2020) that maximise energy capture. However, this benefit may be compromised, due to control actions that push the WEC into relatively severe operational states, increasing the range of displacements, velocities and forces in the WEC system, and potentially increasing the risk of a fault, thereby having a detrimental effect on the remaining useful life (RUL) of the device.

The survivability of WEC systems is affected by structural stresses induced by extreme weather conditions, highly variable load cycles, corrosion and biofouling (Yemm et al., 2012; Johanson et al., 2019; Tang et al., 2020). Consequently, the system may experience various types of failure, with sensor and actuator failures being the most common (Xu et al., 2022). Moreover, considering similarities to the offshore wind turbines industry, the ageing of internal electrical and electronic components during operation is also critical, since they are often found to fail more frequently than mechanical components (Faulstich et al., 2011; Ramirez et al., 2020). Furthermore, for a given failure rate, offshore devices will experience more downtime than onshore devices, due to the dependence of accessibility on favourable weather conditions (Sørensen, 2009; Ambühl et al., 2015a).

WEC systems are projected to incur high operation and maintenance (O&M) costs, i.e., around 27% of the LCoE (Tang et al., 2020). Risk-based O&M plans (Sørensen, 2009; Ambühl et al., 2015a) and condition-based maintenance (CBM) (Johanson et al., 2019) can significantly impact the economic feasibility of wave energy developments. Moreover, condition monitoring (CM) methods are able to predict or detect fault scenarios, alerting operators to take remedial action. Nevertheless, if maintenance is not possible due to weather conditions, and the fault is not eliminated in a timely manner, the device may fail to achieve the desired performance or, most likely, cease power production, resulting in LCoE elevation.

For all the reasons mentioned above, it is desirable to have a fault management system, such as a fault-tolerant control (FTC) mechanism, in WEC systems, providing a recoverability property to the system, along with improving its survivability and reliability, contributing to a lower LCoE. This is possible thanks to the ability to reduce maintenance or repair actions on the device, as well as increasing the energy extracted from the WEC, by recovering from impaired performance operation to a level closer to nominal, and reducing the possibility of complete shutdown.

Building on the above discussion, it is evident that a comprehensive review of fault management for wave energy systems is essential to identify the current state-of-the-art and uncover opportunities for further development. A recent study in Papini et al. (2024) provides an extensive review of fault diagnosis and identification (FDI) and FTC for wave energy systems, contextualising the reviewed literature from a control theory perspective. However, it overlooks other important aspects of fault management, such as identifying faults in components critical to function, identification of hardware redundancy, prognosis, and condition monitoring. In this regard, the primary objective of this paper is to investigate fault management for wave energy systems; in particular, identifying fault components *critical to function* and the potential for redundancy in these components. Furthermore, the paper reviews fault management systems related to diagnosis, prognosis, and FTC for wave energy converters (WECs).

The main contributions of this paper are summarised as follows:

- Identification of fault components critical to function in the wave-to-grid (W2G) powertrain.
- Identification of potential areas of faults which can benefit from redundancy.
- A comprehensive review of fault *management* strategies for WECs is presented, including:
    - Fault diagnosis, including fault detection, isolation, and estimation.
    - Fault prognosis and condition monitoring.
    - Fault tolerant control.
- Finally, future directions are suggested based on needs, with the objective of reducing wave LCoE.

The remainder of this paper is structured as follows: Section 2 describes potential fault components in WECs, grouped by the energy conversion stages involved. Section 3 overviews fault management for WECs, including Sections 3.1, 3.2, 3.3 and 3.4 exploring redundancy, fault diagnosis (FD), fault prognosis and condition monitoring, and FTC methods for wave energy conversion systems, respectively. Finally, Section 4 concludes the work with a discussion and suggested further directions.

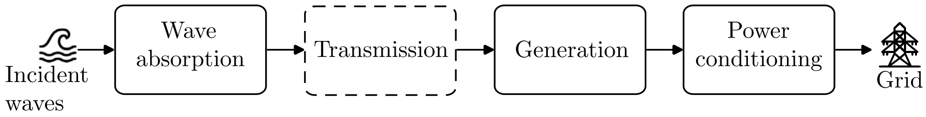

Fig. 1. Typical energy conversion stages in WEC systems. The transmission stage, indicated by the dashed box, can either be present (e.g., in hydraulic or pneumatic transmissions) or absent (e.g., in a direct drive powertrain), resulting in four-stage conversion or three-stage conversion, respectively. Adapted from Said and Ringwood (2021).

2. Potential fault sources in WECs

This section highlights the potential fault sources in wave energy conversion systems. In particular, components *critical to function* are identified for various parts of the wave-to-grid (W2G) powertrain, including wave absorption, transmission, generation, and power conditioning stages, shown in Fig. 1.

A typical wave-to-grid (W2G) wave energy conversion system contains multiple stages responsible for converting raw wave power into useful electric power (Said and Ringwood, 2021). Possible energy conversion stages are described as follows (Penalba and Ringwood, 2016):

- **Wave absorption:** This stage concerns the WEC technology used to harness the wave resource, by converting wave power into absorbed mechanical power, including the WEC body, moorings, and mechanical components of the power take-off (PTO) system.
- **Transmission:** The absorbed power may be converted into pneumatic or hydraulic power in this stage, by means of various transmission mechanisms.
- **Generation:** This stage concerns the transmission power conversion into electricity, using a generator.
- **Power conditioning:** The generated electrical power is adapted for delivery into the grid, under specific grid requirements (Said and Ringwood, 2021).

In some cases, i.e. a direct-drive powertrain, the WEC is directly connected to a generator (linear generator) using a mechanical link, or through gears and pulleys (rotary generator), resulting in three-stage conversion, as depicted in Fig. 1.

To a greater or lesser extent, components within each stage of the energy conversion system are susceptible to failure. Table 1 provides a summary of WEC fault components, grouped by the stage in which they occur. It is noticeable, for instance, that no mechanical transmission faults are reported in the wave energy literature. Reasons for such a lack of information can be associated with the low degree of maturity of the WEC industry, the relative lack of ocean testing experience, and the paucity of studies reported on FD or FTC. Another obstacle lies in the scarcity of measurement data, especially *failure data* (statistics on fault frequency, time to repair and mean time between critical failures), which are crucial for designing and validating new data-driven fault management techniques. To this end, the following Sections (2.1, 2.2, 2.3) aim to identify faults *critical to function* and review already reported faults in different stages of the powertrain. However, it is imperative to acknowledge that the wide variety of wave absorber technologies and associated PTO mechanisms makes it nearly impossible to identify all faults for every potential combination of WEC/PTO.

2.1. Wave absorption stage

Wave absorption refers to the part of the WEC system, primarily comprising the WEC body, that absorbs energy from the ocean waves. A large number of WEC prototypes exist (Drew et al., 2009; de O. Falcão, 2010; Zhang et al., 2021; Guo et al., 2022; López et al., 2013); therefore, diverse structural components are exposed to hostile marine conditions, in which peak energy levels in stormy situations are typically 100 times the levels encountered during normal operation (Yemm et al., 2012). Due to the diversity of WEC prototypes, various classifications have been proposed in literature, e.g., based on device geometry, proximity to the coast, working principle, and inertial characteristics. Fig. 2 shows a WEC classification scheme based on operating principle, adapted from de O. Falcão (2010) and Guo and Ringwood (2021). Fig. 2 categorises WECs into three types: oscillating water columns (OWCs), wave-activated bodies, and overtopping devices, with examples of each type at the pre-commercial stage.

Several WEC structural failures have been reported (Guo and Ringwood, 2021), as detailed under absorption column (relating to the WEC body) in Table 1, which suggests that the survivability problem is more critical than the energy-efficiency conversion problem (Guo et al., 2022) from a fault management perspective. For example, a water tank perforation fault is considered in González-Esculpi et al. (2020) in the Archimedes Wave Swing (AWS) point absorber (de Sousa Prado et al., 2006; Beirão, 2007). Water brake failure is also examined for the AWS system (González-Esculpi et al., 2020, 2021, 2022, 2023), which protect the device from large forces by sea waves. Water infiltration into the WEC can also cause faults. A water level indicator is developed in Lindblad et al. (2014) to detect water leakage that may affect the generator. Marine debris and biofouling may also produce additional friction between moving parts and wear, as considered in Tang et al. (2020), including in the hinge of the Wavestar WEC (Kramer et al., 2011). Furthermore, Zadeh et al. (2023) considers a sudden increase in floater drag for a two-body point absorber (Anon, 2023b,a), due to the float becoming entangled in debris.

The consequences of structural failure vary depending on the type of WEC. For instance, structural failure in an onshore device, such as a fixed OWC device, may not be as detrimental as in an offshore device due to easier maintenance/intervention accessibility. Nonetheless, structural failures must be managed (monitored, diagnosed, and rectified) to enhance the operational lifespan of the device.

2.2. Transmission stage

Different technologies can be employed to convert the mechanical motion induced by waves into useable energy. Sections 2.2.1, 2.2.2 and 2.2.3 explore the transmission systems employed by WECs, and their potentially faulty components.

2.2.1. Pneumatic transmission

Oscillating water column (OWC) devices contain air chambers as a *pneumatic* gearbox that converts the slow internal free surface motion to high-speed air motion through the air turbine (Gareev, 2011). The oscillating and reversible nature of the airflow through the turbine is a major and unique design challenge that is not typically encountered in the wide range of turbine applications. To overcome this challenge, almost all OWC prototypes tested so far have been equipped with self-rectifying air turbines (Gareev, 2011), which are able to maintain unidirectional rotation of the rotor in reversible airflow conditions. Comprehensive reviews of air turbines can be found in Gareev (2011), Takao and Setoguchi (2012), Falcão and Gato (2012) and Falcão and Henriques (2016).

In pneumatic transmission systems, typically used with OWCs, three components are critical to the function of the OWC, including the turbine (the most important), pressure sensor, and rotational speed sensor. These speed and pressure sensors are crucial for OWC energy maximising control systems, since most OWC controllers rely heavily

Table 1
Summary of fault components surveyed in WEC literature.

Absorption	Transmission			Generation		Conditioning
	Pneumatic	Hydraulic	Mechanical	Rotary	Linear	
• Drag and bending force impact on the WEC structure (Lindblad et al., 2014). • Force transductor (Christensen et al., 2005). • Water leakages (Lindblad et al., 2014). • Water tank perforation (González-Esculpi et al., 2020). • Water brakes (damping subsystem) (González-Esculpi et al., 2020, 2021, 2022, 2023). • Additional friction (Tang et al., 2020). • Entanglement with debris (Zadeh et al., 2023).	• Runaway speed of Wells turbines and a biradial turbine (Falcão et al., 2016).	• Corrosion on the turbine shaft (Tedd et al., 2006). • Biofouling on the water turbine draft tubes (Tedd et al., 2006). • Wear-out of hydraulic oil seals (May et al., 2014). • PTO damping (Ettefagh et al., 2016).	No reports	• Generator overspeed (Forehand et al., 2016; Carrelhas et al., 2023).	• Overheating of the stator winding (Lindblad et al., 2014). • Water leaking into the generator (Lindblad et al., 2014).	• Power switches (Adaryani et al., 2021; Ramirez et al., 2020).

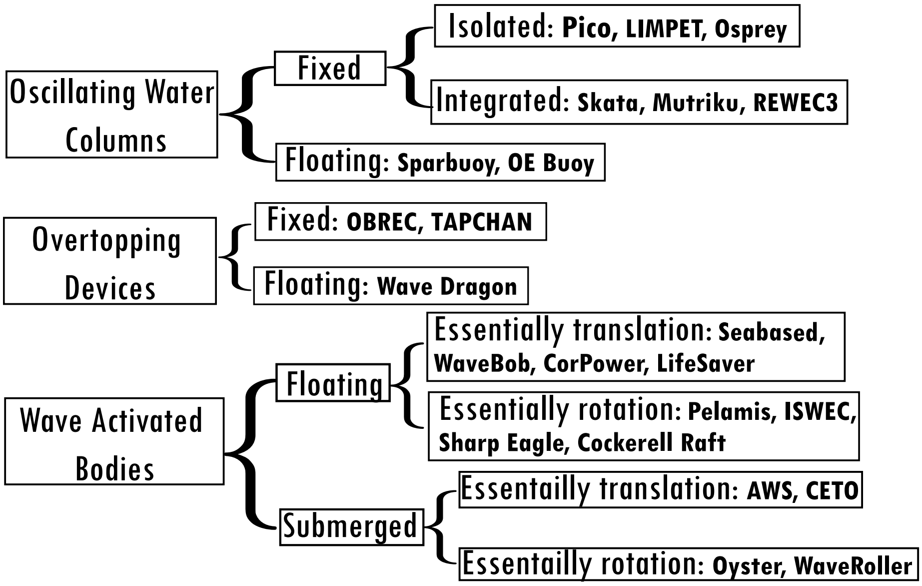

Fig. 2. WEC classification. Inspired by de O. Falcão (2010) and Guo and Ringwood (2021).

on turbine rotational speed and chamber pressure information (Rosati et al., 2022). Failure in either of these sensors can be catastrophic to safe device operation. However, the existing WEC literature includes only one study (Falcão et al., 2016) that examines the runaway speed of two types of Wells turbine, and one biradial turbine. The runaway speed is caused by the electrical generator torque vanishing, due to the possible malfunction of the electrical equipment, or failure in the electrical grid connection. The increase in speed beyond a safe level implies a risk for both the turbine and the generator. The effects of other turbine faults (excluding runaway speeds) and sensor faults have yet to be explored for OWC WECs.

2.2.2. *Hydraulic transmission*

Hydraulic turbines and high-pressure oil hydraulics are distinguished as follows:

- **Hydraulic turbines** are used as the prime mover in overtopping WECs (Margheritini et al., 2009; Christensen et al., 2005), and in other devices that pump water to shore station reservoirs, such as some oscillating wave surge devices (Wei et al., 2013). The two main types of hydraulic turbines employed are reaction and impulse turbines (O'Sullivan et al., 2010; de O. Falcão, 2010; López et al., 2013):
  - Reaction turbines operate on the principle of fluid pressure change as the fluid flows through the turbine. They must be encased to contain the water pressure, or must be fully submerged

in the water flow. The two most common types of reaction turbines are Francis and Kaplan turbines. Francis turbines are suited for high-head applications; thus, they are not typically suited to ocean energy applications. Kaplan turbines are more suited to ocean energy devices as they can produce highly efficient power output in low-head applications, as in the sea slot-cone generator (SSG) WEC (Margheritini et al., 2009).

- Impulse turbines operate on the principle of converting the kinetic energy of a high-velocity fluid jet into mechanical energy. The fluid jet strikes the turbine blades, causing them to rotate. The most common type of impulse turbine is the Pelton turbine, as used with the Oyster WEC (Cameron et al., 2010), where the water is pumped to an onshore hydraulic power plant, driving the turbine.

Similar to air turbines in pneumatic transmission systems, hydraulic turbines used with overtopping devices are critical components. Corrosion and marine growth are reported to affect the hydraulic turbines of the Wave Dragon device (Tedd et al., 2006). The corrosion mainly impacts the shaft of the turbine, while the turbine draft tubes may experience marine growth, increasing friction losses and reducing performance.

- **High-pressure oil-hydraulics** are an energy conversion method particularly suitable for converting large forces or moments applied by waves to slowly oscillating bodies (in translation or rotation) (Drew et al., 2009; O'Sullivan et al., 2010; de O. Falcão, 2010; López et al., 2013), i.e. high-force, low-velocity scenarios. Oil-pressure hydraulic PTO systems have been widely used in wave energy applications with multiple devices, due to their high force density for low velocities, and ease of power flow rectification (Penalba and Ringwood, 2016). The device motion is converted into hydraulic energy by a hydraulic cylinder, or by multiple cylinders. A hydraulic motor drives an electrical generator, transforming the hydraulic power into electrical power. To provide energy storage, /or to maintain a constant flow to the hydraulic motor in order to generate even power output, a gas or oil accumulator system that stores energy over a few wave periods is typically inserted between the hydraulic cylinder and the motor. Implementation of an oil-hydraulic PTO system can be found in the Pelamis WEC (Henderson, 2006).

Hydraulic circuits in WECs present specific challenges (Drew et al., 2009) due to the variety of components involved. In addition, the set of components critical to function also varies with the control philosophy which, in turn, varies with the type of component used. For example, with conventional hydraulic cylinders operating as a passive pump, the control PTO force/torque induced in the hydraulic motor is determined by the pressure difference between the two chambers of the cylinder (Penalba and Ringwood, 2016). However, other control strategies, such as phase control and force control, enhance controllability by incorporating active valves, accumulators, and discrete displacement cylinders (Hansen et al., 2013), albeit at the expense of an increase in the component count critical to function for the system.

In the wave energy literature, some studies (Tedd et al., 2006; May et al., 2014; Ettefagh et al., 2016) reported faults in the different components of hydraulic PTOs, as detailed in Table 1. Wear or damage in hydraulic seals can have serious impacts on devices, such as leakage across pistons, introducing a flow deadband that can lead to servoing errors (May et al., 2014), in addition to potential environmental issues. For example, a percentage reduction in the damping coefficient in the Pelamis PTO is assumed in Ettefagh et al. (2016), due to leaks or valve faults in the hydraulic system. Hydraulic hoses are also known to fail (McConnell and Prewett, 1983), and are suggested to be replaced by rigid steel piping (Salter et al., 2002).

2.2.3. Mechanical transmission

Mechanical transmission systems may be one of the best-known technologies due to their application in several diverse, but relatively mature, industrial sectors, such as the automotive industry. Nevertheless, due to the reciprocating motion of WECs, traditional mechanical transmission systems may not be adequate. A variety of conventional transmission mechanisms, such as rack and pinion, ratchet wheel, or ball-screw mechanisms, have already been suggested for use in WECs (Penalba and Ringwood, 2016). For example, the CorPower WEC utilises a rack and pinion mechanism (Albady and Öhman, 2015), while the WEPTOS WEC uses a ratchet wheel system (Pecher et al., 2012). However, the greatest challenge of rack and pinion mechanisms is their relatively short lifetime (Penalba and Ringwood, 2016).

As shown in Table 1, to the best of the authors' knowledge, there is an obvious lack of information in the WEC literature, with no documented reports, on mechanical transmission faults. It is worth noting that mechanical transmission systems, like other transmission mechanisms, have diverse critical components, required for optimal function, depending on the mechanical mechanism utilised and the energy-maximising control strategy employed.

2.3. Generation stage

The generation stage involves conversion into electric energy, primarily utilising various types of electrical generator, either rotary or linear. Rotary generators require a transmission mechanism, such as pulleys and gears, possibly including a mechanical motion rectifier (Li et al., 2020), between the absorber and the generator (Fig. 1), if the fundamental motion of the absorber is not rotary. On the other hand, if the fundamental motion of the absorber is rotary, such as in a cyclorotor WEC (Ermakov and Ringwood, 2021), the rotary generator can be connected to the same shaft without the need for a separate transmission mechanism. Similarly, linear generators are generally directly connected to the absorber (Fig. 1), simplifying the transmission system.

2.3.1. Rotary generators

Synchronous and induction machines are the most common generators considered for WEC applications (López et al., 2013; Mérigaud and Ringwood, 2016), among the following possibilities:

- Doubly Fed Induction Generators (DFIGs).
- Squirrel Cage Induction Generators (SCIGs).
- Permanent Magnet Synchronous Generators (PMSGs).
- Field Wound Synchronous Generators (FWSGs).

DFIGs are very common in wind turbines (Mérigaud and Ringwood, 2016), but their utilisation in WECs has the disadvantage of requiring brushes for commutation. Brushes can be a liability in offshore environments, requiring replacement about twice a year (López et al., 2013), while corrosion can be harmful to the neodymium magnets of PMSGs. Nevertheless, PMSGs can be suitable for WECs, due to their energy efficiency and variable speed operation. Synchronous generators and SCIGs have similar behaviour (López et al., 2013).

Electrical machines are typically subject to different types of faults (Bellini et al., 2008), described below:

- **Stator faults:** Stator winding open or short-circuit faults.
- **Rotor electrical faults:** Rotor winding open or short-circuit faults in wound rotor machines, broken bars or cracked end-rings for squirrel-cage machines.
- **Rotor mechanical faults:** Bearing damage, eccentricity, bent shafts and misalignment.

A comprehensive review of these faults, focusing on induction machines, is available in Bellini et al. (2008). In particular, induction generators in WECs are typically required to work in non-stationary

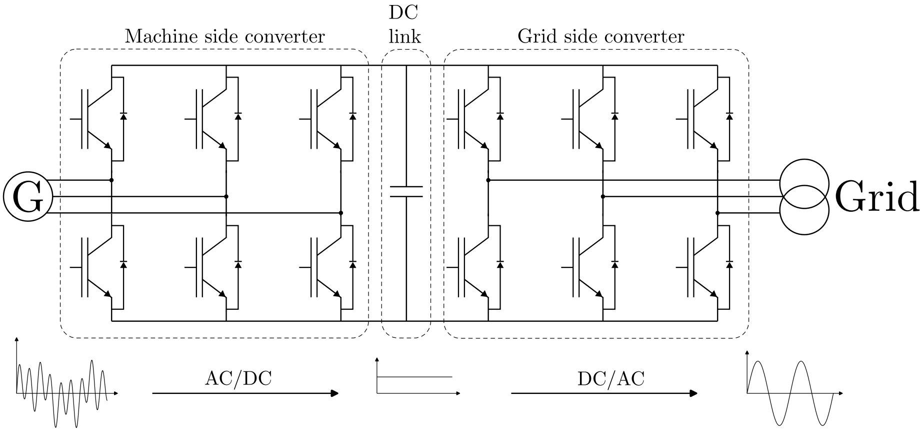

Fig. 3. Full-bridge back-to-back power converters between the generator (G) and the grid.

conditions (e.g., random loads, speed fluctuations), and fault diagnosis under these conditions can be difficult (Riera-Guasp et al., 2013). Moreover, the loss of the counter torque setting point of a SCIG is considered in Carrelhas et al. (2023) in the Mutriku OWC system (Torre-Enciso et al., 2009), which may cause the turbine-generator set to reach runaway speed. Similarly, overspeed due to loss of excitation is observed in Forehand et al. (2016). Regarding synchronous generators, a review of fault detection methods is available in Mostafaei and Faiz (2021).

2.3.2. Linear generators

Linear generators (LGs) enable the direct conversion of absorbed power into electrical power. Although LGs eliminate the need for intermediate transmission, they require a more sophisticated power conditioning stage to be able to connect to the grid (Said et al., 2022).

Specific issues with the LG of the L10 WEC are addressed in Lindblad et al. (2014), such as the risk of overheating due to high currents in the stator windings, and the detection of water leaking into the LG. The study utilises different transducers to measure the translator position of the LG, phase currents, temperature, and water level in the LG.

2.4. Power conditioning stage

The power conditioning stage concerns power quality improvements in the generated power to be injected into the grid. For example, generated power from LGs is variable both in amplitude and frequency and cannot be connected directly to the grid. Fig. 3 shows a typical full-scale back-to-back power converter structure for permanent magnet generators (rotary or linear) (López et al., 2013; Ramirez et al., 2020); the generated waveform is rectified to be converted into a sinusoid, fixed in voltage and frequency and compatible with grid requirements.

The most likely components to fail in power converters are electrolytic filtering capacitors and power switches, open and short-circuit faults being the most typical in power switches (Yang et al., 2011). Short-circuit faults are typically very destructive, and require action to shut down the converter immediately; open-circuit faults do not necessarily lead to a system shutdown, and can remain undetected for an extended time. However, such faults can lead to secondary faults in other converter components, which can eventually lead to significant repair costs (Estima and Cardoso, 2013).

Concerning WECs, Adaryani et al. (2021) and Ramirez et al. (2020) have reported open and short-circuit faults in power switches, albeit tested primarily in simulation or laboratory prototypes.

3. Fault management for WECs

A fault can be defined as an event that changes the behaviour of a system, such that it no longer satisfies its purpose. In a dynamic system, a fault is a deviation of the system structure or the system parameters from the nominal situation (Blanke et al., 2016). Under such a definition, disturbances and model uncertainties may have similar effects on the system (González-Esculpi et al., 2023; Zhang et al., 2023; Xu et al., 2022). While disturbances and uncertainties are typically ubiquitous, and their impact on the nominal performance of the system is suppressed by appropriate measures, like filtering or robust design (Garcia-Violini and Ringwood, 2019), faults, on the other hand, must be detected and their effects removed utilising remedial actions, e.g., using FTC. Based on the level of severity, faults can be classified into three categories: Abrupt faults, intermittent faults, and incipient faults, as illustrated in Fig. 4.

- **Abrupt faults**: These faults are characterised by sudden changes in parameter values, occurring faster than the nominal system dynamics and pose a significant challenge for most detection techniques based on residuals (Abbaspour et al., 2020).
- **Intermittent faults**: Intermittent faults occur at irregular intervals and are a common malfunction in many systems. Various factors, such as fragile electrical wire connections to sensors or actuators, can result in such faults.
- **Incipient faults**: Typically, incipient faults, also known as *soft faults* (Lan and Patton, 2021), develop gradually within processes, often at low rates and frequencies, and are usually unnoticed during their early stages. Sensor/actuator inaccuracy, or partial failure, are primary sources of incipient faults (Safaeipour et al., 2021). If diagnostic tools or monitoring systems fail to detect them, these faults may only become detectable once their effects become severe, potentially leading to catastrophic system damage.

Faults can also be classified (Blanke et al., 2016), based on where they appear in the powertrain, as follows:

- **Plant faults**: Faults that change the dynamical input–output behaviour of the system.
- **Sensor faults**: The sensor readings have substantial errors.
- **Actuator faults**: The influence of the actuator on the plant is interrupted or modified.

Note that the above-mentioned common fault classifications are utilised in the following Sections 3.1, 3.2, 3.3, and 3.4 to address faults from various fault management perspectives. For example, in Section 3.1, hardware redundancy is identified for various kinds of faults (plant, sensor, and actuator) in wave energy conversion systems. Furthermore, to maintain the focus of this paper on fault management strategies, no quantifiable index is proposed here to evaluate fault severity, as evaluating faults themselves is beyond the scope of this study.

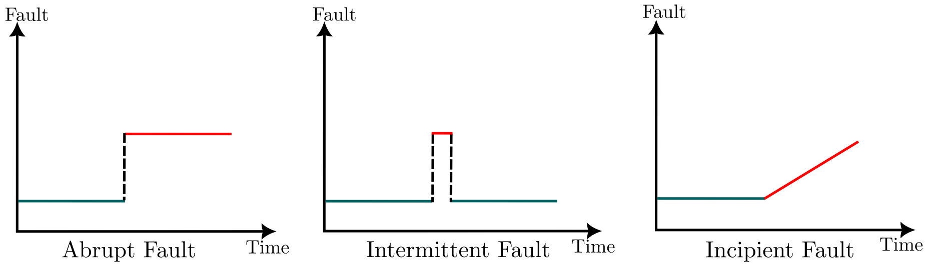

Fig. 4. Graphical representation of faults classification based on severity. Inspired by Abbaspour et al. (2020).

3.1. Redundancy

Redundancy in a system entails incorporating additional components that are not strictly required for regular operation but serve as backups in case of failure in other components. Given the harsh ocean environment, and limited O&M opportunities, a degree of redundancy is desirable for components critical to function. However, it is crucial to acknowledge that not all components can feasibly have additional redundancy, primarily due to untenable costs. Therefore, the decision to implement redundancy must be economically and technically justified. In this regard, the following three areas for faults are identified for wave energy systems, which can benefit from having some level of *potential* redundancy:

- Sensor faults,
- Actuator faults, and
- Mooring line faults.

When considering sensor faults, understanding the typical instrumentation utilised for measurement in a wave energy conversion system is crucial. The choice of sensors depends on the type of WECs, PTOs and the specific measurements of interest. A comprehensive review of offshore wave measurements, for experimentally tested prototypes, is available in Lindroth and Leijon (2011). Generally, most projects prioritise measuring incoming waves at the test site. In OWC systems, standard measurement parameters include chamber pressure and turbine rotational speed (Rosati et al., 2022; Falcão et al., 2020). Buoy systems typically monitor the motion of the floating body (Tyrberg et al., 2011), while overtopping systems focus on measuring the water level in the reservoir (Soerensen et al., 2003). In addition, depending on the transmission mechanism, measurements and sensor modalities change. For instance, in high-pressure hydraulic transmission systems, typical measurements are pressure difference and oil pressure (Lindroth and Leijon, 2011), while translator speed is typically the measurement of interest in LG systems (Soerensen et al., 2003). Regarding sensor redundancy, the cost of sensors is an important consideration. ken provides an overview of some of the most commonly used sensor/control element costs for a wave energy system (with hydraulic transmission) and shows that the typical costs of these sensor modalities range from several tens (e.g., inductive speed sensor) to thousands of Euros (e.g., torque transducer). In order to illustrate the benefits of sensor redundancy, consider an example of an OWC WEC. As previously mentioned in this section, typical measurements in an OWC system include rotational speed and chamber pressure, typically measured using encoders and pressure sensors, respectively. Additionally, the capital cost of these sensors (hundreds of Euros) is significantly lower than the overall cost of the OWC structure, air turbine, and generator (millions of Euros). In the absence of redundancy, a fault in one of these sensors could lead to a failure of the control system and potentially result in a shutdown for safety reasons. Therefore, incorporating sensor redundancy, particularly for critical functions, is essential to prevent such failures from a fault management perspective. Similar arguments can be made for other WECs (wave-activated bodies and overtopping devices) utilising various sensors critical to their function.

Providing redundancy for actuator (PTO) faults is not as straightforward as sensor faults, primarily due to the high capital costs associated with actuators. From an economic perspective, having two full-scale PTOs, for instance, may not be feasible. Furthermore, identifying actuator redundancy is complicated by the wide range of PTO mechanisms available in the literature and the scarcity of data on PTO failures. Even within the same broad wave absorber technology, such as point absorbers, numerous PTO technologies are reported in the literature (Guo et al., 2022; Ahamed et al., 2020). Therefore, identifying potential PTO redundancy requires a certain level of *specificity* regarding both the wave absorber technology and PTO mechanism utilised. *Modular PTO design* has been reported in the literature for various devices (Harne et al., 2014; Vella et al., 2022; Scriven et al., 2020; Rodríguez et al., 2019; Zapata et al., 2022; Zapata and Pérez, 2022; Anon, 2024c), which may be useful for potential redundancy. In particular, Harne et al. (2014) provides a PTO mechanism using a coupled system architecture to enhance system performance. In Vella et al. (2022), multiple modular PTOs are proposed for observation and navigation buoys, while in Zapata and Pérez (2022) and Zapata et al. (2022), modular multilevel converters (MMC) are proposed with direct-drive LG systems to control each coil in the LG stator separately and generate a medium voltage for transmission. Furthermore, in Ocean Harvesting technology, i.e. the infinity WEC (Anon, 2024c), a point absorber uses a ball-screw mechanism with a rotary generator as a PTO mechanism. This wave energy conversion system utilises four smaller PTOs instead of a single large PTO. The primary reasons for using modular PTOs for different devices vary, such as lowering fatigue levels and improving power capture, to name a few. However, modular design lends itself nicely to redundancy purposes; if one module experiences a fault, the others may still be able to provide power until the fault is rectified. Incorporating PTO redundancy for fault management, especially in an FTC framework, can be very useful for wave energy systems, considering PTO force (torque) is the *control input* in most energy-maximising WEC controllers.

Finally, faults in mooring lines can significantly impact wave energy conversion systems, making a degree of redundancy desirable for individual devices and essential for WEC array schemes (Harris et al., 2004). Moreover, energy-maximising WEC controllers impose additional loads on mooring lines due to exaggerated device motion (Papini et al., 2023a). Some expertise from the offshore technologies, such as offshore wind and oil & gas, can be ported to wave energy sector. In particular, safety factors, defined by Det Norske Veritas Germanischer Lloyd (DNVGL[1]) codes are also applied to wave energy, considering their potential as a maritime navigational hazard, and the need for strict station keeping. Interestingly, according to DNVGL codes, mooring system redundancy can be made *optional* for floating offshore wind turbines (FOWTs) by considering an increased safety factor (typically 20%) (Ma et al., 2021). However, it is crucial to design mooring systems to prevent single-line failures from cascading into subsequent failures in other lines. In addition, a recent study (Piscopo and Scamardella, 2021)

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[1] DNVGL is recognised as a leading player in maritime risk assessment and certification.

Table 2
Summary of FD studies on WECs.

Ref.	Device	Fault components			Fault diagnosis	
		Sensor	Plant	Actuator	FDI	FE
Tang et al. (2020)	Wavestar point absorber	Position	Additional friction		Data-based	
González-Esculpi et al. (2020)	AWS point absorber	Position, velocity	Water brakes, tank perforation	PTO (LPMG)	SA & first order filter	
González-Esculpi et al. (2021)	AWS point absorber	Position, velocity	Water brakes	PTO (LPMG)	SA & Luenberg observer	SMUIO
González-Esculpi et al. (2022)	AWS point absorber		Water brakes			SMUIO
González-Esculpi et al. (2023)	AWS point absorber		Water brakes			SMUIO
Zhang et al. (2022)	Point absorber	Position, velocity		PTO		UIO
Zhang et al. (2023)	Point absorber	Position, velocity	Model uncertainties	PTO		UIO
Papini et al. (2023b)	Point absorber	Velocity		PTO		UIO
Xu et al. (2022)	2-body point absorber	Position		PTO		AO
Xu et al. (2023)	2-body point absorber			PTO		AO

shows that installation costs are comparable for both redundant (9-line) and non-redundant (3-lines) station-keeping systems for FOWTs. Therefore, having a redundant mooring system for wave energy conversion system is imperative, given the nature of ocean environment and additional loads imposed by the action of WEC controllers.

3.2. *Fault diagnosis for WECs*

As the name implies, a fault diagnosis system is designed to detect faults, determine their location, and assess their significance within a system. In the existing literature (Chen and Patton, 1999; Blanke et al., 2016; Lan and Patton, 2021), various steps involved in fault diagnosis are categorised as:

- **Fault detection**: Decide whether or not a fault has occurred.
- **Fault isolation**: Identify the component in which the fault has occurred; i.e., the fault location.
- **Fault identification and fault estimation**: Identify the specific faulty component and estimate its magnitude.

The relative importance of the above three tasks is inherently subjective (Lan and Patton, 2021). However, detection is an absolute necessity for any practical system, and isolation holds nearly equal importance. While undoubtedly helpful, fault identification and estimation may not be essential if no reconfiguration (control) action, i.e. FTC, is required. Fault detection and isolation (FDI) are often performed simultaneously, but FDI does not inherently include fault estimation (FE). Consequently, FE is preferred over FDI for FTC purposes, since it comprises both detection and isolation to accurately estimate the fault (Lan and Patton, 2021).

Table 2 summarises FD studies covered in the WEC literature. Noticeably, FE outnumbers FDI in applications, verifying the preference for FE methods over FDI, due to the fact that most FE studies also includes FTC (control reconfiguration). FDI applications are typically based on structural analysis (SA) (González-Esculpi et al., 2020, 2021), and on data-based methods (Tang et al., 2020). On the other hand, FE methods, as depicted in Table 2, are based on state observers, with the unknown input observer (UIO) being the most commonly applied strategy (Zhang et al., 2021, 2022; Papini et al., 2023b), which can be implemented through sliding modes (SMUIO) (González-Esculpi et al., 2021, 2022, 2023). Additionally, adaptive observers (AO) are also reported (Xu et al., 2022, 2023). Table 2 also highlights that FD research efforts are concentrated only on point absorber WECs. Furthermore, within the point absorber category, the only specific device considered is the AWS device. Thus, tank perforation and faults in the water brakes of the AWS are the only device-specific faults reported.

The following Sections 3.2.1 and 3.2.2 explore the FDI and FE methods, respectively, that compose Table 2.

3.2.1. *Fault detection and isolation*

FDI concerns the ability to detect and isolate a fault, i.e., to decide whether or not a fault has occurred, and identify the faulty component (or location), respectively. Model-based FDI methods in the wave energy literature mainly rely on residual generation. Residuals are signals that, when there are no faults present, exhibit deviations from zero primarily because of model uncertainty. These deviations typically hover around zero or are very close to zero when the system is operating normally. However, when a fault arises, these residuals deviate *significantly* from zero, displaying a magnitude that allows detection of the new condition, distinguishing it from the fault-free operating state. It is worth noting that residual generation can also be data-driven, e.g., in Li et al. (2019), where a data-driven residual generation approach is proposed for a wind energy conversion system.

Fig. 5 depicts a fault diagnosis structure based on residual generation (Blanke et al., 2016), where a *decision system* is in charge of fault detection and isolation. The detection of the fault is accomplished by comparing the value of the residual to a threshold (fixed or adaptive), when the residue deviates from zero. Isolation is achieved when the effect of faults on residuals is unique, i.e., different faults impact residuals differently. Otherwise, if faults affect residuals in the same manner, faults are detected but not isolated.

In the wave energy literature, residuals are typically based on mathematical models of the system and use techniques such as analytical redundancy (González-Esculpi et al., 2020, 2021), or state observers (González-Esculpi et al., 2021) (both using SA). SA is a framework to achieve FDI (Blanke et al., 2016), which concerns the analysis of the structural model of a dynamical system. SA attempts to find algebraic or differential equations that express redundancy in the system, termed *analytical redundancy relations* (ARRs), and residual signals are generated based on these ARRs. Thus, the fault detection procedure verifies whether ARRs are satisfied or not; the fault isolation procedure identifies the potentially faulty system components. Applications of FDI, based on SA, in an AWS WEC are studied in González-Esculpi

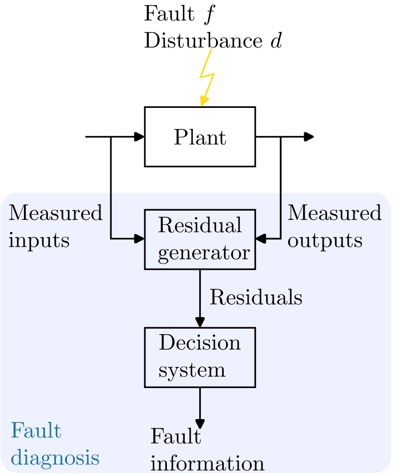

Fig. 5. Structure of a residual-based fault diagnosis system. Adapted from Blanke et al. (2016).

Table 3
Faults considered in the AWS WEC (González-Esculpi et al., 2020).

Fault	Fault component
f_1	Position sensor multiplicative fault
f_2	Velocity sensor multiplicative fault
f_3	LPMG fault
f_4	Upper water brake
f_5	Lower water brake
f_6	Central tank perforation

et al. (2020) and in González-Esculpi et al. (2021). Table 3 depicts the faults considered in González-Esculpi et al. (2020), and the same faults are covered in González-Esculpi et al. (2021), except for tank perforation. Since same WEC is utilised in both studies, the authors utilise the same system ARRs for building the residuals. The difference between methods concerns the implementation of the residuals to avoid computation of the measured signal derivative, which is sensitive to noise. The residuals in González-Esculpi et al. (2020) are generated through a first-order filter structure based on Sundstrom et al. (2014), while González-Esculpi et al. (2021) utilises a Luenberger observer to estimate the residuals. Nevertheless, both studies (González-Esculpi et al., 2020, 2021) assume wave excitation force estimation in the residual formulation. In addition, González-Esculpi et al. (2020) only considers faults taking place sequentially, while González-Esculpi et al. (2021) includes water break faults occurring simultaneously, although no information is gives as to whether these simultaneous faults occur in real-life.

Additionally, a solitary study, i.e. Tang et al. (2020), uses a data-based approach, utilising a test statistic, i.e. spectral distance, to detect a fault for FDI; however, the data used in this case study is generated using Simulink (not actual fault data). This data-based approach applies a spectral graph theoretic approach (Tootooni et al., 2018; Montazeri and Rao, 2018) to the Wavestar point absorber, to distinguish between healthy and fault conditions. As depicted in Table 2, Tang et al. (2020) considers bias and scaling in the position sensor, and additional friction in the device.

In summary, FDI methods reported for WECs are both data-based and model-based. Both model-based studies (González-Esculpi et al., 2020, 2021) implement SA-based FDI in an AWS device, in which the considered faults are successfully detected and isolated. However, model-based approaches, including SA-based methods, are sensitive to model uncertainty (leading to false alarms) and often struggle to detect incipient (soft) faults (Lan and Patton, 2021), which are not addressed in these studies. On the other hand, the data-based FDI approach presented in Tang et al. (2020) requires historical fault data, posing challenges due to the relative immaturity of wave energy technology. Thus, the applicability of these results in real systems remains uncertain. Moreover, none of the FDI studies in the wave energy literature address the *quality of detection*, such as the probability of detection and of false alarms, or time to detect and time between false alarms, to name but a few.

3.2.2. Fault estimation

As mentioned in Section 3.2, FE concerns the ability to identify and measure fault magnitude, and is usually coupled with a control action reconfiguration (FTC) mechanism. In general, FE involves estimation of the fault signals, based on system observer methodologies (Chen and Patton, 1999; Blanke et al., 2016; Lan and Patton, 2021). Most approaches to FE treat the faults as auxiliary states, augmenting the system state-space representation. This relies on the assumption that the faults are differentiable and casts FE as a state estimation problem (Lan and Patton, 2021). As shown in Table 2, adaptive observers (AOs), unknown input observers (UIOs) and sliding mode unknown input observers (SMUIOs) are considered in the WEC literature for FE.

In the AO-based FE developed in Xu et al. (2022), an adaptive law is established to deal with actuator failure in the design of the FE module. In the designed AO, the augmented system state includes information on the faulty system state, actuator failure, and sensor failure (Xu et al., 2022). A two-body point absorber WEC (Richter et al., 2014) is used as a case study, where the sensor fault affects the relative position measurement of the bodies, and the actuator fault is considered as an efficiency coefficient on the control input. Additionally, Xu et al. (2023) extends (Xu et al., 2022) considering a lock-in-place fault of the PTO actuator, using the same observer structure.

Concerning the UIO, the most chosen observer according to Table 2, the principle is to decouple the state estimation error from the unknown inputs (Chen and Patton, 1999). In González-Esculpi et al. (2021), the water brake faults in the AWS device are estimated by utilising an UIO with sliding modes, thus obtaining a SMUIO. The deviation of the damping force, denoted as Δ_{WB}, is incorporated into one of the residuals used for FDI (González-Esculpi et al., 2021) and, under the SMUIO formulation, Δ_{WB} is considered as the unknown input and is estimated. The residual generator in González-Esculpi et al. (2021), used to estimate Δ_{WB}, assumes the wave excitation force signal to be measurable which, in practice, is not feasible (Pena-Sanchez et al., 2020a). Consequently, González-Esculpi et al. (2022) analyses the utility of two estimation methods for the excitation force by comparing the effect of two different estimation methods from a FE perspective. These methods are:

S_1: Filtered estimates from predicted wave elevation.
S_2: Smoothed estimates from the available measurements of the wave elevation.

Thus, González-Esculpi et al. (2022) estimates the damping force deviation Δ_{WB} according to González-Esculpi et al. (2021), and includes estimation of the individual faults in the upper and lower water brakes, Δ_{WB}^{up} and Δ_{WB}^{lo}, respectively, using a Kalman filter. Researchers in González-Esculpi et al. (2022) conclude that the performance of the estimations of Δ_{WB}^{up} and Δ_{WB}^{lo} are superior under S_2, at the price of a trade-off between the desired quality of the fault estimates and the time delay inherent to the S_2 method (González-Esculpi et al., 2022). Lastly, these results are replicated in a similar FE module by the same authors in González-Esculpi et al. (2023), where fault estimate knowledge is utilised for a FTC approach.

An UIO-based FE is implemented in Zhang et al. (2022) for estimation of faults in position and velocity sensors, and in the actuator, of a point absorber. The state-space linear model of the WEC is augmented to incorporate the fault states and their first derivative with respect to time. It is important to note that, in the linear model considered in Zhang et al. (2022), the wave excitation force and the control input affect the system-augmented states in the same way. Thus, the UIO is able to reconstruct the PTO fault under the requirement of knowing the wave excitation force signal. In addition, authors in Zhang et al. (2022) consider a real surface elevation from sensor data, and calculate the excitation force according to the method presented in Pena-Sanchez et al. (2018). Finally, Zhang et al. (2023) complements (Zhang et al., 2022) by proving the robustness of the UIO to model uncertainties in the stiffness, the floating mass, and the added mass parameters of the WEC. Moreover, another UIO-based FE is also applied in Papini et al. (2023b) to a point absorber, considering a velocity sensor and actuator as the faulty components. In contrast to Zhang et al. (2022), Papini et al. (2023b) avoids the requirement of knowing the wave excitation force by considering a new augmented state vector. Although Zhang et al. (2022) and Papini et al. (2023b) consider the same linear model of the system, Papini et al. (2023b) also considers a dynamical model for the PTO, which permits the construction of a new augmented state vector, composed of the WEC system states and the PTO states. The observed actuator and velocity signals are compared to the actual signals to build the residual signal (Papini et al., 2023b). To build robust residual signals, the availability of a displacement measurement is required, as well as the nominal control action (Papini et al., 2023b). Lastly, the UIO proposed in Papini et al. (2023b) possesses a limited bandwidth in the measurement input channel, implying a limitation if high-frequency fault components are present in the velocity measurement.

In summary, FE methods applied to WECs utilise three types of observers. The UIO and the UIO, implemented through sliding modes (SMUIO), are the most popular observers, followed by the AO. Almost all observers require knowledge of the wave excitation force, adding complexity to the FE system. The only exception is Papini et al. (2023b), where the observer requires no excitation force estimate. It is worth noting, from Table 2, that all the FD studies, including FDI and FE, within the wave energy literature, focus exclusively on one specific type of WEC, namely the point absorber, indicating that there is a paucity of information concerning application of FD and FE methods to other kinds of devices, particularly some nearing commercialisation (e.g., see Fig. 2).

3.3. Fault prognosis and condition monitoring

Fault prognosis (FP) refers to the idea of utilising current and historical data to predict the behaviour of a system or a component in terms of its condition, degradation, or failure by estimating the RUL of the system or component, anticipating potential future faults or failures, and guiding decision-making on maintenance, repair, or replacement actions. To illustrate the scope of the diagnostic and prognostic domains, Fig. 6 demonstrates the failure progression timeline of a typical system component (Butler, 2012). Initially, the component is assumed to function properly. Over time, an incipient fault condition may develop, gradually worsening in severity until the component ultimately fails, posing a risk of further damage to other components/subsystems. Typically, the fault diagnosis system domain starts when a component failure occurs while the domain of prognosis, on the other hand, includes the interval between the detection of an incipient fault condition and the occurrence of failure (Butler, 2012). However, it is worth mentioning that modern diagnostics systems can detect incipient faults (Safaeipour et al., 2021).

On the other hand, condition monitoring (CM), or condition-based maintenance (CBM), entails collecting operational data from a system or a component in real-time to detect changes which indicate developing faults or sub-optimal performance, enabling early identification of potential component failure and facilitating the implementation of predictive and preventive maintenance strategies. Both FP and CM concepts fall under the broader umbrella of *predictive maintenance*, aimed at enhancing reliability, reducing downtime, and optimising asset performance. Given the harsh ocean environment, and limited opportunities available for maintenance, CBM is critical for marine energy systems, including wave energy. A review of CBM methods for marine renewable energy modalities is presented in Mérigaud and Ringwood (2016), concluding that new marine technologies can benefit from CBM methods already applied to relatively mature offshore wind energy systems, especially for common powertrain components, such as generator systems and grid interface. CM can be on a system level, that requires monitoring of the complete system, or on a component level, that requires monitoring of a critical component (Johanson et al., 2019). Additional capabilities, beyond diagnostics and prognostics, such as the opportunities for scheduled maintenance (weather windows), are essential to fully embrace the benefits of a CBM approach for wave energy application. Furthermore, CBM requires data on the most common failures and failure modes, typically achieved through failure modes and effects analysis (FMEA) or failure modes, effects and criticality analysis (FMECA)[2] (Abdullah et al., 2020). Due to the nascent development stage of wave energy technology and the considerable diversity of WEC devices and PTO mechanisms, FMECA analysis is carried out on very few WEC devices, such as the mechanical WEC in Chandrasekaran and Harender (2015), Kenny et al. (2016b) for an articulated WEC, and a heaving buoy in Okoro et al. (2015, 2017), on a very superficial level, i.e. no operational data is used. A systematic FMECA, from a *sister application* such as offshore wind (Leimeister and Kolios, 2018; Scheu et al., 2019), could benefit wave energy, since both WECs and wind turbines experience similar environmental loads. However, operational loads on WECs are expected to be higher due to the implementation of energy-maximising controllers that exaggerate device motion (Ringwood et al., 2023).

In the wave energy literature, only a handful of studies focus on CBM methods (Ambühl et al., 2015b; Gray et al., 2017; Rinaldi et al., 2018; Johanson et al., 2019; Xu et al., 2021). In particular, Johanson et al. (2019) explores a software-centric CM approach, which provides flexibility in implementation by utilising existing sensors. In Ambühl et al. (2015b), an O&M strategy is presented for the Wavestar WEC, but failure modes and failure rates are *assumed* for the simulation study. In addition, Gray et al. (2017) presents an O&M tool as a ‘maintenance manager’ to evaluate availability, revenue, operational expenditure (OPEX), failures, and weather windows for specific sites using the failure rate data obtained from the Pelamis P2 testing programme at the European Marine Energy Centre (EMEC). However, the failure rates of components are assumed to be constant over the project lifetime which, in general, is not true, considering that most components will fail more towards the end of a device lifetime. Similarly, various maintenance-related metrics (reliability, availability and maintainability) are evaluated for a spar-buoy (OWC) wave farm in Rinaldi et al. (2018) using a probabilistic model (Monte Carlo simulation). Again, using failure rate data from other applications limits the validity of these results. In Xu et al. (2021), a triboelectric nanogenerator-based WEC technology is presented, which includes an additional feature of ocean wave condition monitoring, which is typically not the primary purpose of a CM module.

Supervision of the structural components falls under the scope of structural health monitoring (SHM). While, in the offshore wind turbine industry, SHM is widely used (Mérigaud and Ringwood, 2016), in the wave energy literature, few studies have been dedicated to SHM. Among these efforts, Lindblad et al. (2014) develops a measurement system for the mooring line force of an L10 WEC (Hong et al., 2013; Boström et al., 2010), which evaluates how the WEC structure withstands drag and bending forces from the buoy line. Similarly, Christensen et al. (2005) reports the failure of a force transductor in the main mooring lines with the anchor block in a Wave Dragon WEC (Kofoed et al., 2006). In Walsh et al. (2015, 2017), acoustic emission-based SHM for a *Lifesaver* WEC is presented as a case study,

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[2] FMECA is an extension of FMEA, which includes critical analysis to identify critical failure points and their probability.

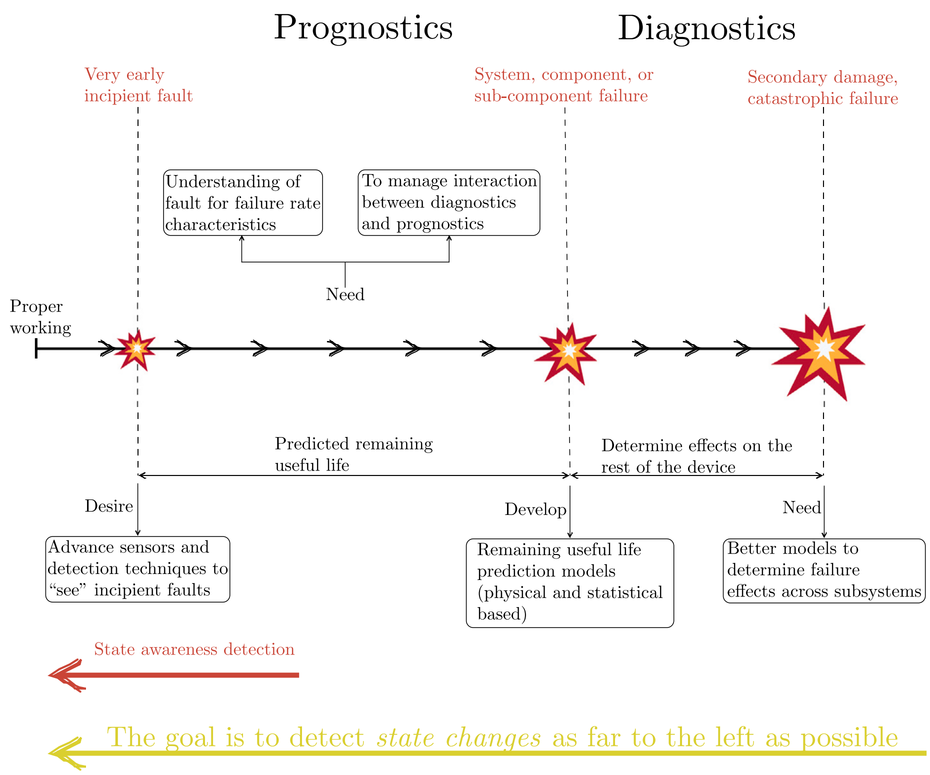

Fig. 6. Failure progression timeline. Adapted from Butler (2012).

utilising data from the offshore deployment of the WEC at Falmouth Bay test site, concluding that the acoustic emission characteristics of powertrain components containing a broad range of frequencies could be used for CM in remote locations. In addition, Meekins et al. (2017) proposes an SHM technique, based on the electromechanical response of piezoelectric transducers, that can estimate new structural damage, and its severity, to inform maintenance.

In summary, CM (or CBM) methods are crucial for lifetime enhancement of emerging technology, such as wave energy. CBM methods for wave energy must encompass FMECA, prognosis, diagnosis, and considerations for scheduled maintenance constraints, fostering a *proactive* approach to fault detection, isolation, and maintenance, rather than being reactive. However, the paucity of component failure data, owing to minimal operational experience in the wave energy sector, hinders the development of such CBM approaches. Insights from other offshore technologies, such as offshore wind, can be leveraged to inform the development of CBM methods for wave energy applications in the future.

3.4. Fault-tolerant control for WECs

A fault-tolerant system has the ability to maintain performance of a system under a fault scenario (Blanke et al., 2016; Lan and Patton, 2021). A performance system perspective of FTC, from Blanke et al. (2016), is illustrated in Fig. 7, where x_1 and x_2 are system performance variables. The system should remain in its required performance region during operation. The nominal controller keeps the system in this region, despite disturbances and model uncertainty encountered in the controller design. Eventually, a fault may take the system from the required performance region to a degraded one. FTC should be able to initiate recovery actions that prevent further performance degradation towards unacceptable or dangerous regions, ideally moving the system back into the nominal performance region. Otherwise, a safety system should interrupt operation to avoid danger for the system, and its environment.

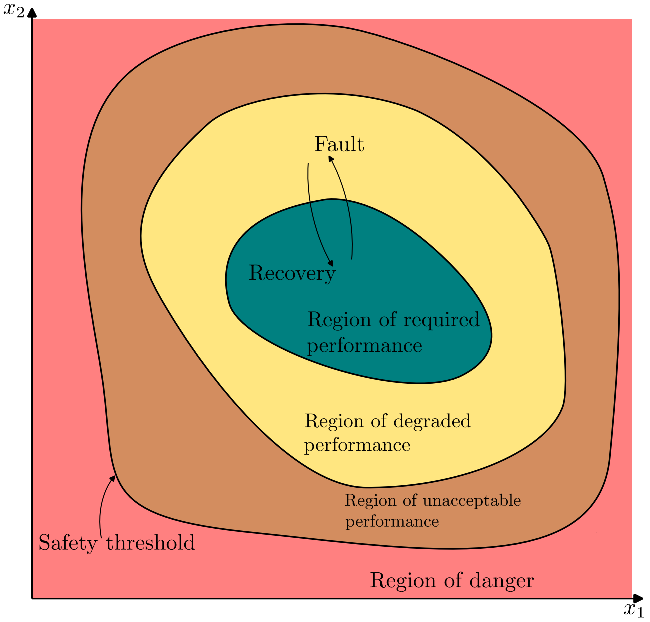

Fig. 7. Performance regions in terms of performance variables x_1, x_2. Adapted from Blanke et al. (2016).

Generally, FTC systems are broadly classified into passive FTC (PFTC), active FTC (AFTC) and hybrid FTC (HFTC) (Blanke et al., 2016; Lan and Patton, 2021), as shown in Fig. 8. In PFTC, the system objective is achieved with either the same control law (robust design) or multiple controllers (of the same process) designed a-priori for healthy and faulty situations. Typically, PFTC relies on the physical redundancy available in various components (control, plant, actuator, sensor, etc.) of the powertrain and does not rely on the fault information (Abbaspour

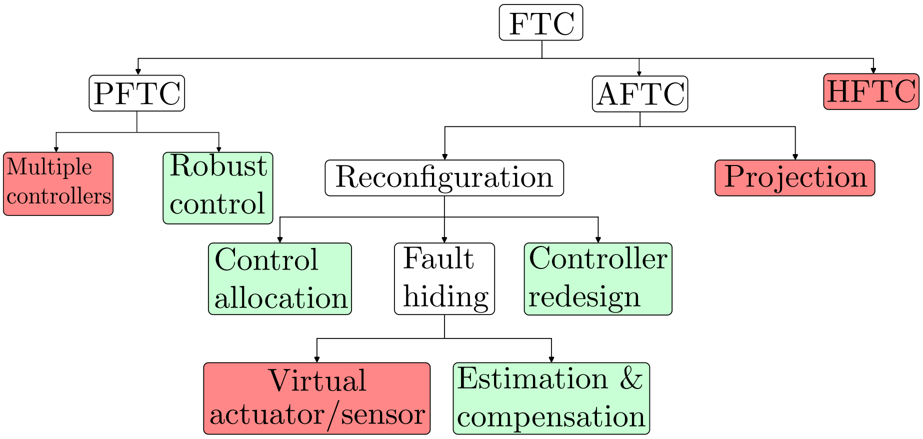

Fig. 8. Classification of FTC methods. Green-highlighted methods are currently utilised for WECs, while the methods in red remain unexplored in the wave energy literature.

et al., 2020). From Fig. 8, it is evident that robust PFTC (green box) has been implemented on WECs (González-Esculpi et al., 2023; Adaryani et al., 2021), whereas multiple controller-based PFTC (red box) has not yet been implemented. In AFTC, on the other hand, the control law is *modified* when a fault occurs, utilising fault information from an FDI/FE module. According to Fig. 8, AFTC methods are further sub-classified as follows:

- Projection: In projection methods, a fault diagnosis unit (e.g., FDI) detects the fault, and the fault is compensated by a switching mechanism that selects the appropriate control action from a pre-computed controller set.
- Reconfiguration: As shown in Fig. 8, there are three reconfiguration methods:
  - Control allocation: In this method, the required control actions are *re-allocated* from the faulty actuators to the healthy ones, according to the fault diagnosis results (Ramirez et al., 2020). Control re-allocation requires physical redundancy, potentially expensive, and limited in application.
  - Controller redesign: Redesigning the controller involves the calculation of new controller parameters, according to the fault occurring (Zadeh et al., 2022, 2023).
  - Fault hiding: This method aims to *hide* the fault from the baseline controller. Two methods are proposed for fault hiding:
    - Virtual actuator/sensor (VAS): In VAS, the fault information is fed into a virtual (i.e., software) actuator/sensor module, which is placed between the actual actuator/sensor and the baseline controller. The fault signal is corrected in the VAS module, such that the fault effect is removed.
    - Estimation & compensation: This method estimates the fault signal to compute a control action that compensates for the fault effect (González-Esculpi et al., 2021; Zhang et al., 2022; Xu et al., 2022, 2023).

Finally, an HFTC approach combines the benefits of both passive and active FTC approaches (Yu and Jiang, 2011). HFTC includes a PFTC as a *safe controller* until a reliable AFTC, based on fault information from FDI/FE, is configured. HFTC approaches have not yet been explored for wave energy applications, as illustrated by the red box in Fig. 8.

FTC applications in WECs are summarised in Table 4, which shows that AFTC applications outnumber those utilising PFTC. In addition, no HFTC studies have been reported in the wave energy literature. Furthermore, similar to the FD applications covered in Table 2, most applications utilise point absorbers as the preferred choice at the absorption stage (see Fig. 1). The AFTC studies on point absorbers (González-Esculpi et al., 2021; Zhang et al., 2022; Xu et al., 2022, 2023) also require a FD stage, and studies typically present both FD and AFTC together. The only other WEC type, other than a point absorber, is the OWC, concerning faults in the power switches of the machine side converter (MSC) and voltage source converters (VSCs).

Subsequent Sections 3.4.1 and 3.4.2 describe passive and active FTC methods applied to WECs, which are detailed in Table 4. In general, FTC improves the performance of the system under fault conditions, or maintains maximum energy extraction. However, specifications related to the type of WEC model/controller utilised for energy maximisation differ between studies.

3.4.1. PFTC approaches for WECs

As mentioned in Section 3.4, and depicted in Fig. 8, PFTC approaches applied to WECs rely on robust control to handle faults that may occur (Blanke et al., 2016; Lan and Patton, 2021). Fig. 9 shows the PTFC approach , which may have redundancy in the control system, actuators, plant, and/or sensors. Fault information is not used for PFTC; however, an FDI module can be valuable for maintenance purposes, such as CBM (Mérigaud and Ringwood, 2016; Kenny et al., 2017).

A PFTC implementation for a WEC is documented in González-Esculpi et al. (2023), where AWS WEC water brakes are considered to fail. The robust controller is based on a nonlinear servocompensator (NSC), which provides position and velocity reference signal tracking for energy capture maximisation. Computation of the position and velocity reference signals requires estimation of the wave excitation force (Pena-Sanchez et al., 2020a,b). Moreover, robustness to a fault in the MSC switches of an OWC WEC, due to an open or short-circuit, is considered in Adaryani et al. (2021). Although the fault-tolerant capability of the system is not the central point of the study, PFTC capability is improved by a direct model predictive controller for the MSC.

In a fault scenario without active fault compensation, PFTC must ensure that the system can continue useful operation (Schulte and Gauterin, 2015). In this sense, an input-to-state stability (ISS) condition for PFTC of renewable energy systems is proposed in Schulte and Gauterin (2015). The study in Schulte and Gauterin (2015) introduces a PFTC design method for nonlinear models in the Takagi–Sugeno form (Lendek et al., 2011), where faults are treated as norm-bounded structured model uncertainties, and the ISS is guaranteed by a set of linear matrix inequalities. The theoretical formulation of the method is addressed for both wind turbines and WEC systems, while the application example only considers a wind turbine (Schulte and Gauterin, 2015).

In summary, to the best of the authors' knowledge, González-Esculpi et al. (2023) is the sole study implementing PFTC on a WEC, based on

Table 4
Summary of FTC studies on WECs.

Ref.	Device	Fault components				FTC	
		Sensor	Plant	Actuator	Converter	Type	Description
González-Esculpi et al. (2023)	AWS		Water brakes (damping)			PFTC: Robust control	Nominal controller based on a nonlinear servocompensator
Adaryani et al. (2021)	OWC				MSC	PFTC: Robust control	The robustness of the MSC is improved through model predictive controller
Schulte and Gauterin (2015)	Generic wind/wave energy system		System parameters change due to faults			PFTC: Robust control	ISS condition to verify if the PFTC design maintains stability in the presence of parameter changes caused by faults
González-Esculpi et al. (2021)	AWS		Water brakes (damping)			AFTC: Estimation & compensation	The controller compensates the damping force deviation.
Zhang et al. (2022)	Point absorber	Position, velocity		PTO		AFTC: Estimation & compensation	The control action that compensates for the faults is added to the optimal controller.
Xu et al. (2022)	2-body point absorber	Position		PTO		AFTC: Estimation & compensation	Multicontroller feedback low
Xu et al. (2023)	2-body point absorber			PTO		AFTC: Estimation & compensation	Iterative learning control
Zadeh et al. (2022)	2-body point absorber			PTO		AFTC: Controller redesign	Reinforcement learning
Zadeh et al. (2023)	2-body point absorber	Position	Damping	PTO		AFTC: Controller redesign	Reinforcement learning
Ramirez et al. (2020)	Floating OWC				VSC	AFTC: Controller allocation	The converter requires extra TRIACS to handle the faulty phase

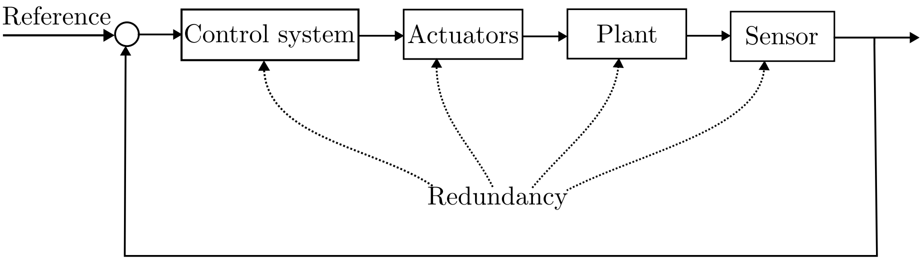

Fig. 9. General scheme of a PFTC. Inspired by Abbaspour et al. (2020).

a NSC robust controller. On the other hand, the controller in Adaryani et al. (2021) is not designed from a PFTC perspective, although the FTC capability of the system is improved. Additionally, an ISS condition for PFTC for renewable energy systems is available in Schulte and Gauterin (2015), in which the results are transferable for WECs. Similar to other applications, PFTC approaches used for WECs prioritises robustness across all potential scenarios within the designated fault parameters, rather than striving for optimal performance in response to specific faults and can be considered a robust type of control design. This PFTC approach accounts for various fault scenarios *and* normal conditions, so compromises must be made even under normal operating circumstances. Consequently, the inherent nature of PFTCs results in a degree of *conservatism* in system performance, typical of robust controllers. Furthermore, it is worth noting that fault data is not readily available for wave energy technologies, nor common failure modes; therefore, an unexpected (not considered in the PFTC approach) fault could potentially lead to system failure.

3.4.2. *AFTC approaches for WECs*

As described in Section 3.4, AFTC approaches utilise FE/FDI module for fault estimation module to estimate faults, and modify the control law accordingly to work under fault scenarios. Most AFTC systems in the WEC literature adopt an FE-based FTC scheme (González-Esculpi et al., 2021; Zhang et al., 2022; Xu et al., 2022, 2023), namely estimation and compensation (see Table 4), illustrated in Fig. 10. In this

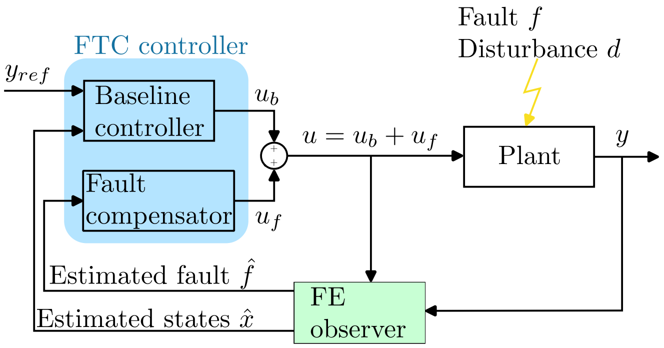

Fig. 10. General scheme of FE-based FTC systems (estimation and compensation) utilised for WECs. Adapted from Lan and Patton (2021).

scheme, the baseline controller is responsible for maintaining nominal system performance, and the fault compensator is automatically activated once a fault is detected and estimated by the FE observer.

In González-Esculpi et al. (2021), a fault in the water brakes of an AWS WEC produce a damping force deviation, and the controller compensates for this deviation through the LPMG. In the fault scenario, the authors of González-Esculpi et al. (2021) report an improvement in the system performance, due to the FTC controller ability to compensate for some unmodelled dynamics induced by faults. Additionally, although FTC compensation does not enhance energy extraction compared to the fault-free scenario, the uncompensated reduction of the mechanical damping leads to a greater risk of overall structural failure. It is worth noting that the baseline controller used for maximum power extraction under fault-free operation is a suboptimal one, which may cause suboptimal energy extraction.

Another estimation and compensation based controller reconfiguration AFTC is reported in Zhang et al. (2022), where the controller compensates for faults in position and velocity sensors, and in the actuator, of a point absorber WEC. The proposed AFTC approach uses a fault observer to estimate sensor and actuator faults in real-time and compensates a baseline non-causal optimal controller to work under faults, resulting in comparable performance between fault-free and fault scenarios. Multiple sensor/actuator fault types are considered to illustrate the effectiveness of the approach, but no information is available on the *practicality* of simulated faults. Additionally, the non-causal WEC controller lacks consideration of hard constraints, with only *soft constraints* addressed through controller parameters tuning.

Compensated control action in Xu et al. (2022), for a 2-body point absorber WEC, is implemented by means of a multiple controller feedback law, considering a ‘loss of effectiveness’ fault of the actuator (i.e., a percentage reduction in the magnitude of the control input). The study in Xu et al. (2023) extends (Xu et al., 2022), where an iterative learning control strategy with multiple controllers is developed for the same WEC, using two adaptive laws, to cope with the actuator loss of effectiveness and lock-in-place (i.e., the actuator breakdown). Additionally, studies in Xu et al. (2022, 2023), guarantee the asymptotic stability of the closed-loop faulty system with an appropriate H_∞ performance index. Again, the proposed AFTC approach does not consider any constraints (position, velocity or PTO force), which are an essential for WEC control (Ringwood et al., 2023).

A control re-design approach is presented in Zadeh et al. (2022, 2023), based on model-free reinforcement learning (RL), for a two-body point absorber (Neary et al., 2014). In model-free RL control approaches, control is learned through interactions between the controller and the environment. In Zadeh et al. (2022), only PTO fault are considered, while Zadeh et al. (2023) also considers a fault in the relative position/velocity sensors between the two bodies of the WEC, float/plate excitation force sensors (although perfect knowledge of (unmeasurable) excitation force is assumed) and a sudden increase in the system damping, due to entanglement in debris. The WEC system utilises two PTOs, and the proposed AFTC approach utilises this PTO redundancy when considering the loss of one PTO. The RL controller is evaluated in a hardware-in-the-loop (HiL) real-time testbed in Zadeh et al. (2023), in which the RL agent adapts its policy during fault conditions and compensates for the power loss. Nevertheless, the RL approach requires updating a large number of parameters, resulting in a control action that is only updated every 120 [s] in addition to using the simulation data for training. Moreover, the energy-maximising WEC controller utilised here is passive,[3] i.e. no power is required from the grid-side, which can lead to suboptimal power absorption.

Using a controller reconfiguration approach (see Fig. 8), Ramirez et al. (2020) adapts a controller for an electrical fault in a floating OWC WEC. The fault scenario considers one, or a maximum of two, power switches from the same phase of any of the VSCs, either the MSC or the grid side converter (GSC), or even in both VSCs at the same time. Once the open switch fault is detected in one or two insulated-gate bipolar transistors (IGBTs) of the same phase in the MSC or GSC, the corresponding faulty phase is connected to the DC link of the converter (see Fig. 3), resulting in a new converter topology. In the new topology, a model predictive controller tasks both VSCs and is adapted to handle the fault using the remaining available phases. The implementation of the new controller requires modifications (redundancy) to the original hardware, such as adding triodes for alternating current (TRIAC), to connect the faulty phase to the DC link. Even though the extra components increase the cost of the overall system, such a cost may be compensated by avoiding disconnection to the grid and continuing to deliver energy in the fault scenario.

From a control methodology perspective, the area of *adaptive control* lends itself naturally to fault-tolerant control applications (Shen et al., 2017), since it is used typically for systems that have uncertainty (modelling, measurement etc.) or time-varying behaviour. Adaptive controllers for WECs have already developed (Davidson et al., 2018; Zhan et al., 2018) to counter modelling uncertainty, with a further opportunity for possible FTC application. Similarly, utilising system identification (SI) for fault-tolerant control applications is another area that deserves attention in the wave energy field. Typically, SI algorithms are incorporated in FTC approaches to estimate model parameters under fault conditions, and the control is *reconfigured* according to the ‘new’ system parameters, as explained in Appel (2013).

In summary, most AFTC applications on WECs are FE-based, allowing the controller to compensate for faults. The only different AFTC approaches involve control allocation and controller redesign. According to the classification of FTC methods shown in Fig. 8, several methods remain unexplored in wave energy, e.g., multiple controllers as a PFTC approach, projection, and virtual actuator/sensor emulation (similar to virtual inertia emulation in renewable energy modalities (Parwal et al., 2019)) for AFTC and HFTC approaches. Among the FTC approaches utilised for WECs, there are issues related to the *practicality* of simulating various types of faults, WEC models and energy-maximising WEC controllers. Hence, there is a huge opportunity regarding the development of an FTC framework that addresses these issues. Furthermore, most applications are applied on point absorbers WECs. The only other WEC considered for FTC is OWC; however, the faults considered in the OWC system are on the power converters, not the OWC itself. Therefore, developing FTC methods for other types of WECs, close to commercialisation (see Fig. 2), holds another opportunity for future developments.

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[3] For a detailed discussion on the differences between passive and reactive WEC controllers, readers are referred to Said et al. (2022).

4. Discussion and further directions

Throughout the present study, an overview of fault management, in terms of typical fault components reported, redundancy to critical functions, fault diagnosis, fault prognosis, condition monitoring, and fault-tolerant control for wave energy systems is presented. Fault management is crucial for wave energy systems, considering the harsh ocean environment and the limited opportunities for maintenance.

From Section 2, identification of fault components critical for a wave energy conversion system differ for various WEC structures, powertrain configurations, and energy-maximising controllers, requiring a level of specificity. In addition, it is noticeable that the literature reporting real fault occurrences in WECs is sparse. Faults in air and hydraulic turbines, and mechanical transmissions, are barely covered. This is, perhaps, to be expected, given the relative immaturity and minimal ocean deployment experience in the industry. Therefore, identifying failures and common failure modes in WECs requires further research and the accumulation of real ocean experience.

Identifying redundancy is essential from a fault management perspective, since redundancy in critical functions allows for operation under fault scenarios. Three potential areas of redundancy are identified in this paper, including redundancy in sensors, actuators, and mooring lines. Sensor redundancy makes the most *economic* sense, considering the economic cost/benefit. On the other hand, implementing actuator and mooring line redundancy may have significant cost implications. Still, modular PTO design and additional loads on the mooring lines due to energy-maximising WEC controllers may impact the decision to implement redundancy in these components. The decision to implement redundancy depends on the identification of elements critical to function, which vary with the type of WEC, PTO technology, and control philosophy. In addition, hardware redundancy management for wave energy systems through FTC is an area for future research that has yet to be explored.

In general, FDI/FE modules gather considerable information about the health of system components, in addition to detecting and estimating faults. This information is very useful for preventing potential damage by informing maintenance decisions. In the wave energy literature, FE methods are preferred over FDI methods because FE encompasses both detection and isolation while also estimating the fault magnitude. Nevertheless, the key benefit of utilising FE strategies is to combine them with AFTC approaches, as argued in Lan and Patton (2021). Regarding FE methods in wave energy literature, observer-based methods (UIOs, SMUIOs and AOs) are most commonly used (see Table 2). Among these FE strategies, UIO allows for fault estimation without the need for wave excitation force knowledge (Papini et al., 2023b), enabling the rejection of unmodelled excitation force dynamics during fault estimation. This characteristic of UIO is particularly important from a WEC control perspective, as separating wave and control contributions without excitation force estimation is non-trivial. However, in fault estimation applications, the relative insensitivity of an UIO needs to be carefully considered. If the signals corresponding to actuator faults (control input) superimpose with those of the excitation force (e.g. via the same channels in the system input ‘B’ matrix), the UIO may become insensitive to actuator faults, compromising its effectiveness. In addition, the use of a specific FE structure may have unrealistic implications for the considered faults by restricting the fault characteristics to specific dynamic behaviour. For example, fault signals for both actuator and sensor faults, in Xu et al. (2022), are considered as differentiable, which may not be true for all sensors/actuator faults. Furthermore, FE and FDI methods reported in the wave energy literature do not specify the quality of detection in terms of false alarms and time to detect (essential for real-time FTC applications). While establishing thresholds for residuals is crucial for change detection in a deterministic setting, FDI from a statistical perspective, where no deterministic model is present, necessitates a *test statistic* to determine the quality of detection. A specification of detection quality should include, for instance, probabilities of detection and false alarms or time to detect and time between false alarms and/or the magnitude of changes in residuals that should be detected. To the best of the authors’ knowledge, information regarding the quality of detection, whether relating to magnitude of changes in residuals that should be detected or probabilities of detection and false alarms, is not yet covered in the wave energy literature. Therefore, further research should explore more suitable FDI/FE formulations for WECs, which include details on the realism of faults and quality of detection and estimation.

For early detection of faults, fault prognosis is imperative; however, fault prognosis for wave energy systems has not yet been explored. Prognosis is especially valuable in a wave energy context, given the relative remote installation locations, and the limited weather windows available for maintenance. In addition to fault diagnosis and prognosis, CBM is an integral part of fault management systems for WECs. For WECs, a comprehensive CBM approach should include component fault (failure) data, prognosis, diagnosis, and opportunities for scheduled maintenance. However, given the relative immaturity of wave energy technology, and scarcity of available fault data, most CBM approaches in the wave energy literature only provide a superficial treatment of CBM. Thus, fault prognosis and CBM should be explored in more detail as wave energy technology matures in the future.

FTC methods, applied to WECs, were explored in Section 3.4, including both passive and active FTC. To the best the of authors’ knowledge, González-Esculpi et al. (2023) is the sole study addressing the proposed FTC problem using PFTC, using a robust controller. Consequently, it is likely that further significant improvement in this area could be achieved, given the simplicity of PFTC. Nevertheless, the sensitivity of both approximate complex-conjugate control (ACC), and approximate optimal velocity tracking (AVT) control structures (Ringwood et al., 2020), two well-known model-based control structures, applied to a single-body floating WEC in Hals et al. (2011), do not encourage reliance on the robustness of the closed-loop system. In fact, sensitivity degradation is considered a control paradox in wave energy control (Ringwood et al., 2023). Additionally, due to the inherent nature of robust control design, utilising robust PFTC may result in conservative energy absorption under nominal (fault-free) conditions. However, PFTC can be combined with AFTC to make a HFTC approach, combining the benefits of simplicity and real-time control from PFTC with the control reconfiguration property of AFTC, and further research is required to quantify the benefits of such HTFC approaches.

Moreover, as depicted in Table 4, most AFTC methods are based on the FE-based FTC approach. Such results are promising, and since FTC of WECs is an emerging field, AFTC of WECs deserves further research. It is worth mentioning that, similar to FDI/FE studies for WECs, AFTC approaches for WECs also have problems related to the realism of the faults, WEC models, and energy-maximising controllers considered. For instance, the energy-maximising WEC control problem differs significantly from a conventional reference tracking problem and is usually tackled with various optimisation formulations in the literature (Ringwood et al., 2023). Additionally, handling issues related to excitation force estimation, motion and actuator force constraints, and closed-loop sensitivity degeneration are essential for optimal WEC control. A comprehensive FTC approach should not only include fault-resilience capabilities but also energy maximisation, while also addressing these above-mentioned issues. In the existing wave energy FTC literature, these problems are partially covered, presenting a significant opportunity for the development of a comprehensive FTC framework for wave energy conversion systems. Furthermore, optimality considerations for the energy-maximising WEC control problem under faults have yet to be explored, as WEC optimal controllers are typically exclusively designed for fault-free systems. There is a case to be made in relation to the use of already developed WEC controllers (be it simple (García-Violini et al., 2020), optimal (Faedo et al., 2017) or adaptive (Davidson et al., 2018)) for fault-tolerant control purposes, considering the *peculiarity* of the WEC control problem, which

Table 5
A subset of diverse WEC/PTO combinations with different control possibilities.

WEC	Working principle	PTO mechanism	Control possibilities
CorPower C4 WEC (Anon, 2024a)	Point absorber	Rack and pinion mechanical PTO	Passive and reactive control
Anaconda WEC (Mendes et al., 2017)	Bulge-wave attenuator device	Pneumatic PTO	Turbine control
MOcean Blue Horizon (Anon, 2024b)	Hinge-barge device	C-GEN[a] direct drive PTO	Passive and reactive control
MUTRIKU WEC (Rosati et al., 2022)	Fixed OWC	Self-rectifying air turbine/generator PTO	Turbine/optimal control
SWINGO (Carapellese et al., 2023)	Internal reaction mass	Gyropendulum PTO	Passive and reactive control

[a] https://www.c-gen.co.uk/.

is significantly different to a conventional reference tracking control problem.

Regarding the suitability of specific FDI/FTC strategies for wave energy applications, it is challenging to determine a best technique due to the wide diversity of wave energy devices, their PTO mechanisms, control possibilities, and the types of available measurements (sensors) in the W2G powertrain. The decision to implement an FDI/FTC strategy will be influenced by choices for each of these components. These choices are linked to the mathematical structures of the system since the selection of primary movers, secondary movers, and PTO mechanisms in the W2G powertrain results in disparate model structures. For example, the difference between an OWC and a point absorber is significant in terms of the components involved and their respective model structures, as illustrated in Table 5. In addition, taking control possibilities as an example, there are various options, such as passive or reactive WEC controllers. Even within the class of reactive WEC controllers, there are further choices, such as simple (García-Violini et al., 2020) and optimal (Faedo et al., 2017) WEC controllers. Thus, these choices will dictate the feasibility of a potential FTC strategy implementation. In order illustrate these choices, Table 5 presents a *subset* of WECs (of various working principles) with their diverse PTO mechanism, and control possibilities. Note that each row in Table 5 represents a specific type of WEC, PTO mechanism, and possible control mechanism available in the literature, for a particular WEC/PTO combination. Similar WEC types may have different PTO (Guo et al., 2022) and control mechanisms, highlighting the difficulty in choosing a suitable FDI/FTC strategy. Another difficulty lies in selecting a specific FTC method, since most FTC techniques are designed to handle particular faults and are tailored to specific application areas. Therefore, a combination of different strategies to achieve both fault-resiliency and energy-maximisation objectives for wave energy applications may be more appropriate, and requires significant further research.

Finally, most studies covered in this study focus on energy conversion from the motion of the waves to the PTO. Therefore, FDI and FTC, from a W2G perspective, are aspects that deserve further research, with motivation to fully understand how faults interact across the different conversion stages in the multi-disciplinary WEC application domain. Lastly, since almost all of FD and FTC studies reviewed in Tables 2 and 4, respectively, use point absorber WECs, further research is required to examine the extent to which FD and FTC methods can be extended to other WEC types, or whether alternative WEC concepts present new challenges, or opportunities for FD/FTC.

In conclusion, given the nascent development stage of wave energy systems in general, and WEC fault management in particular, there is considerable opportunity to reduce the LCoE for wave energy systems, by utilising fault management strategies, which can help to prolong power production time during fault condition, being especially mindful of the limited opportunity for device maintenance.

CRediT authorship contribution statement

Hafiz Ahsan Said: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Augusto C. Sardá:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **John V. Ringwood:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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.

Acknowledgements

Thanks are due to CarrieAnne Barry from the Centre for Ocean Energy Research (COER) at Maynooth University for providing language help and proofreading the article. This work was supported by Science Foundation Ireland, Ireland under Grant No. 21/FFP-A/8997 and through the Marine Renewable Ireland (MaREI) Centre under Grant 12/RC/2302_P2.

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