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Review

Offshore renewable energies: A review towards Floating Modular Energy Islands—Monitoring, Loads, Modelling and Control

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ABSTRACT

Floating Modular Energy Islands (FMEIs) are modularized, interconnected floating structures that function together to produce, store, possibly convert and transport renewable energy. Recent technological advancements in the offshore energy sector indicate that the concept of floating offshore energy islands has the potential to become more cost-effective and more widespread than previously anticipated. This review is specifically meant as a basis for the development of new approaches to the sustainable exploitation of multi-energy sources in the offshore environment leveraging the know-how of existing technologies and, at the same time, exploring new solutions for the specific challenges of FMEIs. The paper critically analyzes the current state of data-driven approaches and structural health monitoring techniques in the offshore energy sector. It also covers topics such as met-ocean data, loads estimation, platform dynamics, coupling actions, nonlinear dynamics of mooring lines, modelling considerations, and control of electrical subsystems. It is believed that this systematic and multidisciplinary review will facilitate synergies and further enhance research and development of offshore renewable energies.

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1. Introduction

To reach the European Union's climate neutrality goal by 2050 and to meet the ever-increasing global energy demand, offshore renewable energy is expected to play a crucial role. Offshore renewable energy includes several sources, such as wind, waves, solar and others, which are all at different stages of development. With offshore wind energy, the total installed capacity reached 14 GW in the EU in 2021 and it is expected to increase by 25 times by 2030 (European Commission, 2020). For other emerging ocean energy technologies, such as wave energy converters, commercial utilization is relatively lower (Aderinto and Li, 2018), but it has the potential to reach a competitive price of about 0.15 Euro per kWh by 2030 (European Commission, 2022). The recent technological advances in the offshore energy sector show that the concept of floating offshore energy islands, i.e. offshore wind power combined with other renewable energy sources and energy storage, has the potential to become more cost effective and much more widespread than expected.

This paper seeks to provide a comprehensive analysis of some key topics relevant to the concept of the Floating Modular Energy Islands (FMEIs) sketched in Fig. 1. FMEIs are interconnected floating structures designed to collectively generate renewable energy, store it, and potentially convert and transport it. The FMEI concept demands effective collaboration across various engineering disciplines and industries within construction, marine, and renewable energy sectors. This innovation aims to maximize renewable energy potential in offshore locations and capitalize on shared floating, mooring, storage, and energy transport infrastructure. The specific configuration of a FMEI, including the number of modules, types of renewable energy devices, geometry, and construction materials should be tailored to each site and based on a thorough techno-economic analysis. One of the distinguishing features of FMEIs is its modular design, which allows for adjustments to the island's overall capacity over time by adding new modules. A conceptual design of a FMEI aiming to energy independency in Crete has been presented in Kurniawati et al. (2023), whilst the growing significance of affordable and flexible floating islands, particularly in the North Sea have been analysed in Flikkema and Waals (2019). Although FMEIs are a relatively new concept, there is extensive literature on other floating structures with similar and distinct features, which will be utilized in the review herein, such as very large floating structures (VLFSs), floating offshore wind turbines (FOWTs), wave energy converters (WECs), and floating solar photovoltaic (FPV) energy devices. Providing in a unified framework a systematic presentation of these multi-disciplinary offshore energy sources and related technologies, all relevant for the development of FMEIs, is the main gap this review attempts to fill.

FMEIs will host various industrial systems and infrastructure that need to be operated and maintained. They will need to be operated in harsh environments with limited accessibility for maintenance staff. At the same time, high reliability, integrity, safety and secure operation will be required from these systems at all times and under all expected weather conditions.

The focus of this paper is placed on structural health monitoring, structural dynamics, nonlinear cable dynamics, and electrical control. The structure of this paper is as follows. In Section 2, data-driven approaches and structural health monitoring techniques are discussed. Metocean data and loads estimation, needed for FMEIs design and construction, are presented in Section 3. Section 4 provides a comprehensive review on the nonlinear dynamics of cables and stability of floating platforms to create a solid background for the complex problem of FMEIs mooring system. Finally, Section 5 discusses electrical control issues of the renewable energy sources that will be installed on FMEIs.

2. Data-driven approaches and structural health monitoring techniques

Condition monitoring and condition-based maintenance play a crucial role in enabling cost-effective operation strategies for complex systems like FMEIs. Moreover, it is noted that, similarly to multipurpose offshore platforms (Aryai et al., 2021), the design of FMEIs should also be based on a system-level reliability approach able to consider specific requirements for all the ocean resources (food, energy, etc.) while adopting specific construction and structural requirements as well as specific reliability targets.

In this section, the recent condition-monitoring methods previously proposed and that are relevant to FMEIs are reviewed. The focus is placed on the main structural components when they are under intense loads. These components can be divided in two groups: (a) the floating platform and its sub-structures, and (b) the structural components of the energy harvesting devices that can be installed on the floating platform. In this context, several monitoring techniques which are proposed for floating offshore wind turbines are reviewed, as they are, to some extent, structurally similar to the floating platforms of FMEIs. Regarding the second group, the main sources of energy that can be harvested in FMEIs are (a) wind, (b) waves, (c) currents and (d) solar. From this list, the structural components used for wind (wind turbines), waves (wave energy converters), and currents (tidal turbines) can be exposed to extreme loading conditions. Therefore, the literature reviewed in this section is mostly focused on these components, with emphasis on wind turbines as they are more mature technologies in industry compared to wave and current energy harvesters.

Inspection and maintenance costs associated with future FMEIs may be reduced by making use of appropriate Structural Health Monitoring

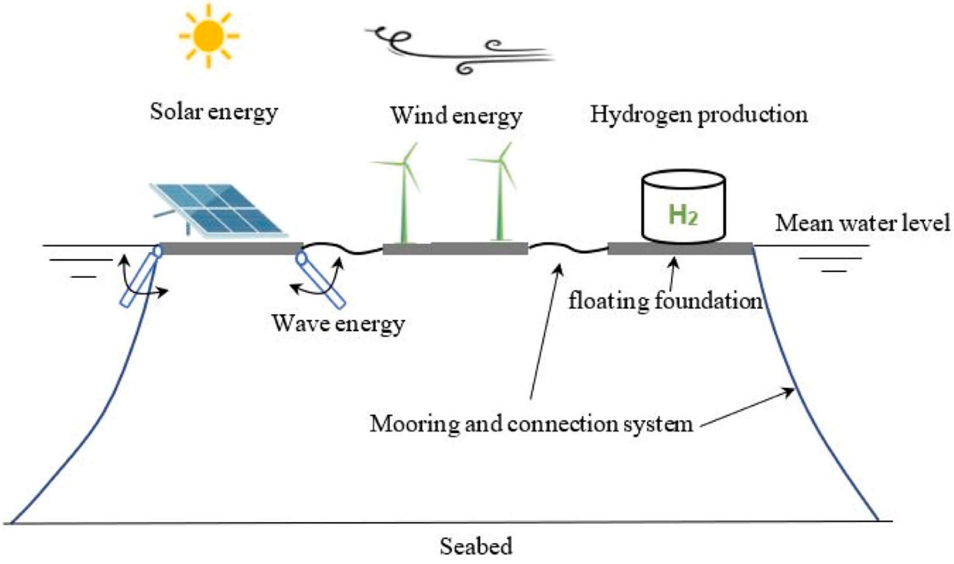

Fig. 1. Schematic of a floating modular energy island with synergies of multiple renewable energy conversion and production devices (note that size of the components and mutual distances are not in a realistic scale).

(SHM) techniques. Dominant condition monitoring strategies that are exploited in the energy industry can be categorized into two groups: (a) Non-Destructive Evaluation (NDE) schemes that include acoustic emission monitoring, ultrasonic methods, Lidar and thermal imaging methods, etc., and (b) continuous SHM schemes, where the dynamic response, such as strain and acceleration measurements, are used to track changes in dynamic properties of the structure. Martinez-Luengo et al. (2016) have provided a comprehensive review of SHM techniques and data collection strategies for FOWTs that can be especially relevant for monitoring FMEIs.

When it comes to SHM approaches, fault detection and diagnosis across floating structures at large, can be implemented following one or more of three main schemes: (1) model-based methods, (2) data-driven methods, and (3) knowledge-based methods. In the first scheme, engineering models, often relying on physics, are used to complement monitoring information and assess a system's condition. The advantage of these methods is that they rely on the fundamental physics of the system and normally provide accurate results which can be interpreted. However, creating high-fidelity models in such complex environments is extremely challenging and computationally expensive. Therefore, implementation of these methods might not be always feasible. In the purely data-driven scheme, no complementary information is offered from physics, and any assessment relies exclusively on information that is latent or uncovered in the acquired data. As these methods can be only trained using the historical data collected from the structure, there has been an increasing interest in them. They also require high computational capacity, but reduced dimension models can be used to overcome this challenge. Although they can be effectively used in condition monitoring of dynamic systems, they might provide false results as they purely rely on trends in the dataset without any physical interpretation. In the third scheme, expert feedback (e.g., in the form of inspections) is brought into the assessment loop. In this scheme, visual inspections play an important role. When it comes to harsh environments (e.g., offshore), implementation of visual inspection is labour expensive and even dangerous. In addition, the inspection highly depends on the engineering judgement of the operator. Therefore, the results might not always be accurate. In most cases, data collection plays an important role in the success (or effectiveness) of the scheme being used. Therefore, in the following, a review of data collection approaches relevant to FMEIs is presented, followed by a discussion of model-based and data-driven based SHM techniques that can be used for future FMEIs.

2.1. Data collection

Real time condition monitoring of FMEIs will highly rely on the quality and quantity of data collected from the floating structures. In general, two types of data can be collected: (a) structural data such as strain, acceleration, displacement etc., which can be used for model-based SHM approaches, and (b) environmental and operational condition data such as wind speed, wind direction, power output etc., which can be directly used for anomaly detection, or to be combined by data-driven approaches to remove the influence of operational and environmental conditions. As FMEIs are emerging systems, there are currently no SHM systems installed in real life that we can refer to. However, Fig. 2 provides an example from Offshore Wind Turbines (OWTs) which could be a good example of potential data that can be collected on FMEIs. Several studies are focused on collecting structural data for online monitoring of offshore structures. For example, Hines et al. (2023) installed a continuous structural monitoring system at the Block Island Wind Farm, which includes several jacket-based OWTs. They installed wired and wireless accelerometers, strain gauges and inclinometers on the turbines and combined the dynamic measurements with SCADA (Supervisory Control and Data Acquisition) data. In another study, de N Santos et al. (2023) employed acceleration and SCADA data collected from an OWT for long-term fatigue estimation of the turbine.

While purely data-driven modelling brings the highest potential for automation, it relies on availability of a large amount of data, which should in fact cover different operational states and health conditions of the monitored system. This is non-trivial to acquire, particularly when failure data for operational instances of such young systems (especially floating systems) is still scarce. A source for such data is found in SCADA systems, which can be widely employed to accumulate relevant operational data in real-time from different parts of the future FMEIs with a relatively small number of sensors installed. A drawback of these systems is that they are more suitable for aggregation of operational and environmental information, rather than collecting information from the structural components of FMEIs (e.g., rotor blades and towers, tidal turbines, etc.) Nonetheless, such compressed information is indicative of the system's performance and condition. SCADA provides useful data, such as environmental parameters (e.g., wind speed and wind direction), electrical characteristics (e.g., active power output, power factor and voltage frequency), part

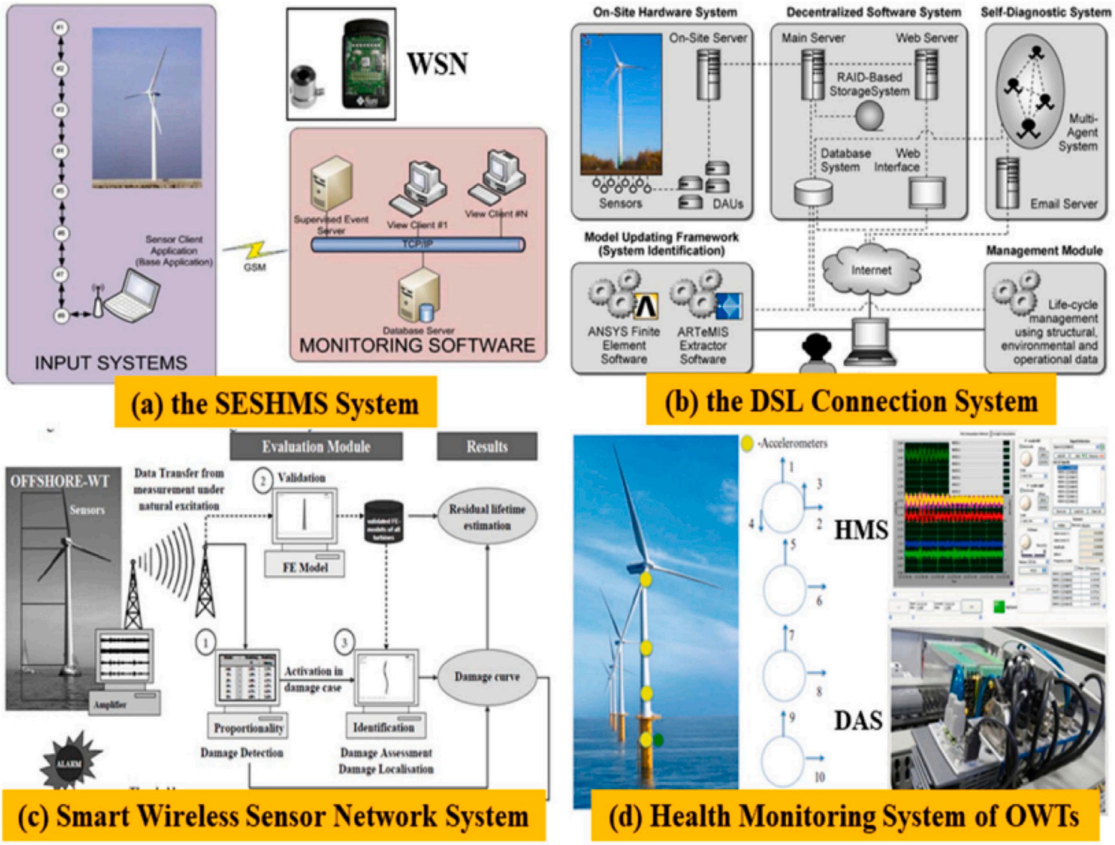

Fig. 2. SHM systems for OWTs (Lian et al., 2019; Salameh et al., 2018; Smarsly et al., 2013; Rolfes et al., 2007).

temperature (e.g., gearbox bearing and generator winding) and control variables (e.g., pitch angle and rotors shaft speed) at normally 10-minute resolution. SCADA data is generally considered as a low-cost solution which requires no additional sensors (Tautz-Weinert and Watson, 2017; Zhang et al., 2020).

2.2. Model-driven structural health monitoring techniques

Model-driven SHM of energy infrastructure has been studied extensively so far, in an effort to deliver efficient condition assessment and decision support tools for operation and maintenance of these systems. However, the application of SHM methods to floating structures such as FOWTs or future FMEIs remains limited since instances of such systems and related instrumentation solutions are still scarce. However, similarly to the practice followed for non-floating systems, the inspection and maintenance cost associated with FMEIs could be reduced exploiting appropriate SHM techniques.

Kim et al. (2019) used operational modal analysis with numerical sensor signals to perform SHM on a FOWT. The curvature mode shapes (CMS) of the tower and blades are found to be the most effective modal properties for damage localization. Jawalageri et al. (2022) studied the effect of scour erosion on dynamic properties of offshore wind turbines such as natural frequencies and mode shapes. They employed a fully coupled numerical model of a 5 MW OWT considering soil–structure interaction. The effect of scour on modal properties of the structure under different soil properties and environmental conditions are assessed. On the prognostics front, Avendaño-Valencia et al. (2021) proposed a data-driven model to predict the short-term fatigue Damage Equivalent Loads (DEL) on a wake-affected wind turbine based on wind field inflow sensors and/or loads sensors deployed on an adjacent up-wind wind turbine. Gaussian Process Regression (GPR) with Bayesian hyperparameters calibration is proposed to obtain a surrogate from input random variables to output DELs in the blades and towers of the up-wind and wake-affected wind turbines. A sensitivity analysis based on the hyperparameters of the GPR and Kullback–Leibler divergence is conducted to assess the effect of different inputs on the obtained DELs. Mylonas et al. (2021) suggest using Graph Networks (GNs) to enable the fusion of prior knowledge on effects dominating the wind farm dynamics (e.g., formulas governing wake effects) with probabilistic modelling using a Variational Bayes (VB) approach. They show applications related to the structured probability density modelling for simulated and real wind farm monitoring data, as well as on the meta-learning of simulated Gaussian Process data. Choe et al. (2021) proposed a sequence-based modelling approach for SHM of blades installed on a FOWT. They use Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU). For this purpose, they simulated several damage scenarios for training the deep learning algorithm and tested the model on a real FOWT.

A relevant aspect for SHM for wind energy structures concerns the prediction of the response in unmeasured locations, also known as Virtual Sensing (VS) (Vettori et al., 2023). This technique combines a limited set of measurements with a numerical model of the structure, typically based on the Finite Element Method (FEM). This can be used to build a Digital Twin of the operating system able to reproduce representative response under real loading scenarios. Different approaches to VS exist. Modal Expansion (ME) is one approach for reconstructing response in unmeasured locations by mapping the response measured in a finite set of limited measured locations onto numerical normal modes (derived from an FE model) (Iliopoulos et al., 2016). Such an approach has been used in Tarpø et al. (2020) for building virtual strain sensors for fatigue analysis of an offshore oil platform scaled mockup, as well as for on a mixed accelerations—strains dataset with the purpose of fatigue-life prediction of an offshore monopile-supported wind turbine (Maes et al., 2016). As an alternative, Bayesian filtering methods form a go-to scheme for real-time VS, as explored in an array of works, which combine a state equation derived from an engineered model with an observation equation, which represents measured (typically vibration-based) data (Dertimanis et al., 2019; Papadimitriou et al., 2011; Tatsis et al., 2021, 2019, 2020; Cumbo et al., 2019; Risaliti et al., 2019).

Mooring lines are fundamental components of future FMEIs. They are needed to anchor the islands to the sea bed, meaning that they will be exposed to a variety of loading conditions, from mild to extreme ones. Therefore, it is important to develop effective techniques to continuously monitor their structural condition. Several researchers have studied SHM approaches for monitoring mooring lines in floating structures. Some principles and methods currently adopted for FOWTs, which in some part go back to oil and gas industry, can be potentially used for FMEIs, but the significant differences in terms of dynamic response of a multi-modules, interconnected floating elements must be properly taken in to account. Existing SHM approaches can be used for both inspecting mooring line loads, which can provide further information about its dynamics and breaking detection (Ciuriuc et al., 2022). These methods normally consist in installing a strain gauge as a load cell directly on the mooring line. Chung et al. (2021) used numerical sensors signals from the tendons of tension leg platform FOWTs for real time health monitoring. FE beam models are adopted to assess the displacement between the nodes (sensors). Sakaris et al. (2021) investigated damage detection of damaged tendons of a FOWT under varying environmental and operating conditions. They also used simulated damage scenarios by modelling the damage as a stiffness reduction. They developed a damage detection algorithm using the Functional Model Based method. Rezaee et al. (2021) employed fuzzy classification and Arma parametric modelling for damage detection in mooring lines of a spar type FOWT. O'Donnell et al. (2021) assessed the dynamic behaviour of a scaled floating platform using response amplitude operator (RAO). The authors also performed damage detection of a catenary moored spar platform (Fig. 3) in a different study (O'Donnell et al., 2020), by comparing the dynamic responses of the structure before and after damage using a statistical approach.

As mentioned before, tidal turbines are among the potential energy harvester devices that can be installed on FMEIs. For these systems, a few researchers have developed SHM techniques for different components. Syed and Goggins (2024) developed an artificial intelligence-based condition monitoring method for tidal energy turbines. The proposed method was developed for monitoring rotors and blades of tidal energy turbines. The authors showed that the results can be used for performance, reliability, availability, maintainability and survivability of these turbines. Kim et al. (2018) studied the structural integrity of hybrid offshore wind and tidal-current turbines (HOTTs). They used laboratory experiments for the supporting structures of a scaled HOTT in a water flume. They estimated the dynamic properties (such as natural frequencies) of the model using least-squared frequency domain decomposition (LS-FDD) of the measured responses. They studied two main approaches for damage detection in this system including a coherence-based method and an improved autoregressive (AR) model based method. Nachtane et al. (2017) used a finite element based method to simulate dynamic behaviour of the composite nozzle of a tidal turbine by the implementation of a failure criterion. In another study (Farinholt et al., 2016), responses collected by piezoelectric transducers are used for SHM of composite materials which are used in the fabrication of wave energy converters. The proposed method was employed for damage detection and classification of damages such as holes and slots within composite plates, and fatigue damages that evolves due to manufacturing flaws (e.g., delamination and laminate waves).

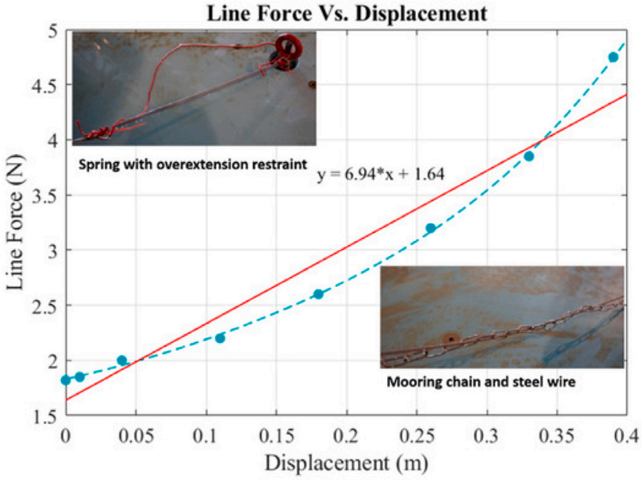

Fig. 3. Best-fit approximation of the spring constant of the designed mooring lines (O'Donnell et al., 2020).

2.3. Condition monitoring and data-driven approaches for condition-based maintenance

Condition-based maintenance is a preventive maintenance strategy that takes into account the current condition of the industrial systems to be maintained. Fig. 4 provides an overview of condition-based maintenance as compared to more traditional maintenance strategies based on the EN 13306 standard (PN-EN13306, 2010). The time when condition-based maintenance is required is not predetermined but it is determined based on the actual condition of the system. Condition-based maintenance is performed in various industrial sectors to optimize maintenance resources and ensure a reliable and safe operation of the maintained systems. It requires that the condition of the systems can be monitored around the clock, and that the monitored state variables are suitable indicators of relevant developing faults and ideally also provide information on their severity. The system design stage should include a failure mode analysis and its effect on the system performance (Scheu et al., 2019; Moubray, 2001). It should ideally be decided, as a part of the system design process, which subsystems are to be monitored and which monitoring techniques and equipment are available to this end. Developers of energy islands will need to identify which subsystems, failure modes and failure paths to focus on and which state variables monitor to monitor in those subsystems as indicators of developing faults.

Condition monitoring technologies and methods are needed to put condition-based maintenance strategies into practice. Operators of commercial wind farms aim to reduce the cost of maintenance and improve the uptime of their wind farms (Carroll et al., 2016; Pfaffel et al., 2017). Likewise, operators of future energy islands will have similar expectations and strive to constantly remotely monitor their critical industrial systems and infrastructure in order to spot condition degradation, operational issues, safety or security breaches in time to enable informed decision-making and timely responses.

The implementation of condition-based maintenance strategies can be strongly facilitated by automating condition monitoring and diagnostics techniques. As explained in Section 2.1, data from sensing units and from SCADA systems can serve as a basis for automating the condition monitoring and for the early detection of maintenance needs. In wind farms, for example, those systems usually provide information on active power generation, mechanical and electrical state variables, vibration amplitudes, wind velocities, and other environmental conditions (Qiao and Lu, 2015; García Márquez et al., 2012). SCADA data can be applied for fault detection and condition-monitoring tasks as low-cost substitutes for specialized condition monitoring systems, see,

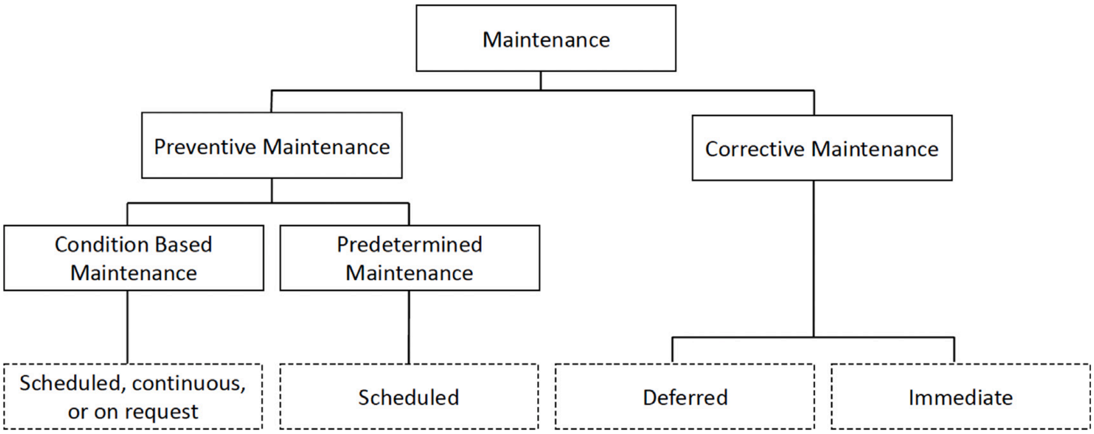

Fig. 4. Maintenance strategies for critical infrastructure based on the EN 13306 standard (PN-EN13306, 2010).

e.g., Zaher et al. (2009), Schlechtingen et al. (2013b), Tautz-Weinert and Watson (2017) and Maron et al. (2022). SCADA systems provide continuous streams of condition and control data at high temporal resolution, which makes them a valuable source of information in system health monitoring.

Normal behaviour modelling is one of the most relevant approaches to data-driven condition monitoring and fault detection for condition-based maintenance in practice (Tautz-Weinert and Watson, 2017; Helbing and Ritter, 2018; Stetco et al., 2019). It involves establishing accurate models of the normal operating behaviour of the monitored system in the absence of malfunctions or developing faults. Normal behaviour models (NBMs) are learned based on sensors or SCADA system data collected during the past system operation. If a system's operation behaviour deviates significantly from its expected behaviour as predicted by a NBM, then this deviation can indicate condition degradation and incipient faults. NBMs of power generation, drive train temperatures and further condition-related variables derived from the SCADA system have been proposed in Zaher et al. (2009), Lydia et al. (2013), Schlechtingen et al. (2013a,b), Schlechtingen and Santos (2014) and Meyer (2021). Jonas et al. (2023) recently introduced NBMs of vibration responses for wind turbines and demonstrated the detection of developing faults with those NBMs. Condition monitoring based on NBMs is a popular approach in practice because it enables accurate and turbine-specific fault detection and diagnostics for remotely monitored industrial systems and infrastructure. We expect it will also play a significant role in the monitoring and maintenance of industrial systems and infrastructure of FMEIs.

In the context of historical SCADA data, numerous machine learning and statistical models have been developed to understand the current system behaviour and predict future damages. Wang et al. (2018) applied a simple Principal Component Analysis (PCA) scheme on SCADA data in order to propose a reduced set of variables that can effectively predict faults in wind turbines. Astolfi et al. (2022) collected SCADA data spanning over 10 and 7 years for 6 Senvion MM92 and 11 Vestas V52 wind turbines, respectively, to understand the degradation in the system's performance due to ageing effects. Operation Curve analysis and support vector regression were the tools adopted to this end. Pandit et al. (2022) reviewed the challenges associated with various machine learning techniques: neural networks, probabilistic models and decision trees applied to SCADA data obtained from wind turbines in performance monitoring. Earlier, Tautz-Weinert and Watson (2017) reviewed the performance of ANN, ANFIS, cluster centre fuzzy logic and NSET for damage detection in wind turbines. Udo and Muhammad (2021) used the SCADA inputs in an attempt to construct a robust fault detection model, by using three machine learning algorithms: Multiple Linear Regression, extreme gradient boosting and long short-term memory. Their implementation is demonstrated on data collected for a 1 year period, with 83 sample variables for the selected four turbines. Santolamazza et al. (2021) implemented ANNs and SPC (Statistical Process Control) for detecting anomalies and faults in gearbox and generator.

3. Loads estimation, platform dynamics and modelling considerations

As already mentioned, FMEIs are complex offshore systems composed of modular floating energy structures with the objective of producing energy from different renewable sources. Their structural response is deeply influenced by the complex dynamic loading stemming from the combined action of wind, waves and currents. The stochastic nature of these actions requires appropriate methods to define design loads both for normal and extreme conditions.

Compared to the more standard offshore structures, FMEIs internal loads will much depend also on the structural solution adopted to stabilize and connect each single floating module, on mooring systems and on the island layout. In order to provide a comprehensive review on the load estimation and the dynamics FMEIs, the state of the art of standard floating energy systems is described in the following, focusing the attention on Floating Offshore Wind Turbines (FOWTs), Wave Energy Converters (WECs) and Floating PhotoVoltaic (FPV) systems.

3.1. State of the art on floating energy systems

Although there are distinguishing differences, Very Large Floating Structures (VLFSs) and standard floating energy structures present some features shared with FMEIs. VLFSs have been firstly developed for military applications (floating airports and docks) (Wang and Tay, 2011; Zhang et al., 2015; Cappietti et al., 2019) and are now becoming attractive also for the development of self-sufficient floating cities (Wang and Tay, 2011). From the structural point of view, attention is being paid to modularization, design of platforms and connections, transforming the design paradigms of VLFSs towards FMEIs (Flikkema and Waals, 2019). As introduced in Section 2, standard floating energy structures can be grouped based on the renewable source that is used to produce electricity. They are FOWTs, WECs and FPVs. Among these three, the FOWT technology is undoubtedly the most advanced and developed in the offshore renewable energy sector, thanks to the high power output and to the exponential evolution of Wind Turbines (WTs) in the last decades. FOWTs are complex multi-body systems consisting in three main components: the WT itself (rotor-nacelle-assembly and tower), the floating platform and the anchoring system (mooring lines and anchors). The structural response of such structures is markedly dynamic, under the joint action of wind and waves, and is deeply influenced by the interaction of the WT with the floating foundation (platform and mooring lines). Based on this aspect, FOWTs can be categorized according to the hydrostatic properties of the substructure. The first installations concerned ballast- and buoyancy-stabilized solutions, where the hydrostatic equilibrium is mostly provided by the floating platform and achieved by lowering the centre of gravity of the entire system or by increasing the waterplane area of the floater. These are the spar (Jonkman, 2010; Robertson and Jonkman, 2011; Pham and Shin, 2019) and the barge (Jonkman, 2009; Robertson and Jonkman, 2011) technologies, respectively. Hybrid solutions are the semisubmersible FOWTs, achieving stability with a combination of the above-mentioned principles (Robertson and Jonkman, 2011; Ferri et al., 2022). Relatively new solutions involve Tension Leg Platforms (TLPs), where the hydrostatic stability is achieved by taut mooring lines, allowing for lighter and slender floaters (Robertson and Jonkman, 2011; Matha, 2010), and suitable for installations in very deep water. TLPs are generally stiffer in the heave degree of freedom compared to spar, and semisubmersible substructures and extremely sensitive to resonance.

The above-mentioned substructure technologies can be adopted also for FMEIs modules, hence, their different structural behaviour must be taken into account especially for the design of inter-modules connections.

WECs allow to harvest energy from waves and can possibly be co-located with OWTs (Wan et al., 2016; da Silva et al., 2022; Gubesch et al., 2023). Based on the operational principle, two technologies can be identified, Oscillating Water Column (OWC) type and floating body type (Qiao et al., 2020). The first is generally adopted in coastal site. The most common OWCs consist in a chamber where the water enters and, compressing the air inside, activates a turbine which produces electricity. Floating body WECs are anchored through mooring lines to the seabed or directly connected to offshore structures. In this case, the power take-off (PTO) mechanism is similar to the one of WTs, since the mechanical energy of the oscillating object under waves is transformed into electricity (Xu et al., 2019a). Even if these solutions are found to be less efficient compared to OWCs, they can be directly equipped on the modules composing the FMEIs. Moreover, since the PTO system subtracts energy from the incoming waves, they can be effectively adopted as passive dampers in FMEIs at the small (module) and large (island) scale (Wang and Tay, 2011). In combination with FOWTs modules, they can effectively reduce oscillations that would reduce the power-production of the WT (Jonkman, 2009; Pham and Shin, 2019). A double-use floating breakwaters—WECs, specifically designed to protect the inner part of a floating energy archipelago, has been recently proposed and investigated in Russo et al. (2024b) and Russo et al. (2024a).

FPV systems are solar panels installed on floating substructures. While most of the installations are restricted to freshwater basins (Kaymak and Şahin, 2021), few concepts have also been proposed for open-sea applications and for a large scale deployment (Abbasnia et al., 2022; Sree et al., 2022). FPVs present many advantages such as the integration with other offshore energy structures, high solar performances and the reduction of exploited land compared to standard onshore PVs. On the other hand, critical issues related to effects of seawater and the sensitivity to wind loads of high-deck solar panels must be taken into account in the design for offshore applications. Compared to FOWTs, FPVs require a large surface to achieve a comparable power production. While this aspect can be seen as a drawback of FPVs, it seems to be extremely promising for FMEIs, where, the large surface between FOWTs modules (required to avoid power loss of WTs due to wake effects) can be used to locate FPVs. Moreover, such kind of modular structures are characterized by a lower centre of gravity compared to FOWTs, resulting in more stable structures that can be possibly adopted to mitigate the motions of other interconnected modules.

3.2. Metocean data and loads

To predict the dynamic response of such complex systems and associated internal loads through numerical simulations, the environmental actions and response can be described either by using methods that explicitly consider all external conditions along with direct integration of the response (given such conditions) to arrive at estimates of the probability of exceedance (IEC, 2005) or by using inverse methods (see, e.g., Ferri and Marino (2023) and Liu et al. (2019)). Both approaches require metocean data to obtain statistics related to the environmental conditions in order to define the design loads (Li et al., 2013; DNV, 2016). Three to five environmental variables are generally sufficient to represent long-term loads acting on an offshore structure—most commonly, they include wind speed, significant wave height and peak spectral period of the incoming waves. If wind-wave misalignment must be considered, wind and wave heading directions are also necessary. Once these variables are selected and described statistically, target turbulence spectra and irregular wave spectra can be established and stochastic simulation of wind fields and wave kinematics can be carried out. In offshore engineering, Kaimal or von Kármán spectral models are used for wind (IEC, 2005), while Pierson–Moskowitz or JONSWAP spectra are most commonly used for waves (DNV, 2016; Jonkman, 2007).

Turning to data related to loads, site-specific measurements or hindcast data of extreme wind and wave events are often characterized by uncertainty. Therefore, an adequately large dataset is needed for accurate prediction of extreme conditions and to establish joint environmental variable probability distributions, see Li et al. (2015). Among various databases (Hahmann et al., 2020; Hersbach et al., 2020) the Norwegain hindcast archive (NORA3) (Haakenstad et al., 2021) is one that was generated using a numerical weather prediction model. Such a database allows a fully probabilistic description of metocean conditions in the North Sea, the Norwegian Sea, and the Barents Sea with high temporal and spatial resolution (Breivik et al., 2022). Recently, Cheynet et al. (2024) analysed the NORA3 database and demonstrated its application potential to describe metocean conditions in evaluating offshore wind farms. The associated long-term probability distributions based on these wind and wave data can be applied in load assessment for floating modular energy islands.

3.3. Platforms dynamics and modelling considerations

To assess the loads on the supporting platforms (e.g., the FMEIs modules), the Wave–Structure Interaction (WSI) problem is generally addressed by using the potential flow theory. This implies that, under the assumptions of inviscid and incompressible fluid, and considering irrotational flow, the WSI problem is governed by a fully nonlinear, free-surface Boundary Value Problem (BVP) (Marino et al., 2013a,b, 2011). If the characteristic length of the floating object is small compared to the incoming wave, e.g., for monopile-supported wind turbines (see Marino et al. (2018) for a review), it is possible, in general, to use semplified, semi-empirical models. In this case the resulting hydrodynamic forces exerted by sea currents and waves can be calculated according to Morison's equation (Morison et al., 1950; Mockutė et al., 2019; Xu et al., 2019b) (Fig. 5). It is warned that attention must be paid to the limits of linear or weakly nonlinear potential flow-based wave theories, used in combination with Morison's equation, in capturing phenomena like vortex-induced vibrations (VIV) (Kharazmi and Ketabdari, 2022) or ringing (Bachynski and Moan, 2014; Mockutė et al., 2019; Ghadirian and Bredmose, 2020) triggered by higher harmonic load components. A review of loading considerations can be found in Si et al. (2018). On the other hand, if the characteristic dimensions of the elements composing the structure are large enough to significantly influence the kinematics of the surrounding fluid flow, a more complex WSI problem results and it is generally simplified by introducing additional assumptions which lead to linear (or weakly nonlinear) BVPs. In

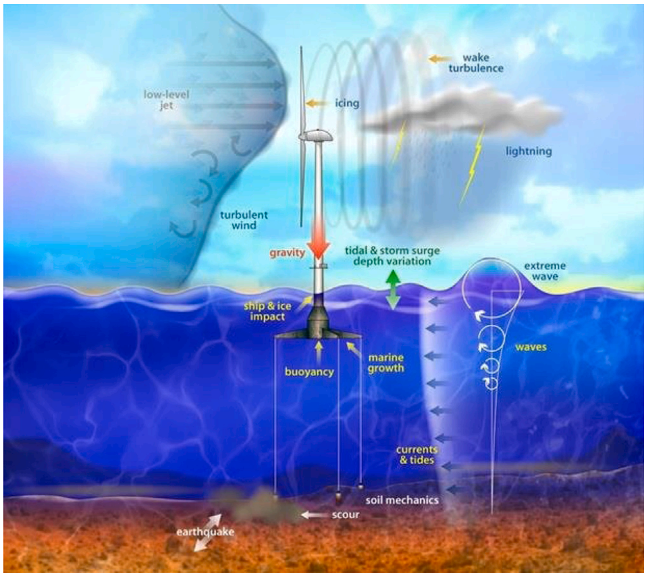

Fig. 5. Possible environmental loads acting on an offshore energy structure: the case of a FOWT (illustration by Joshua Bauer, National Renewable Energy Laboratory).

this case, due to the linearization of the free-surface boundary conditions and by neglecting the quadratic velocity term in the force balance equation, the first-order hydrodynamics is described by a radiation and a diffraction problem (Faltinsen, 1993); the former allows estimation of inertial and damping contributions related to the fluid mass oscillating in phase with the platform motion, while the latter allows evaluation of a linear transfer function between the waves and the floating object, i.e., the so-called diffraction and Froude–Krilov forces (Faltinsen, 1975; Jonkman, 2009). In frequency-domain computations, the sea surface elevation power spectrum combined (multiplied by) this hydrodynamic transfer function leads to frequency-dependent wave-induced loads. In a similar manner, quadratic transfer functions (QTFs) can be computed by solving a second-order potential flow problem (Kim, 1991), which allows evaluation of loads resulting from interacting wave components at different frequencies (Zhou et al., 2021).

It should be noted that, with the increase in power (size) of future wind turbines and supporting platforms, nowadays, commonly adopted analysis methods may fail in capturing the actual physics of the WSI (Veers et al., 2023). For example, the wave-induced loads described so far rely on the assumption of a rigid platform; however, especially for pontoon-type very large floating structures, this assumption may not be valid and may require considering hydroelasticity effects, where the deformation of the floater and the wave kinematics influence each other. Adopting the plate theory and making use of the zero-draft assumption (Watanabe et al., 2004), the hydroelastic problem can be solved by coupling a FE (finite element) model with the potential-flow BVP where the free-surface boundary condition is modified to account for plate deflections.

4. Dynamics of mooring lines and modelling considerations

FMEIs need to be moored to the sea ground to avoid drift due to the wind thrust and sea waves and currents. For what concerns this aspect, they are not very different from classical FOWT, even though the larger number of degrees of freedom of FMEI requires a more complex systems of mooring lines that takes into account the relative motions between each floating component of the FMEI, and thus has a much more involved dynamical behaviour. In any case, the mooring is inevitable done by submerged cables, exploiting different stabilizing principles, that can be taut or slag. This section is devoted to a detailed discussion of these important structural components, while the analysis of the whole mooring systems is not addressed. Furthermore, because of their slenderness and of the Fluid–Structure Interaction (FSI), they naturally undergo nonlinear dynamics, which is very important since remaining in the linear realm means missing many important (and potentially dangerous) phenomena. Thus, focus is on the nonlinear behaviour. To have an overall picture of the considered topic, this section is divided in two parts, the first (Section 4.1) more theoretically oriented, while the second (Section 4.2) tailored on applications of nonlinear dynamics of cables for mooring lines. While Section 4.1 focuses primarily on describing the physical nonlinear phenomena, which are valid for any type of submerged (and, to a certain extent, also for non-submerged) cable, including for example transmission lines, pipes or rises, in offshore engineering applications, Section 4.2 specifically addresses mooring lines for floating energy islands.

Actually, there are various mooring configurations that can be used in real cases, and the most common are depicted in Fig. 6. It is possible to observe that, apart from different technological aspects, that are of course very important from a practical point of view, from the modelling point of view there are two categories of mooring lines, those using slack cables ((a), (b) and (c)) and those using taut cables (d). Those reported in Fig. 6 are the most commonly used configurations, but many others are possible.

Recently, the concept of shared mooring lines, which is very appealing for FMEIs, has attracted large interest because of the possibility to optimize the economical aspects in floating offshore wind farms. A review of this technique is given in Xu et al. (2024) and Hall et al. (2021), which are referred to for further details and deepening. It is worth noting that, from the cable modelling standpoint, for shared mooring lines new challenges may arise due to the more complex topology and geometry of the entire mooring system, requiring more advanced computational approaches such as those based on geometrically exact, curved beam theories (Gay Neto, 2016; Martin et al., 2021; Marino et al., 2019a,b; Ferri and Marino, 2024). Additional critical aspects may stem from coupling of these models with the remaining components of the FMEI.

4.1. Nonlinear sources and effects in underwater cables

There are basically three sources of nonlinearities when the dynamics of submerged marine cables are studied. The first source is of geometrical nature which is a consequence of the fact that the cables commonly work in a very large displacement framework which affects the model of the considered cable. In most of the cases, a linear response is expected from the deployed material, which means that there are no nonlinearities at the material level. However, for some synthetic ropes, some nonlinear material model should be adopted. The second source is related to the loads involved in the FSI, and in particular the ones induced by the waves and submarine currents. This aspect also involves the so-called Vortex Induced Vibrations (VIV) and other phenomena. Finally, the third source of nonlinearity is where the cable touches the seabed, at the so-called Touch Down Point (TDP), where the unilateral behaviour of the soil introduces nonlinear effects. There have been many studies on these sources (Patel and Seyed, 2007), and the following sections are a brief review on them.

Nonlinear dynamics of sagged cables. Sagged elastic cables are flexible structural elements with a dynamic behaviour governed by some main aspects of their geometric configuration, i.e., (i) the initial curvature also existing in shallow cables, (ii) the asymmetry generally occurring in practical realizations, (iii) the non-shallowness associated with arbitrarily sagged configurations. All of them significantly affect the linear and, mostly, nonlinear dynamic regimes of cables with sole extensional rigidity.

In linear dynamics, the initial curvature of a symmetric (horizontal) configuration leads to a modal spectrum of transverse in-plane natural frequencies. This spectrum, influenced by a cable elastogeometric

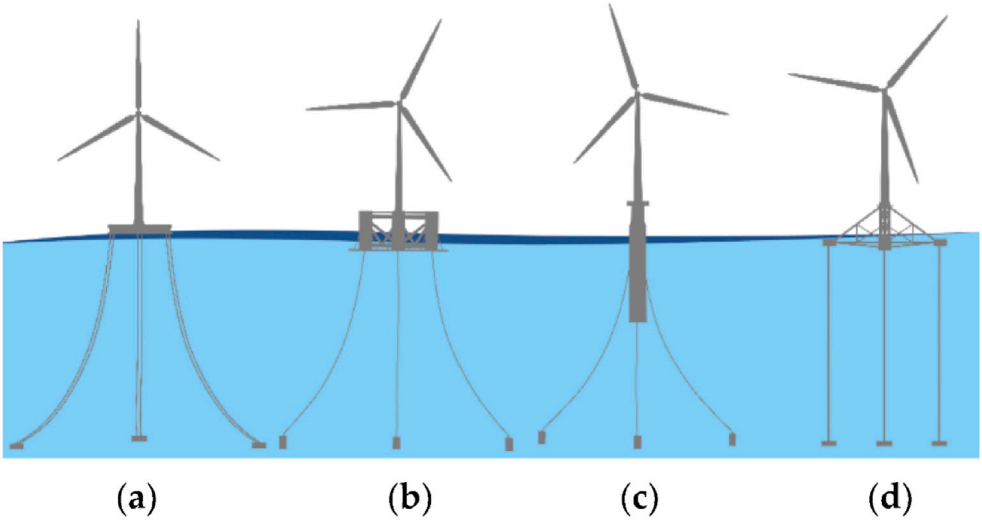

Fig. 6. The most common mooring configurations for FOWTs. (a) Barge, (b) semi-submersible, (c) SPAR, (d) Tension Leg Platform (TLP).
Source: Reproduced under the terms of the CC-BY license (Chen and Kim, 2022).
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parameter, shows the phenomenon of frequency crossovers for the associated symmetric and antisymmetric modes (Irvine et al., 1974). In the nonlinear regime (Rega, 2005), this corresponds to the occurrence of several conditions of 1:1 internal resonance (i.r.) between the two involved modes, in which non-planar modes also take part, thereby entailing an overall condition of multiple i.r., which turns out to be always activated. Generally speaking, in a sagged cable there is an important number of two-mode 1:1, 2:1, 3:1,…, internal resonances activable in the nonlinear regime (Lacarbonara and Rega, 2003).

The cornucopia of nonlinear phenomena highlighted by the 'simple' single-mode model is substantially enhanced when considering multi-mode models allowing to address the strong in-/out-of-plane nonlinear interactions which characterize cable 3D response occurring in technical applications, with non-negligible contributions of also non-directly excited modes even away from any related i.r. Rega (2004). In Rao and Iyengar (1991), an approach similar to that of Benedettini and Rega (1987) is used, but considering both internal and external resonances. A meaningful improvement towards a reliable analysis of internally resonant responses is obtained by directly solving cable PDEs with multiple scales, without preliminarily getting a ROM via an assumed mode technique (direct vs discretized perturbation approach). The advantages ensue from the possibility to capture the spatial dependence of cable motion and the associated tension, by including the effects of a high number of modes.

The inherent asymmetry of inclined sagged cables entails an important qualitative modification in the natural frequency spectrum, with the crossover of symmetric horizontal cables being replaced by the frequency veering of asymmetric inclined ones (Triantafyllou and Grinfogel, 1986). The latter entails the occurrence of hybrid modes, which result from a mixture of symmetric and antisymmetric shapes and meaningfully affect the system nonlinear response, too. In turn, arbitrarily sagged cables are to be addressed via the formulation of richer ROMs based on the catenary configuration assumption inducing geometric nonlinearity effects also on linear vibrations (Mansour et al., 2018), and on a refined kinematical description of cable deformation (Rega, 2012). Longitudinal and (in/out-of-plane) transverse dynamics are nonlinearly coupled, and induce the presence of quadratic nonlinearities (in addition to cubic ones) in the absence of a cable initial sag, too. The cable model is referred to as kinematically non-condensed to distinguish it from the condensed one considered in the shallow cable literature.

Bending and torsional rigidities of cables have been also taken into account, both in linear vibrations via finite element analyses (Alkharisi and Heyliger, 2023), and with regard to important nonlinear effects unveiled through the computational implementation of a geometrically exact modelling (Arena et al., 2016).

Overall, the huge amount of available results on modelling, analysis and phenomenology of cable nonlinear dynamics can be classified according to different criteria, distinguishing between a variety of involved features. (i) Horizontal/inclined, and (ii) small-/large-sag, configurations; (iii) axial/bending/torsional rigidities; (iv) condensed/non-condensed kinematics; (v) analytical/numerical/geometrical/experimental techniques; (vi) single-/multi-mode ROMs; (vii) free/forced, and (viii) planar/nonplanar, dynamics; (ix) internally non-resonant/resonant (single or multiple) dynamics, under (x) external/parametric/combination excitations; (xi) weak/strong nonlinearities; (xii) 'exact'/approximate solutions; (xiii) uncoupled/coupled, and (xiv) regular/non-regular, response regimes; (xv) local/global bifurcation scenarios and the ensuing dynamics. Nonlinear interaction occurring in the cable-flexible support coupled dynamics ensuing from cable- or support-induced boundary modulations has also been addressed via asymptotic boundary modulation techniques (Guo et al., 2017); it is different from the topic of previous sections since here the boundary is not meant as the TDP. The ensuing two prototypical kinds of cable—support coupled dynamics correspond to refined versions of two typical degenerate cable dynamics, i.e., cables excited externally with fixed supports and cables excited by ideal moving supports, which are of interest in the nonlinear dynamic analysis of mooring cable-floating platform systems.

Nonlinearity in the interaction with the fluid. Interaction between a submerged cable and a fluid has been studied mostly in connection with flow-induced effects mostly occurring when the cable is exposed to the excitation due to transportation by a vessel (Ibrahim, 2004). For a 'stationary' (i.e., suspended under water) cable, it makes sense to consider the 'conventional' excitation exerted by external driving forces in a quiescent fluid. For a complete description of the ensuing dynamics, FSI must be considered, via a coupled formulation in which problems in fluid and structural dynamics are solved simultaneously. Coupling already affects the linear regime (Sorokin and Rega, 2007), with a nontrivial influence of the viscous fluid on cable eigenfrequencies, modal added mass and modal damping coefficients.

Apart from analytical solutions (Wilde, 1995; Wang, 1968; Sumer and Fredsøe, 2006), which are quite rare and apply in specific cases, there are basically two (approximate) ways to consider the cable–fluid interaction.

The first one makes use of numerical simulations, in the framework of Computational Fluid Dynamics (CFD) (Bazilevs et al., 2013), that can be 2D or 3D, even if this latter is so computationally demanding that is only rarely considered (Lu and Ling, 2003). CFD results for the oscillating cable are reported in Pierro et al. (2017) using the open source software OpenFOAM, while more sophisticated numerical schemes are considered in Rashid et al. (2011) and Lu et al. (1997), where large-eddy simulation (LES) is employed when the flow is turbulent. Other computational papers where vorticity is considered for the problem of a cylinder oscillating in a fluid are Justesen (1991), Baba and Miyata (1987) and Wu et al. (2007). A combined experimental and computational study is reported in Dütsch et al. (1998). Applications in the field of underwater towed systems can also be quoted (Yang et al., 2022), since they have similar mechanical behaviour even with different objectives. CFD are also used to study VIV vibrations (Postnikov et al., 2017; Vijay et al., 2020).

The second approach consists of using simplified, heuristic models. They are approximate and not always founded on a solid physical background, but have the advantage to be simple, easy to use and practical. In certain cases, they can also lead to analytical solutions of the governing equations, with clear advantages. We can divide this category in two sub-models.

The first is where the action of the fluid is imposed on the cable, commonly as a (nonlinear) viscous force, without considering the interaction with the cable, which is often used with in-line (along the current) motion. The most famous in this realm is the Morison model (Morison et al., 1950), which assumes that the hydrodynamic force is quadratic with respect to the relative velocity. It has been compared with experimental results (Sarpkaya, 1986; Wolfram and Naghipour, 1999), and used in various applications (Lo and Leonard, 1982), including cable for a submerged floating tunnel (Wu and Mei, 2017), underwater floating structures (Chen et al., 2020; Terro and Abdel-Rohman, 2007), and in mooring lines of floating offshore wind turbine (Chen et al., 2018; Trubat et al., 2020) (including optimization Ferri et al., 2022; Ferri and Marino, 2023), which is the most important case for this review paper. Improvement of the Morison equation due to the vicinity of the sea bottom have been obtained in Wilde (1995) for the inviscid problem, and in Pierro et al. (2017) for a viscous fluid. In the former case an analytical approach is used, while in the latter case CFD is used to generate data from which a regression formula is obtained, thus linking CFD and simplified models. Comparison of CFD and Morison model is also reported in Zhang and Paterson (2015).

The second modelling approach, on the other hand, takes the interaction into account, although to an approximate level, and often deals with cross-flow motion. A famous one is the Facchinetti model (Facchinetti et al., 2004a), which introduces an artificial wake van der Pol oscillator to simulate the fluid behaviour; in this respect, various of its "predecessors" must be quoted (Hartlen and Currie, 1970; Skop and Griffin, 1973; Landl, 1975; Skop and Griffin, 1975), all using a wake oscillator. It has been largely used in the recent past, including cables (Facchinetti et al., 2004b). Tuning of the wake oscillator model with the experimental result is reported in Ogink and Metrikine (2010), while optimization is addressed in Kurushina et al. (2022) and calibration with CFD in Postnikov et al. (2017). Experiments of vortex-induced vibrations with a semi-immersed long flexible cylinder subjected to constant current profiles in condition of internal resonance are presented in Franzini et al. (2015). The bifurcations involved in the wake model of a VIV have been studied in depth in Wang et al. (2021). Other more sophisticated models are reported in Falco et al. (1999) and Lu et al. (2019). Interaction of VIV and nonlinear dynamical behaviour of the mechanical systems is the subject of Srinil and Zanganeh (2012) and Opinel and Srinil (2020).

Nonlinear dynamics of taut cables. In the previous subsections we addressed the nonlinear dynamics of sag cables, and dedicated a lot of attention because nonlinear phenomena easily appear due to low stiffness of the system, and so they are most "dangerous" or "interesting" from a nonlinear point of view. However, nonlinear phenomena can occur, although to a minor extent, also in taut cables, when displacements are no longer small. In offshore mooring applications the cables are commonly quite long and, when inclined, a sag is present because of the self-weigh, which is small – but not null – when the tension is large, so that they are almost taut. The nonlinear dynamics of nearly taut cables has been investigated in Mirhashemi and Haddadpour (2023) by considering a reduced order model based on a classical integro-differential equation, under parametric aerodynamic excitation. The introduction contains an overview or early works on the subject. In Yi and Liu (2023) the effect of an axial support excitation is addressed, and the nonlinearity comes from the initial configuration. Taut cables are initially perfectly straight only in vertical configurations, as in the Tension Leg Platforms (see Fig. 6). In this case, the most relevant phenomenon in the parametric excitation, namely the (periodic) change of the tension due the vertical motion of the buoy caused by the sea wave, inducing instability. A lot of attention has been paid to this important phenomenon, starting from the early works of Hsu (1975) and Rainey (1978), this latter being focused on TLP and showing good agreement with experimental data. In Patel and Park (1991) a TLP tether is investigated by means of the Galerkin's method, assuming a constant tension along the structure, while in Simos and Pesce (1997) the variation of tension is considered. The axial dynamics if taken into account in Chatjigeorgiou and Mavrakos (2002), showing how the coupling between transversal and axial modes affect the stability. The internal resonance is investigated in Chatjigeorgiou (2004), while the nonlinear resonance is addressed in Chatjigeorgiou and Mavrakos (2005). A refined analysis has been done in Vernizzi et al. (2020), where also the bending stiffness is taken into consideration.

Nonlinearity at the TDP. The nonlinearity at the TDP due to the unilateral behaviour of the soil has been deeply studied in a series of papers, where approximate analytical (Lancioni and Lenci, 2007; Demeio and Lenci, 2007, 2008) and numerical solutions (Lancioni and Lenci, 2007, 2010) are obtained by considering the unilateral behaviour of the foundation, which is modelled by a (unilateral) Winkler model and so is assumed to be deformable. Although the focus was on TDP dynamics, also the nonlinear resonance problem has been studied (Demeio et al., 2011; Demeio and Lenci, 2013). While in previous works attention is devoted only to the neighbourhood of the TDP and on the wave propagation to the resting part, a full cable model, up to the buoy, is considered in Chen et al. (2018) and Gobat and Grosenbaugh (2006), again with an unilateral Winkler soil and following the same approach of Webster (1995). The full problem has been considered also in Lenci and Callegari (2005), but in the static case. A comparison between numerical and experimental results is reported in Gobat and Grosenbaugh (2001). In Aranha et al. (1997), attention is focused on the boundary layer type of the bending moment at the TDP, using an analytical approach that has been later compared with numerical simulations (de A Campos and Martins, 2001), while in Yu and Tan (2006) a two-dimensional finite element model is utilized. In the frequency domain, a simple empirical model for the interaction of a catenary mooring with the seabed is investigated in Han and Grosenbaugh (2006). Actually, the considered problem belongs to the more general realm of beams resting on unilateral soil; here, both force vibrations (Celep et al., 1989; Coşkun, 2003) and wave propagation (Lenci, 2021; Demeio and Lenci, 2022) problems have been investigated.

4.2. Mooring cables

Mooring cables used to restrain and mitigate the response of floating offshore structures at specified locations are constantly subjected to arbitrarily complex combined loading such as wind-wave and current. They consist in a set of slack or taut moorings, connecting the platform to the seabed by means of anchors. Catenary lines are effective for stabilizing the system in the horizontal direction, providing restoring forces in surge and sway. Depending on their dead weight, anchors can be designed to withstand only horizontal forces. Due their moderate stiffness in surge-sway direction, catenary lines are particularly sensitive to severe sea states inducing large platform motions. Under such wave loads, extreme forces in the moorings due to shock loads caused by a temporary slackness in the line followed by a sharp spike in tension may occur, leading to an increase of the maximum stresses of more than the 50%. Thus, understanding their nonlinear behaviour considering the FSI, as well as its interaction with the sea-bed, is of paramount concern, as already discussed in a general way in the previous section.

Actually, in this field of investigation the solutions are mainly numerical, and very few analytical solutions are available. However, in the following we prefer to divide the literature review by grouping the papers that are mainly devoted to modelling and phenomena, even if they use numerical simulations, and those that are instead more concerned with numerical aspects, even if they have some – minor – modelling or phenomenological aspects.

Modelling, including geometrical and dynamical aspects, and metocean conditions. An elastic cable combines soft transverse stiffness with a strong axial stiffness, coupled through the curvature of the cable configuration, and so has small bending and torsional stiffnesses, and carries load mainly by adapting its geometrical shape.

Walton and Polachek (1960) studied the dynamic behaviour of bottom anchored submerged mooring lines considering both material and geometrical nonlinearities under the effects of different wave heights using finite difference approximation. Chang et al. (1997) developed a fluid–cable interaction model to understand the nonlinear dynamic response of submerged cables under the action of hydrodynamic force. The numerical simulation highlighted that the cable experiences a flutter oscillatory motion for fluid flow speed more than critical value. Liu and Bergdahl (1997) discussed the effects of current and seabed friction on the mooring cable response. The study revealed that energy dissipation increased due to the seabed friction which is a function of the excitation amplitude. To validate this theory, both time and frequency domain analysis are performed.

Ran et al. (1999) developed a coupled moored spar model and evaluated the nonlinear response of the mooring cable (chain–wire–chain combination) with and without colinear currents in both time and frequency domain. Finite element method-based software package WINPOST is used to solve the mooring dynamics with random waves. It is observed that heave response increased in the presence of currents. The effect of mooring induced damping on the response of the floating body is studied by Sarkar and Eatock Taylor (2002). Frequency domain analysis is employed to understand the dynamics of composite mooring cable. The effect of current speed and seabed friction on drag coefficient under random frequency and excitation amplitude is evaluated. Kreuzer and Wilke (2003) performed numerical investigation using multi-body system to determine the dynamic response of the homogeneous mooring lines taking in to account the hydrodynamic force exerted by the liquid in motion.

The load–deformation behaviour of elastomeric mooring cables is studied, and the breaking strength is determined depending on the selected working load. Gobat and Grosenbaugh (2006) used finite difference method for analysing the nonlinear dynamics of electro-optical-mechanical cables under the effects of current and combined wind-wave loading. Chen et al. (2019) proposed a nonlinear frequency domain multi harmonic balance method to understand the dynamics of submerged homogeneous mooring cable. It is a 3D approach which provides promising results when compared to the time domain analysis. Wang et al. (2019) developed a numerical method based on the finite element method to evaluate the dynamic response of the moored cables anchored to the seabed under seismic and wave excitation. Effects of sag to span and inclination angles on the development of tensile force are determined.

The initial developments of the mooring cable analysis, especially for slack lines, included analytical catenary equations that consider self-weights but the effect of bending stiffness for such cables is ignored. Among the existing linear and nonlinear beam theories in the literature, the generalized Cosserat rod theory (Cosserat, 1909) and geometrically exact Simo-Reissner beam theory (Simo, 1985; Simo and Vu-Quoc, 1988), accounting for large deformations, shear, bending and torsional deformations can be relevant to model flexible marine cables. Martin and Bihs (2021) and Martin et al. (2021) used the Cosserat rod theory and quaternion-based rotation formalism to model the static and dynamic analysis of riser cables. In all the aforementioned references, the hydrodynamic loads due to sea currents in the form of drag and lift forces and modelled using Morison's equation, and numerous example test cases manifesting the capabilities of coupling between risers and marine environment are also presented.

Metocean conditions as well as wind-wave misalignment have been shown to also directly influence the overall dynamic characteristics of integrated systems comprised of floating platforms and various mooring line configurations. Liu and Manuel (2018) studied precisely this problem for a large (13.2 MW) floating offshore wind turbine supported on a semisubmersible platform with three alternative mooring systems and for selected environmental conditions. Various 50-year return period values for various system response measures were studied for the integrated system. The dominant and different alignment of wind and waves greatly influences extreme response levels as has been found by others, with interesting aerodynamic, hydrodynamic and gyroscopic influences as well. Interestingly, fairlead and seabed anchor strains are also affected by the interline angle of the selected the mooring system's geometric and spatial layout.

Computational models and methods. Because of the complexity of the system, numerical models play a fundamental role for the prediction of the complex dynamic behaviour of both slack and taut mooring systems.

Apart from commercial software Orcaflex (OrcaFlex) and in-house academic codes, open-source packages like MoorDyn (Hall, 2015) and Moody (Palm and Eskilsson, 2018) are widely used for marine riser analysis. In MoorDyn (Hall, 2015), a lumped mass modelling approach ignoring bending deformations is used for modelling risers. Moody, on the other hand, is developed from contributions from Palm et al. (2017) and Palm (2017), where a hp-adaptive discontinuous Galerkin method assuming negligible bending stiffness is used to model risers.

Behind commercial and open-source software, there has been a large amount of research in developing (or adopting) numerical codes. We refer to Davidson and Ringwood (2017) for a review on various numerical models used to analyse mooring systems. Ablow and Schechter (1983) developed a finite difference code in 3-D which can simulate a 1.07 km long towed cable considering the drag effects and evaluate the tension developed at different locations of the cable at any instant of time. Tsukrov et al. (2005) used aqua-FE that combines the Lagrangian approach for large deformation under the action of waves and currents. Finite-difference schemes addressing the ill-posed problem due to low tension were proposed in Sun and Leonard (1998) and Tjavaras et al. (1998).

Numerical models can be based on a variety of theories and methods leading to different levels of accuracy. Due to their simplicity and efficiency, quasi-static mooring lines models have been developed and widely employed (Masciola et al., 2013). In this case, under the hypotheses of a completely submerged cable in a homogeneous fluid undergoing a plane motion, by neglecting hydrodynamic forces, inertia and damping contributions, the nonlinear system of equations of the catenary is enforced to obtain the vertical and horizontal components of the cable tension at the fairlead. This allows to retrieve, solving the static equilibrium at a fixed time, position and tension of each section of the cable. Since inertial and damping terms are neglected, the mooring system contributes to the equation of motion of the entire system with restoring forces and moments (Jonkman, 2009) that are proportional to the tension at the fairlead and to the motion of the floating structure, i.e., providing only additional stiffness.

Even though the previous method allows to consider taut lines, as well as slack lines suspended or partially resting on the seabed, dynamic contributions and hydrodynamic forces are found to be significant for the prediction of the system response (Hsu et al., 2017; Cevasco et al., 2018; Bruschi et al., 2020). For this reason, advanced numerical tools able to solve the dynamic motions of the mooring lines have been developed employing lumped mass (Hall and Goupee, 2015). In this case, the cable is modelled with concentrated masses connected together by means of springs, reproducing both geometrical and elastic stiffness, and dampers. In this way, also materials with nonlinear constitutive laws, such as synthetic fibers, can be considered (Nguyen and Thiagarajan, 2022; Xiong et al., 2018).

More recently, a vector form intrinsic finite element (VFIFE) method suitable for large rigid body motions and large deformations has been presented in Zhang et al. (2022). Among other numerical approaches, Isogeometric Analysis (IGA) (Hughes et al., 2005) has gained enormous popularity over the last years due to its potentialities in terms of accuracy, efficiency and geometrical flexibility. IGA features these attributes by employing the same smooth (B-splines or NURBS) basis functions to describe both geometry and field variables of the differential problem. Recent extensions of IGA to the dynamic problem of geometrically exact beams (Simo, 1985; Marino et al., 2019a,b), where the even more efficient collocation scheme (Auricchio et al., 2012; Marino, 2017) was deployed, make this technique an appealing computational solution (see, e.g., Agrawal et al. (2024)) to model nonlinear mooring lines of offshore structures with the possibility to efficiently incorporate nonlinear material models and curved initial geometries (Ignesti et al., 2023).

Integrating the modelling of mooring cables with the oceanic environment requires a multi-physics (FSI) approach Eskilsson and Palm (2022) and Eskilsson et al. (2023). The FE techniques are popular for modelling solids whereas, Finite Volume (FV) based discretization techniques are popular for modelling fluid flows and only recently are also effectively used for simulating deformations in solids (Cardiff and Demirdžić, 2021). Bali et al. (2022) uses the FV discretization approach to model quasi-static, slender beams subjected to large displacements and rotations in the open-source software OpenFOAM (a popular CFD toolbox). This recent contribution has the potential to model multi-physics problems like mooring risers in the offshore environment under one unified approach allowing fluid–solid interaction to be addressed using a single numerical technique.

5. Control of electrical subsystem

In addition to structural dynamics and FSI-related issues discussed above, the electrical aspects of FMEIs play also a central role. Beside the strong impact of control systems on the dynamics of energy structures (e.g., blade pitch of wind turbine or tilt angle for solar panels), the control of electrical subsystems allow power flow control between various sources, adjustment of voltage levels, and AC/DC adaptation to integrate particular energy sources with the rest of the system. To effectively pursue these tasks, data collected from SCADA and SHM systems are fundamental for a proper identification of the operating points of each component of the FMEI.

5.1. FMEIs as Hybrid Energy Systems (HESs)

There could be different types of generators within an energy island: wind turbines, PV generators, wave energy generators, fuel cells, and possibly storage elements (like batteries). These generators are in fact creating a new structure which may be denoted as hybrid source (Golubovic, 2014). The schematic of a hybrid source structure is given in Fig. 7. Power electronics interfaces (PEI) are connecting generators to a Direct Current (DC) bus which is used to supply power to DC loads. On the other hand, there is an additional PEI to connect the DC bus to AC (Alternating current) bus through which AC loads are supplied. Control requirements for the DC bus are defined by the voltage to be maintained at the bus. On the other hand, the main control requirements for the AC bus are inherited from the demands of the grid synchronization and load supply, assuming that AC load is in fact an electrical grid to which the hybrid source is connected. In this case, the hybrid source is working as a current source, its voltage is defined by the grid and the current supplied to the grid is determining the power supplied from the generator to the grid. However, if the hybrid source is operating in an island mode, it is in fact a voltage source and produced voltage has to satisfy predetermined requirements in terms of voltage amplitude and frequency. The voltage and load parameters define the power supplied from the generator to the load.

5.2. Control system

The control system can be divided into two major parts: controlling electrical and mechanical parts of the system. Control of mechanical parts means in fact control of the mechanical components of the hybrid source so that input non-electrical power is controlled.

This review will go towards the electrical part of the system, which is based on the control of power electronic interfaces (PEI). These interfaces are represented by power converters of different topologies used to connect different types of generators to the DC bus, and then to provide an interface between the DC bus and the AC bus. This means that the major topologies of the power converters are AC–DC, DC–DC and DC–AC. These power electronics interfaces are used to control and connect the various components of the system and enable reliable and high quality power exchange between the sources and loads.

There are two main issues involving either directly or indirectly with the DC–AC converter (inverter), namely the DC-link voltage control (if it is not being managed with DC–DC converter separately) and the AC-power control. Considering the AC-power flow control from source converter to a grid, a DC-link/bus voltage can be considered as a stiff DC-source. Thus, the DC-link voltage control can be considered in outermost loop to ensure the availability of a stable DC voltage at the input of the DC–AC converter. The frequency and voltage droop-control techniques have been suggested and tested in autonomous or in grid-supporting modes (Vasquez et al., 2009; El-Hawary, 2014; Bhatti et al., 2016; Marwali and Keyhani, 2004; Kazmierkowski and Malesani, 1998; Justo et al., 2013; Planas et al., 2013).

Another method of converter control, the direct power control (DPC) resulted in analogy to the famous direct-torque-control (DTC) technique utilized for the operation of electric drives (Noguchi et al., 1998; Malinowski et al., 2004). All of these methods could not work fine until complemented with additional controllers to provide the voltage ride through (VRT) capability in case of temporary or permanent voltage or power instabilities in the power network. To handle these imbalances in the power-system, different circuital topologies such as capacitor mid-point clamped three-phase inverter, four-leg inverter and three single-phase H-bridge inverters have been used in the literature along with the controllers (Zhong et al., 2005; Hintz et al., 2016; Vechium et al., 2005).

In short, all of the converter topologies and the advanced control methods of voltage source converters found in the literature are quite complicated either due to more sized capacitors, more switches, complicated switching algorithms, delays by positive, negative sequence separations and the cascaded structures. Finally, it is important to highlight that all of the existing grid-connected control solutions are case specific i.e. different controllers work in balanced and unbalanced grid scenarios.

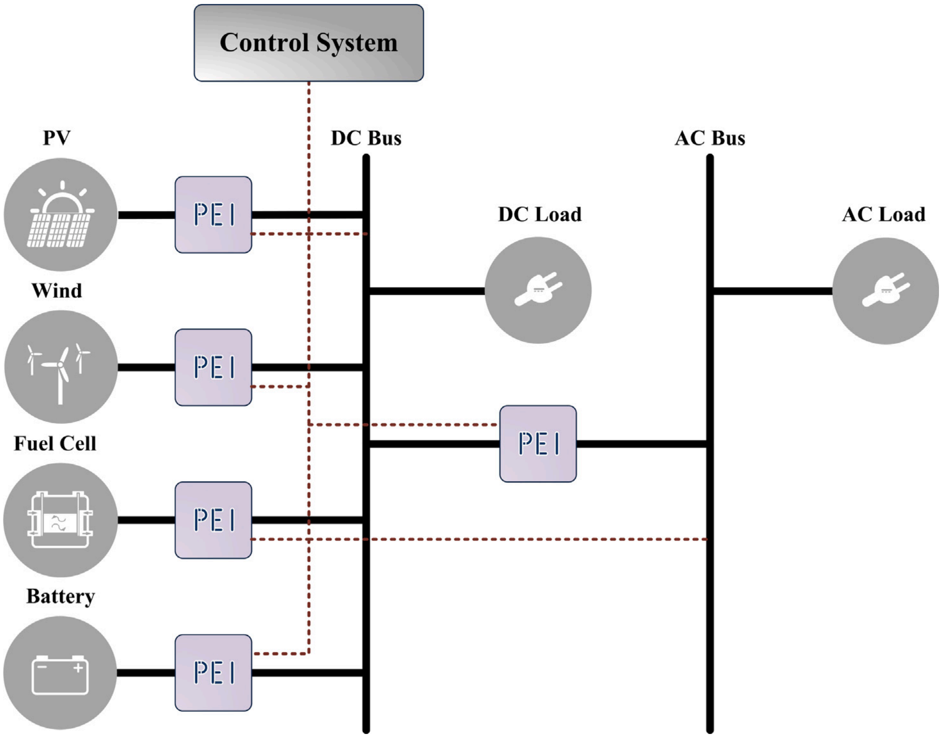

Fig. 7. Hybrid source structure (Golubovic, 2014).

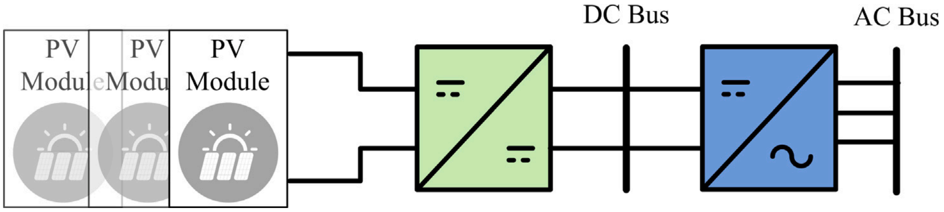

Fig. 8. String configuration of PV modules (Golubovic, 2014).

Let us for example discuss integration of PV modules to the structure. String configuration of the modules with PEI is represented in Fig. 8. DC–DC converter (coloured in green) is managing the control of DC bus voltage, while the DC–AC converter (coloured in blue) ensures the desired AC voltage at the output. Similar structures can be illustrated for other types of generators.

General structure of HES (Hybrid Energy System) describing integration of different sources through power electronics interfaces is depicted in Fig. 9. Input side converters (n in total for n sources) are interfacing sources to DC bus. Each one of them has a controller attached to it. On the other hand, there is a single output side converter interfacing DC and AC bus with its respective controller.

6. Conclusions

The concept of FMEIs refers to modularized, interconnected, floating structures that function together to provide renewable energy generation, storage, and possibly conversion and transport. The implementation of such a concept requires the effective synergy of multiple engineering disciplines and industries in the construction, marine and renewable energy sectors. The present paper focuses on a series of key structural and electrical-related topics relevant to the FMEIs.

Although FMEIs are still at the developing stage, it is shown in this work that many of the concepts already developed in other similar contexts such as offshore wind energy, can be highly relevant to FMEIs. Specifically, the concepts and knowledge of existing technologies, such as Floating Offshore Wind Turbines (FOWTs), Wave Energy Converters (WECs) and Floating Photovoltaic systems (FPVs) are adopted and compared. While FPVs require a significant surface area to achieve comparable power production, this characteristic holds considerable promise for FMEIs, where the large surface area needed between FOWT modules to reduce wake effects could be utilized for positioning FPVs.

Since FMEIs are emerging systems, there are currently no operational SHM (Structural Health Monitoring) systems available for reference in real-world installations. The applicability of current data collection techniques for structural assessment and monitoring to FMEIs is comprehensively discussed in this paper. Several sensing technologies such as accelerometers, strain gauges, and their potential applications to FMEIs are reviewed. In addition, the review shows that SCADA (Supervisory Control and Data Acquisition) systems can be employed to accumulate relevant operational data in real-time from different components of the future FMEIs with a relatively smaller number of sensors installed in different energy harvester. It is generally concluded that condition monitoring and condition-based maintenance methods can be extensively employed in the future FMEIs.

The second topic reviewed is the complex loading conditions at which FMEIs will operate. To assess the loads on the supporting platforms of FMEIs modules, the Wave Structure Interaction (WSI) problem can be addressed by using the potential flow theory and, when necessary, higher fidelity Fluid–Structure Interaction (FSI) models. In contrast to conventional offshore structures, the internal loads of FMEIs

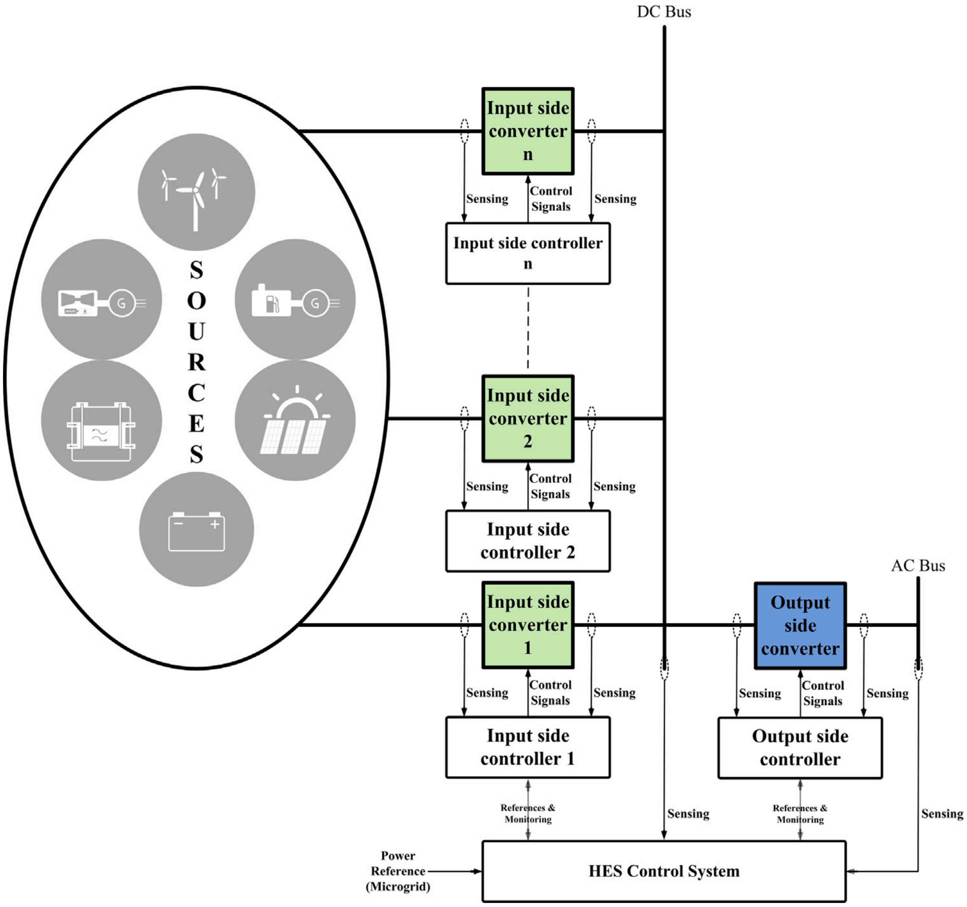

Fig. 9. HES structure - source integration - PEI (Golubovic, 2014).

will significantly depend on the structural approach chosen to stabilize and interconnect each individual floating module, mooring systems, and the layout of the islands. The review also includes another extensive discussion about the environmental loads that should be considered in the design and analysis of FMEIs. It is also concluded that metocean data play a critical role in statistics related to the environmental conditions.

It is also discussed the importance of nonlinear cable dynamics in the design and stability analysis of FMEIs. Potential nonlinear sources are reviewed with a fundamental discussion of each source. It is concluded that the nonlinear behaviour of the cables, in the interaction with the fluid and at the TDP (Touch Down Point), plays a critical role in understanding the dynamics of FMEIs. Moreover, from the modelling standpoint, new challenges may arise for FMEIs due to the more complex topology and geometry of the entire mooring system (e.g., for shared mooring lines), requiring more advanced computational approaches.

Finally, the power electronics interfaces for different types of generators that will potentially be installed in FMEIs, are reviewed. This also includes discussions about the control systems that can be used for the electrical parts. Although control systems are discussed less extensively than other sections, the review offers a starting point upon which future concepts can be developed.

CRediT authorship contribution statement

Enzo Marino: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Michaela Gkantou:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Abdollah Malekjafarian:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Seevani Bali:** Writing – original draft, Methodology. **Charalampos Baniotopoulos:** Writing – original draft, Methodology. **Jeroen van Beeck:** Writing – original draft, Methodology. **Ruben Paul Borg:** Writing – original draft, Methodology. **Niccoló Bruschi:** Writing – original draft, Methodology. **Philip Cardiff:** Writing – original draft, Methodology. **Eleni Chatzi:** Writing – original draft, Methodology. **Ivan Čudina:** Writing – original draft, Methodology. **Florea Dinu:** Writing – original draft, Methodology. **Evangelos Efthymiou:** Writing – original draft, Methodology. **Giulio Ferri:** Writing – original draft, Methodology. **Helena Gervásio:** Writing – original draft, Methodology. **Junlin Heng:** Writing – original draft, Methodology. **Zhiyu Jiang:** Writing – original draft, Methodology. **Stefano Lenci:** Writing – original draft, Methodology. **Ivan Lukačević:** Writing – original draft, Methodology. **Lance Manuel:** Writing – original draft, Methodology. **Angela Meyer:** Writing – original draft, Methodology. **Mariela Méndez-Morales:** Writing – original draft, Methodology. **Adnan Osmanović:** Writing – original draft, Methodology. **Vikram Pakrashi:** Writing – original draft, Methodology. **Amiya Pandit:** Writing – original draft, Methodology. **Giuseppe Rega:** Writing – original draft, Methodology. **Davor Skejić:** Writing – original draft, Methodology. **Luana Tesch:** Writing – original draft, Methodology. **Viorel Ungureanu:** Writing – original draft, Methodology. **Tarik Uzunović:** Writing – original draft, Methodology. **Amrit Shankar Verma:** Writing – original draft, Methodology.

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.

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