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Review

Overview of modelling and control strategies for wind turbines and wave energy devices: Comparisons and contrasts

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ABSTRACT

Increasingly, there is a focus on utilising renewable energy resources in a bid to fulfil increasing energy requirements and mitigate the climate change impacts of fossil fuels. While most renewable resources are free, the technology used to usefully convert such resources is not and there is an increasing focus on improving the conversion economy and efficiency. To this end, advanced control technology can have a significant impact and is already a relatively mature technology for wind turbines. Though wave energy systems are still in their infancy, significant benefits have been shown to accrue from the appropriate use of control technology. To date, the application communities connected with wind and wave energy have had little communication, resulting in little cross fertilisation of control ideas and experience, particularly from the more mature wind area to wave. This paper examines the application of control technology across both domains, both from a comparative and contrasting point of view, with the aim of identifying commonalities in control objectives and potential solutions. Key comparative reference points include the articulation of the stochastic resource models, specification of control objectives, development of realistic device models, and development of solution concepts. Not least, in terms of realistic system requirements are the set of physical and legislative constraints under which such renewable energy systems must operate, and the need to provide reliable and fault-tolerant control solutions, which respect the often remote and relatively inaccessible location of many offshore deployments.

1. Introduction

With the continuing decrease in the stock of global fossil fuels, issues of security of supply, and pressure to honour greenhouse gas emission limits (*e.g.*, the Kyoto protocol), much attention has turned to renewable energy sources to fulfil future increasing energy needs. Wind energy, now a mature technology, has had considerable proliferation, with other sources, such as biomass, solar, and tidal, enjoying somewhat less deployment. Waves provide previously untapped energy potential and wave energy has been shown to have some favourable variability properties (a perennial issue with many renewable, especially wind), especially when combined with wind energy Fusco, Nolan, and Ringwood (2010).

While wind and wave energy share certain characteristics *i.e.* the raw resource is both free and somewhat unpredictable, their development has followed quite different paths, especially regarding the level of maturity achieved. Wind farms, both offshore and onshore, are now commonplace, and wind turbine design, with a few exceptions, has largely converged on the horizontal–axis device. In contrast, at the time of writing, no commercial wave farms are in existence, though a number of commercial wave farms are currently under development. In addition, the current poor state of wave–energy technology development is highlighted by the availability of just a few commercially available Wave–Energy Converters (WECs), including the Wave Dragon Soerensen (2003), Pelamis Yemm, Pizer, and Retzler (0000), Oyster Whittaker and Folley (2012), the SeaBased device Leijon and Bernhoff (2006) and Wavestar Kramer, Marquis, and Frigaard (2011). The stark contrast in the operational principles of these five devices, as well as the diversity in appearance and operation of the 147 prototypes listed in Koca et al. (2013), provides further evidence of the relative immaturity of wave-energy technology.

One common misconception, in effective renewable energy converter design, is that converters must be optimally efficient. However, since the resource itself (wind and wave) is free, the main objective is to minimise the converted cost of the renewable energy *i.e.* the cost per kWh, taking into account the lifetime costs (capital, operational and commissioning/decommissioning costs) as well as energy

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receipts (value of energy sold). Nevertheless, for a given capital cost, maximising the energy receipts (assuming relative insensitivity of operational costs) is an important economic objective and control system technology has an important role to play in this regard. In an ideal world, one should consider the design of a complete system from the top down. However, convention has it that physical systems are usually designed by the discipline–specific experts and the control problem is then addressed in a subsequent step by control engineers, working in collaboration with the discipline–specific experts. Such an approach, though prevalent in the bulk of industrial applications of control, is non–optimal, even if there are some notable exceptions. Some preliminary studies do suggest a strong interaction between the fundamental design of renewable energy conversion machines and the algorithms and systems used to control them, both for the wind Bianchi, Battista, and Mantz (2007), Pao and Johnson (2011) and wave Garcia-Rosa, Bacelli, and Ringwood (2015a), Garcia-Rosa and Ringwood cases. In any case, given the relatively low cost of control systems technology (sensors, actuators, computer, software) compared to the cost of the renewable energy converters (approx. \$5m–\$16m/MW for wave, \$1.3m–\$2.2m/MW for wind World Energy Council (2013)), it will be assumed in this paper that the focus is on increasing the energy conversion capacity of a given wind or wave energy device. However, this relatively simple implementation modality masks both the capability of control systems and the high level of engineering underpinning the development of a suitable control algorithm. For example, many high–performance model–based control design methods require an accurate mathematical model of the system to be controlled and a significant number of man–hours can be absorbed in modelling. Nevertheless, there is usually a good case to be made for the incorporation of control technology to improve the performance (both technical and economic), reliability and safety of a system Odgaard (2012). By taking into account commonalities and contrasts in particular for wind turbines and wave energy devices, this work will consider the role that modelling and control engineering can play in making energy conversion systems more competitive and effective.

There are a number of economic issues associated with the introduction of control systems for renewable energy devices which need to be considered. One important factor is that many wind and wave devices are situated in relatively remote and/or inaccessible areas, with consequent implications for maintenance. As a result, the implemented control systems should be reliable and there is a need for fault–tolerant control Blanke, Kinnaert, Lunze, and Staroswiecki (2006), Odgaard (2012). In addition, any increases in duty cycle, velocities or forces associated with energy converter components need to be considered and these may impact operational cost via additional maintenance requirements.

Both wind turbines and wave energy devices exhibit nonlinear behaviour and are required to operate over a wide range of excitations. Wind and wave energy systems also have particular physical constraints (displacements, velocities, accelerations and forces) which must be strictly observed if such systems are to operate effectively and have economically attractive useful operational lifetimes. The motivation for this paper comes from a real need to have an overview on the modelling and control challenges for wind turbines and wave energy devices, which present common and different requirements related to renewable source power conversion efficiency into electric energy.

In general, in the fields considered in this paper, power conversion is converting renewable sources to electric energy, regulating also the voltage and frequency. Therefore, a power converter is an electro–mechanical device for converting wind/wave energy to electrical energy. The power converter includes an electrical machinery that is used to convert and control both frequency and voltage.

It is worth noting that the combination of wave and wind energy systems will not be considered in this paper, as addressed *e.g.* in Nolan and Ringwood (2005), Fusco et al. (2010), Teillant, Costello, Weber, and Ringwood (2012). Moreover, floating wind turbine concepts, which present important and challenging aspects for both the modelling and control points of view, see *e.g.*Matha (2009), Schlipf et al. (2013), are also beyond the scope of the current review.

With this view, the work will focus on commonalities and contrasts for wind and wave energy systems. Wind turbine systems seem relatively mature from the modelling point of view, whilst wave energy devices present unique, interesting and challenging aspects. Therefore, the final aim is to see what modelling and control aspects might be common with a view to utilising some ideas, born in one domain, within the other. These issues have begun to stimulate research and development in the wider control community in each domain, and the main results will be summarised in this work. In particular, a proper mathematical description of these energy conversion systems should be able to capture the complete behaviour of the process under monitoring, thus providing an important impact on the control design itself.

Therefore, the analysis of the commonalities and the contrasts between these two fields will be performed according the following items, which describe also the structure of the paper:

- Requirements of the generic control problem: unique aspects to wind turbine and wave energy systems;
- Purpose of the models for wind turbines and wave energy systems;
- Models for the renewable resources: comparisons and contrasts of wave and wind model characteristics;
- Control strategy development: objectives and available tools for wind turbine and wave energy systems;
- Conclusions: are these two domains really comparable? On what basis – modelling and/or control, and/or the intermittent resource that drive them? Are there some fundamental issues, from a control perspective, that explain why wind turbines are now commonplace, but wave energy devices are not?

1.1. Overview of wind turbine systems

The main components of a horizontal–axis wind turbine that are visible from the ground are its tower, nacelle, and rotor, as can be seen in Fig. 1. The nacelle houses the generator, which is driven by the high–speed shaft. The high-speed shaft is in turn usually driven by a gear box, which steps up the rotational speed from the low–speed shaft. The low-speed shaft is connected to the rotor, which includes the airfoil–shaped blades. These blades capture the kinetic energy in the wind and transform it into the rotational kinetic energy of the wind turbine Bianchi et al. (2007).

Wind turbine control goals and strategies are affected by turbine configuration Munteanu and Bratcu (2008). horizontal–axis wind turbines may be ‘upwind’, with the rotor on the upwind side of the tower, or ‘downwind’. The choice of upwind versus downwind configuration affects the choice of yaw controller and the turbine dynamics, and thus the structural design. Wind turbines may also be variable pitch or fixed pitch, meaning that the blades may or may not be able to rotate along their longitudinal axes. Although fixed–pitch machines are less expensive initially, the reduced ability to control loads and change the aerodynamic torque means that they are becoming less common within the realm of large wind turbines. Variable–pitch turbines may allow all or part of their blades to rotate along the pitch axis Bianchi et al. (2007), Burton, Sharpe, Jenkins, and Bossanyi (2011).

Moreover, wind turbines can be variable speed or fixed speed. Variable–speed turbines tend to operate closer to their maximum aerodynamic efficiency for a higher percentage of the time, but require electrical power processing so that the generated electricity can be fed into the electrical grid at the proper frequency. As

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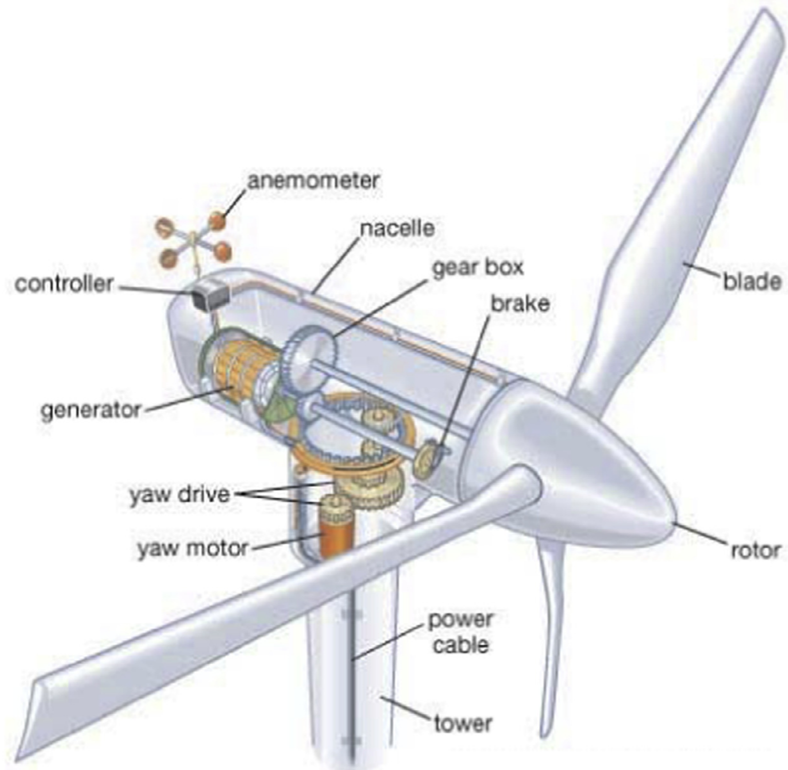

Fig. 1. Wind turbine main components.

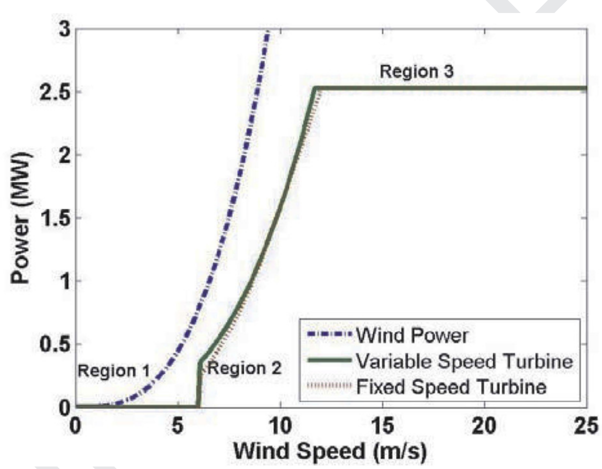

Fig. 2. Example power curves. The wind power curve shows the power available in the wind for a turbine of the same size as the two example turbines.

generator and power electronics technologies improve and costs decrease, variable–speed turbines are becoming more popular than constant–speed turbines at the utility scale Bianchi et al. (2007).

Fig. 2 shows example power curves for a variable–speed and a fixed–speed wind turbine, as well as a curve showing the power available in the wind for this 2.5 MWh example turbine. For both turbines, when the wind speed is low (in this case, below 6 m/s), the power available in the wind is low compared to losses in the turbine system so the turbines are not run. This operational region is sometimes known as Region 1. When the wind speed is high, Region 3 (above 11.7 m/s in this example), power is limited for both turbines to avoid exceeding safe electrical and mechanical load limits Odgaard, Stoustrup, and Kinnaert (2013).

Note that the example turbines in Fig. 2 produce no power in low winds because they are not turned on until the wind speed reaches a certain level. Further, power is limited to protect the electrical and mechanical components of both turbines in high wind speeds. Both turbines produce the same power at the design point for the fixed speed turbine, but the variable speed turbine produces more power over the rest of Region 2 Pao and Johnson (2009).

The main difference in Fig. 2 between the two types of turbines appears for mid-range wind speeds, Region 2, which encompasses wind speeds between 6 and 11.7 m/s in this example. Except for one design operating point (10 m/s in this example), the variable–speed turbine captures more power than the fixed-speed turbine. The reason for the discrepancy is that variable–speed turbines can operate at maximum aerodynamic efficiency over a wider range of wind speeds than fixed-speed turbines. The maximum difference between the two curves in Region 2 is 150 kWh. As shown in Section 2.1, for a typical wind speed distribution with a Weibull distribution, the variable–speed turbine captures 2.3% more energy per year than the constant–speed turbine, which is considered to be a significant difference in the wind industry.

Not shown in Fig. 2 is the ‘high wind cut–out’, a wind speed above which the turbine is powered down and stopped to avoid excessive operating loads. High wind cut–out typically occurs at wind speeds above 20–30 m/s for large turbines, with many factors determining the exact value.

Even a perfect wind turbine cannot fully capture the power available in the wind. In fact, actuator disk theory Froude (1889) (*i.e.* a theory used in fluid dynamics used for describing a mathematical model of an ideal actuator disk, such as an helicopter rotor) shows that the theoretical maximum aerodynamic efficiency, which is called the Betz Limit, is approximately 59% of the wind power Betz and Randall (1966). The reason that an efficiency of 100% cannot be achieved is that the wind must have some kinetic energy remaining

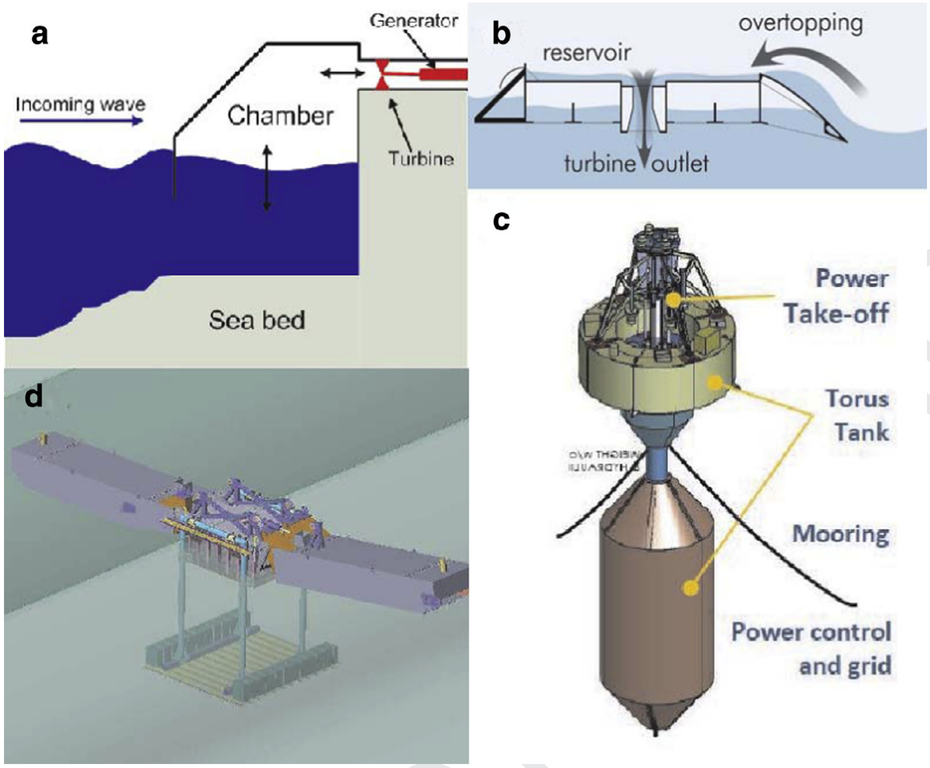

Fig. 3. Various WEC devices, based on diverse operating principles (a) OWC, (b) overtopping device, (c) self-reacting point absorber, (d) hinged–barge connected structure.

after passing through the rotor disc; if it did not, the wind would by definition be stopped and no more wind would be able to pass through the rotor to provide energy to the turbine.

The most common mathematical description of the complete wind turbine model will be provided in Section 3.2.

1.2. *Overview of wave energy systems*

Current wave energy prototype devices are diverse in operation and principle Koca et al. (2013), Drew, Plummer, and Sahinaya (2009). Some oscillating devices are shore-mounted and harness the motion of an enclosed Oscillating Water Column (OWC), while others operate offshore and can be bottom or fixed platform referenced, or self-reacting multi-body structures. Others utilise overtopping of a floating reservoir to rectify the oscillating power flux of the waves. Fig. 3 shows a small selection of WEC devices.

While operating principles vary, WECs usually rely on the hydrodynamic wave force to create a variation in the displacement between the WEC and a (fixed or relatively fixed) reference. In some case, the reference is provided by the seabed while, in other cases, the variation is between two components of the same device, tuned to resonate at different frequencies. In the OWC case, the water column itself provides the movement, with the body of the device remaining relatively fixed. The relative motion is then harnessed into a useful form using some form of pneumatic, hydraulic or electrical Power Take–Off (PTO) system.

Like wind turbines, wave energy devices have to operate under a wide variety of resource characteristics but, in the wave case, devices are subject to both wave amplitude and wave period variations. In addition, there may be more extreme sea states where the device must be put into a 'safe' mode, where power production is abandoned and the device configured to minimise the likelihood of damage. There is also a need to ensure that the rated power of the electrical system is not exceeded in power production mode, articulated by the flat portion of a typical wind turbine power curve, as described in Section 1.1. Since the wave period changes frequently, it is difficult to design a device to 'resonate' over all wave periods well; either a device in its natural form can resonate very well at a particular frequency, or it can resonate poorly across a wide band of frequencies. However, control systems may be employed to artificially adjust the resonant frequency of the device, preserving good power capture performance over a range of typical sea conditions. Unlike wind turbines, the power flux incident on a wave energy device is reciprocating, usually described (using linear wave theory) as a sum of sinusoids. However, like the wind turbine problem, there is a need to match the device load to the available excitation and this presents itself as an *impedance–matching* problem Ringwood, Bacelli, and Fusco (2014), compared to the resistance matching problem for wind turbines, reflecting the unidirectional motion of wind turbines and the (usually) reciprocating motion of wave energy devices. Further clarification on the impedance matching problem is given in Section 4.3.1. This load matching is the effective means by which the resonant period of a WEC is altered. We can note that there is a significant interaction between the control problem and the optimal geometric design (in particular size) of the device, for a specific wave climate Garcia-Rosa and Ringwood.

In addition to adjusting the loading on the device, a WEC control system must also observe the physical constraints on a device, primarily force and excursion constraints. However, velocity and acceleration constraints may also be relevant. In many cases, some control considerations can be used to optimise the trade-off between force and excursion constraints (noting that increased resisting force results in lower amplitude excursions) to maximise power capture Bacelli and Ringwood (2013c).

Like wind turbines, wave energy devices are deployed in farms, to maximise the economy of scale in the high costs associated with electrical infrastructure and mooring systems. Like wind farms, the objective is to maximise the performance of the whole farm, considering the prevalent direction of the incoming wave resource. However, unlike wind farms, WECs operating in a farm structure produce both

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Significant wave height (H_{sig}, m) \ Power period (T_{pow}, s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Fig. 4. Power matrix for the Pelamis wave power device.

destructive *and constructive* interference, since devices in motion radiate waves which can constructively interfere with the incident waves experienced by other devices. In fact, the farm containing n_d devices can have a better performance than n_d isolated devices, for particular wave directions and climates. As a result, the problem of controlling a WEC array does not reduce to the individual control of each device in the array, but should also consider the interactions between the devices, if maximum power capture is to be attained Bacelli, Balitsky, and Ringwood (2013a), Bacelli and Ringwood (2013a). In addition, a significant interaction between the optimal array layout and the control system has also been identified Garcia-Rosa et al. (2015a).

Since the power production of WECs is sensitive to both wave amplitude and period, power production characteristics are defined by two input parameters, sometimes articulated in the form of a look–up table, as shown in Fig. 4.

1.3. Specification of the generic control problem

In general, control science attempts to devise algorithms that force a system to follow a desired path, objective, or behaviour modality. Traditionally, the control problem is defined by a tracking problem, where the objective is for the system output to follow the reference input Kuo (1995). While problems of this type do occur in energy conversion applications, for example speed control of both wind and tidal turbines, it is useful to broaden the set of problem descriptions and potential solutions a little, in order to assess the potential of control engineering in the general energy conversion context.

In general, the control problem definition requires the maximisation or the minimisation of a prescribed performance objective (such as the max. energy, min. error) subject to proper system constraints (see *e.g.* amplitudes, rates, forces, etc) *i.e.* a constrained optimisation problem. The definition considered here is not inconsistent with the purpose of a classic controlled system with a feedback loop, where the objective function is usually some measure (*e.g.* a quadratic measure) of the difference between the controlled output and its desired value, *i.e.* the tracking error, with respect to the reference or the set–point. In this way, the desired performance of the tracking system in closed–loop can be specified in a variety of ways Kuo (1995):

1. Desired transient response;
2. Desired steady–state response;
3. Desired closed-loop poles (roots of the closed–loop transfer function);
4. Trade-off between control energy and tracking error;
5. Minimisation of the sensitivity of the closed–loop system to variations in the system description;
6. Minimisation of the sensitivity of the closed–loop system to external disturbances.

Items 5 and 6 in the list above relate to the system robustness and specific control methodologies to address these objectives have been developed since the late 1970s. In most cases, control design methods provide an explicit solution for the feedback controllers, while some methods solve the more general optimisation problem defined at each time step. In the following, specific or general solutions, which can be useful in the control of wind turbines and ocean energy devices, will be recalled and analysed.

We propose a generic control problem framework, as shown in Fig. 5, consisting of an upper (optimal) setpoint generation stage and a lower control loop to ensure tracking of the setpoint. Both sets of control calculations must be mindful of physical constraints in the system. In the wind energy case, for variable speed turbines, an optimal rotational speed is first calculated (for Regions 2–3 of the power curve in Fig. 2), and torque and/or blade pitch control used to achieve the required rotational speed. In the wave energy case, an optimal velocity *profile* is calculated for a device and the PTO system modulated to follow the desired velocity profile.

Note, finally, that many control methods require a mathematical model of the system, in order to determine the control algorithm and

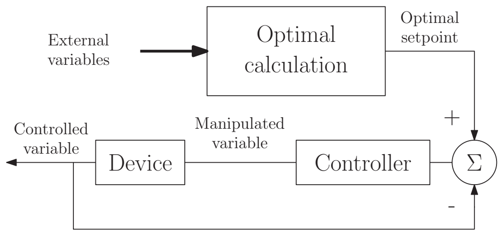

Fig. 5. Hierarchical control structure, showing the optimal setpoint (feedforward) calculation and the servomechanism section.

such methods are termed model–based. The requirement for an accurate mathematical system model often involves considerably more work than the calculation of the controller itself, though system identification techniques Simani, Fantuzzi, and Patton (2003), Fusco and Ringwood can be employed to determine a black–box model, *i.e.* a model which has no structural relationship to the physical system. The combination of system identification techniques with a mathematical procedure for controller determination can be used to develop adaptive controllers, which have the capability to adapt to unknown (in 'self-tuning mode') or time–varying systems. Adaptive control schemes based on linear system models also have the capability to track variations in a linear model due to the presence of nonlinearity, though nonlinear systems are best controlled with a dedicated fixed–parameter nonlinear controller. Significant care and attention must also be paid to adaptive schemes to ensure stability and convergence over all operating regimes Ioannou and Sun (1996).

1.3.1. *Unique aspects to wind turbine systems*

The goal in this tutorial is to introduce control engineers to the technical challenges that exist in the energy conversion industry and to encourage new modelling strategies and control systems research in this area. In fact, wind turbines are complex structures operating in uncertain environments and lend themselves nicely to advanced control solutions. Advanced controllers can help achieve the overall goal of decreasing the cost of wind energy by increasing the efficiency, and thus the energy capture, or by reducing structural loading and increasing the lifetimes of the components and turbine structures Bossanyi (2003).

Although wind turbines come in both vertical- and horizontal-axis configurations, the work will focus on Horizontal–Axis Wind Turbines (HAWTs). HAWTs have an advantage over Vertical-Axis Wind Turbine (VAWTs) in that the entire rotor can be placed atop a tall tower, where it can take advantage of larger wind speeds higher above the ground. Some of the other advantages of HAWTs over VAWTs for utility-scale turbines include pitchable blades, improved power capture and structural performance. VAWTs are much more common as smaller turbines, where these disadvantages become less important and the benefits of reduced noise and omni–directionality become more pronounced. Active control is most cost–effective on larger wind turbines, and therefore this work will refer to wind turbines with relatively large capacities. As remarked in Pao and Johnson (2009), active control refers to those active actions allowing conversion energy systems to achieve optimal power capture and structural performance, such as the use of pitchable blades, power and torque control techniques. On the other hand, the term active has been extended to fault diagnosis and fault tolerant control fields Chen and Patton (1999), Mahmoud, Jiang, and Zhang (2003), Zhang and Jiang (2008), Ding (2008), as outlined also in Section 5.1.

It is worth also noting that the mathematical description used for wind turbine modelling and control is quite basic, as the paper focusses on the related fundamental aspects. On the other hand, real system cases require much more complex modelling and control considerations, which have been highlighted through proper bibliographical references.

1.3.2. *Unique aspects to wave energy systems*

For ocean energy systems, the modelling effort can be considerable, since hydrodynamic modelling is involved. While a variety of comprehensive nonlinear modelling methodologies are available for hydrodynamic modelling, including Smooth Particle Hydrodynamics (SPH) or Computational Fluid Dynamics (CFD) approaches, the difficulty of incorporating such models into a control formulation suggests the use of more compact and structurally simple models. In addition, the very significant computational complexity of SPH or CFD models preclude their direct use for real–time controller implementation. Instead, model–based control strategies usually use compact linear models, which are based on either local linearisation about an operating point (see, for example, Bianchi et al., 2007; Leithead and Connor, 2000 for the turbine case, or linear boundary-/element models Eriksson, Waters, Svensson, Isberg, and Leijon, 2007 for the wave energy case). Even modest nonlinear extensions to linear boundary element methods can result in models which are computationally intractable for real–time control Merigaud, Gilloteaux, and Ringwood (2012), while some specific parameterisations (*e.g.* to include viscosity effects Bhinder, Babarit, Gentaz, and Ferrant, 2012) give nonlinear parametric forms that may be possible to incorporate in model-based control schemes.

To summarise, WEC control systems must vary the PTO force in order to match the WEC to an incoming wave excitation in order to maximise power capture, mindful of physical constraints. If operating in an array, the WEC control system must also consider inter-device hydrodynamic coupling. In essence, the calculation of the optimal PTO force (or, more commonly, the optimal velocity profile for the WEC to follow) is a feed–forward problem, involving a calculation based on the some parameters of the incoming wave variations and the system model. Following this feedforward calculation, a traditional feedback controller is employed to ensure that the optimal velocity profile is followed.

2. Models for the renewable resources

In the following, the mathematical descriptions for the renewable resources that drive the models provided above will be briefly highlighted.

2.1. *Wind models*

The differential heating of the Earth's atmosphere is the driving mechanism for wind. Various atmospheric phenomena, such as the nocturnal low-level jet, sea breezes, frontal passages, and mountain and valley flows, affect the wind inflow across a wind turbine rotor plane Manwell, McGowan, and Rogers (2002), which spans from 60 to 180 m above the ground for megawatt utility-scale wind turbines. Given the large rotor plane and the variability of the wind, hundreds of sensors would be required to characterise the spatial variation of the wind speed encountered over the entire span of each blade.

The available wind resource can be characterised by the spatial or temporal average of the wind speed; the frequency distribution of wind speeds; the temporal and spatial variation in wind speed; the most frequent wind direction, also known as the prevailing wind direction; and the frequency of the remaining wind directions Manwell et al. (2002). The probability of the wind speed being above a given turbine rated wind speed can be used to predict how often the turbine operates in Region 3 at its maximum, that is, rated power capacity. The capacity factor CF is defined by the ratio:

$$CF = \frac{E_{\text{out}}}{E_{\text{cap}}} \tag{1}$$

where E_{out} is a wind turbine energy output over a period of time and E_{cap} is the energy the turbine would have produced if it had run at rated power for the same amount of time.

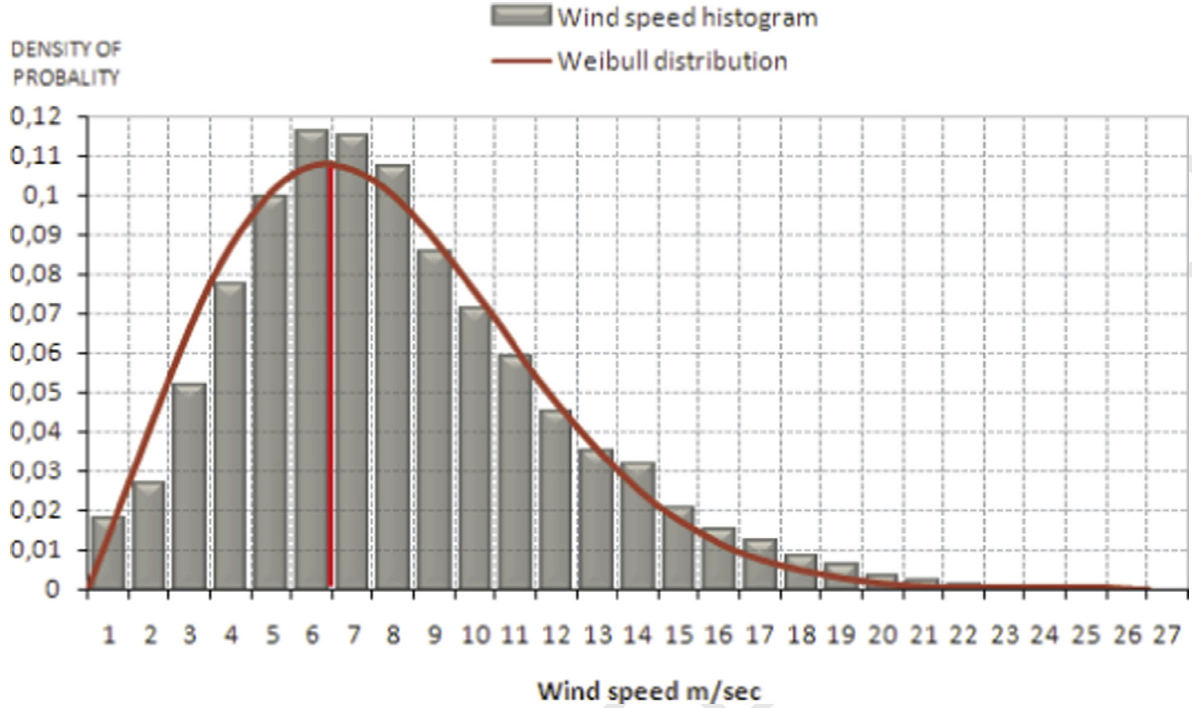

Fig. 6. Sample histogram of wind speed and Weibull function.

To predict the capacity factor and maintenance requirements for a wind turbine, it is useful to understand wind characteristics over both long and short time scales, ranging from multiyear to subsecond. Determining whether a location is suitable and economically advantageous for siting a wind turbine depends on the ability to measure and predict the available wind resource at that site. Significant variations in seasonal average wind speeds affect a local area's available wind resource over the course of each year. Wind speed and direction variations caused by the differential heating of the Earth's surface during the daily solar radiation cycle occur on a diurnal, that is, daily time scale. The ability to predict hourly wind speed variations can help utilities to plan their energy resource portfolio mix of wind energy and additional sources of energy. Finally, knowledge of short-term wind speed variations, such as gusts and turbulence, is used in both turbine and control design processes so that structural loading can be mitigated during these events.

Therefore, it is very important for the wind industry to be able to describe the variation of wind speeds. Turbine designers need the information to optimise the design of their turbines, so as to minimise generating costs. Turbine investors need the information to estimate their income from electricity generation.

If you measure wind speeds throughout a year, you will notice that in most areas strong gale force winds are rare, while moderate and fresh winds are quite common. The wind variation for a typical site is usually described using the Weibull distribution, as shown in Fig. 6. This particular site has a mean wind speed of 7 metres per second, and the shape of the curve is determined by a so–called shape parameter of 2.

Fig. 6 shows that 6.6 m/s is the median of the distribution, which is skewed, *i.e.* it is not symmetrical. Sometimes, very high wind speeds occur, but they are very rare. Wind speeds of 5.5 m/s, on the other hand, are the most common ones. 5.5m/s is called the modal value of the distribution. The probability distribution function has the form of (2):

$$p(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^k} \tag{2}$$

where $A > 0$ and $k > 0$ are the scale and shape parameters, respectively, which determine the function form. In particular, k determines the decrease rate of the function, whilst A represents the function skewness. Properly chosen parameters and a value for k indicates that the average speed and wind energy calculated from the gross Weibull distribution will be equal to that calculated from the histogram of the example in Fig. 6.

The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface. The Weibull distribution may thus vary, both in its shape, and in its mean value. If the shape parameter is exactly 2, as in Fig. 6, the distribution is known as a Rayleigh distribution. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution.

It is worth noting that more detailed model of the wind are not usually exploited in the related literature, as shown for example in Odgaard et al. (2013), Odgaard and Stoustrup (2013), Odgaard and Stoustrup (0000). However, in the remainder of this section, a typical wind description is briefly outlined Burton et al. (2011). Wind can be modelled as the sum of a steady state mean wind and a perturbation wind, accounting for turbulence and/or gusts. The deterministic component of the wind field implements the transients specified by IEC 61400–1 Bottasso, Croce, and Savini (2007), the exponential and logarithmic wind shear models, and the tower shadow effects, which include the potential flow model for a conical tower, the downwind empirical model Bottasso et al. (2007), or an interpolation of these two models. Their expressions will be omitted for brevity. The stochastic component of the wind field can be described according to the Von Karman or Kaimal turbulence models.

In this way, the wind model generates, from a scalar mean wind speed at hub height, a time–varying matrix that contains the wind speed for each point in the wind field:

$$\begin{aligned} V_{\text{field}}(t, R, \theta) &= v_{\text{mean}}(t) + V_{ws}(t, R, \theta) + V_{ts}(t, R, \theta) \\ &\quad + V_{wk}(t, R, \theta) \end{aligned} \tag{3}$$

where V_{field} is the total wind speed field, v_{mean} is the mean wind speed, V_{ws} is the wind shear component, V_{ts} is the tower shadow

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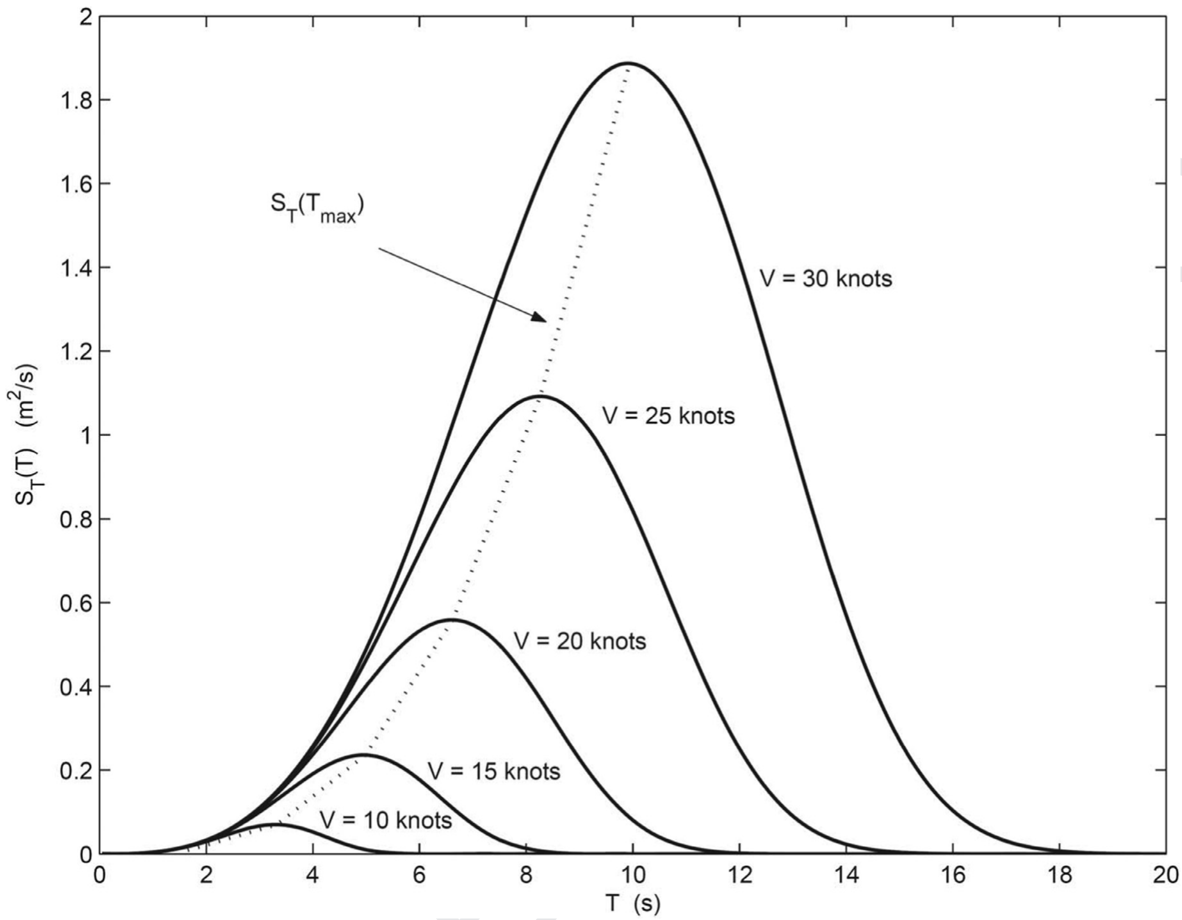

Fig. 7. Typical Pierson–Moskowitz wave spectra, from (5), for different steady–state wind velocities. Both the wave amplitude and period increase with an increase in the driving wind speed.

component, and V_{wk} is the far wake component of one preceding wind turbine (relevant for the case of wind farms). Notice the dependence on the rotor radius R, and rotor azimuth angle θ. When required, the simplified wake model is represented as a part of the wind field (*i.e.* a circle) with a lower wind speed Friis et al. (2011). The wake is centred around a point (R_0, φ) placed on the rim of the wind field, and with the form of (4):

$$R^2 - 2\,R\,R_0 \cos\left(\theta - \varphi\right) + R_0^2 = W^2 \tag{4}$$

where R_0 is the radial coordinate for the centre of the wake, φ is the angular coordinate of the centre of the wake, and W is the radius of the wake.

Finally, stochastic variables can be added to the wind components except tower shadow, giving a closer to reality parameterisation of the wind speeds throughout the rotor plane. In this way, the wind field is converted to equivalent winds signals that acts on two distinct parts of the blades, namely the tip and root sections, in order to obtain a linearisable model description.

2.2. Wave models

The two measurable properties of waves are height and period. Researchers and mariners usually characterise wave heights by the average of the highest one–third of the observed wave heights. This statistically averaged measure is termed the *significant wave height* and usually denoted as $H_{\frac{1}{3}}$ or H_s. In addition, real ocean waves do not generally occur at a single frequency. Rather, a distributed amplitude spectrum is used to model ocean waves, with random phases. Energy spectra are widely used to represent sea states Bretschneider (1952), Pierson and Moskowitz (1964), Hasselmann (1973), Ochi (1998). A typical *wave spectral density* (or wave spectrum) has the form

$$S_T(T) = AT^3 e^{-BT^4}, \tag{5}$$

with the coefficients A and B, for example, given for the Pierson–Moskowitz model by Pierson and Moskowitz (1964) as

$$A = 8.10\text{x}10^{-3}\,\frac{g^2}{(2\pi)^4} \tag{6}$$

$$B = 0.74\left(\frac{g}{2\pi V}\right)^4, \tag{7}$$

where V is the wind velocity measured 19.5 m above the Still–Water Level (SWL), g is the acceleration due to gravity, and T is the wave period in seconds. Some typical wave spectra generated from this model are shown in Fig. 7. Note that the available wave energy increases (approximately) exponentially with wave period T.

Not all waves are well represented by the spectral models of the type shown in (5). In some cases, where swell and local wind conditions are relatively uncorrelated (which can often be the case, for example, on the West Coast of Ireland International (2005)), 'split spectra,' consisting of spectra containing two distinct peaks, can occur. The variety of spectral shapes, some of which are illustrated in Fig. 8, presents a significant challenge to both the WEC designer and control engineer.

All of the aforementioned wave spectral models are for *fully developed waves*; in other words, the fetch (the distance over which the waves develop) and the duration for which the wind blows are sufficient for the waves to achieve their maximum energy for the given wind speed. In addition, linear wave theory is assumed, meaning that

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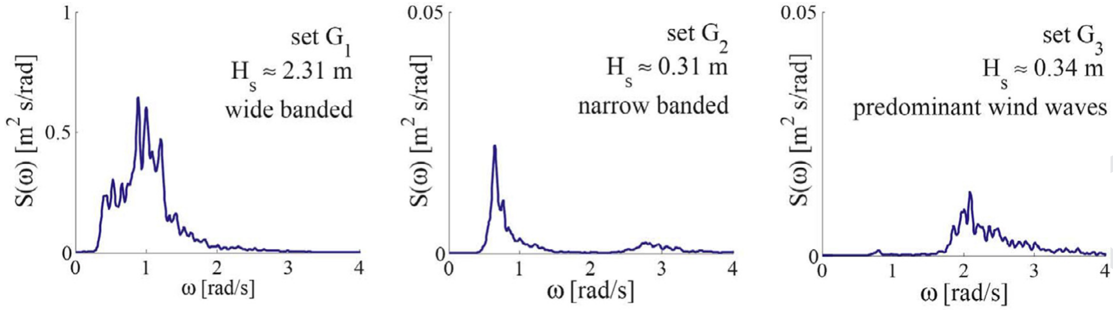

Fig. 8. Real wave spectra recorded at Galway Bay in Ireland. In general, low frequency waves have the highest power. Narrow–banded seas make wave forecasting and WEC control more straightforward, allowing a focus on a predominant single frequency.

waves are well represented by a sinusoidal form, which relies on the assumption that there are no energy losses due to friction, turbulence, or other factors, and that the wave height H is much smaller than the wavelength λ.

However, not only is the 'wind-wave' component in Fig. 8 for set G_3 at odds with the spectrum shown in Fig. 7, there are three distinct low frequency components in set G_1. Directional wave analysis Gilloteaux and Ringwood (2009) can be used to reveal the individual components. In general, with regard to wave directionality, directional wave devices are tethered with nondirectional moorings, which allow the devices to face the predominant wave direction (weather vaning), or devices are nondirectional, such as heaving buoy–type devices.

There are a number of exceptions to this general rule, including shore-mounted oscillating water-column devices and, while many devices can be considered nondirectional, the (fixed) moorings to which they are attached are rarely truly nondirectional.

In general, a wave spectrum is assumed to be stationary for up to 3 h. Time–frequency analysis via the wavelet transform Nolan, Ringwood, and Holmes (2007) can be used to examine spectral variability. For longer durations, such as a year, wave scatter diagrams (see Fig. 9) provide a joint probability table of significant wave heights and characteristic periods for a particular wave site. For example, the data shown in Fig. 9 show two predominant wave climates which exist at a particular site.

The energy in an ocean wave, consisting of both potential and kinetic energy, is *proportional to the square of the wave amplitude*McCormick (1981) *and proportional to the wavelength*,

$$E_w = E_p + E_k = \frac{\rho g H^2 \lambda b}{8}, \tag{8}$$

where H is the wave height above SWL, λ is the wavelength, ρ the water density, and b the crest width. In deep water, the energy in a linear wave is equally composed of potential energy (exhibited by the wave height) and kinetic energy (dependent on the motion of the particles), so that

$$E_p = E_k = \frac{\rho g H^2 \lambda b}{16}. \tag{9}$$

For simulation purposes, wave spectra are usually discretized and individual sinusoidal components used, where the amplitudes are determined from the spectral density (such as in Fig. 7), and random initial phases employed for the individual components.

2.3. *Comparisons and contrasts of wave and wind model characteristics*

The wind and wave models described in Sections 2.1 and 2.2 can be used to evaluate how much the available raw power can be converted into the actual extracted power from hypothetical wind and wave farms. For example, regarding the power extracted from wind, the relatively mature state of wind turbine technology permits the use of well established power curves, and wind distribution functions, as shown in Sections 2.1 and 3.2, respectively. Computing the extracted power from wave energy devices, on the other hand, is not quite as straightforward, mainly because of the fact that there is little established commercial wave technology and the operating principles of the available devices are very diverse, so that it is difficult to find a standardised measure of the extracted power. In addition, instead of the single resource parameter (wind speed) in the case of wind energy, a minimum of two parameters are needed to quantify the wave power, from (8). This leads to the use, by some WEC developers, of the power matrix (for example in the case of the Pelamis device), though some studies suggest that the two parameters usually used to model sea spectra (for example, as in (5)) are insufficient to correctly detail power production capabilities De Andres, Guanche, Vidal, and Losada (2015). This observation reflects that fact the oscillatory WECs, which make up the bulk of WEC types, are highly responsive to the spectral content of waves.

In order to determine the power extracted from wind or wave farms, the power from single devices must be projected to the corresponding number of wind turbines and wave energy converters. Usually, the yearly average power output levels of the farms are considered. The reason why the rated capacity is not used is that the capacity factors for wind turbines and wave devices are not the same, due to the significant differences in the probability distribution of their produced power values. Wind turbines, most of the time, work either at low level or at full capacity, whereas the wave power output is mostly concentrated at average levels, so that a comparison based solely on the capacity and not taking into account the capacity factor, would be quite unjust and might return misleading results.

Moreover, the evaluation of the extracted power levels depend on the particular device. In the case of wind, the well advanced state of the technology resulted in a certain convergence of the performance of the off–shore wind turbines available on the market, so that their power curves are quite comparable. The field of wave energy, on the other hand, is still an assortment of different devices, based on rather diversified operating principles, so that their power characteristics are very different and can also be very site specific.

One other contrast, between wind and wave systems, should be noted in relation to resource quantification. For both wind and waves, directionality plays an important role. However, while HAWTs can yaw to face the wind, and VAWTs have no directional sensitivity (though the site itself may be sensitive), many wave devices are highly sensitive to wave direction. As already mentioned, though the device itself (for example a point absorber) may be insensitive to wave direction, the moorings which tether the device are not, leading to a directional sensitivity.

3. Models for wind turbines and wave energy systems

In this section, the main models and their mathematical descriptions for wind turbines and wave energy devices will be briefly

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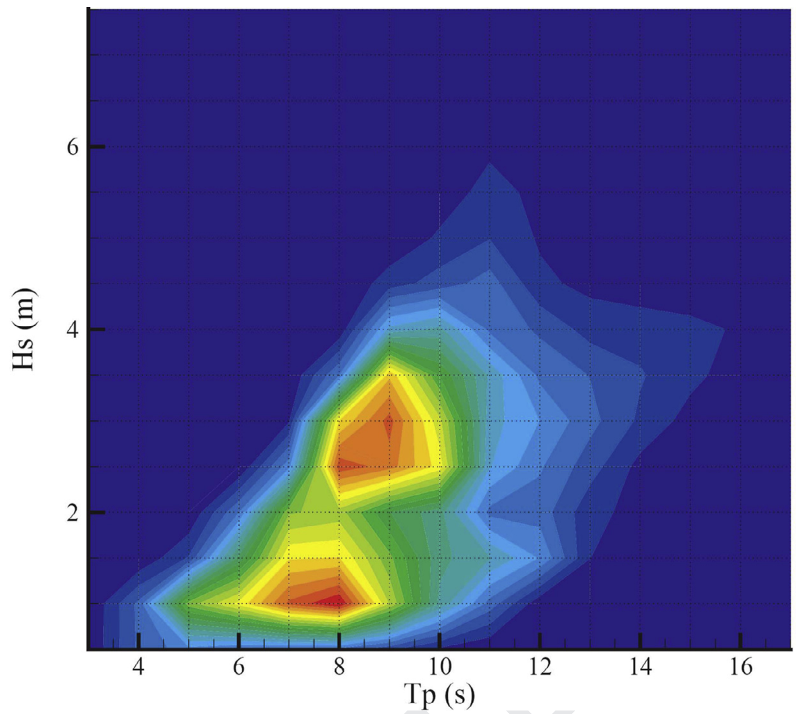

Fig. 9. Sample scatter diagram for the Atlantic Marine Energy Test Site (AMETS) at Belmullet, Ireland. In general, both peak period, T_p, and significant wave height, H_s, increase together. Typical Atlantic waves cover a period span of 6–12 s.

recalled, in order to highlight their main purpose oriented to the design of control strategies.

3.1. Purposes of models

Prior to the design and application of new control strategies on real wind turbines, the efficacy of the control scheme has to be tested in detailed aero–elastic simulation model. Several simulation packages exist that are commonly used in academia and industry for wind turbine load simulation. One of the most used simulation package is the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) code Jonkman and Buhl (2005) provided by the National Renewable Energy Laboratory (NREL) in Golden (Colorado, USA), since it represents a reference simulation environment for the development of high–fidelity wind turbine prototypes that are taken as a reference test–cases for many practical studies Jonkman, Butterfield, Musial, and Scott (2009). FAST provides a high–fidelity wind turbine model with 24 degrees of freedom, which is appropriate for testing the developed control algorithms but not for control design. For the latter purpose, a reduced–order dynamic wind turbine model, which captures only dynamic effects directly influenced by the control, is recalled in this section and it can be used for model–based control design Bianchi et al. (2007). We can also note that the FAST tool has been evolved to deal with wave energy devices and also complimented with the WECSim tool, also developed by NREL.

The main issues used for highlighting similarities and differences of the models that describe the behaviour of wind turbines and wave energy devices will be articulated in the following.

3.2. Wind turbine models

Due to the competitive nature of the wind turbine industry and possible confidentiality issues, the modelling available in the wind turbine literature is usually kept at a conceptual level. For more detailed modelling of pitch regulated wind turbines see, *e.g.*, Burton et al. (2011), Muljadi and Butterfield (1999), Knudsen, Bak, and Soltani (2011). It is worth noting also that, in the wind turbine area, there have been a number of IFAC and IEEE publications with sessions and special issues starting from 2009, based also on competition studies, *e.g.*Ostergaard, Stoustrup, and Brath (2009), Pao and Johnson (2011), Odgaard and Odgaard (2012). These sessions and special issues have led to important results and publications that will be briefly summarised below, in order to give readers a basic research review.

Previous studies have shown that linear aero-elastic models used for the analysis of wind turbines are commonly of very high order. Multibody dynamics coupled with unsteady aerodynamics (*e.g.* dynamic stall) are among the recently developments in wind turbine aero-elasticity Rasmussen et al. (2003), Bianchi et al. (2007), Hansen (2011). The resulting models contains hundreds or even thousands of flexible modes and aerodynamic delays. In order to synthesise wind turbine controllers, a common practice is to obtain linear time–invariant (LTI) models from a nonlinear model for different operating points. Modern control analysis and synthesis tools are inefficient for such high–order dynamical systems; reducing the model size is crucial to analyse and synthesise model–based controllers. The most interesting modelling solution available in the literature relies on the Linear Parameter Varying (LPV) framework, as it has shown to be suitable to cope, in a systematic manner, with the inherent varying dynamics of a wind turbine over the operating envelope Bianchi et al. (2007), Ostergaard et al. (2009), Adegas, Sloth, and Stoustrup (2012), Adegas, Sonderby, Hansen, and Stoustrup (2013). Wind turbine LPV models are usually simple, first–principles based, often neglecting dynamics related to aerodynamic phenomena and some structural modes. This in turn restricted LPV control of wind turbines to the academic environment only. A procedure to encapsulate high–fidelity dynamics of wind turbines as an LPV system would be beneficial to facilitate industrial use of LPV control.

Other modelling approached that one may find in the literature are based on some type of simplified wind turbine descriptions Pedersen and Fossen (2012). These may have the form of lookup–tables as in Bianchi et al. (2007) or linear models obtained from complex numerical simulation tools Namik and Stol (2010). Hybrid models blending lookup tables with mechanical models have also been used Bottasso et al. (2007). These and even simpler approaches

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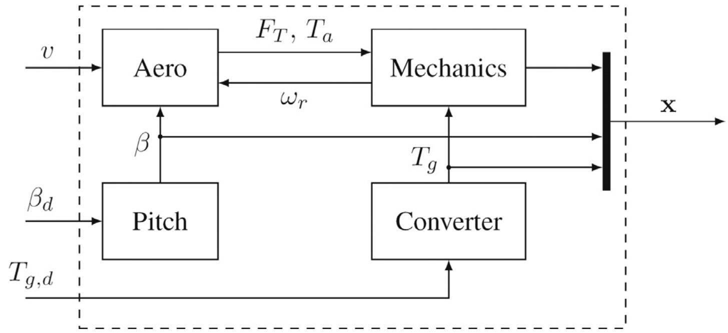

Fig. 10. Block diagram of the complete wind turbine model.

predominate. Linear models can be valid in a small envelope around the linearisation point, which requires several individual models to cover the operational domain of the turbine Pintea, Popescu, and Borne (2010).

However, most of the control algorithms for modern variable–pitch wind turbines, that one may find in the literature, are usually based on some type of simplified wind turbine linear model. Therefore, after these considerations, this section will address the most important components of a HAWT used for the linear modelling of a wind turbine installation. They consist of the wind turbine tower, its nacelle, and the rotor, visible from the ground, as depicted in Fig. 1.

As sketched in Fig. 10, the complete wind turbine model consists of several submodels for the mechanical structure ('Mechanics'), the aerodynamics ('Aero'), as well as the dynamics of the pitch system ('pitch') and the generator/converter system ('converter'). The generator/converter dynamics are usually described as a first order delay system. However, when the delay time constant is very small, an ideal converter can be assumed, such that the reference generator torque signal is equal to the actual generator torque. In this situation, the generator torque can be considered as a system input, whilst the generator is the device that converts mechanical energy from the aerodynamic torque to electrical energy.

Fig. 10 reports also the wind turbine inputs and outputs. In particular, v is wind speed, F_T and T_a correspond to the rotor thrust force and rotor torque, respectively; ω_r is the rotor angular velocity, x the state vector, T_g the generator torque, and $T_{g,\,d}$ the demanded generator torque. β is the pitch angle, whilst β_d its demanded value.

The drive–train, consisting of rotor, shaft and generator is modelled as a two–mass inertia system, including the shaft torsion θ_Δ, where the two inertias are connected with a torsional spring with spring constant k_S and a torsional damper with damping constant d_S. The angular velocities ω_r and ω_g are the time derivatives of the rotation angles θ_r and θ_g. The drive–train can be thus described as the following linear system:

$$\begin{bmatrix} \dot{\omega}_r(t) \\ \dot{\omega}_g(t) \\ \dot{\theta}_\Delta(t) \end{bmatrix} = \begin{bmatrix} -\dfrac{B_S + B_r}{J_r} & \dfrac{B_S}{n_g J_r} & -\dfrac{k_S}{J_r} \\ \dfrac{\eta_{dt}\, B_S}{n_g J_g} & \dfrac{-\frac{\eta_S B_S}{n_g^2} - B_g}{J_g} & \dfrac{\eta_S\, k_S}{n_g J_g} \\ 1 & -\dfrac{1}{n_g} & 0 \end{bmatrix} \begin{bmatrix} \omega_r(t) \\ \omega_g(t) \\ \theta_\Delta(t) \end{bmatrix} + \begin{bmatrix} \dfrac{1}{J_r} & 0 \\ 0 & -\dfrac{1}{J_g} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T_a \\ T_g \end{bmatrix} \tag{10}$$

where is J_r the moment of inertia of the low speed shaft (rotor), B_g is the viscous friction of the high speed shaft (generator), J_g is the moment of inertia of the high speed shaft, and η_{dt} is the efficiency of the drive train. The rotor torque T_a is generated by the lift forces on the individual blade elements, whilst T_g represents the generator torque. The ideal gearbox effect can be simply included in the generator model by multiplying the generator inertia J_g by the square of the gearbox ratio n_g.

In pitch–regulated wind turbines, the pitch angle of the blades is controlled only in the full load region to reduce the aerodynamic rotor torque, thus maintaining the turbine at the desired rotor speed. Moreover, the pitching of the blades to feather position (*i.e.* 90°) is used as main braking system to bring the turbine to standstill in critical situations. Two different types of pitch technologies are usually exploited in wind turbines, *i.e.* hydraulic and electromechanical pitch systems. For hydraulic pitch systems, the dynamics can be modelled by means of a second–order dynamic model Odgaard et al. (2013), which is able to display oscillatory behaviour. For electromechanical pitch systems, which are more commonly used, a first–order delay model is sufficient. In this work, the first–order delay model is recalled:

$$\dot{\beta} = -\frac{1}{\tau}\,\beta + \frac{1}{\tau}\,\beta_d \tag{11}$$

where β and β_d are the physical and the demanded pitch angle, respectively. The parameter τ denotes the time constant.

An explicit model for the generator/converter dynamics can be included into the complete wind turbine system description. Note that for mere simulation purposes, this is not necessary, since the generator/converter dynamics are relatively fast. However, when advanced control designs are considered, an explicit generator/converter model might be required in order to take into account the fast generator torque dynamics. In this case, a simple first order dynamic model can be sufficient, as described *e.g.* in Odgaard et al. (2013):

$$\dot{T}_g = -\frac{1}{\tau_g}\,T_g + \frac{1}{\tau_g}\,T_{g,d} \tag{12}$$

where $T_{g,\,d}$ represents the demanded generator torque, whilst τ_g the delay time constant.

The aerodynamic submodel consists of the expressions for the thrust force F_T acting on the rotor and the aerodynamic rotor torque T_a. They are determined by the reference force F_{st} and by the aerodynamic rotor thrust and torque coefficients C_T and C_Q Gasch and Twele (2012):

$$\begin{cases} F_T = F_{st}\, C_T(\lambda,\ \beta) \\ T_a = F_{st}\, R\, C_Q(\lambda,\ \beta) \end{cases} \tag{13}$$

The reference force F_{st} is defined from the impact pressure $\frac{1}{2}\,\rho\, v^2$ and the rotor swept area $\pi\, R^2$ (with rotor radius R), where ρ denotes the air density:

$$F_{st} = \frac{1}{2}\,\rho\,\pi\, R^2\, v^2 \tag{14}$$

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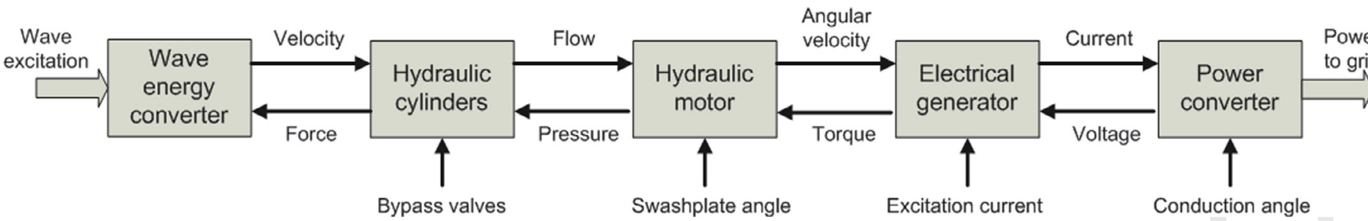

Fig. 11. Wave–energy PTO system components and potential control inputs. In general, only one of these control inputs is used by the energy–maximising control.

It is worth noting that, for simulation purposes, the static wind speed v is used. The aerodynamic maps C_T and C_Q used for the calculation of the rotor thrust and torque are usually represented as static 2–dimensional tables, which already take into account the dynamic contributions of both the tower and the blade motions.

As highlighted in the expressions (13), the rotor thrust and torque coefficients (C_T, C_Q) depend on the tip speed ratio $\lambda = \frac{\omega_r R}{v}$ and the pitch angle β. Therefore, the rotor thrust F_T and torque T_a assume the following expressions:

$$\begin{cases} F_T = \dfrac{1}{2}\,\rho\,\pi\,R^2\,C_T(\lambda,\ \beta)\,v^2 \\ T_a = \dfrac{1}{2}\,\rho\,\pi\,R^3\,C_Q(\lambda,\ \beta)\,v^2 \end{cases} \tag{15}$$

Note that the rotor thrust in (13) and (15) is a horizontal force, *i.e.* a structural load, which should be mitigated, as suggested in Section 4.2 Bossanyi (2003).

The expressions (15) highlight that the rotor thrust F_T and torque T_a are nonlinear functions dependent on the wind speed v, the rotor speed ω_r, and the pitch angle β. These functions are usually expressed as two–dimensional maps, which must be known for the whole range of variation of both the pitch angles and tip speed ratios. These maps are usually a static approximation of more detailed aerodynamic computations that can be obtained using, for example, the Blade Element Momentum (BEM) method. In this case, the aerodynamic lift and drag forces at each blade section are calculated and integrated in order to obtain the rotor thrust and torque Gasch and Twele (2012). More accurate maps can be obtained by exploiting the calculations implemented via the AeroDyn module of the FAST code, where the maps are extracted from several simulation runs Laino and Hansen (2002).

It is worth noting that for simulation purposes, the tabulated versions of the aerodynamic maps C_Q and C_T are sufficient. On the other hand, for control design, the derivatives of the rotor torque (and thrust) are needed, thus requiring a description of the aerodynamic maps as analytical functions. Therefore, these maps can be approximated using combinations of polynomial and exponential functions, whose powers and coefficients are estimated via *e.g.* modelling Heier (2014) or identification Simani and Castaldi (2014) approaches.

Wind turbine high–fidelity simulators, which were described for example in Odgaard and Johnson (2013), consider white noise added to all measurements. This relies on the assumption that noisy sensor signals should represent more realistic scenarios. However, this is not the case, as a realistic simulation would require an accurate knowledge of each sensor and its measurement reliability. To the best of the authors' knowledge, all main measurements acquired from the wind turbine process (rotor and generator speed, pitch angle, generator torque), are virtually noise–free or affected by very weak noise.

3.3. *Wave energy device models*

Since PTO systems for wave energy converters are quite nonstandard, the focus here will be on the hydrodynamic part of the WEC model, though modelling aspects concerning the generator/converter system from Section 3.2 are also relevant.

Mathematical models of wave-energy devices, as in the wind energy case, are required for a variety of purposes:

1. Assessment of power production
2. Assessment of loading forces under extreme sea conditions
3. Simulation of device motion, including evaluating the effectiveness of control strategies
4. For use as a basis for model-based control design.

Mathematical models for wave–energy devices should, ideally, encompass the water/device (hydrodynamic) interactions and the PTO system, and may also include a model for connection to an electrical grid, thus presenting a total 'wave-to-wire' model Josset, Babarit, and Clement (2007). While the PTO and grid (or possibly other downstream energy consumers, such as reverse osmosis units) may be modelled using more traditional physical lumped-parameter modelling methodologies, the determination of the hydrodynamic model for a WEC, or array of WECs, is nontrivial. A variety of modelling methodologies are available, most of which involve the solution to partial differential equations across a numerical mesh.

Among the possible hydrodynamic solvers with the highest fidelity are algorithms based on smooth particle hydrodynamics (SPH) Cleary, Prakash, Ha, Stokes, and Scott (2007) or computational fluid dynamics (CFD) Agamloh, Wallace, and von Jouanne (2008). Such approaches can articulate the full range of nonlinear hydrodynamic forces in three dimensions. However, given the significant computational overhead of such approaches (typically a second of simulation time takes around an hour of computation time), they are not ideal either as a basis for model-based control design, nor as a simulation tool to evaluate the effectiveness of various control designs. However, CFD models have been used to develop simpler parametric models, which can provide a basis for control design and simulation Davidson, Giorgi, and Ringwood (2013).

The remainder of this section is primarily devoted to the development of hydrodynamic models. An outline of a possible PTO system is shown in Fig. 11, and shows the possible inclusion of mechanical, hydraulic, and electrical components. In many cases, for example for the SeaBased device Trapanese (2008), the WEC is directly coupled to a linear generator, eliminating the hydraulic components. Given the many potential changes of energy form evident from Fig. 11, bond graphs have been shown to be a powerful tool in providing a systematic graphical procedure to determine mathematical models for wave-energy PTO systems Bacelli, Gilloteaux, and Ringwood (2008), or complete wave-energy systems Hals (2010).

3.3.1. *Linear models and cummins' equation*

Consider a single–body floating system oscillating in heave, schematically depicted in Fig. 12. Energy is extracted from the relative motion with the sea bottom, through a generic PTO mechanism. The external forces acting on the WEC are the excitation from the waves and the control force produced by the PTO, namely $f_{ex}(t)$ and $f_u(t)$. Additional hydrodynamic and hydrostatic forces, which arise due to the motion of the body in the water, are the radiation force $f_r(t)$, the diffraction force $f_d(t)$, the viscous force $f_v(t)$, and the buoyancy force $f_b(t)$ Falnes (2002).

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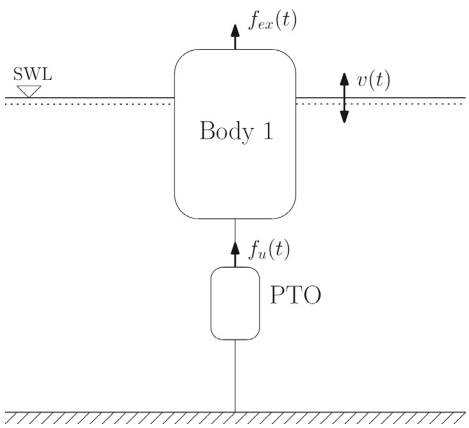

Fig. 12. One–degree–of–freedom floating system for wave-energy conversion. The lower side of the PTO is anchored to the sea bed, which provides an absolute reference for device motion.

The radiation force $f_r(t)$ is a damping/inertial force associated due to the fact that device motion, resulting in the production of radiated waves, is affected by the surrounding fluid. Such radiation forces are present even in the absence of incident waves and can be estimated using free response tests. The diffraction (or scattering) force $f_d(t)$ describes the force experienced by the device when scattering incident waves, and is independent of the device motion. The viscous damping force $f_v(t)$ is a nonlinear force, and becomes significant with increased device velocity. It is particularly relevant where the body surface contains discontinuities (such as flanges), which result in the creation of vortices. Finally, the buoyancy force is related to the deflection of the device from its equilibrium (still water) position and is a balance between the Archimedes buoyancy force and the gravity force.

The equation of motion, following Newton's second law and where a superposition of forces is assumed, in one degree of freedom is:

$$M\dot{v}(t) = f_m(t) + f_r(t) + f_d(t) + f_v(t) + f_b(t) + f_{ex}(t) + f_u(t) \quad (16)$$

where $v(t)$ is the heaving velocity and M is the WEC mass.

With the assumptions associated with linear potential theory Falnes (2002), namely that the fluid is irrotational, incompressible, and inviscid; the WEC body has a small cross-sectional area (or equivalently, the wave elevation is constant across the whole body); and the body experiences small oscillations (so that the wetted surface area is nearly constant); the equation of motion simplifies to

$$f_{ex} + f_d(t) = \int_{-\infty}^{+\infty} h_{ex}(\tau)\eta(t-\tau)d\tau \quad (17)$$

$$f_r(t) = -\int_0^t h_r(\tau)v(t-\tau)d\tau - m_\infty \dot{v}(t) \quad (18)$$

$$f_b(t) = -\rho g S_w \int_0^t v(\tau)d\tau = -K_b x(t) \quad (19)$$

$$f_v(t) = 0 \quad (20)$$

In (17), the excitation (and diffraction) force is related to the incident wave free surface elevation $\eta(t)$ through the excitation kernel function $h_{ex}(t)$. The expression (18) expresses the radiation force as a linear convolution of the radiation kernel $h_r(t)$ with the device oscillation velocity $v(t)$. Note that $h_{ex}(t)$ and $h_r(t)$ effectively describe the impulse responses in excitation force and radiation force to impulses in free surface elevation and device motion, respectively. Added mass, denoted by m_∞ in (18), reflects an effective increase in the device inertia since an accelerating floating body moves some volume of the surrounding fluid. In general, added mass is a frequency-dependent quantity but is often approximated by its infinite frequency asymptote m_∞.

The buoyancy force $f_b(t)$ in (19) models the hydrostatic equilibrium, related to the heaving position through a linear coefficient that depends on the gravity acceleration g, the water density ρ, and the surface area of the body cut by the mean water level S_w. Note the noncausality of the expression for the excitation force in (17), where $h_{ex}(t) \neq 0$ for $t \leq 0$ Falnes (2002). The expression in (16), excluding the mooring force $f_m(t)$ and the viscous damping force $f_v(t)$ results in the widely used Cummins' equation Cummins (1962):

$$(M + m_\infty)\dot{v}(t) + \int_0^{+\infty} h_r(\tau)v(t-\tau)d\tau + K_b x(t)$$
$$= \int_{-\infty}^{t} h_{ex}(\tau)\eta(t-\tau)d\tau. \quad (21)$$

which provides a linear integro-differential model for the motion of a WEC in response to variation in free-surface elevation $\eta(t)$, excluding the applied resisting PTO force, $f_u(t)$.

To focus on the control problem, the mooring force $f_m(t)$ is omitted from the following analysis, while the viscous damping force $f_v(t)$ is discussed in the next subsection. Typically, $h_{ex}(t)$ and $h_r(t)$ are calculated numerically using boundary-element potential methods such as WAMIT WAMIT (2002), which performs the calculations in the frequency domain, or ACHIL3D Clement (2009), where time-domain calculations are used. The relation (21) can also be used to model multibody systems Bacelli and Ringwood (2013c) or arrays of devices Bacelli and Ringwood (2013b), with the modification that M, m_∞, K, and the hydrodynamic parameters represented by $h_{ex}(t)$ and $h_r(t)$, all increase in dimension accordingly.

3.3.2. Radiation damping approximations

Typically, for both simulation and control applications, the radiation damping convolution term in (18) is replaced by a closed form (finite order) equivalent. This replacement has several advantages. The integro–differential equation in (21) is replaced by a higher order differential equation, making analysis more straightforward, the resulting finite-order dynamical system is faster to simulate, and the closed-form dynamical equation can be used as a basis for model-based control design.

In general, $h_r(t)$ (and its Fourier transform, $H_r(\omega)$) are nonparametric in form, being the result of a numerical calculation on a distributed system. Approximations can be determined in either the time or frequency domain, depending on the manner in which $h_r(t) \leftrightarrow H_r(\omega)$ was determined, and the intended (time/frequency domain) use of the finite–order approximation. For example, WAMIT (2002) uses a frequency-domain analysis to determine $H_r(\omega)$ directly and approximations based on WAMIT data are usually based on frequency-domain error criteria. In such a case, state-space forms Perez and Fossen (2007) or transfer function forms McCabe, Bradshaw, and Widden (2005) may be determined using frequency–domain identification Levy (1959).

Alternatively, if $h_r(t)$ is directly produced, for example from a time-domain code such as ACHIL3D Clement (2009), time–domain impulse-response fitting can be employed, typically using the method in Prony (1795). In general, an order 4–10 linear approximation to $h_r(t)$ is used, for both time- and frequency-domain approaches. In some cases a second-order approximation is adequate and has the added advantage of giving a pole pair, which has a strong connection with the radiation damping transient response. Taghipour, Perez, and Moan (2008) provides an overview of, and background to, the calculations of finite-order approximations to $h_r(t) \leftrightarrow H_r(\omega)$. Taghipour et al. (2008) also considers finite-order approximation to the excitation force kernel $h_{ex}(t)$ (with Fourier transform $F_{ex}(\omega)$), as does McCabe et al. (2005).

3.4. Comparison of wind and wave device models

There is a stark contrast in the modelling focus within the wind and wave communities. For wind turbines, the static relationship between the optimal rotation speed, pitch angle and incident wind speed is well understood and is enumerated for each wind turbine. In the wave energy case, there is a complex dynamic relationship between the free surface elevation and the device motion. As a result, models for wind turbines focus more on the turbine mechanics, rather than the aerodynamics. In the wave energy case, considerable effort is expended on accurately modelling the hydrodynamics of the system and, in contrast, there are a relatively small amount of studies with modelling the PTO section, which forms part of the lower control loop in Fig. 5. No doubt, one of the reasons for such a lack of generic PTO models is the lack of convergence or standardisation of PTO systems for wave energy devices, which may be appreciated from the possibilities articulated in Fig. 11. In addition, few devices have reached the stage of full scale prototype and, in many of those cases, most attention is focussed on the physical (device and PTO) design, with the control aspects receiving secondary attention.

On notable comparative feature, but contrasting in specific number, is the overall theoretical maximum percentage of energy which can be usefully converted from wind and wave systems. The well-known Betz limit Betz and Randall (1966) for wind turbines, which limits the converted power to 60%, contrasts with the 50%, obtained under optimal control conditions (shown in Section 4.3 Falnes (2002)) for wave energy devices.

4. Control strategies

While Section 3 focusses mainly on energy conversion system modelling and Section 1 has recalled the classical control problem of regulation of some variable to a desired value, and indeed such problems are encountered in both wind and ocean energy applications, there is a broader set of problems which can also be addressed by control system technology. The purpose of this section is to present this broad problem definition and examine how this problem may be addressed, or broken down into smaller parts which may be more easily solved.

4.1. Background to strategy development (objectives and available tools)

In the case of both wind and wave energy, the general problem is to maximise energy capture, subject to grid and environmental constraints. However, we might modify the objective of energy capture maximisation to that of maximisation of economic return Costello, Teillant, and Ringwood (2012), which requires a balance to be achieved between maximising energy capture and minimising wear on components. However, the move to an economic performance function also requires the accurate articulation of capital and operational costs, which is quite onerous for the relatively immature field of ocean energy, and significantly complicates the optimisation problem. Instead, for the current analysis, in order to retain a focus on the fundamental control issues, this section is focussed on the problem of energy capture maximisation.

There are two broad approaches, which may be taken to solve the energy maximisation problem:

1. Overall extremum seeking control Pao and Johnson (2011), with little use of a detailed model of the system;
2. Determination of an optimal setpoint for the system, which gives maximum energy capture, followed by a regulator to make sure this setpoint is achieved Bossanyi and Hassan (2000).

Approach 1 is attractive from the point of view of the lack of requirement for a detailed model, but may have dynamic performance limitations in convergence rates and may have difficulty finding a global maximum over a non–convex performance surface. For example, in wind turbines, this issue is important when the system is working below the rated wind speed, as recalled in Section 4.2. On the other hand, in a wave energy application, the controller may not converge to the appropriate setting before the instantaneous wave frequency changes.

Interestingly, a common framework for both wind and wave energy may be adopted for the item 2, as shown in Fig. 5. The particulars for wind and wave control solutions are detailed in Sections 4.2 and 4.3, respectively. For the standard feedback regulation part of Fig. 5, any one of the techniques mentioned in Section 1 can be chosen, based on the particular system description, the level of control fidelity required and the appetite for computational complexity. Since both wind turbine and wave energy device dynamics are relatively slow (with the possible exception of the electronic power converter section), there is much scope for the implementation of complex control strategies.

4.2. Control strategies for wind turbines

In the case of a wind turbine, optimal blade pitch, β, and rotor velocity (via the tip/speed ratio, λ) are set based on the incident wind flow velocity, in order to maximise the power coefficient, C_Q. The manipulated variable for the pitch control is the power to the pitch actuators (voltage and/or current). For torque control, the generator excitation is used as a control actuator. It is worth noting that the relationship between β, λ, and C_Q is specific to each wind turbine, and must be determined for each particular case. However, this relationship is then fixed, though some slight variation may occur due, for example, to component wear or installation errors. Note also that when a wind turbine reaches its rated power (*i.e.* above the rated wind speed), the turbine needs to be 'depowered' in order to avoid exceeding any rated specifications. In this situation, it is not required to maximise power conversion (*i.e.* the wind power that can be converted into electric energy) and, for variable pitch turbines, blade pitch can be adjusted in order to limit power converted.

As already remarked in Section 3.2, in the wind area there have been a number of IFAC and IEEE publications, sessions and special issues starting from 2011, based also on competition studies, addressing basic and advanced wind turbine control issues, *e.g.* Odgaard and Stoustrup (2011), Diaz-Guerra, Adegas, and Stoustrup (2012), Biegel, Madjidian, Spudic, Rantzer, and Stoustrup (2013), Pao and Johnson (2011), Adegas and Stoustrup (2012), Odgaard and Odgaard (2012).

On the other hand, previous investigations *e.g.* Muljadi and Butterfield (1999), Leithead and Connor (2000), Bossanyi and Hassan (2000), Bianchi et al. (2007) have shown that linear, time–invariant methods provide good closed–loop results when observing local behaviour. A natural choice for controller design covering the entire operating envelope is therefore to design linear controllers along a chosen operating trajectory and then to interconnect them in an appropriate way in order to get a control formulation for the entire operating region. This approach is denoted as gain scheduling and in Cutululis, Ceanga, Hansen, and Sorensen (2006) this is done by interpolating the outputs of a set of local controllers (either by linear interpolation or by switching). Alternatively, parameters of the controller are updated according to a pre–specified function of a measured/estimated variable Leithead and Connor (2000). A systematic way of designing such parameter–dependent controllers is within the framework of LPV systems, already recalled in Section 3.2. In this case, the model is represented by a linear model at all operating conditions and a controller with similar parameter dependency is synthesised to guarantee a certain performance specification for all possible parameter values within a specified set. A major difference to classical gain scheduling is that it is possible to take into account that the scheduling parameters can vary in time

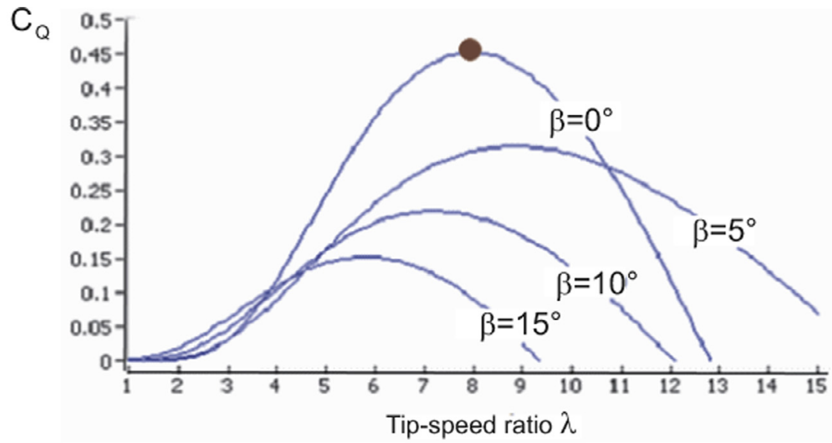

Fig. 13. Example of power coefficient curve.

Ostergaard et al. (2009). Other controllers with different structures, *e.g.* linear quadratic, and repetitive model predictive, to mention a few more Adegas and Stoustrup (2012), Diaz-Guerra et al. (2012), Adegas and Stoustrup (2011), were also designed and applied to wind turbine systems.

After these considerations, control systems for wind turbines seem now well developed Bianchi et al. (2007) and the fundamental control strategies are sketched below, in order to provide the readers a basic research review.

The primary Region 2 control objective for a variable–speed wind turbine is to maximise the power coefficient, and in particular the C_Q map in (13). The relationship between C_Q and the tip–speed ratio λ is a turbine–specific nonlinear function. C_Q also depends on the blade pitch angle in a nonlinear way, and these relationships have the same basic shape for most modern wind turbines. An example of C_Q surface is shown in Fig. 13 for a generic wind turbine.

As shown in Fig. 13, the turbine will operate at its highest aerodynamic efficiency point, $C_{\max}$, at a certain pitch angle and tip–speed ratio. The pitch angle is easy to control, and can be reliably maintained at the optimal efficiency point. However, the tip–speed ratio depends on the incoming wind speed v and therefore is constantly changing. Thus, the Region 2 control is primarily concerned with varying the turbine speed to track the wind speed. When this approach is used, the controller structure for partial load operation follows the sequential optimal calculation and regulation shown in Fig. 5.

On utility–scale wind turbines, Region 3 control is typically performed via a separate pitch control loop. In the Region 3, the primary objective is to limit the turbine power so that safe electrical and mechanical loads are not exceeded. Power limitation is achieved by pitching the blades or by yawing the turbine out of the wind, both of which can reduce the aerodynamic torque below what is theoretically available from an increase in wind speed. In the Region 3, the pitch control loop regulates the rotor speed ω_r (at the turbine 'rated speed') so that the turbine operates at its rated power.

In this way, the overall strategy of the wind turbine controller is to use two different controllers for the partial load region and the full load region. When the wind speed is below the rated value, the control system should maintain the pitch angle at its optimal value and control the generator torque in order to achieve the optimal tip–speed ratio (switch to Region 2).

At low wind speeds, *i.e.* in partial load operation, variable–speed control is implemented to track the optimum point on the C_Q–surface for maximising the power output, which corresponds to the λ_{opt} value. The speed of the generator is controlled by regulating the demanded torque $T_{g,d}$ on the generator through the generator torque controller. In partial load operation it is chosen to operate the wind turbine at $\beta = 0^o$, since the maximum power coefficient is obtained at this pitch angle:

$$T_{g,\,d} = \frac{1}{2}\,\rho\,\pi\,R^2\,\frac{R^3}{n_g^3\,\lambda_{\text{opt}}^3}\,C_{\max}\,\omega_g^2(t) - d_S\left(\frac{1}{n_g^2}+1\right)\omega_g(t) \tag{22}$$

with n_g is the gear–ratio of the gearbox connecting the rotor shaft with the electric generator/converter, R is the rotor radius, and $\omega_g(t)$ the electric generator/converter speed Johnson, Pao, Balas, and Fingersh (2006). The advantage of this approach is that only the measurement of the rotor or generator speed is required.

On the other hand, for high wind speeds, *i.e.* in full load operation, the desired operation of the wind turbine is to keep the rotor speed and the generated power at constant values. The main idea is to use the pitch system to control the efficiency of the aerodynamics, while applying the rated generator torque. However, in order to improve tracking of the power reference and cancel steady–state errors on the output power, a power controller is also introduced.

With reference to the speed controller, it is implemented as a PI controller that is able to track the speed reference and cancel possible steady–state errors on the generator speed. The speed controller transfer function $D_s(s)$ has the form:

$$D_s(s) = K_{ps}\left(1 + \frac{1}{T_{is}}\,\frac{1}{s}\right) \tag{23}$$

where K_{ps} is the PI proportional gain and T_{is} is the reset rate of the integrator.

The power controller is implemented in order to cancel possible steady–state errors in the output power. This suggests using slow integral control for the power controller, as this will eventually cancel steady–state errors on the output power without interfering with the speed controller. However, it may be beneficial to make the power controller faster to improve accuracy in the tracking of the rated power. The power controller is realized as a PI controller, whose transfer function $D_p(s)$ has the standard form:

$$D_p(s) = K_{pp}\left(1 + \frac{1}{T_{ip}}\,\frac{1}{s}\right) \tag{24}$$

where K_{pp} is the proportional gain of the PI regulator, whilst T_{ip} is the reset rate of the integrator.

Note finally that speed and power control can be coupled. However, as shown in Odgaard et al. (2013), they can be considered as decoupled, as their dynamics are different. However, more advanced control techniques can exploit multivariable (or decoupling) control, as addressed in Bianchi et al. (2007), Pao and Johnson (2011). It is worth noting that, from the previous considerations, the research issues of wind turbine control may seem very mature. However, the latest generation of giant offshore wind turbines present new dynamics and control issues.. Moreover, new wind turbine solutions, which

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use further wind turbine state information from the sensing system, have been suggested, also within EU projects, see *e.g.* Plumley, Leithead, Jamieson, Bossanyi, and Graham (2014), Chatzopoulos and Leithead (2010). This improved state information is used to control the wind turbine blades and at the same time reducing the design bearing fatigue and extreme structural loads that are affecting the structure of the wind turbine Valencia-Palomo, Rossiter, and Lopez-Estrada (2014), Khan, Valencia-Palomo, Rossiter, Jones, and Gondhalekar (0000). This control problem will be solved in a multivariable way, by optimising the conflicting control objectives of power optimisation while keeping the different loads below the design requirements. The control goal is to ensure that the controller will guarantee that extreme load requirements are not violated during eventually emergency stops of the wind turbine, as well as during severe wind gusts. The interesting challenge is to be able to use the rotor system to control the turbine, so that in effect the rotor performs like a 'high level' sensor. In other words the goal is to be able to use the rotor itself (along with the enhanced sensor set) to make the control system perform well. A part of this challenge is to ensure that real–time compensation of loading and gust disturbances is put into effect in a suitable time window, taking account of the close spectral content of the disturbance and control. This becomes a very significant challenge for very large rotor wind turbines (>10 MW) as the required control and disturbance bandwidths become close, a problem similar to the structural filtering and control used in high performance combat aircraft Shi and Patton (2015).

4.3. Control strategies for wave energy devices

As demonstrated in Fig. 5 the control problem first requires an optimum velocity profile to be calculated and this is then followed by controlling the PTO force. As documented in Section 3.4, there is significant focus on the hydrodynamic modelling aspects and this is also reflected in the balance of control studies devoted to the higher-level and lower-level depicted in Fig. 5. As a result, the focus here is mainly on hydrodynamic control (in Section 4.3.1), though some comments about lower level PTO control are given in Section 4.3.2.

4.3.1. Velocity profile calculation

Ignoring system constraints for the moment, a start can be made on the energy maximisation problem by considering the force-to-velocity model of a WEC, which is obtained from (21) in the frequency domain Falnes (2002) as:

$$\frac{V(\omega)}{F_{ex}(\omega)+F_u(\omega)} = \frac{1}{Z_i(\omega)} \tag{25}$$

where $Z_i(\omega)$ is termed the *intrinsic impedance* of the system. In (25), $V(\omega)$, $F_{ex}(\omega)$, and $F_u(\omega)$ represent the Fourier transform of the velocity $v(t)$, excitation force $f_{ex}(t)$, and control force $f_{PTO}(t)$, respectively. Unless stated otherwise, the Fourier transform of time-domain signals or functions will be denoted by the corresponding capital letter, namely $X(\omega) \triangleq \mathcal{F}\{x(t)\}$.

The intrinsic impedance $Z_i(\omega)$ of the model in (25) is specified as (see Falnes (2002) for the full derivation):

$$Z_i(\omega) = B_r(\omega) + \jmath\omega\left[M + M_a(\omega) - \frac{K_b}{\omega^2}\right] \tag{26}$$

where $B_r(\omega)$ is the radiation resistance (real and even) and $M_a(\omega)$ is the frequency–dependent added mass, often replaced by its high-frequency asymptote m_∞.

The model in (25) allows the derivation of conditions for optimal energy absorption and the intuitive design of the energy–maximising controller in the frequency–domain: Falnes (2002) as:

$$Z_{PTO}(\omega) = Z_i^*(\omega), \tag{27}$$

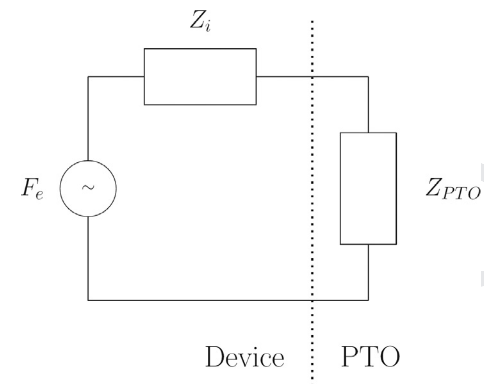

Fig. 14. Impedance matching problem for wave energy device.

where $(\,)^*$ denotes the complex conjugate. The choice of Z_{PTO} as in (27) is referred to as *complex conjugate control*, but many (especially electrical) engineers will recognise this choice of Z_{PTO} as the solution to the impedance–matching problem represented by Fig. 14. In Fig. 14, F_e represents the wave excitation force, while Z_i defines the relationship between this force and the device velocity, as determined by the WEC dynamics (see (26)). Under condition (27), maximum power is transferred from the device to the load, defined by Z_{PTO}, which is a well-known result for AC circuits.

The result in (27) has a number of important implications:

- The result is frequency dependent, implying that there is a different optimal impedance for each frequency, which raises the question of how to specify for irregular seas containing a mixture of frequencies;
- Since $h_r(t)$ is causal, $h_c(t) = \mathcal{F}^{-1}(Z_{PTO}(\omega))$ is anticausal, requiring future knowledge of the excitation force. While this knowledge is straightforward for the monochromatic case (single sinusoid), it is more problematic for irregular seas. However, some solutions are available, including those documented in Fusco and Ringwood (2010);
- Since force and velocity can have opposite signs in Fig. 14, the PTO may need to *supply* power for some parts of the sinusoidal cycle, which is akin to reactive power in electrical power systems. Such a phenomenon places particular demands on PTO systems, not only in terms of the need to facilitate bidirectional power flow, but also that the peak reactive power can be significantly greater than active power Shek, Macpherson, and Mueller (2008), Zurkinden, Guerinel, Alves, and Damkilde (2013). The optimal *passive* PTO is provided by $R_{PTO} = |Z_i(\omega)|$, which avoids the need for the PTO to supply power, but results in a suboptimal control;
- The optimal control in (27) takes no account of physical constraints in the WEC/PTO, where there are likely to be limitations on displacement or relative displacement, and the PTO force, and there may be external constraints imposed by electrical grid regulations;
- The maximum theoretical power recovered in an oscillating wave energy device is 50%, which represents the optimal matched condition in Fig. 14. Under such a condition, equal power is dissipated in the PTO and wave radiation, noting that a good wave energy absorber is also a good radiator Falnes (2002).

The condition in (27) can alternatively be expressed in terms of an optimal velocity profile as:

$$V^{opt}(\omega) = F_{ex}(\omega)/(2\,R_i(\omega)), \tag{28}$$

where $R_i = 1/2\,(Z_i + Z_i^*)$ is the real part of Z_i. The condition in (28) is a condition on the amplitude of $V^{opt}(\omega)$, with the restriction that $v^{opt}(t)$ be in phase with $f_{ex}(t)$, since R_i is a real (and even) function. This phase condition, considered separately, forms the basis for some

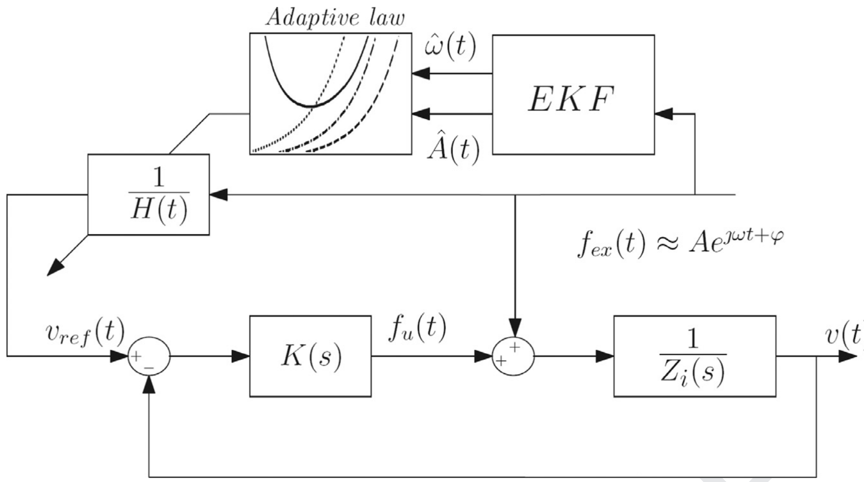

Fig. 15. Proposed control architecture for the simple controller. The EKF effectively tracks the wave frequency and amplitude as in (29), while the $1/H(t)$ block provides an adaptive feedforward gain to determine the optimal velocity profile.

simple WEC *phase control* strategies, such as *latching* Budal and Falnes (1975), Babarit, Duclos, and Clement (2004).

While the *complex conjugate control* resulting from the impedance matching problem provides the conceptual framework for optimal WEC control calculations, its implementation is not straightforward, for the reasons mentioned above. As a result, many alternatives have been proposed, many based on complex conjugate control, with the aim of being more suitable for implementation or real-time calculation.

A simple development of the basic condition in (27) is suggested in Fusco and Ringwood (2013), which carries the assumption that $f_{ex}(t)$ is a narrow-banded harmonic process, defined by time-varying amplitude $A(t)$, frequency $\omega(t)$, and phase $\varphi(t)$ as:

$$f_{ex}(t) = A(t)\cos(\omega(t)t + \varphi(t)) \tag{29}$$

The optimal reference velocity can then be generated from the adaptive law

$$v_{ref}(t) = \frac{1}{H(t)} f_{ex}(t), \qquad \frac{1}{H(t)} = \frac{1}{2R_i(\hat{\omega})} \tag{30}$$

where the value of the constant $H(t)$ is calculated from the curve $1/2B(\omega)$, based on a real–time instantaneous estimate of the peak frequency of the wave excitation force. An on-line estimate of the frequency $\hat{\omega}$ and amplitude $\hat{A}$ is obtained with the extended Kalman filter (EKF) Quine, Uhlmann, and Durrant-Whyte (1995). Based on the narrow-banded assumption of (29), the excitation force can be expressed in complex notation as:

$$f_{ex}(t) = \Re\left\{Ae^{\jmath\varphi}e^{\jmath\omega t}\right\}, \qquad \hat{F}_{ex} \triangleq Ae^{\jmath\varphi} \tag{31}$$

where $\hat{F}_{ex}$ is the complex amplitude of $f_{ex}(t)$, denoting $f_{ex}(t)$ as a single sinusoid with amplitude A and phase φ.

As a consequence of the proportional reference–generation law in (30), the complex amplitude of the velocity $\hat{V}$ and position $\hat{U}$ can be expressed as:

$$\hat{V} = \frac{A}{H}e^{\jmath\varphi} \tag{32}$$

$$\hat{U} = \frac{\hat{V}}{\jmath\omega} = \frac{A}{\jmath\omega H}e^{\jmath\varphi} \tag{33}$$

Suppose that the vertical excursion of the WEC is limited to $\pm\, U_{lim}$ from equilibrium. From (33), the position constraint can be written as an equivalent velocity constraint:

$$\hat{U} = \frac{\hat{V}}{\jmath\omega} \leq U_{lim} \quad \Leftrightarrow \quad |\hat{V}| \leq \omega U_{lim} \tag{34}$$

and an upper bound for the variable gain, $1/H$, involving the amplitude and frequency of the excitation, can be derived from (32) as:

$$\frac{1}{H} \leq \frac{\omega U_{lim}}{A} \tag{35}$$

The reference generation strategy, based on (28), (30), and (35) can therefore be modulated to keep the amplitude of the velocity within the bound specified in (34). A real–time estimate of the frequency $\hat{\omega}$ and amplitude $\hat{A}$ of the excitation, can be obtained through the EKF Budal and Falnes (1982), Fusco and Ringwood (2010) and the feedforward gain $\frac{1}{H(t)}$ adjusted according to:

$$\frac{1}{H(t)} = \begin{cases} \dfrac{1}{2R_i(\hat{\omega})}, & if \ \dfrac{\hat{\omega}U_{lim}}{\hat{A}} > \dfrac{1}{2R_i(\hat{\omega})} \\ \dfrac{\omega U_{lim}}{\hat{A}}, & otherwise \end{cases} \tag{36}$$

According to (36), when in the unconstrained region, the velocity is tuned to the optimal amplitude given by complex–conjugate control, as in (28). Otherwise, the maximum allowed velocity (lower than the optimal) is imposed, while keeping the velocity in phase with the excitation force. The control structure is illustrated in Fig. 15.

Other control architectures have also been proposed, including, for example, those based on numerical optimisation. Though the performance function to be maximised is somewhat non-traditional, namely:

$$J(T, f_{pto}) = \int_0^T f_{pto}(t)\, v(t)\, dt \tag{37}$$

where f_{PTO} is the PTO force and $v(t)$ the velocity profile of the device, a number of control methods having their origins in mainstream control have been customised for use in a wave energy context. These include model predictive control Hals, Falnes, and Moan (2011), Cretel, Lightbody, Thomas, and Lewis (2011), Brekken (2011), Richter, Magaña, Sawodny, and Brekken (2013a), Li and Belmont (2014) and a numerical optimisation method using a pseudo-spectral parameterisation Garcia-Rosa et al. (2015a). A reasonably comprehensive review of control strategies for WECs is given in Ringwood et al. (2014).

One of the significant challenges in wave energy control is that of the assumption of model linearity. Many hydrodynamic models are linearised around the SWL. This follows a relative normal practice in traditional control, but is somewhat less valid in the case of wave energy, where the general objective is to exaggerate the device motion, rather than drive the system to an equilibrium point. More recently, control algorithms for WECs have begun to emerge which deal with various nonlinear aspects, including:

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- Nonlinear hydrodynamic restoring force Richter, na, Sawodny, and Brekken (2013b);
- Viscous drag resulting from relatively high body/fluid motions Bacelli and Ringwood (2014);
- Non-ideal PTO effects ao and Henriques (2015), Genest, Bonnefoy, Clément, and Babarit (2014), Becelli, Genest, and Ringwood (in press).

However, controllers dealing with fully nonlinear hydrodynamics (for example, incorporating nonlinear dynamic Froude–Krylov forces) have yet to be developed.

4.3.2. PTO force control

Given the range of PTO control inputs as shown in Fig. 11 and the wide variety of PTO systems employed on prototype WECs, there is little convergence on PTO control system design. However, PTO control represents a traditional tracking control problem, to which a wide variety of conventional control strategies can be employed.

A number of studies have documented lower-loop control strategies for WEC PTO systems, including solutions based on Internal Model Control (IMC) Fusco and Ringwood (2013), ao, Mendes, Valério, and Costa (2007) and Proportional–Integral–Plus (PIP) control Taylor, Stables, Cross, Gunn, and Aggidis (2009). A robust control strategy, using a passivity–based controller, is presented in Fusco and Ringwood. In some cases an integrated high/low-level controller is employed as, for example in Falcão (2007), for a two-body WEC with a hydraulic PTO system.

4.4. Comparisons and contrasts of wind and wave control systems

Given the more mature development of wind turbines, considerably more attention has been focussed on the wind turbine control problem, resulting in refined control systems which can undertake a variety of functions, including:

- Optimal set–point generation;
- Turbine speed and torque control (setpoint following);
- Supervisory control of the turbine, considering the different operation requirements under the various scenarios in Fig. 2.

In addition, various advanced strategies, such as fault tolerant control, have also been developed for wind turbines, as articulated in Section 5.1.

It is clear that various 'levels' of control are required in both ocean energy and wind turbine applications. There is a top level of supervisory control which assesses the incident energy resource and may curtail the operation of the device in the face of extreme conditions. Such curtailment may be requirement in order to preserve the device integrity, ensure safe operation, or be required by legislation, as in the case of wind turbines. This is the case when wind turbines work in full load conditions, *i.e.* above the rated wind speed. On the other hand, they are designed to operate in the energy capture mode, *i.e.* below the rated wind speed. This working condition is similar to the WECs, where maximum–energy transfer is required. However, wave energy devices will frequently encounter sea states which are outside their normal operational envelope and some supervisory strategy may be necessary to ensure that device integrity is retained. Such supervisory control is important, and it can represent an important issue also for the safety of wind turbines, as briefly outlined in Section 5.1.

Finally, one control aspect which is contrasting between wind and wave applications is the relative benefit of controlling an array of devices in a co-ordinated way. For wind farms, only destructive interference occurs between neighbouring turbines due to wind shadow effects. For wave energy device farms, however, both constructive and destructive interference may occur. The optimal operation of both wind and wave farms is a significant function of the farm layout, which depends on the land topography and the wind direction probability distribution. However, in the wave energy case, for a given device layout, co-ordinated control of device motions may optimise constructive device interference (since each moving device radiates waves), resulting in potential gains of up to 20% in captured energy Bacelli et al. (2013a), Bacelli and Ringwood (2013a). It has also been shown that, for the wave energy case, that there is significant interaction between the control system employed and the optimal WEC array layout, from and energy capture perspective Garcia-Rosa et al. (2015a).

It is worth noting that, with reference to wind farms, the turbines are usually positioned to minimise down–wind interaction, so the interaction effects are minimal. This means that the distributed and de–centralised control of farms is mainly a subject of electrical load balancing rather than distributed aspects of aero–mechanical rotor control. However, some recent studies have been performed in order to decouple the interaction effects among the wind turbines of a wind farm Simani, Farsoni, Castaldi, and Mimmo (2015b), Simani, Farsoni, and Castaldi (2015a). The situation with arrays of wave energy converters is different, where the interaction between relatively close WECs (point absorbers, *etc*)in an array can be considered to be significant. Oscillating WECs generate radiation waves covering a significant area, with resulting possibilities for both positive and negative reinforcement of the incident wave excitation, for any particular device.

To this end, wave energy arrays need to be carefully laid out, but centralised (global) array control algorithms can play a significant part in maximising the benefit of mutual radiation effects Bacelli, P. Balitsky, and Ringwood (2013b), Bacelli and Ringwood (2013d), where a complete model of the hydrodynamic interactions is available. It has also been shown that there is significant interaction between the optimal WEC array layout problem and the global WEC array control problem i.e. the optimal WEC array layout depends on the WEC array control strategy employed Garcia-Rosa, Costello, Dias, and Ringwood (2015b).

5. Towards the future

The variability of the power produced from renewable sources and its uncontrollable nature negatively affects their effectiveness in reducing the requirement for thermal plants (it reduces their capacity credit) and makes them a less attractive and a potentially more expensive alternative. Wind and wave energy, however, offer important and significant energy resources and can be of major assistance in mitigating climate change, so it is imperative that maximum effort be devoted to refining the technology (including control technology) used to convert these resources to a useful and economic form.

This paper focusses on the analysis and the comparison between the two resources, considering also the variability of the power extraction when wind or wave offshore farms are adopted, with respect to the exploitation of the renewable resources. It can be noted that, in some cases, wave systems where the predominant (from an energy point of view) part is composed of large swell systems, generated by remote wind systems, have little correlation with the local wind conditions. This means that the two resources can appear at different times and, if considered together, their integration in combined farms allows a more reliable, less variable and more predictable electrical power production Babarit et al. (2006), Fusco et al. (2010). The reliability is improved thanks to a significant reduction of the periods of null or very low power production (which is a problem with wind farms). The variability and predictability improvements derive from the smoothing effect due to the integration of poorly correlated diversified sources. To this end, a number of combined offshore wind/wave platforms have also been proposed Soulard, Babarit, Borgarino, Wyns, and Harismendy (2013). Combined wind/wave installations also have the significant benefit of sharing electrical and

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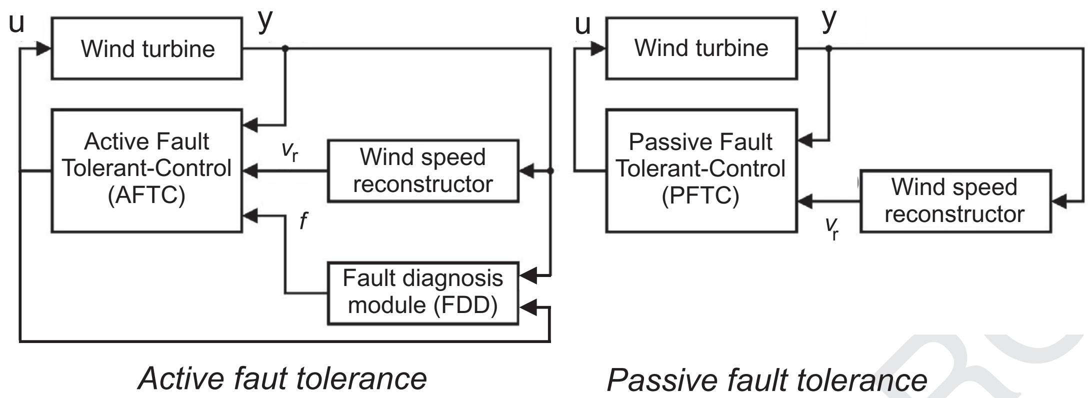

Fig. 16. Structure of the active and passive fault–tolerant control systems.

civil engineering infrastructure. This may help to reduce overall costs, though it is also likely that there is some compromise in the level of optimality of the individual wind or wave resources, in such cases.

On the other hand, in some other cases, the combination of wind and waves does not appear to be an attractive solution, due to a limited wave energy resource, which is strongly correlated to the local wind conditions Fusco et al. (2010). The conclusion is, then, that the potential benefits of the integration of wind and wave resources, where the climate of the location is appropriate, are too important to be neglected. This paper attempts to highlight the quantification of these benefits, particularly from a raw resource assessment point of view. With wave energy technology becoming more mature, it should be possible to develop a more complete analysis where these benefits are integrated, together with the actual costs of the different wave and wind technologies, in a global functional, whose optimisation should lead to a proper dimensioning and design of offshore combined farms, given the energy climate of a particular location.

Note finally that, as the world's power supply depends to an every greater extent on renewable resources, it is consequently and increasingly important that these are as reliable and predictable as possible, so that effective economic dispatch can be performed. So-called Fault Tolerant Control (FTC) Blanke et al. (2006) can play a substantial part in increasing reliability of modern wind turbines and wave energy devices. This is especially true for remote marine locations, where access and weather windows make regular and immediate maintenance problematic, and FTC can significantly increase energy conversion productivity by providing some level of energy supply during certain fault conditions.

Benchmark models for wind turbine and wind farm fault detection and isolation, and FTC have previously been proposed Odgaard and Stoustrup (2013), Odgaard and Stoustrup (0000). Based on this benchmarks, an international competitions on wind turbine fault diagnosis and FTC were announced Odgaard and Odgaard (2012), Odgaard and Shafiei (0000). Under these considerations, Section 5.1 summarises advanced methods that show potential for wind turbine fault diagnosis and FTC. In addition, as they highlighted good performance, these approaches are also relevant for industrial usage. This means that the wind turbine controller can continue operation as in the fault–free case.

In contrast, however, there have been few studies which compare either different modelling or different control strategies for WECs. This is a significant limitation in making an assessment of true progress in the state-of-the-art. While there are a wide variety of WEC concepts, and different WECs may benefit from different customised modelling and control solutions, some benchmark comparisons are necessary. Some progress, in this regard, is being made with the recent COER hydrodynamic modelling competition Garcia-Rosa et al. (2015b), which provided a benchmark data set from tank testing of a WEC-like device, while a WEC control benchmark competition is currently in the early stages of organisation.

However, while FTC (and associated benchmark problems) are becoming popular in wind turbine control research, wave energy systems lag far behind, in spite of perhaps a greater imperative for fault-tolerant systems, due to more severe access limitations. However, the benchmark problems and FTC solutions developed in the wind energy research community can provide a useful model that the wave community can learn from.

5.1. Advanced methods in wind turbine control

Over the last decade, many studies have been carried out on wind turbine fault diagnosis, with the most relevant including Gong and Qiao (2013), , Estima, and Cardoso (2013). In addition, the FTC problem for wind turbines was recently analysed with reference to an offshore wind turbine benchmark *e.g.* in Odgaard et al. (2013). In general, FTC methods are classified into two types, *i.e.* Passive Fault Tolerant Control (PFTC) scheme and Active Fault Tolerant Control (AFTC) scheme Mahmoud et al. (2003). In PFTC, controllers are fixed and are designed to be robust against a class of presumed faults. In contrast to PFTC, AFTC reacts to the system component failures actively by reconfiguring control actions so that the stability and acceptable performance of the entire system can be maintained. Therefore, the term 'sustainable' is used to characterise wind turbine control, and it represents a challenging task.

In order to outline and compare the controllers developed using active and passive fault–tolerant design approaches, they should be derived using the same procedures in the fault–free case. In this way, any differences in their performance or design complexity would be caused only by the fault tolerance approach, rather than the underlying control solutions Bianchi et al. (2007), Galdi, Piccolo, and Siano (0000).

The two FTC solutions have different structures as shown in Fig. 16. Note that only AFTC relies on a fault diagnosis algorithm (FDD). This represents the main difference between the two control schemes.

The main connection between AFTC and PFTC schemes is that an AFTC relies on a fault diagnosis system, which provides information about the faults *f* to the controller. In the considered case, the Fault Detection and Diagnosis (FDD) system contains the estimation of the unknown input (fault) affecting the system under control. The knowledge of the fault *f* allows the AFTC to reconfigure the current state of the system. On the other hand, the FDD is able to improve the controller performance in fault–free conditions, since it can compensate modelling errors, uncertainty and disturbances. On the other hand, the PFTC scheme does not rely on a fault diagnosis algorithm, but is designed to be robust towards any possible faults.

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This is accomplished by designing a controller that is optimised for the fault–free situation, while satisfying some graceful degradation requirements in the faulty cases. However, with respect to the robust control design, the PFTC strategy provides reliable controllers that guarantee the same performance with no risk of false fault detection or reconfigurations.

Clearly, the issues addressed by such FTC schemes for wind turbines are no less relevant for wave energy applications. In fact, the issue is likely to be even more manifest where wave energy devices are located far offshore (the location of the greatest wave energy) and access for maintenance and repair may be difficult Odgaard (2012). Such an issue is, of course, also relevant for those wind turbines located offshore though, in such cases, preference is usually given to sites which present relatively shallow water depth. However, recent developments in floating wind and wave platforms Soulard et al. (2013) may present composite challenges, but they are not considered in this paper.

5.2. Overall economic considerations

While control systems are ostensibly added in order to maximise power capture, care must be taken that such control systems have no adverse effect on the system. Though raw wind and wave energy are essentially free, the systems to convert this raw energy are not and, ultimately, the receipts from energy sales are balanced to some extent by significant capital and operational costs. In the offshore environment, it is estimated that capital and operational costs are in roughly equal proportion.

One important aspect in this economic perspective is to consider if the addition of a control system may drive the system more aggressively in an attempt to increase energy capture, perhaps leading to shortened device lifetimes. While the addition of control to a wind turbine is likely to be relatively benign, the use of motion–exaggerating control for a reciprocating wave energy device can have a dramatic effect on device motion. Consequently, the balance between increased energy capture (income) and increased device wear (cost) needs to be carefully considered. Is also known, for example, that the use of reactive control, where some energy from the grid side is used to exaggerate device motion (capturing more net energy overall) in WEC control brings significantly increased requirements in system power capacity Shek, Macpherson, Mueller, and Xiang (2007).

While potentially effecting more aggressive device motion, there are some redeeming features of control which may help the designer in practical applications. For example, physical constraints can be explicitly included in many control formulations, resulting in a control action that respects (and is optimal within) the physical system constraints. In addition, for both wind turbines and WECs, most optimal control formulations allow some explicit trade-off between control action and the main objective (*e.g.* setpoint tracking, energy maximisation, *etc*), which provides a design handle on the level of aggressiveness of the control. Control science also provides a body of knowledge relating to the design of control systems which are tolerant (in some respect, but usually with reduced performance) to system, actuator or sensor faults or malfunctions, as described in Section 5.1.

It has also been shown that there is often significant interaction between the optimal (uncontrolled) device design and the control system used to optimise its behaviour. For example in the wave energy context, where controllers are effectively used to extend the bandwidth of WECs so they can operate effectively across a wide variety of sea conditions, the uncontrolled (open loop) device resonant frequency should be carefully placed, so that the controller can take maximum advantage Garcia-Rosa and Ringwood. For example, latching control Babarit and Clement (2006) can extend the WEC frequency response in the direction of lower frequencies, suggesting that the (uncontrolled) resonant frequency of the WEC should be small. This has a double benefit in ensuring an optimal WEC/controller combination, while also requiring a smaller device, with potentially lower capital costs.

In the wind turbine case, significant advances in turbine control have led to a situation where turbine developers are providing progressively less control power, so that control energy consumption is minimised. However, this reaction, in turn, leads to highly nonlinear control action, since the control signals are regularly saturating, increasing the control challenge still further Leithead and Connor (2000).

6. Conclusion

The motivation for this paper came from the need to have an overview about the main challenges of modelling and control for wind turbines and wave energy devices. In order to present common and different requirements over power conversion efficiency (*i.e.* the renewable source power that can be converted into electric energy, the work focussed on commonalities and contrasts for these two fields.

Therefore, the analysis of the commonalities and the contrasts between these two fields was mainly performed according the items below:

- System model purpose;
- Renewable resource descriptions;
- Control strategy development.

On the basis of these items, the following considerations have been finally outlined. On one hand, wind turbine systems seem relatively mature from the modelling point of view, whilst wave energy devices still present challenging modelling issues. This remark is valid for medium size wind turbines: large rotor installations can drive challenging and complex modelling and control issues.

Both wind turbine and wave energy control systems can share a common structure. In addition to these components, a further level of supervisory control is required to correctly select the control strategy appropriate to the model of operation, usually dictated by the prevalent wind or wave resource measure. For the wind turbine case, such operational modes are well defined, as articulated in terms of the various sections of the power curve. However, though the overall number of operational modes may be lower, wave devices also have a cut–in power level below which energy conversion is not economic/possible, a main power production region where energy conversion should be maximised, a region where energy conversion must be curtailed due to the capacity of (for example) electrical components and, finally, a survival mode where energy production is abandoned and system motion configured to avoid potential structural damage. The means by which survivability is managed in the wave case is not as straightforward as in wind, due to the wide variety of wave devices and the difficulty of finding an orientation or configuration which avoids the destructive influence of high wave energy fluxes.

Despite the differences in relative maturity of wind and wave energy, both share many fundamental principles, including the fact that only a fraction of the raw wind (60%) and wave (50%) resources can be usefully converted, at best. These limitations relate to basic aerodynamic (wind) and hydrodynamic (wave) considerations.

In general, both wave and wind energy conversion systems require a high degree of availability, as it significantly affects the final energy cost. Moreover, these systems have highly nonlinear dynamics, with stochastic inputs, in the form of wind and wave driving forces. Suitable control methods should provide the optimisation of the energy conversion efficiency over wider than normally expected working conditions. Moreover, it was shown that proper mathematical descriptions were necessary to capture the complete behaviour of the systems under consideration, thus providing an important impact on the control design itself.

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On the basis of these considerations, it seems that the considered two domains can be only partially compared. The modelling of these systems is quite different, but the control principle (if limited to the wind turbine partial load condition) is similar. Also the intermittent resources that drive them are, in many cases, uncorrelated, leading to the advantageous combination of both technologies. However, the technological challenge, from a modelling and control perspective, coupled with the high cost of offshore deployment and maintenance, helps to explain why wind turbines are now commonplace, whilst wave energy devices are not.

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