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Review of control strategies for wave energy conversion systems and their validation: the wave-to-wire approach

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ABSTRACT

Ocean waves are a promising source of renewable energy. In this paper, we briefly introduce the characteristics of ocean wave energy and summarize the principles of harvesting ocean energy by wave energy converters. We also review the prototypes or commercial devices deployed in real sea between 2005 and July 2016.

In addition, we present the concept of a wave-to-wire model as a framework to systematically review and compare control strategies for wave energy conversion systems, with a focus on the numerical and experimental validation.

1. Introduction

Renewable energy sources, e.g. wind and sunlight, exist over wide geographical areas, and can be used to provide electrical power (on-grid or off-grid), cool water, heat water, and enable transportation. Compared to traditional energy sources, they produce less waste products such as chemical pollution and carbon dioxide, which means the negative influence on the environment is minimal. Due to the urgency to act against climate change caused by the growing carbon dioxide in the atmosphere, renewable energy is gaining attention all over the world. For instance in the European Union, the Renewable Energy Directive establishes an overall policy for the production and promotion of energy from renewable sources. It requires the European Union to meet at least 20% of its total energy needs with renewables by 2020. As shown in Fig. 1, all EU countries have a target of at least 10% of the gross consumption of energy coming from renewable sources by 2020. In the Nordic Countries, Sweden has a high target of 49%. Besides that, Norway has a target of 67.5% by 2020.

Among all the renewable sources, ocean wave energy is a promising one. It has a high power density and a huge potential. Its worldwide potential is estimated to be 2 TW [1], and has the ability to make a significant contribution to supply the world's energy demand. The use of ocean energy through wave energy converters (WECs) has been numerically and physically validated over the past decades. The results indicate that ocean wave power can be captured efficiently by the WECs and used for desalination [2] or converted into electricity (usually the latter). Now, the use of wave power is drawing more attention all over the world. The Department of Energy in United States for example, has initiated a new program, the Water Power Program, to develop and deploy a portfolio of innovative technologies for clean, domestic power generation [3]. Another example is the Blue Growth Program, funded under Horizon 2020 in the EU, which also supports, among others, several schemes to encourage harvesting ocean energy [4].

Over the past decades, many WEC concepts have been proposed or validated by numerical or physical experiments [6]. These experiments show the feasibility of WECs and investigate the influence of system parameters and control methods on performance enhancement. However, the majority of these experiments focus on different sub-systems separately, e.g., they focus on the fluid-structure interactions between ocean waves and absorbers, on control methods to maximize the power captured from ocean waves, or on linear generator technologies suitable for wave energy conversion. To investigate the system dynamics, optimize the performance and improve the overall efficiency at the same time, there is a need to take into account all the components, from ocean waves to the electrical network. This process of converting ocean wave power into electricity, is referred to as "wave to wire" (W2W).

The W2W model consists of the input and output of a wave energy conversion system, where the latter is the electrical power injected into grid or supplied to electrical machines. This model takes into account the interactions between the hydrodynamic part, the mechanical part, the electrical part, and the power electronics. It also makes it possible

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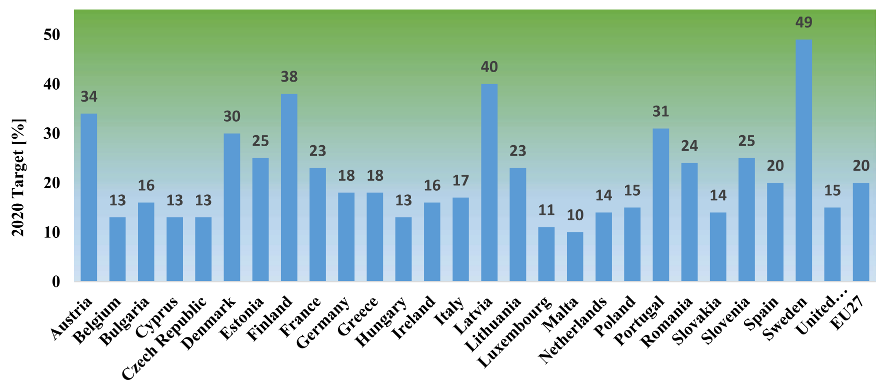

Fig. 1. 2020 renewable energy target for European Union members. Data are from "DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC" [5].

to study the coupling issues of the entire system. Another advantage is that, advanced control strategies can be embedded in the W2W model, to improve the system performance, to meet the grid code, or to meet the internal operating requirements of the subsystems.

Some work on the W2W model has been reviewed in [7,8], and introduced in [9,10]. In [7], the W2W model is divided into four stages, i.e., the absorption stage, the generation stage, the transmission stage, and the conditioning stage. The components related to these four stages and their dynamics and constraints, including grid constraints, are identified. The objective is to examine the current literature and the available models to see if a complete W2W model, suitable for advanced control, is available or can be assembled. In [8], the authors provide an overview of many aspects that feed into the W2W model and also give a summary of some tools for calculating hydrodynamic parameters. A new numerical tool is developed to calculate the power output from a specified WEC under specified ocean wave conditions, to assess and optimize the performance of a WEC design and to provide knowledge of the WEC behaviour under specific wave conditions. In [9], some issues on the hydrodynamic system, the power take-off (PTO) system, the mooring system, and the system reliability are investigated separately, and some works on the W2W model are also briefly introduced, including economic optimization and a brief overview of numerical and experimental tools. In [10], the author states that the WEC breakdown of a wave-activated-body type has six main subsystems. He studies a set of issues on three of them, i.e., the hydrodynamic subsystem, the PTO subsystem, and the reaction subsystem, and presents some available numerical and physical modelling techniques. An optimization methodology based on a modification of the control strategy is indicated to minimize the cost of energy. Refs. [8,9], and [10] were published in 2014 by a research group in Denmark, and some works are overlapping. As these four references show, various WECs using different operation principles and consisting of different primary capture systems, PTO systems, and power electronics are under development, so a W2W tool has to be very flexible, or composed of blocks with a focus on system parts such as the PTO design, or array interaction effects.

Unlike these works, our main focus is to provide a state of the art of control strategy suitable for wave energy conversion, especially for implementation in the W2W model. In addition, we investigate the numerical and experimental validations, while mathematical models of components like generators, voltage controllers and current controllers are left aside. It should be noted that the control of the hydrodynamic part is also reviewed, which is ignored in some articles.

The structure of this paper is as follows: ocean wave energy is introduced in Section 2. The ways to capture wave energy by WECs are summarized in Section 3, mainly according to the working principle of the primary and secondary conversion system. Then we review the representative WECs deployed in real sea between 2005 and July 2016. Section 4 describes the W2W model, including a review on this. In Section 5, control strategies suitable for W2W are summarized, with a focus on their numerical and experimental validations. Additional issues are discussed in Section 6, and Section 7 presents concluding remarks.

2. Ocean wave energy

Ocean waves can be generated by different mechanisms, e.g., earthquakes or planetary forces, but the majority of them are driven by wind blowing over an area of a fluid surface, referred to as wind waves. Their velocity depends on the wavelength and the depth of the ocean, which is expressed through the dispersion relation:

$$v = \sqrt{\frac{g\lambda}{2\pi}}\tanh\left(2\pi\frac{h}{\lambda}\right), \tag{1}$$

where λ is the wavelength, g is the acceleration of gravity, and h is the water depth.

As shown in Fig. 2, the diameter of a water particle motion circle decreases with water depth. Calculation results indicate that about 95% of the energy in the waves is available between the surface and a depth equal to a quarter of the wavelength for deep water [11]. The total energy of unity width below one wave length of ocean surface is expressed as:

$$E = \frac{1}{\lambda}\int_0^{\lambda}\int_0^1 \frac{1}{2}g\rho\eta^2 dxdy + \frac{1}{\lambda}\int_0^{\lambda}\int_0^1\int_{-\infty}^0 \frac{1}{2}(v_x^2 + v_y^2 + v_z^2)dxdydz, \tag{2}$$

where ρ is the ocean water density, η is the wave elevation, and v_x, v_y, v_z are the velocity in the x, y, z direction, respectively. The first term on the right side in the equation is the potential energy, and the second term is the kinetic energy.

However, the ocean surface waves driven by wind are usually irregular. They have a certain amount of randomness: subsequent waves vary in height and period. One way to describe the irregular wave

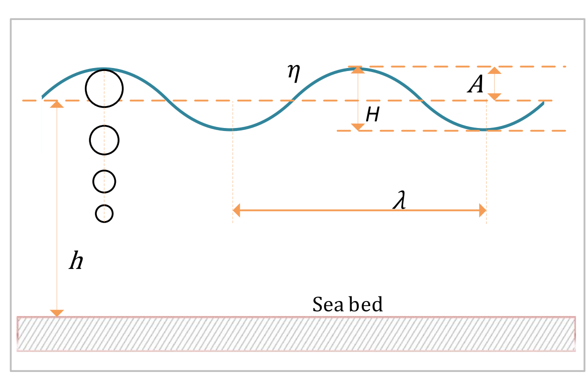

Fig. 2. A regular wave with finite depth [12]. The particle orbits are indicated for the deep-water case.

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