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Modeling and Control of Marine Current Turbines and Energy Storage Systems [⋆]

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Abstract: Swells in the marine current can cause unanticipated fluctuations in the power generated by Marine Current Turbines (MCTs). While the marine current in a single point under swell effect can be captured through a well-defined model, realistic aggregated models that capture the spatial distribution of the turbines that compose a MCT farm have not been proposed yet. This paper aims at filling this gap. The proposed model also helps design Energy Storage Systems (ESSs) included in MCT farms to level the power fluctuations caused by swells. Results highlight that there is the need for more detailed models of the correlation of marine currents in a farm of MCTs.

Keywords: Marine current turbine (MCT), swell effect, energy storage system (ESS)

1. INTRODUCTION

1.1 *Motivations*

Ocean-based renewable energy sources exist in various forms, i.e. tidal, wave and thermal energy. Among these, tidal energy is considered to be the most promising [WEC (2016)]. Tidal generation is dependent on marine current. The marine current can be subjected to short-term fluctuations due to swells in the ocean. These fluctuations can effect the power quality and stability of power systems. The swells in the current in a single point have been modeled in the literature. However, the aggregated current of a MCT farm has not been modeled and is therefore the subject of this paper.

1.2 *Literature Review*

One of the main advantages of marine current energy compared to other prominent renewable energy sources (wind, solar, etc) is its high predictability. This is because marine currents are mostly driven by the tidal phenomenon, which depends on astronomical forces making it predictable within 98% accuracy [Benelghali et al. (2011)]. However, the marine current speed is subject to short-term disturbances caused by the swell phenomenon. The fluctuations in the power originated by the swell can be viewed as *forced oscillations* that need to be effectively damped to ensure a stable and reliable operation of the system [Ghorbaniparvar (2017)].

The Stokes model coupled with the JONSWAP spectrum [Zhou et al. (2013a); Anwar et al. (2016); Zhou et al. (2013b)] is typically utilized to model the swell effect in one point. This model captures the effect of swells for a single turbine, not a whole park of MCTs. The aggregation of the marine current for a park of MCTs remains an open research question.

Coupled with the issue of properly modeling the swell effect, there is the need to design an effective control to reduce active power fluctuations. An efficient solution is to install a ESS at the point of connection of the MCT farm with the grid. With this regard, several energy storage technologies have been discussed in the literature. In [Zhou et al. (2013b); Pham et al. (2017)], electrochemical capacitors are proposed and in [Anwar et al. (2016)] lithium-ion batteries. These publications have identified the size of the ESS to have to be approximately half of the size of the MCT farm if no additional control is used. However, references [Anwar et al. (2016); Zhou et al. (2013b); Pham et al. (2017)] can be prone to overestimate the capacity of the storage device because a detailed model of the aggregated MCT farm current is not considered.

1.3 *Contributions*

The goal of this paper is to understand the limitations of single-point models of marine currents for MCT power plants. The specific contributions of this paper are threefold:

- Propose an approach to aggregate the marine current speed of a MCT farm.
- Study the effect of the swell phenomenon on a modified 9-bus 3-machine test system for the worst and best case scenario of swells.
- Discuss the design of ESSs for levelling the swell-induced power fluctuations.

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1.4 Paper Organisation

The remainder of the paper is organized as follows. Section 2 outlines the model of the marine system, including marine current, aggregated current and the generator model. In Section 3 the ESS used to smooth the power fluctuations induced by swells is presented. The case study is outlined in Section 4 and further discussion on the results are provided in Section 5. Finally, in Section 6 conclusions are drawn and future work is outlined.

2. MARINE SYSTEM MODELING

In this section, the components of the implemented marine system model are presented. First the marine current model for a single turbine with the swell-induced short term oscillations is presented in Section 2.1. An aggregated marine current model is proposed in Section 2.2 to better represent the effective marine current in a park of MCTs. The aggregated marine current is the input to the aggregated marine generator model outlined in Section 2.3.

2.1 Current speed models

Two kinds of periodical fluctuations can be identified in the marine current. On a daily time scale the current varies with a period of 6 or 12 hours due to the tidal astronomical phenomenon. These fluctuations are highly predictable. On a smaller time scale, that is in a matter of seconds, the marine current fluctuates due to wind waves and ocean swells. It is the swell induced fluctuations that are of interest in this paper.

Swells are long wavelength waves that originate in a remote region of the ocean and propagate out of their area of generation. The intensity of the swell waves varies as they move through the ocean. Low frequency components of the wave propagate faster than the high ones. Therefore, the swell effect at a fixed point has a narrow frequency spectrum characterized by a sharp peak.

The JONSWAP spectrum is a well-accepted analytical model for the swell wave spectrum [Hasselmann et al. (1973)]:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\Bigg(-\beta \left(\frac{\omega_p}{\omega}\right)^4 \Bigg) \gamma^Y \ , \tag{1}$$

where ω is the wave angle frequency, α is the intensity of the spectra, g is the acceleration due to gravity, β is the shape factor and ω_p is the frequency at the peak of the spectrum. The parameter γ is the peak enhancement factor which controls the sharpness of the peak and

$$Y = \exp\Bigg(-\left(\frac{\omega - \omega_p}{\sqrt{2}\omega_p \sigma}\right)^2 \Bigg) \ , \tag{2}$$

where

$$\sigma = \begin{cases} 0.07 \text{ if } \omega \le \omega_p \\ 0.09 \text{ if } \omega > \omega_p \ . \end{cases} \tag{3}$$

The JONSWAP spectrum used in this paper is shown in Fig. 1. It has a sharp peak and a narrow frequency range as is the case for swell waves. This spectrum has $\omega_p = 0.5$ rad/s ≈ 0.08 Hz. Thus, the swells introduce oscillations with frequencies in the range $0.05 - 0.1$ Hz. Based on the swell spectrum, the horizontal current velocity can be derived through the super positioning of m frequency components.

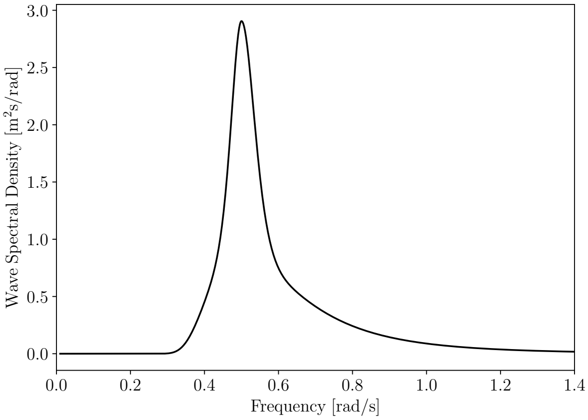

Fig. 1. The JONSWAP spectrum.

The first order Stokes model is used to model the marine current. The marine current is represented through the following combination of the tidal speed and the swell effect:

$$u_j(t) = u_{\text{tide}} + \sum_{i=1}^{m} \omega_i a_i \frac{\cosh(k_i(z+d))}{\sinh(k_i(z+d))} \cos(\omega_i t + \phi_i) \ . \tag{4}$$

Above, u_{tide} represents the predicted tidal speed (which is taken to be the zero-frequency component of any current model and constant in the case study in Section 4). With

$$a_i = \sqrt{2S(\omega_i)\Delta\omega_i} \ , \tag{5}$$

being the amplitude of the i-th frequency component defined from the JONSWAP spectrum (1); ω_i is the frequency of the i-th component, k_i is the wave number of the i-th component, z is the vertical distance from the sea surface to the hub height of the MCT, d is the depth from the ocean floor and ϕ_i is the initial phase angle of the i-th frequency component.

2.2 Aggregated Current Model

The model in (4) captures the marine current for a single MCT. Most often, a number of MCTs are installed close to each other to form a park of MCTs. An aggregated generator model is used to represent all the turbines in the park using a single generator (see Section 2.3). To account for the averaging effect of considering the MCT park as a whole an aggregated model for the current speed is proposed in this paper. This model is based on a similar model used for aggregating wind turbines [Rousi et al. (2014)].

The aggregated marine current for n individual currents is:

$$u_{\text{agg}}(t) = \sum_{k=1}^{n} u_{j_n}(t)/n \ , \tag{6}$$

where the n marine currents $u_{j_n}(t)$ are defined in (4). All n current models have identical parameters except for the phase angle. The phase angle of each frequency component