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Master-slave wave farm systems based on energy filter with smoothed power output

Zuanhong Yan[1], Xiao-Ping Zhang[2]

1. Electric Power Research Institute, China Southern Power Grid, Guangzhou, P.R China.
2. University of Birmingham, Birmingham, B15 2TT, U. K.

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Abstract: Wave energy is an important renewable energy source. Previous studies of wave energy conversion (WEC) have focused on the maximum power take-off (PTO) techniques of a single machine. However, there is a lack of research on the energy and power quality of wave farm systems. Owing to the pulsating nature of ocean waves and popular PTO devices, the generated electrical power suffers from severe fluctuations. Existing solutions require extra energy storage and overrated power converters for wave power integration. In this study, we developed a master-slave wave farm system with rotor inertia energy storage; this system delivers self-smoothed power output to the grid and reduces the number of converters. Two control methods based on the moving average filter (MAF) and energy filter (EF) are proposed to smooth the output power of wave farms. RTDS simulations show that the proposed systems and control methods facilitate simple and smooth grid integration of wave energy.

Keywords: Wave farm, Energy storage, Power smoothing, Power quality, Energy quality.

1 Introduction

Ocean wave energy is a significant renewable energy source. Compared with wind and solar, wave energy is more predictable, continuous, and has higher power density. The total global wave resource is estimated to be approximately 2000 GW, which is more than the total installed capacity of China in 2018, and the long-term projected wave energy cost is 0.10–0.15 US dollar per kWh [1]. Over the past decade, pilot projects have been implemented along the western coast of Europe (e.g., Portugal, France, UK, Norway) and the northwestern coast of the USA (Oregon and Washington states) [2–6]. These places enjoy the highest wave power density on Earth owing to the open sea environment and westerlies. In the UK, the 750 kW Pelamis project was established in 2004, and the first commercial wave farm Ceto6 will be put online in 2018. In Japan, there are currently more than 1000 commercially operated wave power generators. China is exploring potential applications of wave energy to power its islands in the South China Sea, and recently a 2-year project “key techs and demos of smart microgrids on islands including wave energy conversion systems” was initiated by the China Southern Power Grid (CSG). Furthermore, in addition to electrical power generation, wave energy is suitable for the desalination of seawater, heat generation, hydraulic pumping, and offshore platforms services.

However, despite its potential, wave energy conversion (WEC) is still in the early developmental stage, and to date there is no clear convergence on prototypes. Existing prototypes can be classified into 4 categories: oscillating wave columns (OWC), overtopping devices, hinged contour devices (e.g., Pelamis), and point absorbers, as shown in Fig. 1. Details of each category have been presented in previous reviews [2, 7].

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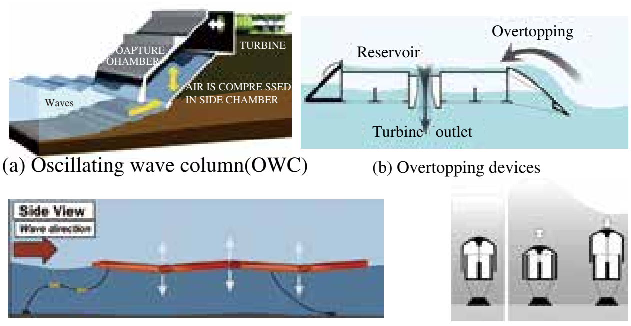
Zuanhong Yan
yanzh1@csg.cn

Xiao-Ping Zhang
X.P.Zhang@bham.ac.uk

Until recently, research publications on wave energy have very much been limited to single electric machine design and maximizing the power take-off (PTO) efficiency [8, 9]. Designs of direct-drive linear switched reluctance machines [10], tubular linear generators [11], and double-sided permanent magnet linear generators [12] have also been discussed. On the other hand, there are number of studies on the grid side power and energy quality of WEC and wave farms. Studies focusing on maximizing PTO efficiency have suffered from poor power quality and huge power fluctuations to the grid; or in some cases, have ignored discussion of these issues [13, 14]. The stability issue and power smoothing control of a single wave generator (or aggregated wave farm) using external flywheel storage was studied in [15]. [16] considered the optimal layout of individual machines in a wave farm in order to maximize the energy capture efficiency, but did not consider electrical side behaviors. The grid impact of a real wave farm test site was reported in [17] without additional devices to support power quality, and power fluctuations and pulses were observed. In [18], a new wave power transmission method was proposed using a series of connected generation units. The energy storage in wave farm was roughly discussed in [19, 20] without specific storage devices, models, or control methods.



(a) Oscillating wave column(OWC) (b) Overtopping devices

(c) Hinged contour devices (d) Point absorbers

Fig. 1 Mainstream power take-off (PTO) devices for wave energy conversion [7]

Two points remain to be investigated for the further development of wave energy. Firstly, wave energy should be harvested by wave farms with their own features and behaviors as a whole, rather than by individual machines. Secondly, in addition to high PTO efficiency at the prime mover side, the grid adaptation of wave energy, including good power quality, controllable power factor, and smoothed power flows, should be ensured. Wave power fluctuations cause frequency variations, voltage flickers, thermal excursions, wasted equipment capacities, and other instabilities in the local grid [21]. It is necessary to integrate short-term energy storage devices (energy buffers) with the fast response of a typical wave period (5~12 s) in a wave farm system. Studies have been conducted on electrical energy storage such as batteries [6] and capacitors [22]. However, these solutions are limited by the short life-cycle of batteries and large space required by capacitors. Moreover, machines and rectifiers have to be overrated to tolerate peak power, since the power flow is not smoothed before the DC link of the converters.

In order to achieve good grid-side power quality from wave farms in a cost-effective manner, there is a need to reduce the number of power converters and develop a solution of durable, compact, and electrically controlled energy buffers. In this study, a master-slave wave farm systems and control methods was developed to address these challenges; the proposed system has a number of advantages: (1) it is able to deliver smoothed active power and controllable reactive power to the grid; (2) there is no overrated device or extra energy storage system (ESS) required, but the rotor inertia is used as an energy buffer; (3) it is compatible with most existing PTOs and could have a reduced number of converters with specific selections of PTO; and (4) the energy filter control of wave farms can quantitatively smooth the output power without mechanical measurements at electrical machines.

2 Master-slave wave farm structure

The proposed system consists of two masters and three slaves (referred to as '2M3S system'), as shown in Fig. 2. Power outputs from all masters and slaves are collected at the point of common coupling (PCC) and smoothed by appropriate control of masters and then transmitted to the onshore grid via a HVAC or HVDC cable, depending on the distance to the coast and the power capacity of the system [23].

2.1 Slaves

Slaves are wave power generation units directly connected to the PCC without energy buffers. They produce highly fluctuating power flows and consume variant reactive power. All of the mainstream PTOs discussed (see Section 1) are applicable, but their mechanical structures could be further simplified since no energy buffer is required. The mechanical control of manifolds in Pelamis [24] and other similar hydraulic PTOs could be removed. For a point absorber, power converters are no longer necessary if they are used for fast energy storage or reactive power compensation. However, converters are still necessary if they are for controlling the electrical machine to maximize power take-off efficiency or phase-order alteration (e.g., PTO with linear machines). The proposed system is compatible to all mainstream PTOs but friendlier to hydraulic PTOs and directly connected induction generators.

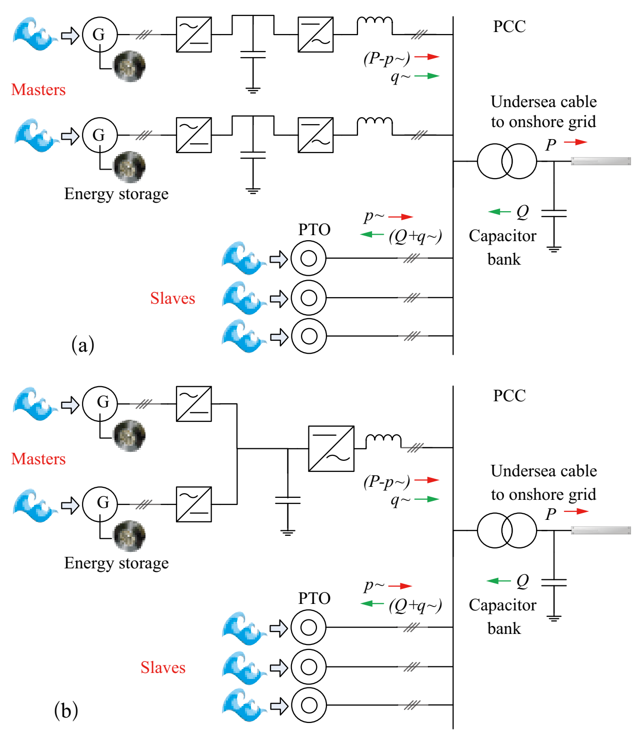


Fig. 2 Overview of master-slave wave farm system for (a) each master with converters, and (b) multiple masters with a common DC link

2.2 Masters

Masters are wave power generators that deliver controlled power to the PCC. The difference between the power delivered to the PCC and the wave power captured is balanced by the energy buffer, which in this study was implemented by the rotor inertia of the masters. Flywheels can be added to rotors to increase the energy storage capacity depending on the magnitude of the master inertia and the capacity ratio between masters and slaves. Compared with other energy buffers, the rotor inertia of masters have the following advantages: (1) long cycle-life (in contrast, considering that the typical period of an ocean wave is short (5–12 s), a battery with the same storage capacity could be worn out in days); (2) high energy density and compact design; and (3) the power is smoothed from the stator of machines, and thus no device needs to be overrated. The power from masters could be transmitted to the PCC through either independent converters or a DC microgrid. In both cases, power flow is controlled by the machine side rectifiers and the DC voltage is maintained by the grid side inverter(s).

The proposed master-slave system has the following two features. Firstly, the master is only compatible with rotating machines. Secondly, for OWC, there are requirements on the rotor speed of machines for maximum PTO efficiency, which conflict with the requirements of energy storage. However, this can be solved by setting the rated speed at an optimal point, with the real-time speed varying up and down around this point at a small cost of efficiency loss. This has been demonstrated by a number of studies [25, 26].

2.3 System operations and engineering feasibility

The total power output is smoothed by controlling the energy buffers of masters. Slaves deliver all of the wave power they harvest to the PCC while masters only deliver controlled power to keep the total power output tracking a smoothed reference given by the wave farm control. In a case when slaves consume variant reactive power Q due to the periodic wave drive, the master power converters are in charge of the dynamic Q compensation, while the capacitor bank on the PCC covers the fixed major part of the reactive power. Compared with previous studies in which every PTO device requires a power converter, the proposed system allows a few of the master converters to improve the power quality of the whole system with a vast number of slaves. It reduces the total installation and maintenance cost.

The engineering feasibility of the rotor flywheel is demonstrated below. The rotor inertia must be large enough to hold temporally stored energy within a reasonable range of speed variations; meanwhile, it must be small enough to be size-feasible and cost effective. For the given maximum, minimum, and rated mechanical speeds of master rotors $\omega_{\max}$, $\omega_{\min}$, ω_{rat}, and given the required energy storage capacity E_0, the rotor inertia I must be larger than:

$$I > \max\left\{\frac{2E_0}{(\omega_{\max}^2-\omega_{\text{rat}}^2)}, \frac{2E_0}{(\omega_{\text{rat}}^2-\omega_{\min}^2)}\right\} \tag{1}$$

The required inertia of the PTO is usually small enough in engineering practice that it can be provided by the rotor with a coupled flywheel in a reasonable size. In this study, each wave power generator was rated at 350 kW, which is about the same order of that in the existing projects [2]. We demonstrated the stability of a 2.8 MW, 2M6S (with two masters and six slaves) system with master rotor inertias of 300 kg·m^2. For comparison, the rotor inertia of a 350 kW generator is 86.6 kg·m^2 [27]; thus, only an extra rotor flywheel with an inertia of 213.4 kg·m^2 is needed. For a cylinder shape flywheel, its inertia can be derived as:

$$I_{\text{flywheel}} = \frac{1}{2}\pi\rho h R^4 \tag{2}$$

where ρ is the material density, h the thickness, and R is the radius. The inertia can effectively be made big enough by enlarging the radius. In this case, a solid steel (ρ=8.0 g/cm^3) flywheel with h=0.5 m and R=0.43 m is required, which is size-feasible for installation in most of existing WECs.

Based on this topology, a larger wave farm with higher installed capacity could be achieved by increasing masters and slaves proportionally.

3 Converter and system control

The objectives of the converter control and the system control in a wave farm system are different. The former is to make the voltage, current, and power provided by the converters track the given references; the latter is to determine these references at a system level. We considered two different reactive power controls of the converters based on state-of-the-art *dq* decoupling [25], and two system control methods, namely the moving average filter (MAF) and the energy filter (EF).

3.1 Converter controls

The converter control can be separated in four items depending on which side and which axis it is on:

- ***Grid side d-axis control:*** This is to balance the input and output power of the back-to-back converter by stabilizing the DC link voltage.
- ***Grid side q-axis control:*** This is to control the grid side reactive power according to the local voltage or power factor requirement.
- ***PTO side q-axis control:*** This is to control the electric torque and consequently the power from/to the machine.
- ***PTO side d-axis control:*** This is to control the excitation mode of the machine. In this study, the minimum current mode was selected by referring the d-axis current to zero.

At the grid side, the q-axis controls the reactive power Q and usually there are two strategies. One is to keep a constant power factor, which in a popular case is unity. However, with this strategy the wave farm is not able to stabilize the PCC voltage when the real power changes. Another strategy is to keep the PCC voltage constant, which requires a larger converter capacity.

In this study, unity power factor control was adopted. Generally, when a relatively small-scale power source is connected to a PCC with other units, it is asked to give a constant power factor and the PCC voltage is regulated by other devices, such as a STATCOM or large-scale synchronous generators.

3.2 System control #1: Moving average filter

The system controller generates an appropriate reference of the total power output of the wave farm, which is allocated to master converters as their inputs.

The key question is how to ensure this reference to track the average total harvested wave power; otherwise, the average storage level will keep going up or down until the system breaks. Over the long-term, a wave farm should deliver the average of the power that it absorbs from the wave P_{avg} to the grid, and leave the power fluctuation in the buffers. One idea is to use MAF (Fig. 3), which is a data processor that calculates the average of a sampled time series within a fixed-length moving window [24]. An MAF process is determined by two parameters: the sampling frequency, and the length of the moving window.

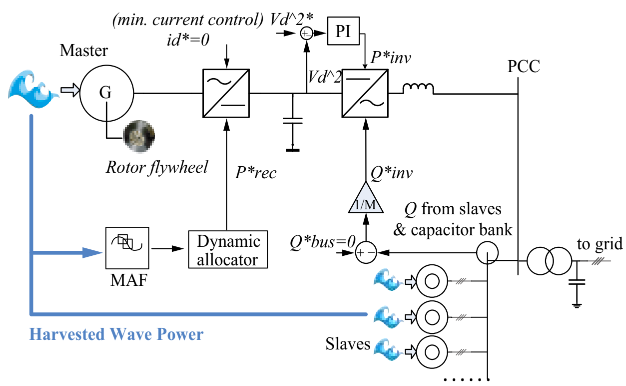


Fig. 3 System control based on a moving average filter (MAF)

Accordingly, this method needs to measure the total harvested wave power on the primary side of the wave farm. For slaves, this can be done by measuring the generated electric power with the reasonable assumption that it is the same as the mechanical power from the wave. This is desirable because the electrical power measurement is much easier and cheaper than the mechanical one. However, for masters, the mechanical power measurement on the primary side is inevitable, representing is a severe drawback of this method.

Since the slaves generate fluctuating power P_{slv}, the masters are controlled to generate the difference $P_{mst} = P_{avg} - P_{slv}$, which is dynamically allocated among all of the masters. The allocation follows the principle that those masters with higher storage levels take a greater share, which can be expressed as:

$$P_{mst,i} = \frac{\omega_i^2}{\sum_{i=1}^{M} \omega_i^2} \cdot P_{mst} \quad (3)$$

where $P_{\text{mst},i}$ is the real power reference for the i^{th} master, ω_i is the rotor speed of the i^{th} master, and M is the total number of masters.

3.3 System control #2: Energy filter

The MAF method suffers because it has to measure the mechanical power on every master machine, which is difficult to be implemented in an offshore environment; therefore, we propose an alternative system control method, the EF approach.

Fig. 4 shows the power flow through the proposed master-slave system in per unit value, where P_{in} is the total harvested wave power, P_{bus} is the total output power, $H\frac{d}{dt}\sum\omega_i^2$ represents the rotating kinetic power stored by the master rotors, and H is the inertia constant of the master rotors.

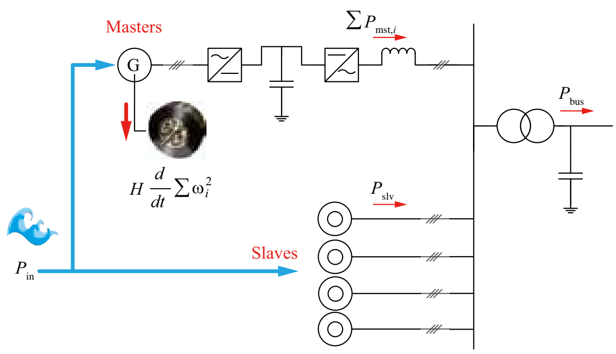


Fig. 4 Power flow through the proposed master-slave system

By ignoring the power loss, we have:

$$P_{\text{in}} = H\frac{d}{dt}\sum\omega_i^2 + P_{\text{bus}} \tag{4}$$

For the system level control, it is reasonable to assume an immediate tracking of the power reference by the converter control. With this assumption, we defined the total power output P_{bus} to be controlled as (in per unit):

$$P_{\text{bus}} = P_{\text{bus}}^{\text{ref}} = \frac{H}{T}\sum\left(\omega_i^2 - \omega_0^2\right) + P_0 \tag{5}$$

where T is the time constant, and ω_0 and P_0 the rated master rotor speed and rated total power output, respectively. With this, Eq. (4) can be re-written as:

$$P_{\text{in}} = T\frac{d}{dt}P_{\text{bus}} + P_{\text{bus}} \tag{6}$$

or in the s-domain as:

$$\frac{P_{\text{bus}}}{P_{\text{in}}} = \frac{1}{Ts+1} \tag{7}$$

It has the form of a 1st-order lowpass filter (LPF). Thus, the proposed system behaves like an LPF of the power flow. It smoothies the power output with a controllable time constant T. The control laws of the total power output given by Eq. (5) is a family of straight lines through the rated operating point ($\sum\omega_0^2, P_0$) with a slope of H/T, as shown in Fig. 5.

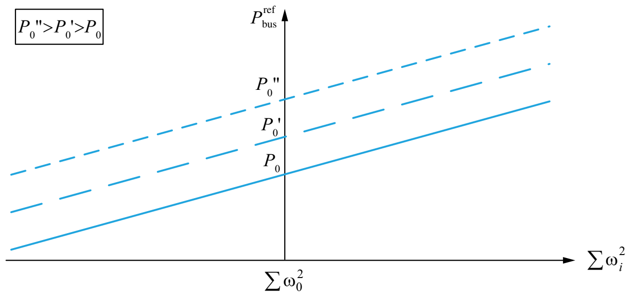


Fig. 5 Control laws of energy filters as a family of straight lines

Eq. (5) defines the control law of the total power output of the system, which is allocated to all masters as:

$$P_{\text{mst},i} = \frac{\omega_i^2}{\sum_{i=1}^{M}\omega_i^2}\cdot\left(P_{\text{bus}}^{\text{ref}} - P_{\text{slv}}\right) \tag{8}$$

The complete control system is shown in Fig. 6.

In contrast with the MAF method, EF enjoys does not need to measure the mechanical power, but only needs to measure the master rotor speeds and the electrical power outputs of the slaves, both of which can be easily obtained.

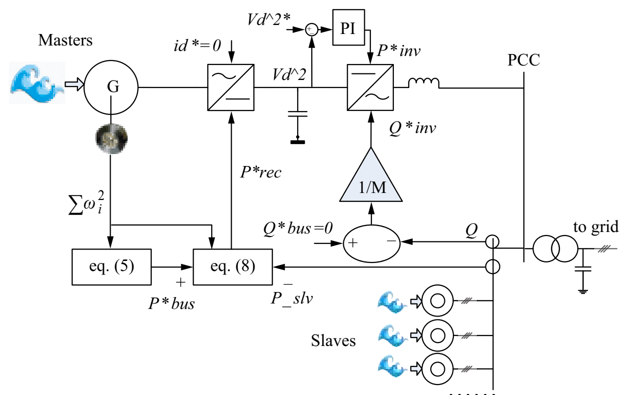


Fig. 6 System control based on the energy filter (EF)

3.4 Rotor speed sensitivity

Eq. (5) and Eq. (8) together determine the power control of each master. For the measured rotor speed and inertia, system performances under this control law are dependent on two control parameters: the time constant T and the rated total output power P_0. P_0 is a constant obtained according to the local wave power profile, and could also be a piece-wise constant changing on a sea-state-to-sea-state basis.

The selection of T is a trade-off between the power smoothing effect and the sensitivity of the rotor speed. From Eq. (5), the sensitivity of the rotor speed is defined as:

$$\frac{d\sum \omega_i^2}{dP_{\text{bus}}} = \frac{T}{H} \tag{9}$$

Eq. (9) describes how much the master rotor speeds will deviate from their rated values when the total power output of the wave farm changes. Accordingly, T must be large enough to achieve a good power smoothing effect, yet small enough to avoid a too large sensitivity of the rotor speed. Large rotor inertia is also helpful for suppressing the sensitivity.

4 Case studies

A 2M6S wave farm system based on independent converters was built and simulated on RTDS. The model consists of OWC wave generators, master converters, a transformer, the capacitor bank, undersea cable, and the local grid (Fig. 2). The undersea cable parameters refer to the real project Wave Hub in the UK [4]. The local grid is modeled as an infinite voltage source with a short-circuit ratio (SCR) of 10.0. A group of sinusoidal mechanical torques with different frequencies and magnitudes are applied to the generators to model the interactions between the devices and the wave under regular sea conditions. The frequencies are selected within a typical range of the wave period.

The 300-s real-time simulation results are presented in Fig. 7–9 and consist provide insights into: (1) the starting process, (2) operations under the rated input wave power (regular wave), and (3) operations under an increased input wave power with the same control parameters (strong wave). Finally, we performed a quantitative analysis on the selection of time constant T.

4.1 Moving average filter

The sampling frequency and length of the moving window for the MAF process were 10 Hz and 12 s, respectively. Fig. 7(a) shows the input wave power and the total output electrical power of the wave farm system over 300 s. The total output power was smoothed when the input wave power fluctuated, and the grid side reactive power was controlled to be zero. After 150 s, when the input wave power increased the system output power was able to track the average of the input power.

Fig. 8(a) presents the per unit rotor speed of one master machine in the system, which varied with time to store and release energy. The rotor flywheels of the master machines work as the energy buffers of the wave farm system.

Fig. 9(a) shows the real and reactive power on the grid side inverter of this master machine, which is time changing to compensate for the fluctuating power from the slaves. In particular, its real power could become negative when the master machine was operated as a motor to absorb the peak power from the slaves. The average Q approached zero since the capacitor bank was dimensioned to minimize the apparent power of the inverter.

4.2 Energy filter

EF control was performed under the same other operating conditions. The system operations are presented in Fig. 7(b), Fig. 8(b) and Fig. 9(b) in comparison with those of MAF. The time constant T was 12 s with the same length of moving window as used in the MAF method.

The results confirm the capabilities of power smoothing and unity power factor control for EF. Conclusively, EF has similar control characteristics as MAF, but avoids the mechanical power measurements for the master machines.

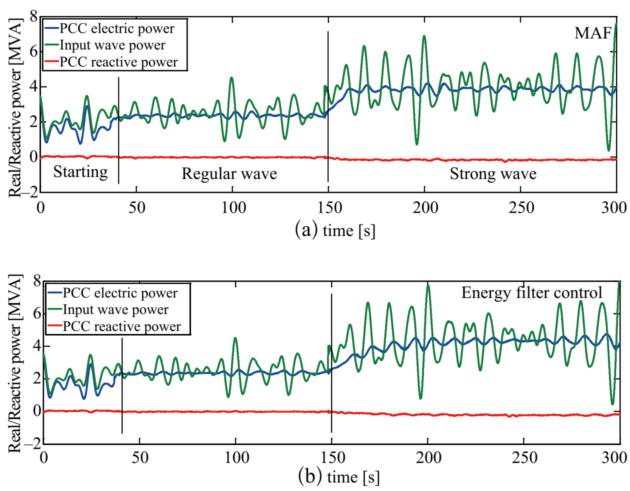


Fig. 7 Input wave power and total output of real and reactive power (*P*&*Q*) for the system under (a) moving average filter (MAF) control and (b) energy filter (EF) control

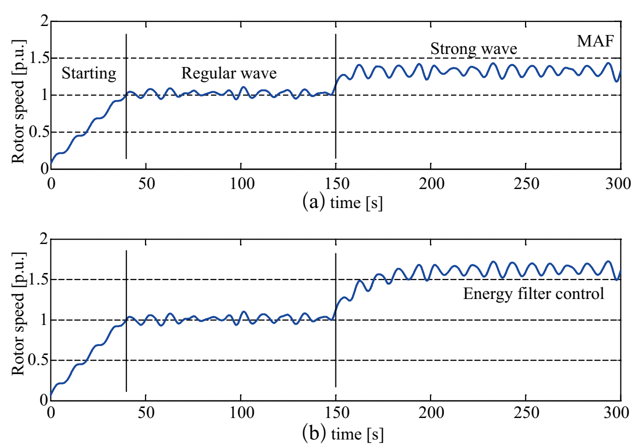


Fig. 8 Per-unit rotor speed of master machine #1 under (a) moving average filter (MAF) control and (b) energy filter (EF) control

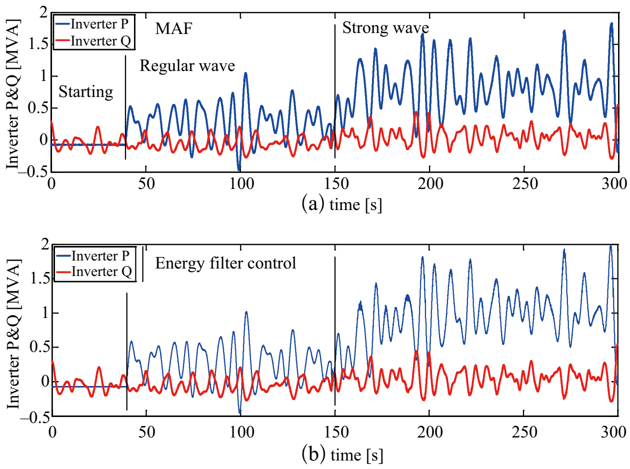


Fig. 9 Real and reactive power from master inverter #1 to the point of common coupling (PCC) under (a) moving average filter (MAF) control and (b) energy filter (EF) control

Table 1 presents a quantitative comparison between the two controls. Given the randomness in the frequencies and phases of the driving torques, there was a marginal difference between the average input powers under the two controls. The power smoothing capability of the proposed system was quantified by the index σ, which is defined as the ratio between the standard deviations of the harvested wave power and that of the total output power. Accordingly, both control methods significantly reduced the standard deviation of the power flow; however, the energy filter was better than the MAF, having a larger σ and a better power smoothing capability.

4.3 Determining the master-slave ratio

When PTO devices of master machines are OWCs, conventionally, rotor speeds must follow MPPT control to maximize the power capture. When EF control is used to smooth the output power of the wave farm by manipulating the rotor speeds of masters, the rotor speeds go away from the optimum points set by the MPPT control. This leads to a loss of MPPT efficiency, as presented in Fig. 10. The MPPT efficiency η_{mppt} is the ratio of the total output energy of the wave farm over 300 s under EF control over that

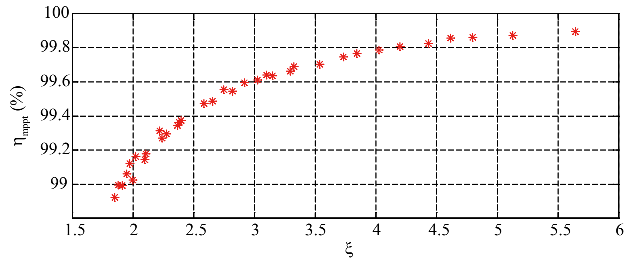


Fig. 10 MPPT efficiency loss of oscillating wave column (OWC) wave power generation under energy filter (EF) control

under MPPT control. The master-slave ratio ξ is defined as the installed capacity ratio of masters over slaves. Here, the MPPT efficiency loss was less than 1% as long as $\xi > 20$.

4.4 Time constant selection for EF control

In order to study how the selection of the time constant under EF control affects the power smoothing capability and the rotor speed sensitivity, simulations were conducted with different values of *T*. Referring to (6.5) and (6.9), in these simulations, the average input wave power was set to 10%, 20%, or 30% larger than the rated total power output *P* in the control law. This mismatch in P_0 for the control law and the actual average input wave power is called the power error, for which the average master rotor speed deviated from 1.0 p.u. and the speed bias depends on the rotor speed sensitivity *T/H*. With a given power error, for each value of *T*, statistical data were collected and averaged from 3 periods of 120 s steady state operation; $H=21.15$.

The simulation results for the actual data and their linear regression are presented in Fig. 11. We found a positive and almost linear correlation between the time constant and both the smoothing effect and the speed sensitivity. As has been discussed, a larger time constant of the system controller leads to both better power smoothing capability and larger speed bias of the master rotors. The selection of *T* would be a trade-off between these two variables according to a quantitative analysis, as given in Fig. 11. For example, when the estimated power error is under 30% and the maximum allowed average rotor speed is 1.2 per unit, the maximum *T* would be 9.

Table 1 Arrangement of channels

Control method	avg. *Pin*	avg. *Pbus*	SD. *Pin*	SD. *Pbus*	η	σ	SD. ω
MAF	2.418	2.379	0.6711	0.0855	98.40%	7.849	0.0708
EF	2.330	2.286	0.6905	0.0800	98.10%	8.631	0.0379

* *Pin* the input wave power (MW); *Pbus* the total output power on the PCC (MW); ω the per unit speed of #1 master rotor.
* avg. stands for the average value; SD. stands for the standard deviation.
* η is the wave farm system efficiency, which is the ratio of avg. *Pbus* over avg. *Pin*.
* σ is the index of the power smoothing capability, which is the ratio of SD. *Pin* over SD. *Pbus*.

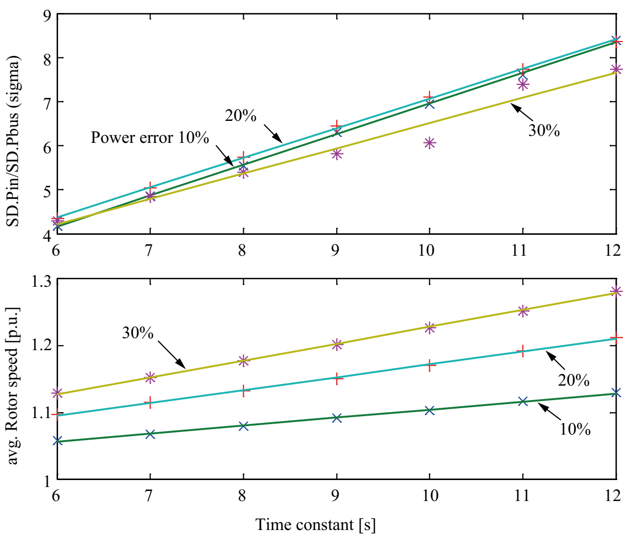


Fig. 11 Power smoothing capacity of the system assessed by sigma σ and the speed bias under different values of *T* and power error

5 Conclusion

In this study, we developed a master-slave wave farm with rotor inertia energy storage to facilitate large-scale exploitation of wave energy. Two control methods were developed. The proposed system and controls are able to deliver smoothed active power to the grid and actively control the power factor at PCC. The master-slave structure reduces the number of power converters. Comparatively, our new wave farm system requires no extra energy storage, but instead uses the rotor inertia of its own generators to achieve short-term energy storage. Another advantage is that the power flow is smoothed directly from the output of electric machines. To make the total output power of wave farms track the average of the total captured wave power, two system control methods were proposed and compared. The moving average filter (MAF) method, whose power smoothing effect represents the standard to be compared with, suffers because of a need for mechanical power measurements. In contrast, EF control does not require mechanical measurements and only needs to measure the rotor speed of master machines and the electrical power output of slaves, both of which can be easily obtained. The proposed wave farm system was simulated on RTDS; time domain simulations and quantitative analysis have confirmed the control methods.

Acknowledgements

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Biographies

Zuanhong Yan received his bachelor degree from Huazhong University of Science and Technology, Wuhan, China and the University of Birmingham, Birmingham, UK both in 2012, master degree from University of Manchester, Manchester, UK in 2013, and Ph.D. degree from University of Birmingham, Birmingham, UK in 2018. He is now a research fellow with Electric Power Research Institute, CSG, China. His research interests include renewable energy conversion & integration, wind/wave farm systems, and energy storage control.

Xiao-Ping Zhang (M'95-SM'06) is currently Professor of Electrical Power Systems at the University of Birmingham, UK. He is also Director of Smart Grid, Birmingham Energy Institute and Co-Director of Birmingham Energy Storage Centre. He received the bachelor, master and Ph.D. degrees in Electrical Engineering from Southeast University, China in 1988, 1990, 1993, respectively. He is co-author of the 1st and 2nd edition of the monograph "*Flexible AC Transmission Systems: Modeling and Control*", published by Springer in 2006, 2012, respectively, and co-author of the book "*Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models*", published by IEEE Press/Wiley in 2010.

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