Development of OIST Wave Energy Converter Monitoring System for Maldives Island Experiment

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Abstract: This paper describes experiments with our self-built Wave Energy Converter (WEC) monitoring system in the Maldives and demonstrates how we developed a horizontal-axis type, half-scale, wave energy converter (WEC) that generates electricity in the coastal breaking wave zone. In order to measure this power generator and turbine’s efficiency, voltage and current were measured by pulling the generator with a 35 cm diameter turbine (half scale). We obtained data showing 400 W peak power in water speed of 3.1 m/s. Consequently, we assembled two sets of WEC, placed them near the shoreline on Kandooma Island in the Maldives in May 2018, and measured the wave energy at the breaking wave zone. A monitoring system was set up in one rack for the two sets of WECs, connected simultaneously. Two outputs of the generators were rectified and connected to power resistors and internal LED displays. The outputs could also be switched to connect to 24 electric double layer capacitors (EDLC), in order to perform a continuous lighting test of external high-power LED lights. The wave power data were continuously saved by an automated data logger and could be transferred from the installation site, to Japan via the Internet. The wave power was measured on Kandooma Island in the Maldives for a long period, and is still ongoing. Examples of the obtained data are shown in this paper.

Key words: Generator, WEC, wave energy converter, breaking wave, turbine, sustainable energy, EDLC, super-capacitor, Maldives, OIST, Internet remote monitoring.

1. Introduction

While wave or tidal energy technology is being heavily researched [1-3], we believe that energy harvesting from breaking waves is also very important and deserves research attention [4, 5]. For generation of electricity in the coastal breaking wave zone, we begin by briefly reporting on some initial preparatory measurements that we carried out near our home institute in Japan. Specifically, we measured water speeds near the breaking wave zone in Okinawa, Japan, using ADCPs and electro-magnet water speed meters in Autumn 2016 and Summer 2017 [6]. In those measurements, we found a calculated water speed at the breaking zone (above the S2 ADCP) as seen in Fig. 1. These prior studies were too short to get sufficient data in order to measure and understand the water behaviors in larger waves. Also, we had intended to measure water speeds near the breaking wave zone, using H-ADCP (horizontal and narrow beam angle ADCP) in Seragaki, Okinawa, 2017. Nevertheless, there were some difficulties regarding the cabling system for water-speed measuring devices, connected from the land for long periods, and compounded by the difficult typhoon season in southern Japan.

In 2017, the Maldives government and Kokyo-Tatemono Co. Ltd. offered us the possibility of doing a WEC experiment in the Maldives1. The Maldives is an excellent location for WEC experiments, as there are usually no typhoons nor other extreme weather conditions, and medium scale waves come continuously almost all the year. Around that time, we had developed a horizontal-axis type half-scale waterproof WEC that generates electricity in the coastal breaking wave zone. So, we decided to

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1 Kokyo Tatemono Company Limited (Kokyo) supports this work of OIST, and its experiment shall be performed in collaboration with Ministry of Environment & Energy (MEE) of the Government of the Republic of Maldives under MOU agreed by and among MEE, OIST and Kokyo.
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Fig. 1 Cross-sectional view of ADCP positions and seabed depth along the ADCP transect at Seragaki shore in Okinawa, Japan. Depths of the ADCPs were 40 m, 30 m, 20 m, 4 m and 5 m for S4, S3, M, S2, and S1, respectively.

Fig. 2 Water flow measurement of the half-scale turbine in Nagasaki.

Fig. 3 $C_p$ vs. tip speed ratio $\lambda$ of the half-scale turbine. Data at 2.85 m/s exceeded the water tank flow specification for valid measurement.

use the horizontal-axis turbine type generator as a water speed meter for measurements in the Maldives.

Previously, we had also measured the half-scale turbine performance at the West Japan Fluid Engineering Laboratory (Fig. 2) in February 2017.

The obtained power coefficients ($C_p$), versus the tip speed ratio ($\lambda$), at water speeds in the range 1-2.85 m/s, are shown in Fig. 3. According to the water tank flow specification, measurements were valid up to 2.7 m/s for this turbine diameter.

Also, we have performed a turbine-generator combined test, carried out with different load resistors by pulling boat-side, described in Section 2.

2. Boat Side Calibration

In order to measure this power generator’s performance, voltage, current and rotation speed were measured in October 2017 by pulling the generator and 35 cm diameter half-scale turbine and a water speed current meter (Fig. 4) beside a boat (Fig. 5).

Drag force was also measured by a load cell combined with a pulling rope attached to the neck of the generator’s supporting bar. We obtained data showing 400 W peak power in a water speed of 3.1 m/s, using a local power monitor box (Fig. 6).

Fig. 7 shows obtained output power in 3 types of power consumption resistors (7.4, 16.5, 32 $\Omega$) as a function of water speed (1.2-3.7 m/s).

Fig. 8 shows measured rotation speed in 4 types of power consumption resistors (7.4, 16.5, 32, > 51 $\Omega$) as

Fig. 4 A half-scale generator with 35 cm diameter turbine (left figure), and water speed meter (right figure) set beside the boat.
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Fig. 5  Configuration of the WEC, support bar and turbine type water speed meter on a diving boat. The drag force of the WEC was measured by a load cell.

Fig. 6  Generator output was connected to a power monitor box, which has a three-phase rectifier and resistors (cooled by an aluminium heat sink plate). AC voltage, current, DC voltage and DCCT-probe are measured by 4 ch isolated inputs oscilloscope. Also we can directly see the power by the lighting up of the LED bar lights.

Fig. 7  The half-scale generator output power as a function of water speed was measured, in a boat-side experiment. An electrical power output of 400 W was measured at 3.1 m/s. The red and blue lines show fitting curves for 32 Ω and 16.5 Ω data, respectively.

3. Configuration for Maldives Experiment

We prepared to install the WEC and monitoring system on Kandooma Island in the Maldives (Fig. 9). We subsequently assembled two sets of half scale WECs (Fig. 10), as described in the previous section, with supports as shown in Fig. 11, at the breaking wave zone, facing southeast towards the Indian Ocean, in May 2018.

A connection diagram of the two WECs, cable connection box and WEC monitoring system rack (located in next to the power plant house) are shown in Fig. 12. A metal corrugated power cable (65 m long, 3-phase, 3.5 mm² each) was laid on the sea bottom between the WECs and the connection box (near the beach). This box has three-phase lines breaker circuits and terminals. It can be connected temporarily with a local monitor box and oscilloscope or LEDs. The same corrugate cable (200 m-length) is used between this connection box and the WEC monitoring system rack at the power plant house.
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Fig. 9  WEC experiment site on Kandooma Island in the Maldives. Two sets of the generators and supports were set in breaking zone. Two sets of 300 m length (3.5 mm², 3-lines, metal corrugate) power cables were connected to a power monitoring system, beside the power plant facility of the nearby hotel.

Fig. 10  Two sets of WEC (1.3~1.6 kW peak power) unit with 5-blades high-tensioned aluminum alloy turbine.

Fig. 11  The half-scale generator support and socket. The heights of the WEC1 and WEC2 are 1.5 m and 1.0 m, respectively. And 100 mm diameter socket is fixed into coral reef rock (of 400 mm depth hole) by epoxy cement.

Fig. 12  Connection diagram of the WEC, the cable connection box (on beach-side) and the WEC monitoring system rack beside the island’s generator plant house on Kandooma Island in the Maldives.

4. Monitoring System Design

As already mentioned, the two generators of the half scale WEC are connected to a remote monitoring system. Both outputs of the generators are rectified and connected to series-resistors and internal LED displays (Fig. 13). Also they can be switched to a voltage limiter (< 55 V) circuit and electric charge bank in order to perform a continuous lighting test of external LED lights. The power output from both WECs can be connected to one EDLC (Electric Double Layer Capacitor) circuit simultaneously. They were installed in one rack (EIA, 150 cm height, Fig. 14).

Twenty-four sets of EDLCs, were connected in series. Each EDLC is 40 F, 2.7 V, and there is a 5.1 V protection Zener diode for every three EDLCs, as shown in Fig. 15, lower-right. Twenty-four sets of capacitors (each 40 F) in series result in a total capacitance of 1.7 F, and the total voltage of the Zener diodes is 61.2 V (but we limit to 55 V to protect the external LED-lights). The power of the generator (peak: 1.3~1.6 kW, duty: 1.5~3 sec, period: 7~10 sec) is smoothed by these capacitors.

The generator output, AC voltage, DC voltage, DC current, leakage current of the generator coils and cables, and temperature are monitored continuously by an automated data logger (HIOKI; 2300 and Windows PC) and transferred to our home institute (OIST, Japan), via the Internet, for analysis.
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Fig. 13  Block diagram of the two channel WECs monitoring system. Two outputs of the generators are rectified and connected to power resistors and internal LED displays. Also they can be switched to a voltage limiter circuit (55 V), 24 electric double layer capacitors (EDLC) in serial connection (each 40 F, 2.7 V with protection Zener diodes) in order to perform a continuous lighting test of external high-power LED lights. External output can be connected to a DC-DC converter and/or DC/AC converter instead of the high-power external LEDs in future.

Fig. 14  WEC monitoring system EIA rack (60 cm width, 70 cm depth, 150 cm height). Two channel WEC input powers, voltage, and current values are displayed on the front panel. Leakage currents of the generator coils and cables are also indicated. LED bar lights are adopted for demonstration.

The system monitors not only output DC voltage and current, but also AC voltage waveform of the generator’s output (using HIOKI Waveform Module: 2321, 400 kHz-max sampling). Then we can measure the precise rotation speed of the turbine with a generator of 20 poles permanent magnets.

In preparation for the Maldives experiment, data were already measured at the generator manufacturing company (Ichinomiya Denki), and at the OIST campus. To simulate the wave power time structure, the generator was rotated directly by an external motor. The charged voltage and current to the EDLCs and

Fig. 15  Twenty-four electric double layer capacitors (each 40 F, 2.7 V and protecting 5.1 V Zener diodes for every three EDLCs) are connected in series. Total capacitance is 1.7 F and total voltage of the EDLCs and Zener diode is 61.2 V.
Fig. 16 Generated AC voltage (green), DC current (red) and charged DC voltage (blue) on EDLCs (electric double layer capacitor) were measured as a function of time. The rotation of the generator was directly coupled by a motor as a simulation of wave power. Neither the series resistors nor the 55 V voltage limiter circuit was installed at this time. The LED power consumption was 0.1–48 W (0.03–1 A, 38–48 V).

LEDs of the monitor system were measured. Fig. 16 shows the generated AC voltage (green), DC current (red) and charged DC voltage (blue) of the EDLCs as a function of time (neither the series resistors nor the 55 V voltage limiter circuit was installed at this time). After 55 seconds from the start (capacitor charge zero), the charged voltage exceeds 40 V, and while the generator’s rotation was stopped, all LEDs were turned on continuously by means of the charged electricity from the capacitor.

At $t = 1.9$ s, the DC voltage was 36.5 V and the DC current was 5.6 A, and the impedance was calculated to be 6.5 $\Omega$. At $t = 50.8$ s, the DC voltage was 57.9 V and the DC current was 3.9 A, then the impedance was calculated to be 14.8 $\Omega$. At $t = 80.4$ s, the DC voltage was 66.4 V and the DC current was 3.9 A, then the impedance was calculated to be 16.8 $\Omega$. The DC voltage is 1.22 times the AC voltage. In the factory, the rotation speed was 250–300 rpm. However, if input impedance was too low at the beginning of charging capacity, the turbine may stall as seen in Figs. 7 and 8. Therefore, we should put serial resistor of 5 $\Omega$ or more.

5. Maldives Experiment

We assembled WEC supports and generators at the Kandooma Island in the Maldives on 8th May 2018. Fig. 17 shows WEC1 rotating in the water, driven by the wave power. Before connecting the WECs to the WEC monitoring system rack, we took prior measurements using a local measuring box at the connection box near the seaside beach where we can see waves coming to both WECs.

Fig. 18 shows heights of two WECs on the seabed for WECs prior setting. Initially, WEC1 (height = 1.5 m) and WEC2 (height = 1.0 m) were set 10 m apart (distance along wave propagate direction) on the first two days (on 8th and 9th May 2018). The time difference between the WEC1 and WEC2 peak output voltages is 2.8 s, as seen in Fig. 19, which corresponds to a wave traveling speed of 3.6 m/s. The repetition period was also found to be 9.8 s on that day.

After this initial wave traveling speed measurement, we subsequently moved WEC2 to a slightly deeper point (actually to the same depth as WEC1, see Figs. 20 and 21).

Now we are getting a continuous stream of useful data via the Internet and are analysing. Fig. 22 shows
Fig. 19  Time difference of WEC1 and WEC2 output voltages is 2.8 s, so that we found the wave travelling speed 3.6 m/s.

Fig. 20  Final height configuration of two WECs after the preliminary wave propagation speed measurement, previously shown in Figs. 18 and 19. They were set at the same depth on 9th May 2018.

Fig. 21  WEC supports and generators were assembled at the Kandooma Island in the Maldives on 9th May 2018.

Fig. 22  Example of WEC monitoring display (remote desktop). For both WEC1 and WEC2, AC peak voltage histogram, instantaneous DC voltage, DC current, temperature and leak current detector voltage are updated every second. AC voltage waveform (1 ms sample) is also indicated for 15 s when the voltage exceeds 300 V. Fig. 23 shows an example of the WEC1 AC voltage waveform. On 14th June, 2018, at $t = 0.09$–$0.12$ s (14:24:47 data), the output AC voltage was 512 V (peak).

Fig. 24 shows a magnified view of the output AC voltage (512 V peak) at $t = 0.09$–$0.12$ s of the data of Fig. 23. The frequency is 232 Hz (23.2 rps due to the 20-pole magnet rotor) so that 1,392 rpm was calculated for the turbine rotation speed. Figs. 25 and
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Fig. 23  WEC1 AC peak voltage waveform vs. time(s) at 14:24:47 on 14 June, 2018. At time $t = 0.09$–$0.12$ s, the output AC voltage was 512 V (peak).

Fig. 24  Magnified for time(s) output AC voltage (512 V peak) at $t = 0.09$–$0.12$ s of the data of Fig. 23. The frequency is 232 Hz.

Fig. 25  WEC1 AC voltage data are plotted on pre-measured characteristics of the half-scale generator and turbine. A maximum AC peak voltage (512 V) was found at the spring tide on 14 June, 2018.

Fig. 26  WEC1 rotation speed data are plotted using pre-measured characteristics of the half-scale generator and turbine as seen in Fig. 7. A maximum rotation speed 1,392 rpm corresponds to water speed of 9 m/s.

Fig. 27  WEC1 (red) and WEC2 (green) output peak AC-voltages are plotted in 1-s intervals for 24 hours in spring tide on 14 June 2018. The difference level between high and low tide is about 0.8 m.

Fig. 28  WEC1 (red) and WEC2 (green) output peak AC-voltages are plotted in 1-s intervals for 24 hours in neap tide on 21st June 2018. The difference level between high and low tide is about 0.3 m.

Fig. 29 and 30 show an RMS of the WEC1 (red) and WEC2 (green) output AC-voltage, in 1-s intervals for 24 hours, during the spring tides on 14th and 21st June 2018. It is about 40–48% of the peak value.

The peak AC voltage and RMS (Root Mean Square) voltage of WEC1 and WEC2 are measured by the data logger’s instantaneous module in every 1 s and accumulated for 24 hours each day. Fig. 27 shows WEC1 (red) and WEC2 (green) output peak AC-voltages, every 1 s for 24 hours, in spring-tide on 14th June 2018. The difference level between high and low tide is about 0.8 m in spring tide.

Fig. 28 shows those in neap tide on 21st June 2018. The difference level between high and low tide is about 0.3 m in neap tide.

Root mean square (RMS) AC voltage could mean an effective index for wave energy. Figs. 29 and 30 show an RMS of the WEC1 (red) and WEC2 (green) output AC-voltage, in 1-s intervals for 24 hours, during the spring tides on 14th and 21st June 2018. It is about 40–48% of the peak value.
Fig. 28 WEC1 (red) and WEC2 (green) output peak AC-voltages are plotted in 1-s intervals for 24 hours during the neap tide on 21 June 2018. The difference level between high and low tide is about 0.3 m.

Fig. 29 WEC1 (red) and WEC2 (green) RMS of the AC-voltages, are plotted in 1-s intervals for 24 hours, during the spring tide on 14 June 2018.

Fig. 30 WEC1 (red) and WEC2 (green) RMS of the AC-voltages are plotted in 1-s intervals for 24 hours, during the neap tide on 21 June 2018.

Fig. 31 The maximum (upper) and RMS (lower) water speed of WEC1 (red) and WEC2 (blue) are plotted for 12 hours on afternoon of 14 June 2018, during spring tide, respectively.

The water velocity can be estimated by using turbine characteristics, measured in advance. Fig. 31 shows WEC1 (red) and WEC2 (blue) of the maximum and RMS water speed during spring tide on the afternoon of 14th June 2018. These are calculated from the maximum voltage (Fig. 27) and RMS voltage (Fig. 28) by using the WEC performance factor even if it includes some error bar (see Fig. 25).

6. Conclusion

We had intended to measure water speeds near the breaking wave zone, using H-ADCP (horizontal and narrow beam angle ADCP) in Seragaki, Okinawa, 2017. However, there were many bubbles after the breaking wave, so the ADCP could only successfully measure before the breaking zone. Therefore, we decided to use horizontal axis turbine type generator as a water speed meter. Fortunately, we were developing a half-scaled waterproof generator with a 35 cm-diameter turbine. Before installing them into the sea, for calibrations of the turbine and the generator characteristics, we performed measurements
by pulling beside a boat in the sea with water speed meter.

The WEC monitoring system for Maldives experiments is designed not only for measurement of output DC voltage and current, but also AC voltage waveform supplied from the generator’s stator windings in order to know precise rotation speeds and the performance. We successfully installed two WECs and monitoring system in May 2018, with getting data via the Internet. On 14th June in a spring tide, we found maximum voltage 512 V (AC) and a rotation speed of the turbine 1,390 rpm. The water speed was estimated as 9 m/s. So, it might be performed by wave top falling water at breaking wave just hit the turbine. It can be seen in a water speed simulation “REEF3D” [7] for a breaking wave in a shallow zone (slope = 1/10, wave height = 1.5 m, wave length = 44 m, period = 7.5 s, still water level = 3.8 m). Also RMS voltages 100~200 V of generator’s AC voltage are found on the same day which could be effective values of wave energy. Regarding to the data in spring tide and neap tide, the turbine and generators positions (height and distance from the leaf edge) are also being optimized. Only some initial examples of the monitoring wave data are shown in this paper. We now continue to do measurement and data analysis.

Acknowledgments

Authors express our deep gratitude to Onna-son Fishing Association and Seragaki port staff (Yasufumi Matsuda). We also thank the machine shop staffs at OIST, AIDEN Co. Ltd., Ichinomiya Denki, Nagahama Works, and other colleagues for various types of assistance. This work was supported by Kokyo Tatemono Co. Ltd. and the Okinawa Institute of Science and Technology Graduate University.

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