# Wave power measurement at breaking wave zone in Maldives using horizontal-axis turbine WEC

Hideki Takebe, K. Shirasawa, J. Fujita, S. Misumi, P. Halder and T. Shintake

*Abstract-* **In order to investigate water velocity at the seashore breaking wave zone, we performed first experimental testing of a wave energy converter (WEC) with a horizontal turbine design, in June 2015 in Okinawa, Japan. Subsequently from May 2018, we began long-term experiments with two half-scale (35cm diameter) turbine generators at the breaking wave zone on the coast of K ndooma Island in the Maldives. The AC peak voltages output by those WECs were measured by a data logger every 1ms, for 15 seconds, started by event driven procedure. Averaged DC voltages and currents from both WECs were continuously saved every 1s, 24 hours a day. The observed peak voltages were 70~500V with a 35cm diameter half scale turbine at 200~1300 rpm and the maximum water speeds were 1.4~9 m/sec, estimated by using turbine characteristics, which were measured in advance. In November 2018, full-scale (60cm diameter) WECs were installed at a shallower location. This wave power measurement is being continued on Kandooma Island for an extended period, and is still ongoing at time of writing. This paper describes experiments with our self-built WEC monitoring system and obtained wave energy histogram data.**

*Keywords*—**Breaking wave, EDLC, generator, Maldives, Internet, OIST, remote monitoring, super-capacitor, sustainable energy, turbine, WEC, wave energy converter.**

## I. Introduction

WE believe that energy harvesting from breaking waves is an important research topic with a lot of potential [1]-[3]. In order to investigate water velocity at the seashore breaking wave zone, we performed first experimental tests of a wave energy converter (WEC) using a horizontal turbine in June 2015 [4,5], in Okinawa, Japan. In 2016, we placed ADCP water speed measurering devices around the reef edge, and we observed a water speed of 3.8m/s near the breaking zone [6]. In summer 2017, we confirmed ADCP water speed data, using electro-magnet (EM) water speed sensors mounted on a pole near the reef edge. However, this pole was tilted from its original position by a typhoon in October 2017, so we began planning to have an experiment with the half-scale turbine generators at a breaking wave zone on the coast of Kandooma Island in the Maldives in May 2018.

As background, in 2017 the Maldives government and Kokyo-Tatemono Co., Ltd. offered us the possibility of doing a WEC experiment in the Maldives*1. The Maldives is an excellent location for WEC experiments, as the weather is usually stable, without typhoons or other extreme weather events, and medium scale waves come continuously almost all year round. Around that time, we had developed a horizontal-axis type half-scale waterproof WEC (35cm diameter turbine) that generates electricity in the coastal breaking wave zone. So, we decided to use the horizontal-axis turbine type generator as a water speed meter for measurements in the Maldives. We also have performed a half-scale turbine-generator combined test carried out with different load resisters by pulling boat-side before the Maldives experiment [7]. After these initial half-scale tests, subsequently, we developed and installed a full-scale WEC (60cm diameter turbine, 8kW) in November 2018 [8]. This paper presents results from both the half-scale (Section III) and full-scale (Section IV) turbines. Firstly, we introduce the measurement configuration (Section II).

## II. Configuration For Maldives Experiment

We prepared to install the WECs and monitoring system on Kandooma Island in the Maldives in May 2018 (Fig.1). We assembled two sets of half scale WECs (Fig.2) with supports of 1m and 1.5m height, respectively, at the breaking wave zone, facing southeast towards the Indian Ocean. A connection diagram of the two WECs, cable connection box and WEC monitoring system rack (located in next to the power plant house) is shown in Fig.3. A metal corrugated power cable (70m long, 3-phase, 3.5mm$^2$ cross-

ID 1492, WDD (Wave Device Development and testing).

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section area per individual wire) was laid on the sea bottom between the WECs and the connection box (near the beach).


Fig.1. WEC experiment site on Kandooma Island in the Maldives. Two sets of the generators and supports were set in breaking zone. Two sets of 270m length (3.5 mm$^2$, 3-lines, metal corrugate) power cables were connected to a power monitoring system, beside the power plant facility of the nearby hotel.

This box had three phase lines breaker circuits and terminals. It could be connected temporarily with a local monitor box and oscilloscope or LEDs. The same corrugate cable (200m-length) was used between this connection box and the WEC monitoring system rack at the power plant house.

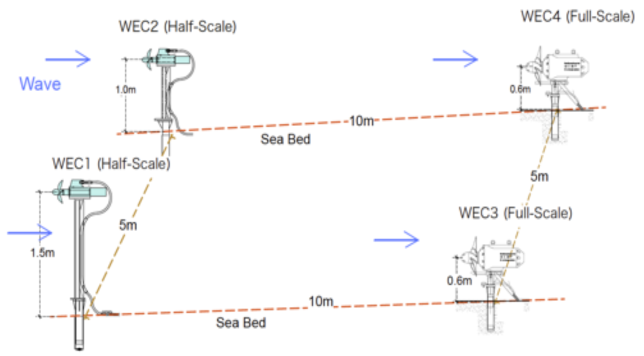


Fig.2. (left) Half-scale generator support and socket. The heights of the WEC1 and WEC2 were 1.5m and 1.0m, respectively. 100mm diameter socket was fixed into coral reef rock (of 400mm depth hole) by epoxy cement.

Fig.2 (right) Full-scale WEC3 and WEC4 were installed 10m behind the half-scale WECs on 16th November (6 months after the half-scale WECs installation).

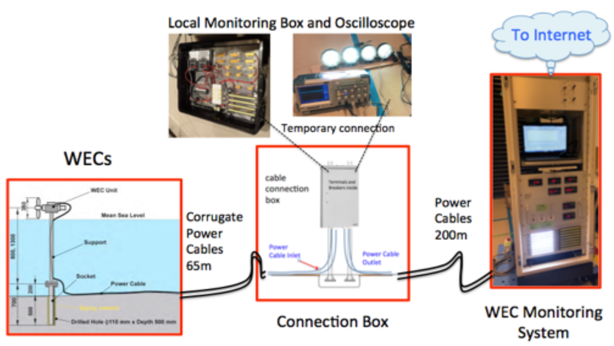


Fig.3. Connection diagram of the WEC, the cable connection box (on beach-side) and the WEC monitoring system rack beside the island's generator plant house on Kandooma Island in the Maldives.

The two generators of the half scale WECs were connected to a remote monitoring system. Both outputs of the generators were rectified and connected to series-resistors and internal LED displays. Also they could be switched to a voltage limiter (<55V) circuit and electric charge bank (EDLC: Electric Double Layer Capacitor) in order to perform a continuous lighting test of external LED lights. Since installation, we have been getting a continuous stream of useful data via the Internet for analysis (this data stream is still active now, at time of writing). 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. 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, 400kHz-max sampling). Then we can measure the precise rotation speed of the turbine with a generator of 20 poles permanent magnets.

Fig.4 shows an example of the WEC monitoring display (remote desktop). For both WEC1 and WEC2, the AC peak voltage histogram, instantaneous DC voltage, DC current, temperature and leak current detector voltage are updated every second. AC voltage waveform is also indicated for 15s when the voltage exceeds 300V [7].

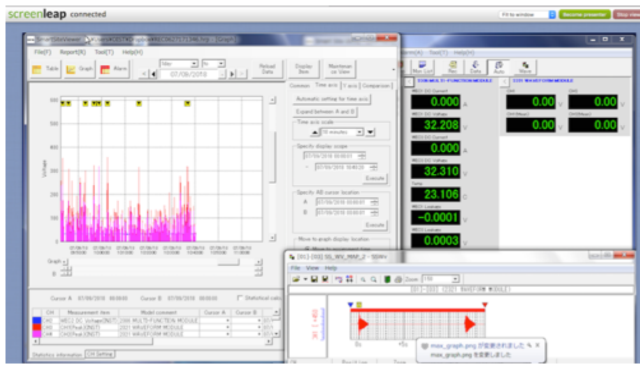


Fig.4. Example of WEC monitoring display (remote desktop). For WEC1 and WEC2 AC peak voltage histogram, instantaneous DC voltage, DC current, temperature and leak current detector voltage are updated every second. AC voltage wave form (1ms sample) is also displayed for 15s when the voltage exceeds 300V (lower right).

## III. Half Scale WEC Experiment Results

As described in the previous section, we assembled two half-scale WECs at the Kandooma Island in the Maldives on 8th May 2018. Before connecting these WEC outputs to the monitoring system, we took prior measurements using a local measuring box, placing the half-scale WEC2 at a position 10m behind the WEC1, in order to measure wave traveling speed. After this initial measurement, we subsequently moved WEC2 to a slightly deeper point (actually on the same transversal line as WEC1, see Fig.2

and Fig.5). Fig.6 shows a front view of the WEC1 and WEC2. WEC1 is positioned 50cm higher than WEC2.

Fig.5. Half-scale WEC supports and generators were assembled at Kandooma Island in the Maldives on 9th May 2018.

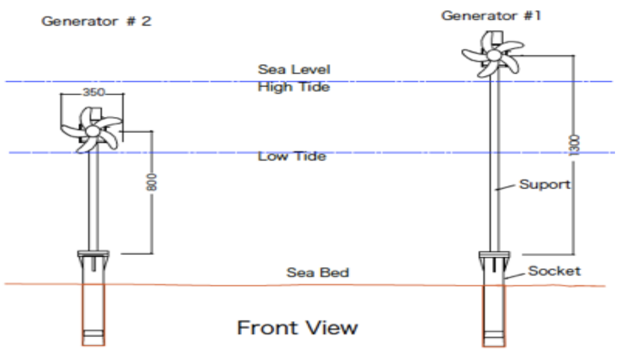


Fig.6. Front view of two half-scale WECs. Heights from the sea-bed are 1m and 1.5m.

Fig.7 shows an example of the WEC1 AC voltage waveform, with data sampling time of 1ms. On 14th June, 2018, at t=0.09~0.12s (14:24:47 data), the output AC voltage was 512V (peak). Fig.7 (lower) shows a time scale magnified view of the output AC voltage (512V peak) at t=0.08~0.13s. The frequency is 232Hz (23.2rps due to the 20-pole magnet rotor) so that 1392 rpm was calculated for the turbine rotation speed.

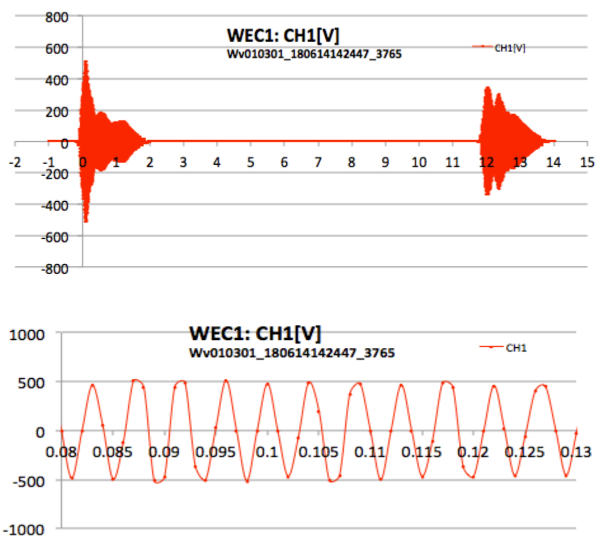


Fig.7. (upper) WEC1 AC peak voltage wave form vs. time(s) at 14:24:47 on 14 June, 2018. At time=0.09~0.12s, the output AC voltage was 512V (peak).

Fig.7. (lower) Magnified for time(s) output AC voltage (512V peak) at t=0.09~0.12s of the upper figure. The frequency is 232Hz, then the rotation speed is 1392 rpm.

The peak AC voltage and RMS (Root Mean Square) voltage of WEC1 and WEC2 were measured by the data logger's instantaneous module every 1s, and accumulated for 24 hours each day. Fig. 9 shows WEC1 (red) and WEC2 (green) output peak AC-voltages, every 1s for 24 hours, in spring-tide on 14th June 2018. The difference level between high and low tide was about 0.8~1m in spring tide.

Fig. 10 shows those in neap tide on 21st June 2018. The difference level between high and low tide was about 0.3m in neap tide.

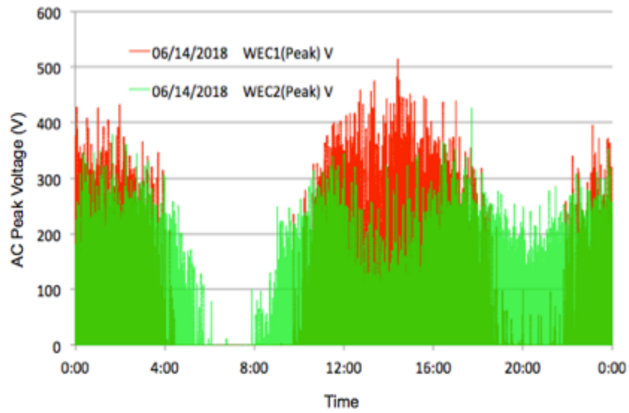


Fig.9. WEC1 (red) and WEC2 (green) output peak AC-voltages are plotted in 1s intervals for 24 hours in spring tide on 14 June 2018. The difference level between high and low tide was about 0.8~1m.

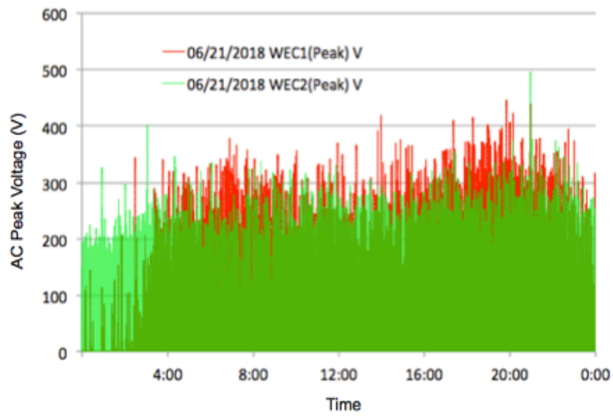


Fig.10. WEC1 (red) and WEC2 (green) output peak AC-voltages are plotted in 1s intervals for 24 hours during the neap tide on 21 June. The difference level between high and low tide was about 0.3m.

We had measured the half-scale turbine characteristics (turbine rotation speed vs. water velocity), with a water flow chamber at the West Japan Fluid Engineering Laboratory in Nagasaki, in advance. Prior measurements were also done in a boat-side calibration experiment at Seragaki port, Okinawa, Japan. Fig.11 shows obtained water velocity data as a function of half-scale turbine rotation speed.

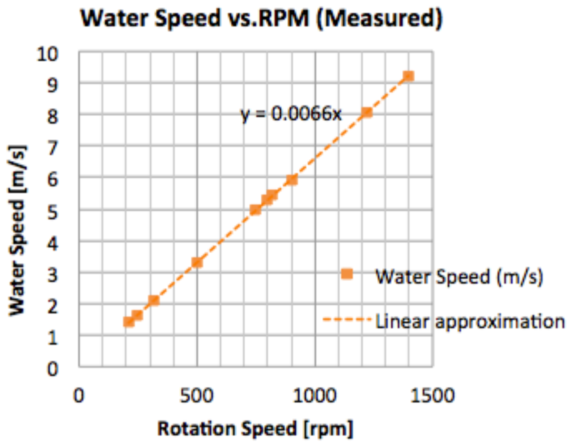


Fig.11. WEC1 rotation speed data are plotted using pre-measured characteristics of the half-scale generator and turbine. A maximum rotation speed 1392rpm corresponds to water speed of 9m/s.

Fig.12 shows the estimated water velocity from the rotation speed on the same day of the Fig.9.

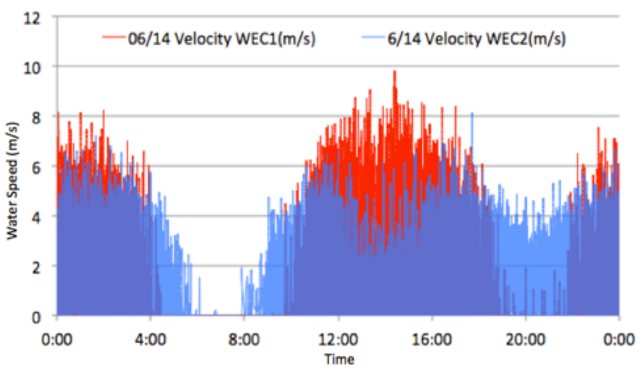


Fig.12. Water peak velocities, calculated from the output peak AC-voltages and rotation speed of the half-scale WEC1 (red) and WEC2 (blue), are plotted in 1s intervals for 24 hours in spring tide on 14 June 2018.

A maximum water velocity of more than 9m/s was seen on WEC1, which is positioned 50cm higher than WEC2. This might be related to "falling water" from the top of the breaking wave just hitting the turbine. This effect can be seen in a water speed simulation "REEF3D" [9] for a breaking wave in a shallow zone as seen in Fig.13 (slope = 1/10, wave height = 1.5 m, wave length = 44 m, period = 7.5 s, still water level = 3.8 m).

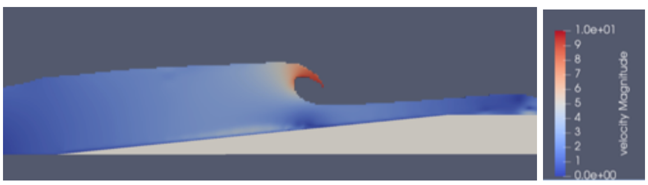


Fig.13. Water speed simulation (REEF3D) graph of a breaking wave in a shallow zone.

## IV. Full Scale WEC Experiment Result

We assembled full-scale 8kW WECs at the same location but at a shallower point (10m behind the half-scale WECs) on 16th November 2018 (named WEC3 & 4, as illustrated in Fig.2, right). Fig.14 shows the dimensions of the full-scale WEC with lower support. The 100mm diameter sockets (same as the half-scale WEC), were fixed into coral reef rock and two extra-pods were added behind. The inputs of the monitoring system were changed to receive voltage signals from these full-scale WECs outputs.

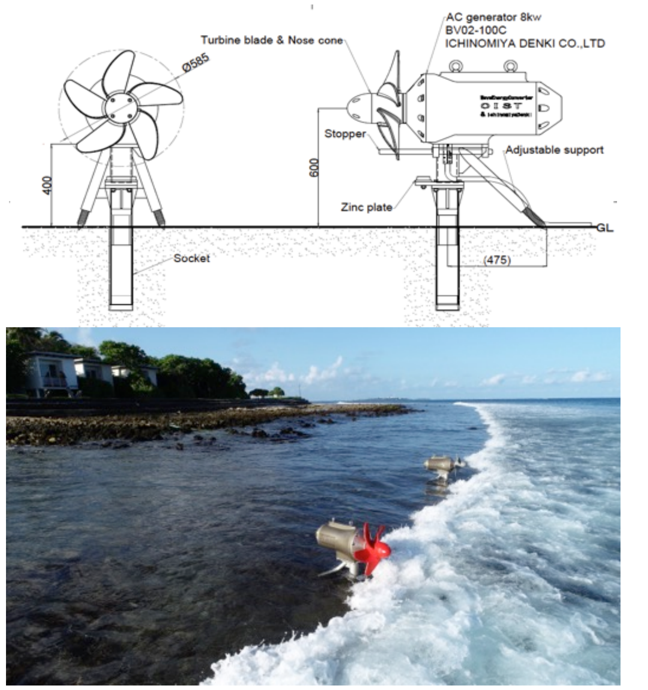


Fig.14. Full-scale 8kW generator support and socket. The turbine horizontal axis is positioned 0.6m above the sea-bed. The support socket is the same as the half-scale WECs.

Fig.15 shows full-scale WEC3 (red) and WEC4 (green) output peak AC-voltages, every 1s for 24 hours, in spring-tide on 25th November. The difference level between high and low tide was about 0.8m in spring tide.

Fig.16 shows an example of the WEC3 AC voltage waveform (1ms sampling) data at 12:22:20 on 27th November, which stored data for 15 seconds, after an event driven by trigger level 200V. Fig.16 (lower) shows magnification for time(s) of output AC voltage at t=0.26~0.4s. The frequency is 20Hz so that the turbine rotation speed is 300 rpm (5 rps due to the 8-pole magnet rotor).

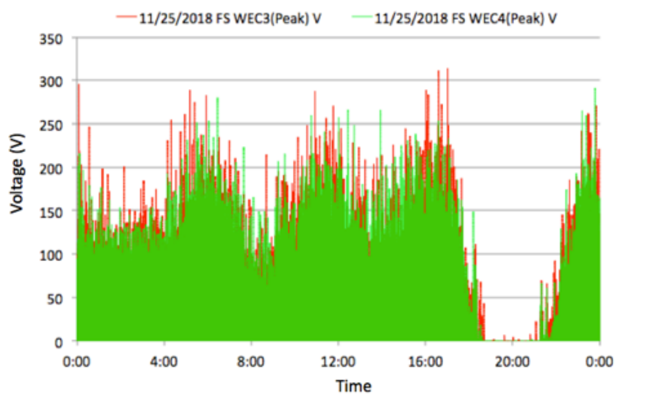


Fig.15. Full-scale WEC3 (red) and WEC4 (green) output peak AC-voltages are plotted in 1s intervals for 24 hours in spring tide on 25

November 2018. The difference level between high and low tide is about 0.8m.

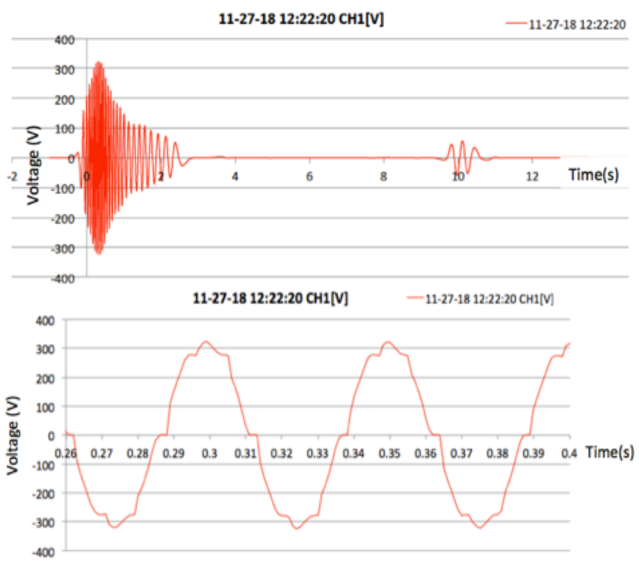


Fig.16. (upper) Full-scale WEC3 AC peak voltage (CH1) wave form vs. time(s) at 12:22:20 on 27 November, 2018. At time=0.3s, the output AC voltage was 315V (peak). Fig.16 (lower) Magnified for time(s) output AC voltage at t=0.26~0.4s. The frequency is 20Hz and rotation speed is 300 rpm.

Fig.17 shows measured AC peak voltage of the full-scale WEC (red) and the half-scale WEC (blue) as a function of rotation speed. As the full-scale turbine shape was designed for larger diameter and lower rotation speed generator, the rotation speed is lower than the half-scale, but the maximum current and power can be large.

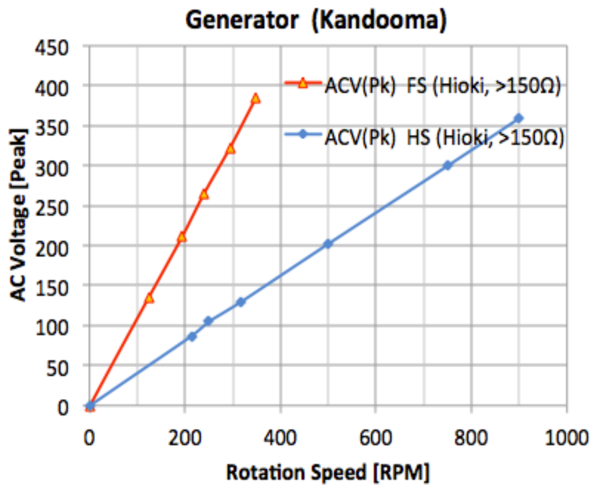


Fig.17. Full-scale (red) and half-scale (blue) AC voltages are plotted as a function of rotation speed.

The output voltage (RMS), current and power of the full-scale generator were measured at the factory previously (Fig.18). In these figures, load resistances $R_{3ph}$, for the factory measurements, were set in a three-phase star circuit. So, the DC equivalent resistance, $R_{dc}$, becomes $\sqrt{3}$ x $R_{3ph}$. The voltages at open circuit, or resistances larger than 60 Ω, are almost same as those at $R_{dc}$ =60 Ω.

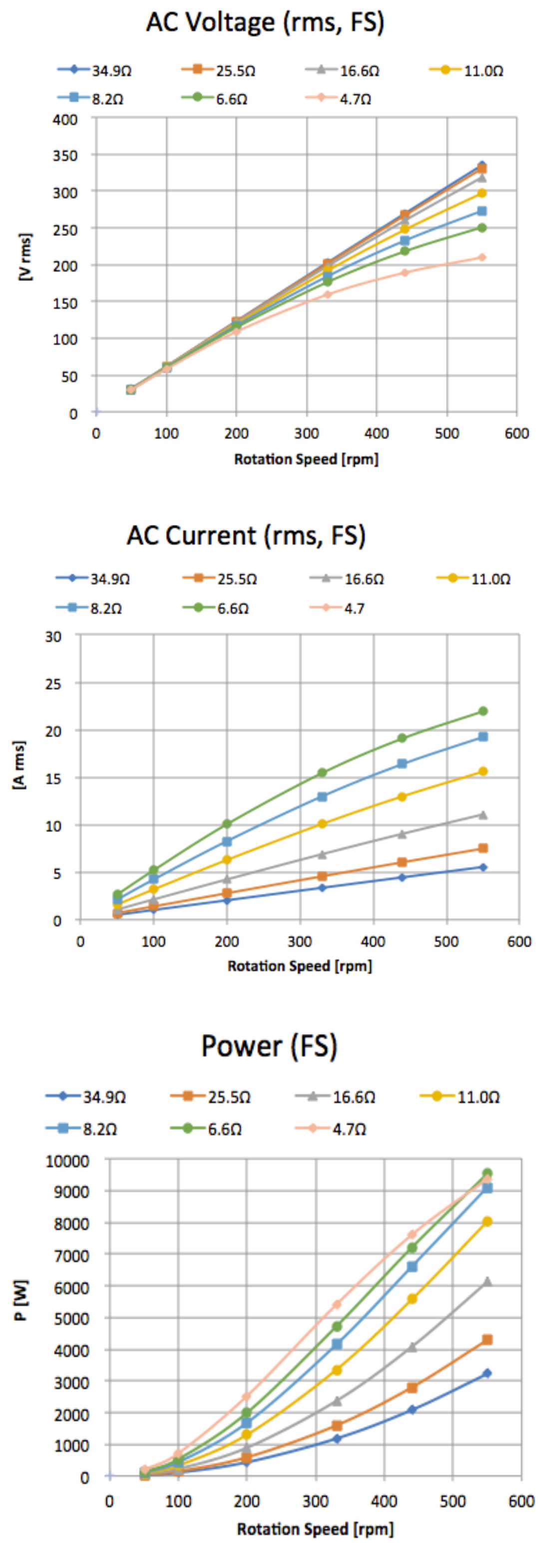


Fig.18. Measured output AC voltage (RMS), current and power of the full-scale generator at the factory in various load resistances: $R_{3ph}$ = 4.7~34.9 Ω. The resistance, $R_{3ph}$, was set in a three phase circuit, then a DC equivalent resistance ($R_{dc}$) is $\sqrt{3}$ times larger.

As we don't yet have experimental data on the full-scale turbine characteristics, the rotation speed as a function of the water velocity was estimated by using a CFD calculation, based on the turbine shape. The CFD-calculated water velocity, as a function of rotation speed, is shown in Fig.19. The data in Fig.19 was generated using the measured power of the generator and the full-scale turbine shape as shown in Fig.20.

The electric load, $R_{dc}$, was larger than 150 Ω for the measurements in the Maldives. The water velocity could then be estimated by using a function obtained in Fig. 19, because the voltages at open circuit are almost the same as those when $R_{3ph}$=34.9 Ω ($R_{dc}$ =60 Ω). Fig.21 shows the estimated water velocities calculated from the rotation speeds and voltages measured on 25th November 2018 (same day as Fig.15).

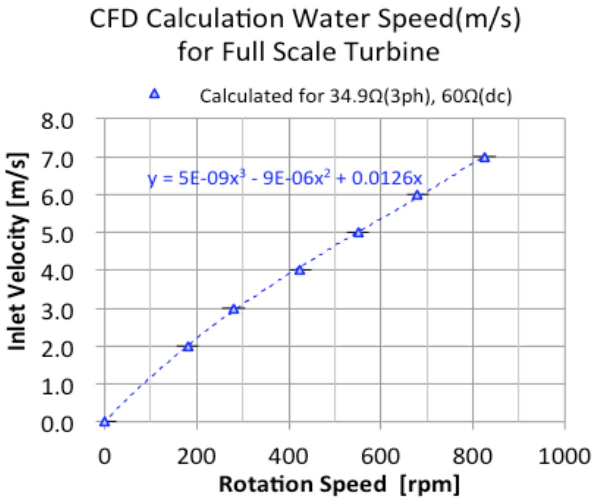


Fig.19. CFD estimated water velocity vs. rotation speed for the full-scale turbine with a load resistance of 34.9 Ω ($R_{3ph}$), corresponding to DC resistance ($R_{dc}$) =60 Ω.


Fig.20. Full-scale turbine shape, used for the CFD calculation.

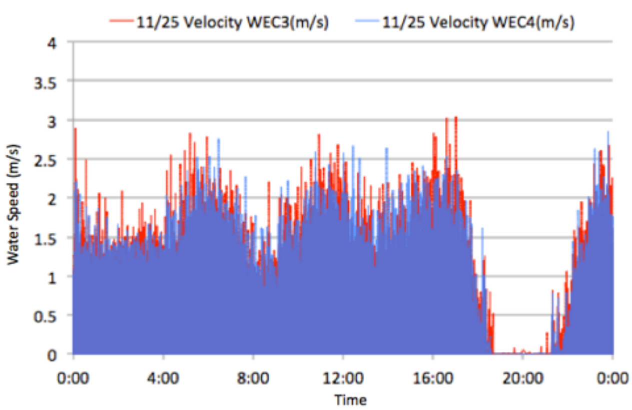


Fig.21. Water peak velocities, calculated from the output peak AC-voltages and rotation speed of the full-scale WEC3 (red) and WEC4 (blue), are plotted in 1s intervals for 24 hours on 25 Nov. 2018.

Fig.22 shows estimated rotation speed vs. inlet water velocity of the full-scale turbine, for electric load resistances $R_{3ph}$ of 4.7, 11, 34.9 Ω, from the CFD calculation. If we were to set the full-scale WEC at the point of WEC1, close to the breaking wave zone, higher values of water speed would be expected. Nevertheless, if we take larger electric load, $R_{3ph}$ = 4.7 Ω or 11 Ω for example, the rotation speed will be reduced to lower velocities (<5m/s).

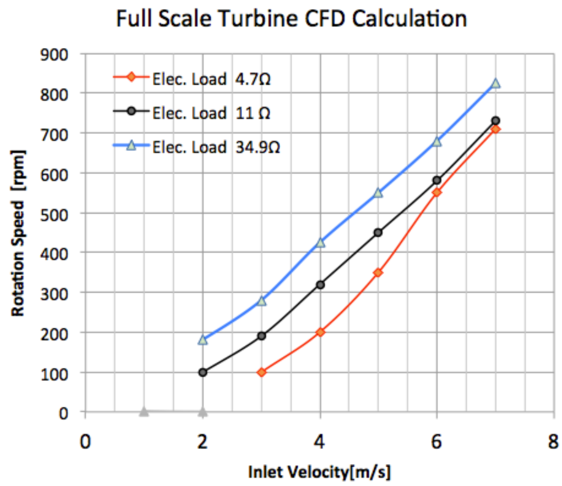


Fig.22. Calculated rotation speed vs. inlet water velocity of the full-scale turbine, for electric load resistances ($R_{3ph}$) of 4.7, 11, 34.9 Ω.

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## V. Conclusion

We successfully installed two half-scale WECs and associated monitoring electronics in May 2018, getting data via the Internet. On 14th June in a spring tide, we found maximum voltage 512V (AC peak) and a rotation speed of the turbine 1390 rpm. The water speed was estimated as 9m/s. So, it might be caused by wave-top falling water from the breaking wave just hitting the turbine. Subsequently, we installed two full-scale WECs and changed the monitoring system inputs to acquire data from them, in November 2018. The output power specification of the full-scale generator is so large, that we could not measure the real power at the monitoring system rack because it is just the beginning of the project at the remote site. Nevertheless, we have measured detailed data of the generator power at the factory. Then we could calculate output power of the full-scale generator with a CFD calculation of the turbine shape. The rotation speed and water velocity at WEC3 and WEC4 were not so large because of their location in quite shallow water. Regarding the data in spring tide and neap tide, the WEC positions (height and distance from the reef edge) are also being optimized. In case of installing the full-scale WEC at the breaking point (at the half-scale WEC's point), an estimation of the full-scale WEC peak power will be more than 8kW at 580rpm at 6m/s water speed and $R_{3ph}$=11 Ω, as seen in the measured water speed histogram at the WEC1 and 2.

We now continue to accumulate and analyse data for peak, RMS, average voltage and those incident counts on each day. Also, we are checking the waterproof seal mechanism of the turbine axis shaft, and the robustness of the half and full-scale generators, supports and cables. For the future, we are planning the next phase of the project with a tapered inlet duct affixed in front of a full-scale WEC [8], and designing WEC power conditioner specification.

## ACKNOWLEDGMENTS

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