International Journal of Electrical Components and Energy Conversion
2021; 7(1): 10-16
http://www.sciencepublishinggroup.com/j/ijecec
doi: 10.11648/j.ijecec.20210701.12
ISSN: 2469-8040 (Print); ISSN: 2469-8059 (Online)

Ocean Power from Breaking Waves and Electrical Energy Conversion

Balakrishnan Shankar

HMTD Engineering Private Ltd., Mumbai, India

Email address:
balakrishnansr7@gmail.com

To cite this article:
Balakrishnan Shankar. Ocean Power from Breaking Waves and Electrical Energy Conversion. *International Journal of Electrical Components and Energy Conversion*. Special Issue: *Emerging Electrical and Energy Conversion Technologies in Development of Smart Cities*. Vol. 7, No. 1, 2021, pp. 10-16. doi: 10.11648/j.ijecec.20210701.12

Received: October 5, 2020; **Accepted**: December 24, 2020; **Published**: January 30, 2021

Abstract: This paper presents a practical application of Harvesting Ocean Power of Break Waves in the Indian ocean shores, conversion into Electrical Energy, and distribution to the Coastal States. The Indian peninsula has ten coastal states that can generate electricity from Wave Energy Converters (WEC). Unlike Western countries, off-shore WECs of each more than 500 kW are built-in Oscillating Water Column (OWC) of Floating Wind Power, Heavy Buoy Device, etc. We employ 30 to 35 numbers array of PM alternators of each 30 to 50 kW. They are positioned in a zigzag pattern at 100 to 150 meters long on the Shallow Water shore, where the Breaking Sea Waves evolve to give one MVA power or more. The generated power is brought to the shore stations for conditioning and converting to three-phase 440 Volts 50 Hz power for distributions. We have the potential to transform Break Wave Power of 40,000 MVA through the length of the Indian Ocean shore.

Keywords: WEC, Wave Energy Converters, Breaking Waves, PM Alternators, Energy Conversion

1. Introduction

The first Wave Energy Converter (WEC) was with a Float and a Hydraulic System [1] in 1898. Another WEC that used Trapped Column air above surging waves was the impulse turbine by Selogucgi in 2001 that provides unidirectional rotation of motion. Floating Wind Turbine – Wave Energy Converter has been combined, as discussed by Jocelyn Maxine Kluger [2].

Small power WECs have been recently studied and developed by the Okinawa Institute of Science and Technology (OIST), Japan, and a model for less than 20 kW was presented by Tsumosu Shintake [3, 4]. This paper gives the lead for the approximate design of Turbines for Break Wave Applications. The complete Wave Theory on linear and non- linear systems of waves and various forces and energy in the sea wave for off-shore, nearshore, and onshore, have been detailed by M. C Deo [5]. The Waves and Structures of Ocean Waves are shown by Rick Solman [6].

The direct-drive online Permanent Magnet (PM) Generator by Asko Parviainen [7] is for small Hydro Power applications with the Grid Connection. The water immersed PM Alternators are available to the specifications of Voith [8]. The various design parameters in our work are for low-speed, high- power water immersed PM Alternators. The design is for the optimized parameters. The precautions in stopping the ingress of seawater in the WECs have been considered by HMTD [9]. The interesting studies on breaking waves in surf zone by Pengzhi Lin[10], the investigation of Turbulance in aplunging breaking wave by Toomas LIIV [11] are referenced. The Power Ministry, Govt. of India [12] recently notified that the Ocean Energy as Renewable energy is an added motivation for installing WECs all over Indian Coasts to harvest the Ocean Break Wave Power. The works on breaking waves by authors referred [13-15] have also been referenced.

The development of the power generator from Ocean Break-Waves in seashore with PM Alternators is designed and manufactured for the pilot project successfully. The vast power generated with this technology will be a renewable energy. source. The uninterrupted generated power is easily transported to supply power to smart cities near the coastal area, or the clean power can be connected to the national grid.

2. Power of the Break Wave from the Ocean Shore of Indian Coast

The Government of India notified [10] that the Ocean Energy is the Renewable Source of Energy. The three types of ocean energy for electricity generation are Tidal Energy with 12,455 MW, Potential Wave Energy along the Indian Coast with 40,000 MW, and the Ocean Thermal Energy Conversions with180,000 MW.

Figure 1 shows the Indian coastal states where Ocean Energy is a promising renewable energy source. The Indian seashore length in the mainland is 5423 KMs and in the Island is 2094 KMs. The coastal states in India are Gujarat 1215 KMs, Andhra Pradesh 974 KMs, Tamil Nadu 907 KMs, Maharashtra 653 KMs, Kerala 570 KMs, Odessa 476 KMs, Karnataka 280 KMs, Goa 161 KMs, West Bengal 158 KMs, Pondicherry 31 KMs, Andaman 1962 KMs, and Lakshadweep 132 KMs. With this long seashore, India has vast Ocean Power available near the Coastal State, and we can harness and distribute the same.

Figure 1. *Indian Coastal States.*

These coastal lines can generate electricity from Break Waves in the shallow water near the shores. The Electric Power can be produced on 365 days, 24 hours as sea waves never stop even when the sun and wind stop. The Power-stricken coastal districts can benefit from this technology, where the cost of transmission lines of power is minimal with huge savings otherwise.

3. Small Power WECs and Advantages Using in Indian Sea Shores

There are two types of sea waves. They are wind sea-wave that is generated locally and swells and waves due to distant winds. The WECs are developed and used by many countries, and most of the countries develop Off-Shore Wind Turbines, each more than 500 K Watts power in deep water, more than 25-meter depth, and 40 KMs inside the sea from the seashore and investing billions of Euros. Many countries employ a large Floating Buoys and massive constructions, which require huge investments. The magnitude of wave energy during storm conditions increases many folds. Several instruments have been employed to predict storm conditions to save people's lives, but not protect the equipment.

We employ a cost-effective smaller WECs and install in the seashore floor in the shallow water after thoroughly surveying every Indian Coastal Lines. The advantages of installations of smaller WECs are:

i. The Indian Industries have well-developed computer-aided design and manufacturing facilities for anti-corrosive Turbines, well-protected water immersed PM alternators, anti-corrosive, waterproof cables, and power conversion electronic equipment for distributions or through the grid.

ii. We can employ standardized smaller WECs, 30 to 35 numbers of each 30 to 50 K Watts in an array in the seashore on Concrete Structure on the seafloor level to capture the Break Wave Energy to give a power of One MVA and pass it on to the shore stations for further distributions. The cost of these WECs, the cables to the shore, and the power conditioning electronic equipment are low in installations and maintenance. Multiples of 1 MVA can be built throughout the available seashores all over the length of the Indian Coastal lines.

iii. Individual WEC is protected from the seawater corrosion, salt crystals, miniature sands, seaweeds, barnacles, shellfish, etc.,

iv. Energy conversion efficiency increases by optimally designing the standardized Special Water Turbines, PM Alternators, Anti-corrosive cables, and the power conditioning electronic equipment.

v. All the WECs are connected in parallel, and therefore, there is no interruption in case of failure of one WEC in the array. The defective WEC is automatically switched off and can be set right or replaced in a day connected to the system.

vi. These WECs in an array partially protect the seashore from erosion as most of the Kinetic Energy from the waves have been absorbed by the WECs, and no Tetra pod may be needed.

4. Linear Wave Theory and Breaking Sea Wave Power

The Hydrodynamic wave theory was developed in the 18^{th}

Century using the Continuity Equation on Conservation of Mass and Navier - Stokes Equations on Conservation of Momentum. The wave theory and development of equations to our applications on energy conversion from the Breaking Wave Zone of the sea wave is discussed.

Figure 2 shows the moving sea-wave towards the seashore.

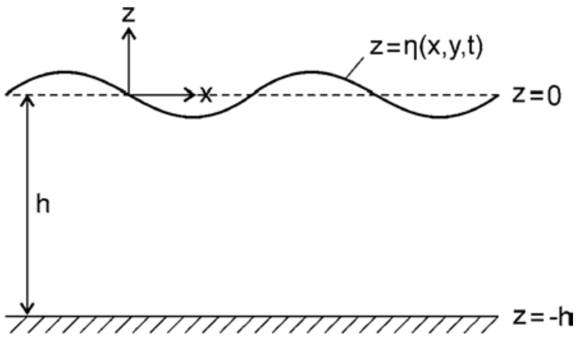


Figure 2. *Sea Wave Movements and Boundary Conditions.*

A moving wave equation in the right direction towards the seashore is

$$Z = A \sin(kx - \omega t + \alpha)$$

α=initial phase angle where the wave starts

A=Max. The amplitude of the wave, k=wave number=2π /λ, λ – wavelength.

ω=Angular frequency=2π /T, T=Period of the wave, f=1/T, Velocity, V=λ f

k, ω, A, λ, v, and finally, the quantum of energy available in the Break wave is found from the Continuity Equation. The Navier - Stokes equation derived for our application of the sea wave and finding the solutions to the second-order differential equation after applying the Boundary conditions for the shallow water. The sea wave medium, i.e., the seawater having the potential flow is assumed to be in viscid, ir rotational, and incompressible. Our potential for the conversion of energy is the Kinetic Hydro Power, i.e., the Velocity Vector V (x, y, z, t) is three independent fields u(x, y, z, t), v(x, y, z, t) and w(x, y, z, t) with the mass density ρ (x, y, z, t) and the mass moves with the velocity V (u, v, w) in the x, y, and z directions. However, under the assumption, all the three components of the velocity vector are determined by a single scalar field Φ (x, y, z, t). The velocity vector has the potential defined as V=∇Φ.

The Continuity Equation which states conservation of mass: Ref. [5]

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, v) = 0 \quad (1)$$

$\frac{\partial \rho}{\partial t}=0$ (As seawater is incompressible)

$$\nabla \cdot (\rho\, v) = \rho\, \nabla.(\nabla\emptyset) = 0,\ \rho \text{ being constant} \quad (2)$$

$$\nabla \cdot \nabla\emptyset = \nabla^2\emptyset = \frac{\partial^2\emptyset}{\partial x^2} + \frac{\partial^2\emptyset}{\partial y^2} + \frac{\partial^2\emptyset}{\partial z^2} = 0 \quad (3)$$

$$\nabla^2\Phi = 0 \text{(Laplace form of continuity equation)} \quad (4)$$

The Navier- Stokes theorem for the sea wave states that

The forces acting on an element of water are forces due to pressure and forces due to gravity, and this is equal to mass x acceleration.

$$\frac{dV}{dt} + (v.\nabla)\, V = \frac{1}{\rho}\nabla P + \frac{1}{\rho} f \quad (5)$$

f=∇P (P is force per unit area, pressure)

The theorem is Newton's 2^{nd} law of motion for the liquid and reduces to linearized Bernoulli's equation after applying velocity potentials

$$\frac{\partial\emptyset}{\partial t} + \frac{1}{\rho} P + gz = b, \text{ b being constant} \quad (6)$$

The boundary conditions for Solving Eqns. (3) and (6) for shallow water are:

The wave height from Crest to Trough is H

P is the pressure, and P_0 is the atmospheric pressure at sea level. The free surface wave η (x, z, t), η are small, and the higher-order terms can be ignored.

This leaves the linear approximation:

$$\frac{\partial \eta}{\partial t} = \frac{\partial\emptyset}{\partial z} \mid at\ z=0 \quad (7)$$

In the sea bed there is no vertical movement of water

$$\frac{\partial\emptyset}{\partial z} = 0 \mid \text{at } z=-h \quad (8)$$

$$\text{This leaves } \frac{\partial\emptyset}{\partial t} \mid \text{at } z=\eta \mid + \frac{1}{\rho}p_0 - b = -\ g\ \eta \quad (9)$$

$$\frac{\partial\emptyset}{\partial t} \mid \text{at } z=0 \mid + \frac{1}{\rho}p_0 - b = -\ g\ \eta \quad (10)$$

For calm sea, i.e., there is no surface motion, we find that

$$\frac{\partial\emptyset}{\partial t} = \eta = 0 \rightarrow b = \frac{1}{\rho}\, p_0 \rightarrow \frac{\partial\emptyset}{\partial t} = -\ g\eta \quad (11)$$

$$\text{i.e., } \eta = -\ \frac{1}{g}\frac{\partial\emptyset}{\partial t} \text{ at } z=0 \quad (12)$$

This in combination with equation (8) yields the surface boundary condition

$$\frac{\partial^2\emptyset}{\partial t^2} + g\frac{\partial\emptyset}{\partial z} = 0, \text{ at } z=0 \quad (13)$$

The Laplace's eqn. (4) is solved with boundary conditions together with (9) and (12) and then with (13), we get the following solutions,

$$\omega = \frac{gh}{2\omega}\frac{\cosh\,(k(h+z))}{\cosh(kh)} \sin\,(k\,x - \omega\, t) \quad (14)$$

$$\eta = \frac{H}{2}\cos\,(k\,x - \omega\, t) \quad (15)$$

$$\omega^2 = g\,k \tanh\,(h\,k) \quad (16)$$

From the above equation we derive the group velocities

$$U = \frac{\partial\emptyset}{\partial x} = \pi H\, \frac{\cosh\,(k\,(h+z))}{T\sinh(kh)} \cos\,(kx - \omega t)) \quad (17)$$

$$W=\frac{\partial \phi}{\partial z}=\pi H\ \frac{\sinh(k(h+z))}{T\ \sinh(kh)}\sin(kx-\omega t)) \qquad (18)$$

$$\dot{U}=\frac{\partial u}{\partial t}=2\pi^2 H\ \frac{\cosh(k(h+z))}{T^2\ \sinh(kh)}\sin(kx-\omega t)) \qquad (19)$$

$$\dot{w}=\frac{\partial w}{\partial t}=2\pi^2 H\ \frac{\sinh(k(h+z))}{T^2\ \sinh(kh)}\cos(kx-\omega t)) \qquad (20)$$

The four preceding equations represent the particle or group velocities that are different from the wave velocities. The speed with which the entire wave motions advances and is a single value for a given H, T and h. The particle kinematics vary from point to point and from time to time. Wave energy is transmitted by individual particles which possess potential, kinetic and pressure energy. Shallow water is defined when $h < \lambda/20$ or $kh < \pi/10$. For small kh, the values of sinh (kh), cosh (kh) and tanh (kh) take the limiting values and are ≈ kh, 1 and kh respectively. Using these approximations in the above equations (17, 18, 19 and 20) for shallow water, we end up with approximate formulae for wave velocities near the shore and the wave's power.

Immediately before the wave breaks near the shore, water velocity closely approaches the group velocity $v \approx \sqrt{gh}$

We found $v \approx 4.4$ m/sec in two meters depth $and\ v \approx 5.4$ m/sec in three meters depth. Typically wavefront speed is 4 to 8 m/sec, near the Break Wave Zone. Using the Power density formula $P=\frac{1}{2}\rho v^3$, the estimated power density at these speeds are between 32 and 256 KW/m^2. The power density in the renewable energy source is unique and motivates us to harvest the power by using WECs in the breaking wave-zone.

5. Survey in the Indian Shore for the Installation of WEC

India has a long seashore with different climatic and geographic conditions that change the seashore's wave profiles and slope. A survey with measuring instruments is needed to locate the exact location of the break-wave zone to install WECs to get the uninterrupted power supply.

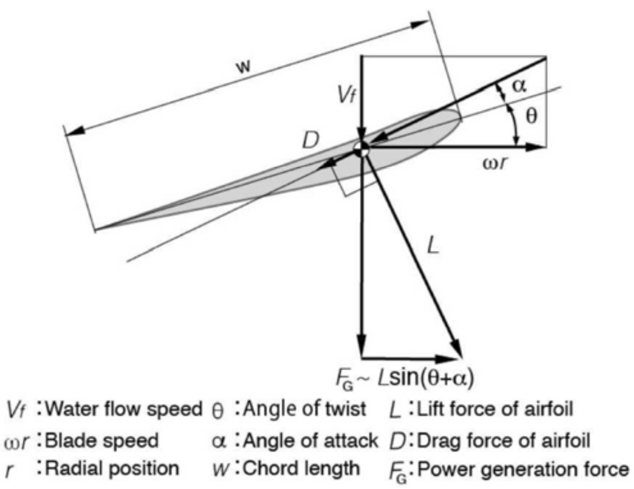
We have designed a data logging equipment that measures the linear velocity of seawater and the rotational speed simultaneously at a given point in the sea. We place the equipment at low- tide time at selected three to four places. This equipment will record the seawater's linear speed and the rotational speed of the turbine at every minute for 24 hours. The equipment will cover two low -tides and two high-tides. The data are recorded in a data logger kept in the seashore. The same test is repeated at two or three places to have the maximum power from the WEC. The data are analyzed in a computer to design our turbine, Generating equipment, and the Electronic Power Converters.

6. Design and Development of Turbine

The velocity and the power density is high in the Break Wave Zone. The turbine absorbs the breaking wave to impart the power to the PM Alternator. The most critical parameters in the Turbine Design are the number of blades for the turbine's solidity and the twist angle for the optimum quantity of seawater to generate the designed power. The sea wave's power density is much higher (250 KW/m^2) than the wind power, and the seawater is 850 times heavier than air. A smaller wave turbine with an optimum twist angle is used even though the basic design is followed from the wind turbine blade.

Forces Acting on Turbine Blade

Figure 3 shows the forces acting on the turbine blades. Figure 4 gives the dimensions of the turbine for the wave energy converter (WEC).



(Courtesy: OIST, Japan)

Figure 3. *Forces are acting on Turbine Blade.*

With a sectional area of the turbine blades **S,** the power output from the turbine:

$P_O = \frac{1}{2}\ \eta\ \rho\ S\ V^3$, $\eta = 0.6$, as the turbine is continuously in the flow of water.

The turbine's optimum diameter is 1200 mm, and the rotation speed of the turbine is given by $\omega=\sigma\ V/R$, σ=Tip speed/water speed, R=Radius of the turbine. Table 1 shows the design parameters of the turbine.

Table 1. *Design parameters of the Turbine.*

S. No	Description	Symbol	Min. value	Max. value
1	Turbine Diameter	D	1200 mm	1200 mm
2	Turbine Hub Diameter	A	260 mm	260 mm
3	Water speed just before break wave	V_O	4.5m/sec	6.5m/sec
4	Tip speed ratio	Σ	2	2
5	Tip Speed $\omega=\sigma\ V_O/R$	Ω	15 rad/sec	21.7 rad/sec
6	Turbine sectional area $\pi\ (R^2 - a^2)$	S	1.08 m^2	1.08 m^2

S. No	Description	Symbol	Min. value	Max. value
7	Water Speed at Turbine Blade 2/3 V_O	V_f	3 m/sec.	4.5 m/sec.
8	Incoming Wave Power	P_{in}	50.4 KW	152 KW
9	Power Conversion Efficiency	η	0.6	0.6
10	Turbine output power	P_O	30 KW	91 KW
11	Turbine Speed	N	150 RPM	210 RPM
12	Torque Output	To	2067 Nm	4378 Nm
13	Total Drag Force With Lift Po/V_f	F_d	1054 Kgs	1491 Kgs
14	Drag Force at Stall	F_{ds}	1164 Kgs	2428 Kgs
15	Twist angle $\tan \theta = V_f/(\omega r)$	θ	58.0 to 18.4 degrees	

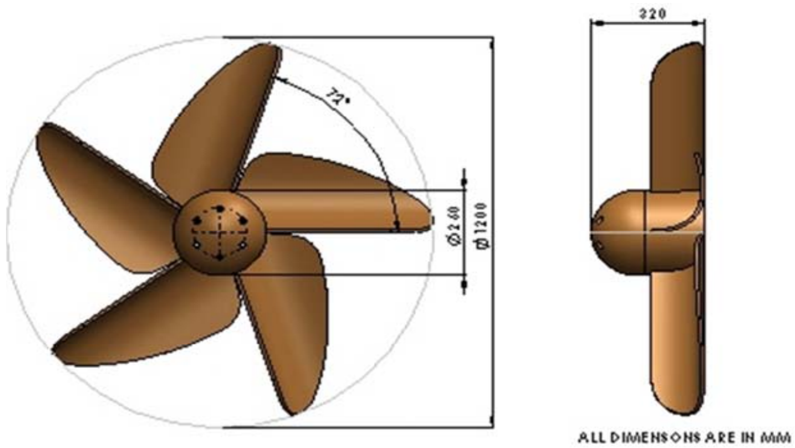


Figure 4. *Turbine for Wave Energy Converter.*

7. Design and Development of Low - Speed PM Alternator

The Design of a low-speed high-power PM Alternator is possible only by using powerful Nd Fe B Magnets with high Br (remanence) value to give the maximum magnetic loading in the air gap. We use the eight-pole rotor with magnets arranged to provide optimum air gap flux density. It is mounted on a stainless steel shaft. The outer diameter of the rotor stamping is punched with a special air-gap to give sinusoidal back-emf. The Stator has forty-eight slots and wound with one slot short pitch with class H insulating materials and copper. The complete assembly is housed in a stainless steel body with a mechanical seal near bearings and oil seals on end-covers to avoid seawater's ingress. The terminals are terminated outside the frame with a waterproof cover and are taken to the seashore through the watertight pipe and anti-rusting cables. The drive-side of the shaft is mounted with a coupler to mount the turbine assembly. The Alternator is filled with silicon oil with a pressure slightly more than one bar for cooling the winding and the magnets. The silicon oil at high pressure lubricates the bearings and mechanical seals and protects from seawater's entry inside the PM Alternator.

7.1. Specification of PM Alternator

Table 2 gives the detailed specifications of the PM Alternator.

Table 2. *Specification of PM Alternator 30 kW to 50 kW.*

S No.	Type and Ratings	Values
1	Type of Alternator	PM with high Br magnet (NdFeB)
2	Rated power	30 KW at 150 RPM and 50 kW at 250 RPM
3	Rated Voltage	440 Volts, 3 phase, variable frequency
4	Rated speed	150 to 350 RPM
5	Enclosure	Waterproof and watertight
6	Housing & Components	Anti-corrosive against seawater
7	Mounting	Foot Mounting
8	Class of Insulation	Class H
9	Cooling	Silicon oil cooled& sea water-cooled
10	Input Drive	Turbine Directly Mounted with Hub
11	Bearings	Axial thrust load Bearings

7.2. Outline Dimensions of PM Alternator

Figure 5 gives the dimensions of the PM Alternator. Figure 6 shows the block diagram of the control panel for the Inverter.

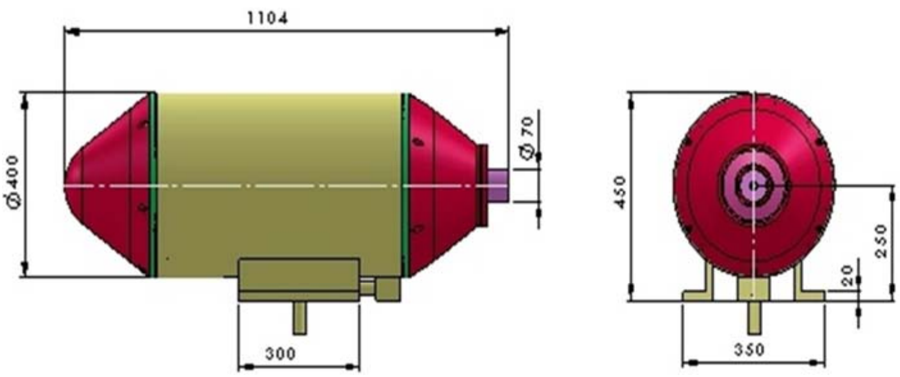


***Figure 5.** Outline drawing of PM Alternator.*

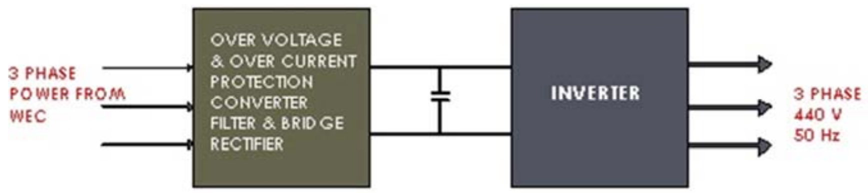


***Figure 6.** Control Panel to receive the WEC Voltage and Conversion.*

8. Experimental Setup and Testing of PM Alternator

We designed and manufactured a water-cooled PM Alternator and tested in our laboratory for the Turbine speed of 150 to 250 RPM and up to 300 RPM. The load tests were done at speeds in steps of 25 RPM up to 300 RPM. The results are given at various loads. It provides encouraging results that work in the sea when the waves just break or just before breaking. Figure 7 shows the results of the load characteristics.

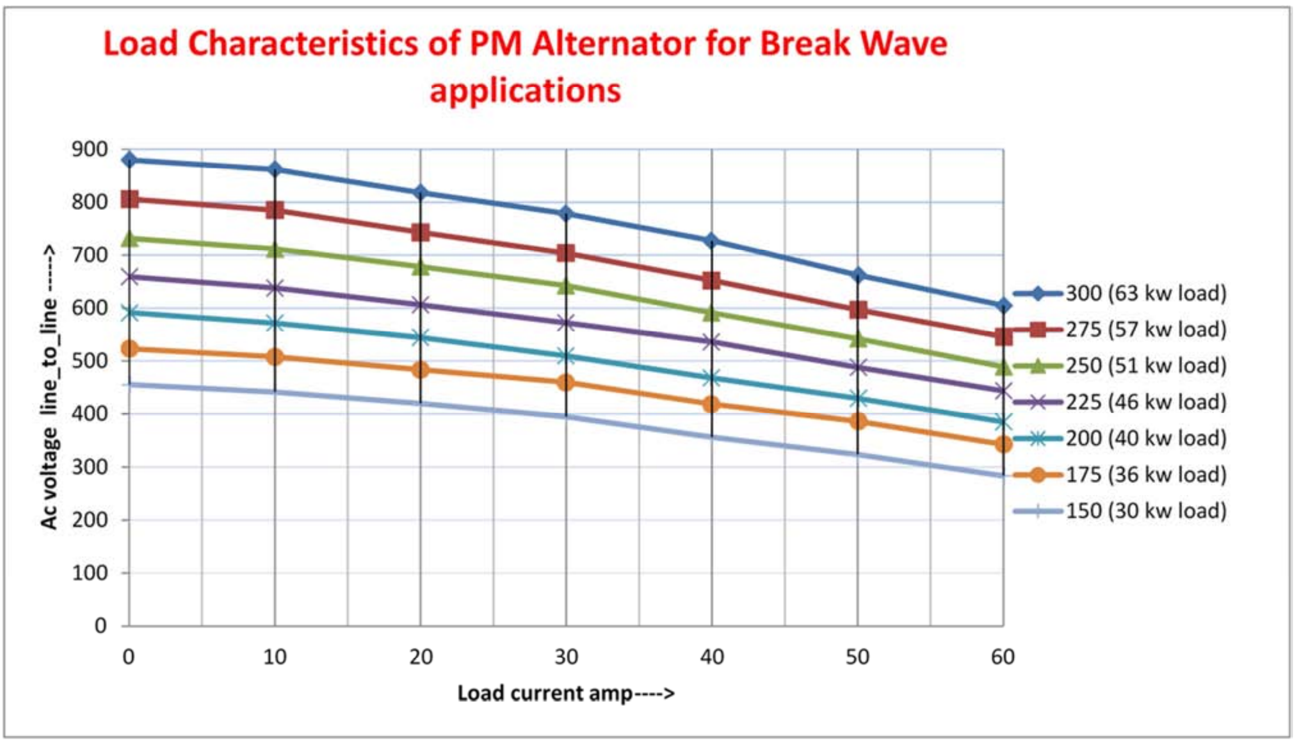


***Figure 7.** Load Curves from the Test Results.*

There will be an average of 30 to 35 WECs are mounted on the seashore to get the power of one MVA or more. The WECs are mounted in a zigzag pattern, as shown in Figure 8, to produce power at varying speeds depending on the progressing wave positions. The total energy of 40,000 MVA from the Indian Ocean is available to harvest and distribute to the seashore states and India.

Figure 8. *Array of Wave Energy Converters for One MVA.*

9. Conclusion

The design and manufacture of a turbine and PM Alternator that work on the break-wave at a speed of 3m/sec and 6m/sec in the shallow water near the seashore have been developed. The system was tested in the laboratory up to 300 RPM to generate up to 50 KW for high-wave speed. The average power up to 1 MVA is possible with 30 to 35 WECs installed in an array.

The Government of India has notified that the Break-Wave Energy up to 40,000 MVA is available on the Indian Coast. We can produce clean energy from Break-waves in all the 365 days and 24 hours. The initial cost and the maintenance cost only are high, but the operation cost of generation is minimal. The renewable energy produced with this technology are useful to supply uninterrupted power to smart cities in a separate grid.

The work presented in this paper is useful to researchers and manufacturers of PM alternators and power engineers for generating power from renewable energy sources.

References

[1] John Ring Wood "Practical Challenges in Harvesting Wave Energy" National University of Ireland Maynooth Co. Kildare, Ireland.

[2] Jocelyn Maxine Kluger "Synergistic Design of a Combined Floating Wind Turbine (FWT) – Wave Energy Converter" Ph.D. thesis, 2017, MIT, USA.

[3] Tsumosu Shintake, Okinawa Institute of Science and Technology, Japan and others"Harnessing the Power of Breaking Waves" Proc. of 3rd Asian Wave and Tidal Energy Conference, AWTEC (2016).

[4] Tsumosu Shintake, Okinawa Institute of Science and Technology, Japan and others "Technical R and D on a Surf Zone WEC. European Wave and Tidal Energy Conference (2017).

[5] Dr. M. C Deo Prof. Civil Engineering, Indian Institute of Technology, Mumbai, Wave and Structures.

[6] Rick Solman, Introduction to Ocean Waves, Scripps Institution of Oceanography, University of California, SanDiego.

[7] Dr. Asko Parviainen Axko Motors Oy, Finland,'Direct on line PM Generators for Small Hydro Power" Paper presented in the Conference on Hydroenergia, June 16-19, 2010 Lausanne, Switzerland.

[8] Engineering for SH Operations, Specifications for Voith's New Stream Diver Technology.

[9] HMTD Design Sheets for PM Alternators for low speed for water immersed applications.

[10] Pengzhi Lin, A numerical Study of breaking Waves in Surf Zone, Sichuan University , Phillip L.F Liu National University of Singapore, Journal of Fluid Mechanics 359-239-264 March 1998.

[11] Toomas LIIV , Investigation of Turbulence in a Plunging Breaking Wave, Institute of Mechanics, Tallinn Technical University, Estonia Proc. Estonian Acad. Sci. Eng; 2001, 7, 1, 58-78.

[12] The notification dated August 22nd, 2019, includes the Ocean Energy in the Renewable Source of Energy by the Power Ministry, Govt. of India.

[13] Rafael Waters, Energy From Ocean Waves, Digital Comprehensive Summaries of Uppsala Dissertations from the faculty of Science and Technology, 580. Full-Scale Experimental Verification of a Wave Energy Converter.

[14] Arshit Ambalia, Jay Dolar, Mehul Koladiya, Shahnawaz Ansari, Prof. Zaid Ansari, Department of Mechanical, Theep College of Engineering, Boisar, Maharashtra, India. Generation of Electricity from Ocean Waves. International Research Journal of Engineering and Technology, Vol. 3, Issue 4, April 2016.

[15] Dr. Khaled M Khader, Power Generation from Sea Waves Using Experimental Prototype of Wells Turbine or Suggested Special Rotating Mechanism. International Journal of Mining, Metallurgy and Mechanical Engineers, Vol. 3, Issue 3, 2015.