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A PREFEASIBILITY STUDY ON OCEAN WAVE POWER GENERATION FOR THE SOUTHERN COAST OF SRI LANKA: ELECTRICAL FEASIBILITY

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ABSTRACT

This paper presents the details of a prefeasibility study carried out about the ocean wave power generation for the southern coastal area of Sri Lanka. It includes a brief review on wave energy devices appropriate for wave climate around the country and the electrical feasibility of integration of wave energy power plants to the national grid based on some of the selected sites along the southern coast. Social and environmental impacts of wave energy power plants are also discussed. Further, depth studies are suggested to be done prior to the implementation.

1 INTRODUCTION

In recent years, the global issues such as environmental deterioration, and fossil fuel crisis forced people to develop clean energy sources. As a result, clean and renewable energy sources such as hydro, wind, solar, wave, tidal, geothermal and biomass are becoming attractive. Among them, the hydro power generation is technologically at its peak compared to other renewable energy sources. Wind and solar power generation technologies are being developed to harness maximum power whereas the wave, tidal, geothermal and biomass power generation are relatively immature [1 and 2].

Utilisation of wave energy resources has a long history in which the first known patent goes back to 1799 [3]. However, an early application device on wave power was constructed around 1910 by Bochaux-Praceique to light and to power his house in France [4]. The oil crisis in 1970's reinvigorated the renewable energy technology and researches introduced numerous wave energy utilising techniques during that period. Subsequently, the Kyoto protocol on CO_2 and oil crisis in 2007 served as driving forces for the wave energy and for all the renewable energy technologies.

Estimates have proven an extractable potential for wave energy in the order of 10000 TWh along the coastlines of the world [5]. As production of clean and renewable energy is a major engineering challenge in the 21st century, the attention towards utilization of wave energy is rapidly increasing.

Recent studies on wave energy utilization in Sri Lanka reveal that the southern coastline is suitable to erect wave energy power plants [6]. Although off-grid power plants are the most common targets of wave energy, in an extensive context, integration with the main electrical power grid is a motivating option. This paper attempts to review the wave energy devices that are suitable for the wave climate around Sri Lanka and to investigate the electrical feasibility of integration of wave power plants from southern coastal area to the national power grid.

2 ESTIMATION OF WAVE ENERGY POTENTIAL IN SOUTHERN COASTAL AREA

2.1 Wave climate in Sri Lanka

Long and thorough measurements are needed to investigate the most suitable place for a Wave Energy Power Plant (WEPP). Since such detailed information was not available, in this study, alternative solutions such as wave data prediction based on wind data have been investigated. Using the geographical location of Sri Lanka, a first estimation was made to find where the most energetic waves hit the coast. The north western part of Sri Lanka is in the shadow of India and the east side is relatively closer to Malaysia, Indonesia and Burma (see Figure 1). It is more difficult to get larger swells due to the restricted fetch in north west and north east areas. Therefore, it restricts the energy content in the waves. However, there may be localised spots where wave energy density is concentrated. On the other hand, southern part of Sri Lanka opens all the way to Antarctica, which enables a long fetch to have good waves.

Since Sri Lanka is affected by two monsoon periods; the north east monsoon and the south west monsoon [7], the waves in the southern coastline is affected by the north east monsoon from October to February whereas the waves generated by the south west monsoon affect the same coastal line from May to September (see Figure 1).Thus, uninterrupted winds blow throughout the year over a long stretch of open sea all the way from Antarctica confirming a very long fetch blowing for a long period. This means that the southwest monsoon strengthens the southern winds and waves from May to September. Conclusions were drawn from the larger wind patterns, stating that the south, south west and south east coasts would theoretically be the most suitable areas for WEPPs, since it is affected by both monsoon periods and thereby have a more stable wave climate.

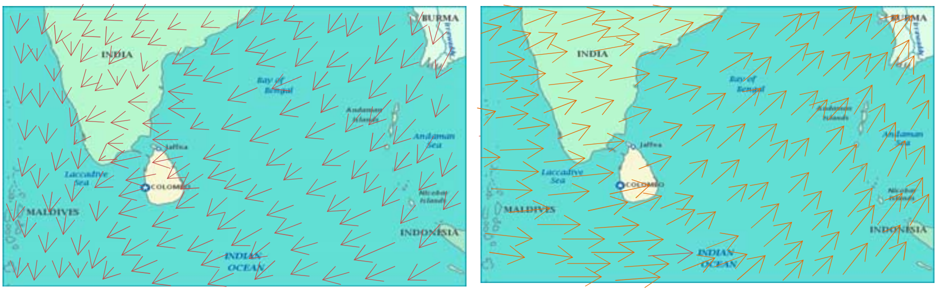


Figure 1: *Wind patterns around Sri Lanka during two monsoon periods: (a) North east, (b) South west [8].*

2.2 Estimation of wave power

2.2.1 Wave data

The available wave data in Sri Lanka are limited only for some locations, but the directional wave climatic study done by CCD-GTZ coast conservation project in the southern coastal area provides an overall wave climatic data of the region [9]. Furthermore, the study in [10] on the estimation of near shore wave climate of the Southern coast of Sri Lanka shows that the south west coast has good swells. According to CCD_GTZ data, moderately high waves are common along the south to south west coast throughout the year [9].

Site specific wave climatic data are usually required to estimate the wave characteristics of the candidate locations studied in this endeavour (see section 4). However, due to the unavailability of such data, as an alternative, the available seasonal wave climatic data were modelled with NWWIII (Noaa Wavewatch III) [11]. The NWWIII modelling had a resolution of 1^0 which covered an area of 96.6 x 96.6 km^2. NWWIII uses information about wind and ocean depth, and a minimum depth of 25 m deep-sea approximation is used [12]. The used data was modelled in every three hours from year 1997 to 2006. Those data contained the wind and wave directions, the significant wave heights, the peak periods and the wind strengths [11]. Figure 2 shows the seasonal wave height data and peak period data of off Galle obtained from the above modelling method. Figure 3 shows the scatter diagram of significant wave period with the significant wave height for swells of off Gale by the study of CCD_GTZ [9] and the results obtained from the modelling method were within the acceptable margins of the measured data [9].

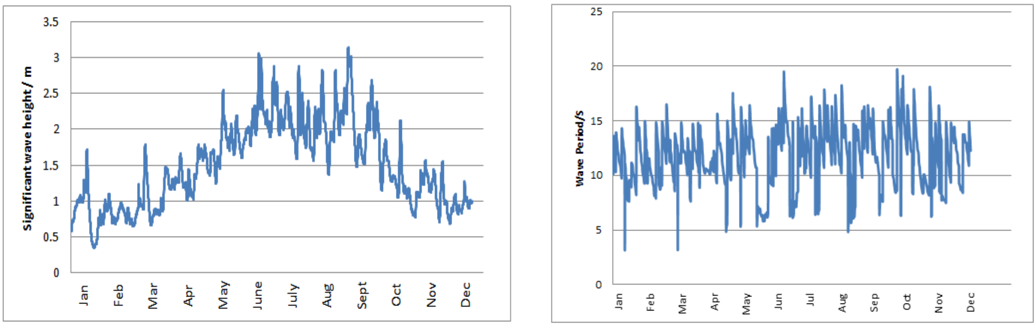


Figure 2: *Seasonal wave height data and wave period data.*

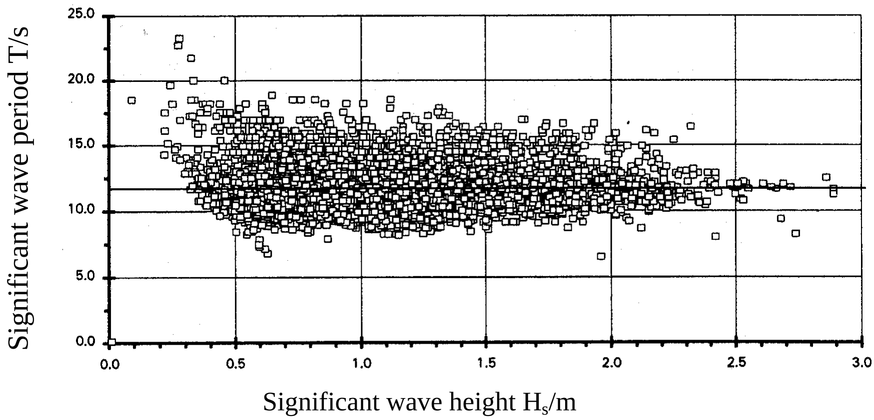


Figure 3: *Significant wave period vs Significant wave height [9].*

2.2.2 Wave power

The sea is usually considered as a combination of waves in different directions with different frequencies. Therefore, the power or energy quantification is different from a single sinusoidal wave. The wave energy (E) transportation per meter of wave breadth quantifies the amount of mechanical energy available in waves can be estimated as described in equation 1 [13].

$$E = \frac{\rho g^2}{32\pi} T H^2 \tag{1}$$

ρ - density, g - gravitational acceleration,

H - significant wave height

In order to have a clear idea about the energy content at a particular location of the sea, wave measurements conducted for a longer period is required and the wave spectrum can be obtained by Fourier analysis. Not only wave spectrum data, but also the time series wave data on a particular site is also important in designing and implementation of control strategies of wave energy devices [14]. Figure 4 shows the seasonal wave energy flux (E) of off Galle area with annual average power of 15 kW per meter of wave breadth. The swell wave period is within 8 s to 17 s.

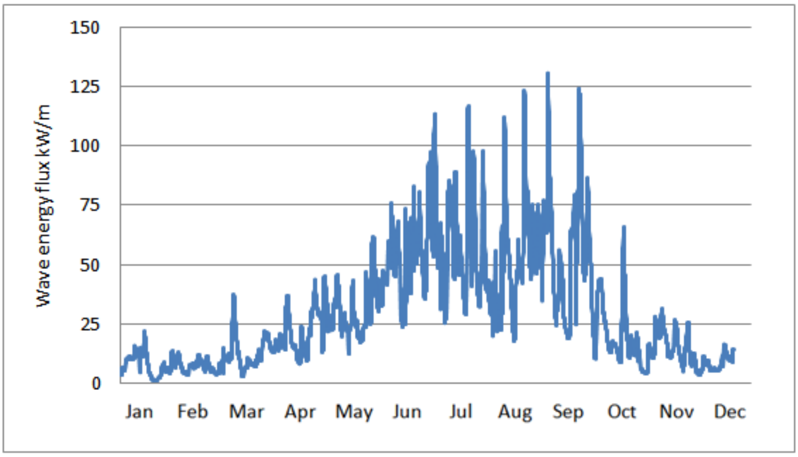


Figure 4: *Seasonal wave energy flux (energy transportation).*

3 AVAILABLE TECHNOLOGIES AND POSSIBLE OPTIONS FOR SRI LANKA

3.1 Overview of wave energy device types

As the wave characteristics across the globe differs, methods of harnessing the wave power also change. It is known that offshore wave power levels reach 30-100 kW/m at latitudes 40° - 50°, and lesser toward south and north regions of the earth. Most of the tropical seawater has an average power level below 20 kW/m [14]. Sri Lanka also falls into this category and therefore selection of efficient technologies (devices) is essential to make the economically viable wave power plant.

Wave energy devices can be categorised according to different criteria such as location, energy conversion method, power take off system, etc. However, the two most common categorisation methods are according to the location and the operating principle. Regardless of the imprecise definitions for the near shore and offshore regions (locations), these devices can be categorized according to the operating principle for easy understanding. Figure 5 shows an overview of wave energy devices with different power take off systems.

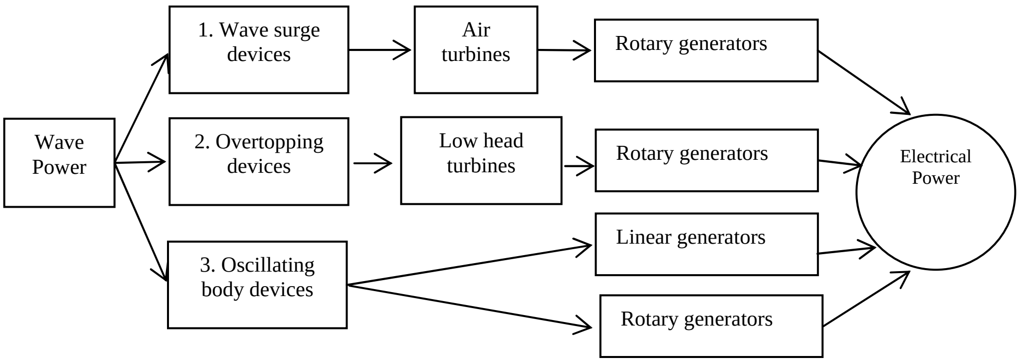


Figure 5: *Overview of different wave energy extraction systems.*

The first type is mainly about the Oscillating Water Column (OWC), which is the most widely researched and tested in the world [15]. In OWC, an airflow trapped inside a chamber is forced to move according to the wave surge via an air turbine as shown in Figure 6. OWCs are usually robust. However, secondary conversion of the power via air turbine significantly reduces the overall conversion efficiency mainly due to inherent low efficiency of air turbines. Hence, the cost vs. effectiveness of this type of device is a matter especially in low energetic seas.

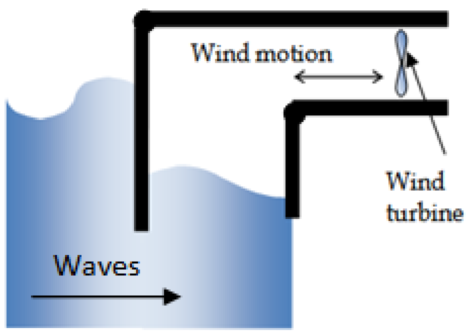


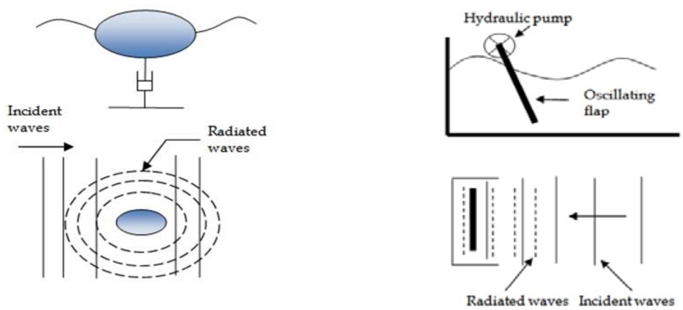
Figure 6: *A simple oscillating water column device [16].*

The second type is mainly on the wave channeling systems, generally identified as overtopping devices. The kinetic energy of the wave drives the water to an elevated location and spill through low head turbines. Examples of such devices are Wave Dragon [17] and Tapchan. The Tapchan device is highly site specific and natural locations for suitable sites are very limited. Also, the secondary power conversion through low head turbines again lowers the overall efficiency of such devices. Further, the wave power should be sufficiently high to get sufficient head for more efficient power conversion.

The third type of wave energy systems consist of oscillating bodies that directly interfere with the incident waves and produce oscillations to the energy extracting mechanism. The principle behind such devices is that a device capable of producing good waves by mechanical excitations in calm water is a good candidate to be an efficient energy extractor. On the other hand, to achieve better wave energy conversion, radiating waves should destructively interfere with the incident waves.

The floating body shown in Figure 7 (a) heaves with the wave and radiates ring shaped waves outwards. It needs to get all the incident waves to be in a radial direction to have a maximum power conversion. Although with the wave focusing effect, the power capture ability improves, it can be improved further by setting arrays of such devices [14].

The other type of oscillating body system is flap type devices such as "Pendulor" shown in Figure 7 (b). The radiating waves from such device are in the opposite direction of the incident waves. Hence, it can interfere almost completely in destructive way with the incoming waves as shown in Figure 7 (b). Thus, such systems convert energy with high efficiency [14].



(a) (b)

Figure 7: *(a) Point absorber and wave field (b) Pendulor type device and wave.*

Further, the above types of wave energy devices can be categorized according to the Power Take Off systems (PTO). Hydraulic PTO systems are the most widely used, because of the intrinsic ability of hydraulic oil to store energy as the hydraulic pressure. Some of the devices use linear electrical generators to convert the energy directly to electricity. Various other proposals have similar types of power take off systems with minor differences.

3.2 On shore or Offshore?

Generally, near-shore wave activities are less energetic due to the effects from reflections, diffractions and seabed frictions. However, due to the effects on local topographical and wind climatic conditions, high energy concentrated hot spots are available at several near shore locations.

Near shore devices have the inherent maintenance simplicity as a promising aspect. On shore line devices have lesser maintenance and capital investment to be done at the expense of operating under inconsistent wave power capacity. When the shore line devices are operated under shallow water waves, they have less probability of interfering with extreme ocean conditions. This particular type can also be used as breakwater device, which makes them for dual purposes [6].

Due to the less power fluctuations and high wave power levels at off-shore sites, off-shore devices are favoured despite of their relatively high cost on plant, maintenance and power transmission. Moreover, offshore devices can be built in mass scale because they are not significantly site specific as of on shore devices. Some tested offshore devices are McCabe pump, Pelamis and Archimedes Wave Swing (AWS). Figure 8 shows an artistic view of Pelamis wave energy device. The relative motion among the attached buoys drives a hydraulic power take off system to run the electric generator.

In order to achieve required economic feasibility levels in low wave climatic conditions similar to Sri Lanka, the power conversion efficiency of a device is the key factor to be concerned [6]. Therefore, oscillating body devices are good candidates than indirect type devices.

Figure 8: *Pelamis wave power device [18].*

4 ELECTRICAL FEASIBILITY OF WEPP

The Ceylon Electricity Board (CEB), as the power utility in Sri Lanka, allows a maximum of 10 MW grid connected power under distributed generation category to the 33 kV distribution network. Large power plants have to be connected to the transmission network (132 kV and 220 kV), which incurs more cost for small power plant with capacity of just above 10 MW. Therefore, the maximum power output from the WEPP is confined to 10 MW from the generator technology used.

Figure 9 shows the expected average power output from a typical WEPP from 1st of January (00.00 am) to 31st of December (23.59pm) according to the wave data used in this study. Due to maximum 10 MW power constrain, the output power was clipped at 10 MW (see the Figure 9). However, the excess power can be effectively stored in energy storage devices such as battery banks, fly wheels etc. by using power electronic convertors [19 and 20]. A detailed study of energy storage is recommended before implementation. Moreover, this study only deals with the long term fluctuations of wave power. In order to analyse the short term fluctuations of wave power, more precise wave data is required. Therefore, a separate study is required with more precise data to analyse the power quality issues such as voltage flicker and voltage sag, which may arise due to short term fluctuations of wave power.

The study of electrical feasibility was carried out in order to select the suitable sites for WEPP which gives minimum voltage fluctuation to the CEB network. Six different grid locations along the southern coast were selected in the CEB transmission and distribution network as shown in Figure 10.

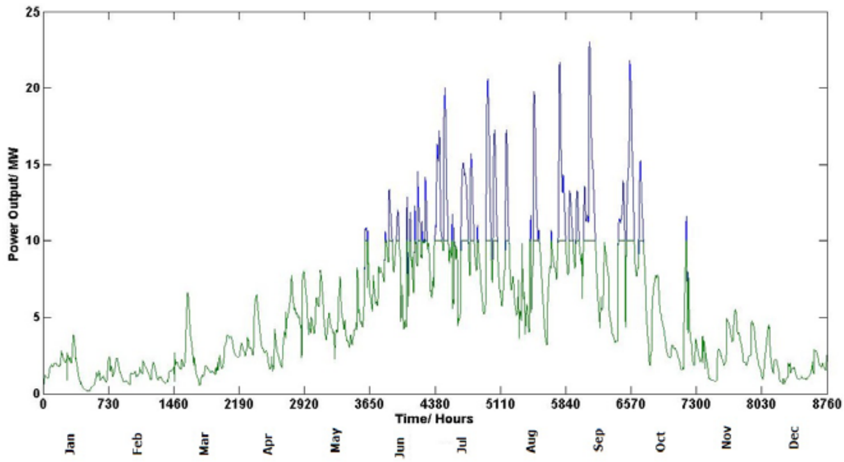


Figure 9: *Wave Power Vs Time.*

Figure 10: *Proposed WEPP's in Southern Coastal Area in Sri Lanka.*

The selected sites are:

1. Matugama
2. Galle/Unawatuna
3. Matara
4. Hambantota
5. Bundala
6. Palatupana

First, the electricity transmission network was modeled using the Integrated Power System Analysis (IPSA) software. The predicted Sri Lankan power systems network for 2016 was used for the simulations [21].

Each WEPP was connected to the nearest 33 kV busbar of the network as a single generator with rated output power of 10 MW and synchronous reactance of 0.1 p.u. (with respect to system base of 100 MVA) through a three phase transformer. The details of the grid connections are given in Table 1. The generator busbar voltage was kept at 1 p.u.

Table 1: *WEPPs' Connected Bus Bars*

WEPP	***Connected Bus Bar***
Matugama	Matugama_33
Galle/Unawatuna	Galle_33a
Matara	Matara_33
Hambantota	Hambantota_33
Bundala	Bundala_33
Palatupana	Palatupana_33

Except Matugama, Matara and Hambantota WEPPs, some slight modifications had been done on the actual transmission network predicted for 2016. Since Unawatuna and Galle are nearby, both WEPPs were connected to Galle_33a existing busbar. Bundala is about 20 km away from Hambantota and Palatupana is about further 20 km away from Bundala. Therefore, two new 33 kV busbars were added to the proposed 2016 electricity transmission network with predicted loads as shown in Figure 11.

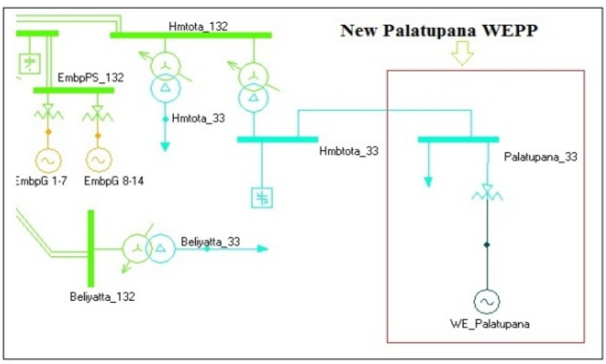


Figure 11: *Newly added Palatupana WEPP to the existing Sri Lankan network.*

Load flow analysis was carried out under normal operating conditions for each proposed WEPP site. This was done for power generation starting from 0 MW (with no power produced) to 10 MW with the steps of 2 MW. An example of power and busbar voltages conducted at Hambantota 33 kV busbar is shown in Table 2. Similarly, the voltages of nearest 33 kV and 132 kV busbars around WEPPs were taken into consideration. Figure 12 shows the voltage variation of the closest busbars of two selected locations i.e. Matugama and Hambantota, which were identified as the locations with maximum and minimum voltage fluctuations in this study. Finally linear interpolation technique was used to obtain the voltage variation at each busbar with respect to the time. Here the time variation of available wave power was taken from Figure 9. Separate plots were drawn for the selected busbars for the period of one year. Figure 13 shows the variation of the bus bar voltages for two selected locations, where the maximum and minimum voltage variation was observed.

Table 2: *Variation of Bus bar voltage with Power Output in Hambantota WEPP*

Power Output/ MW	*Busbar Voltage/ p.u. (Hambantota_33 kV)*
0	1.002
2	1.002
4	1.002
6	1.003
8	1.003
10	1.003

The feasibility of electrical grid connection was checked based on the voltage fluctuations. According to the CEB standards, the maximum allowable voltage fluctuation for 33 kV and 132 kV are respectively 6% and 10% [22 and 23].

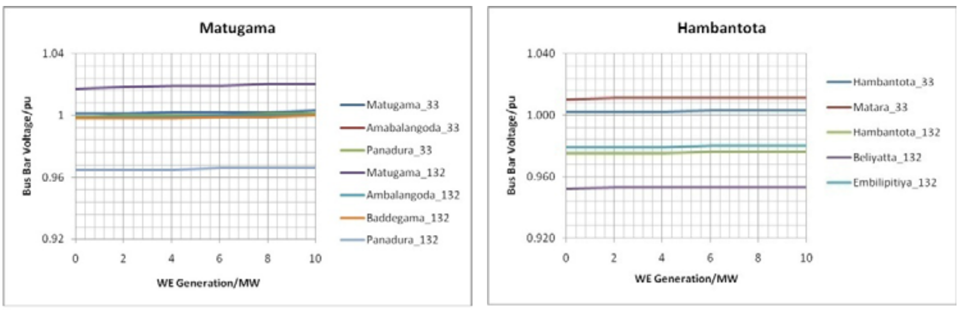


Figure 12: *Voltage variation of the closest busbars of Matugama and Hambantota.*

According to Figure 13, the highest voltage fluctuation noted in the Matugama 33 kV busbar was within the allowable limit. Therefore, voltage fluctuations of the busbars of all proposed locations exist within the allowable limits.

For further analysis, the fault levels of the selected sites were obtained using IPSA fault level calculations. A three phase line-line-line symmetric fault was applied for each WEPP interconnected busbar with a fault time of 100ms, with zero fault impedance. The corresponding fault currents were obtained and results are shown in Table 3.

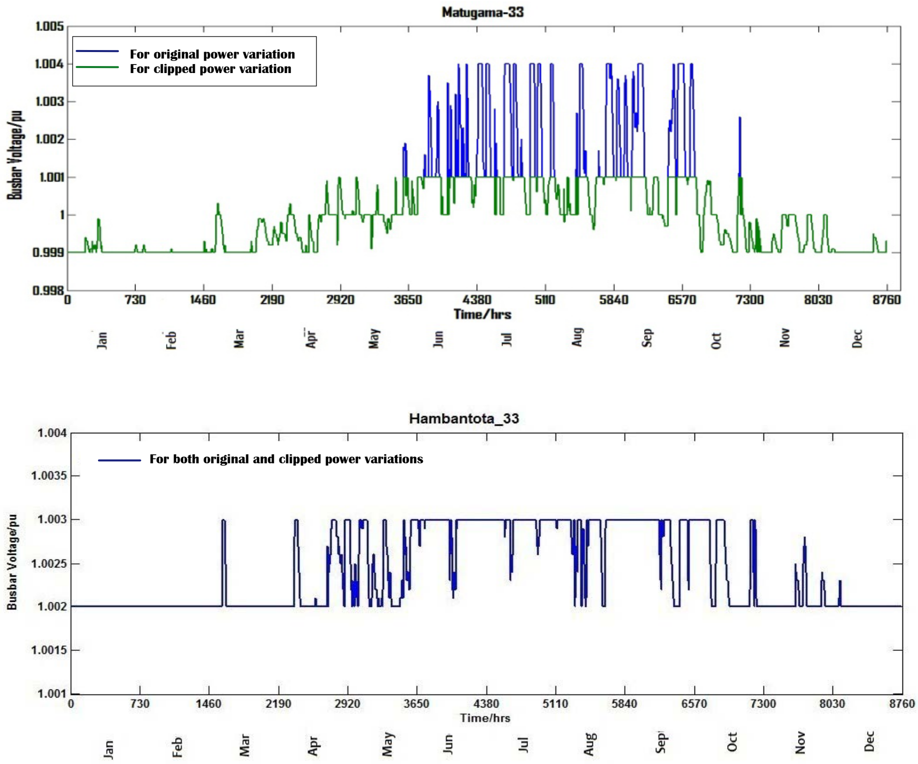


Figure 13: *Variation of 33kV bus voltage during a year for Matugama_33 and Hambantota_33 WEPP.*

Table 3: *Comparison of fault currents*

Interconnection Bus Bar	*Fault Level/ kA*	
	Before the WEPP	*After the WEPP*
Matugama_33	12.244	22.435
Galle_33a	9.301	19.620
Matara_33	10.641	20.941
Hambantota_33	7.200	18.637
Bundala_33	5.194	17.140
Palatupana_33	4.549	16.617

According to the CEB regulations, the fault level for 33 kV and 132 kV should be less than 25 kA. Therefore, the results of the fault level analysis are within the allowable fault current levels.

By analysing all the simulation results, this electrical feasibility study resulted that it is feasible to connect a WEPP with a capacity of 10MW to the grid from any of the proposed locations.

5 SOCIAL AND ENVIRONMENTAL CONCERNS

The social and environmental concerns of establishing WEPPs have to be considered before implementing the WEPPs. These issues can arise in the areas such as coastal activities, marine biology, water pollution, visual effects and land uses. Environmental impacts of wave energy conversion devices are mainly based on the specific site and the technology. Structural born environmental impacts of wave energy plants are similar to other shore line or offshore structures, by virtue of their physical presence in the water. By proper site selection and design, it is possible to avoid or reduce the negative impacts to the environment. Many such issues are very common in all over the world.

Despite being an offshore structure with above issues, it is still a clean energy producer with some other specific advantages. According to the specifications given for some specific devices, all boat traffic must cease in the plant area, which in-turn makes the wave power buoys to function as fish attracting devices. This will be an added advantage for fisheries in the long run.

6 DISCUSSION AND CONCLUSIONS

Wave data of particular sites has to be obtained to determine the feasibility of a particular site. However, currently such data is not available for Sri Lanka and therefore an estimated set of data for the southern coastal area was used in this study. Economic and environmental feasibility of specific sites were not investigated due to practical limitations. Therefore, before the real implementation of such WEPPs, it is necessary to investigate whether they are economical when compared to other energy sources.

The wave power utilization has not been implemented in competitive commercial products; nevertheless the attempts on studying the economics of other renewable energy sources have made inroads to the economic analysis of wave power harnessing. Two different types of analysis are being involved in economic studies: (i) economics of plant design, equipment costs and construction costs (cost of power) and (ii) economics of power marketing (market value) [15].

When considering the cost of power, usually it is compared with the cost of most likely thermal alternative sources. Alternatively marginal cost representation of the market price of capacity and energy can be used as a market value analysis.

In this study, Feasibility of WEPPs has been investigated based on mechanical, electrical and sociological aspects. It is concluded that WEPPs with a capacity of 10 MW are electrically feasible for any of the proposed site.

7 REFERENCES

[1] W. Li, K.T. Chau, J. Li, X. Zhang: *“Wave Power Generation and its Feasibility in Hong Kong.”* 8th International Conference on Advances in Power System Control, Operation and Management (APSCOM 2009), China, 8-11 Nov. 2009.

[2] H. Rahman: *“Alternate Sources of Electric Energy.”* IEEE Potentials, Volume 7, Issue 2, pp. 22 - 25,1988.

[3] A. Clement, P. McCullen, A. Falcao, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewish, K. Nielsen, S. Petroncini, M.T. Pontes, P. Schild, B.O. Sjostrom, H.C. Sørensen, T. Thorpe: “*Wave Energy in Europe: Current Status and Perspectives.*” Renewable and Sustainable Energy Reviews, pp 405 - 431, 2002.

[4] J.M. Leishman, G. Scobie: *“The Development of Wave Power.”* Economic Assessment Unit, National Engineering Laboratory, East Kilbride Glasgow, Scotland, 1976.

[5] M. Rahm, C. Bostrom, O. Svensson, M. Grabbe, F. Bulow, M. Leijon: “*Offshore Underwater Substation for Wave Energy Converter Arrays.”* IET Proceedings on Renewable Power Generation, Volume 4, Issue 6, pp. 602 - 612, 2010.

[6] T. Watabe, H. Yokouchi, S.D.G.S.P. Gunawardane, B.R.K. Obeyesekera, U.I. Dissanayake: *“Preliminary Study of Wave Energy Utilization in Sri Lanka.”* Proceedings of the eleventh International Offshore and Polar Energy Conference, Stavanger, Norway, pp. 596 - 603, June 17-22, 2001.

[7] R. Suppiah, M. Yoshino: *“Rainfall Variations of Sri Lanka Part 1: Spatial and Temporal Patterns.”* Meteorology and Atmospheric Physics, Vol. 34, pp 329 - 340, 1984.

[8] http://www.yourchildlearns.com/online-atlas/sri-lanka-map.htm, accessed in February 2012.

[9] H.J. Scheffer, K.R.M.D. Fernando, T. Fittsehen: *“Directional Wave Climate Study South West Coast of Sri Lanka.”* Sri Lankan German Cooperation, CCD_GTZ Coast Conservation Project, 1994.

[10] P.P. Gunaratne, D.P.L. Ranasinghe, T.A.N. Sugandika: *“Assessment of Nearshore Wave Climate off the Southern Coast of Sri Lanka.”* IESL Engineer Journal, pp. 33 - 42, April 2011.

[11] www.magicseaweed.com , data collected on 2011-05-15.

[12] Environmental modelling centre 2009: http://polar.ncep.noaa.gov/waves/implementations.shtml , accessed in May 2011.

[13] J. Falnes: *"Ocean Waves and Oscillating Systems."* Cambridge University Press, July 2005.

[14] J. Falnes: *"A Review of Wave-Energy Extraction."* Marine Structures Journal, Vol. 20, pp. 182 - 201, June 2007.

[15] M.E. McCormick, Y.C. Kim: *"Utilization of Ocean Waves - Wave to Energy Conversion."* American Society of Civil Engineers, pp. 142 - 154, 1987.

[16] http://taperedchannelwaveenergy.weebly.com/index.html, accessed in February 2012.

[17] http://en.wikipedia.org/wiki/Wave_Dragon accessed in December 2013.

[18] http://www.pelamiswave.com/image-library, accessed in February 2012.

[19] A. Arulampalam, M. Barnes, C. Fitzer, X.G. Wu, N. Jenkins: *"Automated Control Technique to Coordinate Microgrid Sources - Grid Connected and Islanded Operation."* International Journal of Distributed Energy Resources, Vol. 1, No., ISSN 1614-7138, pp. 133 - 148, April - June 2005.

[20] A. Arulampalam, M. Barnes, A. Engler, A. Goodwin, N. Jenkins: *"Control of Power Electronic Interfaces in Distributed Generation Microgrids."* International Journal of Electronics, Vol. 91, No. 9, pp. 503 - 523, September 2004.

[21] C. Vivekananthan, M. Anparasan, S. Arunprasanth, M.A.R.M. Fernando, A. Atputharajah, U.R. Ratnayake: *"Incorporating Pumped Storage Power Plant in the Sri Lankan Electricity Sector."* Annual Transactions of IESL, pp 488-495, 2011

[22] Planning and Development branch, Distribution Region 1, Ceylon Electricity Board: *"Medium Voltage Distribution System Development Plan 2010-2011."* pp. 10, April 2011.

[23] Transmission Planning Section, Transmission and General Planning Branch, Transmission Division, Ceylon Electricity Board: *"Long Term Transmission Development Plan: 2008-2016."* pp. 2 - 3, March 2009.