IJESRT: 9(5), May, 2020 ISSN: 2277-9655

International Journal of Engineering Sciences & Research Technology

(A Peer Reviewed Online Journal)
Impact Factor: 5.164

IJESRT

Website: www.ijesrt.com Mail: editor@ijesrt.com

IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

TOLERANCE ANALYSIS OF A LINEAR WAVE POWER GENERATOR

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DOI: 10.5281/zenodo.3828891

ABSTRACT

The world's ever increasing demand for useful energy carriers have put a focus on the renewable energy conversion technologies. Numerous research groups have tried to convert the energy from the ocean waves and a series of concepts and techniques have over the years been developed. A research group at Uppsala University has designed a wave energy conversion system based on a linear permanent magnet generator, driven by a point absorbing buoy. This paper presents sensitivity analysis of the mechanical and magnetic design of the linear generator, performed to increases the knowledge of the sustainability and sensitivity of the machine. The present results show a non-negligible impact on both the mechanical design and the wave energy converter's energy conversion.

KEYWORDS: Linear Generator, Wave Power, Electrical Machine.

1. INTRODUCTION

The ocean waves are an attractive renewable energy source as it offers high utilization, no fuel cost as well as a high power density, and a number of different research groups around the world are currently investigating the possibilities to convert this energy to electric energy [1-3].

A research group at the Division of Electricity, Uppsala University, has developed a wave energy conversion system based on a linear permanent magnet generator, direct driven by a point absorbing buoy [4-6]. The direct driven approach reduces the mechanical parts to a smallest amount, believed to increase the lifetime of the power plant. The latest full scale prototype, presented in Fig 1, was deployed outside the Swedish west coast in March 2013.

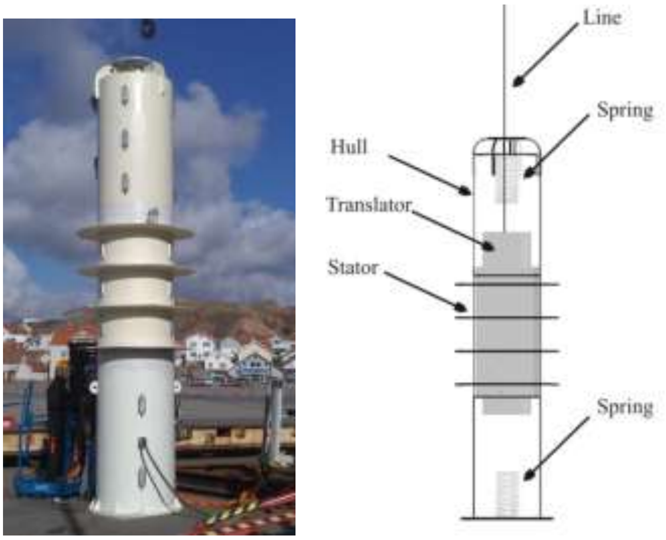

Figure 1. The full scale prototype L12

This paper presents a sensitivity analysis of the generator's stator and the translator. As the variations, tolerances, of the different mechanical parts in the generator accumulate; the final product will vary [7]. It is necessary to investigate the tolerances of the different parts carefully, i.e. perform a tolerance analyse, to get a true picture of the generators mechanical and magnetic design.

2. THE STUDY

As the magnetic part of the generator, the translator, heaves up and down through the stator, an attractive magnetizing force between the two parts is achieved. With knowledge of the dimensions and material parameters in the magnetic circuit, the magnetic field density in the air gap, B_{ag}, the magnetic energy in the air gap, W_m, and the amplitude of the attractive force, $\vec{F}_r$, can be found: [8,9]

$$B_{ag} = \frac{B_m l_m A_m / (\mu_0 \mu_m A_m)}{2 * l_{agI} + 2 * \left(\frac{A_{ag} l_{agII}}{\mu_0 A_{agII}} + \frac{A_{ag} l_s}{\mu_0 \mu_s A_s} + \frac{A_{ag} l_{ps}}{\mu_0 \mu_{ps} A_{ps}}\right)} \quad (1)$$

$$W_m = \frac{{B_{ag}}^2}{2\mu_0 \mu_r} \quad (2)$$

$$\vec{F}_r = \frac{dW_{magnetic}}{dr} \quad (3)$$

where μ_0 represents the permeability, μ_r , μ_m , μ_s and μ_{ps} represents the relative permeability of each part whereas A_{ag} , A_{agII} , A_{ps} , A_s and A_m represent the different cross-section-areas. The length parameters l_m, l_{agI}, l_{agII}, l_s and l_{ps} as well as the directions are defined in Fig 2 and Fig 3.

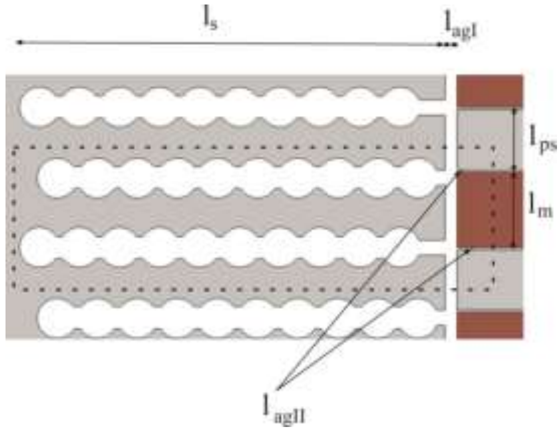

Figure 2. A picture of the magnetic circuit

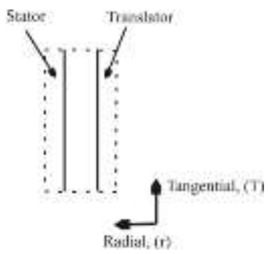

Figure 3. The introduces directions

The stator and translator is divided in three sections, where each section represents one phase. Each section is in turn divided in three sides, illustrated in Fig. 4, i.e. the generator is a nine side-construction. The symmetry of the generator shall in the ideal case eliminate the resulting magnetic force on the translator. In reality is, however, a small displacement of the translator relative the stator expected, illustrated in Fig 5, as tolerances in all mechanical parts are more or less impossible to avoid.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

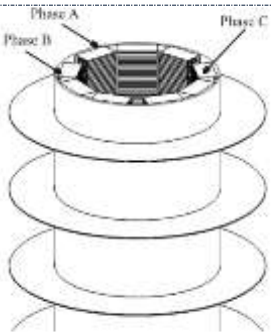

Figure 4. The nine-side construction

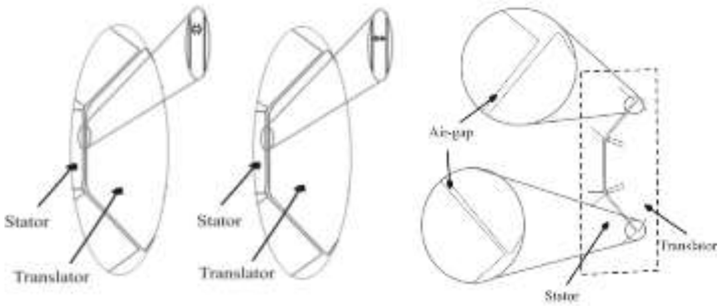

Figure 5. Possible scenarios

With different length of the air gap, the magnetic field density and therefore the magnetic force differ from width to width. The mechanical design of the generator shall therefore be dimensioned for a non-zero resulting radial magnetic force, i.e. support structure between the stator and translator is required. To dimension this support structure in a correct way, it is necessary to investigate the tolerances of the different parts carefully to get a true picture of the complete system.

As the induced voltage is linear to the magnetic field density, the study further presents a sensitivity analysis of the output voltage and power, P, of the machine.

$$U = -N\frac{d\Phi}{dt} = -N\frac{dB_{ag}A}{dt} \tag{4}$$

$$P = \frac{U^2}{Z} \tag{5}$$

U represents the induced voltage, N numbers of turns, $\frac{d\Phi}{dt}$ presents the time-depended magnetic flux and Z is the total impedance of the circuit.

The study includes two different scenarios. The first one, *The Worst-case analysis*, is performed to investigate the extreme values in the system. The second study, *The Statistical analysis* has been performed to reach results more likely the reality.

Worst-case analysis

The individual variables tolerance limit, T, are summed in order to make the deviation,σ , as large as possible:

$$\sigma_{\max imum} = \sum |T_i| \tag{6}$$

The largest, L_{max}, respectively the smallest, L_{min}, airgap is defined as:

$$L_{\max} = L_{air-gap} + \sigma_{\max imum} \tag{7}$$

$$L_{\min} = L_{air-gap} - \sigma_{\max imum} \tag{8}$$

Statistical analysis

The estimation of the deviation, ,$\sigma_{\text{statistical}}$, adds the value of the tolerance, T, as presented in Eq (9).

$$\sigma_{statistical} = \sqrt{\sum \left(\frac{T_i}{3} \right)^2} \tag{9}$$

The largest, L_{max}, respectively the smallest, L_{min}, airgap is defined as:

$$L_{\max} = L_{air-gap} + \sigma_{statistical} \tag{10}$$

$$L_{\min} = L_{air-gap} - \sigma_{statistical} \tag{11}$$

Since the equation considers the statistical deviation of the different combinations, the results are more likely the reality. [7,10]

Information about further utilization of two-dimensional [7] and multi-dimensional [11, 12] tolerance analysis in both academy and in industry can be found in literature.

3. RESULTS AND DISCUSSION

Table presents the resulting force on the support structure in per unit, p.u., normalized to the statistical value.

Table 1. The resulting force

	Absolute value	**Radial direction**	**Tangential direction**
$F_{resulting\_force,WorstCase}$, p.u	3.31	3.4	3.38
$F_{resulting\_force,statistical}$, p.u	1	1	1

As presented in Eq (1) and Eq (4), the induced voltage is linear to both the magnetic flux density and the air gap width. The greatest induction shall be gained as the tolerances minimizes the air gap, and vice versa, the smallest induction shall be gained when the tolerances maximizes the air gap. Table II presents the induced voltage and the output power at the different scenarios in p.u, normalized to the air gap set point.

Table 1I. The induced voltage and output power

	Maximum airgap	**Setpoint**	**Minimum airgap**
Voltage, p.u	0.83	1	1.17
Power, p.u	0.69	1	1.36

As presented, the worst case scenario represents an 3.31 times greater absolute value of the force, compared to the statistical analysis.

The delivered power is greatly affected of the different tolerances scenarios. A larger air gap can be retrospect adjusted with help of the stator fixture, but if the air gap becomes too small, a similar retrospective choice is not an option with the current design. Hence, to ensure a stable and reliable operation of the linear generator, the solution adopted by the authors has been to dimension the mechanical design to withstand this larger, worst case, force. The drawback of this design approach is the required component tolerance, increasing manufacturing costs, material costs and time-consuming inspection processes.

4. CONCLUSIONS

The paper presents two different analyses, performed to investigate the impact of the tolerances in a linear permanent magnet generator, installed in a wave power system. The first study, *The Worst-case analysis*, is performed to investigate the extreme values in the system whereas the second study, *The Statistical analysis* has been performed to reach results more likely the reality. The results are aimed to improve the machine's quality and reduce the overall cost as the tolerances will influence the final assembled product, the production, method and setup cost as well as inspection during the mounting.

The presented results show a non-negligible impact on both the mechanical design and the energy conversion, knowledge required to include during the design stage of the machine. As the worst case scenario represents an 3.31 times greater force compared to the statistical, an underestimation of the resulting magnetic force can result in a mechanical break down.

5. ACKNOWLEDGMENTS

This research was carried out as part of the Statkraft Ocean Energy Research Program, sponsored by Statkraft. (www.statkraft.no) The support is gratefully acknowledged. The authors would also like to thank The Swedish Research Council, Grant No 2009-3417, Swedish Centre for Renewable Electric Energy Conversion, Swedish Governmental Agency for Innovation Systems, Stand Up for Energy strategic government initiative, Swedish Energy Agency, Draka Cable AB, the Göran Gustavsson Research Foundation, Statkraft AS, Fortum, Stiftelsen Olle Engkvist Byggmästare, Stiftelsen J. Gust Richert, Inno Energy CIPower, Ångpanne föreningens Forskningsstiftelse, Seabased, Civilingenjörsförbundets Miljöfond, and the Wallenius Foundation for its financial support.

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