Coupled Magneto-Mechanical Modeling of a TPMLG for Wave Energy Conversion

Bachir Ouartal[a], Meziane Hamel[b], Mustapha Zaouia[a], Ratiba Fellag[c], Riad Moualek[a], Ahmed Nait Ouslimane[d]

[a]*Laboratory of Advanced Technologies in Electrical Engineering, University of Tizi-Ouzou, Algeria.*
[b]*Laboratory of Energy and Mechanical Engineering, University of Boumerdès, Algeria.*
[c]*Laboratory of Robotics and Industrial Automation, Advanced Technology Development Center, Algeria.*
[d]*Department of Electrotechnics, University of Tizi-Ouzou, Algeria.*

This article explores the design and simulation of a Tubular Permanent Magnet Linear Generator (TPMLG) for wave energy conversion using the Finite Element Method (FEM). The TPMLG is modeled with the T-Ω formulation and a mechanical model to analyze electromagnetic-mechanical coupling. Experimental data validate the accuracy and reliability of the T-Ω formulation in modeling TPMLG behavior. The proposed approach offers an efficient and accurate way to design and simulate TPMLGs for wave energy conversion, which can significantly advance the development of this promising technology.

Keywords: Tubular linear generator; finite element method; T-Ω formulation; wave energy conversion.

1. Introduction

The global shift toward renewable energy has intensified research into wave energy conversion systems, including point absorbers, oscillating water columns, and overtopping devices. Among these, TPMLGs have emerged as a leading solution due to their high efficiency, direct drive capability, and superior power density [1]. Their ability to convert the oscillatory motion of waves directly into electricity makes them particularly attractive for sustainable energy harvesting.

A critical challenge in TPMLGs development lies in accurately modeling their electromagnetic and mechanical behavior under dynamic wave conditions. The FEM has proven indispensable in this regard, enabling high-fidelity simulations of complex electromagnetic-mechanical interactions [2]. However, traditional FEM demands substantial computational resources, often making iterative design optimization impractical.

To address this limitation, the T-Ω formulation has emerged as an advanced mathematical approach, significantly reducing computational overhead while preserving accuracy [3]. By simplifying the governing equations of electromagnetic systems, this method enables faster simulations without compromising predictive reliability.

This paper explores the performance of a TPLMG for wave energy conversion. The TPMLG is modeled using the T-Ω formulation, and the simulations are validated using experimental data to demonstrate the accuracy and reliability of this approach. In addition, a mechanical model is incorporated to investigate the coupling between the magnetic field and the structural mechanics of the generator. The proposed approach offers a more efficient and accurate way to design and simulate TPMLGs, and has the potential to advance the development of this promising technology.

2. Results and discussion

The T-Ω formulation describes the physics through the use of the electric vector potential T and the magnetic scalar potential Ω. This formulation has the advantage to permit a reduction of computing cost by decreasing the degrees of freedom from three to one in all the non-conducting region.

In eddy current region, the system to solve is given by equations (1) and (2):

$$\vec{\nabla} \wedge \left(\frac{1}{\sigma}\vec{\nabla} \wedge \vec{T}\right) - \overrightarrow{\nabla(\frac{1}{\sigma}\vec{\nabla}.\vec{T})} + \mu\frac{\partial}{\partial t}\left(\vec{T} - \overrightarrow{\nabla\Omega}\right) = 0 \qquad (1)$$

$$\vec{\nabla}.\left(\mu\left(\vec{T} - \overrightarrow{\nabla\Omega}\right)\right) = 0 \qquad (2)$$

In current-free regions the magnetic field can be found from the scalar potential:

$$-\vec{\nabla}.\mu\overrightarrow{\nabla\Omega} = 0 \qquad (3)$$

Figure 1 illustrates the comparison between the FEM simulated output power and experimental measurements under irregular wave conditions. The results show a maximum output power of nearly 3 watts, meeting the design specifications [4]. Notably, the numerical results align closely with the experimental data, demonstrating the accuracy and reliability of the FEM model in capturing the generator’s real-world performance.

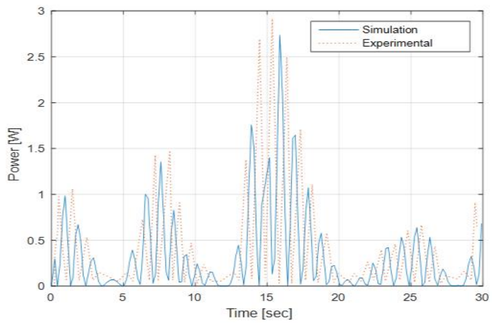

Figure 1: Electrical output power of the TPMLG.

References

[1] L. Chunyuan, Y. Chen, R. Dong, B. L Ye, Renewable Energy, **216** (2023), 119087.
[2] S. Qiu, W.Zhao, C. Zhang, J. K. Shek, H. Wang, IEEE Transactions on Energy Conversion, **37** (2021), 24-35.
[3] P. Bettini, R. Benato, S. D. Sessa, R.Specogna, IEEE Transactions on Magnetics, **53** (2017), 1-4.
[4] J. M. Kim, M. M. Koo, J. H. Jeong, K. Hong, I. H. Cho, J. Y. Choi, AIP Advances, **7** (2017), 056630- 056635.