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A fully floating system for a wave energy converter with direct-driven linear generator

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ABSTRACT

Wave energy is one of the most promising renewable energy for power generation. This research develops a novel power take-off methodology to surmount the problems associated with mooring, seawater corrosion and access for maintenance in conventional WEC (wave energy converters) with direct-driven linear generators. Its prototype consists of two bodies, the floating body acting as a buoy to extract the wave energy, while the inner body undergoes a forced oscillation, whose relative motion generates the electronic power. Its feasibility is investigated theoretically by coupling the dynamics of the wave, the floating and the inner bodies and the electromagnetic characteristics of the linear generator. As a result, the generator can induce a highly sinusoidal voltage. Furthermore, the performance of the system is investigated in detail under different conditions. The results show that, a resonance has been achieved in the case with the spring constant of 12,633 N/m, with a maximum power capture ratio of 57%. The performance of the system is shown to be sensitive to the load resistance, the wave height, and the spring constant.

1. Introduction

Nowadays, with global attention being drawn to climate change and the rising level of CO_2, the focus on generating electricity from renewable sources is once again an important area of research [1–3]. Among the emerging electrical power generation choices from renewable energy, the energy included in the oceans is one of the most promising [4,5]. Among the different forms of ocean energy, wave energy is the most conspicuous [6]. Waves are generated by winds, which in turn are generated by solar energy [7]. The potential worldwide wave energy resource is estimated to be 2 TW [8].

A number of different PTO (power take-off) mechanisms connected to the WEC (wave energy converter) have been studied, such as hydraulics, turbines, and direct-driven linear generators. An example of the WEC with hydraulics is the Pelamis [9]. The types of devices using turbines include OWCs (oscillating water columns) and overtopping devices. For instance, the LIMPET on Islay is a case of OWCs [10]. Both hydraulics and turbines act as a form of gearing to match the low-speed reciprocating motion of the wave device to high-speed rotary motion to drive conventional rotary electrical generators. It is argued that the increased complexity of hydraulics or turbines systems introduces reliability and maintenance issues [11,12]. The direct-driven linear generators offer the possibility of directly converting mechanical energy into electrical energy, with no intermediate steps between the primary interface and the electrical machine. During early researches, the direct-driven linear generators were considered as too heavy, inefficient, and expensive [13]. However, with the development of high-energy density permanent magnets, such as Neodymium–Iron–Boron (Nd–Fe–B), and the reduced costs of frequency converting electronics, the advantages of the direct-driven linear generators become more obvious [14].

A diversity of direct-driven linear generator systems has been developed for WEC. The AWS (Archimedes Wave Swing) was the first WEC using a linear electrical generator [15]. It is a fully submerged heaving device and consists of a floater and a basement, as shown in Fig. 1. The floater is pushed down under a wave crest and moves up under a wave trough. A prototype of the AWS was deployed and tested at the northern coast of Portugal in the second half of 2004 [16].

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Nomenclature

a	wave amplitude (m)
A	water plane area (m^2)
C	damping coefficient caused by mooring system (N s/m)
D_1, D_2 and D_3	diameters of the air gaps (m)
e	induced voltage (V)
E	effective value of induced voltage (V)
f_e	non-causal impulse response function (N/m)
F	force (N)
g	gravitational acceleration (m/s^2)
g_1 and g_2	air gaps (m)
H	wave height (m)
i	electric current (A)
I	effective value of current (A)
I_m	current amplitude (A)
k_{em}	electromagnetic force coefficient (N/A)
k_s	spring constant (N/m)
k_w	wave constant (W/(m^3 s))
L	inductance (H)
m	mass (kg)
N	coil turns
P	power (W)
R	generator resistance (Ω)
R_d	radiation damping coefficient (N s/m)
RAO	response amplitude operator
S_b	buoyancy stiffness (N/m)
$s + l$	half of the length of the air gap (m)
t	time (s)
T	wave period (s)
T_r	relative motion transmissibility
x	displacement (m)
$\dot{x}$	velocity (m/s)
$\ddot{x}$	acceleration (m/s^2)
X_m	displacement amplitude (m)
z	thickness of the permanent magnet (m)

Abbreviations

AWS	Archimedes Wave Swing
FEM	Finite Element Method
KVL	Kirchhoff's Voltage Law
Nd–Fe–B	Neodymium–Iron–Boron
OWCs	Oscillating Water Columns
PTO	Power Take-Off
WEC	Wave Energy Converter

Greek

ω	angular frequency (rad/s)
ρ	density (kg/m^3)
η	wave elevation (m)
Φ	magnetic flux (Wb)
φ	phase angle (rad)
$\Delta\varphi$	phase difference (rad)

Subscript

1	floating body
2	inner body
a	added
d	damping
des	design
e	excitation or electrical
em	electromagnetic
g	generator
h	hydrostatic
i	current
l	load
n	nature
r	radiation or relative
rat	ratio
s	spring
t	total
w	wave
x	displacement

Another direct-driven linear generator system was developed by Waters, as shown in Fig. 2. Its prototype was installed at a depth of 25 m, 2 km off the Swedish west coast in the proximity of Lysekil [17]. However, this single-body heaving system may raise some difficulties due to the distance between the free surface and the sea bed. Therefore, the two-body heaving systems may be used instead, in which the energy is converted from the relative motion between the two heaving bodies. The hydrodynamics of the two-body systems was theoretically analyzed in detail by Falnes [18]. However, additional problems associated with mooring, seawater corrosion, access for maintenance and the need of long underwater electrical cables have hindered their development.

In order to reduce the problems in the conventional WECs with direct-driven linear generators, we tentatively put forward a novel system as an alternative in this paper. We aim to test the feasibility of this system. The performance of the system is investigated in detail under different conditions in the present study.

2. Physical model

2.1. WEC structure

In consideration of the design constraints, the system is designed according to the R. Redlich motor [19]. The conceptual schematic of the novel WEC is shown in Fig. 3. It consists of a bottom-fixed spar and a floating system. The floating system is free to heave along the spar, but is constrained in all other degrees of freedom by a linear bearing system. The floating system consists of two bodies, the floating body acting as a buoy to extract the wave

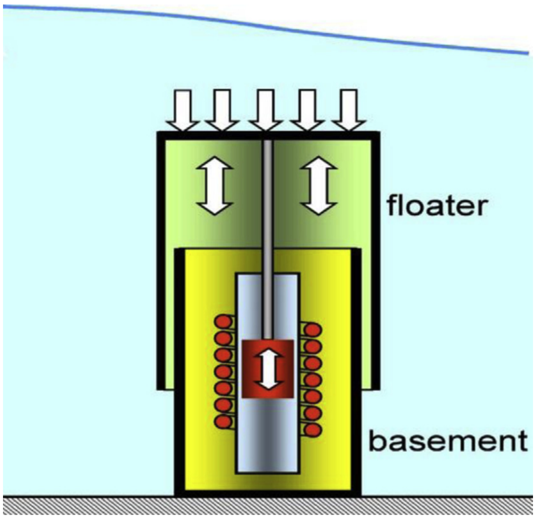

Fig. 1. A schematic of the AWS.