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Development and experiment of a 60 kW horizontal-axis marine current power system

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A B S T R A C T

A 60 kW horizontal-axis marine current power system is designed, built and tested to provide potentially cost-competitive electrical power for residents in remote islands. This power system mainly consists of a three-bladed marine current turbine, a drive-train system, power electronics and a control console. The turbine blade parameters are reasonably calculated and optimized based on the blade element momentum theory. The hydrodynamic performances of this turbine are predicted over a wide range of operating conditions. An adequate drive-train system is carefully designed to make the marine power system work smoothly and quietly even under harsh marine current conditions. The control console is also developed to facilitate the condition monitoring and generator power and speed regulations for this power system by adequately controlling the onshore power electronics. This power system has been tested under real marine current conditions to thoroughly evaluate its dynamic characteristics and effectiveness.

1. Introduction

Horizontal-axis marine current power systems are rotating devices that are primarily designed to extract and convert the kinetic energy from high-density marine currents into electricity. These power systems are obviously advantageous in minimal visual pollution and require no significant alterations of the maritime environment [1]. These systems have also been made more cost-effective and reliable due to recent technological advancements and system level optimization [2]. Therefore, massive marine energy exploitation using such systems offers a sustainable and promising alternative to other renewable energy technologies.

In recent years, research and development of such power systems have undergone significant growth and have led to improvements in various aspects of these systems. Several marine current energy systems with different features and dimensions have been designed, built and tested over the recent years [3,4]. However, most of them are still in the pilot stages and their technical details or configurations are not available due to commercial confidential reasons. Other researchers have conducted numerical analysis or lab-scale experiments of the marine current turbine performances in a towing tank and cavitation tunnel. These investigations mainly include the system design and modelling methods [5–8], hydrodynamics [9–11], flow and cavitation effects [12–14] and power smoothing control method [15]. Although relatively rough performance prediction results of the turbine systems could be provided by these experimental or analytical investigations, they were not thoroughly evaluated by sea trials under real operating conditions and hence were only applicable to a limited extent.

In this paper, a 60 kW marine current power system is designed, built and tested under real marine current conditions. Unlike the aforementioned systems in the literature, the overall design procedure of this 60 kW marine power system including the turbine blades, electromechanical systems and experimental setup is detailed and thoroughly analyzed. The entire power system has also been experimentally evaluated by off-shore sea trails and detailed experimental results are provided.

2. Marine current turbine design

2.1. Turbine description

Marine current turbine is an essential component for capturing marine current energy and its hydrodynamic characteristics highly influence the overall efficiency of the 60 kW marine power system.

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Nomenclature

a	the axial induction factor
a'	the tangential induction factor
a_m	the modified axial induction factor
a'_m	the modified tangential induction factor
a_{opt}	the optimum axial induction factor
a'_{opt}	the optimum tangential induction factor
c	the blade chord length
C_D	the drag coefficient
C_L	the lift coefficient
D	the rotor diameter
D_h	the hub diameter
dF_a	the blade local force normal to the turbine rotation plane
dF_D	the local drag force
dF_L	the local lift force
dM	the local torque
dr	the blade radius increment
dT	the local thrust
F	the correction factor that characterizes the loss effects
k_G	the constant associated with the hydrodynamic characteristics
N	the number of blades
P_R	the rated power
r	the blade local radius
R ($\mu = r/R$)	the total blade radius
v	the marine current speed
v_{max}	the maximum marine current speed
v_R	the rated marine current speed
v_{rel}	the relative velocity of the marine current
α	the angle of attack
β	the pitch angle
λ_R	the rated tip speed ratio
μ	the relative blade radius
ρ	the density of seawater
φ	the flow angle
ω	the turbine rotating speed
ω_R	the rated turbine rotating speed

As shown in Fig. 1, the 60 kW marine current turbine mainly consists of three blades and a support hub. The blades are directly bolted onto the support hub and are made of fiber glass reinforced plastics with high strength-to-weight ratio. The support hub rotates about the horizontal axis and is covered by a nose cone that is designed primarily to reduce external disturbances for the hub. The support hub is made of ductile cast iron to mitigate high-level vibrations and is fastened to the main shaft through a flange.

This three-bladed turbine is designed to improve the system stability and efficiency and minimize the possibility of cavitation inception [16]. The major turbine parameters are tabulated in Table 1. As illustrated in this table, the rotor diameter (D) is designed to be 7.2 m based on the system power rating and the hub diameter is practically selected as 10% of the rotor diameter. The rated turbine rotating speed is designed to be 30 rpm according to the generator speed limitation. The blade hydrofoil should also be carefully selected to maximize turbine performance and offer enough strength to avoid structural failures under time-varying operating conditions. Therefore, the blade lift-drag ratio should be maximized to capture the maximum marine current energy while considering the cavitation criteria [16] over a wide range of operating conditions. Therefore, NACA 63-4 series foil is selected to define the primary blade shape due to its relatively high structural strength and high lift to drag ratio [17].

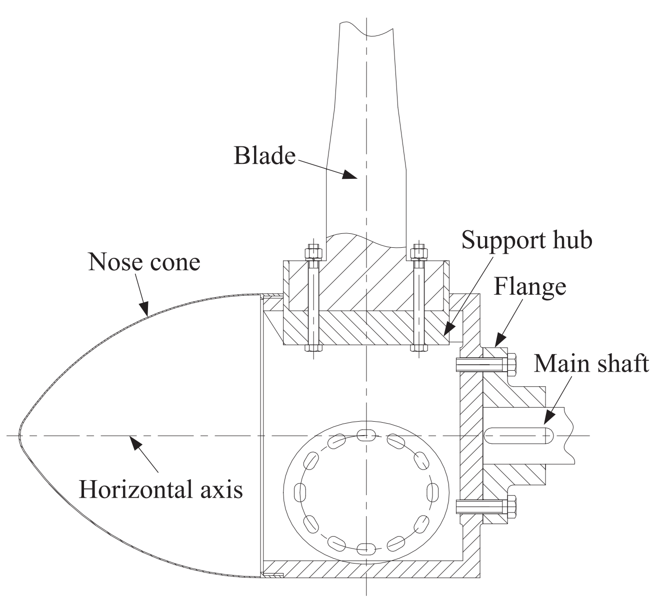

Fig. 1. Configuration of the 60 kW marine current turbine.

2.2. Turbine blade design

The turbine blade parameters can be reasonably calculated or optimized based on the blade element momentum theory that describes the blade hydrodynamics through the combination of blade element theory and momentum theory [18]. The local thrust and torque acting on an annular blade element can be calculated by using the momentum theory. Thus,

$$dT = 4\pi\rho v^2 a\cdot(1-a)r dr \tag{1}$$

$$dM = 4\pi\rho v\omega a'\cdot(1-a)r^3 dr \tag{2}$$

where dT and dM denote the local thrust and torque, respectively, ρ and v denote the density of seawater and the marine current speed, respectively, a and a' denote the axial induction factor and tangential induction factor, respectively, ω, r and dr denote the

Table 1
The major turbine parameters.

Turbine parameters	Specifications
The rated marine current speed v_R	2 m/s
The maximum marine current speed v_{max}	3.5 m/s
The rated power P_R	60 kW
The rotor diameter D	7.2 m
The hub diameter D_h	0.72 m
The number of blades N	3
The rated turbine rotating speed ω_R	30 rpm
The rated tip speed ratio λ_R	6.1
The pitch angle β	$-4°-2°$
The blade hydrofoil	NACA 63-4 series