Renewable Energy 81 (2015) 31–42

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A novel hydraulic-mechanical hybrid transmission in tidal current turbines

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ARTICLE INFO

Article history:
Received 18 February 2014
Accepted 24 February 2015
Available online 25 March 2015

Keywords:
Hydraulic-mechanical hybrid transmission
Tidal current turbine (TCT)
Maximum power point tracking
Power control
Power split device

ABSTRACT

Tidal current energy is a promising renewable energy, and it has become a research hotspot all over the world. Tidal current turbines (TCTs) are the devices that capture tidal current energy and convert it into electricity. Power train is one of the key technologies, and a gearbox is traditionally used. Because of the disadvantages of the gearbox, several *soft* power transmission methods have been studied, such as hydraulic power train and direct-drive train. Aiming for maximum power point tracking (MPPT) and constant frequency simultaneously, this paper introduces the hydraulic-mechanical hybrid transmission for TCT. Different from the traditional mechanical transmission, the hydraulic-mechanical hybrid transmission uses a two-degree-of-freedom planetary gear (TDPG) as the power split device. In this transmission, the rotor speed can be regulated by hydraulic pump displacement control to realize the MPPT, and the power can be stabilized through the hydraulic system. In this paper, the hydraulic-mechanical hybrid transmission is introduced, and the characteristics of the TDPG are analyzed first. Then, the control strategy of TCT is proposed. Finally, the system is modeled and constructed, and the simulation results confirm the validity of the hydraulic-mechanical hybrid transmission of TCT.

1. Introduction

More than 70% of the Earth is covered by oceans, which are considered to possess vast renewable energy, such as tidal energy, tidal current energy, wave energy, thermal energy and chemical energy. Tidal current energy is induced by the rising and falling of the tide [1]. Unlike other renewable energy such as wind energy and wave energy, tidal current energy has the characteristics of high power density, predictability and stability [2], which makes it particularly attractive to exploit. A tidal current turbine (TCT) is a device used to capture the kinetic energy of the tidal current and convert it into electricity [3]. Within the last decades, the study of tidal current turbines has flourished. Thus far, several prototypes have been tested or have been prepared for testing, such as Seaflow (300 kW, 2003) and SeaGen (2 × 600 kW, 2008) by the MCT company [3–6], the Blue project (300 kW, 2003) by Strøm/Statoil/ABB in Norway Hammerfest [7] and the Roosevelt Island Tidal Energy Project (35 kW started in December 2006) by Verdant Power Company in the East River of New York [8]. The utilization of tidal current turbines (TCTs) for electrical power production offers a sustainable option to augment traditional energy technologies and enhance the expansion of renewable energy [9].

In China, research on tidal current energy started in the 1980s at Harbin Engineering University (HER), and the research has mainly focused on the vertical axis tidal turbine, such as Wanxiang II (40 kW, 2005, HER, China). The study of horizontal axis tidal turbines started in the last 10 years and was first conducted by Zhejiang University and subsequently by the Ocean University of China and Northeast Normal University.

Currently, the gearbox is widely used as the power train of TCTs and transfers the power of the low speed shaft to the high-speed generator. However, the reliability of the gearbox is a problem to be solved. Another transmission that can be adopted is hydraulic transmission. Different from mechanical transmission, hydraulic transmission can transform the low variable speed of the turbine into the constant high speed of the generator. In document [10], the efficiency and performance of a digital displacement hydraulic transmission system were investigated for tidal current energy. In 2010, Zhejiang University in China also designed and tested a 20-kW horizontal axis tidal current turbine to study the performance of hydraulic transmission [11]. The low efficiency of approximately 70% is still the main problem for hydraulic transmission compared

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http://dx.doi.org/10.1016/j.renene.2015.02.059
0960-1481/

Nomenclature

n_s	sun gear speed
n_r	ring gear speed
n_H	planet carrier speed
i	ratio of ring gear tooth to sun gear tooth
T_s	sun gear torque
T_r	ring gear torque
T_H	planet carrier torque
J_H	equivalent moment of inertia
α	angle of attack
β	blade pitch angle
v	current velocity in far field
u	tangential current velocity
v_a	axial current velocity
v_r	resultant current velocity
$\mathrm{F_L}$	lift force
$\mathrm{F_D}$	drag force
$\mathrm{F_a}$	axial force
$\mathrm{F_t}$	tangential force
t	time
P	rotor power
ρ	water density
S	swept area of the turbine
β_e	bulk modulus of the fluid
C_p	power coefficient
λ	tip speed ratio
λ_{opt}	optimal tip speed ratio
T_{turb}	turbine torque
T_f	Coulomb friction torque
B	viscous friction coefficient
ω	turbine speed
T_{reac}	reaction torque of the turbine
J_{r_e}	equivalent inertia moment in the motor
k	ratio of sun gear speed to pump speed
n_{pump}	speed of the hydraulic pump
J_p	pump equivalent moment of inertia
T_{pump}	reaction torque of the hydraulic pump
q_{pump}	displacement of the hydraulic pump
p_{sys}	pressure of the hydraulic system
η_{pm}	mechanical efficiency of the pump
P_{mot}	output power of the hydraulic motor
T_{mot}	torque of the hydraulic motor
q_{mot}	displacement of the hydraulic motor
η_{mm}	mechanical efficiency of the motor
n_{mot}	speed of the hydraulic motor
V	fluid volume of the hydraulic system

with the greater than 90% efficiency of the gearbox [11]. Therefore, a hydraulic-mechanical hybrid transmission can be studied to combine the gearbox transmission and the hydraulic transmission. A dynamic simulation model of a hydro-mechanical transmission was built and compared with a hydrostatic transmission by the University of Minnesota [12]. WIKOV company designed a hydrostatic continuous variable transmission (CVT) gearbox to realize the control of the gearbox ratio and reduce the dynamic transmitted load in which the mechanical power was split into a hydrostatic power train and a mechanical power train [13]. In this paper, a new hydraulic-mechanical hybrid transmission used for the TCT was proposed. First, the characteristics of hydraulic-mechanical hybrid transmission were analyzed and compared with the mechanical transmission. Then, the control strategies of the TCT hydraulic-mechanical hybrid transmission were studied to capture the maximum power and output the constant generator speed. Finally, the simulations were conducted to verify the performance of the hydraulic-mechanical hybrid transmission, and the results were analyzed.

2. Hydraulic-mechanical hybrid transmission of a tidal current turbine

2.1. Transmissions in a tidal current turbine

The principles of the mechanical power transmission and the hybrid power transmission in TCTs are compared in Fig. 1 and Fig. 2. In the mechanical transmission, two planetary gear sets are used to transfer the captured energy of the turbine to the permanent magnet synchronous generator (PMSG). In this type of transmission, the rigid transfer of the loads is unamiable for mechanical components of the TCT. Moreover, for a TCT adopting the gearbox transmission, the rotor speed control that captures the maximum power and the PMSG speed control to output the constant frequency cannot be achieved simultaneously by controlling the PMSG only. For an on-grid TCT, the variable-speed constant-frequency can be realized by using a complicated power electronic device. However, for the off-grid TCT, it is difficult for the gearbox transmission to realize the variable-speed constant-frequency.

To improve the load characteristics of the TCT, capture the maximum power, and output the constant generator frequency at the same time, the hydraulic-mechanical hybrid transmission is proposed (Fig. 2). This transmission will solve the problems mentioned above. In a TCT using hydraulic-mechanical transmission, the turbine transfers the captured power to the PMSG through two parallel transmission lines, which are mechanical transmission and hydraulic transmission. From Fig. 2, a planetary gear transmission (PGT) that is coupled with the turbine and a two-degree-of-freedom planetary gear (TDPG) that is coupled with a generator and a hydraulic pump through the gear pairs are used in hydraulic-mechanical hybrid transmission. The hydraulic system will be used to adjust the speed of the turbine and smooth the fluctuated torque. Physically, the hybrid transmission is a variable construct of the traditional transmission consisting of 2-stage planetary sets and 1-stage fixed ratio sets. The difference between them is the location of the fixed ratio sets. Generally, the fixed ratio gear is used as the last stage of the gearbox, while for the

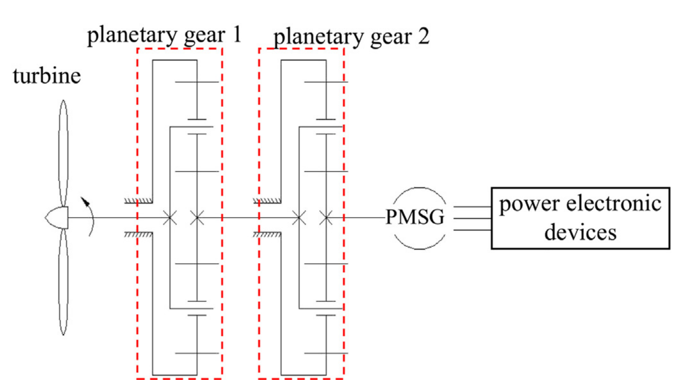

Fig. 1. Schematic diagram of the mechanical transmission in a TCT.