Energy 90 (2015) 258–265

Contents lists available at ScienceDirect

Energy

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

Fuzzy terminal sliding mode control for extracting maximum marine current energy

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ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form
16 June 2015
Accepted 18 June 2015
Available online 19 August 2015

Keywords:
Marine current power system
Maximum marine power extraction
Fuzzy logic controller
Sliding mode current controller

ABSTRACT

A new fuzzy terminal sliding mode control strategy is proposed to extract the maximum marine current energy. The control strategy mainly consists of a fuzzy logic controller for deriving the reference *q*-axis generator current and a non-singular terminal sliding mode current controller capable of accurately tracking the derived reference generator current. A swell filter is also involved in the control strategy to improve the generator power quality in case of swell effects. The detailed design process and stability condition analysis of this control strategy have been thoroughly investigated. The effectiveness of the proposed control strategy has been evaluated in a 60 kW marine current power system. Comparative results demonstrate that the proposed control strategy can be employed to more effectively capture the maximum marine current power and to considerably eliminate the generator power fluctuations as compared with a conventional second-order sliding mode control method.

1. Introduction

Nowadays, marine current power systems represent an important and promising renewable energy technology for future electricity generation and have recently gained worldwide attention [1]. Since the marine current energy has relatively higher power density and appreciably higher predictability than wind energy, the marine current power systems are generally more efficient as compared with wind power systems [2]. The electricity generated from such systems depends not only on the hydrodynamic forces arising from the marine currents, but also highly depends on the applied control methods. Therefore, MPPT (maximum power point tracking) control methods [3] become especially important for harnessing the maximum marine energy over a wide range of operating conditions.

In Refs. [4,5], S. Benelghali et al. designed a high-order sliding mode control method to maximize the marine power extraction for a doubly-fed induction generator-based marine current power system. However, the control method was designed based on particular marine current conditions and was not experimentally validated. In Ref. [6,7], the Matlab-Simulink simulator of a 7.5-kW PMSG (permanent magnet synchronous generator)-based marine current power system was evaluated by experiments. A second-order sliding mode speed control method was proposed to increase the generator power and the power conversion efficiency. However, the detailed implementation procedure of the speed control method was not thoroughly analysed and the experimental results were obtained from a specific marine site and hence were not general. In Ref. [8], the optimum generator torque was calculated based on the turbine optimum coefficient and the measured generator speed in a PMSG based marine energy system. The q-axis current of the PMSG was controlled in order to maintain the optimum torque curve and harness the maximum marine power. However, the oscillation problems existed in the control method and the experimental results were not solidly justified. In Ref. [9], an adaptive backstepping control algorithm was designed to capture the maximum power of a PMSG based marine current energy system. Although the control system stability can be guaranteed by using a Lyapunov function, the control efficiency and reliability due to the estimation of uncertain parameters have not been experimentally evaluated. In Ref. [10], a look-up table based MPPT control method was used to track the optimal rotor speed and hence to capture the maximum marine power. However, the implementation principle required the prior knowledge of the marine current speed and generator speed. The applicability of the method has also not been justified under harsh marine conditions. In Ref. [11], the maximum power points were obtained by measuring the DC voltage and DC current in a marine energy system with a dc battery.

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http://dx.doi.org/10.1016/j.energy.2015.06.068
0360-5442/

Nomenclature

A	the rotor swept area
C_P	the power capture coefficient
$F(s)$	the transfer function of a swell filter
e_q	the q-axis current tracking error
k_1 and ξ ($k_1 > 0$, $\xi > 0$)	two positive constant coefficients
k_2 ($k_2 > 0$)	a positive constant coefficient
$k_{f1} k_{f2}$	the quantization factors
k_s	the scaling factor
P_m	the captured mechanical power
P_{max}	the maximum captured mechanical power
p	the number of pole pairs
P_g	denotes the generator power
ΔP_g	the generator power variation over a sampling period
R	the resistance of the generator stator winding
v	the incoming marine current speed
ρ	the density of seawater
ω_g	the generator rotating speed
k_{opt}	the optimum power gain
ψ_f	the flux linkage generated by the permanent magnet
u_d, u_q, i_d, i_q and L	the direct and quadrature axes components of the stator voltage, current and the inductance
η	the transmission efficiency of the drive-train system
$\Delta\omega_g$	the generator rotating speed variation over a sampling period
$P_g[k]$, $P_g[k-1]$	the generator power at the sampling instants k and $k-1$
$\omega_g[k]$, $\omega_g[k-1]$	the generator rotating speed at the sampling instants k and $k-1$
Δi_{qref}	the reference q-axis stator current increment
τ_f	the time constant of this filter
s	the Laplace operator
α_1 ($\alpha_1 > 0$) α_2 ($\alpha_2 > 0$)	design constants
β_1,γ_1	positive odd integers
τ	a dummy variable for the integration
e_d	the d-axis current tracking error
β_2, γ_2	positive odd integers
ε	a positive constant parameter
T, n	the sampling period and the sampling instant
$e_d[n]$, $e_q[n]$, $e_d[n-1]$ and $e_q[n-1]$	the current tracking errors at the sampling instants n and $n-1$
$i_d[n]$, $i_d[n-1]$	the d-axis stator currents at the sampling instants n and $n-1$
$u_q[k]$, $u_{q1}[k]$, $u_{q2}[k]$ and $\omega_g[k]$	the q-axis stator control voltages and the generator rotating speed at the sampling instant k
$i_{qref}[k]$ and $i_{qref}[k-1]$	the reference q-axis stator currents at the sampling instants k and $k-1$
$u_d[k]$, $u_{d1}[k]$, $u_{d2}[k]$ and $i_q[k]$	the d-axis stator control voltages and the q-axis stator current at the sampling instant k
$u_{qM}[k]$, $u_{dM}[k]$	the modified q-axis and d-axis stator control voltages at the sampling instant k
V_{dc}	denotes the DC-bus voltage

A hill-climbing searching algorithm was then employed to track the derived maximum power points. However, the inability issues also existed in the searching algorithm due to the fixed step size under rapidly changing environment conditions. The control system could also exhibit large oscillations around the maximum power points. In Ref. [12], a MPPT control strategy based on resource prediction was proposed. Two MPPT methods including both variable pitch angle and variable rotating speed were combined to improve the overall control performances. While the analyzation and detailed steps of the MPPT methods were just like some equivocation. General rules could not be obtained from the results because of the specific marine current condition.

This paper presents a new fuzzy logic sliding mode control strategy for extracting the maximum marine current energy. The control strategy mainly includes a fuzzy logic controller for deriving the reference q-axis stator current i_{qref} and a non-singular terminal sliding mode current controller that is designed to accurately track the reference q-axis stator current i_{qref} and hence to achieve the MPPT control. Unlike the aforementioned MPPT control methods, the proposed control strategy can not only adaptively track the maximum marine current points with high accuracy, but can also smooth the generator power fluctuations caused by swell effects.

2. System design and modelling

2.1. System design

As illustrated in Fig. 1, the marine current power system mainly includes a marine current turbine, a PMSG, power converters and a drive-train system consisting of the main shaft, a gearbox and the high-speed shaft. The marine current turbine is utilized to convert the marine current power into rotating mechanical energy that can be subsequently converted into electrical energy through the PMSG. The drive-train system can be directly placed between the turbine and the PMSG for increasing the generator rotating speed. The output of the PMSG can then be regulated to supply different electric appliances and loads through power converters.

In general, the active and reactive electrical powers from the PMSG can be reasonably controlled by the voltage-source power converters. The generator side converter provides the variable-frequency voltage to control the generator output power and hence to track the maximum power points below the rated marine current speed. Above the rated marine current speed, the turbine rotating speed should be limited to maintain the constant generator rotating speed, ensuring that the generator power is kept around the rated value [13].

This PMSG-based marine current power system has significant advantages such as relatively high power density, light weight, reduced maintenance costs and full capability for MPPT control.

2.2. Marine current turbine

The mechanical power harnessed by this horizontal marine current turbine can be calculated as

$$P_m = \frac{1}{2}\rho A v^3 \cdot C_P \tag{1}$$

where P_m is the captured mechanical power, v is the incoming marine current speed, ρ is the density of seawater, C_P denotes the power capture coefficient, A is the rotor swept area.