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Adaptive neuro-fuzzy approach for ducted tidal turbine performance estimation

Obrad Anicic*, Srdjan Jovic

Faculty of Technical Sciences, Kosovska Mitrovica, University of Priština, 38 220 Kosovska Mitrovica, Kneza Milosa 7, Serbia

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ABSTRACT

The potential of marine power to produce electricity has been exploited recently. One of the ways of producing electricity is by using tidal current turbines. In this study, the hydrodynamic performance of a novel type of ducted tidal turbine was investigated. Tidal energy has become a large contender of traditional fossil fuel energy, particularly with the successful operation of multi-megawatt sized tidal turbines. Hence, quality of produced energy becomes an important problem in tidal energy conversion plants. Several control techniques have been applied to improve the quality of power generated from tidal turbines. In this study, the adaptive neuro-fuzzy inference system (ANFIS) is designed and adapted to estimate power coefficient value of the ducted tidal turbines. The back propagation learning algorithm is used for training this network. This intelligent controller is implemented using Matlab/Simulink and the performances are investigated. The simulation results presented in this paper show the effectiveness of the developed method.

Contents

1. Introduction

The population of the world is increasing with an alarming rate. This trend demands more resources for establishment of mankind. In the past, non-renewable energy resources were the major source of power production. The wide use of fossil fuels has led to various diseases such as skin cancer, respiratory diseases [1,2]. In this regard, alternative renewable resources are required to fulfill the growing demand of energy. Renewable sources such as biomass, sunlight, wind, ocean energy are the natural resources which are available in abundance and can be renewed in measurable time period [3–6].

Tidal barrages were widely used for harnessing ocean energy [7,8]. The principle of tidal barrage was similar to dams. The drawbacks for both technologies are the same. In early 1950s the first tidal turbine was used. It gained significant attention in late 1970s when the proof of concept of SeaGen was given [9,10]. The horizontal axis tidal turbines were designed to harness kinetic energy from tidal currents caused by gravitational interaction among the sun, the moon and the earth [11]. Horizontal tidal turbine were used due to the higher efficiency compared to the vertical counterparts. However, recently vertical axis tidal turbines gained more attention due to the same principle of operation with wind turbines which are in the advanced stage of implementation and usage [12,13]. The invention of tidal turbine brought a new era in ocean energy.

* Corresponding author.
E-mail address: oanicic@gmail.com (O. Anicic).

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Numerical methods are being widely used because of its better accuracy when compared with empirical equations. These techniques require multiple environment variables for predicting the performance of tidal turbines. Nevertheless, the accuracy of numerical method in prediction of the output variables highly relies on the input data. Numerical methods involve high computation resource and multiple exogenous parameters. In addition, these numerical models involve large number of meteorological and oceanographic data. Therefore, there is need for putting forth new method for estimating performance of tidal current turbine, which is simple yet shows better accuracy than traditional approaches.

Recent research works were proposed using simpler method for predicting power coefficient of tidal current turbine using soft computing methods. One of the methods for predicting the performance is by using the machine modeling. In [14], the firefly algorithm is used to predict the wind turbine generation. In 2013 Tan et. al designed the optimized power generation by renewable energy by using firefly algorithm [15]. Long et al. also predicted the sea level by using the same approach [16].

The concept of ducted turbines has been studied for decades with no commercially successful designs to date. The first in-depth study of ducted turbines was done in the context of wind power by Lilley and Rainbird [17], who developed analytical models based on one-dimensional momentum theory and potential flow methods in the 1950s. This study suggested that a reasonable duct could provide at least a 65 per cent increase in power over an ideal unshrouded turbine with the same rotor diameter. Attempts to develop ducted wind turbines have been unsuccessful for a number of reasons, the most important of which is arguably the immense loading on the duct in storm conditions or in yawed flows. There is renewed interest in ducted turbines in the context of tidal power generation since the direction and magnitude of tidal flows are quite predictable and tidal turbines would not be subject to such extreme storm loads as wind turbines. There are several prototypes for vertical axis tidal turbines; however, the dominant design and focus of this article is the ducted horizontal axis tidal turbine concept. This requires special considerations in blade design to ensure that the turbine can operate on both ebb and flow tides.

Analytical models have been developed to characterize the performance of ducted turbines by Lilley and Rainbird [17], Foreman et al. [18], Lawn [19], van Bussel [20], and Jamieson [21]. However, all these models require empirical parameters to capture the effects of flow separation, base pressure, and viscous loss. At present, there is little experimental or numerical data to support a fundamental understanding of how these factors vary with changes to duct geometry. The models presented by Jamieson and van Bussel are based on a modified version of the standard actuator disc momentum analysis [22].

The tidal systems are non-linear power sources that need accurate on-line identification on the optimal operating point [23,24]. Also, the power from tidal varies depending on the environmental factors such as the fluctuation of wind velocity. Aiming at optimizing such systems to ensure optimal functioning of the unit, new techniques are used today such as the fuzzy logic (FL) [25], artificial neural network (ANN) [26] and neuro-fuzzy [27].

Artificial neural networks are flexible modeling tools with capabilities of learning the mathematical mapping between input and output variables of nonlinear systems. One of the most powerful types of neural network system is adaptive neuro-fuzzy inference system (ANFIS) [28–53]. ANFIS shows very good learning and prediction capabilities, which makes it an efficient tool to deal with encountered uncertainties in any system. ANFIS, as a hybrid intelligent system enhances the ability to automatically learn and adapt.

The key goal of this investigation is to establish an ANFIS for estimation of the tidal turbine pressure coefficient C_{pc}. An attempt is made to retrieve correlation between pressure coefficient C_{pc} in regard to thrust coefficient and outer diffuser surface angle of the tidal turbine. That system should be able to forecast the pressure coefficient in regards to the main turbine parameters.

Fuzzy Inference System (FIS) is the main core of ANFIS. FIS is based on expertise expressed in terms of 'IF–THEN' rules and can thus be employed to predict the behavior of many uncertain systems. The advantage of FIS is that it does not require knowledge of the underlying physical process as a precondition for its application. Thus ANFIS integrates the fuzzy inference system with a back-propagation learning algorithm of neural network. An ANFIS model will be establish in this study to predict the tidal turbine pressure coefficient in relation to the two main turbine parameters. The experimental training and checking data for the ANFIS network are obtained from analytical analysis of the tidal turbine power output.

The basic idea behind the soft computing methodology is to collect input/output data pairs and to learn the proposed network from these data. The ANFIS is one of the methods to organize the fuzzy inference system with given input/output data pairs. This technique gives fuzzy logic the capability to adapt the membership function parameters that best allow the associated fuzzy inference system to track the given input/output data.

In Section 2, ducted tidal turbine pressure coefficient is explained in detail. The main principle of the adaptive neuro-fuzzy inference system (ANFIS) is presented in Section 3. Section 3 also presents the ANFIS model of the tidal turbine pressure coefficient estimation. Section 4 summarizes the results and provides the synthesis of measurement data. Finally, Section 5 offers some concluding remarks and future-work directions.

2. Methodology

2.1. Ducted tidal turbine

Blade is the most crucial part of the turbine. The water velocity of the tidal currents strikes the turbine blades and lead to the rotation of turbine. This converts the kinetic energy of the tidal currents into rotational energy for the generator and eventually into the electricity. The power produced by such turbines is given by

$$P = 0.5 C_p \, \rho \, A \, V^3 \tag{1}$$

where, P (W) is the power produced, C_p (dimensionless) is the coefficient of power, A (m^2) is the flow contact and V (m/s) is the inlet velocity for the turbine.

Therefore, the properties of the turbine blades have a major effect on the performance of the turbine. In this study, a collapsible blade with three foldable entities was taken. The lower most entity was 260 mm and the scaling factor of 0.95 was followed for each succeeding blade. The turbine has the capacity to be folded up to half of its installed size. Table 1 represents the parameters of the turbine studied.

The analytical framework for this study is based on the ducted turbine model as presented by Lawn [19], which is similar to an earlier derivation by Foreman et al. [8]. The model is developed by analyzing the variation of pressure through the duct. From the free stream condition (p_0, u_0) the flow either expands or contracts approaching the rotor disc plane. The variation in pressure is related to the change in velocity by Bernoulli's equation modified with an efficiency term which parameterizes viscous loss in the inlet section.

The pressure change across the actuator disc is defined according to the standard definition of the thrust coefficient C_T. The pressure difference between the far wake, defined where full expansion back to $p = p_0$ has occurred, and the diffuser outlet is parameterized as a base pressure coefficient C_{pc}. This definition reflects the assumption of full pressure recovery in the wake to the