Electric Power Systems Research 126 (2015) 38–44

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Micro-hydrokinetic river system modelling and analysis as compared to wind system for remote rural electrification

Sandile Phillip Koko, Kanzumba Kusakana*, Herman Jacobus Vermaak

Department of Electrical, Electronic & Computer Engineering, Central University of Technology, Private Bag X20539, Bloemfontein 9300, Free State, South Africa

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 26 April 2015
Accepted 28 April 2015
Available online 17 May 2015

Keywords:
Modelling
Micro-hydrokinetic river system
Wind system
Permanent magnet synchronous generator
Rural electrification
Simulation

ABSTRACT

Micro-hydrokinetic river (MHR) system is one of the promising technologies to be used for remote rural electrification. In rural areas with access to both wind and flowing water resources, wind generation is selected as a first electrification priority. The potential benefit of generating electricity using flowing water resource is unnoticed. Hence, this paper presents the modelling and performance analysis of a MHR system as compared to wind generation system using MATLAB/Simulink software. These performances are compared to generate the same amount of electrical power. A permanent magnet synchronous generator (PMSG) has been chosen or used to investigate the behaviour of each system under variable speeds. The developed model includes horizontal turbine model, drive train model and PMSG model. The simulation results illustrate the ability of a hydrokinetic turbine driven PMSG to generate electricity markedly better and cheaper than a wind driven PMSG within South Africa. Hence, the MHR system presents a cheap electrification opportunity for poor rural households.

1. Introduction

Electrification can play an important role to support economic and social development of isolated rural societies. To improve the living conditions of poor rural households, it is important to provide the affordable and reliable electricity. A clean and sustainable solution for remote rural electrification is made possible by means of small-scale renewable energy sources. Among various renewable energy technologies, hydropower generation holds prime position in terms of the world's electricity generation [1,2].

Some rural areas might be situated in close proximity to flowing water with little or no elevation at all. A conventional hydroelectric system cannot be used in such rivers or water flow. This results in neglect of flowing water resource. Additionally, it has been proved that one-third of the world's population without electricity does have access to flowing water resource [3]. Apart from conventional hydroelectric system, hydrokinetic is a new category of hydroelectric system to be used in waterways with little or no elevation at all. It generates electricity by making use of underwater wind turbines to extract kinetic energy of flowing water instead of potential energy of falling water. Hence, no construction of dams or diversions is necessary. It means that theoretically there is huge number of potential sites available for micro-hydrokinetic system compared to conventional hydroelectric system. Additional, this reveals that the ecological footprint created by hydrokinetic system is less than that of conversional hydroelectric system.

Hydrokinetic technology is still in the development stage. Most of the available modelling and simulation tools are not equipped with hydrokinetic modules. Additionally, many researchers and project developers are unaware that hydrokinetic technology can generate electricity markedly cheaper than wind system counterpart. It has also been proved that there is still a lack of hydrokinetic application in rural electrification [4]. Hydrokinetic technology can be captured from waves, tides, oceans, marine thermal gradients, flow of water in rivers or artificial channels [5,6]. Kinetic energy of flowing water is converted into electrical energy by making use of a turbine coupled to a generator via drive-train.

This study focuses only on small-scale hydrokinetic system since it is suitable for low-income remote rural residents. For small-scale electrification, free-flowing rivers/waterways are the possible sources. Small-scale turbines are generally available within power range of 1–10 kW [7]. Hydrokinetic turbines are available in either horizontal or vertical configurations. In this study, a horizontal-axis turbine has been chosen due to its self-starting capability compared to vertical-axis turbines. Additionally, a permanent magnet synchronous generator (PMSG) has also been selected due to its high efficiency, reliability and capability of operating at low speeds [4].

---

* Corresponding author. Tel.: +27 515073241; fax: +27 515073254.
E-mail addresses: skoko@cut.ac.za (S.P. Koko), kkusakana@cut.ac.za (K. Kusakana), hvermaak@cut.ac.za (H.J. Vermaak).

http://dx.doi.org/10.1016/j.epsr.2015.04.018

This study aims to demonstrate the hydrokinetic potential for remote rural electrification in South Africa. Hence, the benefits of using the proposed off-grid micro-hydrokinetic river (MHR) system in remote areas with access to both wind and flowing water resources is demonstrated through the use of the developed model. The effect of PMSG's pole pairs on the performance of the MHR system has also been shown using the developed model. The developed model has been applied in MATLAB/Simulink software. The performance of the proposed MHR system has been compared to the one of the wind system to generate the same amount of electrical power. Hence, the modelling of power electronic converter and storage devices is beyond the scope of the study.

2. Description of the micro-hydrokinetic river system model

The modelled structure of MHR system consists of a horizontal turbine, mechanical drive-train, and PMSG components. Since a PMSG can operate at low speeds depending on the number of pole pairs, the rotor shaft can be directly coupled to the turbine. To measure the generated output voltage and current, a three-phase balanced resistive load has been connected to the output of the generator.

Most of the available modelling and simulation tools used for mechanical and electrical systems are not equipped with hydrokinetic module. Hence, the mathematical model for each component of MHR system is developed using MATLAB/Simulink library. Hydrokinetic technology operates similar to wind technology in terms of operation and rotor blade configurations. The difference is that water is approximately 800 times denser than air while the wind speed is greater than the water flow speed [3].

2.1. Hydrokinetic turbine model

Zero head turbines are generally used to extract and transform the kinetic energy of flowing water into mechanical energy. This mechanical energy is useful to drive the generator. The kinetic energy of flowing water is expressed as:

$$E_k = \frac{1}{2}mv^2 \tag{1}$$

where m = water mass (kg), v = water velocity (m/s).

Hence, the power of the flowing water (by assuming constant speed) is expressed as follows:

$$P_W = \frac{\mathrm{d}E_k}{\mathrm{d}t} = \frac{1}{2}\rho A v^3 \tag{2}$$

where ρ = water density (1000 kg/m^3), A = swept area of turbine blades (m^2).

The swept area of a horizontal-axis turbine is expressed as:

$$A = \pi r^2 \tag{3}$$

where r = turbine blade radius in (m).

Hydrokinetic turbines can only harness a fraction of the total kinetic power due to losses entailed. So, the rotor power coefficient of the turbine is expressed using Eq. (4) below [8]. Based on Betz law, this power coefficient is limited to 16/27 = 0.593 (59.3%).

$$C_P = \frac{P_m}{P_W} \quad C_p < 1 \tag{4}$$

where P_m = mechanical power captured by water turbine.

By substituting Eq. (2) into Eq. (4), the mechanical power captured by water turbine from water flow is then expressed as:

$$P_m = \frac{1}{2}\rho A v^3 C_P \tag{5}$$

C_P depends non-linearly on the tip-speed ratio, λ and the blade pitch angle, β (degrees) and can be expressed as follows [9,10]:

$$C_P(\lambda, \beta) = c_1\left(c_2\frac{1}{\lambda_i} - c_3\beta - c_4\right)e^{\left(\frac{-c_5}{\lambda_i}\right)} + c_6\lambda \tag{6}$$

where c_1 to c_6 are the empirical power coefficients' parameters of the turbine.

In our case, β = 0 degrees, in order to achieve maximum power extraction from a variable speed turbine. The empirical coefficients of a typical horizontal turbine c_1 to c_6 were 0.5176, 116, 0.4, 5, 21 and 0.0068, respectively [9,11].

The parameter $\left(\frac{1}{\lambda_i}\right)$ can be solved by making use of the following equation [10,12,13]:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{7}$$

The tip speed ratio can be determined as follows [12,13]:

$$\lambda = \frac{\omega_m . r}{v} \tag{8}$$

where ω_m = mechanical angular speed of the turbine shaft in (rad/s)

Fig. 1 shows the water turbine power coefficient model. Hence, when β = 0 degrees, the maximum power coefficient of this turbine, $C_{P(\max)}$ is found to be 0.48 at a tip-speed ratio (λ_{opt}) of 8.1 as shown in Fig. 2. The $C_{P(\max)}$ value was then entered as a constant to assume maximum power extraction at variable speeds. Mechanical torque of the turbine shaft can be expressed as follows:

$$T_m = \frac{P_m}{\omega_m} \tag{9}$$

2.2. Drive-train model

The role of the drive-train within hydrokinetic generation system is to enable the conversion of kinetic energy of flowing water into useful mechanical energy. Drive-train can either be geared or direct driven. The gearbox within the drive train connects the low speed shaft (on the turbine side) with the high-speed shaft (on the generator side). This enables the provision of high rotational speed required by the generator to provide electricity up to certain level. A drive-train can be modelled by means of different methods such as three-mass, two-mass or one-mass drive train model [9]. Since the aim of this study is to see the interaction between water density

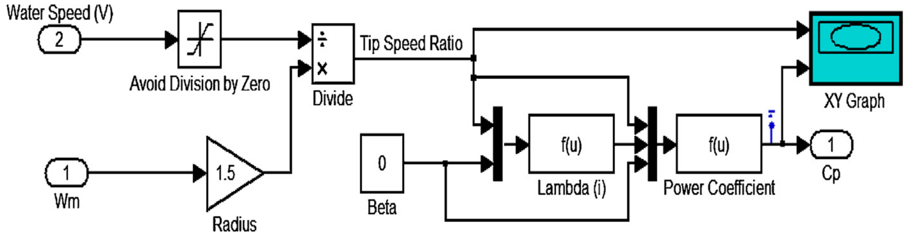

Fig. 1. Simulink block diagram of a turbine power coefficient model.