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

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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].

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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:

$$E_k = \frac{1}{2} m v^2 \tag{1}$$

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:

$$P_W = \frac{dE_k}{dt} = \frac{1}{2}\rho A v^3 \tag{2}$$

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

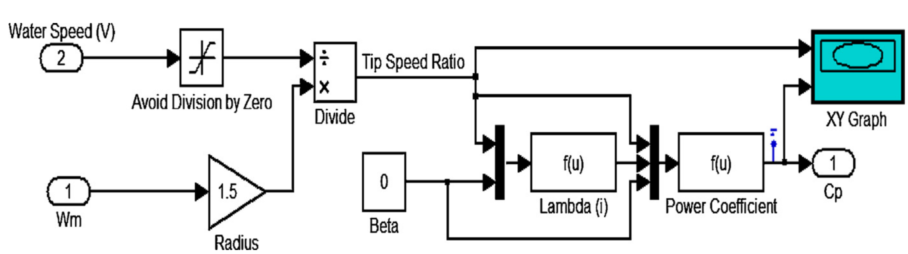

Fig. 1. Simulink block diagram of a turbine power coefficient model.

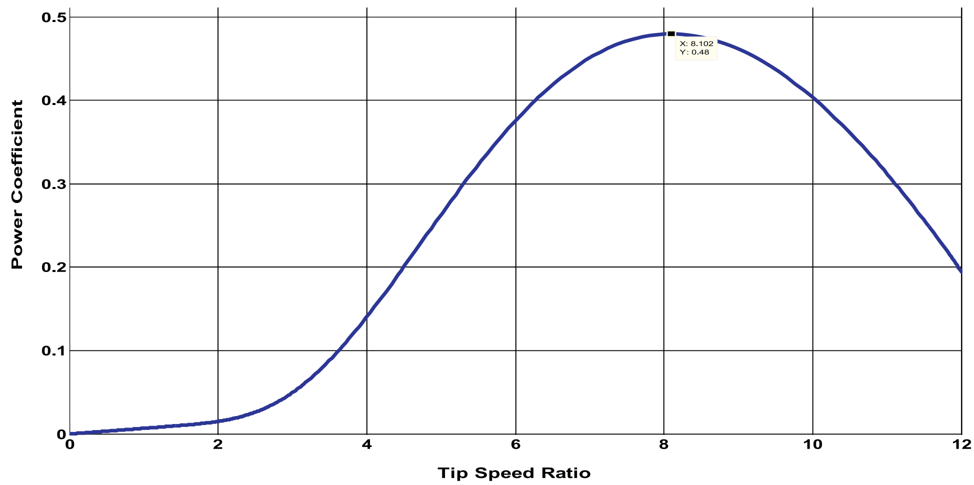

Fig. 2. Power coefficient versus tip-speed ratio of the turbine (with $\beta = 0^\circ$).

and electrical output energy, the drive train was treated as a one-mass drive train model. This means that all inertia components are modelled as a single rotating mass.

The angular acceleration of the generator shaft can be expressed as follows [8]:

$$\frac{d\omega_g}{dt} = \frac{T_e - T_{w:g}}{J_{eq}} - \frac{B_m}{J_{eq}}\omega_g \tag{10}$$

where T_e = electromagnetic torque in (N m), $T_{w:g}$ = mechanical torque from water turbine to the generator in (N m), J_{eq} = equivalent rotational inertia of the generator and turbine in (kg m^2), B_m = damping coefficient in (N m/s), ω_g = rotor angular speed of the generator in (rad/s).

One of the advantages of the PMSGs is that they are low inertia machines. Usually J_{eq} is almost equals to the turbine inertia since PMSG's inertia is negligibly small [14]. The rotational damping coefficient was assumed to be equals to zero as shown in Fig. 3.

By neglecting all inertia effects of the chain, the rotor angular speed of the generator can be expressed as follows:

$$\omega_g = \omega_m \cdot G \tag{11}$$

where G = gear ratio.

2.3. Permanent magnet synchronous generator (PMSG) model

Power system model for synchronous machines is usually based on assumption such as damping effect is negligible (of both the rotor and the magnets), the magnetic flux distribution in the rotor is sinusoidal, magnetic circuit is unsaturated, iron losses are negligible and field current dynamics are absent [15,16]. The park transformation method is commonly used for three-phase machine modelling. It is used to transform the parameters and equation from the stationary form into direct-quadrature (dq) axis [17]. It converts the three phase alternating current quantities into direct current quantities, meaning ABC to dq transformation. The d and q voltage equations of the PMSG are expressed as follows [9,18]:

$$v_d = R_s \cdot i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{12}$$

$$v_q = R_s \cdot i_q + L_q \frac{di_q}{dt} + \omega_e . \psi_{PM} + \omega_e L_d i_d \tag{13}$$

where v_d and v_q = stator terminal voltages in the d, q axis reference frame in (V), i_d and i_q = stator terminal currents in the d, q axis reference frame in (A), L_d and L_q = d, q axis reference frame inductances in (H), ω_e = electrical angular speed of the generator in (rad/s), ψ_{PM} = permanent magnet flux in (Wb), R_s = stator resistance in (Ω)

The relationship between the electrical angular speed and rotor angular speed (ω_g) of the generator is expressed as follows:

$$\omega_e = p \cdot \omega_g \tag{14}$$

where p = the number of pole pairs.

The equation for the developed electromagnetic torque is expressed as follows [19]:

$$T_e = \frac{3}{2} p \left(\psi_{PM} i_q + (L_d - L_q) i_d i_q \right) \tag{15}$$

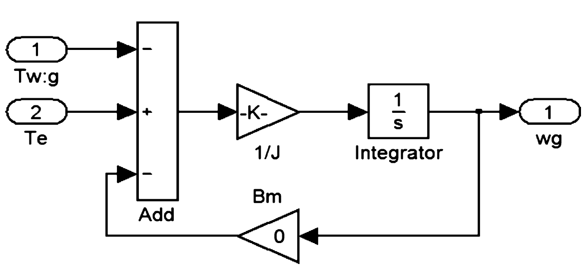

Fig. 3. Simulink block diagram of a drive train model.

3. Results and discussion

This paper provides an overview of the proposed MHR system model as implemented in MATLAB/Simulink. In this section, variable speed responses of the proposed system are presented. The main objective is to study the performance of the proposed MHR system as compared to the one of a wind generation system. The results highlight the system that generates electricity better than the other one for the same amount of electrical power generation. The block diagram of the developed MHR system model is shown in Fig. 4. A 2 kW three-phase balanced resistive load is directly connected to the output of the generator to represent a full-load. Simulink signal builder has been used for variable step input in order to see how the system responds to a change in water flow speed. The step input signal and the selected time range were used for simulation purpose only.

This paper also provides an overview/understanding regarding the selection of a PMSG depending on the water flow velocity of the site. Hence, the performance of MHR system using a PMSG with large number of pole pairs has been simulated against the one that used fewer number of pole pairs.

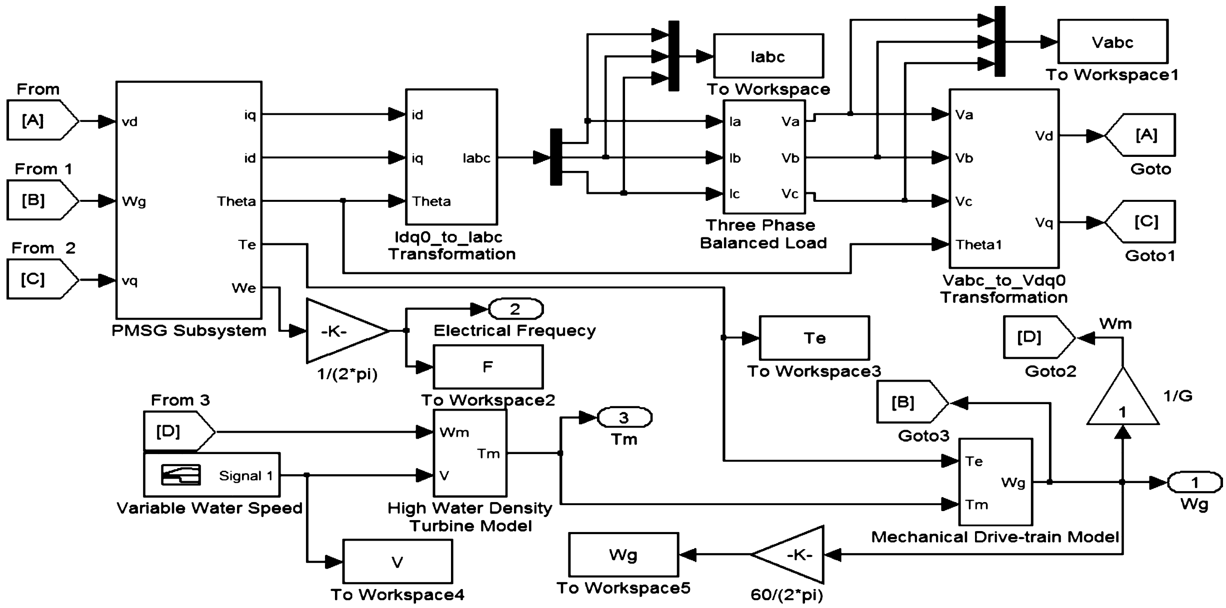

Fig. 4. Simulink block diagram of an overall MHR system model.

3.1. *Off-grid MHR system against off-grid wind system*

This section demonstrates the behaviour of the off-grid MHR system when compared to a wind system for generating the same amount of power. This has been done by studying the systems' dynamic response under variable speeds. The simulated parameters of the system components are shown in Tables 1 and 2 above.

3.1.1. *Dynamic response of the off-grid micro-hydrokinetic system*

The results for the off-grid MHR system dynamic response are shown in Fig. 5. The step input representing variable water flow speed has been increased in steps of 0.65 m/s for 4 s as shown in Fig. 5a. As the water flow speed increases, the generated voltage, load current, and frequency are gradually increasing as well. When the water flow speed increase from 1.95 to 2.6 m/s (from $t = 3$ s to $t = 4$ s), the generator is rotating at its rated full-load speed. At that moment, the generated voltage, frequency and the load current were 126.6 V, 51.23 Hz and 17.58 A, respectively. This demonstrates the effectiveness of the developed model since these parameters are close to the rated ones.

Table 1
PMSG parameter list [20,21].

Stator phase resistance	2 Ω
Number of pole pairs	8
d–*q* axis inductance	1 mH
Permanent magnet flux	0.46 Wb
Rated rotor speed	400 rpm
Rated power	2 kW
Rated phase voltage	120 V
Rated phase current	17 A
Rated frequency	50 Hz

Table 2
Turbine and drive-train parameter list.

Turbine blade radius	1.5 m
Blade swept area	7 m^2
Maximum C_p value	0.48
Optimal tip speed ratio	8.1
Gear ratio	1
Rotational damping coefficient	0
System total inertia	5 kg m^2

3.1.2. *Dynamic response of an off-grid wind system*

To study the response/performance of a wind system as opposed to the MHR system, the same system components parameters have been simulated. The air density was taken to be 1.225 kg/m^3 during simulations. The results are shown in Fig. 6. The step input representing variable wind speed has been increased in steps of 6.075 m/s for 4 s as shown in Fig. 6a. To enable the same PMSG to rotate at its rated speed, the wind speed of 24.3 m/s is required. Such speed is practically impossible within South Africa (SA), since the average wind speed ranges between 4 and 7 m/s [22]. Hence, to enable a wind system to generate the same voltage as generated by the MHR system, techniques such as increasing the turbine blade size, considering a PMSG with larger number of pole pairs and/or adding a gearbox to the system can be applied. However, any of the above-mentioned techniques will results into high/extra additional costs. Furthermore, a gearbox will reduce the efficiency and reliability of the system due to regular maintenance requirement.

3.2. *Selection of a PMSG with certain number of pole pairs*

This section shows the MHR system's performance based on the use of the PMSGs with different number of pole pairs. Two different PMSGs with different numbers of poles and capable of generating 230 V at 50 Hz, were selected. The first case simulation uses a PMSG with large number of pole pairs while the second case comprises of a PMSG with fewer pole pairs. It has been assumed that the water flow velocity varies from 0.45 to 1.35 m/s.

3.2.1. *Case 1: PMSG with a large number of pole pairs*

Case 1 has been simulated by making use of a surface mounted PMSG consisting of 20 pole pairs, stator resistance of 1.107 Ω, stator *d*-axis and *q*-axis of 0.3 mH each and permanent magnet flux of 0.148 Wb. The simulation results are shown in Fig. 7a–e. Based on the operation principle of synchronous generators, the angular speed of the generator together with the number of poles determines the frequency of the induced voltage. Hence, in order for this 20 pole PMSG to induce a voltage at a required frequency of 50 Hz, it needs to be driven at a speed of 150 rpm. Due to low

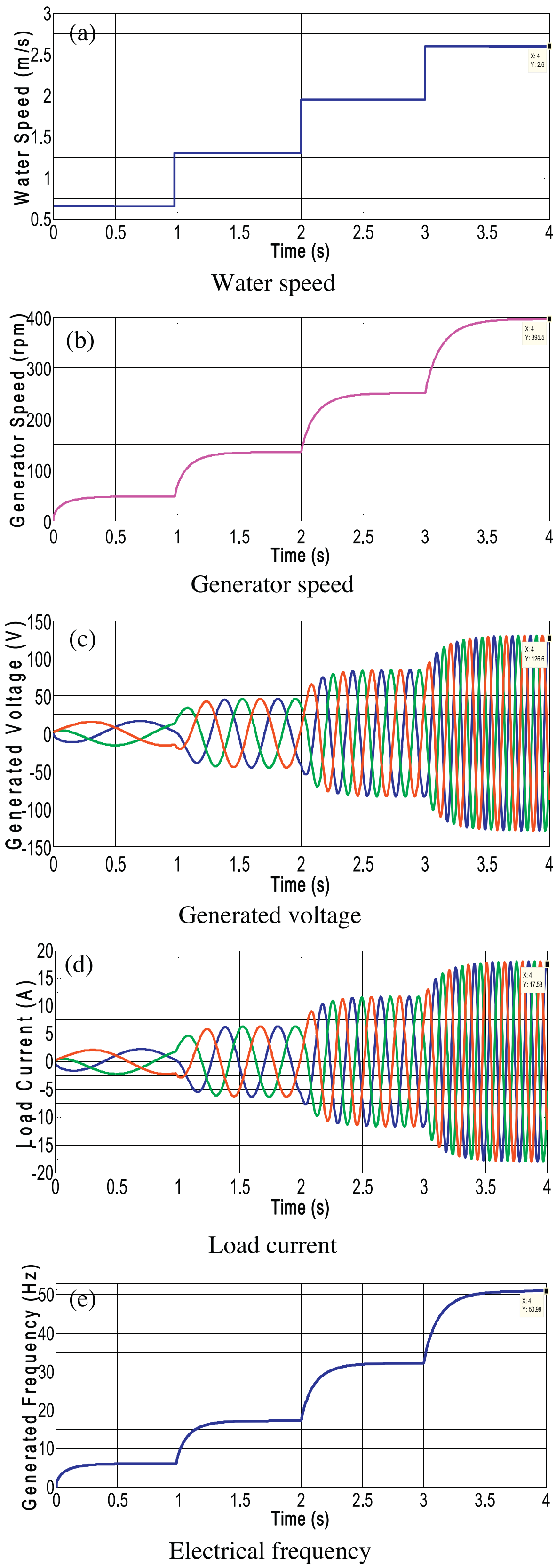

Fig. 5. MHR system response for a step change in water speed from 0.65 to 2.6 m/s.

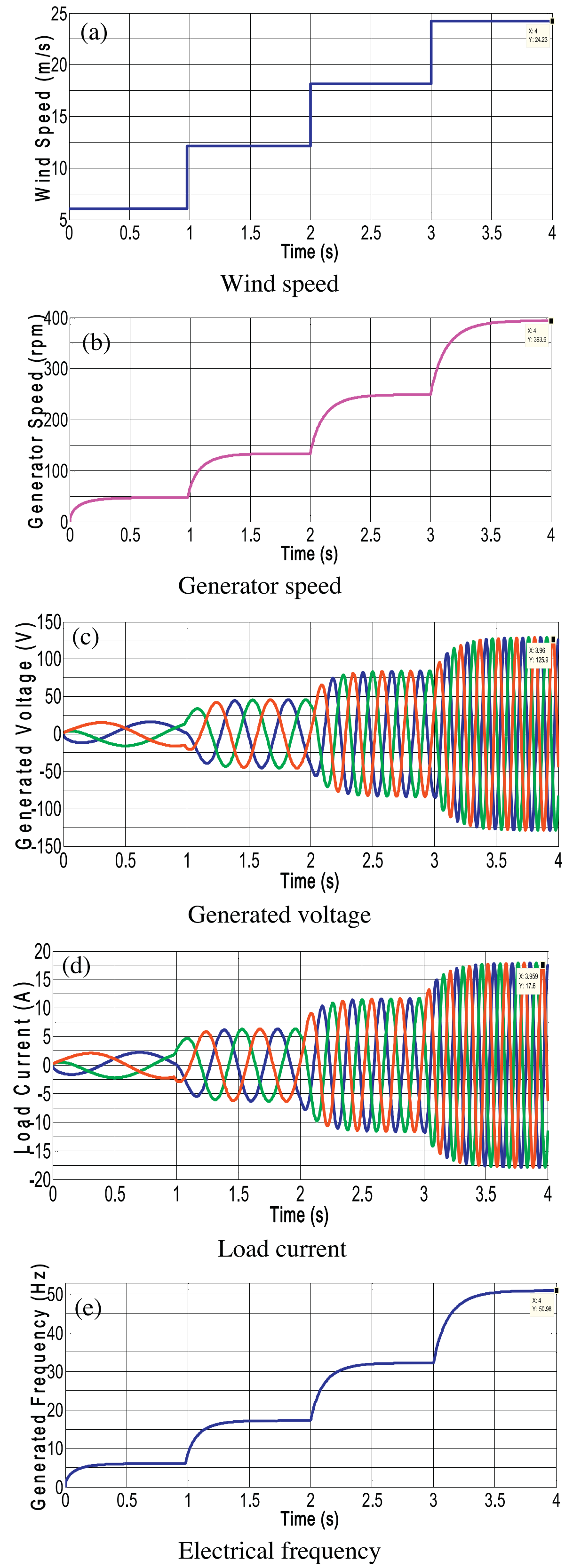

Fig. 6. Wind system response for a step change in wind speed from 6.075 to 24.3 m/s.

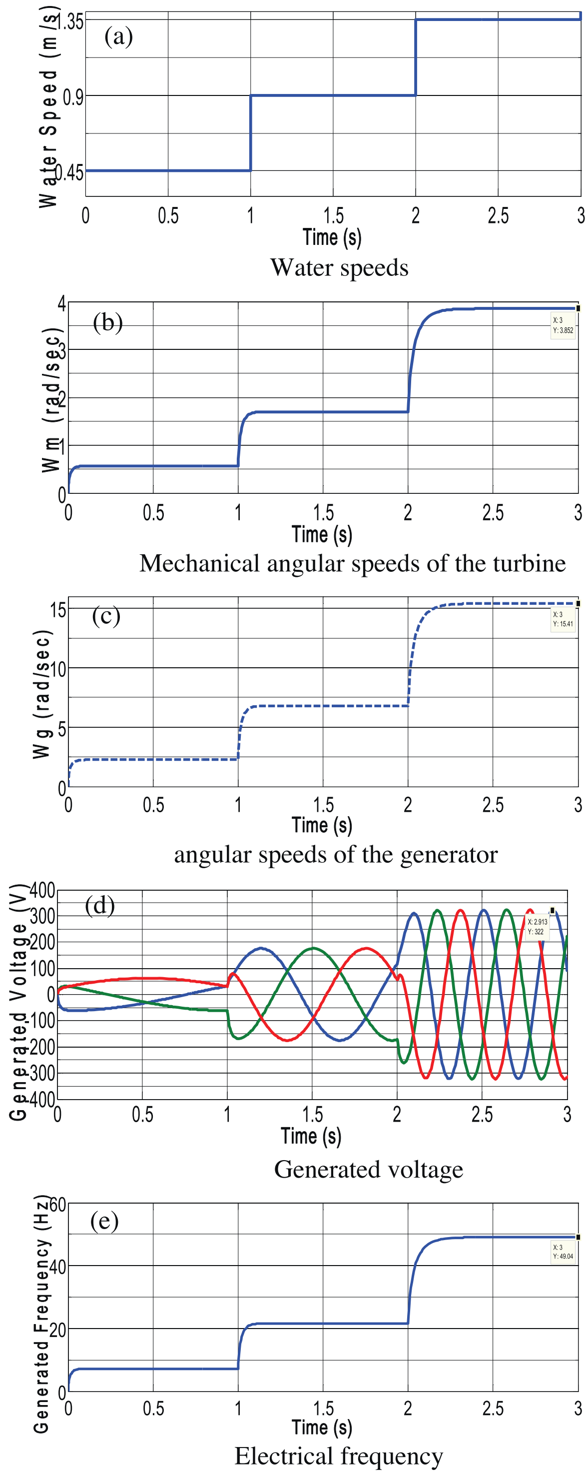

Fig. 7. MHR system response for a PMSG with large number of pole pairs.

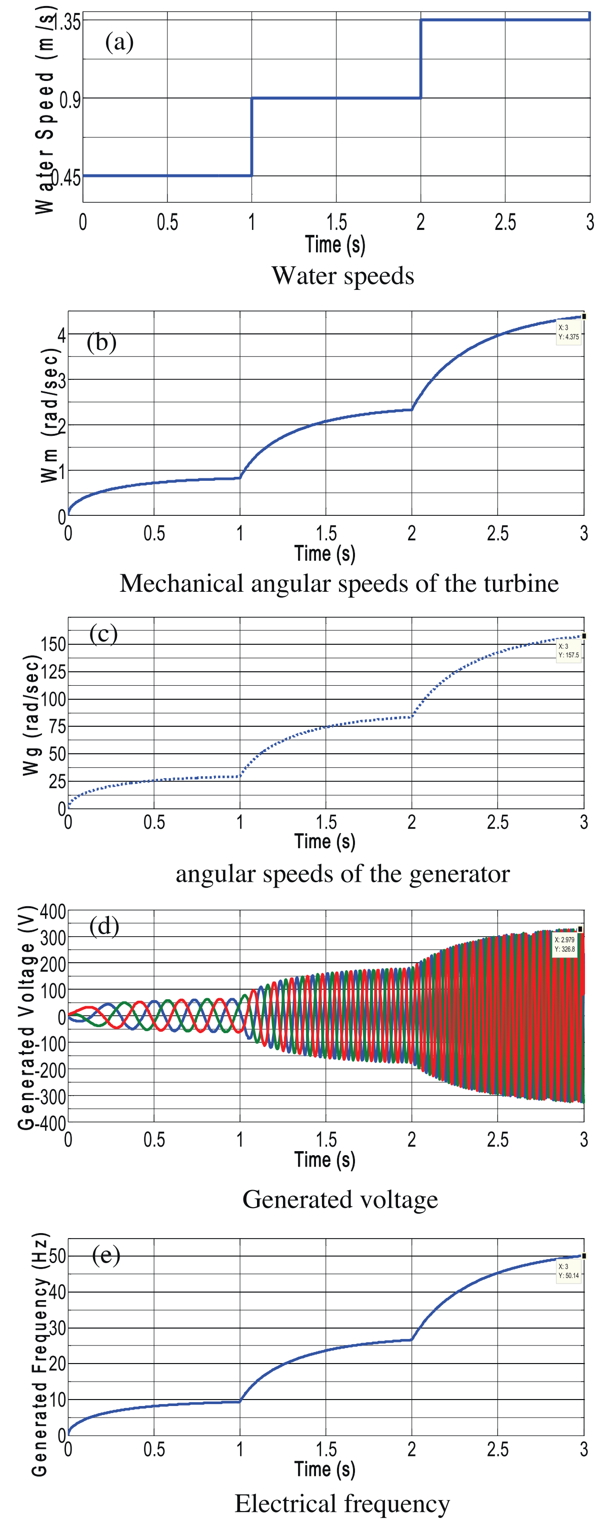

Fig. 8. MHR system response for a PMSG with fewer pole pairs.

water speed steps shown in Fig. 7a, a gear ratio of 1:4 has been used to allow the generator to rotate faster than the turbine speed. From Fig. 7b and c, it can be noticed that, at any point in time, the angular speed of the generator is four times more than the angular speed of the turbine, due to the gearbox ratio. When the speed of the water increases to 1.35 m/s (from $t = 2$ s to 3 s), the generated voltage reached 322 V-peak (228 Vrms) at a frequency close to 50 Hz.

3.2.2. *Case 2: PMSG with a fewer number of pole pairs*

Case 2 has been simulated by making use of a surface mounted PMSG consisting of two pole pairs, stator resistance of 1.85 Ω, stator *d*-axis and *q*-axis of 0.7 mH each and permanent magnet flux of 0.915 Wb. The simulation results are shown in Fig. 8a–e. Based on the simulation results, fewer pole pairs lead to a higher speed requirement. Hence, a gear ratio of 1:36 has been used to allow the generator to rotate at the required speed. From Fig. 8b and c, it can be seen that at any point in time, the angular speed of the generator is 36 times more than the angular speed of the turbine, due to the gearbox ratio. When the speed of the water increases to 1.35 m/s (from t = 2 s to 3 s), the generated voltage was 326.8 V-peak (231 Vrms) at a frequency of 50.14 Hz.

4. Conclusion

This paper presented the developed model for studying the performance of an off-grid MHR system as submitted to varying water velocity. The system consists of a horizontal turbine, drive-train and a PMSG. The performance of an off-grid MHR system as opposed to the one of a wind system has been revealed. The comparison results showed that due to high water density, a small-scale hydrokinetic river system generates electricity markedly cheaper than a small-scale wind system. This simply proves that in isolated rural areas of South Africa with access to flowing water and adequate/inadequate wind resource, hydrokinetic power is the cheaper, reliable and efficient system to consider than a wind system.

It has also been observed that an increase in PMSG's pole pairs leads to a lower required speed even though the size and the cost of the generator will increase. Alternatively, if the number of poles is reduced, the cost of the PMSG will decrease while the gearbox cost and weight of the system is increasing. Hence, it is important for a designer to find a balance between the number of poles and a gearbox ratio in order to minimize the system cost, depending on the velocity of the water flow within the selected site.

Because electricity must be provided with almost constant levels of voltage and frequency; the next step of this research is to look into the modelling of the generator's control to achieve acceptable steady-state and transient performance using maximum power tracking control.

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