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Dynamic simulation of a direct-coupling 3-blade vertical-axis hydrokinetic turbine with a low speed generator

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Abstract

This research paper reports a dynamic simulation of a 3-Blade Vertical-Axis Hydrokinetic Turbine for direct-coupling with a low speed generator. Direct-coupling eliminates the gearbox. Various turbine radii were investigated in water velocities ranging between 0.5 and 2 m/s. A simulation program was done in MATLAB to compute the dynamic parameters such as rotational speed, torque produced and response time. Additionally, a S814 blade profile was used but its coefficients were analytically expanded to cover angles of attack ranging from -180 to +180º using computational fluid dynamic analysis. The results were analysed and a diagram was produced to aid the selection of a turbine radius to suit the water velocity. Larger turbines spun at lower nominal speeds with higher torque. However, high water velocity was the most favorable because it gave turbines a faster response time. To determine the turbine radius, generator characteristics such as nominal speed and torque are required. The response time may not be critical in normal operation because the rotor could be spinning constantly for months. However, it will be crucial in the design of the control system.

Keyword: Hydrokinetic turbine, Turbine radius, Hydrodynamic performance, Dynamic simulation

Nomenclature

R	m	Turbine radius	F_R	N	Resultant force
V	m/s	Water velocity	τ	$N.m$	Torque
λ	-	Tip speed ratio	I	kg/m^2	Second moment of inertia
θ	deg	Azimuth angle	I_s	kg/m^2	Moment of inertia of shaft
α	deg	Angle of attack	I_a	kg/m^2	Moment of inertia of rotor arms
$V_{\mathrm{Re}\,l}$	m/s	Relative velocity of blade	I_b	kg/m^2	Moment of inertia of blades
V_B	m/s	Tip blade velocity	$\sum \tau$	$N.m$	Total torque
C_l	-	Lift coefficient	ω_f	rad/s	Final angular velocity
C_d	-	Drag coefficient	ω_i	rad/s	Initial angular velocity
L	N	Lift force	$\vec{a}$	rad/s	Angular acceleration
D	N	Drag force	Δt	s	Time step
ρ	kg/m^3	Density of water	n_i	rpm	Rotational speed
A_s	m^2	Swept area	n_s	rpm	Nominal speed
C_P	-	Power coefficient	t_R	s	Response time
C_t	-	Torque coefficient			

1. Introduction

Hydropower is one of many renewable energy resources. The widely used form of hydropower is to retain water behind dams to store its potential energy, but due to their adverse effects on forests and public perception, dams are rarely built. However, there are other forms of hydropower called hydrokinetic power [1] using waves, tides and streams. Hydrokinetic power devices extract kinetic energy from flowing water, which is akin to wind turbines. However, because water is denser than air, there is more energy to be extracted from the same swept area (A_s). This idea has received a lot of interest from researchers due to its lower costs and minimal civil construction required. They can be installed in rivers or channels [2].

Rivers with high water velocity are suitable for hydrokinetic turbines, but they are usually in remote areas. Therefore, the systems must be simple to be maintained by local people. They can be divided into two categories, horizontal axis and vertical axis turbines. Horizontal axis

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Table 1 Operational speeds of vertical-axis hydrokinetic turbines.

Performances/ Ref.	[3] 3-blade	[4] 4-blade	[5] 3-blade	[6] 5-blade	[7] 3-blade
Water velocity (m/s)	1.1	0.6	0.3 – 2.5	1	0.6 - 1
Rotor radius (m)	0.8	0.45	0.3 – 0.6	1.2	0.35
Rotor speed (rpm)	525	110	132 - 202	65	100 – 500
Power output (W)	620	150 - 190	240 - 1140	750	50 – 80

turbines are required to turn into the flow of water, which adds machine complexity and costs. Thus vertical axis turbines are more suitable for use in rural areas, even though their hydrodynamic efficiency may be lower [8].

Hydrokinetic turbines have four major components: a turbine, transmission shaft, gearbox and generator. The generator is normally of the radial-flux type, which operates at above 1500 rpm [9], but the turbine rotor spins at a much lower speed. Thus a gearbox is required. As a result, there is an approximate 10% [10] loss of energy compared to a direct drive system.

Analyses of hydrokinetic turbines have been performed on different fronts, starting from the analysis of turbine rotor hydrodynamic performance using CFD and MATLAB (Taylor [11]). Since they are not commercially available, other components must also be designed. Nick, Deglaire and Eriksson [12-15] incorporated an axial-flux generator in their simulation to complete a direct drive hydrokinetic turbine system.

This research project set out to investigate the dynamic behavior of a 3-blade vertical-axis hydrokinetic turbine rotor for use in a directly coupled hydrokinetic turbine system. Thus, the energy losses associated with the gearbox are eliminated. Table 1 presents the operational parameters for this low speed hydrokinetic turbine system. The system was designed to be installed in rivers with water velocities of 0.5-2.0 m/s [4, 16] and operate at 100-500 rpm [9, 17]. The hydrodynamic performance of turbine rotors with various radii were investigated. A simulation was constructed in MATLAB to compute dynamic parameters such as force on the turbine blades, rotational speed, acceleration, torque and the power coefficient, which would provide the ground work for an analysis of the generator. An axial-flux permanent-magnet generator was chosen to be directly coupled with the turbine rotor. Therefore, the generator spins at the same rotational speed. The analysis of the generator will be incorporated at a later stage.

2. Design of the dynamic simulation program

2.1 Simulation program inputs

A dynamic simulation calculates the change in the rotational speed (n_i) of the turbine rotor from at rest to a selected rpm value. Water velocity (V) and turbine rotor radius (R) were specified for each case. As the turbine rotor turned, turbine blades were set at various angles relative to the flow of water. The vector of the relative velocity ($V_{\mathrm{Re}\,l}$) of water on a blade, angle of attack (α), changed and was used to find the lift (L), drag (D) and the resultant forces (F_R) (Figure 1). A hydrokinetic turbine rotor spools up from at rest until the resulting mechanical torque (τ) is balanced by the counter torque of the generator. For the rotor to be operating at its highest power coefficient (C_p), it must be controlled to spin at a particular tip speed ratio (λ). This is true regardless of water velocity, turbine radius or blade profile. For vertical-axis hydrokinetic turbine rotors, the said λ is approximately

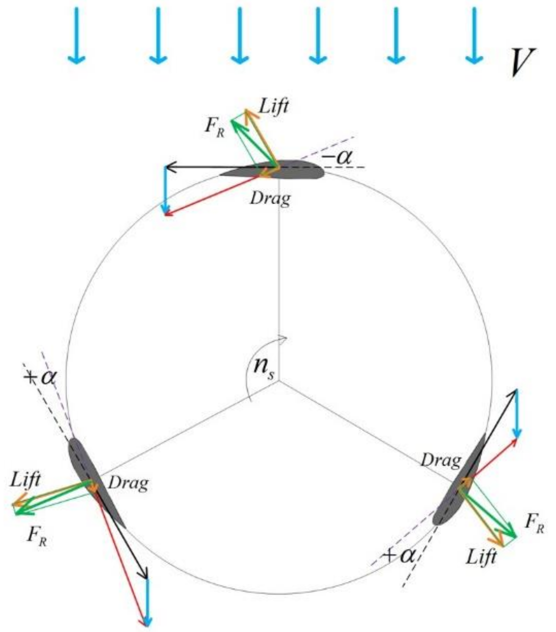

Figure 1 Forces on a rotor blade change in magnitude and direction as it completes a revolution. [18] The green vector is the resultant force, drag (yellow, tangent vector) is the drag force and lift (yellow, normal vector) is the lift force.

6 [19] and hence their nominal speeds (n_s). Unsteady flows and dynamic stall were not included in the simulation at this stage.

To find the forces on the rotor blades, the blade's hydrodynamic data must be available. The blade profiles that are suitable for hydrokinetic turbines are the RISO-A1-24, S805 and S814 types [20]. They have been tested in experiments and are being used by many researchers. The S814 blade profile was used in the design of the turbine rotor in the current study. Its lift and drag coefficients (C_l, C_d) were used as data built into the program. The National Renewable Energy Laboratory (NREL) has produced data for the S814 for general use which covers a narrow range of Reynolds numbers and α values (-20 to 20 degrees). However, as each blade of the hydrokinetic turbine rotor turns a full revolution the α varies beyond the available range of data. Therefore, some of the data must be obtained analytically [21].

A 2D model of the S814 blade profile was analyzed using CFD to obtain its C_l and C_d at α values ranging from -180 to 180^o. The C_l, C_d and the pressure coefficient were validated against the available data [22]. The C_l, C_d and pressure coefficient values beyond +/- 20 degrees have similar performance to that of the DU 97-W-300 airfoil [23].

2.2 Simulation program development

The dynamic behaviors of the turbine rotor were simulated as follows. At rest, water flowed across the rotor.

Table 2 Turbine rotor specifications.

Parameter	Number of Blades [-]	Blade Hydrofoil [-]	Rotor Height, H [m]	Rotor Radius, R [m]	Turbine solidity, σ [-]	Water speed, V_0 [m/s]	Tip speed ratio, λ [-]
Values	3	S814	1	0.5–0.7	0.15	0.5 – 2	6

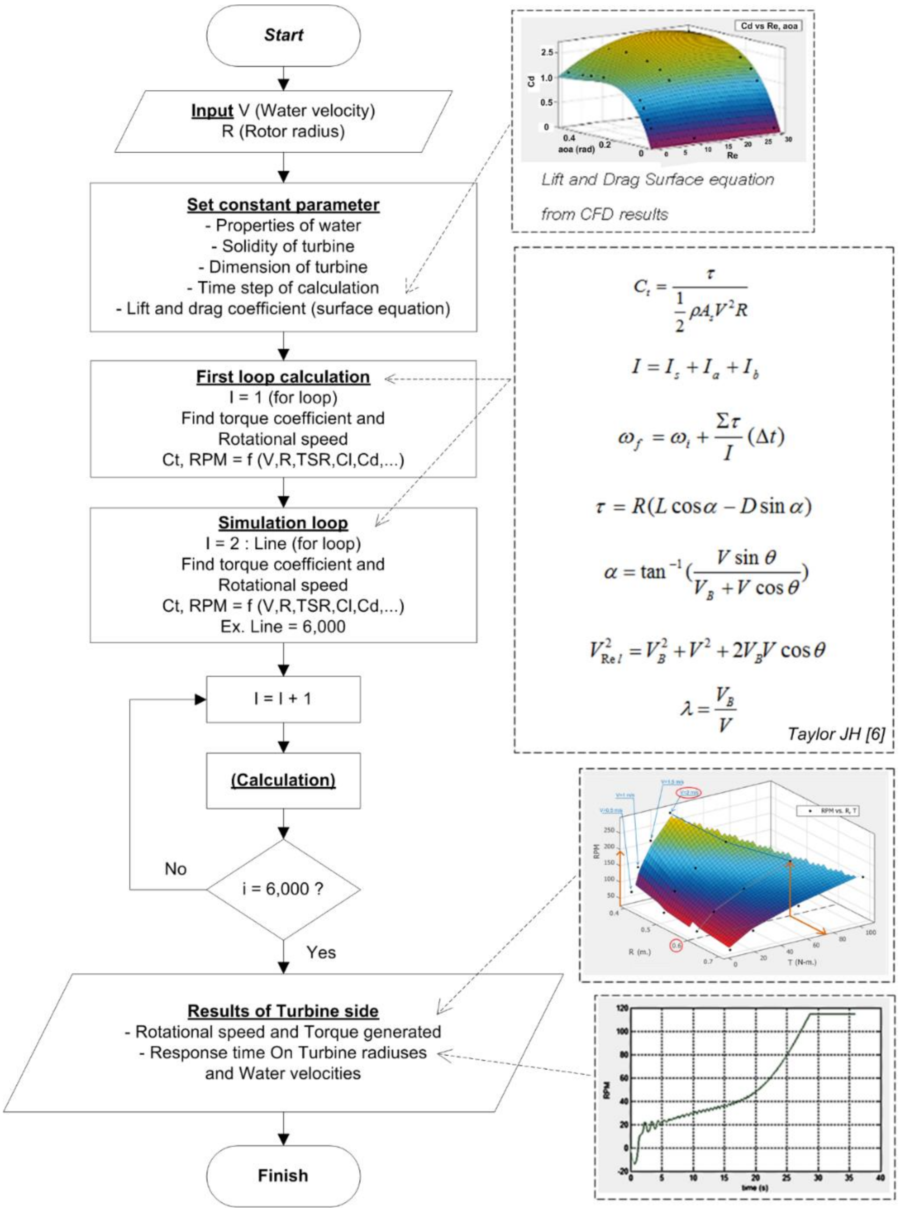

Figure 2 The flowchart illustrates the design of the simulation program in MATLAB.

The acceleration α and forces on the blades were determined. Torque produced by the blades turned the rotor, whose total second moment of inertia (I) dictated the angular acceleration ($\vec{\alpha}$). The angular acceleration was used to compute the rotor's instantaneous angular velocity. The calculations were repeated for all parameters (Figure 2). The specifications of the simulated turbine are listed in Table 2.

The parameters and turbine rotor dynamic behaviors were formulated and a program was developed in MATLAB. The results were plotted for the analysis of the turbine rotor characteristics.

Additionally, one of the crucial settings of the simulation was the time step (Δt). It is the time between each repeated calculation, which significantly affects the accuracy of the simulation. The smallest Δt used in the program was 0.04 ms in the case of high V. The simulation times ranged from 8-50 minutes, which were relatively short and not an issue.

The outputs of the dynamic simulation were:

1. Torque (τ),
2. Nominal speed (n_s),
3. Response time (t_R).

3. Results and discussion

3.1 The effects of turbine radius (R) on torque (τ) and nominal *speed (n_s)*

The torque (τ) and nominal speed (n_s) are the mechanical outputs of the rotor that influence the generator load and speed. Therefore, by carefully choosing the turbine radius (R), the overall system can be designed to be more efficient. The results show that a turbine rotor that operates at a lower n_s produces more τ (Figure 3). In the case of a water velocity (V) of 2 m/s, a 0.7 m-radius turbine rotor generated 106 N-m at 164 rpm, whereas the 0.6 m-radius turbine rotor only produced 75 N-m at 191 rpm. The diagram in Figure 3 was created to aid the selection of the turbine parameters in the design of a directly coupled hydrokinetic turbine system.

The analysis also revealed that these turbines of different R values operated at various V values achieved almost identical torque (0.050-0.055) and power coefficients (0.30-0.33) at their n_s.

3.2 Turbine rotor response time (t_R)

During operation, a directly coupled hydrokinetic turbine was allowed to spool up from rest to its n_s without a load. The timing of the load and the loading profile will be designed at a later stage. The response time (t_R) was computed as the time a turbine took to reach its n_s. Figure 4 shows the influences of R and V on t_R. The turbine radius had a positive effect on the response time. For illustration, the 0.4 m radius turbine took 107 s to spool up to its n_s (72 rpm), where V = 0.5 m/s, whereas the 0.7 m radius turbine used only 48 s (39 rpm) to do so. This was a result of the greater torque produced. The turbines may be started by an external mechanism and once started, they remain operating for a long period of time.

The large R and high t_R could be favourable in some loading scenarios, but the adverse effect was their low n_s, which is a problem for generator design. High V was the most desirable factor for a generator design, because unlike large R, a higher V simultaneously increases t_R and n_s.

The response time may not be critical in normal operation because the rotor could be spinning constantly for weeks or months. However, it is worth noting that the response speed in general will be crucial in the design of the loading scheme and the control system.

4. Conclusion

A hydrokinetic turbine rotor was specifically designed to be directly coupled to a low speed generator. This investigation focused on the effects of turbine radius on nominal speed and torque. The simulation computed the dynamic parameters of the turbine rotor at water velocities ranging from 0.5-2 m/s in the MATLAB environment. The nominal speeds and torque were obtained at various turbine radii, and hence the resulting mechanical power

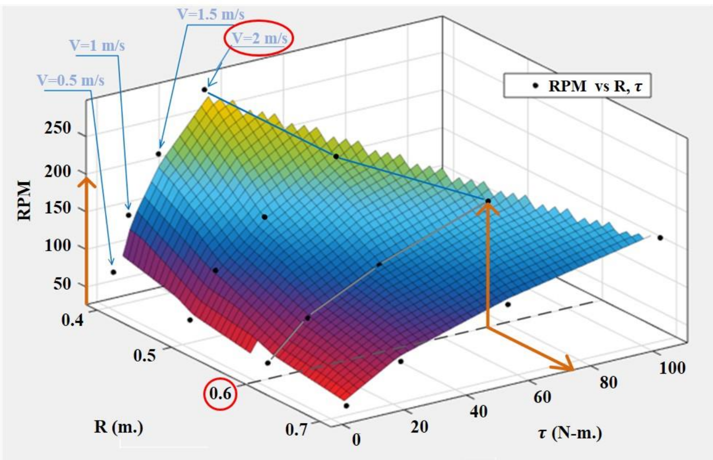

Figure 3 The diagram produced to determine τ and n_s outputs at various R and V.

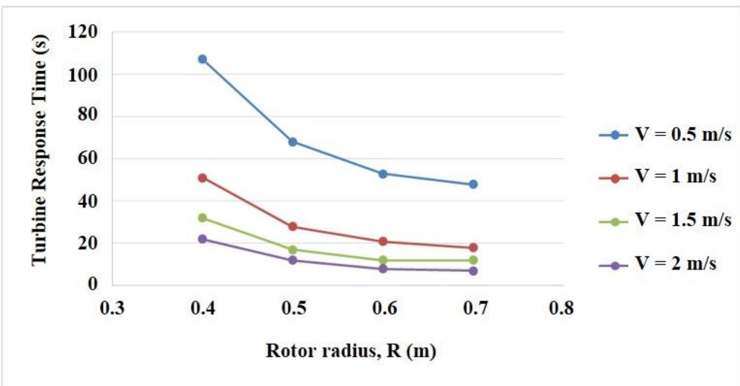

Figure 4 Response time (t_R) changed with rotor radius (R) and water velocity (V). Larger turbines and high water velocities resulted in lower response times.

and power coefficients. A diagram illustrating the relationships between the parameters was produced to aid in the design of hydrokinetic turbine systems. It indicates that a small radius turbine rotor operates at a higher nominal speed, but produces a lower torque. Therefore, careful selection of the turbine rotor radius must be done to suit conditions in the design of the generator. A large R and high t_R could be favourable in some loading scenarios, but the adverse effect was their low n_s, which makes generator design more difficult. A high V value was the most desirable factor for generator design because unlike a larger R, a high V simultaneously increases t_R and n_s. The response time may not be critical in normal operation because the rotor would be spinning constantly for weeks or months. However, it is worth noting that the response speed will be crucial in the design of a loading scheme and control system.

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