Circuit: Jurnal Ilmiah Pendidikan Teknik Elektro
Volume.7 No. 1 September 2022 - February 2023
ISSN: 2549-3698; E-ISSN: 2549-3701
DOI: 10.22373/crc.v7i1.14650

Power Control Study of Hydrokinetic Power Plants in presence of Wake Effect

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Diterima: 03-08-2022 Disetujui: 17-11-2022 Diterbitkan: 03-01-2023

Abstract

Hydrokinetic power plants are able to produce energy only by harnessing the kinetic energy of flowing water. Compared to dam-based hydroelectric power plants, hydrokinetic power plants have minimal impact on several issues e.g. environmental, health, social and political conflict. Similar to wind turbines in a wind farms, hydrokinetic turbines in tidal farms also generate a wake effect, which results in less kinetic energy on downstream turbines compared to upstream turbines. This article shows the simulation results of three hydrokinetic power generation systems installed in series on the same water stream such as river or aqueduct. The upstream turbine generates wake effect and resulting a velocity deficit both in the two downstream turbines. Bastankhah Porté-Agel model for wake effect was used in this study. The simulation results show that the downstream turbine cannot maintain the given voltage reference and loses the stability of the power control if the water velocity decreases. Several recommendations regarding series configuration of the hydrokinetic system are also presented in order to support the control stability.

Keywords*: Hidrokinetic, wake effect, simulation, BPA Model, PI Controller*

Abstrak

Pembangkit listrik listrik tenaga hidrokinetik dapat menghasilkan energi hanya dengan memanfaatkan energi kinetik air mengalir. Dibandingkan pembangkit listrik tenaga air berbasis bendungan, pembangkit listrik hidrokinetik memiliki dampak yang sangat minimal terhadap isu lingkungan, kesehatan, sosial, dan konflik politik. Sama halnya dengan turbin angin pada ladang angin, turbin hidrokinetik pada ladang tidal juga membangkitkan efek bangun, yang mengakibatkan turbin downstream mendapatkan lebih sedikit energi kinetik dibanding turbin upstream. Dalam artikel ini dipaparkan hasil simulasi tiga sistem pembangkit listrik isochronous tenaga hidrokinetik yang dipasang pada suatu aliran air yang sama secara serial, turbin upstream membangkitkan efek bangun dan mengakibatkan defisit kecepatan alir pada dua turbin downstream dibelakangnya. Permodelan efek bangun Bastankhah Porté-Agel digunakan pada penelitian ini. Hasil simulasi menunjukkan bahwa, bila kecepatan aliran air berkurang maka turbin paling belakang tidak dapat mempertahankan referensi tegangan yang diharapkan dan pada akhirnya kehilangan kestabilan untuk mengkontrol daya. Beberapa rekomendasi untuk konfigurasi sistem hidrokinetik secara serial turut dipaparkan agar ketidakstabilan kontrol dapat dihindari.

Kata kunci*: Hidrokinetik, efek bangun, Simulasi, model BPA, Kontrol PI*

Introduction

Currently, the development of power plants with hydro energy sources has become a concern of various groups, namely academics, practitioners, the community, and the government [1]. Indonesia, with its large natural water resources, has the potential to be used as a source of electricity generation. The challenges in the utilization of hydro energy is its fluctuating energy [2] and its highly dependent on natural conditions such as weather [3]. However, with the rapid development of supporting technology and well-planned initial planning, the disadvantages that exist in hydro energy can be compensated so the power plants with a higher availability and efficiency can be reached. It is also important to conduct a survey of the available hydro energy potential and the need for electrical demand in the local area during initial planning [1].

The development of hydroelectric power plants using dams has encountered various obstacles. Not only environmental issues [4], dam-based hydro power plants also have a major impact on health [5], social [6], and political [7]; [8]; [9]) issues. One alternative that can be applied in the use of hydro energy is to implement hydrokinetic power plants. Without massive use of dams and civil infrastructure, hydrokinetic power plants can generate energy only by utilizing the kinetic energy of flowing water [10]. The technology is not only can be applied to river flows, but also to ocean currents [11]. In this article, the author examines the relationship between power control and the wake effect produced by a hydrokinetic power plant. In the first section, the types of hydrokinetic turbine that already exist in the market are described, followed by the proposed system configuration. In the next section, theory of the wake effect is presented. Furthermore, a preliminary study regarding performance of the generation system using the software is presented. At the end, some recommendations are presented based on the results of this study.

Literature Studies

a. Hydrokinetic electric power plant

Hydrokinetic power plant is one of the environmentally friendly power generation solutions. This type of power plant does not require large civil construction costs, does not require a long construction time, does not interfere with water flow, does not change the migration path of fish, and does not hinder the movement of sediment at the bottom of the flow. There are at least two types of hydrokinetic turbines, namely the submerge (or sinking) type turbine and the floating type. Submerge types can also be divided into types with a vertical axis and a horizontal axis. Other literature also introduces a floating type with a horizontal axis, as well as a vertical axis floating type supported by a float and a pendulum [12]. Figure 2 shows an example of a mass-produced hydrokinetic turbine that available on market.

(a) (b) (c)

Figure 1. Hydrokinetic electric power plant (a) Smart-Hydro 5 kW from Germany [13], (b) Guinard-Energies 3,5 kW from France (Guinard, 2017), and (c) NTN 0,4-1,7 kW from Japan [14].

b. Stream Power of Flowing Water

The stream power received by hydrokinetic power plants can be written as (1).

$$P_t = \frac{1}{2} C_p \rho A V^3 \quad (1)$$

Where *Cp* is the power coefficient, *ρ* is the fluid density (water = 998 kg/m3), *A* is the sweep area (m^2) of the turbine blades, and *V* is the fluid flow velocity (m/s). Generation of power capacity can also be increased by paralleling several generating units into a grid [15].

c. Wake Effect

Upstream turbine will cause wake effect that can gives negative impact to other downstream turbine. If the downstream turbines hit by the wake effect, it will generate electricity no larger than the upstream turbine. This effect is known as the wake effect. The Mathematical modelling of wake effects can be simplified by using Bastankhah Porté-Agel (BPA) approach [16]). BPA explains that the velocity deficit $\Delta U/U_\infty$ in wake effect is assumed to meet the Gaussian distribution as (2).

$$\frac{\Delta U}{U_\infty} = C(x)\, e^{-\frac{r^2}{2\sigma^2}} \quad (2)$$

Where , *r* is the radius of the turbine. *C(x)* and *σ* can be described as (3)

$$\frac{\Delta U}{U_\infty} = \left(1 - \sqrt{\frac{C_T}{8\left(k^* \frac{x}{d_0} + 0.2\sqrt{\beta}\right)^2}}\right) \times exp\left(-\frac{1}{2\left(k^* \frac{x}{d_0} + 0.2\sqrt{\beta}\right)^2}\left\{\left(\frac{z - z_h}{d_0}\right)^2 + \left(\frac{y}{d_0}\right)^2\right\}\right) \quad (3)$$

k* is a parameter that states how quick the wake effect can disappear, and this parameter is highly dependent on the physical characteristics of the river, e.g. coefficient of friction and the shape of the water duct. *β* is equal to (4).

$$\beta = \frac{1 + \sqrt{1 - C_T}}{2\sqrt{1 - C_T}} \quad (4)$$

where C_T is the thrust coefficient.

Method

The study uses a simulation approach using Simulink. The configuration of the proposed hydrokinetic power generation system can be seen in Figure 2. Three PMSG power plants which work in isochronous mode are installed in series along the irrigation canal or aqueduct with a certain distance between each other.

The turbine provides mechanical energy to the generator. The PMSG converts mechanical power into electrical power. The fluctuating nature of water energy will be regulated by the converter with PI controller in order to produce constant voltage. Power generated by each generation is only used by the load connected to each generator without any interconnection or Point of Common Coupling (PCC). All of the turbines proposed in this study have the same power rating. The electric load is resistive and constant. There are two scenarios, firstly each turbine is 10 meters away from the other turbines, and then each turbine is moved until 30 meters away from the other turbines.

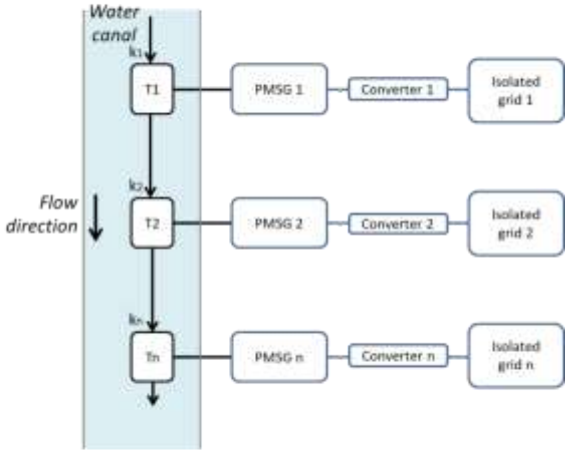

Figure 2. Proposed Hydrokinetic Power Plant Configuration

Results and Discussions

a. Simulation of BPA Model

In this simulation, there are three different characteristics of water flow and they are represented by k* values of 0.0115, 0.023, and 0.46. The turbine radius is 0.5 m. The speed of the water stream is 2.8 m/s. Monitoring points are at a distance of 5 m, 10 m, 15 m, and 20 m. Monitoring points smaller than 5 meters were not considered in this study because the kinetic energy produced was inadequate due to the large turbulence. The simulation results using (3) can be seen as shown in Figure 3, it can be seen that the wake effect can still be felt up to 20 meters behind the turbine.

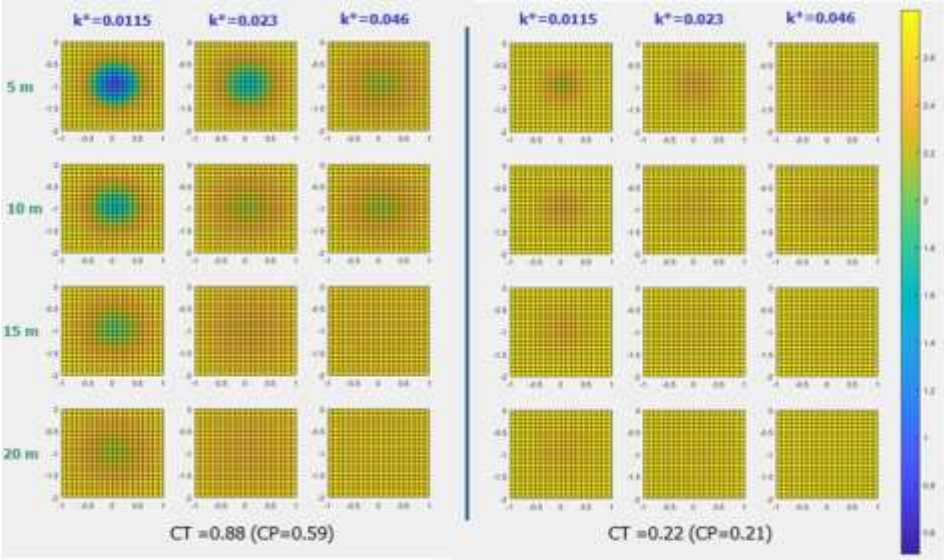

Figure 3. BPA Simulation Result

The stronger the wake effect, the slower the fluid flow behind the turbine, it is indicated by the dark colours (e.g. purple). The wake effect influence will decrease as the increasing of observation point and the decreasing of thrust coefficient. Thrust coefficient C_T is also influenced by how much energy is absorbed by the turbine. A large electrical load will results in more energy being absorbed by the turbine and higher thrust coefficient, and vice versa. The theoretical maximum value of the thrust coefficient is 0.88 where at the same time the wind turbine power coefficient Cp is maximum at 0.59. In addition, the coefficient of k* also affects the recovery time of the wake effect, the greater the k* value, the faster the wake effect disappears and vice versa. In this study the value of k* is 0.023 referring to the Bastankhah publication.

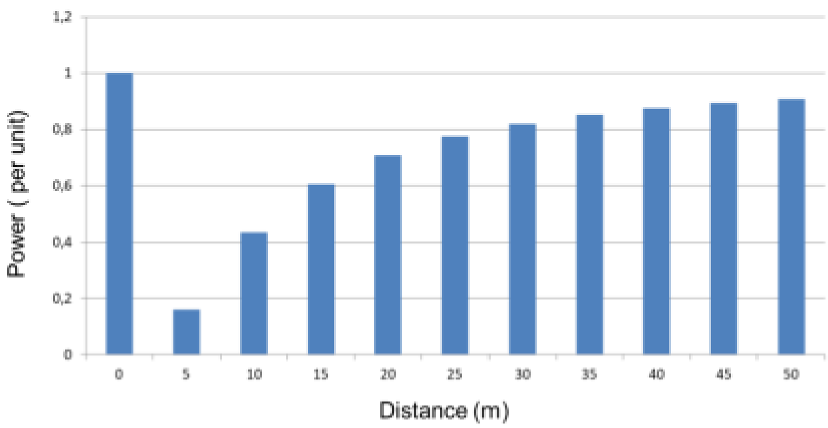

Figure 4. Power Variation Due to Wake Effect

The variation of power due to the presence of wake effects can be seen in Figure 4. If a turbine can produce a power of 1 p.u. at a distance of 0 m, then due to the wake effect the maximum power that can be generated behind the turbine will vary as a function of distance.

b. Simulation of Hydrokinetic Power Generation System

The simulation was carried out twice with different turbine distances, while the other system parameters remain the same. The specifications of the system are listed in Table 1.

Table 1. Simulation parameter

	Parameter	Value / Type
Turbine (Smart Hydro Power, 2016)	rating	5000 W
	diameter	1 meter
	base stream speed	2.8 m/s
	pitch angle	15 degree
	turbine-to-turbine distance	10 meters / 30 meters
PMSG (Prince et al., 2021)	rating	2500 W
	pole pairs	4
	rated speed	150 rad/sec
	moment of inertia	14.2 kg·cm2
	stator resistance	1.43 Ohm
	rotor flux linkage	0.26 Wb
	d- and q-axis inductances Ld = Lq	42.76 mH
Filter	L	8e-4 H
	C	0.2e-3 F
PI Control	reference	240 V
	P	0.1
	I	200
Power electronics	rectifier	6 Pulses diode bridge
	inverter	average-model based VSC
Load	resistive	100 ohm (each)
	rated load voltage	240 V

In the first simulation, the turbine angular speeds, DC link voltages, and the real power generated by the generators are shown in Figure 5. Each turbine is 10 meters apart. Generator 1 receives the maximum stream velocity. Generators 2 and 3 received velocity deficit due to the wake effect which is indicated by the relatively lower rotational speed and lower DC link voltage compared to Generator 1.

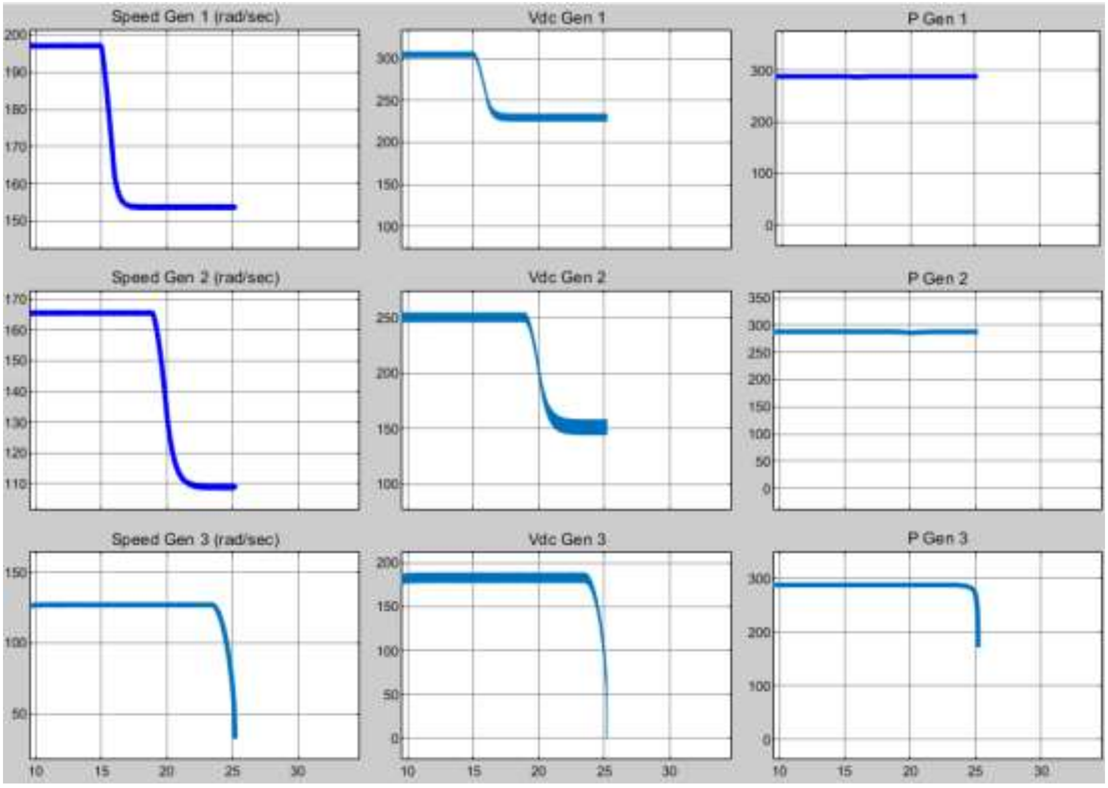

Figure 5. Simulation Results for Turbine Separation Distance of 10 Meters

The scenario carried out is a decrease in stream velocity at t=15 second by 0.5 m/s. Before the velocity decreases, the PI control can still regulate the output power, which indicated by a stable generator power (P Gen). However, after a decrease in stream velocity, Generator 3 also experience a decrease in angular speed followed by a drop in the DC link voltage to 0 V. As a result, the output power is no longer controllable. The decrease in angular speed of Generators 2 and 3 is delayed due to the water flow propagation.

The results of the second simulation can be seen in Figure 6. The distance between the turbines is increased to 30 meters. The addition of distance causes the turbine to experience a relatively smaller velocity deficit than before, this can be seen from the higher angular speed and DC link voltage of generators 2 and 3. Based on this scenario, generator 3 does not fail to operate even though the stream velocity decreases.

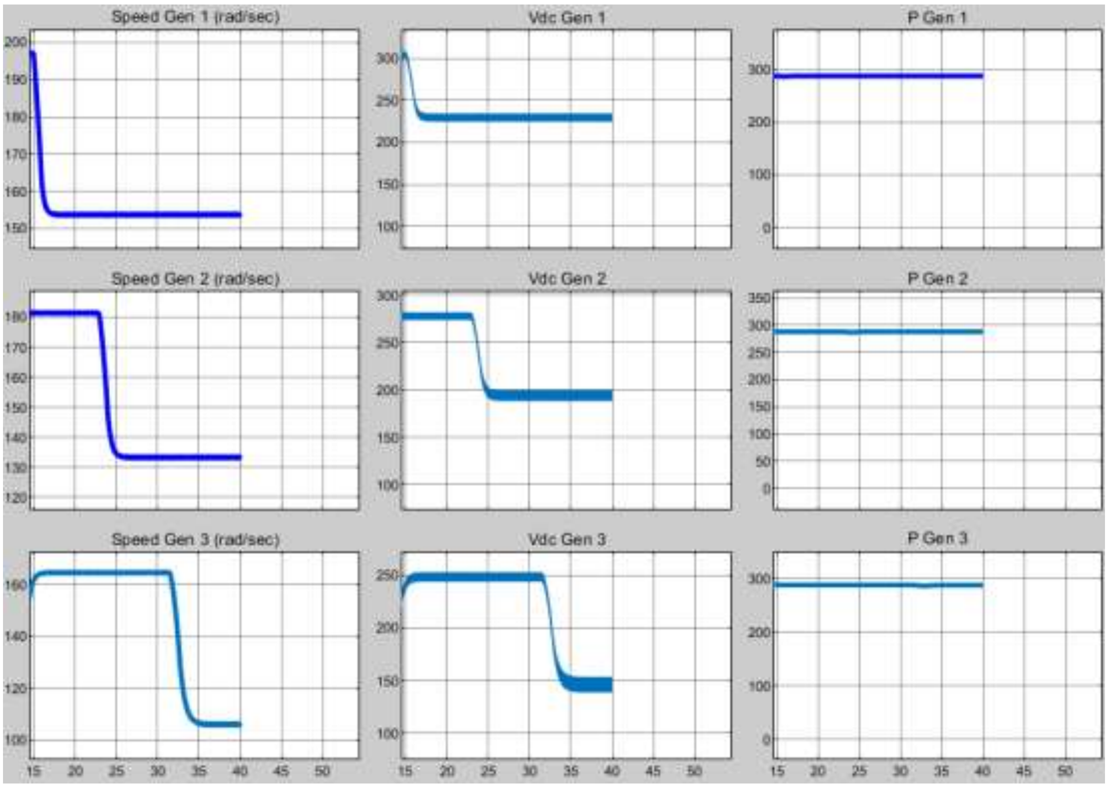

Figure 6. Simulation Results for Turbine Separation Distance of 30 Meters

For serial configurations as presented in this study, the distance between the turbines needs to be considered. The distance of turbines that are too close to each other can result in a very large velocity deficit in the downstream turbine and vice versa. Another influencing factor is the value of k* which can vary greatly depending on the physical conditions of the river or aqueduct that being studied.

Conclusions and Recommendations

In this article, the author examines the correlation between power control and the wake effect generated by a hydrokinetic power plant. The proposed system configuration consists of three hydrokinetic power plants. The generator works in an isochronous manner and isolated from the grid. The wake effect approach is referring to the Bastankhah and Porté-Agel (BPA) model. The performance of the generating system was analysed using Simulink. Two scenarios were run, that is when the distance between each turbine was 10 meters and 30 meters. In both scenarios the water stream velocity is set to decrease from 3 m/s to 2.5 m/s at t=15 s. Instability of PI voltage control is founded in downstream generators when the turbines are 10 meters apart from each other. Meanwhile, when the turbines are 30 meters away from each other, the control of electrical power and voltage is remains stable. Stability can be maintained in the second scenario because the stream velocity deficit decreases as the distance between the turbines increases.

It is recommended that each turbine is not installed too close to each other. The laying distance is of course also very dependent on the physical conditions of the river or aqueduct, whether the flow is straight or there are turns, shallow or deep, as well as the type and volume of sedimentation. Detailed studies at the field need to be carried out prior to installation due to the physical conditions of each river or aqueduct will certainly vary.

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