DESIGN OF HYDROKINETIC ENERGY GENERATION SYSTEM

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Abstract: Along with technological developments and increasing population, people are in need of more energy sources. This need has led researchers to go towards new energy generation methods. One of these methods is hydrokinetic energy generation, which has been studied intensively in recent years. In this study, complete design of a hydrokinetic turbine that converts kinetic energy into mechanical and electrical energy with the most efficiency using tidal water is proposed. Moreover, an undershot water wheel system is designed to gain the least dissipationless conversion of kinetic energy. The design of the hydrokinetic energy generation system is developed considering the environmental and maintenance factors, maximum efficiency and buoyancy. Calculation for the velocity of the turbine is made by using Betz's law, usually used for wind energy conversion systems. Conversion of obtained mechanical energy from the turbine to electrical energy is supplied by using a proper alternator system.

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Introduction

Increasing energy demand around the world and the harmful environmental effects of energy production technologies from fossil fuels causes climate change, global warming and spreading health problems. In order to find alternative solutions, scientists and engineers have studied harmless, non-consuming, cheaper, and sustainable energy production methods. The use of marine and stream energy has gained importance recently; thus, researchers have intensified the development of new technologies for the use of hydrokinetic energy. Hydrokinetic power generation helps to make a considerable contribution to electricity needs, with attractive features such as low installation and maintenance cost, renewability, and almost zero contribution to air pollution. The hydrokinetic method of harvesting energy from streams converts the kinetic energy of flow to mechanical energy by a machine that generates electrical current by a generator mounted on a shaft similar to a wind turbine. Hydrokinetic devices work with greatest efficiency in locations where the water level is high and there is relatively steady flow throughout the year, because the available power depends primarily on the speed of the current (Anyi & Kirke, 2011; Denny, 2003; Ortega-Ashury, McAnally, Davis, & Martin, 2010; Yuce & Muratoglu, 2014).

Various types of designs for water current turbines are available for the extraction of energy from the river. There are two classes in general, based on the alignment of the rotor axis with respect to water flow. These are horizontal and vertical axis turbines. Horizontal axis units are arranged such that the oncoming flow is parallel to the rotor's rotation axis, whereas the oncoming flow is perpendicular to the rotation axis in vertical axis units. The components of hydrokinetic turbines are similar to those of wind turbines because they utilize comparable operating principles, varying only in fluid type. Fan, propeller, and screw-type rotors are common examples of horizontal axis units and Darius, Savonius, Gorlov, and Flipwing types are vertical axis units. Helical blade and Darrieus straight blade water turbines are commonly suitable for extraction of the kinetic energy of flowing water (Behrouzi, Maimun, & Nakisa, 2014; Lopes, Vaz, Mesquita, Mesquita & Blanco, 2015; Nishi, Inagaki, Li, Omiya, & Fukutomi, 2014; Nishi, Inagaki, Li, & Hatano, 2015; Sahim, Ithisan, Santoso, & Sipahutar, 2014; Verma, Garg, & Rajput, 2015).

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In addition to worldwide interest, hydrokinetic energy generation systems have gained significant importance. Several studies have been done in recent years. First of all, Denny (2003) published his researches about the efficiency of overshot and undershot waterwheels. In his study, he proposed that undershot waterwheels were more suitable construction unless there was no gravitational torque. In 2010, scientists at the Mississippi State University published research about the hydrokinetic power systems in the USA (Ortega-Achury et al., 2010). Anyi and colleagues have studied hydrokinetic turbine blades; their aim was to design the best geometry for blades of hydrokinetic turbines in order to obtain greater performance from the system (Anyi & Kirke, 2011). Yuce and Muratoglu (2014) published a technology status review of hydrokinetic energy conversion systems. There are several publications on the undershot turbine, efficiency improvement techniques, experimental study of Darrieus-Savonius water turbine and dynamic behaviour of hydrokinetic turbines (Behrouzi et al., 2014; Lopes et al., 2015; Nishi et al., 2014; Nishi et al., 2015; Sahim et al., 2014; Verma et al., 2015).

In this study, a hydrokinetic power generation system is designed, under the constraint that water flows in the flat direction (no gravitational torque). The system design takes into account the number of blades and turbine geometry that can reach maximum achievable efficiency and power. Moreover, the energy obtained from the turbine is intended to be converted into electrical energy with maximum efficiency by an alternator system.

Theoretical Background

As Denny (2003) writes, water turbines used for small-size hydroelectric power generation are largely categorized into the tube-channel type (Francis and propeller water turbines) and open-channel type (water wheel). Francis and propeller water turbines require large heads, resulting in a decrease in the number of suitable construction sites. On the other hand, open channel water turbines do not require additional facility, so it is easy to install them directly. They also have less environmental impact and are easier to maintain.

Although, the water wheel system was discovered 2000 years ago, it continues to steadily evolve. The undershot waterwheel (the water passes underneath the axle) was described by Vitruvius in 27 BC. Until the 13th century, the undershot waterwheel was more common, but less efficient than the overshot waterwheel system. When used with hydrokinetic turbines, undershot waterwheel systems started to become much more efficient.

Table 1: Nomenclature

ρ	Density	c	Velocity coefficient
v	Tidal water velocity	A	Area
v'	Velocity after turbine	P	Power
v_t	Turbine velocity	E	Energy
F	Force	ε	Efficiency
ω	Angular velocity	R	Radius of the turbine

Source: Authors

It is possible to analyze the example of undershot waterwheel design and its Poncelet modification (Denny, 2003). To estimate the efficiency with respect to Figure 1(a), equations are shown below. First of all, to calculate the mass flow rate and velocity:

$$\dot{m} = \rho\, A\, V = \rho\, A\, (v - v') \quad (1)$$

$$v' = w\, R = c\, v\,, \quad (0 < c < 1\,) \quad (2)$$

Combine (1) and (2), and the force exerted by the water against the vanes is:

$$F = \frac{d}{dt}\left(m\,(v - v')\right) = \rho\, A\, v^2\, (1 - c)^2 \quad (3)$$

The output power of the turbine can be written:

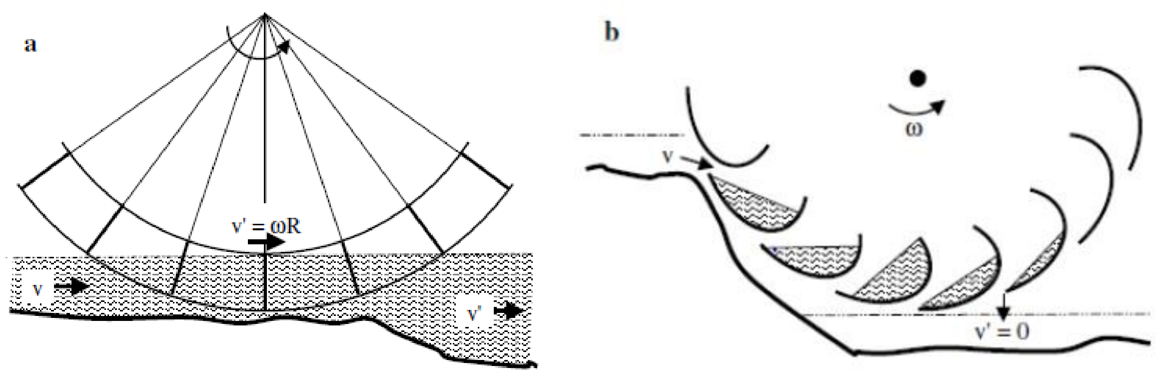
$$P_{out} = F\, v' = \rho\, A\, v^3\, c\, (1 - c)^2 \quad (4)$$

The efficiency estimation can be calculated using the ratio of input and output forces:

$$P_{in} = \frac{1}{2}\,\rho\, A\, v^2 \frac{dx}{dt} = \frac{1}{2}\,\rho\, A\, v^3 \quad (5)$$

$$\varepsilon = \frac{P_{in}}{P_{out}} = 2\, c\, (1 - c)^2 \quad (6)$$

Figure 1: (a) Undershot waterwheel with radial vanes, (b) Poncelet modification



(a) (b)

Source: Denny (2003)

The peak value for equation 6 occurs for c=1/3, so that gives maximum possible efficiency at about 30%.

Therefore, water velocity is the most important factor to determine the load capacity of the system. On the other hand, there are some modifications that can improve the efficiency up to 65% (Ref?), such as the use of a Poncelet wheel (Figure 1(b)).. Because curved vanes hold the water as the wheel rotates, the water falls back with zero speed. It is possible to improve the efficiency though gravitational component of torque is provided as with overshot wheels. However, this design was not suitable for our environmental conditions (no gravitational torque).

On the other hand, It is possible to use Betz's law (Betz, 1966) for calculating the speed of current after the turbine. Betz's law is usually used for wind energy systems, but is also suitable for hydrokinetic energy calculations.

$$\dot{m} = \rho\, A_{in} v = \rho\, A_{out} v' \quad (7)$$

$$F = \rho\, A\, v_t\, (v - v') \quad (8)$$

$$P = \frac{dE}{dt} = F \frac{dx}{dt} = F\, v_t \quad (9)$$

Substitution of the force can be derived from equations 7, 8 and 9:

$$P = \frac{1}{2}\,\rho\, A\, v_t \left(v^2 - v'^2\right) = \rho\, A\, v^2\, (v - v') \quad (10)$$

Also turbine velocity will be the average of the input and output velocities of the system:

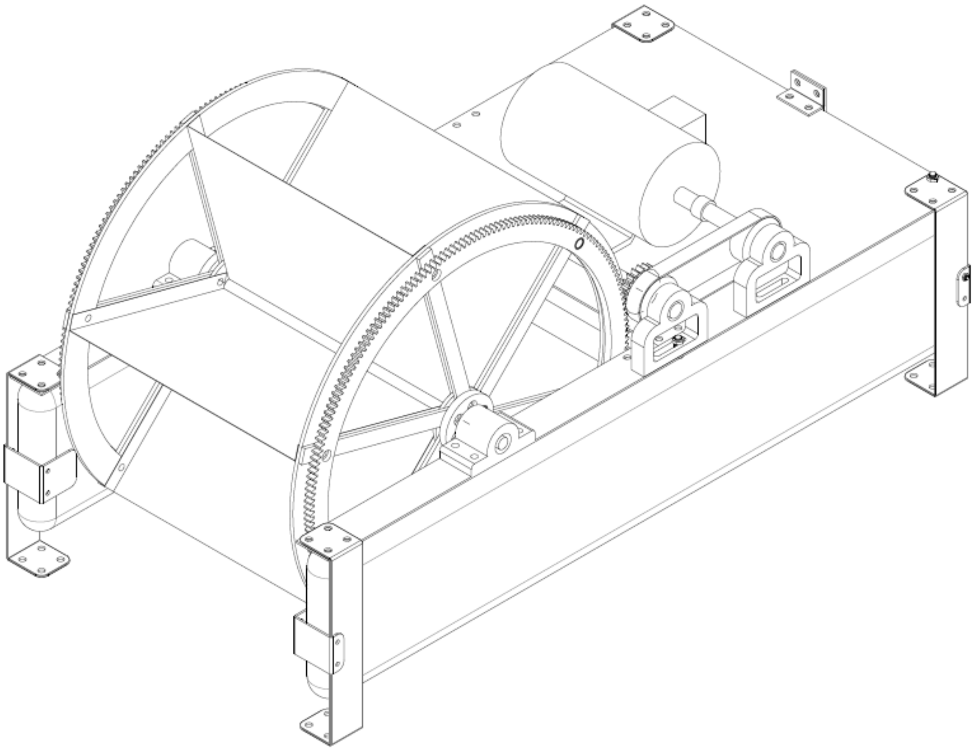
$$v_t = \frac{1}{2}\,(v + v') \quad (11)$$

When the ratio of the input and output velocity of the turbine system ($\frac{v}{v'}$) is 3, maximum power will be obtained (Denny, 2003).

System Design

Design of the system was made on the basis of certain constraints. The technical drawing of the complete system model can be seen in Figure 2. In addition to this, tidal water velocity and dimensions of the system can be seen in Table 2.

Figure 2: Complete system model



Source: Authors

Force and Energy Calculations

The region where the system is used and the specific environmental conditions provided constraints for the design of a system to obtain maximum performance within these constraints. Constraints and calculation results are shown in Table 2.

The drag coefficient (commonly denoted as: c_d, c_x, or c_w) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment, such as air or water. It is used in the drag equation, where a lower drag coefficient indicates that the object will have less aerodynamic or hydrodynamic drag. The drag coefficient is always associated with a particular surface area. The drag coefficient can be derived from equation 12.

$$C_d = \frac{\text{Drag force}}{\text{Dynamic force}} = \frac{F_d}{\frac{1}{2}\rho\, v^2\, A} \quad (12)$$

The drag coefficient value will be 1.9 for this system, with respect to equation 12. Tidal water power and turbine velocity formulation can be seen in equation 13.

$$P_{water} = \frac{1}{2}\rho\, A\, v^3, \quad v_{turbine} = \frac{(v + v')}{2} \quad (13)$$

Table 2: Input, output parameters and variables of the system

Symbol	Parameter	Value
v	River speed	8 km/h → 2.22 m/sec
A	Area	0.5 m^2
C_d	Drag coefficient	1.9
ρ	Density of the water	1000 kg/m^3
r_1	Outside radius	1 m
r_2	Inside radius	0.5 m
$v_{turbine}$	Velocity of the turbine	1.481 m/sec
v_2	Velocity after the turbine	0.741 m/sec
S	Cross sectional area	0.496 m^2
ɵ	Angle of blades	1.047 rad
F_{top}	Gross power on the blades	1.746*10^3 N
$P_{turbine}$	Turbine power	2.586*10^3 Watt
P_{water}	Tidal water current power	2.743*10^3 Watt
w	Angular velocity of the turbine	2.993 rad/sec
r_{gear}	Gear radius	0.495 m
d_{gear} and d_{gear2}	Gear characteristics	0.99–0.11 m
Z_1 and Z_2	Teeth numbers of the gears	198–22

Source: Authors

Ideally, turbine velocity is used in the most efficient way to contribute to the performance of the system. Thus, blade numbers and geometry of the turbine are important factors. The area where the force of water has impact on the blades of the turbine is called the cross sectional area.

$$S = r_1 - \frac{r_2}{\sin\left(\frac{\frac{360}{\text{blade number}}}{360} 2\,\pi\right)} \tag{14}$$

Some of data derived from the calculations of the turbine force can be used with respect to blade numbers. The most efficient blade number of the turbine will be 6 and force on the blades will be as in equation 15.

$$\text{Angle} = \theta = \frac{\frac{360}{\text{blade number}}}{360} * 2\pi \tag{15}$$

Equation 16 gives the force equation, obtained from the blades that are located under the water. Power of the turbine is dependent on this force and the velocity of the turbine (equation 17).

$$F_{top} = \sum_k^1 \left[C_d\ \frac{1}{2}\left(r_1 - \frac{r_2}{\sin(k*\theta)}\right)\ [\sin(k*\theta) - \sin[(k-1)*\theta] * \rho\, v_1^2\ ]\ \sin(k*\theta)\right] \tag{16}$$

$$P_{turbine} = F_{top}\ v_{turbine} \tag{17}$$

The indicated power of the system is approximately 2.5 kW and comparison with the power of the turbine provides the efficiency of the mechanical system.

$$\text{Efficiency} = \frac{P_{turbine}}{P_{water}} \rightarrow 90\% \tag{18}$$

Conversion of mechanical energy to electrical energy is done using an alternator system. Thus, two gears with a belt and belly system provides the connection of the mechanical system to the electrical system. To find the suitable revolution number for the rotor (257 rpm) of the electrical part, gear ratio is selected as 1:9.

$$\text{rpm} = 80 * \text{w} * \frac{60}{2\,\pi} \tag{19}$$

Alternator Selection and Electrical Calculations

As this study was designed to meet the energy requirement of houses located close to the hydrokinetic energy generation system, the daily average energy consumption for nearby houses was important. Daily energy consumption of household appliances in nearby households is shown in Table 3.

Table 3: Daily energy consumption of household electrical appliances

Appliance	**Power**	**Daily use**	**Daily energy consumption**
Oven	2500 Watt	15 minutes	0.625 kWs
Kettle	2200 Watt	10 minutes	0.37 kWs
Dishwasher	1250 Watt	1 hour	1.25 kWs
Washing machine	1200 Watt	1 hour	1.2 kWs
Vacuum cleaner	1000 Watt	15 minutes	0.25 kWs
Iron	1000 Watt	10 minutes	0.17 kWs
Hair dryer	400 Watt	10 minutes	0.07 kWs
LCD Tv	200 Watt	4 hours	0.8 kWs
Lightbulb (10 piece)	100 Watt	5 hours	0.5 kWs
Laptop	75 Watt	4 hours	0.2 kWs
Battery charger	4 Watt	3 hours	0.012 kWs
Refrigerator	40–50 W	24 hours	1 kWs
Total	**9 kW**	**-**	**6.45 Kw (268 watt per hour)**

Source: Authors

Environmental Factors

Altitud : 0–1000 meters

Temperature < 40 °C

As seen from table 4, the relevant coefficient will be equal to 1 according to temperature and altitude conditions.

Output Frequency and Alternator Pole Calculations

In the electrical network in Turkey, output frequency must be equal to 50 Hz; thus, pole number can be calculated dependent on 50 Hz frequency.

$$\text{Frequency} = \#\text{ of poles}\,.\frac{\text{rpm}}{120} \tag{20}$$

It is possible to increase the power using high number pole systems for hydroelectric generators. Alternator systems with 23 poles would be feasible for this structure.

Table 4: Coefficients according to temperature and altitude

P/Pn	**Temperature**			
Altitude	**40 °C**	**45 °C**	**50 °C**	**55 °C**
H=0–1000 m	1.00	0.96	0.92	0.86
H=1000–2000 m	0.96	0.92	0.86	0.79
H=2000–3000 m	0.92	0.86	0.79	0.72
H=3000–4000 m	0.86	0.79	0.72	0.64

Source: Authors

Conversion of Mechanical Energy

Maximum power obtained from the hydrokinetic turbine system will be approximately 2.5 kW with regard to the law of energy conservation. Since operation of the system is continuous, this will potentially increase heat. This means that the alternator's nominal power must be greater than 2.5 kVA.

Multiplying the nominal power by the power factor of the motor produces the output power of the alternator system (power factor is between 0.8–1).

Using these calculations, the alternator characteristics can be as following:

- Output voltage/frequency: 220 V/50 Hz
- Output type: AC
- Rotor speed: 257 rpm
- Phase number: 3 phase
- Type: PMG (permanent magnet generator)
- Pole number: 23
- Outdoor usage and waterproof ability

Finally, a customized 50 Hz, 257 rpm, 23 pole alternator system will be suitable to supply the daily energy consumption of household electrical appliances.

Conclusion

In order to design the hydrokinetic energy generation system, studies were carried out under the influence of various design parameters, such as turbine type, geometry, blades, the weight of the system, and alternator type. Different turbine geometries can be designed with respect to environmental conditions. Literature indicates that an undershot waterwheel system is suitable for our application, because it is the most efficient structure when considering tidal water and the location of the turbine. Conversion of mechanical energy is provided using an alternator system that is suitable for supplying the daily energy consumption of electrical household appliances. For these reasons, a hydrokinetic energy generation system has been designed with respect to various design parameters. It is possible to modify the design easily for different environmental conditions.

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