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A Case Study of Energy Harvesting by Dynamic Tidal Power in the Persian Gulf

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Abstract– **Dynamic Tidal Power (DTP) is one of the most recent methods of exploiting the energy of tides. Although most of the studies regarding this revolutionary method aim at the Yellow and Bohai seas in China, the evaluation of this method in other potential locations in the world is of considerable importance. This study provides preliminary insights and assessments about the use of this method in Faror strait in the Persian Gulf. By using a 3D numerical model of a full-scale domain, the maximum water level difference between the two sides of the DTP dam is found to be about 1.2 meters at the maximum water speed in the strait with a total available power of 760 MW. Furthermore, among the existing technologies for electric generators, a direct-drive permanent magnet synchronous generator has proved to be the best choice for the electric power generation system. Moreover, it has been concluded that power electronic converters are required to make the generated voltage compatible with the grid voltage.**

Keywords*– *Dynamic Tidal Power (DTP), Computational Fluid Dynamics (CFD), Blue Energy, Persian Gulf, Permanent Magnet Synchronous Generator (PMSG), Doubly-Fed Induction Generator (DFIG), Tidal Power Plant, Electric Power Generation.

I. Introduction

Providing sufficient energy for the increasing energy demand of today's world is a daunting task for countries and governments. In addition, the overuse of fossil fuels causes many environmental and health problems. Sustainable energy sources can help us address many of our energy and environment-related issues.

Among sustainable sources of energy, the ocean continues to gravitate many attractions world-widely[1]. There are different sources of energy in the ocean which can be exploited, e.g. wave energy, tidal energy, salinity difference, and ocean thermal energy [1]. Tidal and wave energy harvesting methods have seen a significant evolution in the recent decade; however, the potentials of these sources are far more than the present applications[2]. Currently, there are two operational large-scale tidal power stations, namely Rance, and Sihwa tidal power stations [2] which are located in France and South Korea. Thus, studying methods with lower limitations is of significant importance. This study focuses on a tidal method specifically for application in the Persian Gulf in the south of Iran.

There are two common methods to harness the power of the tides, i.e. free stream turbines and closed basin methods [3]. In recent years, a third method, called Dynamic Tidal Power (DTP), has been added to the previous ones. Free stream turbines are suitable for locations with relatively high-velocity streams and their environmental impact is not significant. They merely utilize the kinetic energy of the tides. Closed basin methods, which can be divided into two groups of *tidal lagoon* and *tidal barrage*, need high tidal range to generate sufficient electricity and they cause numerous environmental problems ranging from blocking the migration path of fishes to changing the marine habitats. This method only uses the static head of the water to generate power [4]. The maximum available power of these methods can be obtained from equations (1) and (2):

$$P_{KE} = 0.5Edu^3 \quad (1)$$

$$P_{PE} = 0.5dgAh^2 \quad (2)$$

where d is the water density, E is the cross-sectional area of the restricted flow, u is the upstream fluid velocity perpendicular to the cross-sectional area, g is the gravitational acceleration, A is the surface area of the basin, and h is the mean tidal range [5].

A. Dynamic Tidal Power

Dynamic Tidal Power is one of the most recent and promising methods for harnessing the power of the ocean tides which was introduced in 2005 by Hulsbergen [6]. This method involves constructing a long dam

[1] International Energy Agency, "Key World Energy Statistics", https://www.iea.org/publications.
[2] Carbon Trust, "Accelerating Marine Energy", https://www.carbontrust.com/media/5675/ctc797.pdf.

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(typically more than 10 km) perpendicular to the coastline to interact with tidal streams in order to generate a dynamic water head, Fig. 1. DTP utilizes the dynamic and static head of the tides based on these considerations:

- Designing an optimal system considering the geographical parameters;
- utilizing a dam of more than 10 km perpendicular to the coastline with multiple turbines inside it;
- generating water level difference between two sides of the dam without using a closed basin; and
- using a twin dam configuration to compensate for the minimum production period of each dam.

Most of the studies on the hydrodynamic characteristics of the DTP pivot around the Yellow and Bohai seas along the Chinese coastline by using a 2D model to predict the water level difference and the environmental impacts [7]. In the present study, the feasibility of using the DTP in Faror strait in the Persian Gulf is investigated by the use of 2D and 3D numerical models based on the flow data provided by the Ports and Maritime Organization of Iran (PMO)[1].

Furthermore, an electric power generation system is proposed, along with the selection of an appropriate generator and power electronic converters, which can be utilized for the system. Numerical data are validated using the Kolkman and Mei analytical methods for the DTP [4, 8].

B. Literature Review

The idea of Dynamic Tidal Power shaped in 1996 and was first presented officially in the 6th European Wave and Tidal Energy Conference in 2005 by Hulsbergen et al. [6]. Hulsbergen demonstrated the basis of the DTP and used the Kolkman theory [4] to predict the water level difference and the generated power for different configurations of the DTP, and modified his prediction by the Zunowak 2D numerical model [4]. He asserted that the maximum generated power in tidal current speed of 1.4 m/s and a maximum depth of 30 meters will be

Fig. 1. Dynamic tidal power concept for the Faror island[2].

[1] https://www.pmo.ir/en/home. (accessed on 2018-8-17)
[2] https://www.google.com/earth. (accessed on 2018-11-9)

around 36 MW with a maximum water head of 3 m for a 45 km dam.

Mei [8] analytically investigated the behavior of tidal waves interacting with a dam perpendicular to the coastline. The results of this study confirmed the authenticity of Hulsbergen's study. In another study in 2010 by Adema [9], 22 potential locations in China's coastline were investigated by a numerical model. Based on this study the maximum water level difference between the two sides of the dam is about three meters and the maximum available power is almost 20 GW.

In a study in 2012 by Zheng et al. [10], the "I" and "T" shapes of the dam have been investigated for Dalian and Liaodong peninsulas and it is reported that by increasing the length of the dam, the water head will increase, correspondingly.

In 2014, Liu and Zhang [11] studied the DTP method from the tidal wave-phase-change point of view, and by using a 2D numerical model, they obtained the water level difference over a Y-shaped dam in Taiwan bay. Based on this study the maximum water head occurs in the case that the two upper branches of the Y-shaped dam are in a 40-degree angle from the main structure of the dam. The most significant result of this study is that a Y-shaped dam will provide more water level difference compared to a T-shaped dam of the same length.

Dai et al. [12] used a 2D numerical model and by implementing a domain decomposition method they improved the quality of the mesh in the vicinity of the dam structure. They studied the hydrodynamic effect of the DTP on the Taiwan bay and validated the numerical results with the measured data and previous numerical studies. This study revealed that the maximum power is obtained in the turbine opening rate of 8% and the maximum power was found to be around 0.89 GW.

Shao et al. [13] studied the environmental impacts of the energy harnessing by DTP. He asserted that the negative impacts and construction costs of this method could be mitigated through constructing several small dams instead of a large one. In another research by Shao et al. [7], they studied the hydrodynamic effects of their previous proposal in detail.

The last published research in the outline of the DTP is Park's study [2] in 2018. Park used a 2D model to investigate different dam shapes for the objective of decreasing the length of the dam while maintaining optimum output power. He concluded that the T-shaped structure will increase the water head up to 10 percent compared to the I-shape structure.

According to the above-mentioned studies on the DTP, there is the necessity for further research on different aspects of this method by considering various parameters. In the following sections, the DTP method is presented along with the results of the numerical simulation, its custom-designed electric power generation system, and different applications for the DTP generated electric power.

II. Structural Design and Hydrodynamics of the Dynamic Tidal Power Plant

Dynamic Tidal Power Plant uses both the static and dynamic head of water flow. Therefore, canals and narrow waterways which are connected to the oceans are splendid locations for utilizing DTP. Based on the measured tidal and flow data provided by the Ports and Maritime Organization of Iran, Faror strait was chosen for the DTP pilot location in this study. Fig. 1 shows the location of the Faror strait and the proposed dam shape. It has to be mentioned that Faror island itself is considered as a part of the dam in order to decrease the construction costs.

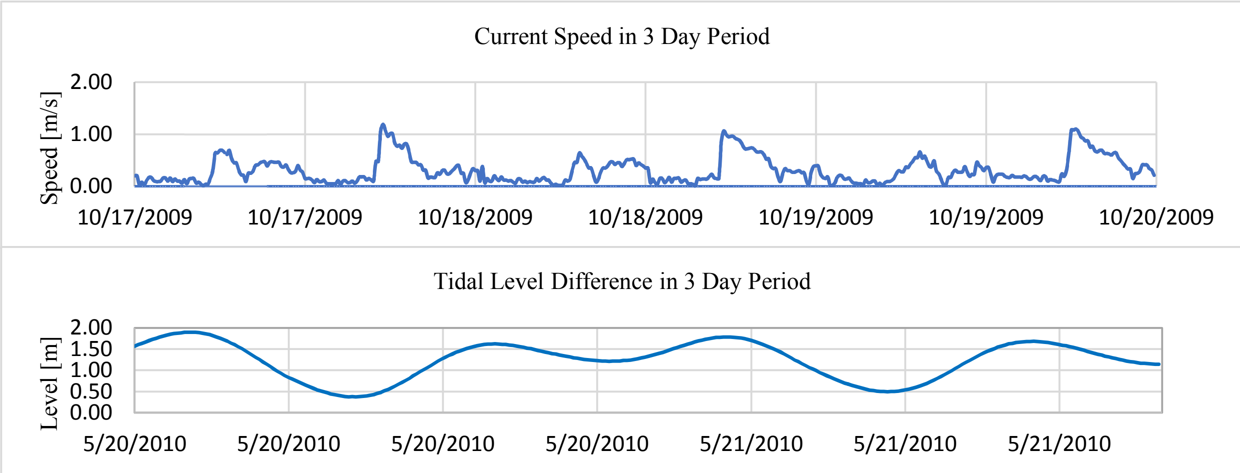

Fig. 3. Typical Tidal level difference and current speed in a 3-day period.

Fig. 2 shows the bathymetry of the region, which is used for modeling the depth of the sea in a 3D numerical model. The average depth of water in the dam location is about 30 meters which is suitable for economical construction. Furthermore, the dam is located in a canal in which there is a strong water current with a maximum speed of 1.19 m/s and a maximum tidal level difference of 2.403 m. Fig. 3 illustrates the tidal level difference and current speed in a 3-days period. From these diagrams, the period of the tidal wave in the region is found to be mostly semidiurnal (12.5 hours).

After determining the primary parameters of the problem, the Kolkman model [4] and Mei analytical model [8] (which has the same results) have been used for determining the maximum water head and the maximum pressure difference for an I-shape DTP structure in the Faror strait. The Kolkman model consists of the following equations:

$$\Delta h_{max} = 6.8\pi R \frac{V_{max}}{gT} \quad (3)$$

$$\Delta P_{max} = 4\pi\rho V_{max} \frac{R}{T} \quad (4)$$

where R is the dam length, T is the tidal period, $V_{\max}$ is the maximum tidal current speed, g is the gravitational acceleration and ρ is the density of water. Also, the Mei equation is:

$$\Delta\xi = 2i\omega m\sqrt{a^2 - x^2} = -\frac{2i\omega}{g} V_{max}\sqrt{a^2 - x^2} \quad (5)$$

in which ξ is the vertical displacement of water, ω is the frequency of the tidal waves, m is a coefficient and a is the length of the dam.

Based on the extracted data from Figs. 2 and 3, the values of the parameters are presented in Tab. 1. The 3D full-scale numerical model is performed after obtaining the appropriate domain size by a 2D transient model. The finite volume method is used, along with the volume of the fluid model for simulating the two-

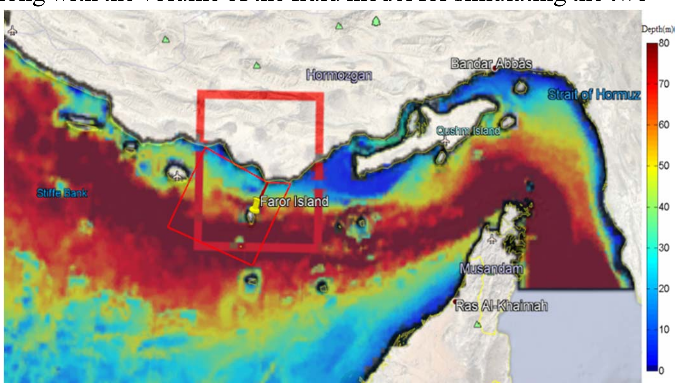

Fig. 2. Bathymetry of the Faror strait [14].

phase water-air interaction. The computational grids for the 2D and 3D models are structured with 159,164 and 1,722,080 elements, respectively. Pressure inlet and outlet boundary conditions are used in the inlet and outlet sides of the domain, which are exposed to the hydrostatic pressure of the water. This transient simulation is performed with the primary time step of 0.01s. The qualitative boundary conditions, contours of velocity, pressure, and streamlines are demonstrated in Fig. 4.

According to the results, the maximum water level difference occurs at the joint point of the dam and the shoreline. The streamlines near the end of the dam have been affected significantly by its structure and the maximum current velocity reaches 10.05 m/s at the south side of the Faror island. However, the effect of the dam in most of the locations near its structure is not considerable and the water velocity varies from 1 m/s to 5 m/s. Therefore, the environmental impact of the DTP structure is low. Additionally, the estimated available power of the DTP plant was found to be 760 MW. This amount is obtained by using the velocity head relation considering the Faror strait measured parameters. The results of the 3D transient numerical simulation are demonstrated in Tab. 2. It should be noted that the Kolkman analytical model does not consider the bathymetry, the free surface effects of the water, different tidal wave constituents, and the Coriolis forces.

TABLE I. WATER HEAD AND PRESSURE DIFFERENCE FOR THE DTP IN THE FAROR STRAIT FROM THE KOLKMAN AND MEI ANALYTICAL MODELS

Maximum Current Speed [m/s]	Dam Length [km]	Period of the Tidal Wave [h]
1.19	30	12.5
Maximum Water Head [m]	**Maximum Pressure Difference [kPa]**	
1.72	9.949	

TABLE II. WATER LEVEL DATA IN DIFFERENT MONITORING POINTS FROM THE 3D NUMERICAL MODEL

Point Coordinates	The water	The water level	Water Head [m]
[illegible]	[illegible]	[illegible]	0.304
[illegible]	[illegible]	[illegible]	0.302
[illegible]	[illegible]	[illegible]	1.119
[illegible]	[illegible]	[illegible]	.2036
[illegible]	[illegible]	[illegible]	0.43
[illegible]	[illegible]	[illegible]	0.808
[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	m]
[illegible]	[illegible]	[illegible]	

Therefore, the estimated head by this model is decreased to a maximum head of 1.204 m which is still sufficient for low head tidal turbines to operate efficiently [15].

III. ELECTRIC POWER GENERATION SYSTEM FOR THE DYNAMIC TIDAL POWER PLANT

Different types of generators which can be utilized in the power generation system of the DTP plant include induction generator (IG), doubly-fed induction generator (DFIG), wound rotor synchronous generator (WRSG), and permanent magnet synchronous generator (PMSG). In Tab. III, the advantages and disadvantages of these generators for tidal power plants are illustrated.

Taking the benefits and drawbacks of the mentioned generators into account, DFIG and PMSG are more suitable choices for the DTP power generation system. Benelghali et al. [16, 17] have conducted a comparative study between DFIG and PMSG in terms of their output power, maintenance requirements and operational limits. The results of this study are as follows:

1. DFIG: It is widely used in wind energy applications. It is able to generate electricity in variable speeds, works in every four quadrants of active and reactive power, and its power electronics losses and the cost of its converters are less compared to a fully-fed synchronous system.
2. PMSG: This type of generator can be direct drive. It requires low maintenance and makes unconventional methods of turbine-generator couplings possible. Moreover, in this design, the generator is completely decoupled from the grid with power electronic converters.

Although DFIG has proved to be efficient in wind turbines, there are numerous limitations in marine applications. Tidal energy converters need to be resistant to severe tidal currents, and their generator should be robust and should require low maintenance. A direct-drive PMSG needs less maintenance compared to a DFIG which needs a gearbox and slip ring. Moreover, the yearly output power of both generator technologies has been calculated for a site in France and the PMSG produced 25% more power than the DFIG [17]. In conclusion, the PMSG complies with the conditions of the DTP plant and, therefore, it is selected in this study.

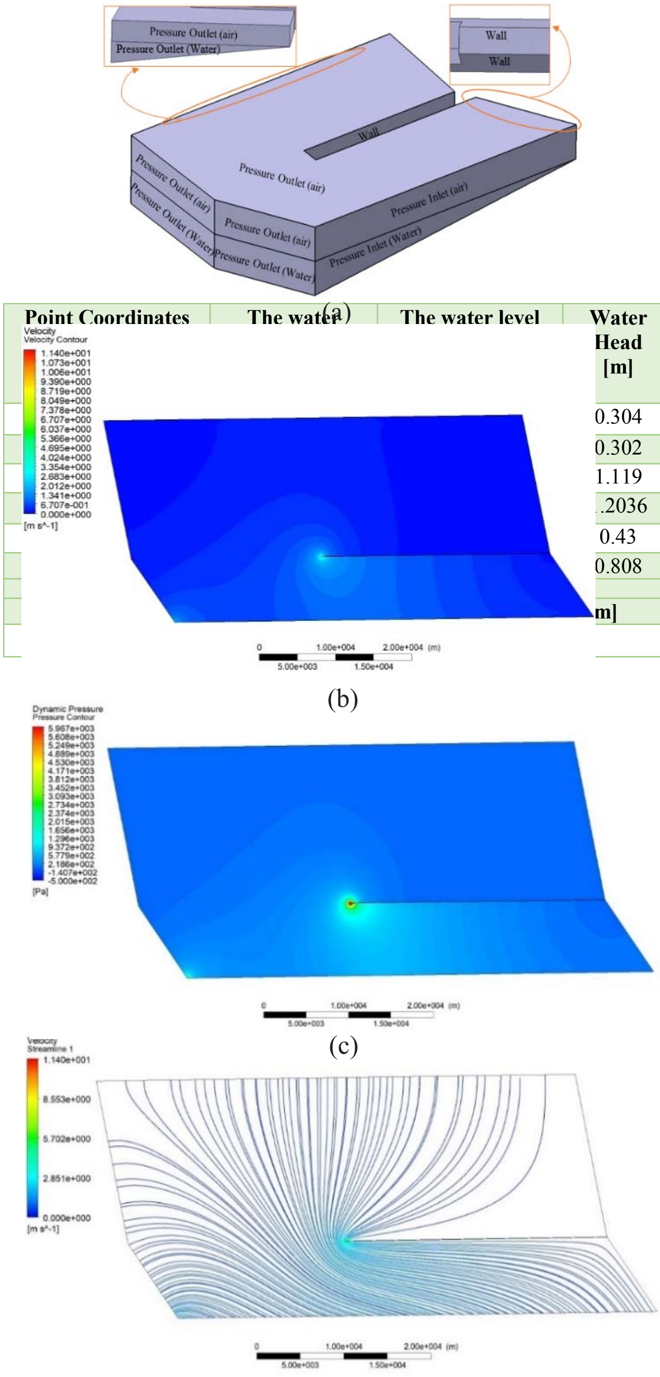

Fig. 4. (a) Qualitative boundary conditions; (b) velocity contour; (c) pressure contour; and (d) stream line contour of the 3D transient numerical model.

TABLE III. ADVANTAGES AND DISADVANTAGES OF GENERATORS FOR TIDAL POWER PLANTS [17, 18]

Type	Advantages	Disadvantages
PMSG	No field power converter	Having a large size and numerous poles in case of being direct drive
	Can be direct drive	Full-scale power electronic converter
	Full speed range	Permanent magnets are required (expensive)
	Higher reliability, efficiency, and robustness	Demagnetization at high temperature or due to the high opposing magnetic field from armature winding
	Less maintenance and operating expenses	-
DFIG	Can produce constant voltage and frequency in the speed range from -30% to 30% around synchronous speed	Needs gearbox
	Cheap low-capacity PWM inverter	Needs slip rings
	Less expensive control thanks to the reduced converter power rating	Regular maintenance required
IG	Relatively low contribution to system faults	Needs gearbox and reactive power
	Lower construction cost	More expensive converters
	Full speed range	Full-scale power electronic converter
WRSG	Full speed range	Having a large size and numerous poles in case of being direct drive
	Can be direct drive	Full-scale power electronic converter

Regarding whether a gearbox should be used or not, its drawbacks such as requiring a bigger turbine volume, higher mechanical power losses, and the cost of maintenance are noticeable. On the other hand, the direct-drive system is considered to be more dependable as the weight of the system, the expenses of installation and maintenance, and the number of mechanical components are reduced. Ultimately, direct-drive generators are able to work with variable loads by utilizing appropriate control approaches, and they can respond to the fluctuations in the tidal currents, immediately. Nevertheless, due to the fact that the direct-drive generators rotate at the same speed as the turbine shaft (from 5 rpm to 50 rpm), they need to have high torque and a large number of poles in order to preserve the preferred frequency. Consequently, they have a larger size [18]. Considering the mentioned merits of a direct-drive generator, the PMSG is suggested to be direct drive.

The power generation system for tidal energy converters is similar to that of the wind energy conversion systems. Among the existing topologies, the system proposed by Muljadi et al. [19] is the best choice for DTP since it can handle variable speeds in tidal currents, maintains the voltage frequency and amplitude at a constant level, and it allows using direct-drive PMSGs. The system includes the following components:

1. A direct-drive PMSG with high reliability and efficiency. The generated variable AC voltage is transferred to the substation at the shore with a submarine cable. Due to the variable-speed nature of the tides, power electronic converters are necessary in order to make the generated voltage compatible with the grid voltage.
2. A rectifier to convert the variable AC voltage to a variable DC voltage. It can be either active or passive. For simplicity, the rectifier is assumed to be a passive diode bridge.
3. A boost converter with a PID controller to change the variable output voltage of the rectifier to a constant DC voltage. This power electronic converter can compensate for the voltage drop that is caused by the distance between the generator and the substation. It also maintains the DC bus voltage at a constant level. It should be noted that the reference voltage of the controller needs to be chosen according to the nominal values of the IGBTs (insulated-gate bipolar transistors). Moreover, the switching frequency of the IGBTs should be between 1 kHz and 50 kHz.
4. A current-source inverter to convert the output DC voltage of the boost converter to a stable AC voltage with the desired frequency and amplitude (a transformer might be needed for adjusting the amplitude). The inverter also decouples the generator from the grid and enables easier fault detection. Finally, a phase-locked loop is used to synchronize the output voltage of the inverter with the grid voltage in terms of phase angle. As a result, any change in the phase angle or frequency is tracked. In Fig. 5, the single line diagram of the proposed power generation system is shown.

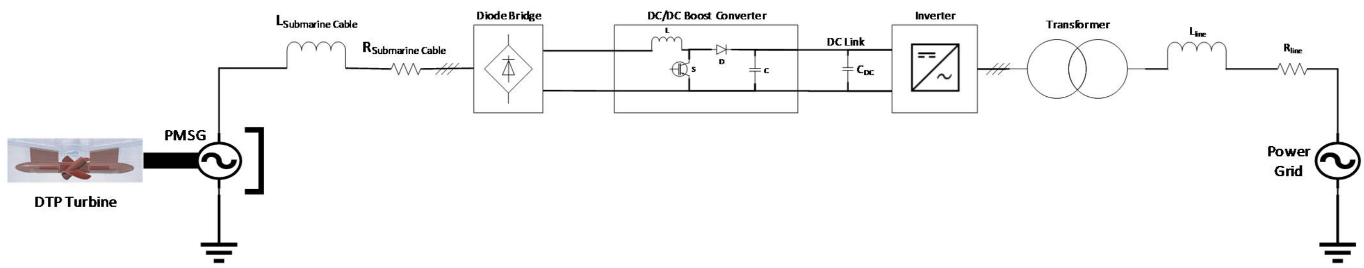

Fig. 5. The single line diagram of the power generation system for the DTP plant.

The benefits of using such a power generation system are optimization of turbine and generator parameters as a result of being decoupled from the grid, along with the optimization of system modes and preventing changes in the output power thanks to the complex control algorithms that can be used [20].

IV. Applications for the Generated Electricity

As the tides occur periodically, the output power of the DTP plant may not necessarily concur with the peak of electricity consumption. The generated electricity of the system can be used in different applications in addition to being delivered to the power grid. The selected applications in this study are as follows:

- **Producing hydrogen:** The electric energy can be used for the electrolysis of water and provide the hydrogen required for fuel cells. The hydrogen can be stored in storage units for future consumption, as well.
- **Water desalination:** There are two common methods for water desalination. The first one is a distillation method, called Mechanical Vapor Compression (MVC), which contains a mechanical compressor that needs almost 8 kWh to 12 kWh energy for purifying 1 m^3 of seawater. The second method is called Reverse Osmosis (RO), which involves passing the water through a membrane. This system needs 3 kWh to 10 kWh energy for purifying 1 m^3 of saltwater [5].
- **Pumped hydro storage:** This is a common technology for electrical energy storage, especially in high-power applications. The system includes two water reservoirs at different elevations, electric pumps, hydro turbines, and generators. When there is low demand from the grid, the generated electricity by the DTP plant will be used to pump the water from the lower reservoir to the upper one. During high demand from the grid, the water flows down from the upper reservoir and passes through hydro turbines to generate electricity.

V. Conclusion

Considering the benefits of DTP, studying different aspects of this method is of significant importance. This study provides basic evaluations of using this method in the Persian Gulf. The maximum water level difference between the two sides of the dam is found to be 1.204 m which is suitable for low head turbines. Furthermore, the velocity of the streamlines near the dam structure is between 1 m/s and 5 m/s. The type of electric generator which is suitable for this application has been specified to be a direct-drive PMSG. In addition, an electric power generation system has been proposed in order to stabilize the generated voltage.

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