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Analysis of Operating Characteristics in Tidal Power Generation According to Tide Level

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Abstract: *Tidal power generation plays a critical role in reducing greenhouse gas emissions. It uses a tidal force generated by gravitational force between the moon, the earth, and the sun. The change of seawater height generates the tide-generating force, and the magnitude of the change is the tide level. The tide level change has the same period as the tide-generating force twice a day, every 29.5 days, every year, and every 18.6 years. Sihwa Lake Tidal Power Station is Korea's first tidal power plant that began commercial power generation in August 2011 and has been accumulating a large volume of data on electricity production, power generation sales, sluice displacement, and tide levels. The purpose of this paper was to analyze the impact of the inefficiency factors affecting production and the tidal level change on tidal power generation and their characteristics using Sihwa Lake Tidal Power's operational performance data. Throughout this paper we show that tidal power generating operation is accurately predicting the trends of magnitude of tidal force to be periodical for each day. determining the drop to initiate the water turbine generator factoring the constraints on the operation of Sihwa Lake, and reflecting the water discharge through the floodgate and water turbine during the standby mode in the power generation plan to be in the optimal condition until the initiation of the next power generation can maximize power generation.*

Keywords: *Tidal Power Generation, Influence of Tide Level, Optimal Generation*

1. Introduction

In today's global climate impact, natural disasters such as droughts and typhoons have severe regional variations. Compared to the past, natural disasters cause extensive damage to human life and material that is unimaginable, and it is a reality that requires astronomical costs to recover from such damage. Such climate change is attributed to the large amount of greenhouse gas emissions due to global industrialization, and the United Nations Framework Convention on Climate Change (UNFCCC) sets and manages quotas for greenhouse gas emissions by country. Among the methods to reduce greenhouse gas, the production of electric energy is shifting from fossil fuel power generation to the renewable energy using solar energy (water, wind, sunlight, etc.).

Tidal power generation, which plays an important role in reducing greenhouse gas emissions, is a power generation method that uses energy called tidal force generated by the gravitational force and centrifugal force between the moon, the earth and the sun. The tidal force is a change in the high and low of the seawater, and the magnitude of the change at this time can be called the tide. It is known that the change of tide has the same cycle as the tidal force with a cycle of 2 times a day, 29.5 days, 1 year, and 18.6 years.

The Sihwa Tidal Power Plant is the first tidal force plant in Korea, and since commercial power generation started in August 2011, massive data on electricity production, electrical power sales, water discharges, tide water levels, etc. have been accumulated. This paper intends to analyze the inefficiency factors that affect production and the effect of tidal power generation by changes in the tides and their characteristics through the vast operational performance data of Sihwa tidal power accumulated. This analysis of past operation characteristics can be used as important data for tidal power generation projects as well as basic research data for tidal power generation at home and abroad.

2. Tidal Power Generation Operation Technology

2.1 Tides and Water Levels

The earth rotates once a day and revolves around the sun every year, and the moon revolves around the earth. It is called the tide phenomenon that the sea water level varies with the gravity between the earth and the sun and moon changes. The tide changes in the form of a sine wave, with the Earth's orbital axis tilted at 23.44° and the equator at an inclination of 28.58°. The moon moves by an average of 13.2° from west to east every day, and it takes 27.3 days for the moon to orbit the earth based on a random star as shown in Figure 1, which is called a sidereal moon. The time it takes from one phase of the moon(new and full moon) to the next one is 29.5, which is called the lunar month, and 18.6 years changes into a long cycle, which is called the Saros cycle.[1,2]

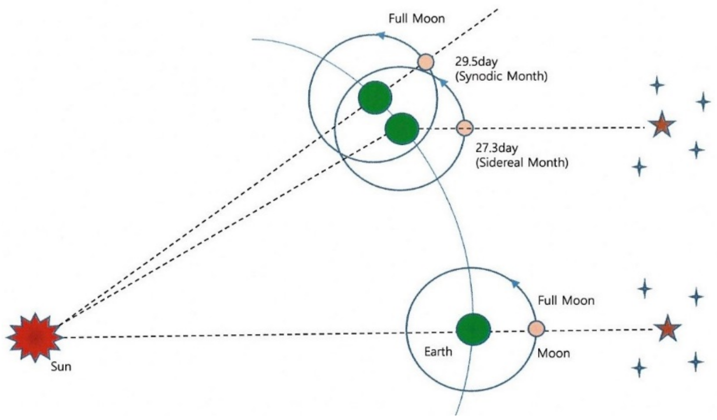

Figure 1. Tidal cycle

As shown in Figure 2, the magnitude of the tide appears highest when the moon and the sun are in a straight line with the earth as the center, and is lowest when the moon and the sun are positioned in a vertical line with the earth as the center. The technology to produce electricity by using the head of the seawater level is called tidal power generation.[3,4]

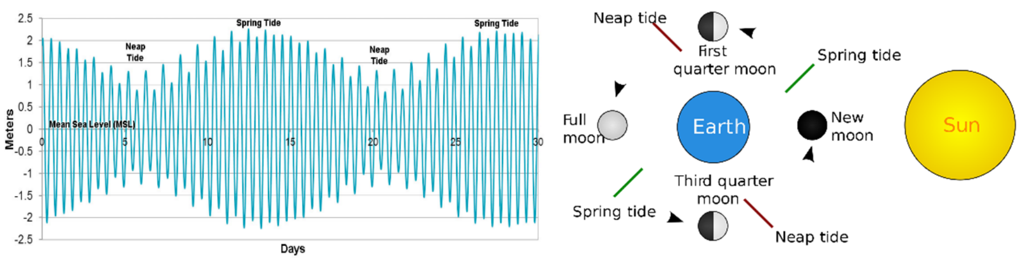

Figure 2. Tide cycle and magnitude changes(Wikipedia, 2019)

2.2. Tidal power generation method

As described above, in the tidal power generation method using the tidal wave caused by the tidal phenomenon, the double-basin system generates electricity in both directions at high tide and low tide using the difference in water level between the sea side and the tidal basin, and the single-basin system generates electricity in only one of the high and low tide directions.The single-basin system are divided into two types: flood generation type and ebb generation type. The flood generation type generates power by using the head in water level between the sea side and the tidal basin at high tide and discharges seawater from the tidal basin to the sea side through a sluice gate and a water wheel at low tide. ebb generation type first fills the tidal reservoir through the sluice gate at high tide, and then generates power using the head in water level between the sea side and the tidal reservoir at low tide.

2.2.1 Double-basin system power generation method

As shown in Figure 3, the double-basin system power generation method can generate power in both directions at high tide (①) and at low tide (②). Therefore, compared to the single-basin system at the same point, the annual amount of power produced may be large, but the construction cost is high.The waiting time (Filling section in Fig. 3) is long until reaching the minimum possible head for power generation at the time of changing high and low tides and the complicated structure of the water turbine generator increases the maintenance cost and reduces the efficiency when reversed direction power generation.The selection should be made by comprehensively considering the geographical conditions of the construction site[3].

The double-basin system has been used at the Lance Power Plant in France, which has been operating since 1966. This power plant has a rated capacity of 240 MW (24 units of 10 MW), a head of 3 to 11 m and an efficiency of 55 to 87% in forwarding direction power generation (ebb generation type). In case of reverse direction power generation (flood generation type), it is shown as 60~73%.[5,6]

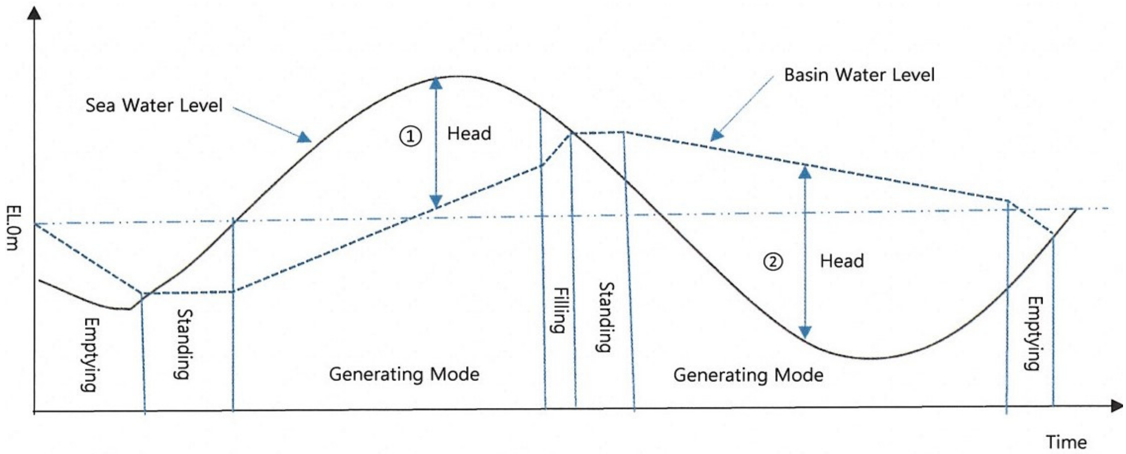

Figure 3. Power generation of double-basin system

2.2.2 Single-basin system power generation method

As described above, the double-basin system power generation method enables bi-directional power generation, whereas the single-basin system power generation method has a flood generation type that operates at high tide depending on the characteristics of the construction area, and a ebb generation type method that operates at low tide as shown in Figure 4.The ebb generation type opens the sluice gate during high tide and fills the tidal reservoir to the maximum level before starting the water turbine. The power plant currently operating in this way is the Annapolis Tidal Power Plant in Canada. The flood generation type that operates at high tide is used in Sihwa tidal power generation in Korea. The installed capacity of this power plant is 254 MW, and the maximum head is 9.0 m, which was completed and operated in 2011.

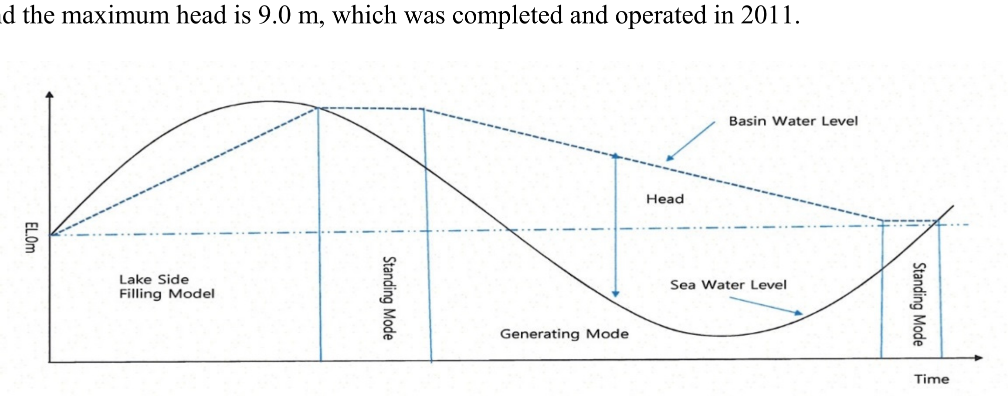

Figure 4. Ebb generation type power generation

2.3. Flood generation type

2.3.1. Birth of Sihwa Lake flood generation type Tidal Power Plant

The Sihwa Lake Tidal Power Generation power plant, which started commercial power generation in August 2011, started the Sihwa District Development Project for the purpose of land expansion through reclamation projects from 1975 to 1994.After the freshwater of Lake Sihwa from 1994 to 1996, the rapid urbanization and lack of environmental facilities in the Sihwa area led to rapid deterioration of the water quality of Lake Sihwa, raising social problems.After converting Lake Sihwa into a seawater lake due to a change in the agricultural water plan from 2000 to 2001, the Sihwa Lake Comprehensive Management Plan for the construction and operation of the tidal power plant for water quality improvement and clean energy production was finalized in 2002, and the construction of the Sihwa tidal power plant began. [8]

The Sihwa Tidal Power is located in the middle of the Sihwa Embankment, which connects Oido Island in Siheung-si, Gyeonggi-do and Daebudo Island in Ansan City. In the power generation facility, 10 units of water turbine generator unit capacity of 25.4 MW are installed, with a total capacity of 254 MW.As a characteristic of the flood generation type, 8 separate sluice gates (15.3m×12m) have been installed and op erated in order to quickly drain the seawater that has flowed into Lake Sihwa at high tide to optimize the next power generation model.

2.3.2. Flood generation type Tidal Power Generation

The double-basin system flood generation type applied to Lake Sihwa generates electricity by rotating the water turbine with the positional energy of the seawater flowing into the lake due to the difference between the sea level and the water level of the lake at high tide and uses the difference between the lake level and the sea level at low tide to generate electricity. It is a power generation method that prepares for the next generation by discharging water.

Lake Sihwa is adjacent to Siheung and Ansan, and the management water level is limited to EL. -1m or less to prevent flooding. Therefore, there is a limit to the amount of electricity produced due to the limit of the amount of seawater inflow for maximizing the amount of power generation.

Figure 5 shows that the inner water level of Lake Sihwa rises during power generation (②) with seawater flowing in from the sea side, and decreases during drainage (④) according to the tidal change. At this time, the amount of power production differs depending on which head the power generation starts at, and the size of the tidal wave in each cycle is different depending on the tide.First, by predicting the size of the tide, the power generation amount is calculated for each power generation start head, and the result is compared to determine the head at which the maximum power generation is produced as the water turbine generator starting head, and then the generator is started[9].

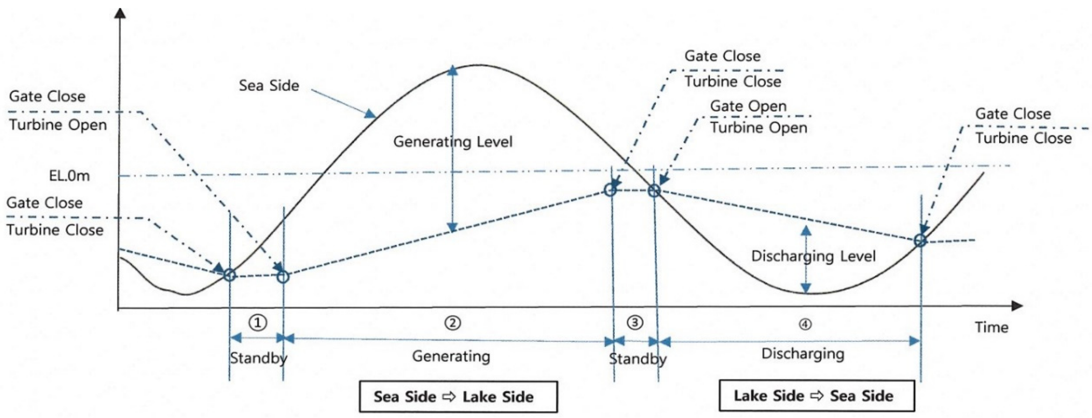

Figure 5. Tidal power generation operation overview according to the tidal cycle

2.3.3. Modeling of the size of the tidal wave and the amount of tidal power generation

Tidal power generation using ebb and flow generates electricity using potential energy between the sea level in the Sihwa area and the water level in Lake Sihwa, which changes from an average maximum tide of EL.+5.366m to EL.-5.645m twice a day. Tidal power generation has the same principle of operation as hydroelectric power generation. When Q is the flow of seawater passing through the water wheel and H is the difference between the sea level and the inland water level, the power generation output is as follows.[2]

$$P = \rho g(QH\eta)[kW] \quad (1)$$

where ρ is the seawater density, gis the gravitational acceleration, and η is the water turbine generator efficiency. In addition, the sea level $h_S(t)$, which changes according to the tides, can be expressed as follows using the time t, the angular velocity w, and the phase p of the j-th tide according to the Harmony Analysis prediction.

$$hs(t) = h_0 + \sum_{j=1}^{m} f_j H_j \cos(w_j t + \theta_j - \delta_j)$$
$$= h_0 + \sum_{j=1}^{m} R_j \cos(w_j - \varphi_j)[m] \quad (2)$$

Here, h_0 is the average sea level height, and f_j is the node factor according to the orbital period of the moon (18.6 years)[10].

The maximum power generation calculation model that can be produced during one cycle using N generators at the start of power generation in Figure 1 is as follows.

$$E = \sum_{n=1}^{N}(\int_{t^1}^{t^2} P(t)dt)$$

$$= k\sum_{n=1}^{N}(\int_{t^1}^{t^2} \eta(t)Q(t)H(t)dt)[kW\,h] \quad (3)$$

Equation (3) can be expressed as a function according to time at the determined power generation start head, where $k = \rho g$ is a constant, $\eta(t)$ is the water turbine generator efficiency, $Q(t)$ is the used flow rate, and $H(t)$ is the difference between $h_S(t)$ and the internal water level $h_L(t)$ that changes depending on the inflow water.

The amount of electricity produced by the tidal power generation is determined by the prediction of the size of the tide change cycle, the operational constraints of Lake Sihwa such as the change in the upstream flow during flooding, and the drainage capacity through the sluice gate.It can be seen that when the operating conditions are the same, the amount of power produced from tidal power generation varies depending on where the power generation start head is determined.

2.3.4. Tide prediction

In the operation of tidal power generation, it is very important to determine the start time of the water turbine generator by predicting the tide level (sea level) close to the actual measurement among various factors that affect the amount of electricity production.

The technology for predicting tides can be broadly divided into mid-to-long-term predictions of more than one year and short-term predictions that predict real-time tides. For mid-to-long-term forecasting, Harmony Analysis, a time series analysis technique, is mainly used.

As a real-time short-term tide prediction technology, The ANN (Artificial Neural Network) method has one intermediate layer between the input layer and the output layer, and connects and analyzes weighted links. Another one is a DNN (Deep Neural Network) method consisting of several hidden layers between the input layer and the output layer. The last one, the Recurrent Neural Network (RNN) method, is a type of artificial neural network specialized for repetitive and sequential data learning and has the characteristic that it contains an internal cyclic structure. As a result of predicting the short-term real-time sea level using these, the Recurrent Neural Network method was analyzed as the method closest to the actual measurement.

In this paper, tide prediction was divided into long-term and short-term forecasts. For long-term tide prediction, harmonic analysis, a time series analysis method, was used, and for short-term prediction, real-time measurement data was used with RNN, which is relatively accurate among artificial neural network methods ANN, DNN and RNN [11].

Table 1. Comparison result of tide prediction RMSE

Analysis technique	ANN	DNN	RNN
RMSE	0.1548	0.1905	0.1547

The field of tidal prediction is being used in various ways, and in connection with tidal power generation, by using the real-time sea level prediction result, the amount of inland water level used for power generation is expanded to the amount that can be discharged through the sluice gate, which has the effect of increasing the storage capacity of the inland water level. Therefore, if the accurate tidal prediction results were linked with the hydrological automatic operation, the generation plan was established and operated, the electricity production of tidal power generation could be improved.

3. Analysis of Operational Characteristics of Tidal Power Ceneration

3.1. Tidal power generation and tidal characteristics analysis result

Tidal power generation is a power generation method using tidal force generated by gravitational force and centrifugal force generated between the moon, the earth, and the sun, and this tidal force is known to change in strength with a certain period.

Figure 6 shows the characteristics of the amount of electricity generated twice a day and the tide, and it can be seen that the magnitudes are different from each other.

This is due to diurnal inequality of tides, and this is a characteristic that occurs because the moon's gravitational force on the earth appears differently depending on the tilt of the earth (23.5 degrees).

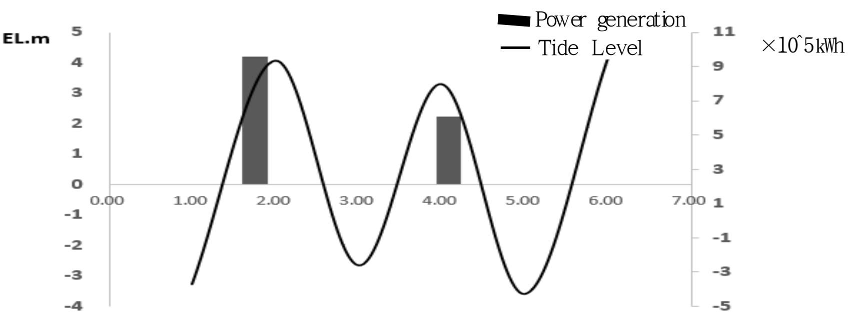

Figure 6. Characteristics of tide and power generation in a day

Figure 7 shows the characteristics of power generation and tides during one month of Sihwa tidal power, and it can be seen that the generation amount and tide change in the same pattern.

If we look at the characteristics of power generation and tide, it can be seen that the power generation and tide on the left side (1-30 cycles for about 14.5 days) and the size of the tide is large, and the generation amount and tide size on the right side (31-60 cycles for about 14.5 days) are small. This is a change according to the gravitational pull of the moon, and when the moon is up and down, the gravitational force is small, but when the moon is up and down, the gravitational force is large.

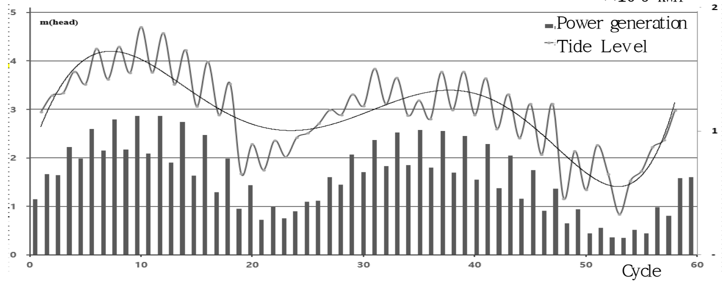

Figure 7. Sihwa Tidal Power Generation and Tidal Characteristics for 1 Month

3.2. Tidal power generation prediction technology

As described above, it can be seen that the amount of energy produced varies according to the operation method of tidal power generation.The Sihwa Lake Tidal Power Plant produces electricity by rotating the water turbine using the water level difference of Lake Sihwa twice a day.According to Equation 1, the amount of power generated at each generator paralleling point (the difference between sea level and lake level) in a specific cycle is calculated at intervals of 1m from 3m to 4m, as shown in Figure 9. From this figure, it can be seen that the total amount of power generation is different for each power generation point or power generation start time.

It can be seen that the total amount of power generated at the lowest head of 3m produces about 390MWh, and the maximum power generation can be produced at 3.5m, which is between 3m and 4m. That is, the power generation start head that produces the maximum amount of power generation is called the optimum power generation start head, and the technology to find this right head is the optimal operation technique for tidal power generation.

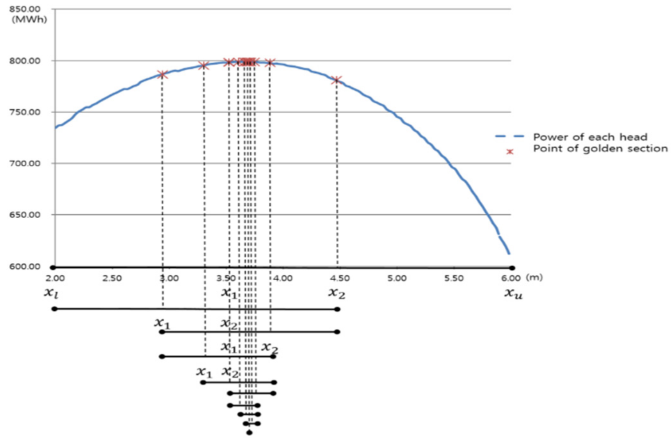

Figure 8. Optimal solution search method for the Fibonacci sequence

It is important to decide at which start water level to the water turbine generator in order to maximize the power generation by reflecting the tide prediction results. The K-TOP, an optimal operation program, was used as a method of determining the water level with the maximum power generation of the Sihwa Tidal Power Plant, and the calculation section between 2 m and the maximum water level was searched using the infinity ratio of the Fibonacci sequence, an optimal solution search method. Analyzed in a way that determines the water level. [12]

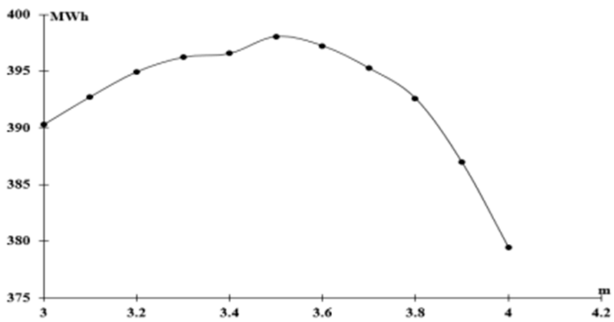

Figure 9. Changes in the amount of power generation according to the time of power generation Paralleling points

In addition to the optimal operation technology, it is also necessary to accurately predict the tide level.The tide generated by the gravitational force between the moon, the earth and the sun can be accurately predicted, whereas the tide changed according to the marine environment is difficult to predict. Figure 10 shows the difference between the predicted tide level and the actual measured tide level for one month, and Table 2 is the average value compared. It can be seen that a prediction error of 3cm at low water level and 9cm at high water level. When calculated by the amount of power generation, there is a significant difference.Figure 11 shows the predicted and measured values for tidal power generation at the same time period (1 month) as in Figure 10.

In Figure 10, it can be seen that the amount of power generation varies considerably depending on the difference between the predicted tide and the measured tide.

Comparing this for one month, there is a difference of 3,094MWh. As shown in Table 2, the difference in the low tide is actually 3cm higher and the difference in the high tide is actually 9cm lower, indicating that the actual power generation has decreased. In other words, the difference between the tide prediction and the actual measurement directly affects the tidal power generation amount. Therefore, if the accuracy of the tide prediction is increased, the accuracy of the prediction of the tidal power generation amount will also be increased.

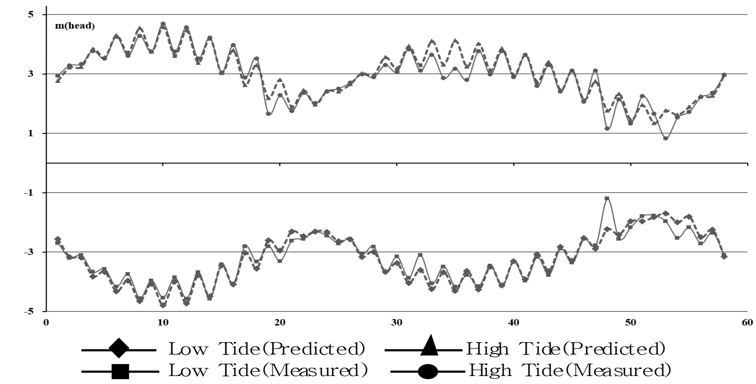

Figure 10. Comparison of predicted and measured tide levels (high and low tide) (1 month)

Table 2. Comparison of low and high tide predictions and actual mean values

	Low tide		High tide	
	Predicted	Measured	Predicted	Measured
Average(m)	-3.23	-3.20	3.03	2.94

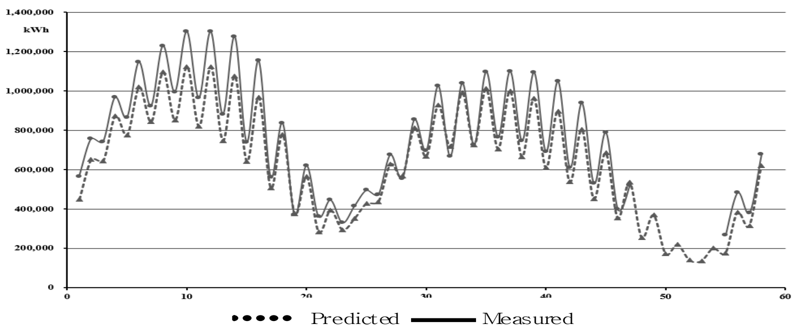

Figure 11. Comparison of the difference between forecast and actual power generation

Table 3. Comparison of predicted power generation and measured power generation (1 month)

	Predicted	Measured	difference
Generation (MWh)	42,188	39,094	3,094

4. Conclusion

Tidal power generation is a power generation method that uses the tidal force generated by the gravitational force and centrifugal force generated between the moon, the earth, and the sun, and is changing with a certain cycle. As a result of analyzing the operational characteristics of the flood generation type tidal power plant operated in Korea, it was found that the amount of power generation also changes in the same way according to the size of the tide. Power is generated using the difference in water level between the sea and the lake in Sihwa Lake twice a day. As a result of analyzing the amount of power produced while changing the generator paralleling time for each water level differently, it was confirmed that the maximum power generation amount was determined when the tidal generator was operated by determining the optimal power generation start head.

Therefore, The amount of power production can be maximized by determining the head of the start of the water turbine generator in consideration of the operational constraints of Lake Sihwa, and reflecting the expansion of the displacement through the sluice gate and aberration during the standby mode into the power generation plan so that the optimal conditions are maintained before the next power generation starts.

Based on this, it is necessary to improve the accuracy of tidal power generation prediction, to improve the efficiency of the water turbine generator, and to study the optimal operation plan considering the power system marginal price (SMP).

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] L. B. Bernshtein, V. V. Silakov, B. L. Erlichman, N. N. Kuznetzov, L. M. Monovsov, S. L. Gelfer, N. N. Marfenin, A. V. Necrasov, L. I. Suponnitsky, L. M. Micots, and I. N. Usachev, "The editors of English translation Drs.E.M. Wilson, W.O. Song," Tidal Power Plants, pp. 9-12, 1996.

[2] H. H. Kim, "A Study on the Optimal Operation for Tidal Generation of Single Action Rising Tide," Ph.D. dissertation, Kangwon National Univ, pp. 6-7, 2015.

[3] K.Y. Han, "An Optimal Operation Model of the Sihwa Tidal Power Plant using the Polynomial Approximation Method," The master's course. dissertation, SungKyunKwan Univ., p. 6, 2015.

[4] Y.C. Jung, "An Optimal Operation Model of the Sihwa Tidal Power Plant using the Polynomial Approximation Method," Ph.D. dissertation, SungKyunKwan Univ., pp. 6-7, 2019.

[5] L. B. Bernshtein, V. V. Silakov, B. L. Erlichman, N. N. Kuznetzov, L. M. Monovsov, S. L. Gelfer, N. N. Marfenin, A. V. Necrasov, L. I. Suponnitsky, L. M. Micots, and I. N. Usachev, "The editors of English translation Drs.E.M. Wilson, W.O. Song," Tidal Power Plants, p. 249, 1996.

[6] H. H. Kim, "A Study on the Optimal Operation for Tidal Generation of Single Action Rising Tide," Ph.D. dissertation, Kangwon National Univ., pp. 11-12, 2015.

[7] K. Y. Han, "An Optimal Operation Model of the Sihwa Tidal Power Plant using the Polynomial Approximation Method," The master's course. dissertation, SungKyunKwan Univ., pp. 12-13, 2015.

[8] K. Y. Han, "An Optimal Operation Model of the Sihwa Tidal Power Plant using the Polynomial Approximation Method" The master's course. dissertation, dissertation, SungKyunKwan Univ., pp. 60-61, 2015.

[9] S. H Lee, J. D Kim, G. S Ock, G. Y Han, J. C Kim, and J. Y Park "Optimal Tidal Power Generation Based on Prediction of Tide Using Harmonic Analysis," KIEE Summer Conference pp. 1,086-1,087, 2014.

[10] L. B. Bernshtein, V. V. Silakov, B. L. Erlichman, N. N. Kuznetzov, L. M. Monovsov, S. L. Gelfer, N. N. Marfenin, A. V. Necrasov, L. I. Suponnitsky, L. M. Micots, and I. N. Usachev, "The editors of English translation Drs.E.M. Wilson, W.O. Song," Tidal Power Plants, p. 124, 1996.

[11] S. H Lee, S. Y Lee, D. S Song, H. G Kim, I. S Kim, and J. J Hong "Tidal Power Operation considering Real-time Sea Level Prediction Based on LSTM," KIEE Summer Conference, pp. 1,410-1,411, 2020.

[12] C. H. Jo, Y. H. Lee, S. I. Lee, and S. J. Hwang, "Development of a General Algorithm for Optimal Operation of Tidal Power Plant," vol. 14, no. 3, pp. 68-77, 2018, doi:https://doi.org/10.7849/ksnre.2018.9.14.3.067.