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A BI-LAYER OPTIMAL CONFIGURATION METHOD FOR DISTRIBUTION NETWORK INCORPORATING TIDAL CURRENT GENERATOR

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ABSTRACT

With the depletion of fossil energy, research on clean energy generation is developing rapidly. Though tidal phenomena contain a great deal of kinetic energy which can generate considerable power, few researches focus on configuration method of tidal generator in distribution network. In this paper, a bi-layer configuration method of tidal current turbine (TCT) in distribution network is proposed. The proposed method includes a TCT output simulation process which obtains the TCT output time-sequence curve based on historic data, and a bi-layer optimal configuration model which not only takes into account of the economics of both TCT and distribution network, but also considers the environment benefit. The configuration model is solved by using genetic algorithm and optimal power flow calculation. And, test results on IEEE 30-bus standard system verify the correctness and effectiveness of the proposed method.

Keywords: Tidal current generation, power grid planning, data mining, bi-layer optimization, optimal power flow

NONMENCLATURE

Abbreviations	
TCT	Tidal Current Turbine
Symbols	
V_i	Tidal flow velocity of TCT
V_{in}	Cutting in speed of TCT
V_{out}	Cutting out speed of TCT
C_p	Energy capture factor of TCT
ρ	Seawater density
C	Annual comprehensive unit power generation cost
C_{invest}	Annual TCT investment cost
C_{maint}	Annual TCT operation and maintenance cost
c_{maint}	Single operation and maintenance cost of the TCT
r	Discount rate
n	Service life of TCT
N_{tidal}	Access set of candidate nodes for TCT
c_j	Investment cost of a single TCT
s_j	The number of TCTs connected to the *j*th candidate node
C_{gt}	Annual cost of gas turbine
c_{gt}	Single operation and maintenance cost of gas turbine
C_{loss}	Annual cost of network loss
$C_{exhausted}$	Benefit for reducing exhaust emissions
N	Accessing node set of gas turbine
s_k	Number of gas turbine connected to the *k*th node
t_i	Running time of the *i*-th time period
T	Total time period
α_{loss}	Network loss price
$P_{loss,i}$	Network loss saved during the *i*-th time period
α_{CO2} , α_{SO2}, α_{NOx}	Unit emission cost of CO_2, SO_2, NOx
E_{CO2}, E_{SO2}, E_{NOx}	Emission reduction of CO_2, SO_2, NOx
f_{1i}, f_{2i}	Active and reactive unit costs of gas turbine
$\Delta U_i(x)$	The maximum node voltage deviation of *x* in the *i*-th population

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1. INTRODUCTION

The existing traditional energy structure based on fossil energy cannot adapt to the current energy environment caused by the increasing load demand. Ocean's coverage of the earth is up to 70%. Subjected to gravitation, seawater exhibits periodic fluctuations which contain huge amount of tidal energy. TCT has the characteristics of high energy density, low-carbon and greater predictability compared with wind and photovoltaic generation, thus has great development potential [1].

Current research on TCT mainly focus on three aspects: TCT device, control system of TCT, and grid-connected planning method [2-3]. Due to the output fluctuation of TCT, reasonable planning methods can effectively improve the utilization of tidal energy. Some of the location optimization method only focuses on the utilization of tidal energy. [4] establishes a computational fluid dynamics model. By modeling turbine arrays and considering wake effect, a certain number of TCT arrangement plan is obtained. However, it ignores the influences on distribution network when TCT accessing to it.

In this paper, a bi-layer optimization model is proposed, which considers the economics of TCT and distribution network, as well as its environmental benefits. By reducing the overall comprehensive cost, the method contributes to the long-term sustainable operation of the tidal power station, and is more suitable for practical application.

2. TCT OUTPUT SIMULATION

Though TCT and wind turbines have similar unit construction and working principles, their output patterns are different due to the diversity of fluid properties. Wind power generation is characterized by strong randomness of wind speed, while tidal power generation is affected by celestial regularity changes, which is characterized by regularity of tidal flow velocity in a degree [5]. Therefore, output simulation of TCT needs to base on characteristics of tidal energy. As for TCT output is mainly determined by tidal flow velocity, the velocity simulation need to be accomplished first.

2.1 Tidal flow velocity simulation

Due to the regularity characteristic of tidal flow velocity, a data-driven improved *k*-means clustering method can be applied to obtain the tidal flow velocity time-sequence curve. The improvement towards original *k*-means clustering method is as follows.

1) Initial clustering center selection. a concept of intensive degree is applied in the process. The intensive degree of the sample point is the farthest distance between it and the nearest certain number of points around it. Smaller value of intensive degree Indicates that the data around the point is denser. And the point with the smallest value of intensive degree is chosen as the initial clustering center.

2) Cluster center update. According to the "3σ rule", the new clustering center can be obtained by calculating the mean of the points within $\left(\mu-3\sigma,\mu+3\sigma\right)$ from the center. Hence, the clustering point of the updated class can contain information about most of the data points in the class, and reduce the impact of outliers.

According to the law of tidal fluctuation, the tide experienced two fluctuations per day, so the number of clusters *k*=2. And through the clustering process, the tidal flow velocity time-sequence curve is obtained.

2.2 TCT Output simulation

The TCT output P_{out} has quantitative relationship with the tidal flow velocity [6], and the mathematical expression is as follows.

$$P_{out}=\begin{cases}0 & 0<V_i<V_{in}\\ 0.5C_p\rho AV_i^3 & V_{in}\le V_i<V_{rated}\\ P_{rated} & V_{rated}\le V_i<V_{out}\\ 0 & V_{out}\le V_i\end{cases} \tag{1}$$

Through the formula (1), the tidal flow velocity time-sequence curve obtained by clustering can be converted into the TCT output time-sequence curve for subsequent tidal generator configuration.

3. BI-LAYER PLANNING MODEL FOR TCT IN DISTRIBUTION NETWORK

In order to fully exploit the potential of TCT output and environmental benefits, a bi-layer planning model for TCT is proposed. The upper-layer model considers the access location and number of TCT in the distribution network. Based on the TCT output time-sequence curve and configuration, the lower-layer model develops an optimal solution for conventional unit output.

Through the iterative solution of two layers, the TCT configuration scheme obtained not only guarantee the economics of the TCT, but also ensures the overall economic operation of the distribution system. In addition, by taking environmental factors into consideration, the resulting configuration scheme has certain significance for low-carbon power generation. The structure of the model is shown in Fig. 1.

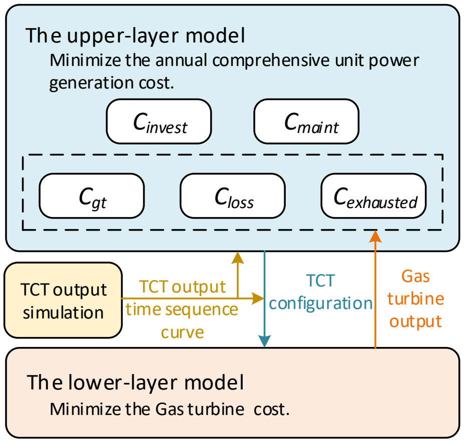


Fig. 1. Structure of the bi-layer planning model

3.1 The Upper-layer TCT planning model

To determine the access location and number of TCT in the distribution network, the upper model considers investment and operation economic indexes of TCT, economics indexes of distribution system and the Environmental benefits. The objective formula and constraints is proposed as follows:

$$MinC = \min\left(\frac{C_{invest}+C_{maint}+C_{gt}-C_{loss}-C_{exhaust}}{P_{tidal}+P_{other}}\right) \tag{2}$$

$$C_{invest} = \frac{r(1+r)^n}{(1+r)^n-1}\sum_{j\in N_{tidal}} c_j s_j \tag{3}$$

$$C_{maint} = \sum_{j\in N_{tidal}} c_{main} s_j \tag{4}$$

$$C_{gt} = \sum_{k\in N} c_{gt} s_k \tag{5}$$

$$C_{loss} = \sum_{i=1}^{T} \alpha_{loss} t_i P_{lossi} \tag{6}$$

$$C_{exhaust} = \sum_{i=1}^{T}\left(a_{CO2}E_{CO2,i} + a_{SO2}E_{SO2,i} + a_{NOx}E_{NOx,i}\right) \tag{7}$$

Subject to

$$\begin{aligned} P_{is} &= U_i\sum_{j=1}^{N} U_j\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \\ Q_{is} &= U_i\sum_{j=1}^{N} U_j\left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \end{aligned} \tag{8}$$

$$\begin{aligned} U_{i,\min} \le U_i \le U_{i,\max} \\ s_i \le s_{\max} \end{aligned} \tag{9}$$

3.2 The Lower-layer model

Based on the TCT output time-sequence curve and configuration, the lower-layer arrange the gas turbine unit output to ensure the economics of the distribution network system. The objective formula and constraints is proposed as follows:

$$\begin{aligned} &\min\sum_i f_{1i}(P_{gi}) + f_{2i}(Q_{gi}) \\ &s.t.\ P(\theta,V) - P_{gi} + P_{di} = 0 \\ &Q(\theta,V) - Q_{gi} + Q_{di} = 0 \\ &V_i^{\min} \le V_i \le V_i^{\max} \\ &P_i^{\min} \le P_i \le P_i^{\max} \\ &Q_i^{\min} \le Q_i \le Q_i^{\max} \end{aligned} \tag{10}$$

To solve the optimization problem, the upper layer model uses genetic algorithm to realize the iterative solution, and the lower layer model uses dual interior point method to calculate the optimal power flow. The flow chart of the solution process is shown in Fig. 2.

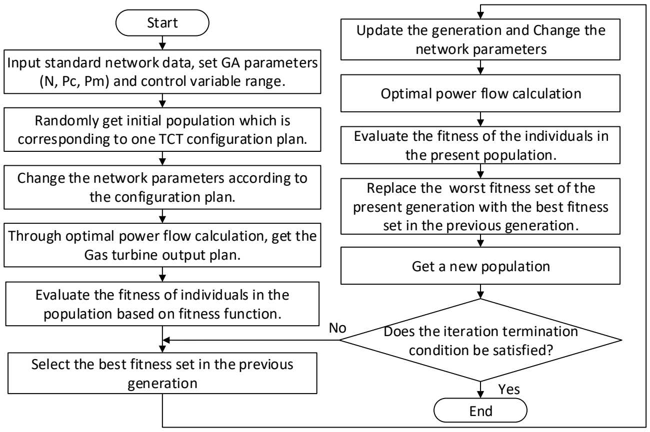


Fig. 2. The flow chart of the solution process

The decision variable is the number of tidal generators connected to each candidate node. To satisfy the constraints, the fitness function is combined with penalty function as shown in (11)-(13). And $p(x)$ and $g(x)$ are penalty function and fitness function

$$p(x) = 1 - \left(\frac{\Delta U_i(x)}{\Delta U_i^{\max}}\right)^{\alpha} \tag{11}$$

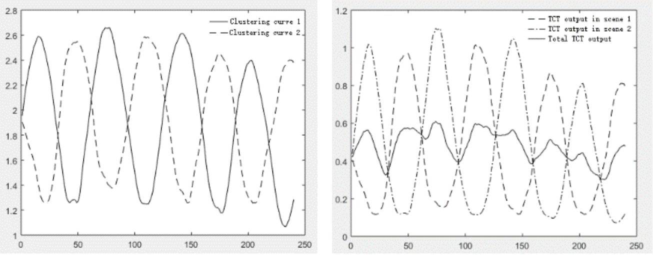
$$\alpha = 1 - \frac{\Delta U_i(x)}{\Delta U_i^{\max}} \tag{12}$$

$$g(x) = \frac{C_{invest}+C_{maint}+C_{thermal}-C_{loss}-C_{exhaust}}{P_{tidal}+P_{other}} \times p(x) \tag{13}$$

4. RESULT ANALYSIS

4.1 Tidal flow velocity simulation

The tidal flow velocity simulation is based on the historical dataset of Mile Point LB 20 tidal current station which contains tidal flow velocity of every 6 minutes a day in a month. By applying the improved k-means method, the time-sequence curves of two typical scenarios of high tide and low tide is obtained, which is shown in Fig. 3(a). Through the formula (1), the TCT output time-sequence curve of the two typical scenarios is shown in Fig. 3(b).



(a) Curves of tidal flow velocity (b) Curves of TCT output

Fig. 3. Time-sequence curves

The figure shows that tidal flow velocity and TCT output fluctuate with peak valley alternatively distributional feature, and the time intervals between each adjacent peak and valley are approximately the same. The features indicate the regularity of tidal flow and TCT output.

4.2 BI-layer optimal configuration of TCT

The IEEE 30-bus standard test system is applied to test the effects of the proposed method. We assume the installable capacity of TCT at each candidate node is equal, and the upper limit of the accessing number is 7. To compare the impact of different indexes on the result, several scenes is set as follows.

Table 1 Scenes setting

Factors	Scene 1	Scene 2	Scene 3
Whether TCT is accessed	Yes	No	Yes
Whether environmental benefits is considered	Yes	/	No

Through the proposed method, the optimal configuration scheme of each scene and the corresponding values of each indicator are shown in Table 2.

Table 2 Configuration result of TCT

	Scene 1	Scene 2	Scene 3
Configuration of TCT	5(6), 7(7), 8(7)	\	5(0), 7(7), 8(7)
Total annual power generation of gas turbine (MW)	1.35×10^5	1.42×10^5	1.41×10^5
Annual total power generation of the system (MW)	2.11×10^5	1.42×10^5	1.92×10^5
annual comprehensive unit power generation cost (dollar)	-26.40	5.09	12.53

By analyzing the result shown in Table 2, several conclusions can be obtained.

1) In scene 1, the access number of TCT is close to the upper limit which indicate that the reduction of other generations' costs, reduction of network losses and benefit of reducing exhaust emissions can make up the high investment cost, and make full use of tidal power.

2) By comparing the result of scene 1 with scene 2, the conventional unit output is reduced by 35%, and the total annual power generation of the system increased by 49% after accessing TCT. Besides, the annual comprehensive unit power generation cost is negative in scene 1, which indicates that the system's revenue is more than expenditure. The economics of accessing TCT and the feasibility of TCT planning are confirmed.

3) The results of scene 1 and scene 3 address that when ignoring the environment benefit, the number of accessed TCT is decreased with lower annual total power generation and higher annual comprehensive unit power generation cost. Besides, the results of scene 2 and scene 3 shows that if environment benefit is ignored, TCT's access will increase the system's annual unit power generation cost by 46%.

5. RESULT ANALYSIS

The obtained TCT output time-sequence curve shows a feature of fluctuation with peak valley alternatively which indicate the regularity of TCT output. Besides, a bi-layer optimal configuration model is stablished, whose objective considers the economics of TCT and the distribution network, and the environmental benefit. According to the result, the method proposed can make effective utilization of tidal energy. In addition, the environment benefit index has a decisive influence on the configuration of TCT in the distribution network.

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