Life Cycle Cost Analysis of Gas Turbine Air Inlet Filtration System

Yunshan Bai, Jiangang Hao, Xin Tian
HuaDian Electric Power Research Institute, Hangzhou, 210037, China

yunshan-bai@chder.com

Abstract. As an important component of gas turbine, air inlet filtration system is of great significance for ensuring the normal operation of gas turbine. However, it is often difficult to select a suitable air inlet filtration system according to the operating characteristics of the unit and the external environment due to the large number of variables. From the perspective of life cycle cost, the main factors to be considered in the selection of inlet filtration system are discussed, and the corresponding calculation model is proposed. Through the cost calculation of a gas-steam combined cycle unit’s inlet filtration system during the whole life cycle, the influence of the initial cost, operation cost, maintenance cost and gas turbine performance degradation cost on the total cost is analyzed. The results show that the cost of gas turbine performance degradation accounts for 90.44%, and the initial cost only accounts for 0.62% in the total cost. Therefore, in the selection of the inlet filtration system, the system economy should be evaluated from the perspective of full life cycle cost. The calculation model has important guiding significance for the selection and cost calculation of the gas turbine inlet filtration system.

1. Introduction
Gas-steam combined cycle unit has high efficiency and low pollution, and has been widely used in the world[1-4]. With the development of technology, the power output of gas turbine continues to increase, and the simple cycle power of GE 9HA.01 gas turbine reaches about 400 MW. With the increase of power output, the intake air flow of gas turbine also increases, and the influence of the intake air quality on the performance of gas turbine becomes more significant [5]. Due to the presence of a large amount of dust, oil and other particles in the air, if it is not efficiently filtered or inhaled by the gas turbine, it will cause problems such as corrosion and fouling of compressor blades, which will lead to a decrease in power output and efficiency, and even affect the safety of gas turbine [6-7]. In order to solve this problem, an air inlet filtration system is usually installed at the inlet of gas turbine to reduce the amount of dust entering the compressor in order to increase availability of the unit.

There are few researches on the selection of gas turbine inlet filtration system and the cost analysis of the whole life cycle in the world. Evaluating the cost of air inlet filtration system properly is of great guiding significance to the selection of the system. Literature [8] compares two inlet filtration systems with filtration accuracy of F9 and H11 respectively. Through economic analysis of the two systems, it is pointed out that improving the filtration accuracy of the inlet filtration system appropriately can significantly improve the economic benefits of the unit. Literature [9] preliminarily discussed factors affecting the life cycle cost of the inlet filtration system, and elaborated on how to select the inlet filtration system properly. In Literature [10], the effects of blade corrosion and fouling on the output and efficiency of the gas turbine were studied. Through theoretical derivation and data observation,
effects of different degrees of corrosion and fouling on the performance of gas turbine were obtained. Literature [11] studies the optimal replacement cycle of inlet filtration system under different operating conditions aiming at minimizing the unit power generation cost within the service cycle of inlet filtration system of a gas turbine. Literature [12] discussed in detail the principle, influence and control method of compressor blade fouling, and discussed the effects of online and offline washing on gas turbine performance recovery respectively, pointing out that the combination of two washing methods is more effective in alleviating the problem of compressor blade fouling.

At present, the life cycle cost calculation is rarely applied in the selection of inlet filtration system. Usually, only the initial cost of the system is considered, the operation and maintenance cost and cost due to efficiency decline caused by poor air filter are rarely be considered and evaluated. In order to solve this problem, this paper puts forward the calculation method of the life cycle cost of the gas turbine inlet filtration system, and discusses the various factors affecting the system cost, and establishes corresponding calculation model through theoretical derivation and practical experience.

2. Life Cycle Cost Analysis

The life cycle cost analysis of gas turbine inlet filtration system refers to the comprehensive evaluation of the costs of procurement, installation, operation, maintenance and treatment from the long-term economic benefits within the expected using time for decision-making and management. The cost of inlet filtration system is a cost incurred continuously over a long period of time, which should take into account the time value of the capital. In the cost analysis, the expenditures of each year in the life cycle of the system are first calculated, and then converted to the net present value of the initial equipment purchase according to the social discount rate and inflation rate. The net present value is calculated as shown in equation (1), where $A$ is the expenditure for the current year, $i$ is the discount rate, and $n$ is the year of expenditure. The calculation of the net present value in equation (2) takes into account the effects of inflation, and $e$ is the inflation rate. If the annual expenditure is a fixed value during the system life cycle, the sum of the net present values of each year can be calculated according to formula (3) (4). The National Development and Reform Commission’s "Economic Evaluation Methods and Parameters for Construction Projects (3rd Edition)" stipulates that the discount rate can be 8% and the inflation rate can be 4% [13].

$$NPV = A(1+i)^n$$ (1)

$$NPV = A(1+(i-e))^n$$ (2)

$$NPV = \frac{A}{i} \left[1-(1+i)^{-n}\right]$$ (3)

$$NPV = \frac{A}{i-e} \left[1-(1+i-e)^{-n}\right]$$ (4)

3. Life Cycle Cost Calculation of Gas Turbine Inlet Filtration System

The life cycle cost of gas turbine inlet filtration system includes initial cost, operation and maintenance cost, downtime cost, gas turbine performance degradation cost, removal and disposal cost, as shown in formula (5), where $NPV_{total}$ is the life cycle cost of the inlet filtration system, $NPV_{init}$ is the initial cost of the system, $NPV_{main}$ is the operating and maintenance cost of the system, $NPV_{down}$ is the cost of downtime, $NPV_{GT}$ is the cost of performance degradation of gas turbine due to the inlet filtration system, and $NPV_{disp}$ is the removal and disposal cost of the system. The calculation methods for each part are discussed in detail below.

$$NPV_{total} = NPV_{init} + NPV_{main} + NPV_{down} + NPV_{GT} + NPV_{disp}$$ (5)

3.1. Initial cost

The initial cost $NPV_{init}$ refers to the sum of all expenditures during the infrastructure period, including the purchase cost of the filter $NPV_{filt}$, the installation cost $NPV_{inst}$, and the commissioning cost $NPV_{comm}$, as calculated by equation (6). The calculation of filter purchase cost can be consulted with the air inlet filtration system supplier or the purchase contract can be viewed. The prices of different
manufacturers and different types of filters are not consistent. Under normal circumstances, for static filters, the final filter element price is 500~1000 yuan, the second stage filter unit price is 150~300 yuan, the first stage filter unit price is 100~150 yuan, a pair of pulse filter is 1200~2000 yuan. The determination of the number of filter elements is related to the model of the gas turbine and the user's preference. In this paper, the number of filter elements of several common types of gas turbines in Jiangsu and Zhejiang provinces is counted, which is shown in table 1. The cost of installation and commissioning can be referred to the previous gas turbine generator set, and the costs are basically the same.

$$NPV_{inst} = NPV_{filt} + NPV_{inst} + NPV_{comm}$$  \hspace{1cm} (6)

3.2. Operation and maintenance cost

Operation and maintenance cost $NPV_{main}$ runs through the entire life cycle of the inlet filtration system and is an important part of the system's life cycle cost. It mainly includes the replacement cost of the filter element $NPV_{repl}$, the periodic inspection cost of the inlet filtration system $NPV_{insp}$ and maintenance cost $NPV_{repair}$. The calculation is shown in equation (7).

In this part, it is important to determine the replacement period of the filter element. Due to the different environmental conditions, unit operation mode, and filtration system configuration in each area, the replacement period of the filter elements is quite different. For newly built gas turbine generator set, the replacement cycle of filtration system can be referred to the previous one. Table 1 shows the filtration system replacement cycle of five gas turbine generator sets in Jiangsu and Zhejiang. It can be seen that the replacement period of these five filtration systems is basically between 3000h to 4000h. The inspection and maintenance costs of the intake housing are relatively low and can be given empirically.

$$NPV_{main} = NPV_{repl} + NPV_{insp} + NPV_{repair}$$  \hspace{1cm} (7)

3.3. Downtime cost

The cost of downtime refers to the loss caused by the abnormal operation of the inlet filtration system or the poor filtration performance, which causes the power loss of gas turbine, including filter replacement and offline water washing. The replacement of the filter needs to stop the gas turbine. For a gas turbine generator set with basic load and long-time running or for winter heating, it will cause loss of power output, thus increase the life cycle cost of the inlet filtration system. This cost can be calculated by the filter replacement cycle and replacement time. Generally the filter replacement can be completed in one day. For the peaking unit, the filter replacement and offline water washing can be performed at night without any increase in cost.

3.4. Gas turbine performance degradation cost

The filter performance of inlet filtration system has a great influence on gas turbine performance, which is reflected in the following two aspects:

(1) The effect of compressor fouling.

It is impossible for the air inlet filtration system to intercept all the particles in the air, so some particles will penetrate the filter and enter inside of gas turbine, and attach to compressor blades to increase the surface roughness of blade, and even change the aerodynamic shape of the blade. As a result, the power output of gas turbine is reduced and gas consumption rate is increased, which increases the operating cost of gas turbine [14-15]. In areas with serious environmental pollution, the average concentration of suspended particulate matter of 0.5 um or above in the air is $3\times10^{7}$/m$^3$. For the filter of F8 class, about $6\times10^6$ suspended particulate matter per cubic meter are inhaled into internal flow channel of gas turbine [8]. Literature [16] points out that the performance degradation of the unit is most obvious within the first 1000 h of operation time. After 1000h, the change gradually tends to be stable, and the degree of performance degradation can be expressed by the exponential form of operation time. Equation (8) (9) gives the calculation method for the cost increase due to compressor fouling. In the formula, $A_{foul}$ is the cost due to compressor fouling in the $j$th year, $C_{kWh}$ is
the on-grid price, \( Q_{\text{std}} \) is the gas consumption of the unit during daily operation, \( C_{\text{scm}} \) is the natural gas price of per cubic meter, \( P \) is the capacity of the power generation unit, \( P_{\text{loss1}} \) is the power loss due to compressor fouling, \( \eta_{q1} \) is the increase of gas consumption due to compressor fouling, and \( T \) is the operation time of the unit in the \( j \)th year.

\[
NPV_{\text{foul}} = \sum_{j=1}^{n} A_{j}^{i} \left[ 1 + \left( i - e \right) \right]^{j}
\]

(8)

\[
A_{j}^{i} = \int_{0}^{T} \left[ P_{\text{loss1}}C_{\text{loss}} - P_{\text{loss1}}(1 + \eta_{q1})Q_{\text{std}} \times C_{\text{scm}} \right] dt + \int_{0}^{T} \left[ P \times \eta_{q1}Q_{\text{std}} \times C_{\text{scm}} \right] dt
\]

(9)

(2) Influence of pressure loss in the inlet filtration system

The inlet air pressure has a great influence on the performance of gas turbine generator set. Literature [17] points out that for every 250 Pa increase in inlet air pressure loss, the power output of gas turbine is reduced by 0.5% and the heat consumption is increased by 0.1%. The inlet air pressure loss generally increases non-linearly with the filter usage time, and the increase in the cost of the inlet filtration system is calculated as follows:

\[
NPV_{\text{p}} = \frac{A_{p}}{i - e} \left[ 1 - (1 + i - e)^{-T} \right]
\]

(10)

\[
A_{p} = \int_{0}^{T} \left[ P_{\text{loss2}}C_{\text{loss}} - P_{\text{loss2}}(1 + \eta_{q2})Q_{\text{std}} \times C_{\text{scm}} \right] dt + \int_{0}^{T} \left[ P \times \eta_{q2}Q_{\text{std}} \times C_{\text{scm}} \right] dt
\]

(11)

3.5. Removal and disposal cost

When the service time of filter reaches the requirement of replacement, the original filters need to be removed and processed. Literature [18] gives the estimated cost of removal and disposal of different types of filter elements. After the operation time of gas turbine reaches its life cycle, the residual value of the equipment exists in the steel structure such as the inlet housing shell and bracket, but the residual value is extremely low, which can be ignored in the cost calculation of the whole life cycle of the system.

### Table 1. Filter number and replacement cycle of different type of gas turbine

| Unit Type | 9E  | 9F  | M701F4 | 6F:03 | V94.2 |
|-----------|-----|-----|--------|-------|-------|
| Filter type | Self-cleaning | Self-cleaning | Self-cleaning | Static | Self-cleaning |
| Course filter | 153 | 144 | filter:153 | filter:144 | filter:504 |
| Fine filter | 464 | 616 | filter:672 | filter:614 | filter:616 |
| Number of filter elements | Fine filter:2800 | Fine filter:2200 | Fine filter:900 | Fine filter:2800 |
| Replacement cycle | 3400 h | 3600 h | 3100 h | 4300 h |

### Table 2. NPV of different items and the corresponding percentage

| item | Initial cost | Operation and maintenance cost | Downtime cost | Performance degradation cost | Removal and treatment cost |
|------|--------------|-------------------------------|-------------|-----------------------------|----------------------------|
| NPV of each part (Ten thousand yuan) | 102.00 | 1438.35 | 0.00 | 14941.56 | 38.01 |
| percentage (%) | 0.62 | 8.71 | 0.00 | 90.44 | 0.23 |
4. Examples and Analysis
The rated power generation of a 9FA gas-steam combined cycle generator set is 390 MW, and the gas turbine power is 255 MW. It is a single-shaft combined cycle generator set with gas consumption rate of 0.18 Nm$^3$/kWh. The inlet filtration system is equipped with self-cleaning filters, in total of 670 pairs of filter elements, and the average replacement cycle of filter elements is 3500h. The average annual running time of the unit is also 3500h, the on-grid price is 0.873 yuan/kWh, and the price of natural gas is 2.17 yuan/m$^3$. The cost of inlet filtration system during life cycle is calculated as follows:

1. Initial cost: The purchase cost of the filter element of the air inlet filtration system is 1500 yuan/pair, plus installation and commissioning costs, the initial cost is 1.02 million yuan.
2. Operation and maintenance cost: Assume that the life cycle of gas turbine is 20 years and the filter element is replaced once a year. In the life cycle of gas turbine, the net present value of the filter replacement cost is 13.71 million yuan, and the inspection and maintenance cost of the inlet housing is the 50000 yuan/year, the net present value of the operation and maintenance costs of the inlet filtration system during the life cycle of gas turbine is 14.33 million yuan.
3. Downtime cost: Because the unit is a peaking unit, the replacement of the filter element and the washing of the compressor can be carried out at night, without affecting the normal power generation of the unit, so the cost of downtime is not considered.
4. Performance degradation cost of gas turbine: In actual operation of the unit, the load rise and fall usually follow instructions of the dispatching. In order to facilitate calculation, assuming that the unit operates at base load, the rate of power loss of the unit is 1.5% per year, and the increase of gas consumption rate is 0.5% per year. According to the formula (8)(9), the net present value of performance degradation cost caused by compressor fouling is 88.378 million yuan. The curves of pressure loss variation with time and the power output and gas consumption variation curve of the unit with pressure loss are shown in figure (1) and (2) respectively. According to equation (10) and (11), the net present value of the performance degradation cost caused by the air pressure loss is 61,036,900 yuan.
5. Removal and disposal cost. Assuming that the cost of removal and disposal of each pair of filters is 30 yuan, the net present value of filter removal and disposal costs during the life cycle of gas turbine is 380100 yuan.

In summary, the net present value of the total cost of the inlet filtration system during life cycle of gas turbine is 16.519.92 million yuan. The net present value and percentage of each item are shown in Table 2. Among the total costs, the performance degradation cost accounted for the highest proportion, which was 90.44%, followed by the operation and maintenance cost, accounting for 8.71%, and the initial cost ratio was only 0.62%. For this type of gas-steam combined cycle generator set, if conditions permit, the cost caused by inlet air pressure loss and blade fouling on the performance of gas turbine should be reduced by increasing the inlet filter area and improving the filtration accuracy, and the various costs of the system should be balanced reasonably.

5. Conclusion
(1) From the perspective of life cycle cost, this paper comprehensively considers the initial cost, operation and maintenance cost, downtime cost, gas turbine performance degradation cost, removal and disposal cost, and proposes a new method to calculate the life-cycle cost of gas turbine inlet air filtration system.

(2) Factors affecting the cost of whole life cycle of the inlet filtration system are discussed, and the calculation model of each part is established based on the actual use of the domestic gas turbine generator set, which solved the problem that the cost of each part cannot be quantified in the previous inlet filtration system selection.

(3) The calculation of life cycle cost of the inlet filtration system of a combined cycle generator set shows that gas turbine performance degradation cost accounted for the highest proportion, reaching 90.44%, and the corresponding initial cost and operation and maintenance cost accounted for 0.62% and 8.71% respectively, the degradation cost of gas turbine performance is a key factor affecting the economics of the inlet filtration system.

(4) In the initial design and selection of the inlet filtration system, in addition to the initial procurement cost, the cost of gas turbine performance degradation caused by the inlet filtration system should be paid more attention. According to the operating characteristics of the unit, it is possible to obtain the optimal air inlet filtration system and the maximum economic benefits by minimizing the total cost and balancing the costs comprehensively within the whole life cycle.

6. References

[1] Wright I G and Gibbons T B 2007. Recent developments in gas turbine materials and technology and their implications for syngas firing. International Journal of Hydrogen Energy.32(16):3610-3621.

[2] JIANG Hongde, REN Jing and LI Xueying 2014. Status and Development Trend of the Heavy Duty Gas Turbine. In: Proceedings of the CSEE. 34(29): 5096-5012.

[3] Xie Daxing, Shi Yongfeng and Zheng Jian 2016. The Latest Development of H-class Gas Turbine. Gas Turbine Technology.29(4):1-3.

[4] Poullikkas A 2005. An overview of current and future sustainable gas turbine technologies. Renewable & Sustainable Energy Reviews.9(5):409-443.

[5] Frumento A 2015. Performance modeling of industrial gas turbine with inlet air filtration system filtration. Case Studies in Thermal Engineering. 5(11-12):160-167.

[6] Heymanns E, Kazmeier F and Schild W 1992. Gas Turbine Axial Compressor Fouling: A Unified Treatment of its Effects, Detection, and Control. International Journal of Turbo & Jet Engines. 9(4):311-334.

[7] Mishra R K 2015. Fouling and Corrosion in an Aero Gas Turbine Compressor. Journal of Failure Analysis & Prevention.15(6):1-9.

[8] Schrot Th and Cagna M 2008. Economical Benefits of Highly Efficient Three-Stage Intake Air Filtration for Gas Turbines. In: ASME Turbo Expo 2008: Power for Land, Sea, and Air. 5177-85.

[9] Wilcox M and Brun K 2011. Gas Turbine Inlet Filtration System Life Cycle Cost Analysis. In: ASME 2011 Turbo Expo: Turbo Technical Conference and Exposition. 675-682.

[10] Zwebek A and Pilidis P 2001. Degradation Effects on Combined Cycle Power Plant Performance—Part I: Gas Turbine Cycle Component Degradation Effects. Journal of Engineering for Gas Turbines & Power. 125(3):651-657.

[11] CHEN Jianhong, CHENG Yuan and SHENG Deren 2014. Research on Update Interval Optimization Strategy Model of Gas Turbine Filtration[J]. In: Proceedings of the CSEE. 34(20): 3302-3307.

[12] Kiakoojoori S and Khorasani K 2016. Dynamic neural networks for gas turbine engine degradation prediction, health monitoring and prognosis. Neural Computing & Applications. 27(8):1-36.
[13] National Development and Reform 2008. *Commission Ministry of Construction. Economic Evaluation Method and Parameter Summary About Construction Projects. 3rd edition.* (Beijing: China Planning Press)

[14] Kiakojouri S and Khorasani K 2016. *Dynamic neural networks for gas turbine engine degradation prediction, health monitoring and prognosis. Neural Computing & Applications.* 27(8):1-36.

[15] Li Shuming, Li Shidong and Zhang Ying 2015. *Quantitative Analysis of Impact Factors of Aircraft engine compressor performance degradation. Science Technology and Engineering.* (32):74-78.

[16] Hepperle N, Therkorn D and Schneider E 2011. *Assessment of Gas Turbine and Combined Cycle Power Plant Performance Degradation. In: ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition.* 569-577.

[17] Wilcox M, Kurz R and Klaus B 2011. *SUCCESSFUL SELECTION AND OPERATION OF GAS TURBINE INLET FILTRATION SYSTEMS. Mass Transport Phenomena in Ceramics. Springer US.* 149-154.

[18] Matela D M and Arnold B D 2005. *Life-Cycle Costing of Air Filtration. Ashrae Journal.* 47(11):30-32.