Analysis and research on the heating principle and causes of over-temperature of wind power converter

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Abstract: In view of the frequent over-temperature faults of ABB wind power converter in the process of using, this paper makes an in-depth study and detailed analysis on the over-temperature faults and solutions and effects of the converter through the analysis of the converter heating principle, technical transformation test, thermal simulation analysis, etc. It is found that there are three main reasons for the converter over-temperature fault which are high operating environment temperature, insufficient ventilation and increased thermal resistance coefficient. The three main causes of the over-temperature fault of the converter are analyzed and the technical modification scheme and operability analysis are put forward. In order to verify the technical modification effect, the operation temperature data of the technical modification unit and adjacent units were collected and compared with FLOTHERM software to simulate the heat change trend of the tower cylinder, and the influence of the scheme on the effect and other parts of the unit was judged. The results showed that the scheme could effectively solve the over-temperature problem of the converter and would not affect the normal operation of the wind turbine.

1. Introduction

Energy is an important material base which is related to the development of national economy and human life. The most prominent problem facing China is the serious shortage of domestic fossil energy supply<sup>[1]</sup>. In order to respond to the national strategy of saving fossil fuels and actively developing new energy, the installed capacity of wind power generation in China is increasing. The converter is an important part of the wind turbine, which plays an important role in the reliable grid connection of the wind turbine, grid voltage fluctuations, maintaining a stable output and input frequency, and low and high voltage ride-through protection. With the continuous increase of the single unit capacity and the total installed capacity of wind turbines, the types, number and capacity of converters are also increasing day by day, and the defects of converters are gradually exposed. Through
research and technical supervision in recent years, it has been found that the failure rate of wind turbine ABB converters is relatively higher, which is about three times of the average failure rate of other converters. In ABB converter faults, over-temperature faults account for about 25% of the overall converter failure rate, and indirect faults account for about 25% of the overall failure rate. Especially in summer, 70% of the converters in wind farms have over-temperature faults, which leads to frequent shutdowns of the units, each of which lasts up to 2-3 hours, which is more difficult to resolve. At the same time, over-temperature also accelerates the aging of electronic components, shortens the service life of circuit boards and IGBT modules, and leads to an increase in the damage rate of converter components. Therefore, after in-depth analysis and research, the article analyzes the problems of ABB converter over-temperature faults [2] from the basic principles of ABB converter heating, working environment, heat dissipation system, maintenance, etc in detail and puts forward the technical transformation plans and test verification.

2. Loss analysis of the converter module

Wind power converter heating is inevitable. The converter is mainly composed of power electronic components, which will generate heat during the working process. The heat source of the converter module is mainly composed of IGBT and the reverse parallel continuous current tube (quick recovery diode), which respectively include switching loss and on-state loss [3][4], and the switching loss plays a major role.

2.1. On-state loss

On-state loss refers to the loss due to the on-voltage drop at the moment of the IGBT or fast recovery diode's turn-on at the time of the converter's operation. The conduction characteristics of wind power converter IGBT and fast recovery diode can be approximated by linear formula.

2.1.1. State loss of IGBT module

If the voltage and current passing through IGBT module at each moment are known, the heat loss can be calculated by integrating, as shown in formula (1).

$$
\int_0^{T_a/2} V_{CE}(t) \cdot i(t) \cdot \delta(t)\,dt
$$

$$
= \frac{1}{T_0} \int_0^{T_a/2} \left( V_{CEO} + r_{CE} \cdot i(t) \right) \cdot i(t) \cdot \delta(t)\,dt
$$

$$
= \frac{1}{2} \left( V_{CEO} \cdot \frac{I}{\pi} + r_{CE} \cdot \frac{I^2}{4} \right) + M \cos \phi \left( V_{CEO} \cdot \frac{I}{8} + r_{CE} \cdot \frac{I^2}{\pi} \right)
$$

$V_{CE}(t)$ — Is the voltage drop at the moment when the IGBT is turned on (the instantaneous voltage between the collector and the emitter);

$i(t)$ — Sine current (IGBT collector current) output when IGBT is turned on;

$\delta(t)$ — Is the duty cycle of the converter bridge output (1 when on, 0 when off);
\( V_{CEO} \) — The voltage between the collector and the emitter when the collector current of the IGBT is 0, that is, the turn-on voltage;

\( r_{CE} \) — The linear slope resistance after linearizing the characteristic curve is also known as the on-state resistance,

\[
r_{CE} = \frac{(V_{CEN} - V_{CBO})}{I_{CN}}
\]

\( V_{CEN}, I_{CN} \) — are the on-state voltage and current values of the IGBT under rated operating conditions.

2.1.2. State loss of quick recovery module

Similarly, the fast recovery diode conduction loss can be obtained from the calculation method in 2.1.1, as shown in formula (2).

\[
P_{cond.\_DIODE} = \frac{1}{T_o} \int_0^{T_o/2} V_{CE}(t) * i(t) * \delta(t)dt
\]

\[
= \frac{1}{\pi} * f_{SW} * (E_{off\_DIODE}(I_{nom}, V_{nom})) * \frac{I}{I_{nom}} * \frac{V_{dc}}{V_{nom}}
\]

2.2. Turn-on and turn-off losses

From the operating characteristics of the IGBT module, it can be known that its switching loss is composed of the loss at the on-time and the loss at the off-time. As the switching frequency increases, the switching loss occupies an increasing proportion in the entire module. For the calculation of loss, the product of current and voltage can be indirectly integrated to calculate the loss. The specific calculation is shown in formula (3).

\[
P_{SW,\_IGBT} = f_{SW,\_IGBT} * \frac{1}{T_o} \int_0^{T_o/2} (E_{on} + E_{off})(t, I)dt
\]

\[
= \frac{1}{\pi} * f_{SW} * (E_{on,\_IGBT}(I_{nom}, V_{nom}) + E_{off,\_IGBT}(I_{nom}, V_{nom})) * \frac{I}{I_{nom}} * \frac{V_{dc}}{V_{nom}}
\]

Among them,

\( f_{SW,\_IGBT} \) — IGBT switching frequency;

\( E_{on} \) — Energy loss during IGBT turn-on;

\( E_{off} \) — Energy loss during IGBT turn-off.

Similarly, the fast recovery diode loss is obtained, as shown in formula (4).

\[
P_{SW,\_DIODE} = \frac{1}{T} \sum_n (E_{off\_DIODE}(I_{nom}, V_{nom})) * \frac{I_n}{I_{nom}} * \frac{V_{dc}}{V_{nom}}
\]

\[
= \frac{1}{\pi} * f_{SW} * (E_{off\_DIODE}(I_{nom}, V_{nom})) * \frac{I}{I_{nom}} * \frac{V_{dc}}{V_{nom}}
\]
In the calculation, the reverse recovery energy of $E_{\text{off,DIODE}}$ and DIODE is not actually proportional to each other, and is equivalent with the following formula.

$$E_{\text{rec}} (I) = E_{\text{rec}} (I_{\text{nom}}) \times (0.45 \times \frac{I}{I_{\text{nom}}} + 0.55)$$

After synthesis, we can get:

$$P_{\text{SW,DIODE}} = \frac{1}{\pi} f_{\text{SW}} \left( E_{\text{rec}} (I_{\text{nom}}) \times (0.45 \times \frac{I}{I_{\text{nom}}} + 0.55) \right) \times \frac{V_{\text{dc}}}{V_{\text{nom}}}$$

2.3. total loss of the system

In the wind turbine system, IGBT of the converters are all integrated rectifier Bridges, including 6 IGBT and fast recovery diode units. The loss of each rectifier bridge $P_T$ is the sum of the on-state and switching losses

$$P_T = P_{\text{cond,IGBT}} + P_{\text{cond,DIODE}} + P_{\text{SW,IGBT}} + P_{\text{SW,DIODE}}$$

(5)

The total loss of the system $P_{\text{TOT}}$ is the sum of the losses of n rectifier Bridges

$$P_{\text{TOT}} = nP_T$$

(6)

In addition to the IGBT module and the quick recovery diode, the filter circuit, the electrolytic capacitor, various board CARDS and other components will also generate heat, but the total heat loss of the converter is relatively small, which can be ignored.

3. Causes analysis of over-temperature of ABB converter

The amount of heat dissipated by the converter and the pros and cons of the heat dissipation performance are affected by various factors such as the working environment temperature of the converter, the flow of the cooling fan, the air density, and the thermal resistance. In practical applications, over-temperature faults of ABB wind power converters are mostly concentrated in hot summer days. Due to poor heat dissipation, heat is accumulated inside the equipment, which directly causes the temperature of the control board and IGBT module to exceed the warning line, which will cause the unit to alarm and cause the unit to stop. As the ABB converter contains heat-resistant components such as filter capacitors, Crowbar circuit boards, and NDCU control boards, long-term over-temperature acceleration capacitors, circuit boards and controllers and other components are aging, which shortens the service life and directly leads to frequent over-temperatures of the unit. malfunction. Through research, it is found that the causes of over-temperature faults in ABB wind power converters mainly include the following aspects.

3.1. High working temperature of the converter and reduced energy conversion rate

Because the over-temperature faults of wind power converters mostly occur in hot summer or when the temperature is high, cold winter rarely occurs. So, it can be judged that the excessive ambient
temperature and the inability to dissipate heat are the main reasons which cause the over-temperature faults in the converter. The wind power converter works in a sealed environment, the converter system and the natural air outside the tower have a single heat exchange method. The external air enters the tower through a fan on the tower door for heat dissipation by the converter. The heat dissipation system of the converter is discharged, suspended around the converter cabinet and naturally convectively diffused with the surrounding ambient air, dissipating heat, causing the ambient temperature around the converter cabinet to continue to rise. In addition, due to the weak air convection capacity inside and outside the tower wall itself, it is not conducive to the heat dissipation of the converter to the outside, which greatly limits the ability of heat exchange and reduces the heat dissipation performance of the converter. With the extension of the operating time, it forms in the converter. The heat accumulation effect and temperature increase directly lead to over-temperature faults in the converter, which indirectly leads to aging of the internal components of the converter and shortens the life. According to the calculation of thermal efficiency loss, ABB converters for 1.5MW doubly-fed units generate about 24.6kW power heat loss. If this heat cannot be quickly discharged, the temperature of the converter will rise rapidly. If the heat cannot be exchanged in time, it will eventually lead to the over-temperature fault of the converter, affecting the converter. Thermal performance and safe and stable operation. The physical life of electronic components is greatly affected by temperature. When the operating temperature increases, every 10 degrees Celsius rises, the life of electronic components will be reduced by half. In the circuit, the working current will generate heat, which is unavoidable. Therefore, the only way to improve the operating environment of the device is to remove the heat generated by the device and reduce the temperature of the device to a reasonably acceptable range.

3.2. Insufficient ventilation of the converter

Insufficient ventilation of the converter may be caused by insufficient fan flow or fan failure, including the unreasonable selection of converter cooling fan flow, dust and blockage in the air inlet filter of the converter cabinet, and single-phase damage to the fan motor. It is not guaranteed that 100% of the air volume will enter the converter. In-depth exchanges with fan manufacturers on possible problems with ABB converter fans revealed that the cooling fans used by ABB converters are centrifugal, with a service life of about 40,000 hours, then fan performance will decline.

3.3. the thermal resistance coefficient of the converter increases and the heat transfer performance decreases

When the converter works, the IGBT power module continuously works in the saturated and disconnected state, which will generate a certain amount of heat loss, which will cause the temperature of the IGBT chip to rise [5], and heat will be transferred from the chip to the substrate, and then from the substrate to the heat sink. And then heat exchange with the air through the radiator to take away the heat.

With the increasing of the service life, the thermal conductivity of the IGBT power module of the converter is dried, and dust, dirt, mosquitoes and other debris are accumulated on the surface of the converter heat sink, which results in an increase in the thermal resistance coefficient of the system and a decrease in the heat conduction and heat exchange capacity. The temperature difference increases, the heat dissipation efficiency decreases, the heat dissipation effect decreases, the heat accumulates,
and the converter temperature keeps increasing, which causes the converter to overheat and fail or be damaged.

![Diagram](image)

Figure 1. Temperature and thermal resistance of converter

The junction temperature of the IGBT module chip [6] is:

$$T_j = \Delta T_{jc} + \Delta T_{ch} + \Delta T_{ba} + T_a$$

(7)

The thermal resistance formula is:

$$R = \Delta T / P$$

(8)

$$R_{djc} = \Delta T_{jc} / \text{loss}$$

$$R_{thch} = \Delta T_{ch} / \text{loss}$$

(9)

$$R_{thba} = \Delta T_{ba} / \text{total loss}$$

It can be seen from equations (7), (8), (9) and figure 2 that the converter's thermal resistance is mainly composed of four parts, which are also affected by its performance. The components of thermal resistance are chip - housing thermal resistance, housing - radiator thermal resistance, and radiator - environment thermal resistance, and ambient air inlet temperature.

The calorific value of the converter is affected by thermal resistance, ambient temperature, chip loss and other factors. The substrate of IGBT module of the converter and the smooth surface of the radiator fin are contacted by thermal conductive silicon grease. When the thermal conductive silicon grease is wet, the IGBT module has good contact with the radiator and good thermal conductivity, which is conducive to heat emission. When the thermal conductive silicon grease is aging, deformed, uneven or insufficient thermal conductive silicon grease, the IGBT module does not have good contact with the radiator, and the heat resistance and heat conduction of the shell and radiator are reduced, leading to the rise of IGBT module temperature difference.

4. ABB Converter Cooling Technology Transformation Scheme

Based on the analysis of the cause of the converter's over-temperature fault, the idea of solving the converter's over-temperature fault by adding exhaust channels, increasing the flow of cooling fans,
installing industrial air-conditioning, and changing the cooling method was proposed, and the details were introduced to the upper part of the tower Exhaust technology reform.

4.1. Analysis of Principles and Ideas of Technical Transformation

The upward exhaust method can improve the ventilation effect, increase the heat convection inside and outside the tower, reduce the working environment temperature of the converter, and improve the heat exchange efficiency of the converter. Increase the fan flow on the tower door to enter more outside air into the tower to improve the working environment of the converter. replace the original paper filter of the converter with a new type of stainless steel filter and regularly clean it to prevent blockages. Effectively open the air inlet channel of the converter to ensure the flow of cooling air. change the fan control mode of the converter INU and ISU to the constant frequency control of the external power supply to ensure the supply of air volume and increase the high temperature and flame retardant hose. The shroud and the axial flow fan are integrated into one, and the heat generated by the converter is quickly discharged into the tower through the axial flow fan. The heat generated by the converter will no longer circulate at the bottom of the tower, which effectively reduces the environment inside the bottom of the tower. The temperature increases the converter's heat exchange capacity and ensures that the converter has good heat dissipation. The design concept of ventilation reconstruction is shown in Figure 2.

Figure 2. Schematic diagram of ventilation modification

In order to verify the effect of the upward air exhaust scheme, prototype tests were carried out in areas with severe overheating of ABB converters in areas such as Liaoning, Jilin, and Xinjiang province, as shown in Figure 3.
4.2. Analysis of Technical Transformation Effect

After the technical transformation of the wind turbine converter, more than one year of operation, the cooling effect is obvious. So far, no over-temperature faults have occurred.

Table 1. Comparison of Technical Modification Effect of Upward Wind Exhaust Mode in a Wind Field in Northeast of China

| Machine number | scheme | Outdoor temperature | ISU temperature | INU temperature | power | torque | Generato r speed | Power generation status |
|----------------|--------|---------------------|----------------|----------------|-------|--------|-----------------|------------------------|
| #A15           | Exhaust air | 25 °C               | 60 °C          | 83 °C          | 193KW | 100%   | 1820            | continuous rating      |
| #A06           | Only add the fan | 25 °C               | 70 °C          | 93 °C          | 1578KW | 100%   | 1826            | continuous rating      |
| #A27           | Pure maintenance | 25 °C               | 87 °C          | 98 °C          | 1587KW | 100%   | 1800            | continuous rating      |
| #A28           | untreated       | 25 °C               | 88 °C          | 99 °C          | 1527KW | 100%   | 1827            | continuous rating      |

Table 1 shows that the comparison between the technically modified units and non-technically modified units of a wind farm in Northeast China. From the data in Table 1, it can be known that the converter module ISU temperature and INU temperature are significantly reduced after the converter heat dissipation transformation. In practical applications, the technically modified units have never been shut down due to high temperature faults of the converter in the previous high winds and high temperatures. Under the conditions of high winds and high temperatures in March-June 2018, a total of 23 units were shut down due to high temperature faults in the wind farm. The unit is in good condition. After up to one year of continuous observation and demonstration, this technical transformation scheme can effectively solve the problem over-temperature of the converter.
Figure 4 shows the comparison of the technical reformation units of Xinjiang Wind Farm. H1-13 unit of a wind farm in Xinjiang adopts the technology of upward air exhaust. The trial operation began in April 2018. The nearby H1-05 fan was selected on the site (there is no technical modification, only the tower door and the converter cabinet door are opened). Comparing the operating temperature, it can be seen that the heat dissipation effect of the technical transformation unit is obvious. At the same time, compared with the unoperated unit when the tower tube door is closed, the converter's operating temperature drops to 10°C-15°C after the technical transformation. After the heat radiation technology reform of Unit H1-13 has been completed, it has gone through summer high temperature verification. It can still run stably when the extreme high temperature reaches 37°C, and no over-temperature fault has been reported.

To sum up, ABB converter adopts the upward exhaust scheme in the tower. The technical transformation effect is good, it can fully meet the requirements of site conditions, reduce the operating environment temperature of the frequency conversion system, and can effectively reduce the frequency of converter over-temperature faults, improve efficiency and stability.

4.3. Analysis of influence of heat on engine room

In order to evaluate the influence of internal upper exhaust of the tower barrel on the operating temperature of the engine room, the Flotherm software was used for simulation verification. With the converter at the bottom of the tower as the source of heat, the calorific value is 25kW (the maximum calorific value of the converter) and the ambient temperature is 35°C. The height and wall thickness of the tower barrel are set according to the actual situation, and the fan is used to transfer the heat upward. The simulation results are shown in figure 5 below.
Figure 5 Analysis of the influence of modification of heat dissipation mode on cabin temperature

According to the simulation calculation, heat can be transferred up about 40 meters at most along the tower cylinder. During the transfer process, the heat radiation through the tower cylinder is transferred to the external air, and the temperature gradually decreases. At a height of 40 meters, it can be equal to the ambient temperature. Since the tower is actually 80 meters to the right, the rising heat will have no effect on the operating temperature of the engine room.

4.4. Introduction to other solutions

4.4.1. Reduce the inlet air temperature and increase heat conversion

Industrial air conditioning enhances air convection and internal and external heat exchange, improves heat exchange efficiency, and can quickly lower the temperature of the tower bottom and the converter. In actual effect verification, the cost is higher.

4.4.2. Reduce the thermal resistance of the converter and enhance heat exchange

The thermal resistance of the converter is closely related to the heating of the converter. In order to reduce the thermal resistance and reduce the accumulation of heat, deep maintenance of the converter can be performed, and the thermal conductivity grease of the IGBT module of the converter should be replaced regularly. Cleaning the inner wall of the radiator is easy to accumulate dust and mosquito, Oil stains and other parts, use an ultrasonic cleaner to clean the radiator to ensure that the surface of the radiator is clean and dry without debris, and fully contact with the air to improve heat dissipation efficiency. Repetitive work is required and the workload is large.

4.4.3. Increase the converter cooling fan flow

When the size of the fan is the same, increase the air intake, and regularly clean or replace the air filter of the converter to prevent dust and debris from accumulating, prevent airflow, and ensure that the air intake channel is unobstructed.

4.4.4. Change the cooling method of the converter

Change the converter air cooling mode to water cooling mode. Under the same heat, the specific heat capacity of water is greater than air, the heat exchange efficiency is higher, and the heat dissipation effect is better. The technical transformation plan is theoretically feasible, but it needs to add water pumps and inlet and outlet pipes, and the construction changes are relatively large.
5. Conclusion
In this paper, through theoretical analysis and practical application of thermal simulation, wind farms and test and verify the way of the wind turbines ABB converter thermal fault are studied, the analysis of the converter thermal failure mainly with the working environment temperature is too high, lack of air volume and converter thermal resistance coefficient increases, puts forward several feasible solutions and ideas, and to the air for the upper tower drum for fitting, prototype validation for a long time and temperature data collection, and the simulation using software FLOTHERM heat change trend, combined with wind turbines running situation, shows that the cooling effect is good, It can effectively solve the over-temperature fault of ABB wind power converter, and also briefly introduce other technical modification schemes, indicating the direction for subsequent research.

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