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Study on the Temperature Measurement of High-Power Permanent Magnet Synchronous Motor Based on Fiber Optic Sensor

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Abstract: In order to ensure high-power PMSM normal operation and monitor its fault online, its stator and rotor temperature is need to in real time high accuracy measurement. The temperature measurement principle of fiber optic sensor has been briefly introduced. The high-power PMSM rotor's temperature measurement adopted semiconductor absorption optical fiber sensor, and its stator temperature measurement adopted optical fiber grating temperature sensor. The temperature measurement systems were designed respectively. The characteristics of the two temperature measurement systems are summarized. When they were applied to actual industrial field, the problems that needed to resolve were pointed. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Fiber optic sensor, Temperature measurement, High-power synchronous motor, Stator, Rotor.

1. Introduction

High-power permanent magnet synchronous motors have high power density, high efficiency, high power factor and so on. In recent years, it has been used in such as ship electric propulsion, traction elevators, electric locomotive traction, electric vehicle drive areas.

Because PMSM has not the slip, the rotor is no the iron and copper consumption of fundamental wave. In the early small-capacity PMSM systems, the temperature rising did not pay enough attention. With the motor power increasing and the permanent magnet's volume increasing, the eddy current losses generated by tooth harmonic wave will cause the rotor temperature to rise, and the rotor cooling is poor. These may lead to the permanent magnet loss of field [1]. The stator temperature rise will limit the single motor capacity improving and endanger the motor's insulation life. Therefore, the various parts' temperatures of the high-power PMSM are one of the important performance indicators of the motor design and operation. To check the motor performance whether qualified, ensure the motor normal operation, and monitor the motor running state, the motor stator and rotor temperature must be accurately detected when the motor is running.

Currently, the accepted four measurement methods of the stator windings and other parts: the thermometer method, the resistance method, the embedded thermometer method, the superposition method (Double Bridging charged thermometry method). On literature [2], the various methods' principles and shortcomings had been described in detail. The temperature measurement methods of the permanent magnet rotor have infrared thermometry and the rotor with a launcher placed the temperature sensor and so on. These methods exist the temperature measurement high cost, and are susceptible to strong electromagnetic interference problems. It is difficult to practical application. In this paper, the measurement methods based on optical fiber sensors can achieve in real time continuous measurement for the high-power permanent magnet synchronous motor's stator and rotor temperature, and the input temperature signal was provided for the motor system's detection and control.

2. Principle of Optical Fiber Temperature Sensor

The working principle of optical fiber temperature sensor is the light of the light source which it is sent into the modulator through the fiber. The measurand temperature and the light which had gone into the modulation zone interact, leading to the light's optical properties (such as light intensity, wavelength, frequency, phase etc.) change. It is called the modulated signal light. And then it is sent into the optic probe through the fiber, after demodulated, the measured temperature is obtained [2].

The optical fiber temperature sensor was divided into two types: transmission type and component type. The former uses the fiber optic as transmission line, and the latter uses the optical fiber as sensitive element [3]. In the temperature measurement of high-power permanent magnet synchronous motor, the rotor's real-time temperature measurement used transmission-type optical fiber sensor, and the stator's temperature measurement used the component-type fiber optic sensor.

Currently, transmission-type optical fiber temperature sensor uses more semiconductor absorption. The transmission capacity of this sensor's semiconductor temperature thin-slice (typically GaAs or InP) varies with temperature. When the light with a constant light intensity was input at the fiber end, the receiving light intensity at the other end of optical fiber changed with the level of the measured temperature. So by measuring output voltage of the receiving component, the sensor location's temperature was able to be measured.

The component-type fiber optic sensor utilizes some of the fiber parameters, such as light amplitude (the fiber core diameter and refractive index change with temperature, leading to the transmission light in optical fiber scatters out due to line uneven, which cause changes in light amplitude), the light polarization plane rotation (the polarization plane of single-mode optical fiber rotates with temperature changes) and optical phase, which they changes with temperature. By light detectors, the measured temperature obtains.

3. Temperature Measurement of High-power Pmsm Rotor

As high-power permanent magnet synchronous motor rotor is not only high-speed rotation at work, but also it is in the strong electromagnetic fields, the measurement methods only adopted the non-contact temperature measurement. Although the general permanent magnet material's Curie temperature (the temperature of making permanent magnet materials to complete loss of magnetism) was higher. In the normal working, the motor temperature will not reach the Curie temperature point. In fact, the actual working temperature of the permanent magnet materiel is much lower than the Curie temperature. The rotor temperature needs to be detected, and avoiding high temperature leads to rotor loss of the magnetic.

3.1. The Temperature Characteristics of Semiconductor Material GaAs

The transmission characteristics of semiconductor material GaAs are shown in Fig. 1, where I(λ), *T(λ, t)* are the transmittance functions of semiconductor material, *t* is temperature. When the temperature rises ($t_1 < t_2 < t_3$), transmittance curve shifted to longer wavelengths direction. Photodetector received light intensity decreasing with temperature increasing. This is the basic principle of temperature measurement.

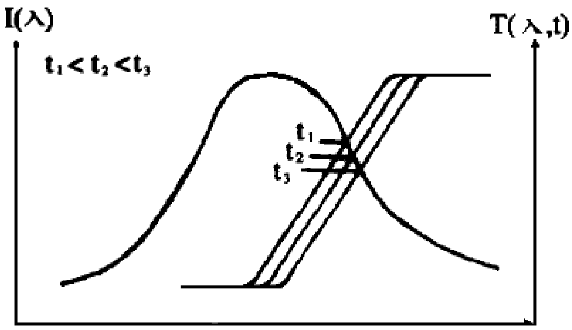

Fig. 1. The transmission characteristics of GaAs.

The absorption rate of semiconductor materials is related to the forbidden band gap E_g, and the forbidden band gap E_g varies with temperature. The relationship between the forbidden band gap E_g of the semiconductor materials GaAs and the temperature *T*, in the temperature range of 20~973 K, can be expressed using a simple formula:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}, \tag{1}$$

$E_g(0)$ is the energy forbidden band gap when the temperature is 0 K, its units is eV ($E_g(0)$ =1.522 eV);

α is the empirical constant, its units is eV/K

(α =5.8×10^{-4} eV/K);

β is the empirical constant, its units is eV/K (α =5.8×10^{-4} eV/K).

The relationship between the maximum point corresponding wavelength λ_T and temperature T satisfy the following formula:

$$\lambda_T = hc / E_T(T) = hc\left[E_g(0) - \Delta E - \frac{\alpha T^2}{\beta + T}\right]^{-1}, \quad (2)$$

where h is the Planck constant; c is the light speed; $E_t(T)$ is the correcting energy forbidden band gap; ΔE is energy factor. From formula (2) can be seen, λ_T change and temperature is the nonlinear relationship.

3.2. Semiconductor Absorption Optical Fiber Temperature Sensor's Working Principle

For the high-power permanent magnet synchronous motor rotor, its temperature measurement uses semiconductor-absorption temperature sensor system. The semiconductor temperature-response material uses GaAs. The working principle of temperature measurement system is shown in Fig. 2.

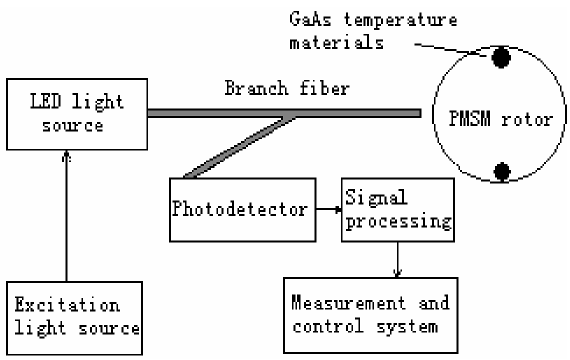

Fig. 2. The schematic of permanent magnet synchronous motor's rotor temperature measurement.

In Fig. 2, the optical fiber adopts the branch structure. One end inputs LED light with a constant light intensity, the other end receives the modulated light by temperature sensitive components. The literature [4] showed that the temperature of the rotor along the radial direction from outside to inside gradually reduced. Therefore, semiconductor temperature sensitive components should be placed in the pre-designed hole of the permanent magnet close to the air gap surface. In the rotor temperature measurement system, the fiber output optical signal, and the optical signals need be converted to electrical signals. Therefore, the signal processing circuit was used, achieving photoelectric conversion and signal amplification. The temperature signals which the control system needs to, can be got.

The semiconductor absorption optical fiber temperature measurement system has good stability, reproducibility and anti-interference characteristic and higher coupling efficiency. In temperature range of the motor, higher precision can be ensured. Under the strong electromagnetic interference situations, the non-contact measurement of rotor temperature was resolved.

4. The High-Power Pmsm Stator's Temperature Measurement

For the high-power motor stator temperature measurement, in the current the embedded temperature sensor method commonly is used. Research indicates that: in the motor stator, the copper winding temperature is highest. Temperature sensors can't be installed close to the copper windings location.

Therefore, the measured temperature is only the surface temperature of the embedded point, and there is a certain gap with the actual temperature of winding. Also, as the sensor size limitations, in the stator only a few temperature sensors can be embedded, and multi-point temperature measurement can't be achieved, or even miss the information of the temperature highest point. Also, in the motor stator high voltage, strong magnetic field environment, the embedded temperature sensor will subject to greater interference. Based on the above reasons, the fiber-optic grating sensor was used measuring the temperature of the high-power PMSM stator.

4.1. Principle of Fiber Bragg Grating Temperature Sensor

FBG (fiber Bragg grating) is the use of the fiber materials photosensitivity. That is, the interaction of outside incident photons and the fiber core cause the latter's refractive index permanent change. Using UV laser direct writing method in the single-mode fiber core forms a spatial phase grating. It is a kind of optical passive components.

FBG's reflection or transmission peak wavelength is related to and grating refractive index modulation period and core refractive index. The changes in external temperature or strain can affect the FBG's refractive index modulation period and core refractive index, causing FBG's reflection or transmission peak wavelength change. This is the basic principle of FBG sensors.

Fiber grating is formed by changing the refractive index of fiber core area and resulting a small periodic modulation. Bragg grating's center wavelength satisfied condition is:

$$\lambda_B = 2n_{eff}\Lambda, \tag{3}$$

where λ_B is the Bragg grating center reflection wavelength, n_{eff} is the effective refractive index of the core, Λ is the grating period. When the fiber grating temperature of their environment is changed, the fiber grating temperature changes itself. Because of the Optical fiber materials' thermal effect, the grating refractive index will change; because of the thermal expansion and contraction effect, the grating period will change, causing n_{eff} and Λ change. By the formula (3) shows, the Bragg wavelength shift may also occur.

Under the same stress conditions, when the temperature acts on the FBG, on the one hand due to thermal expansion effects, the FBG elongates to change its grating constant; on the other hand thermo-optic effect makes refractive index change of the FBG area. At certain temperature range both are directly proportional to the temperature variation.

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T} + \frac{1}{\Lambda}\frac{\partial \lambda}{\partial T}\right)\Delta T \tag{4}$$

Suppose, $\alpha = \left(\frac{1}{\Lambda}\right)\left(\frac{\partial \lambda}{\partial T}\right)$ is the thermal expansion coefficient of optical fiber; $\xi = \left(\frac{1}{n_{eff}}\right)\left(\frac{\partial n_{eff}}{\partial T}\right)$ is thermal coefficient of optical fiber. Equation (4) can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T = K_T \Delta T, \tag{5}$$

where K_T is the temperature sensitivity. By the formula (5) shows, the fiber grating's wavelength offset and the temperature change assumes the linear relationship. So long as the fiber grating's wavelength offset be measured, the temperature change can be measured.

4.2. High-power PMSM Stator Optical Fiber Grating Temperature Measurement System Constitute

FBG uses the wavelength division multiplexing technology realizing the distributed multi-point measurement. Using optical branching device or light switch, the optical path is divided into multiple. Each additional path, the temperature measurement points will be doubled. Therefore, the high-power motor stator temperature measurement system uses distributed measurement, and the measured temperature points can be many.

The temperature measurement system used optical branching device which the light can be divided four path. Each fiber cascaded 8 FBG. It can measure the total 32 point temperature. The system structure is shown in Fig. 3.

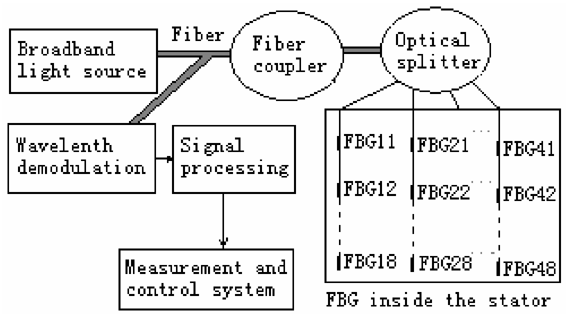

Fig. 3. High-power motor stator's multi-point temperature measurement system structure.

The light emitted by the broadband light source, through 3 dB coupler, and then through optical branching device, reached different optical fiber. Each fiber cascaded 8 FBG. Each reflection center wavelength of the selected FBG is different. The reflected light of the different peak-wavelength, through the optical branching device and the 3 dB coupler, went into the wavelength demodulator. Each peak-wavelengths of the FBG's reflected light were respectively solved by the wavelength demodulator. The distribution period of the refractive index changed with temperature. Its external performance was that the central wavelength of the FBG's reflected light changed with temperature. Therefore wavelength demodulator demodulated out the FBG central wavelength actually expressed as the FBG temperature state in the temperature field. Wavelength demodulator received the wavelength signal (actually indicated temperature), then by the signal processing it was sent into the temperature measurement-control systems. The system completed a high-power permanent magnet synchronous motor stator distributed multi-point temperature measurement.

5. Conclusions

High-power permanent magnet synchronous motor temperature measurement in real time is important. Compared with the traditional stator and rotor temperature measurement methods, in this paper, the semiconductor absorption optical fiber temperature sensor the permanent magnet rotor non-contact temperature measurement, and fiber Bragg grating temperature sensor was used in the stator temperature etc.

Acknowledgements

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