Design of optical voltage sensor based on electric field regulation and rotating isomerism electrode

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Abstract: Temperature, stress birefringence and low frequency vibration have a negative impact on the long-term operation instability of optical voltage sensors (OVS), resulting in large random and fluctuate errors in the output signal. In order to suppress the error, this paper developed a method based on electrical field modulation with high-speed rotating isomerism electrodes and the digital lock-in amplifier technology. This method can shift the frequency band of the measured signal to 2kHz, avoiding the low-frequency (<50Hz) interference from temperature drift, stress birefringence and vibration. The waveform of modulated signal is studied by coupling wave theory and finite element simulation method. And the Simulink results show that digital lock-in technology can suppress the large random interference.

I. INTRODUCTION

Optical voltage sensors (OVS) based on Pockels electro-optic effect have the characteristics of compact size, good insulation performance and high measurement accuracy. Therefore, it is very suitable for smart grid requirements and its development prospect is very considerable [1-2]. However, due to the poor long-term stability, OVS is deployed only in non-critical applications for smart substations. Factors such as temperature, stress birefringence and aging are generally considered as the main reasons affecting the operational reliability of OVS, which seriously hinder its practical application and industrialization process.

In recent years, relevant scholars have proposed the following solutions to solve the impact of the above problems:

1) Stress birefringence suppression: Double optical path [3] and double crystal method [4] are usually used to suppress linear birefringence. But the disturb from stress linear birefringence is random and fluctuation, these two methods could not completely eliminate the interference because the birefringence always differ in the two paths or two crystals, especially for environments with rapidly changing temperatures.

2) Temperature drift compensation method: Bohnert et al. [5] used the temperature drift of dielectric coefficient of quartz divider to make up for the drift of electro-optic coefficient. In addition, the software method is used to compensate for the real-time measurement of crystal temperature [6]. However, these two methods are ineffective for linear birefringence because it only compensate the stable and repeatable errors.

3) Phase modulation method with closed loop control: All-fiber optical current sensor (AFOCS) [7-8] uses square wave phase delay modulation to move the static operating point to the linear region. Closed-loop control is critical due to the stochastic drift generated by linear birefringence. For the constant temperature environment, the AFOCS can maintain high stability, meeting the accuracy grade of 0.2s. But when the environment temperature alters rapidly, the failure of PID feedback parameter would results in the instability of the system, which makes the output signal chaotic.

To overcome the problems of above methods, this paper presents an electric field control technique based on rotating heterogeneous electrodes. Digital phase-locked amplification can be implemented in MCU or DSP to recover the original signal interfered by linear birefringence. The feasibility of rotating electrode OVS was verified by Simulink software. The possible problems and measurement errors of this method are also discussed.

II. CONSTITUENTS OF SENSOR

As shown in Fig. 1, the whole system is composed of semiconductor laser light source, polarization optical elements, BGO crystal, rotating electrode and high voltage stage, photodiode detector (PD), DC motor, digital signal processor (DSP), etc. The electric field modulation system consists of an optical switch and a DSP, in which the optical switch consists of a rotating ground electrode, a motor, a light-emitting diode (LED) and a PD. As the ground electrode rotates, the direction and magnitude of the electric field inside the BGO crystal will change periodically, thus modulating the output optical power. The original measured signal can be recovered by digital lock-in amplifier technology of DSP or MCU.
With constant modulation frequency, the optical switch can not only monitor the speed of the motor, but also provide a reference signal for the lock-in amplifier to recover the measured voltage signal.

The focus of this paper includes the following parts:

1) The waveform of modulated signal. Because of the different shapes of the rotating isomeric electrodes, the output waveform will contain high harmonic components, so the signal waveform will not present a complete sinusoidal signal. Therefore, it is necessary to study the simulation of modulated signal.

2) The waveform of the reference signal. Due to the divergence of the LED light source, there will be a light spot on the rotating electrode blade, which may be larger than the electrode blade itself, resulting in the final reference signal is neither perfect sinusoidal signal nor square wave signal. Further analysis should be required.

3) The principle analysis of the digital lock-in amplifier. Since the modulated signal and the reference signal are neither perfect sinusoidal nor square wave signals, it is necessary to study the principle of the digital lock-in amplifier and analyze the source of errors.

III. PERFORMANCE OF ROTATED ELECTRODE

The sensor head structure of optical voltage sensor based on rotating isomerism electrode can be seen in Fig. 2. The ribbon region in the BGO crystal is the through-light region, and the optical path of the measured electric field is perpendicular to the optical path of the reference signal. The rotating isomeric electrode consisted of unipolar 30 degrees fan blades, where the black arrow in Fig. 2 is the rotating axis of the rotating electrode.

Figure 2. The structure diagram of sensor head

As shown in FIG. 3, when the blade of the rotating electrode directly covers the through-light region, this corresponds to the traditional OVS structure. At this time, the gradient of potential change in the crystal is the largest, which also means that the electric field and the output signal are the largest. With the rotation of the electrode blade, the electric potential in the crystal changes. When the electric field direction is tilted 45 degrees, the electric field and light signal are minimum. The variation relationship of the output optical signal under different electrode angle positions is simulated by electro-optic coupled wave theory as shown in Fig. 4.

Figure 3. The Potential distribution in BGO crystal with rotating electrode at different positions

The relationship of optical signal at different electrode angles

IV. GENERATION OF REFERENCE SIGNAL

In this paper, the reference signal is generated by the optical switch containing LED and PD. When the ground electrode blocks the LED lamp, there is no signal in PD’s current. The relationship between emission intensity and emission angle of optical switch can be written as

\[ I(\beta) = A\cos(k\beta) + c, \]

where \(\beta\) is the emission angle of the LED lamp, \(A\), \(k\) and \(c\) are the fitting parameters. And the fitting results were \(A = 4.113\), \(k = 0.0789*180/\pi\), \(c = 4.227\).

Assuming that the distance between the center of the rotating isomerism electrode and the LED is \(d\), the distance between the center of the rotating isomerism electrode and the center of the LED spot is \(R_0\), and the \(d\) distance from the calculate point to the center of the LED spot is \(r\), then the emission angle \(\beta\) can be expressed as

\[ \beta = \arctan(r/d). \]

In practice, the receiving area of PD is very limited. The light spot may be entirely covered by the blade, in which case the output of the LED light source can be expressed as
The calculation results are shown in Fig. 5, and the parameters are $r_0 = 0.5\text{mm}$, $d = 2\text{mm}$, $R_0 = 6\text{mm}$, and the angle between the fan-shaped electrodes $\theta_{GND} = 30\text{ degrees}$.

![Figure 5. Calculated reference signal](image)

V. PRINCIPLE OF LOCK-IN AMPLIFIER

According to the description of Digital Lock-in Amplifier technology in many relevant literature [9-11]. When the voltage signal to be measured is denoted as $S(t)$, and the modulated signal is denoted as $M(t)$, then the modulated signal to be measured is defined as

$$S_m(t) = M(t)S(t),$$

where $M$ is a periodic function, which is expanded by Fourier series:

$$M(t) = m_0 + \sum_{j=1}^{l} m_j^l \cos(2\pi j f_m t) + m_j^l \sin(2\pi j f_m t).$$

And the reference signal could be considered as the sum of odd and even Fourier components, the even part is

$$R_{even} = \sum_{j=0}^{l} m_j^l \cos2\pi(j - 1)f_m t.$$  

The multiplication of even component of $R$ and modulated signal $S_m(t)$ can obtain the following formula:

$$S_m(t)R_{even}(t) = S(t) \sum_{j=0}^{l} \sum_{k=0}^{l} m_j^l r_k^j \cos(2\pi j f_m t) \cos(2\pi k f_m t)$$

$$+ m_j^l r_k^j \sin(2\pi k f_m t) \cos(2\pi k f_m t).$$

Integrate both sides of equation (8) from 0 to $T_m = 1/f_m$, then we can get

$$S(t) = \frac{\int_0^{T_m} S_m(t)R_{even}(t)}{\sum_j m_j^l r_j^l}.$$  

In particular, the amplitude and phase delay of each harmonic can be expressed as

$$X_{out}^i = S(t)m_x^i = \frac{m_x^i}{\sum_j m_j^l r_j^l} \int_0^{T_m} S_m(t)R_{even}(t) dt$$

$$Y_{out}^i = S(t)m_y^i = \frac{m_y^i}{\sum_j m_j^l r_j^l} \int_0^{T_m} S_m(t)R_{odd}(t) dt.$$  

Thus, the magnitude and phase of the $i$th harmonic can be expressed as

$$M_{out}^i = \sqrt{(X_{out}^i)^2 + (Y_{out}^i)^2}$$

$$A_{out}^i = \arctan(X_{out}^i/Y_{out}^i).$$  

To simplify the calculation process, we preferred a sinewave reference signal without high-order harmonics. Therefore, the denominator of Equation (8) could be reduced to $m_x^1 r_1^1$.

VI. SIMULATION OF SYSTEM

The Simulink model for whole system is shown in Figure 6, which consist of three parts: the reference signal $R(t)$ module (left top), the modulation module (left middle) which generate $S_m(t) = M(t)S(t)$, and the random noise module (left bottom).

The reference signal could be set to 2.5kHz sinusoidal wave or a square wave. The measured voltage signal $S(t)$ is a 50Hz sinusoidal signal and the amplitude set as 1. The frequency of the modulation waveform $M(t)$ is set to 2.5kHz, and the waveform is shown in Fig. 4.

The noise simulation module can be set to random white noise or sine wave with frequency of 10Hz and amplitude of 10. The former represents the random step signal caused by polarization or discharge in DC measurement, while the latter simulates the random fluctuation interference signal caused by linear birefringence.

Modulation signal $S(t)M(t)$ and the noise $N(t)$ can get the final signal. In order to recover the original signal $S(t)$, it is
necessary to integrate the result of multiplying Modulation signal $S(t)$ $M(t)$ and reference signal $R(t)$ in time of $T_m$.

The simulation results of Simulink can be seen in the Fig 7, where the first signal from top to bottom represents the step noise have no concern with the measured voltage. The second is a modulation measurement signal with a frequency of 50Hz. The third is the sum of modulated signal and noise signal. The fourth is restored signal after integration.

The frequency set to 2.5kHz can effectively suppress the spike of the recovered signal, that is close to the frequency of the reference signal, and we only keep the point where the phase is zero. The red curve in the Fig 8 shows the complete recovery signal (shifted up by 3).

Figure 6. The Simulink model for the whole system

Figure 7. Simulation results

VII. CONCLUSION

In order to suppress the interference of low frequency linear birefringence to the measured voltage signal, a new optical voltage sensor based on rotating heterogeneous electrode and digital lock-in amplifier technology is designed in this article. The direction and magnitude of the electric field are modulated by a DC motor drives the ground electrodes to rotate to obtain the modulated optical signal in connection with the measured voltage. And the digital lock-in amplifier technology is used for demodulating the obtained optical signal. Finally, the scheme is confirmed by Simulink model.

Attention should be paid to the grounding problem of highspeed rotating ground motor. The high centrifugal force may form a thin vacuum layer between the carbon brush and the contact wall, which may cause intermittent failure of the grounding system. The modulation waveforms of the electric field are distorted by the reverse electric field shielding of the intermittently generated induced charge. In addition, the low frequency permittivity of the crystal directly determines the magnitude of the modulated electric field, and its response characteristics to the changing high-frequency electric field under high voltage and medium will also affect the modulation effect of the electric field. The underlying physical mechanism needs further study. In addition, the installation error of the rotating electrode will also affect the modulation result, but it can be calibrated by the algorithm.

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