Application research on fiber-optic current sensor in large pulse current measurement

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Abstract. Rogowski coil is usually used to measure pulse current in directed energy weapon experiments, which is lack of direct and low-frequency components in current measurement, and influenced by interferences like outside electromagnetic field and mechanical vibration. To acquire pulse current data with higher accuracy, a new kind fiber-optic current sensor is proposed to achieve large pulse current measurement, and working principle of the sensor is introduced in this paper. A fiber-optic current sensor is fabricated by cooperative agency, which has measuring range from 0 to 200kA and precision better than 1%. Comparison experiment between the fiber-optic current sensor and Rogowski coil made by PEM from England is tested. The experiment results show that main components of pulse current waves measured by two sensors are similar. Current wave measured by fiber-optic current sensor gets less noise signal than Rogowski coil, and has more details with small current. The fiber-optic current sensor could achieve direct and low-frequency component current measurement, but its max response frequency is 500 kHz. According to the research results, compared to Rogowski coil in pulse current measurement application, the new kind fiber-optic current sensor has better character in direct and low-frequency component current measurement, strong anti-interference ability, high sensitivity and ability to acquire current measurement data with higher accuracy. This sensor would satisfy measurement demands of large pulse current measurement in directed energy weapon better, if it gets better frequency response ability.

1. Introduction
Large pulse current measurement in electromagnetic weapon and directed energy weapon is usually realized by Rogowski coil [1]. Rogowski coil could be considered as a current transformer whose primary side is one turn and secondary side is multiple turns, measures current by electromagnetic induction without contact to measured circle [2]. Large pulse current measurement without contact provide well insulation, which gives good protection for measurement system. And Rogowski coil has advantages like large measurement range, high measurement accuracy, wide dynamic and frequency response range, and simple structure which is inexpensive and easy to install [3]. But there are still some problems in Rogowski coil application. The measurement principle of Rogowski coil is sensing change of induction magnetic flux, and measured current is in direct proportion to derivative of magnetic flux, which means that Rogowski coil could not calculate direct current component [4]. And actual integrator used with Rogowski may introduce input compensation voltage to influence frequency response, which causes distortion in low-frequency current component measurement. Sensitivity and accuracy of Rogowski coils is determined by their support structures and coil winding
[5]. Change of support structures caused by temperature or force may change sensitivity of sensor. Manufacturing of coil winding is commonly asymmetrical, induction magnetic flux for winding is also asymmetrical. So the coil may introduce noises coupled by coil and position between coil and measured circle would also influence measurement result [6]. There’s large electromagnetic interference and vibration in electromagnetic weapon application, which would reduce accuracy for current measurement. Nowadays for better battle damage and controllability of electromagnetic weapon application, high accuracy and precision measurement is needed in research and control system. Using Rogowski coil for large pulse current measurement in electromagnetic weapon application has its limitation in promotion of accuracy and precision. Considering problems that Rogowski coil used in electromagnetic weapon application, application of fiber-optic current sensor (FOCS) is proposed in this paper. Pulse current is measured by these two kinds of current sensor is experimented, and according to the comparison between two sensors, feasibility of fiber-optic current sensor for large pulse current measurement in electromagnetic weapon application is analyzed and discussed.

2. Principle and performance of fiber optic current sensor
Fiber optic current sensor is a new kind sensor for current sensing based on Faraday effect [7]. Faraday effect is a kind of magnetic rotation effect which describes interaction between magnetic field and light in optical medium. When linearly polarized lights get through optical medium by the direction of outside magnetic field, speed of left-circularly polarized light and right-circularly polarized light in medium is different, their polarization plane will have a rotation relative to input linearly polarized lights, which is called Faraday effect. The rotation angle is in direct proportion to magnetic field component in light spreading direction, which could be demonstrated as following function [8].

\[ \theta = VHL \] (1)

θ is polarization plane rotation angle from output light to input light. \( V \) is Verdet constant related to characteristic of magneto optical medium, wavelength of light and temperature. \( H \) is magnetic field component in light spreading direction. \( L \) is length of medium.

The realization of the sensor is shown in figure 1.

![Figure 1. realization of FOCS sensor.](image)

Light from source spread to polarizer through PM coupler, polarizer makes light into linearly polarized light. Fiber cable connected to modulator is 45°alignment, light changes into two mutually orthogonal linearly polarized lights when spread into line-maintaining fiber. After polarization switch cable, two linearly polarized lights switch to mutually orthogonal elliptically polarized lights then get into sensor cable. In sensor cable, mutually orthogonal elliptically polarized lights have phase difference by effect of magnetic field based on Faraday effect. Lights spread back from reflect at the end of cable, which makes phase difference double. Relationship between phase difference and measured current could be demonstrated as following function [9].

\[ \phi = 4NVH(t) \] (2)
\[ \phi_I \] is output phase difference, \( N \) is number of turns for cable around measured circuit, \( V \) is Verdet constant, \( I(t) \) is measured current signal.

Reflect mutually orthogonal with phase difference interference in polarizer, detector switch interference light intensity into voltage signal. Signal processor circuit gets phase difference from voltage signal, then we could get current signal measured.

Sensor cable is as shown in figure 2, consist of line-maintaining part, polarization switch part (replacement of fiber optic wave plate) and elliptically-maintaining part (as sensor cable). By introducing progressive increase spiral birefringence fiber structure as polarization switch part, phase difference error introduced by fiber fusion between cable and fiber optic wave plate is avoided. Elliptically-maintaining part introduces large inner regular force to defend random force interference from outside, and its circular polarization component ensures sensing character of sensor cable [10].

![Figure 2. consistent of sensor cable.](image1)

Manufactured Fiber optic current sensor has measurement range from 0 to 200A, 1% measurement precision from 30kA to 200A, dynamic range from DC to 100 kHz. Its sample frequency is 1MHz, and its acquisition bits is 16.

3. Pulse Current experiment results of different current sensor
To compare performance between Rogowski coil and manufactured Fiber optic current sensor, two sensors is used to measure pulse current in experiments. Selected Rogowski coil is CWT-1500B manufactured by PEM (Power Electronic Measurement) from England, which has measurement range from 0 to 300kA, sensitivity of 0.02mV/A, and 1% sensing precision with certificate of calibration.

Experiments of short circuit discharge by PFN (pulse forming network) module is tested. To make two sensors have same measurement current and environment, they were set in the same position of measured bus bar, as is shown in figure 3.

![Figure 3. installation of two sensors.](image2)
Measured results of PFN short circuit discharge current with 20kA peak current are shown in figure 4 above, and measured results of discharge current with 115kA peak current are shown in figure 4 below.

According to experiment results of different current transformer, measured waveforms from two sensors is similar. The performance of two sensor would be analyzed in next section.

**Figure 4.** Measured results of Rogowski coil and FOCS.

### 4. Performance analysis and comparison of different current transformer

Zoom on random noises in different sensor, it’s obvious to figure that noises in Rogowski current transformer is much more than FOCS. In 120kA measurement situation, random noise in Rogowski measurement is with about 550A offset and 180A amplitude. The random noise range of FOCS is about 25A. Considering that sensitivity of Rogowski current transformer is 0.02mV/A, there’s noise whose amplitude is about 3.6mV coupled in the coil, which is common in normal current measurement. Ratio between amplitude of random noise and full measurement range is 0.006, ratio between offset of random noise and full measurement range is 0.0018. For FOCS, 25A noise is floating value in last byte in data, which means that FOCS barely couples noises outside, and ratio between noise and full measurement range is only 1.25e-4 which has little effect to measurement result. Compared to Rogowski coil, FOCS has better performance in noise compatibility.

There’s still some detail differences in the waveforms of two sensors. Though waveforms measured by two sensors have similar peak value and pulse width, waveform of Rogowski coil has faster rising edge, and waveform of FOCS has longer falling edge. For reason that there’s no standard current resource, simulation is used to generate an ideal short circuit discharge current waveform. According to system parameters in reality, model is built in Matlab simlink, and an ideal discharge current waveform is generated. Comparison of measurement results from two sensors and simulation waveform is as shown in figure 5 above, and power spectrum of them are as shown in figure 5 below. In picture, blue line represent FOCS result, bronze line represent Rogowski coil result, purple line represent simulation result.
According to the comparison, waveforms and power spectrum are similar. In Rogowski coil power spectrum, there’s more fluctuation and an unexpected hump from 260kHz to 320kHz which might be noise main component.

5. Conclusion
Large pulse current measurement is an important component in directed energy weapon experiments and applications. Rogowski coil which is usually used in large pulse current measurement, has disadvantages like can’t measure direct and low-frequency components in current measurement, and influenced by interferences like outside electromagnetic field and mechanical vibration. A new kind fiber-optic current sensor proposed in this paper is compared with top class Rogowski coil by pulse current measurement experiment. Results shows that FOCS gets measured waveform closer to simulated one than Rogowski coil, and there’s less noises in FOCS than Rogowski coil. In conclusion, the new kind fiber-optic current sensor has better character in direct and low-frequency component current measurement, strong anti-interference ability, high sensitivity and ability to acquire current measurement data with higher accuracy in pulse current measurement application. This sensor would satisfy measurement demands of large pulse current measurement in directed energy weapon better, if it gets better frequency response ability.

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