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A NOVEL FIBER-OPTIC CURRENT MEASUREMENT INSTRUMENT FOR HIGH-POWER LASER SOURCE

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ABSTRACT

The laser power source is one of the key equipments of the power supply module (PSM), which is crucial to transmit the energy efficiently with high stability and reliability. Therefore, it is important to measure the pulse current quickly with high reliability and accuracy. A novel opto-electronic current transducer (OECT) based on Rogowski coil is demonstrated to measure high-power high-voltage laser source. The CT is placed in the high-voltage side and is used to measure different durations of pulse current with large amplitude for the laser power source. Models with lumped parameters and dynamitic properties of the Rogowski coil with a new type of integrator have been analyzed in detail. The optimizing parameters of the transducer have been introduced. Measurement results of the opto-electronic current measurement instrument are described respectively. The simple sensor geometry gives high accuracy and sensitivity, wide dynamic range, and immunity from slow-variance temperature.

Keywords: *OECT, PSM, Pulse Current, Measurement.*

1. INTRODUCTION

High-voltage-high-power pulse current measurement is often accomplished with conventional ferrous core current transformers (CTs), which are of large size and high cost. As the voltage level of the power line increases, the size, weight, cost, and local power consumption of this type of current sensor are also increased. Furthermore, are not only ratio error and phase error introduced by the ferrous core, but also nonlinear factors of the core, such as eddy current and hysteresis loss, contribute hard-to-predict errors to the measurement [1,2].

PSM is one of the important equipments of the high-power source, which can provide high-power source for the power amplifier [3,4]. The main electric circuits of each power module consist of two parts: preionization loop and primary discharge loop. As usual, the high

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voltage and current with high di/dt or ultra short rise time (less than 10^{-9} s) are indispensable to PSM. Therefore, it is very difficult to measure the pulse current quickly with high reliability and accuracy.

For use in the precision measurement instrument, there has recently been an interest in optical fiber current transducer including two types of transducers: opto-electronic current transducer (OECT) and magnetic optical current transducer (MOCT) discussed in references [5,6].

The principle of adopting a Rogowski coil as a special sensor for measuring currents has been known in references [7~9]. The attraction of using a Rogowski transducer or sensor for measuring currents in excess of several thousand amps with significant high frequency components introduced in reference. The coil has wide bandwidth that depends on its type. It has no core saturation effects and has compact structure. The coil gives it an advantage over other conventional current sensors in several measurement applications, such as measuring transient current, pulse current and so on.

There are some references [10~13] discussing the measurement of fast di/dt, heavy pulse currents in the region of hundreds of kA.A novel opto-electronic current transducer (OECT) based on Rogowski coil will be introduced. The measurement instrument consisting of OECT can measure the pulse current of high-voltage high-power laser source. The instrument employs a new application of frequency-modulated signal transmission over fiber.

2. INTRODUCTION OF THE INSTRUMENT

The principle configuration of the novel fiber-optic current measurement instrument for measuring pulse currents of the high-power high-voltage laser source is illustrated as Fig. 1.

In the instrument, the current is detected by a Rogowski coil, and converted into a light telegram-modulated optical pulse signal, and transmitted via an optical fiber to a low-voltage area where the current signal is recovered by demodulation circuits. There are 100 parallel capacitors adopted as power supply devices in each PSM of the high-power laser source for powering 10 parallel xenon lamps. Fig.1 shows the system schematic diagram for measuring pulse current of the xenon lamp.

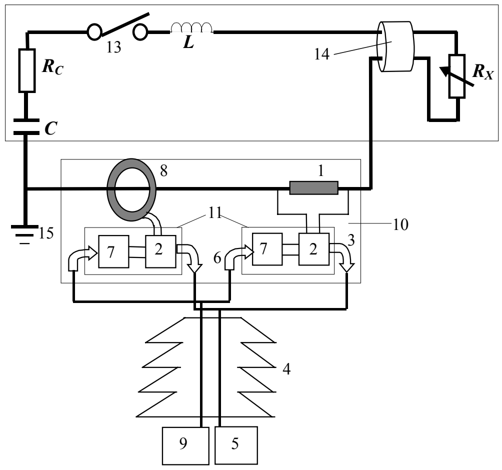


Fig.1: System schematic of the measurement instrument with opto-electronic current transducer. 1: Standard resistor for calibrating optical current sensor; 2: Voltage to light telegram conversion; 3: Fiber optic transmission to ground level; 4: Composite insulator; 5: Signal process system of the optical measurement instrument; 6: Light pulses for power supply; 7: Power supply for sensor head; 8: Rogowski Coil for measuring pulse current; 9: Power supply system; 10: fiber-optic current sensor Measuring System; 11: Sensor Head; 12: Equivalent circuit for powering one xenon lamp; 13: Switch of the discharge circuit; 14: Transmission cable; 15: Ground of the discharge circuit; R_X: Equivalent impedance of one xenon lamp (Ω); R_C: Resistance of the discharge circuit(Ω); C: Capacitance of the discharge circuit (μF); L: Inductance of the discharge circuit (H).

The new optical pulse current measuring system uses a standard resistor, which is integrated into the PSM discharging circuit. The voltage drop across the resistor that is proportional to the pulse current is ensured and digitized by an electronic circuit that is located at high voltage potential. The measured signal is transmitted as a serial telegram via a fiber optic link to ground potential.

3. THEORY OF THE SENSOR HEAD

The opto-electronic current transducer consists of a sensor head, operating power supply, fiber transmission line, electro-optic transformer, phaselocked loop (PLL) demodulation circuit, and power amplifier. An air Rogowski coil is placed in the high voltage side around the electric conductor of the laser source.

The optical pulse signal is transmitted to the low-voltage area through an optical fiber. Since the optical pulse signal has the advantages of both digital format and optical medium, it has high resistance to any form of electromagnetic or environmental interference. Variations of the LED light intensity, which can be caused by environmental disturbances and fiber irregularities, have little to no effect on the recovered signal. Additionally, there is the obvious advantage provided by the fiber, that of insulating the high-voltage area from the low-voltage or ground area. Optoelectronic conversion is accomplished by a PIN, which is used in conjunction with an LED. The LED output is coupled into the optical fiber for transmission to the low-voltage or ground area.

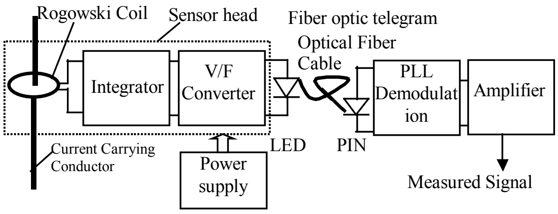


Fig. 2 Configuration of the opto-electronic current transducer

The Rogowski coil is made of copper wire wound in a spiral around a section of plastic pipe and then returns through the center of the pipe to its point of origin. The configuration of the coil sensor illustrated as sensor head in Fig.2 is a simplification diagram.

The shape of the coil is illustrated in Fig.3. It is important to ensure that the winding is as uniform as possible. A non-uniform winding makes the coil susceptible to magnetic pickup from adjacent conductors or other sources of magnetic fields. Electrical connection to the coil is at one end only. The other end is “free” and can be threaded round awkwardly shaped conductors or conductors in confined spaces. Flexible coils do not have to fit tightly round the conductor and their output is not excessively sensitive to position in relation to the conductor. They must, however, encircle the conductor completely.

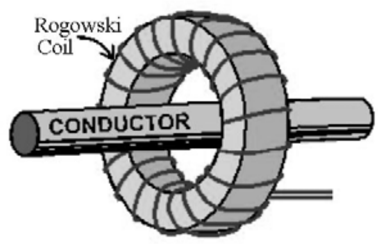


Fig.3 Shape of Rogwski coil

When the coil is uniformly wound with N turns/m on a non-magnetic former of constant cross section area S m^2, and formed into a close loop then the voltage $e\ (t)$ induced in the coil is directly proportional to the rate of change of the measured current ($I_1\ (t)$) passing through the loop based on Eq. (1).

$$e(t) = -\mu_o NS(dI_1(t)/dt) \tag{1}$$

Where e (t) is the induction voltage in the coil. I_1 (t) is the measured pulsed current. M is the mutual inductance of the coil, given $M=\mu_0 NS$. The equivalent circuit of the simplified form of the coil is illustrated in Fig.4. Based on Faraday’s law, e (t) can be expressed as Eq. (2).

$$\left.\begin{aligned} e(t) &= -d\phi/dt = -(\mu_0 NS/2\pi r_0)(dI_1(t)/dt) = -MdI_1(t)/dt \\ e(t) &= -M(dI_1(t)/dt) = L_0(di_2/dt) + (R_0 + R_S)i_2 \end{aligned}\right\} \tag{2}$$

Where L_0 and R_0 represent the distribution inductance, capacitance and its resistance respectively. R_S is the terminating resistance. i_2 is the induced current along the coil. The voltage, u_S, is the sampling voltage of R_S. And given

$$L_0 = \mu_0 N^2 S/2\pi r_0 \tag{3}$$

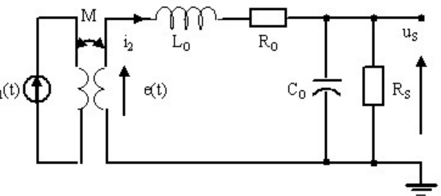


Fig. 4 Equivalent circuit for Rogowski coil

Some researches indicate that the duration of the pulse current of preionization loop unit and primary discharge loop unit of PSM is much longer than 100μs. Therefore, the coils should be adopted for measuring long duration pulsed currents of the high-power laser source. Let L_0 (di_2/dt)<<(R_S+ R_0) i_2□the measured pulse current I_1 (t), can be expressed as Eq. (4).

$$I_1(t) = -[(R_0 + R_S)/M]\int i_2 dt$$

$$= -(R_0 + R_s)RCu_C/(MR_S) \quad (4)$$

Where, u_C is the output voltage from the compound integrator. Assuming that the coil is terminated with an appropriate damping resistance R_S. R and C represent the integrating resistor and capacitance respectively. C_1, is a coupling capacitor.

From Eq. (2), it is clear that the Rogowski coil is equivalent to a current differentiator. Therefore, an active integrator is added at the output terminal of the coil, yielding a voltage proportional to the measured pulse current ($I_1(t)$). This voltage signal is converted into an FM (Frequency Modulation) signal via a V/F converter, and then further converted into an optical pulse signal by driving an LED with the V/F converter output. The LED output is coupled into the optical fiber for transmission to the low-voltage or ground area.

4. DYNAMITIC PROPERTIES OF CT

The detail analysis of the amplitude and phase frequency characteristic of the sensors is very benefit to provide some basis for optimizing electrical and structure parameters of the coil. Based on the equivalent circuit of Fig.3, the expression of i_2 *and* u_S can be deduced below.

$$\left.\begin{aligned} i_2 &= C_0(du_s/dt) + u_S/R_S \\ u_S &= -M(dI_1(t)/dt) \\ u_S &= L_0(u_S/dt) + (R_0 + R_S)i_2 \end{aligned}\right\} \quad (5)$$

Where C_0 is the distribution capacitance of the coil. Based on the equivalent circuit of the sensor with an outer integrator illustrated in Fig.4, the step response for the coil without an integrator can be deduced below.

$$U_g(s) = G(s)/s = [k\omega_n]/[s^2 + 2\xi\omega_n + \omega_n{}^2)] \quad (6)$$

Where, $2\zeta\omega_n=(L_0+ R_SC_0R_0)/(R_S\ C_0\ L_0)$, $k\omega^2_n=M/(C_0L_0)$, $\omega^2n=(R_0+ R_S)/(R_SC_0L_0)$. The optimal damping resistance (R_S) can be deduced below.

$$R_S = (L_0\sqrt{4L_0C_0 - 3R_0^2C_0^2} + L_0C_0R_0)/(2L_0 - 2R_0^2C_0) \quad (7)$$

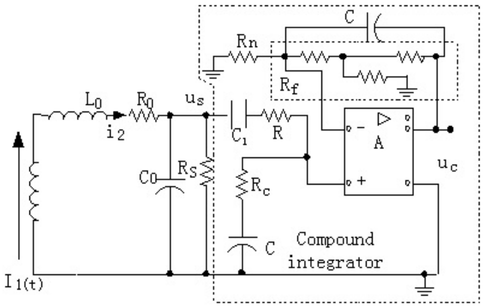


Fig. 5 Equivalent circuit for Rogowski coil with an outer integrator

The transfer function of the coil with an integrator can be expressed as Eq. (8).

$$T(s)=U_C(s)/I_1(s) \quad (8)$$

In Fig.5, the compound integrator can integrate the advantages of non-inverting and the inverting integrator together. Capacitor C_1 and feedback resistance R_f (formed by T type network) are added to the system. Therefore the unit step response of the coil with the compound integrator can be deduced below.

$$\begin{aligned} h_C(t) = k_1[&B_1\exp(s_1t) + B_2\exp(s_2t) \\ &+ B_3\exp(s_3t) + B_4\exp(s_4t)] \end{aligned} \quad (9)$$

Where, $k_1= R_C\ M/[(C_0L_0)(R+R_C)]$, $\tau_1=1/(R_C\ C)$, $s_4=-1/(R_f\ C)$, $\tau_2=(R_f+R_n)/(R_n\ R_f\ C)$, $s_3=-(C_1+C)/[CC_1\ (R+R_C)]$,

$B_2 = s_2(s_2+\tau_1)(s_2+\tau_2)/[(s_2-s_1)(s_2-s_3)(s_2-s_4)]$,

$B_1= s_1\ (s_1+\tau_1)(s_1+\tau_2)/[(s_1- s_2)(s_1- s_3)(s_1- s_4)]$,

$B_3 = s_3(s_3+\tau_1)(s_3+\tau_2)/[(s_3-s_1)(s_3-s_2)(s_3-s_4)]$,

$B_4 = s_4(s_4+\tau_1)(s_4+\tau_2)/[(s_4-s_1(s_4-s_2)(s_4-s_3)]$.

All real parts of s_1, s_2, s_3, *and* s_4 are negative values; therefore, the system is stable. The paper has adopted a typical coil with some optimal parameters as follow: r_0=0.055m, R_0=18.2Ω, M=2.0×10^{-7}(H), L_0=2.8×10^{-4} (H), C_0=3.1×10^{-8}(F), N=4051 (T/m), R□100kΩ, C=0.01µF, R_S =137Ω, R_f=50R, R_C=1/100R□R_n=R.

5. MEASUREMENT RESULTS

Accurately measuring pulse currents of preionization loop and primary discharge loop are critical for the high-voltage high-power laser source. Performance indexes of both the preionization loop and the primary discharge loop are listed respectively in Table 1.

5.1 Degree of linearity of optic-current senor

The output voltage as function of the measured current RMS (root mean square) is shown in Fig.6 at 20ºC room temperature. Fig.6 shows that the degree of linearity of the output voltage with measured sinusoidal current is good over the wide dynamic range. This indicates that the relation of input with output signals of the sensor is linear.

TABLE 1: Performance of preionization loop and primary discharge

Performance indexes	Preionization loop	Primary discharge
Duration of pulse	≤100µs	50±10%
Total peak value	≥16kA	≥150kA
Charge voltage	≥20kV	≥23kV
Total power	≥5kJ	≥400kJ
Lead time for preionization	≥50µs	≥80%
Damping factor	0.75	0.75
Repetition rate	97%	97%

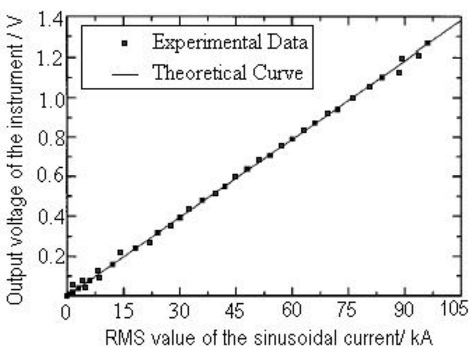


Fig.5 Degree of linearity calibration of optic current senor

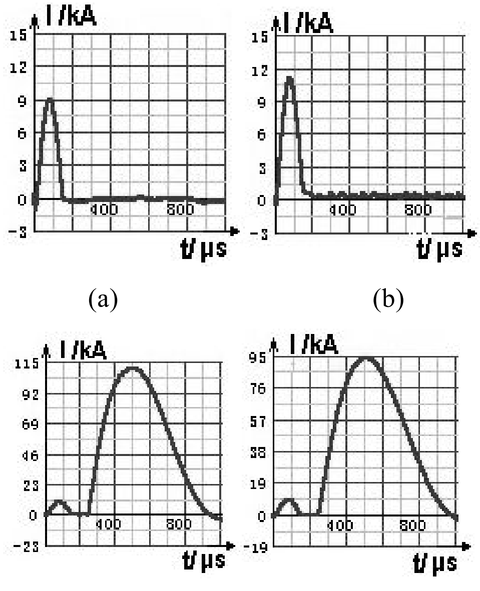
5.2 Measurement Results

Some researches indicate that the maximal durations of the pulse currents including both the preionization loop and the primary discharge loop are longer than100µs. For the outer-integrating coils, the integrating time constant, τ_{outer} , and the rise time, $t_{r\text{-}outer}$, can be calculated below.

$$\tau_{outer} \square RC=1000\mu s \tag{10}$$

$$t_{r\text{-}outer} \approx 2.14\sqrt{L_0 C_0} \approx 6.3\mu s \tag{11}$$

Fig.7 shows the measurement results of both preionization and primary discharge loops. Figure (a) of Fig.7 shows the pulse current waveform of No.9 xenon lamp of the Preionization Loop, whose duration is 120µs, and current peak value is 8.9kA. Figure (b) of Fig.7 shows the pulse current waveform of No.7 xenon lamp of the Preionization Loop, whose duration is 140µs, and current peak value is 11.1kA. Waveform of No.6 xenon lamp of the Primary Discharge Loop is illustrated in figure (c) of Fig.7, whose duration is 600µs, and its current peak value is 110.4kA.Waveform of No.4 xenon lamp of the Primary Discharge Loop is illustrated in figure (d) of Fig.6, whose duration is 640µs, and its current peak value is 92.5kA. Comparing with the computing results, the measurement results are accurate and reliable. The fiber-optic current measurement instrument has been successfully applied to measure the high-power high-voltage laser source in the Pulse Power center of Huazhong University of Science & Technology for more than two years.



(a) (b)

(c) (d)

Fig.7 Measurement results of currents of both preionization and primary discharge loop

Conclusions

The presented method based on the Rogowski coil detector and optic fiber transmission can give good performance to meet an engineering demand for measuring the PSM of the high-voltage high-power laser source. And the measurement results compared with the computing results are accurate and reliable.

The fiber optical pulse current measurement instrument possesses both analog and digital signal outputs. It is not only suitable for existing conventional meters, but also can be fitted to digital meters with appropriate improvements. The instrument system has the following advantages: inherent electrical isolation; compact and light weight construction; reduced installation and engineering costs; improved personal safety; no saturation effects, no resonance; unlimited bandwidth; required light power for the transmitter < 5 mW.

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