Temperature characterisation of an optically-interrogated Rogowski coil

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ABSTRACT

An investigation into the performance of an optically-interrogated Rogowski coil over temperatures up to 80 °C is presented. Preliminary thermal tests reveal that the sensor response is temperature-dependent and the measurement errors are increased at higher temperatures. Compensation of temperature effects is, therefore, necessary in order for the sensors to meet the requirements of protection and metering classes specified by relevant IEC standards over the considered operating temperature range. This can, however, only be achieved when the utilised sensor interrogator is adapted to ensure sufficient resolution and accuracy from a generally low-output transducer. As such, the design of a new multiplexing, interferometric interrogation platform is also proposed in this paper.

Key words: Rogowski coils, optical voltage sensor, fibre Bragg gratings, piezoelectric transducer, protection, metering.

1. INTRODUCTION

Rogowski coils, as an alternative to conventional current transformers (CTs), are widely used in electrical power systems for measuring and protection purposes due to their linear response and the ability to measure very large currents. Since the coils are wound on non-magnetic cores, their mutual inductance is low; hence, the output voltage generated in response to the primary (measured) ac current is also very low. Additionally, since the output voltage of the coil is proportional to the rate of change of the primary current, it must be integrated to recover the measured current. This is usually realised using electronic integrator circuits requiring the provision of electrical power at the coil location which limits their long-distance interrogation. The sensitivity to EMI and other environmental factors can also significantly contribute to measurement errors.

To enable the long-distance interrogation of Rogowski coils, the concept of an optically-interrogated Rogowski coil (ORC) has been recently proposed by the authors[1]. The ORC is formed by connecting an optical low voltage sensor, utilizing a piezoelectric stack transducer and a fibre Bragg grating (FBG), to the Rogowski coil output[1,2]. It requires purely optical interrogation to obtain the primary current measurements, and it has been shown that remote and passive monitoring of the coils by a high-resolution interrogation system is possible[1]. It has also been demonstrated at room temperature that the optically-interrogated Rogowski coils have the potential to ensure conformance with the 5P protection and 0.5 standard classes specified by relevant IEC standards[2,3], with amplitude and phase errors around 0.1 % and 0.1 ° achieved, respectively.

However, a number of parameters such as the piezoelectric stack resistance, capacitance or voltage-induced displacement are dependent on the temperature and voltage levels the components are subject to. Since the low-voltage sensor is used as a burden for the Rogowski coil output, all these parameters influence the performance of the ORC sensor and detailed investigation into the piezoelectric stack performance at different temperature and voltage levels is required to ensure that the sensors are capable of complying with relevant standards over the specified temperature range. In this paper, the preliminary temperature characterisation of the optical sensor is presented and methods for realising temperature compensation are proposed that make use of stable photonic integrated circuit platforms.

2. OPTICALY-INTERROGATED ROGOWSKI COIL

A new-generation low voltage stack (P-885.91 PICMA® from Physik Instrumente Ltd (PI)[4]) comprising fused piezoelectric layers was utilised in this study to monitor the output of a commercially available Rogowski coil producing approximately 1V at a 50 Hz primary current of 1 kA. The stack has a square cross-section profile and a length of 36 mm formed by the parallel connection of 600 layers of 60 µm thickness. It has a maximum ac operating voltage of 30 V_{pk} (21.21 V_{rms}), acapacitance of 3.1 µF, and a resistance of over 100 MΩ. The stack was protected against overvoltage conditions by a 30 V transient voltage suppression (TVS) diode to avoid depolarisation and degradation. A standard 5 mm FBG with a central wavelength of 1550 nm was epoxied to the piezoelectric material using high temperature adhesive (EPOTEK 353ND). Providing that there is no mechanical stress in the piezoelectric material, the strain (i.e. relative elongation $\Delta l / l$) induced by an external electric field is given by $\varepsilon = d_{33} \cdot E = d_{33} \cdot V/l$ where d_{33} is the longitudinal piezoelectric charge constant, E is the electric field, V is the voltage applied across the piezoelectric material and l is the length of the material. A relative change in the FBG peak wavelength, $\Delta\lambda_B/\lambda_B$, due to a change in strain, $\Delta\varepsilon$, and temperature, ΔT, can be expressed by $\Delta\lambda_B/\lambda_B = C_\varepsilon \cdot \Delta\varepsilon + C_T \cdot \Delta T$, where C_ε and C_T are the strain and temperature sensitivities. Thus, voltage (or current) and temperature can be measured with a single device.

Due to the low voltage output of the coil, a high-resolution optical interrogator utilizing an unbalanced Mach-Zehnder interferometer (MZI) formed between 2×2 and a 3×3 single-fusion couplers with a ratiometric output configuration (Figure 1) was employed in this study[1,2,5-7]. The phase difference ϕ between MZI paths is related to the input optical wavelength λ (in this scheme the reflected Bragg wavelength) by the expression: $\Delta\phi=2\pi nd/\lambda$, where n is the MZI core index, d is the physical path difference, and nd is defined as the optical path difference (OPD)[6]. The corresponding voltage on the photodetector outputs, V_{1-3}, can be expressed as a function of phase change $\Delta\phi$. The longitudinal strain in the grating, $\Delta\varepsilon$, is related to the change in the phase difference between MZI paths, $\Delta\phi$, by the expression: $\Delta\varepsilon=\lambda\Delta\phi/2\pi nd\zeta$, where λ is the Bragg wavelength and $\zeta = (\delta\lambda/\delta\varepsilon)/\lambda$ is the stress-optic coefficient (0.78×10^{-6} $\mu\varepsilon^{-1}$)[6]. The change in wavelength can be calculated from the change in phase by $\Delta\lambda=\lambda^2\Delta\phi/2\pi nd$, which for an FBG having a central wavelength of 1550 nm and at the OPD of 3 mm can therefore be calculated by the relationship $\Delta\lambda=127.45$ pm/rad·$\Delta\phi$.

3. TEMPERATURE CHARACTERISATION

During ORC characterisation, the voltage sensor was connected to the Rogowski coil output as a burden, and both components were placed in the oven (Figure 1). The oven temperature was increased in steps of approximately 10 °C from room temperature to 80 °C. An ac current source (APTS3 power amplifier, Relay Engineering Services Ltd.) supplied primary current to the coil. Voltage waveforms generated using the PXI unit (National Instruments) were converted to the current waveforms by the amplifier with a gain of 5 A/V, and comparison of the input and output signals of the coil was realised by monitoring voltage across a 0.1 Ω shunt resistor connected to the primary circuit.
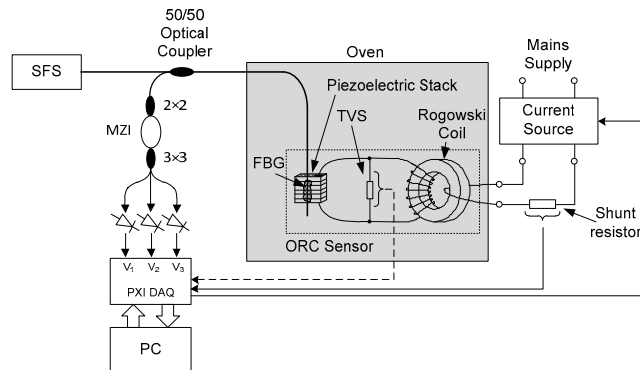

Figure 1. Circuit diagram for the ORC calibration and testing procedure.

As the shunt resistor limited the maximum primary current to 20 A, 50 turns of primary conductor were wound around the coil cross-section and along its circumference to allow the coil to measure currents up to 1 kA, producing approximately 1 V on the coil output. To characterise the optical voltage sensor within a wider voltage range, the

piezoelectric transducer was disconnected from the coil and an ac voltage source was additionally used to supply voltage up to 5 V_{rms} across the stack. During the experiments, the voltage sensor was optically connected to the interrogator employing the MZI and illuminated by a super fluorescent source (SFS). The optical signals reflected from the sensor were converted to electrical signals by three photodetectors (PDs) connected to the MZI. The outputs of the PDs together with the reference voltage were captured by the PXIe data acquisition unit and processed in a PC. The data acquisition and generation rates were set to 100 kS/s. The recorded data was then analysed using another LabVIEW program that plotted the recorded waveforms against each other and calculated the phase displacement (error) between the signals.

Hysteretic behaviour of the low voltage sensor can be clearly seen in Figure 2 (a) where the ac FBG peak wavelengths are plotted against the ac voltages applied to the stack at room temperature. The width of hysteresis increases when the voltage magnitude increases. The hysteresis also rotates slightly with the voltage magnitude increase. Figure 2 (b) compares hysteresis at 5 V_{rms} at two extreme temperatures from the considered temperature range. Slight rotation of the hysteresis accompanied by small change in its width can be noted. The change in amplitude is approximately 7% (Figure 2 (b)). Figure 3 shows phase errors as a function of applied voltages or current at different temperatures.
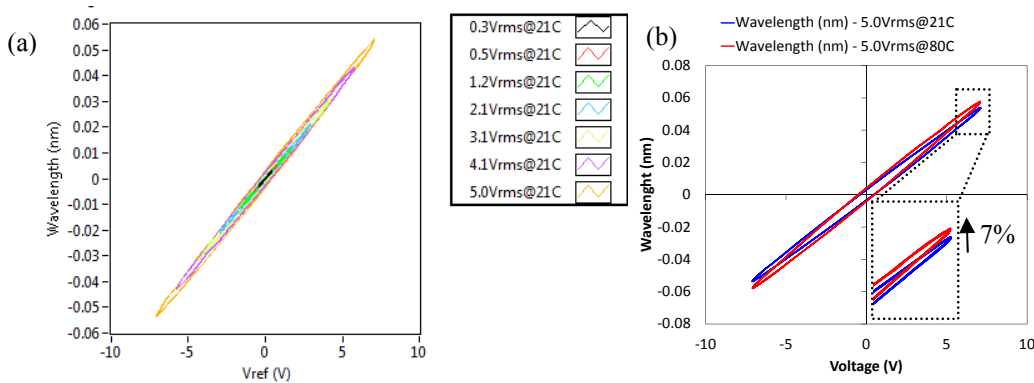

Figure 2. Hysteresis loops for the sensor subjected to: (a) various voltages at room temperature; (b) 5 V (rms) at temperatures of 21 °C and 80 °C.
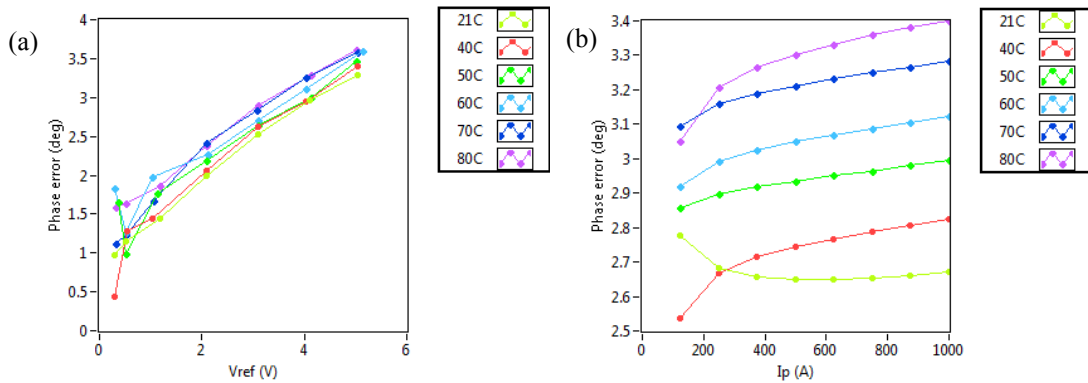

Figure 3. Phase errors for the low voltage sensor (a) and for the Rogowski coil (b) for different reference voltages and primary currents at temperatures between 21 °C and 80 °C.

The phase displacement introduced by the voltage sensor increases almost linearly with an increase in the voltage magnitude. The sensitivity of the phase displacement to voltage and temperature is around 0.5°/V and 0.01°/°C, respectively, and the phase displacement introduced by the coil increases with current almost linearly. The sensitivity of the phase error to current is around 0.2°/kA. The phase error increases with temperature and the sensitivity of the phase error to temperature is around 0.01°/°C. The total phase error will be a combination of the errors introduced by the Rogowski coil and the voltage sensor.

3. DISCUSSION

From the above experiments it is clear that to minimise phase displacements between input and output signals of the ORC, and to therefore comply with relevant IEC standards, temperature compensation will be required. One of the possible solutions is to implement a combined hysteresis and temperature compensation method previously proposed by the authors for the hybrid FBG-piezoelectric voltage transducer[8]. Since the ORC is used to measure ac current, the local temperature can be recovered using time-domain discrimination between the quasi-static and dynamic FBG wavelengths using low-pass filtering. Knowing the thermal behaviour of the sensor, electrical current measurements can be corrected using this local temperature information. This, however, can be realised only when the MZI-based interrogator is stable and accurate. To improve the interrogator accuracy, more advanced system modifications have recently been proposed by the authors[9]. An initial laboratory embodiment achieves a stability of 20 pm (1.6 °C). Further work on improving of the system stability to temperature fluctuations, vibration and polarization instability by implementing the interrogation system on a photonic integrated circuit format (e.g. silicon or InP) is currently underway. This hardware advance, combined with the proposed temperature compensation technique, will have the potential to enable the ORC sensor to meet relevant IEC accuracy classes over the full conventional operating temperature range.

4. CONCLUSIONS

In this paper, an investigation into the performance of an optically-interrogated Rogowski coil at temperatures of up to 80 °C has been presented. Preliminary thermal tests have shown that the sensor response is temperature-dependent and the measurement errors are increased at higher temperatures. The need for compensation of temperature effects has been identified and a combined hysteresis and temperature compensation method has been proposed in order for the sensors to meet the requirements of protection and metering classes specified by relevant IEC standards over the considered operating temperature range. This can be achieved by improving interrogator stability to ensure sufficient resolution and accuracy. Future work will concentrate on implementing the existing MZI architecture on a photonic integrated circuit platform with hysteresis and temperature compensation of the transducer; allowing this device to meet relevant IEC accuracy classes over full standard operational temperature ranges.

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