Power frequency AC voltage measurement based on double wound Rogowski coil

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Abstract: This study presents a technique for power frequency AC voltage measurement. The proposed technique utilises a capacitor having a low capacitance in addition to a double wound Rogowski coil. This technique depends on capacitor current measurement using the double wound Rogowski coil. The voltage across the capacitor that connected in parallel with the system at which AC voltage is intended to be measured is reconstructed. The proposed technique is experimentally evaluated by designing the measurement system and using a digital signal processing board for the reconstruction processes. Moreover, the experimental results based on Rogowski coil measurements are compared with those obtained from reference techniques. Finally, the obtained results validate the efficacy of the proposed technique in power frequency AC voltage measurement.

1 Introduction

Rogowski coil is an air-cored toroidal fashion coil that operates on a simple principle [1]. The induced coil voltage in the coil due to time varying magnetic field produced by the current to be measured is proportional to the rate of change of this current. The coil induced voltage is processed by several techniques [2–13] in order to reconstruct the current to be measured. Integration, either numerical [5–7] or analogue [2–4], is the most common reconstruction technique that rose from the fact of the Rogowski coil performance as a differentiator at low frequencies. There are also other techniques used for current reconstruction such as transfer function estimation [5], model-based transfer function [8, 9], fitted inverse transfer function [9–12], and differential reconstruction method [13].

In fact, Rogowski coil becomes a popular technique for both measuring and protective devices in power frequency applications [5, 7, 14]. It does not suffer from the saturation problem such as the conventional current transformers [5, 13] in addition to lower cost and weight. All these advantages lead to a spread in utilising this coil especially; modern relays do not require high power current transducers and allow applications of low power current transducers. Partial discharge (PD) detection is also one of the most important applications that Rogowski coil is used [15–18]. Hence, it is integrated with computational techniques to detect the location of PD in power lines that use covered conductors or cables with the advantages of low cost and ease of installation. Recently, Rogowski coil is used in other applications such as fault diagnosis in DC–DC converters to detect the faults occur in the power electronic switch [19] and to detect the short circuit current in DC supply system [20, 21].

Although, Rogowski coil has all these promising advantages, it is not used for power frequency AC voltage measurement. One of the most common methods used for power frequency high AC voltage measurement is the use of voltage transformers (VTs) [22–24]. VT contains an iron core that suffers from saturation, and adding an extra weight and cost to this measurement system. Also, with the measurement of high AC voltage, VT is connected via a capacitive divider to reduce the voltage stress on the primary winding. In this case, a compensation inductor is connected at the VT input in order to reduce the measurement errors [22, 25].

Considering the advantages of Rogowski coil, this paper presents a proposed technique for measuring power frequency AC voltage using a low capacitance in addition to a double wound Rogowski coil. The proposed technique depends on capacitor current measurement using the double wound Rogowski coil. The voltage across the capacitor that connected in parallel with the system at which AC voltage is intended to be measured is reconstructed. The proposed technique is experimentally evaluated, using power frequency AC low voltage, by designing the measurement system and using a digital signal processing (DSP). Moreover, the experimental results based on Rogowski coil measurements are compared with those obtained from reference techniques in order to validate the efficacy of the proposed technique in power frequency AC voltage measurement.

2 Double wound Rogowski coil

Fig. 1a shows a schematic diagram for the double wound Rogowski coil. It consists of double windings. The inner one (secondary winding) has a large number of turns, however, the outer winding (primary winding) has low turns. Both windings are wound on a non-magnetic core in the form of a toroidal winding. The reason behind double winding utilisation is to increase the mutual coupling (mutual inductance) between the primary and secondary windings in order to increase the sensitivity of power frequency AC current in the range of mA. The increase in mutual coupling between primary and secondary windings with the use of double windings is validated by using finite element (FEM) analysis method (see the Appendix). A coil having primary winding of 125 turns and secondary turns of 800 is simulated using FEM magnetic package with the dimensions shown in Figs. 1a and b. Another traditional coil with the same dimensions of Fig. 1, having only one winding acts as a secondary winding and a conductor carrying current at its axis acts as a primary winding, is also simulated. The primary winding and the axial conductor are injected with a current in the order of milliamperes (mA) (30 mA). In fact, in the case of using only single winding, the number of secondary turns should be increased to more than eight times the double wound coil to achieve the same mutual inductance which is the main key in determining the coil sensitivity. Therefore, using a double wound Rogowski coil results in a great reduction in the number of coil turns and of course its volume and cost.

Fig. 2 shows the equivalent circuit of the double wound Rogowski coil with lumped parameters that can be adopted with power frequency applications. The induced voltage in the secondary winding \( e(t) \) can be computed from [1]:

\[
e(t) = -M \frac{di_p}{dt}
\] (1)
is very small, the induced emf is calculated from (2) to minimise the errors as explained in the next sections.

\[ e(t) = L_s \frac{dV_o}{dt} + R_s \frac{dV_o}{dt} + V_o \]  

(2)

3 Proposed sinusoidal current reconstruction technique

Numerical integration technique is one of the well-known current reconstruction techniques. This method requires a data acquiring system of high precision and speed [9]. Therefore, an alternative current reconstruction technique is introduced in this paper.

Considering a sinusoidal waveform is integrated. This integration will result in another sinusoidal waveform delayed by 90° at another amplitude (i.e. integration of \( \cos \)) results in \( \sin \). Therefore, the adopted current reconstruction method is shown schematically in Fig. 3 and can be discussed as follows:

- The induced emf in the secondary winding of the Rogowski coil is first filtered using a low-pass digital filter to reduce the effect of external noise that appears as loaded high-frequency components.
- The filtered sinusoidal emf waveform is delayed by 90° and divided by \( \omega \), resulting in its integration and the division of this integration by \( \omega \), resulting in the reconstructed current.

For more illustration, consider the primary current that wanted to be measured has the following form:

\[ i_p = I_{pm} \sin(\omega t + \phi) \]  

(3)

where, \( I_{pm} \) is the maximum current in A and \( \phi \) is its phase angle in radian.

The fundamental component of the induced emf in the Rogowski coil secondary winding can be computed from (1). Therefore, it can be written as:

\[ e(t) = -MI_p \cos(\phi + \omega t) \]  

(4)

If the emf \( e(t) \) is multiplied by \((-1)\), delayed by 90° and divided by \( M_{o} \), it will be equivalent to the primary current.

In fact, this reconstruction technique is applicable to power frequency AC sinusoidal current. This reconstruction technique succeeds in reconstructing primary current after only one quarter of the cycle (i.e. 5 ms for 50 Hz frequency). The reconstruction time for the proposed technique is shorter if compared with numerical integration or digital Fourier transform methods [5] that
are used to reconstruct the primary current. Hence, the reconstruction time using these methods can reach 18.3 ms.

4 Proposed AC voltage measurement system

The proposed measurement technique depends on utilising a small capacitance \( C \), to have a negligible effect on the system reactive power, in parallel at the terminals at which the voltage is intended to be measured. The current passing through the capacitance is measured by using the double wound Rogowski coil by connecting its primary winding in series with it as shown in Fig. 4. To measure the capacitance current \( i_c \) which is equal to the Rogowski coil primary current, the induced emf in the secondary winding is computed from (2). Then, the proposed technique discussed in Section 3 is applied, using a DSP, to reconstruct \( i_c \).

Using the reconstructed capacitance current \( i_c \), capacitor \( C \) voltage that is equal to \( V_c = (1/C) \int i_c \, dt \) can be reconstructed using the DSP-board by applying the same technique presented in Section 3. Hence, the reconstructed capacitance current \( i_c \) is delayed by 90° and the delayed signal is divided by \( 1/\omega C \). In fact, another delay by one quarter of a cycle is achieved. This means that the proposed measurement technique successes in capacitor voltage reconstruction after only one half of the cycle (i.e. 10 ms for 50 Hz frequency). This is still acceptable as it is smaller than one cycle.

Finally, the voltage to be measured \( V_m \) is reconstructed, using the DSP-board, by applying (5) to take the voltage drop in the Rogowski coil primary winding into consideration in order to minimise the error. The computation process is schematically clarified in Fig. 5.

\[
V_m = V_c + R_p i_c + L_p \frac{di_c}{dt}
\]

5 Implemented double winding Rogowski coil and experimental setup

A double winding Rogowski coil is designed as shown in Fig. 6 with the dimensions shown in Fig. 1. It contains an internal secondary winding of 800 turns and an external primary winding of 125 turns. The winding pitch used for both windings is equal to 0.25 mm. These windings are wound on a non-magnetic PVC core with a mean diameter of 4.5 cm and a cross-section of 2 cm × 1 cm. The lumped parameters of the coil are measured and their values are recorded in Table 1. The resistances of both windings are measured using an ohmmeter, but self inductances are measured by AC voltage (50 Hz) injection to each coil. The phase shift between the injected voltage and current is recorded by using an oscilloscope as well as the coil impedance is determined by dividing the R.M.S. values of the injected voltage and current. Coil reactance is computed and of course coil inductance. With respect to mutual inductance measurement, the primary winding is injected by a 100 mA AC current (50 Hz), the maximum value of the induced emf in the secondary winding \( E_m \) is recorded and the mutual inductance \( M \) is calculated from:

\[
M = \frac{E_m}{\frac{di_p}{dt}}
\]
input to a DSP-board model dspace1104 with a sampling rate of 10 kHz. The input signal is digitally processed as described in Section 3 to reconstruct the primary current. The reconstructed primary current is compared with a reference signal obtained by measuring the voltage signal on a 1 Ω resistance to evaluate the measurement accuracy.

Fig. 7 shows the experimental setup used for coil evaluation in power frequency AC low voltage measurement. It is the same setup of Fig. 7 except the function generator is replaced by 400 V, 50 Hz AC variac connected with the proposed voltage measurement system of Fig. 4 in addition to utilisation of the prescribed voltage reconstruction algorithm. The reference signal here is obtained by using a standard voltage transducer (VT) of a ratio (220/6 V/V).

6 Frequency response of the coil

In this section, frequency response of the double wound Rogowski coil is investigated. The investigation is carried out considering four cases; without using terminal resistor or capacitor, using terminal capacitor of 47 µF, using terminal resistor of 10 Ω, and using terminal resistor of 1 Ω. Figs. 8a and b show the frequency response of the double wound coil considering the measured parameters listed in Table 1. Fig. 8a shows the frequency response considering the following transfer function [23].

\[
\frac{V_o(S)}{I_p(S)} = \frac{MS}{L_p C_s S^2 + R_p C_s S + 1} 
\]  

(7)

where, \(V_o\) is the measured voltage across the terminal capacitor (\(C_t\)). It is worth to mention that \(C_t\) is taken as 220 nF [28] when no terminal components are used. From this figure, using terminal capacitor gives a higher output voltage magnitude at low frequencies as compared with the use of terminal resistor as well as providing the best reduction for high-frequency components as previously stated in Section 2. Also, terminal capacitor results in 90° (approximately) phase shift with the primary current. This is desired as discussed before in Section 3.

Fig. 8b shows the frequency response considering the relation between terminal \((V_o)\) and measured \((V_m)\) voltages as expressed in (8). The same conclusion of Fig. 8a is achieved.

\[
\frac{V_o(S)}{V_m(S)} = \frac{MS}{L_p C_s S^2 + R_p C_s S + 1} \cdot \frac{C_s}{L_p C_s + R_p C_s + 1} 
\]  

(8)
7 Experimental evaluation of double wound Rogowski coil for mA current measurement

Based on the experimental setup of Fig. 7a, Fig. 9a shows the reconstructed sinusoidal primary current waveform (indicated by the dotted line) and the reference primary current waveform (indicated by the solid line) which measured by using a 1 Ω series resistor. As illustrated from this figure, the error in the peak value of the reconstructed current as compared with the reference value is about 0.48% and the error in phase angle is recorded as 0.18°. As indicated from these figures, the double wound Rogowski coil can be used for mA current measurement with a good accuracy. This reduced phase error comes as the reconstruction algorithm takes the induced emf (indicated by the black line of Fig. 9b) into consideration. For more evaluation, the coil is tested with another sinusoidal primary current has a different amplitude as shown in Figs. 9c and a good performance is achieved. Also, Table 2 summarises the errors in amplitude and phase at different primary current values. Accordingly, coils with double windings and increased number of turns are suitable for monitoring power frequency AC mA current measurements. This feature can be used to measure a current passing through a small capacitance connected in parallel at the terminals at which voltage is intended to be measured. Then, capacitor voltage is calculated using signal processing as discussed before and as evaluated in the next section.

8 Experimental evaluation of double wound Rogowski coil for power frequency AC low-voltage measurement

In this section, evaluation of double wound Rogowski coil in power frequency AC low voltage measurement is done as an indication for its validity at different voltage levels. The experimental setup of Fig. 7b and the computation technique shown schematically in Fig. 5 were applied. Fig. 10a shows the reconstructed sinusoidal voltage waveform (indicated by the dotted line) and the reference waveform (indicated by solid line) which measured by using a 220/6 V/V VT. Also, Fig. 10b shows Fourier transform of the voltage waveforms. From these figures, magnitude and phase errors are within acceptable limits (0.91% and 0.52°) as well as harmonics due to Rogowski coil measurement have reduced effects. Fig. 11 shows the same results of Fig. 10 but at another voltage level and the same conclusions are achieved. Also, all the carried measurements at different voltage levels validate the good performance as illustrated in Table 3. Finally, it is worth to mentioning that the reactive power injection to the AC source due to the measurement capacitor is of negligible value (approximately 1.38 VAR) that gives a promise to be used in AC high voltage measurement.

9 Conclusions

Power frequency AC voltage measurement sensor based on a double wound Rogowski coil and a small capacitance has been presented. Proposed current and voltage reconstruction techniques have been introduced. The proposed measurement system has been experimentally evaluated either in mA power frequency AC current or power frequency AC low voltage measurements. The obtained experimental results have been compared with measured reference signals. A good accuracy of the measurement system in magnitude, phase and harmonic contents has been found. Also, the reactive power injection to the AC source due to the measurement capacitor has been calculated. It has been found to have a relatively small value. Finally, the efficacy of the proposed measurement system design has been theoretically and experimentally validated.

Table 2 Amplitude and phase errors in measured primary currents

| R.M.S primary current, mA | % amplitude error | Phase error, degree |
|--------------------------|-------------------|---------------------|
| 295                      | 0.48              | 0.18                |
| 260                      | 0.52              | 0.18                |
| 245                      | 0.53              | 0.19                |
| 140                      | 0.61              | 0.22                |
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Table 3 Amplitude and phase errors in measured voltages at different levels

| R.M.S. measured voltage, V | % amplitude error | Phase error, degree |
|---------------------------|-------------------|---------------------|
| 100                       | 0.91              | 0.52                |
| 80                        | 1.15              | 0.57                |
| 60                        | 1.67              | 0.98                |
11 Appendix

11.1 FEM analysis

Figs. 12 and 13 show the flux density distribution for single and double wound Rogowski coil at 30 mA current injected in its primary, respectively. These figures show that a higher flux density is achieved with the double wound coil at the same value of injected current. This means a higher flux linkage and therefore, a higher mutual inductance as described in Section 2. Hence, the mutual inductance between the primary and secondary windings of the double wound Rogowski coil is found to be 194 µH. However, for the single winding coil it is found to be 24 µH.