Design Improvements of the Resistive Shunt Online Impedance Analyzer

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Abstract—Power Line Carrier Communications (PLC) is often used for SmartGrid Communications. To design efficient PLC couplers, the impedance of the power line must be known. The Resistive Shunt Impedance Analyzer (RSOIA) allows such impedances to be measured. This paper describes the design and calibration improvements of an updated RSOIA, which can accurately measure conventional on-line impedances and transfer functions as well as sub-mains-cycle on-line impedance and transfer function variations in the 4 kHz to 20 MHz frequency range. Examples of these measurements are shown.

Index Terms—On-line impedance analyzer; On-line transfer function analyzer; PLC; Resistive Shunt; PLC Coupler; Power Line Impedance; Mains related impedance variation.

I. INTRODUCTION

SmartGrid Communications are being rolled out for meter reading and demand side management. In Europe and China, the SmartGrid communications are done using PLC [1], [2]. PLC is also used inside houses for Ethernet over powerlines, using HomePlug [3]. In order to design efficient and low loss PLC couplers [4] for these applications, the impedance of a power line and its connected load needs to be known. The first version of the Resistive Shunt On-line Impedance Analyzer (RSOIA) was introduced in [5]. The second version is described in this paper; it allows on-line impedance and transfer function measurements as well as sub-mains-cycle impedance and transfer function measurements to be made. The impedance measurements have an accuracy comparable with commercial (offline only) impedance analysers [6].

Most impedance analyzers operating below 20 MHz use the basic circuit of fig. 1 to determine the impedance. The impedance is evaluated using (1). For best accuracy, the magnitude of R and Z should be approximately equal. Since typical powerline impedances range from 0.5 Ω to 200 Ω, a value of 11.2 Ω is used in the RSOIA hardware.

\[ Z = \frac{V_b}{I} = \frac{V_b}{V_a - V_b} R \] (1)

For measuring impedances that are connected to mains voltages, the mains voltage needs to be filtered out from the measurement equipment to firstly prevent damage and secondly provide a suitable signal to mains-noise ratio for accurate measurements. At higher frequencies, S parameter measuring instruments can also be used to determine impedances. For S parameter on-line measurements, the mains voltages can be suppressed sufficiently using a capacitor.

However, a capacitor, being a first order high pass filter, does not give sufficient mains voltage isolation below 1 MHz and higher order filter networks are required. As a result, the third order Butterworth like high pass filters with a cut-off frequency of 10 kHz, shown in fig. 2, is used in the RSOIA to remove the mains frequency from the signal generator and voltage measurements in fig. 1.

![Figure 2](image-url) 

Figure 2. High pass isolating filter for current sensor and signal injection.

II. CURRENT AND VOLTAGE SENSING

Since \( V_a - V_b \) can be very small, the quantization noise of the individual digitized voltages may dominate. To avoid this, the current \( I \) is evaluated by measuring the differential voltage across \( R \), using the circuit in fig. 2 for the current sensor.
The isolation transformer of the filter of fig. 2 provides electrical isolation and allows these small difference voltages to be obtained accurately. Its magnetizing inductance is the inductance required for the high pass filter. Any real transformer will include some leakage inductance and there will be some coupling capacitance $C_{tp}$ between the windings of the isolation transformer. Those secondary effects are included in fig. 2. Since one side of the secondary winding of the isolation transformer is earthed, the winding capacitance causes a capacitive loading across $V_a$, which can change $V_a$ at high frequency, depending on the impedance of the source connected to it. To overcome this, a special high input impedance, differential amplifier is used in this latest RSOIA to improve the high frequency accuracy.

The voltage sensor $V_b$ provide similar mains frequency filtering to the current sensor, to prevent damage to the ADC and provide a suitable signal to noise ratio for accurate measurements. High-speed operational amplifiers are used to provide the mains isolation. A Sallen-Key high pass filter is used for the voltage sensor and computer optimization is carried out to match the frequency response of the current and voltage sensors to $0.01\text{dB}$ from 1 kHz to 10 MHz [5].

Computer simulations of these equations show that when the sampled time $T$ is exactly a whole number of mains cycles, then perfect mains rejection is obtained. For a 12 bit ADC, a 1% timing error in $T$ and with a mains voltage $A_2$ that is 100 times bigger than the wanted signal $A_1$, results in an amplitude error that is $<0.0018\%$ and a phase error that is $< 0.0005^\circ$. This algorithm is thus very noise tolerant and produces extremely accurate results. This correlation algorithm is incorporated in the LabView software [7] that controls both the Inductive Shunt Impedance Analyzer [8] and the RSOIA.

IV. SIMULATION AND CALIBRATION

The whole impedance analyzer block diagram of fig. 3 is simulated, using ideal isolation transformers and operational amplifiers. Different mains impedances are simulated and the resulting performance is shown in fig. 4. The high pass filters in the current and voltage sensors, track perfectly below 10 kHz and as a result impedances can be calculated accurately down to 1 kHz. A full spice simulation of the RSOIA for a frequency range of 1 kHz to 10 MHz shows that the fundamental measurement error, without any calibration, is better than 0.1% for impedances of 0.1 Ω to 100 kΩ.

III. DIGITAL SIGNAL PROCESSING (DSP)

The voltage waveform at the output of a sensor is:

$$A(t) = A_1 \sin(\omega_g t + \theta_1) + A_2 \sin(\omega_m t + \varphi_m)$$

Where $\omega_g$ is the signal generator frequency and $\omega_m$ is the mains frequency. $A_1$ and $\theta_1$ are the sensor output amplitude and phase and $A_2$ and $\varphi_m$ is the mains voltage amplitude and phase appearing at the sensor output. These signals are sampled in ADC’s, over a whole number of mains cycles. In the DSP algorithm, this waveform is multiplied in the software by sine and cosine waveforms that are the same frequency as those generated by the signal generator. The resulting correlation and extraction of the magnitude and phase is described in [7].

The internal wiring of a real impedance analyzer has some series inductance and shunt capacitance associated with it. Fig. 5 shows the circuit that best matches this stray short circuit inductance and open circuit capacitance. Commercial impedance analyzers include open and short circuit calibration procedures to correct for these stray impedances. In addition, real current and voltage sensors will have a slightly different gain than their design value and the respective high pass filters may have a slightly different frequency response than designed. These variations can be calibrated for by measuring an accurate
“reference” resistor $Z_r$. Using the reference resistor, open circuit and short circuit measurements, 3 simultaneous equations can be solved for all the measurement frequencies to obtain the actual sensor gain ratio and correct for the open circuit and short circuit impedances in the measurements. $Z_u$ is the unknown impedance to be measured. The measurement with the reference resistor $Z_r$, results in a voltage sensor output $V_{vr}$ and current sensor output $V_{ir}$ and the resulting measured sensor voltage ratio, $M_r$ is given by:

$$M_r = \frac{V_{vr}}{V_{ir}}$$

Similarly, the open circuit and short circuit measurements result in the sensor voltage ratios $M_{oc}$ and $M_{sc}$ respectively. These sensor voltage ratios are arrays, with each value in the array corresponding to a measurement frequency. These sensor voltage ratios are complex numbers since both magnitude and phase or real and imaginary parts of the sensor ratios are measured. These sensor voltage ratios are used to calculate the *Gain* of the voltage sensor to the current sensor to give an impedance and the open circuit $Z_{oc}$ and Short circuit $Z_{sc}$ impedances for each of the measured frequencies. For the RSIOA hardware $Z_r$ is a surface mount 15 $\Omega$ resistor. $Z_u$ is the resulting measured impedance. $M_u$ is the measured sensor voltage ratio for the measured impedance.

$$Gain = \frac{(M_{oc} - M_{sc})(M_r - M_{sc})}{Z_r(M_{oc} - M_{sc})}$$

$$Z_{oc} = M_{sc} \frac{M_{oc}}{Gain} \text{ and } Z_{sc} = \frac{M_{sc}}{Gain} \quad (5, 6)$$

$$Z_u = Z_{so} \frac{M_u - Gain Z_{sc}}{Gain(Z_{sc} + Z_{oc}) - M_u}$$

The LabView software controlling the RSOIA is shown in fig 14 of [5]. The above equations are incorporated in the latest version of that software and they are used for the measurements presented in this paper, providing a better accuracy than the results presented in [5].

## V. HARDWARE

Fig. 6 shows the prototype hardware of the latest version of the RSOIA analyzer hardware. This version includes 2 voltage sensors, so that on-line transfer functions can be measured as well as on-line impedances. The signal injector is on the left, the current sensor is next to that and the two voltage sensors are on the right of the hardware. For electrical safety and low inductance, 1 kV rated banana safety sockets are connected directly to the PCB. To allow the equipment to operate from a 12V battery, a single 12V supply is required to power the RSOIA. The ADC shown in fig. 6 underneath the RSOIA hardware is a PicoScope 5444B. This incorporates 4 ADCs with an 80 MHz bandwidth and a 20 MHz signal generator.

Fig. 7 shows the impedances measured for a set of resistors using the RSOIA hardware. This plot also includes measurements made of the same resistors using a commercial Hioki [6] impedance analyzer. That impedance analyzer cannot measure impedances while they are on-line and as a result, it is able to measure impedances down to 42 Hz. The decrease in impedance at high frequency and high impedance corresponds to a 0.045 pF uncorrected terminal capacitance of the analyzer and test fixture. Similarly, the measured impedance of a 0.01 $\Omega$ resistor rises at high frequency due to an uncorrected 1.9 nH residual lead inductance. That corresponds to about 2 mm of wire length. A superb measurement accuracy can thus be achieved with the calibration techniques.

## VI. MEASUREMENTS

### A. Online Impedances

To investigate on-line impedance variations, different loads were applied to a power point in the author’s home office and at the University of Adelaide. Fig. 8 shows those measurements. Green curves are the impedance of the reference network of EN50065-1 [9] and the average results from Malack [10]. The red curves are measurements made at The University of Adelaide. The Power Lab power-point or general purpose...
outlet (GPO) 3 curve is a measurement of a 20 Amp socket with no other GPOs on that circuit. The Power Lab GPO 1 curve is a measurement of a 15 Amp socket with several other GPOs and equipment connected, on that circuit. The research area desk is a power-point in a research area with many desks, each with a computer and monitor, connected to that circuit. The blue curves are measurements made at the author’s home office. For the no load curve, all the office equipment is powered from a different circuit using an extension lead. For the load curve, that equipment is powered from the power-point that is measured. The impedance of a GPO that has much equipment connected is much lower than the impedance of a GPO that has no equipment connected. Fig 8 shows that the impedance measured at a GPO without any load connected is up to 10 times lower at low frequencies and up to 10 times higher at high frequencies than the EN50065 [9] standard.

Fig. 8. Impedances at power points.

Fig. 9 shows the off-line impedance of the 240V winding of 240:115V, 3 kVA, 3 phase transformer for different loads. This transformer’s on-line transfer function is shown in fig. 12.

Fig. 9. Off-line Impedance of 240V winding 3phase 3 kVA transformer.

B. Transfer functions.

Razazian [11] indicated that G3 [2] N-PLC signals (10 - 490 kHz) can pass through transformers. Fig. 10 shows the RSOIA in use at the high voltage laboratory at James Cook University, to measure on-line impedances and transfer functions of two 240 V to 33 kV single phase, 10 kVA SWER transformers, connected back to back. By using back-to-back measurements, all measurements are made at 240V and normal mains loads, such as lamps and fan heaters, can be used to load the system.

Fig. 10. Measuring 240V-33kV SWER transformers on-line at JCU.

Fig. 11 shows some transfer function measurements of these transformers. The solid curves are mains to load measurements and the dotted curves are load to mains measurements. The solid lines show a slight gain below 5 kHz, which is due to impedance changes from the mains to the load. These curves also show that applying loads to the transformer reduces the transfer function gain in the 7 to 15 kHz frequency region.

Fig. 11. SWER transformers on-line, back-back, transfer functions.

Fig. 12 shows the on-line transfer function measurements of the same transformer, whose impedance is shown in Fig. 9. To prevent clutter, only phase A is shown. The other phases have a similar performance. This transformer shows a large transfer function variation with transformer load below 2 MHz.

The measurements of figs 11 and 12 show that the attenuation for N-PLC frequencies depends on the construction of the transformer. The SWER transformers of fig 11 have up
to 37 dB attenuation per transformer in the N-PLC frequency band. The transformer of fig. 12 has up to 20 dB attenuation. Off-line measurements of a 200 kVA [12] distribution transformer measured by the author and a 100 kVA transformer measured by Lefort [13] show a typical 35 dB attenuation in the N-PLC frequency band. It is easy to get reliable G3-PLC communications through the transformer of fig. 12 but that is more difficult to achieve through others, like the one in fig. 11 or the ones measured in [12] and [13].

C. Sub-cycle Impedance and Transfer function variations.

Much of the electronic equipment includes full wave rectifiers, resulting in much larger currents being drawn at the peaks of the mains voltages. Since during that short time lower impedance circuits are connected into the mains power, this may cause short-term variations in impedance at PLC frequencies. It is desirable to be able to investigate mains related impedance variations at PLC frequencies.

The RSOIA software [5], [7], which controls the signal generator and ADC’s of the PicoScope, has been modified to be able to analyze impedance or transfer function variations over one mains cycle. The start of the sampling period is triggered by the mains waveform zero crossing. The 20 ms (50 Hz) mains cycle is split into 20, 1 ms intervals and the impedance or transfer function is calculated during each of those intervals with the center of those intervals occur at 0.5, 1.5, 2.5, … 18.5, 19.5 ms after the rising zero crossing of the mains waveform.

Fig. 12 shows that measured sub-cycle impedances for the same GPO and loads of the home office curves shown in fig. 8. The impedance varies over part of the mains cycle, with a larger variation occurring when no office load is placed on the GPO. The RSOIA hardware of fig. 5 also allows sub-cycle variation in transfer functions to be measured.

VII. TIME DOMAIN REFLECTOMETRY

Time domain measurements of power lines can be used to measure distances between line junctions or to determine the distance to a cable fault. The RSOIA hardware can also be used as a filter to isolate mains voltages when doing time domain measurements, while on-line. Conventional impedance measurements with a linear frequency increment can be made and applying an FFT will result in an impulse response of the power line. Calibration techniques like those described above can remove the current and voltage sensors impulse response from the measurements to provide the impulse response of the powerline. Alternately, a pseudo random noise like waveform can be generated by the signal generator and injected onto the powerline using the RSOIA. Correlating the generated and waveforms from the current or voltage sensors can be used to determine any resulting reflections. Both techniques have been shown to work, with the correlation technique giving slightly better accuracy. Results from this ongoing work will be published in the future.

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