MEASUREMENT OF THE HARMONIC IMPEDANCE OF LV DISTRIBUTION SUPPLY SYSTEM (120/240 V)

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ABSTRACT

The use of non-linear loads of industrial, commercial and residential customers is continuously increasing. Harmonic emissions injected in the distribution system by this type of loads increase harmonic voltages to levels exceeding compatibility level. The result is a reduction of the life expectancy of customer equipment as compared to that of normal operating conditions.

Harmonic emission levels represent a major and current problem that regulators, utilities and customers are facing. In response to this problem, several international standards, belonging to the IEC 61000-3 series, have been established to limit these emissions. A key role in the process is played by the harmonic impedance of the low voltage distribution supply system (120/240V) feeding the polluting equipment.

INTRODUCTION

In 1999, Hydro-Quebec initiated a project to develop an instrument and a method to measure the harmonic impedance of the low voltage distribution supply system feeding residential customers (first stage) and to discriminate the customer/network contribution to the harmonic levels at the point of common coupling (PCC) (second stage).

The scope of this project was to determine the low voltage supply circuit harmonic impedances of Hydro-Quebec's distribution system and to compare them to the reference values corresponding to European distribution systems.

In the second stage of the project, the harmonic impedance values were to be used together with the highly accurate harmonic current magnitude and phase angle measurement in order to discriminate between the customer and the network contribution to harmonic levels. The project aimed at measuring the portion of the harmonic voltage related to devices used by residential and commercial customers.

The instrument selected for this project was the Mini-AQO, a power quality analyzer designed and developed at IREQ, Hydro-Quebec's Research Institute. This portable power quality analyzer was modified in terms of hardware and software to allow a highly accurate measurement of very low fluctuations of harmonic voltages and currents required to calculate the harmonic impedance.

HARMONIC IMPEDANCE MEASUREMENT

Several documents [1, 2, 3, 4, 5], published in the last decade have presented techniques to measure network impedances. In summary, these measurement techniques associate the harmonic current fluctuation produced by a load to the harmonic voltage fluctuation at the service entrance. The ratio of the voltage fluctuation ΔU_h to the current fluctuation ΔI_h gives the network impedance, Z_h.

$$Z_h = \frac{\Delta U_h}{\Delta I_h}$$

The main problem of all these techniques results from the uncontrollable fluctuation in the network harmonic voltage, which causes significant errors. In fact, the voltage variation ΔU_h is not solely produced by the current fluctuation ΔI_h. In some cases, the voltage fluctuation produced by the current fluctuation is totally negligible relative to the normal fluctuation in the network. To by-pass this difficulty, the authors of these methods have formulated the hypothesis that the network does not usually add a fluctuation simultaneously to that produced by the current. Several types of filters were designed to sort out the cases which would give a precise measure of the network impedance. To make this sorting, the authors of the methods assumed the precise measure of the impedance having a high occurrence probability. As a result, it was also necessary to assume that the network is static, i.e. with an impedance that does not vary. In fact, capacitors used to correct the power factor also affect the harmonic impedance of the network. These capacitors are regularly operated either to regulate the voltage level or to avoid penalties associated with reactive power. That is why the methods based on the hypothesis of a static network do not always produce reliable results.

A new method, based on the $\Delta V_h/\Delta I_h$ ratio, was developed by IREQ to determine the harmonic impedance. It requires finding a characteristic voltage fluctuation which may not exist on the network without the contribution of the current fluctuation it is usually associated with. The accuracy of this method has been proven in laboratory simulations. Field tests have revealed interesting problems related to accurate harmonic measurements.

HARMONIC IMPEDANCE MEASUREMENT METHOD

The method proposed by IREQ belongs to the group of methods using direct injection of harmonic currents. It consists in taking every 50 ms, a sample of the voltage magnitude of an h order harmonic voltage, for a total of 2048 samples. Applying the Fourier Transform on these samples gives the voltage fluctuation spectrum in the range of 0.01 Hz to 10 Hz. The same type of analysis is also performed on the current. It is necessary to repeat the measurement several times in order to establish a correlation between the voltage and the measured current for every fluctuation frequency. The fluctuation frequency which produces the highest correlation is chosen to calculate the ΔU_h and ΔI_h parameters used to estimate the harmonic network impedance. However, in several cases this correlation is not possible because the load current does not contain a constant fluctuation at a measurable characteristic frequency. It therefore implies to generate a current fluctuating at a frequency which does not exist in the voltage spectrum.

The procedure to measure the impedance of the network in all circumstances is as follows:

1. Perform a DFT (Discreet Fourier Transform) of the voltage signal on consecutive three-cycle windows (50 ms) to accumulate 2048 samples in an interval of 102.4 seconds. Calculate the module of the magnitude for every harmonic order.
2. Perform a DFT on the 2048 modules of every harmonic order. This DFT produces the fluctuation spectrum for each harmonic order.
3. Repeat steps 1 and 2 three times and get the sum of the three results for every harmonic order. Find the fluctuation with the minimal value to determine the characteristic frequency.
4. Generate a harmonic current modulated at the characteristic frequency that was previously determined as having the lowest magnitude.
5. Perform a DFT of the current and voltage in 50 ms windows over 102.4 s to obtain the real and imaginary values of every harmonic order.
6. Subtract the current phase angle from the voltage phase angle for every harmonic order in every window in order to obtain a real value for the current and a complex number for the voltage.
7. Perform a DFT for the characteristic frequency found in step 3 for the current, the real part of the voltage and the imaginary part of the voltage for every harmonic order.
8. Based on the result at step 7, calculate the ratio of the real voltage module and the current module in order to determine the real part of the network impedance.
9. Based on the result at step 7, calculate the ratio of the imaginary voltage module and the current module in order to determine the imaginary part of the network impedance.

NORTH AMERICAN DISTRIBUTION SYSTEM

In North America, the commonly distribution system used for single-family residential and light commercial (up to about 100 kVA) applications is a split phase or a 3-wire single-phase distribution system (refer to Figure 1).

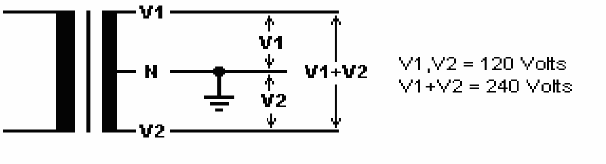


Figure 1: Split-phase distribution system diagram

MINI-AQO MEASURING INSTRUMENT

Inputs

The Mini-AQO power quality analyzer is equipped with four voltage inputs and four current inputs ***ABCN*** and ***abcn***, respectively. The input signals are filtered directly on-board by an anti-aliasing filter (second order), which limits the signal frequency to 40 kHz. At the end, they are converted using a 12-bit A/D.

Signal pre-processing

Low-level data acquisition produces four kinds of raw data: waveform signals, waveform transients, RMS values and frequency. The Mini-AQO uses a PC laptop running on a Windows platform and different drivers to record the signals. A driver gives top priority to data acquisition and accommodates as much as one minute of FIFO buffering, an important asset for continuous signal analysis. The waveform and transient signals are both based on synchronous sampling. To achieve synchronous sampling, the analyzer hardware uses a phase locked loop (PLL) circuit. The analyzer sampling rate was initially tuned at 10240 Hz, which is exactly 12 cycles with 2048 points, for the purpose of PQ analysis.

Spectrum analysis

The real time processing of the spectrum analysis on PC laptops is only possible with the Fast Fourier Transform (FFT) technique. The Mini-AQO's synchronous sampling was designed especially for this purpose.

MINI-AQO UPGRADE

To be able to measure harmonic impedances of residential distribution systems, the instrument underwent hardware and software modifications.

Hardware modification

The MiniAQO's acquisition module includes two printed circuit cards. The card that contains voltage and current inputs underwent design changes. High-pass filters were added to voltage input channels, ***B*** and ***N***, in order to eliminate the voltage fundamental. These filters were of the "All -pole" active filter type, based on a Chebyshev second order filter. They were designed with OP282 and OP482 operational amplifiers. ***A*** and ***C*** input channels remained unmodified. Voltage signals V1 and V2 (refer to Figure 1) must be applied respectively to input channels ***A*** and ***B*** (refer to Figure 2), and to input channels ***C*** and ***N***.

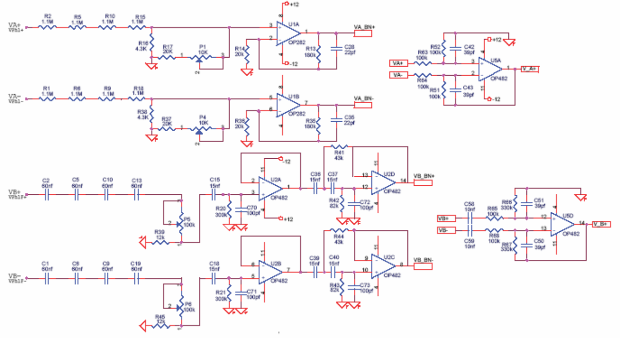
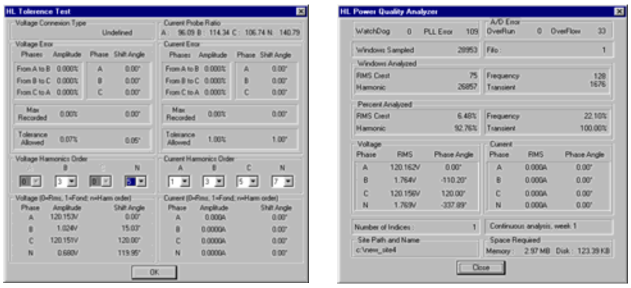


Figure 2: *A* and *B* voltage input channels diagram

Software modification

The software modifications include graphical user interface GUI (see Figure 3), calibration, addition of a new index IMP that required the integration of a new algorithm, etc.



HL Tolerence Test

Voltage Connexion Type: Undefined

Current Probe Ratio: A : 96.09 B : 114.34 C : 106.74 N : 140.79

Voltage Error

Phases	Amplitude	Phase	Shift Angle
From A to B	0.000%	A	0.00°
From B to C	0.000%	B	0.00°
From C to A	0.000%	C	0.00°
Max Recorded	0.00%		0.00°
Tolerance Allowed	0.07%		0.05°

Current Error

Phases	Amplitude	Phase	Shift Angle
From A to B	0.000%	A	0.00°
From B to C	0.000%	B	0.00°
From C to A	0.000%	C	0.00°
Max Recorded	0.00%		0.00°
Tolerance Allowed	1.00%		1.00°

Voltage Harmonics Order: A 0, B 3, C 0, N 5

Current Harmonics Order: A 1, B 3, C 5, N 7

Voltage (0=Rms; 1=Fond; n=Harm order)

Phase	Amplitude	Shift Angle
A	120.153V	0.00°
B	1.024V	15.03°
C	120.151V	120.00°
N	0.680V	119.95°

Current (0=Rms; 1=Fond; n=Harm order)

Phase	Amplitude	Shift Angle
A	0.000A	0.00°
B	0.0000A	0.00°
C	0.0000A	0.00°
N	0.0000A	0.00°

HL Power Quality Analyzer

WatchDog 0 PLL Error 109

A/D Error: OverRun 0 OverFlow 33

Windows Sampled 28953

Filo : 1

Windows Analyzed

RMS Crest	75	Frequency	128
Harmonic	26857	Transient	1676

Percent Analyzed

RMS Crest	6.48%	Frequency	22.10%
Harmonic	92.76%	Transient	100.00%

Voltage

Phase	RMS	Phase Angle
A	120.162V	0.00°
B	1.764V	-110.20°
C	120.156V	120.00°
N	1.769V	-337.89°

Current

Phase	RMS	Phase Angle
A	0.000A	0.00°
B	0.000A	0.00°
C	0.000A	0.00°
N	0.000A	0.00°

Number of Indices : 1

Continuous analysis, week 1

Site Path and Name: c:\new_site4

Space Required: Memory : 2.97 MB Disk : 123.39 KB

Figure 3: Tolerance Test and EMAQO dialog boxes

Calibration

The initial calibration procedure was based on a FLUKE calibrator providing 60 Hz voltage and current fundamentals for different voltage and current scales (120/240/347 Volts and 0.05/1/2 Amps) available on the instrument. The resulting calibration factors used to calculate the measured voltages and currents were corresponding only to the fundamental frequency. These calibration factors produced inaccurate results when measuring voltage and current harmonics of very low magnitude. Both harmonics magnitude and phase angle were inaccurate.

In order to overcome this limitation, a new calibration procedure was developed. The new procedure included harmonic calibration and phase angle error calibration up to the 40th harmonic order, in addition to the initial calibration at 60 Hz. The magnitude and the phase angle error calibration of the voltage and current fundamentals was performed respectively on channels ***A*** and ***C*** for voltage, and on channels ***a***, ***b***, ***c*** and ***n*** for current. The harmonic magnitude and harmonic phase angle error calibration was performed on channels ***B*** and ***N*** for voltage, and on channels ***a***, ***b***, ***c*** and ***n*** for current.

While testing the new calibration procedure, it was noticed that in order to achieve high harmonic measurement accuracy, the magnitude of the reference value of both voltage and current used in the calibration procedure must be in the range of the magnitude variation of harmonics occurring on the local circuit. For a residential customer, the reference values selected for voltage and current should range respectively from 3 to 5 Volts and from 3 to 5 Amps.

Using separate calibration factors for fundamentals and each of the harmonic orders, the accuracy of the measurement of harmonic magnitude and phase angle improved significantly. The Mini-AQO was capable of measuring harmonic voltages and currents (up to the 40th order) as low as 10 mV or 10 mA with errors lower than 0.07% for magnitude and 1% for phase angle.

Harmonic Current Generator

A harmonic current generator was developed at IREQ for the purpose of this project. It was capable of injecting harmonic currents with a magnitude up to 3 Amps in the 120/240 V residential electrical circuit.

The modulation of the injected current at the characteristic frequency is adjustable and is controlled using the serial COM1 port of the power quality analyzer. The diagram of the harmonic current generator is supplied in Figure 4.

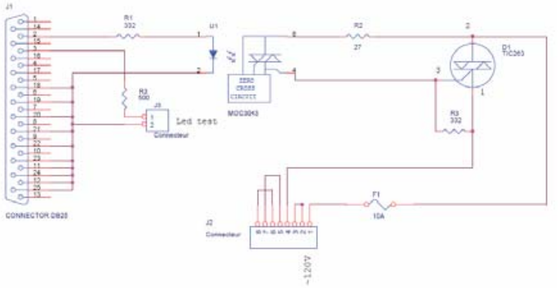


Figure 4: Harmonic current generator diagram

SIMULATION TEST

A software simulator was used to validate the algorithm. The voltage and current input buffers of the instrument were fed with simulated distribution system low voltage (120 V) and load current sampling values. Voltage and current harmonics fluctuating at a frequency of 1 Hz were superimposed over initial voltage and current signals. These harmonics represent simulated harmonic voltages, which would be produced by the harmonic currents injected by the harmonic current generator.

The waveforms illustrated in Figure 5 represent unfiltered channel ***A*** voltage, filtered channel ***B*** voltage, channel ***a*** current and channel ***b*** current (same current as channel a). The voltage waveform from channel ***B*** is the resulting voltage after filtering the 60 Hz fundamental. The harmonic spectrum of the voltage and the current on channels ***A***, ***B***, ***a*** and ***b*** contains harmonics from 3rd up to 15th order.

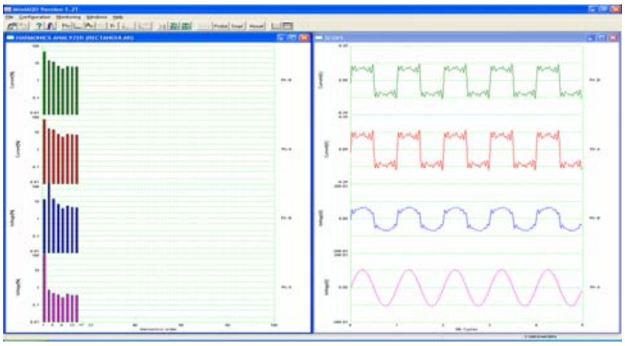


Figure 5: Voltage and current harmonic spectrum and waveforms; channels A, B, a and b

Several simulations were performed using different impedances for the supplying circuit. The results of two of them are presented in Table 1. Impedance values corresponding to the 60 Hz frequency (h=1) were used to create voltage fluctuations presumably generated by the injected harmonic currents at characteristic frequency. The algorithm filtered input data and calculated the harmonic impedances from h=3 to h=15 for simulation 1 and from h=3 to h=9 for simulation 2. The results served to validate the harmonic impedance calculation algorithm.

Table 1: Simulation tests results

Harm	Simulation 1			Simulation 2		
h	**Re**	**Im**	**Imp**	**Re**	**Im**	**Imp**
1	0.0900	0.0250	0.0934	1.932	0.0396	1.9324
3	0.0873	0.0773	0.1166	1.9666	0.1342	1.9711
5	0.0893	0.1219	0.1511	2.1118	0.2417	2.1256
7	0.0944	0.1781	0.2016	2.1389	0.3175	2.1623
9	0.0990	0.2290	0.2495	2.0502	0.3939	2.0877
11	0.0936	0.2908	0.3055			
13	0.0948	0.3233	0.3369			
15	0.0911	0.3747	0.3856			

LABORATORY TESTS

Simulations tests were followed by a few laboratory tests. Results from a laboratory test are graphically illustrated in Figure 6.

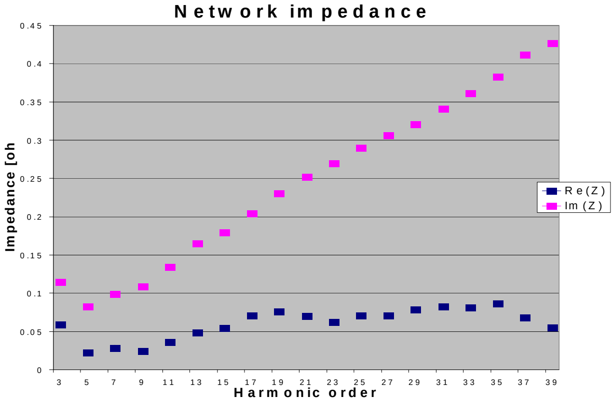


Figure 6: Laboratory test results

The graph shows a linear relationship between the imaginary part (inductance) of the impedance and the harmonic order and an almost constant relationship between the real part (resistance) of the impedance and the harmonic order. The values are within the estimated range.

CONCLUSIONS

The project allowed to draw relevant conclusions:

- Adequate harmonic voltage and current calibration (magnitude and phase angle error factors for each order) is very important in achieving an accurate impedance measurement.
- Filtering the voltage fundamental (60 HZ) significantly increases the measuring instrument's resolution.
- A stable harmonic spectrum of current injected in the circuit affects the harmonic impedance measurement accuracy positively.
- The CT's with gapless core improve the current measurement accuracy.
- Coherent results were obtained from laboratory tests mostly for harmonic impedances of order lower than 15th. The higher orders were frequently affected by resonance conditions.

The second stage of the project, the discrimination of harmonic contribution, was not yet finalized.

REFERENCES

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