The Influence of the Network Impedance on the Nonsinusoidal (Harmonic) Network Current and Flicker Measurements

Ionel Urdea Marcus, Anca Elena Nestor, and Paul Clarkson

***Abstract*—The influence that small variations of the network impedance may have on the nonsinusoidal (harmonic) network current at the point of connection of a harmonic distortion measurement system, as well as on flicker measurements, has been studied. In this respect, an equivalent circuit was devised as a possible low-voltage urban network model. Harmonic disturbances, using three different disturbance sources, and voltage variations that induce the flicker sensation, using square modulation waveforms, were simulated on a computer. The variation with $\pm 10\%$ of the magnitude of the network impedance at 50 Hz was also simulated, and the influence it may have on the spectral distribution of current and power, as well as on the modulation depth generating the flicker sensation, was analyzed.**

***Index Terms*—Flicker, harmonic network current, network impedance, power quality (PQ), power spectra.**

I. Introduction

IN SITU measurements of the power quality (PQ) parameters are performed under the specific conditions of the electricity supply network, which are described using functional parameters such as voltage, current, power, and impedance, while the measurement equipment is calibrated using laboratory setups under reference conditions, defined in specialized standards, including a reference value for the network impedance.

Since a real low-voltage urban network is a sort of a system with "variable geometry" as various consumers are constantly connected or disconnected and a variable number of nonlinear distortion-generating consumers may be connected, the network impedance may differ significantly from the reference value used in calibration. Thus, it is important to know whether these changes in the network impedance may influence the uncertainty associated to the measurement results when the harmonic distortions and the flicker-generating voltage variations are measured in-field. To evaluate this influence, an equivalent circuit that may serve as a model for the network was developed and used to simulate the effect that a variation of the magnitude of the network impedance has on the measurement of harmonic distortions and flicker.

The network model was used in association with several computer-simulated harmonic distortion generators in order to insert into the model the kind of distortions typically induced into a real network by nonlinear loads connected to it. It was also used in association with an appropriate representation of a network load, which could be connected and disconnected by means of a programmable switch, in order to simulate the network voltage drops that may generate the flicker sensation in a real network [1].

II. Network Impedance Model

International Electrotechnical Commission (IEC)-compliant tests of PQ-measurement equipment assume the insertion of the following two types of impedance networks [2]:

1) a reference network defining an impedance of specified value used either in the calculation or measurement of the electromagnetic distortion caused by an appliance [3]–[5] or detecting possible equipment-under-test-damaging resonant phenomena excited by harmonics [6];
2) an artificial mains network which, inserted in the supply mains lead of apparatus to be tested, provides, in a given frequency range (i.e., above the harmonic range, between 2000 and 9000 Hz), a specified load impedance for the measurement of distortion voltages and which significantly attenuates the dominant harmonic components in the harmonic range, allowing the measurement of the considerably lower harmonic components from the supply mains in that frequency range [7].

The impedance of the electricity supply network is defined as the impedance of the supply system as viewed from the point of common coupling. Full knowledge of the elements connected at any time instant at the network up to the point of common coupling is unlikely to be available to the operator performing measurements of the PQ parameters. The network impedance at any time is determined by the characteristics of all the network elements, as well as by the interaction between them, and is likely to change when various consumers are connected to or disconnected from the network or when the operation parameters of some consumers connected to the network vary. Being a dynamically changing and frequency-dependent quantity, the supply network impedance may induce

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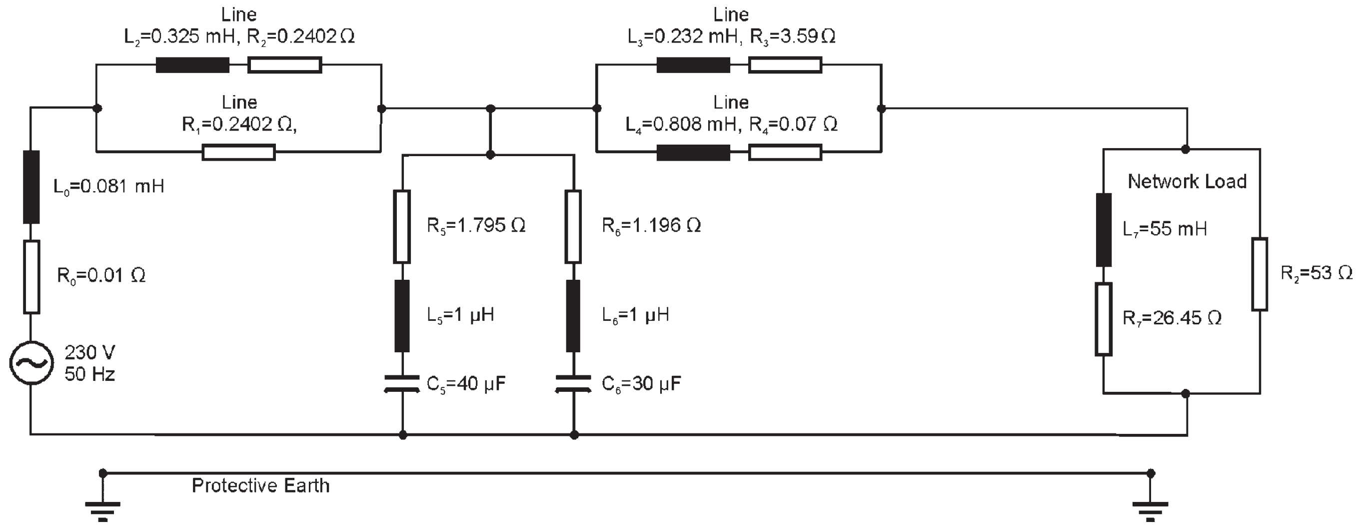

Fig. 1. Network model.

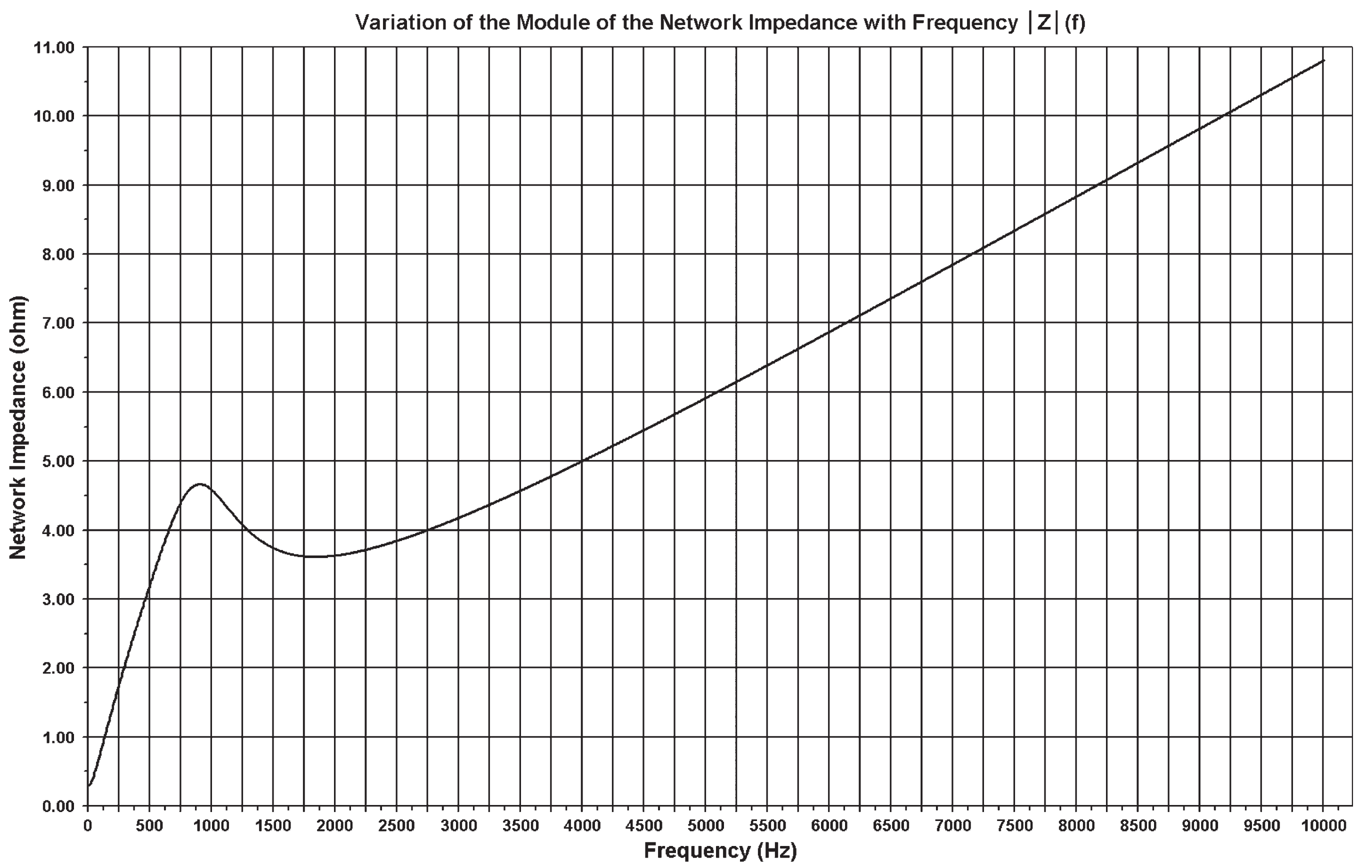

Fig. 2. Overall variation of the module of the simulated network impedance corresponding to the proposed new model within the frequency range (0, . . ., 10 000) Hz.

an "amplification" or an "attenuation" of the effects caused by network harmonics and power fluctuations [8].

In most cases, the supply network reactance is a result of the inductive and capacitive elements present within the network (line and cable impedances, inductive and capacitive loads, and power factor correction schemes). In a typical low-voltage urban network, the inductive component of the reactance tends to be predominant, and therefore, the network tends to be predominantly inductive. In order to compensate this predominantly inductive character of the supply network, the distribution points generally include groups of capacitors that may be switched on or off depending on the state of the network.

These two reactive components (L and C) may determine resonant points in the network and therefore significantly influence the shape of the network impedance magnitude versus frequency curve $Z(f)$. The examples given in the reference literature [9], [10] show that, in low-voltage distribution systems,

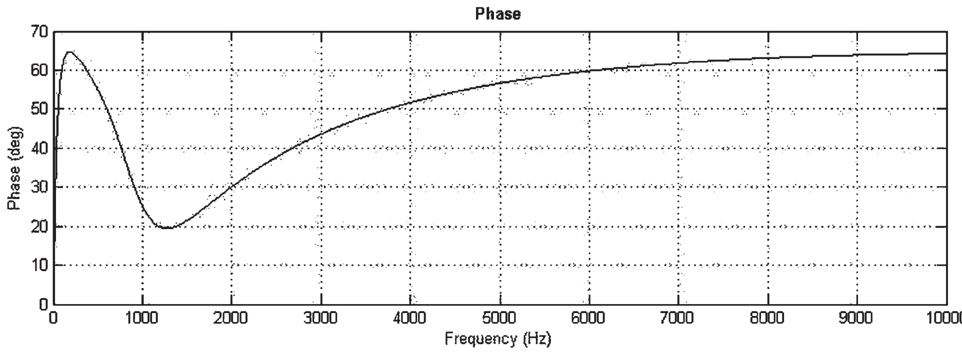

Fig. 3. Variation of the phase of the network impedance with frequency.

within the frequency range (0, …, 10 000) Hz, the $Z(f)$ curve exhibits one net maximum and one net minimum occurring within the harmonic range and then an approximately linear increase up to 10 kHz.

In order to reflect these characteristics of a typical low-voltage urban network, it was considered necessary for any equivalent circuit modeling the network impedance to include resistors, inductors, and capacitors as well, using a topology that would reflect as much as possible the main characteristics of a real network. This implies also a good compliance with the constraints resulting from Annex B of the first amendment to the IEC 61000-4-7 standard and from the IEC 77AWG1 Technical Report [11]. Such a model might be used to simulate and evaluate the effects that possible changes in the network impedance may have on *in situ* harmonic distortions and flicker measurements. Several models were developed and analyzed, with the one providing the best compliance with the standard being shown in Fig. 1.

The proposed model includes representations of a compensating group of capacitors and of a typical load for a low-voltage residential network, absorbing a peak current of about 16 A. The supply voltage and frequency considered were the typical values for phase-to-neutral connection in European low-voltage residential supply networks, i.e., 230 V and 50 Hz, respectively. The internal resistance of the supply generator is $R_0 = 0.01\ \Omega$, and its internal inductance is considered to be $L_0 = 0.081$ mH, complying with the characteristics of the power supply prescribed in Annex B of Amendment 1/FDIS to the IEC 61000-4-7 standard. The constraints regarding the magnitude of its impedance, prescribed in this document, i.e., $|Z| = 0.4717\ \Omega$ at 50 Hz, $|Z| = 3.7451\ \Omega \pm 5\%$ at 2050 Hz, and $|Z| = 3.8687\ \Omega \pm 5\%$ at 2450 Hz, are also observed. The corresponding $|Z|(f)$ curve, represented within the frequency range (0, …, 10 000) Hz, is shown in Fig. 2.

The phase angle of the network impedance was also taken into account. The overall variation of the phase of the simulated network impedance within the same frequency range (0, …, 10 000) Hz is shown in Fig. 3.

III. Study of the Harmonic Current

The influence that small changes in the magnitude of the network impedance may have on the spectral distribution of the nonsinusoidal current was studied using the simulated setup shown in Fig. 4.

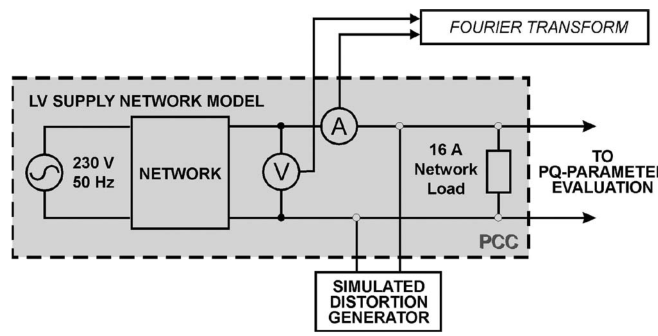

Fig. 4. Representation of the simulated setup used for the analysis of harmonic current distortions.

The distortion generator in Fig. 4 was simulated using a special waveform mix developed by the National Physical Laboratory (NPL), Teddington, U.K., for the calibration of harmonic analyzers [12], a simulated rectifier circuit, and a simulated switched-mode power supply (SMPS) based on a buck converter.

The frequency-domain representation of the distorted current at the point of connection induced by the injection of the simulated IEC 61000-3-2 Class A waveform mix used in NPL calibration service for harmonic analyzers into the network model is shown in Fig. 5.

The frequency-domain representation of the distorted current at the point of connection induced by the simulated SMPS is shown in Fig. 6.

The total harmonic distortion (THD) values obtained for each of the distortion sources used are given in Table I.

The main interest in the simulation work was to check whether the change in the network impedance influences the harmonic structure of the network output current.

Since, in a real network, the change of the network impedance is the result of connecting or disconnecting various loads to the network or the result of changes in the parameters of the circuit components, this leads to changes in both the resistive and reactive components of the impedance. Therefore, the change of the network impedance was simulated by manipulating both the resistive and the reactive components in the model, so that a change of $\pm 10\%$ in the magnitude of the impedance at 50 Hz was obtained, while maintaining the compliance with the aforementioned constraints imposed by the standard and also paying attention to the changes in the phase angle.

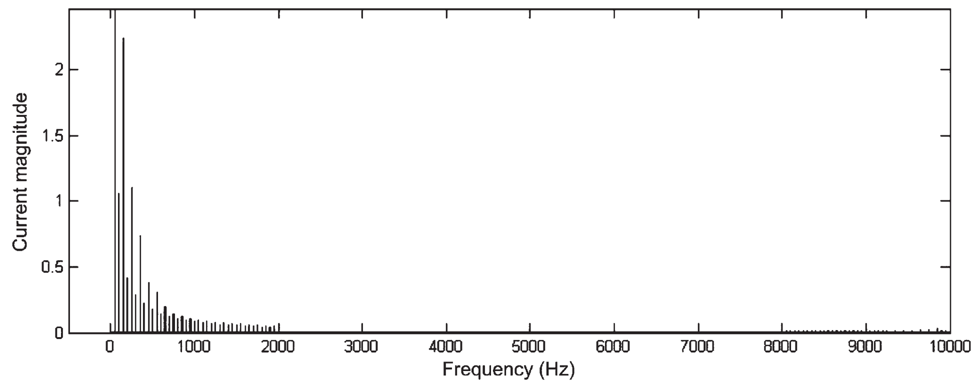

Fig. 5. Frequency-domain representation of the distorted current induced into the network by the injection of the simulated IEC 61000-3-2 Class A waveform mix.

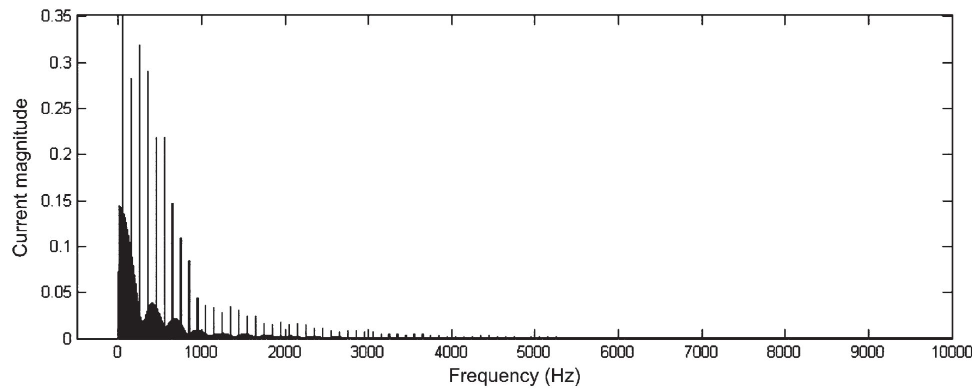

Fig. 6. Frequency-domain representation of the distorted current induced by the SMPS.

TABLE I
THDs

Distortion source	THD values		
	Injected distortion	Output current	Output voltage
NPL waveform mix	132.25 %	23.28 %	1.84 %
Simulated modified rectifier	129.75 %	6.88 %	0.84 %
Simulated switched mode power supply	139.61 %	4.38 %	0.56 %

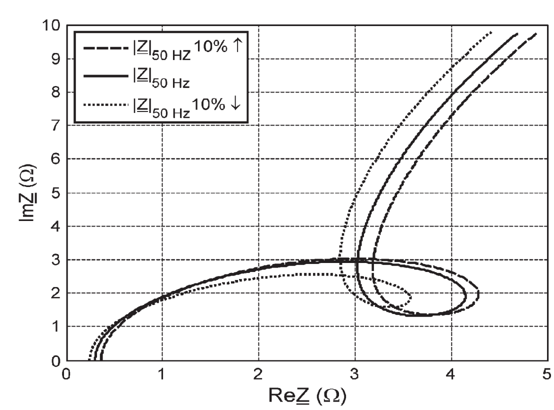

Fig. 7. Change of the complex network impedance plot when $|Z|$ at 50 Hz changes with $\pm 10\%$.

The changes in the real and imaginary parts of $\underline{Z}$, resulting from a change of $\pm 10\%$ in the magnitude of the impedance at 50 Hz, are shown in Fig. 7.

The network output current spectral response was analyzed for each of the distortion generators considered within the study. Thus, when the NPL waveform mix was used as the distortion generator, the relative differences in the spectral current distribution within the harmonic range, resulting from a change in the magnitude of the network impedance with -10% of the nominal value, are shown in Fig. 8.

When $|Z|$ at 50 Hz was changed with $+10\%$ of the nominal value, the relative differences in the spectral current distribution for the same distorting signal are shown in Fig. 9.

The relative differences resulting from the change in $|Z|$ at 50 Hz with -10% and with $+10\%$, when, for example, the connection of the SMPS was simulated, are shown in Figs. 10 and 11, respectively.

One should take into account the fact that inserting the NPL waveform mix into the network does not change its topology, since no additional impedances are connected. On the other hand, when the connection of the rectifier circuit or the SMPS is simulated, one should take into account that new impedances are added to the network.

The relative differences at 50 Hz are small, not exceeding 0.3%, but while the maximum values in the case of the NPL waveform mix are $+1.51\%$ and -0.43%, both at 900 Hz, the maximum values for the SMPS are significantly higher, i.e., $+28.86\%$ at 1050 Hz and -6.85% at 800 Hz.

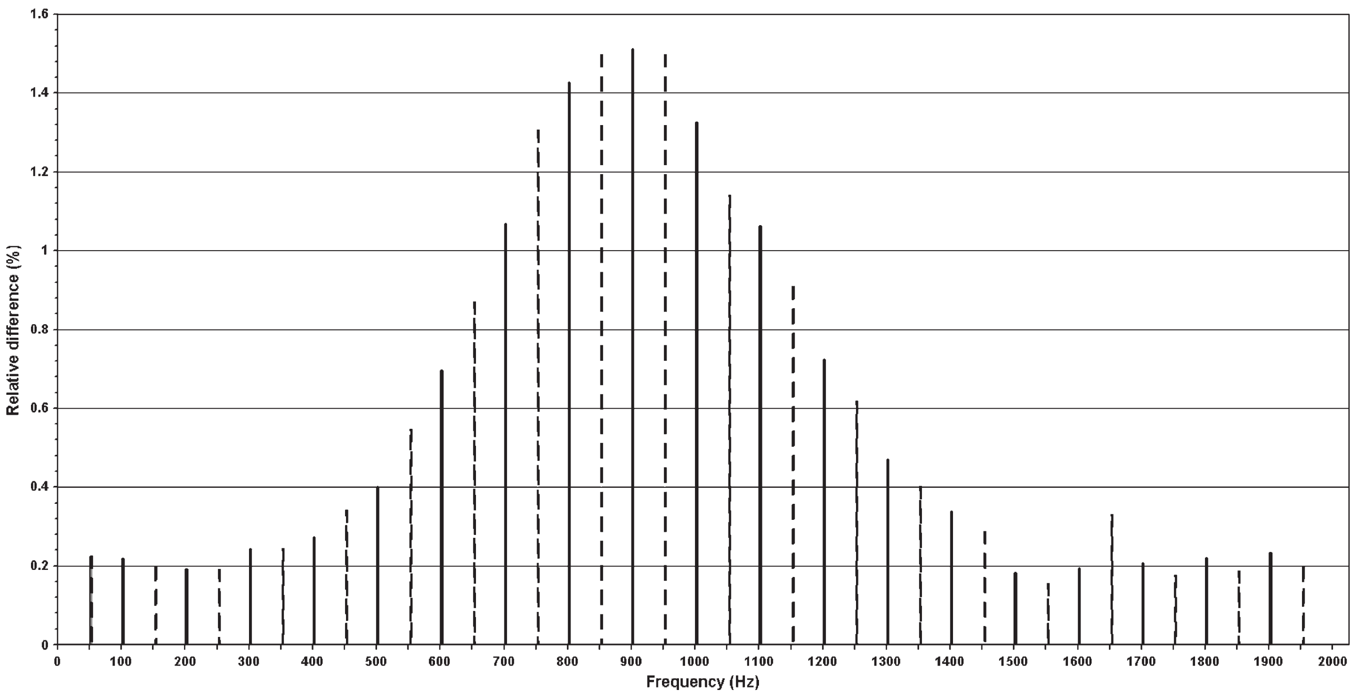

Fig. 8. Relative differences in current spectrum values for the NPL waveform mix in the harmonic range, when $|Z|$ at 50 Hz is 10% lower. (—) Even harmonics. (– –) Odd harmonics.

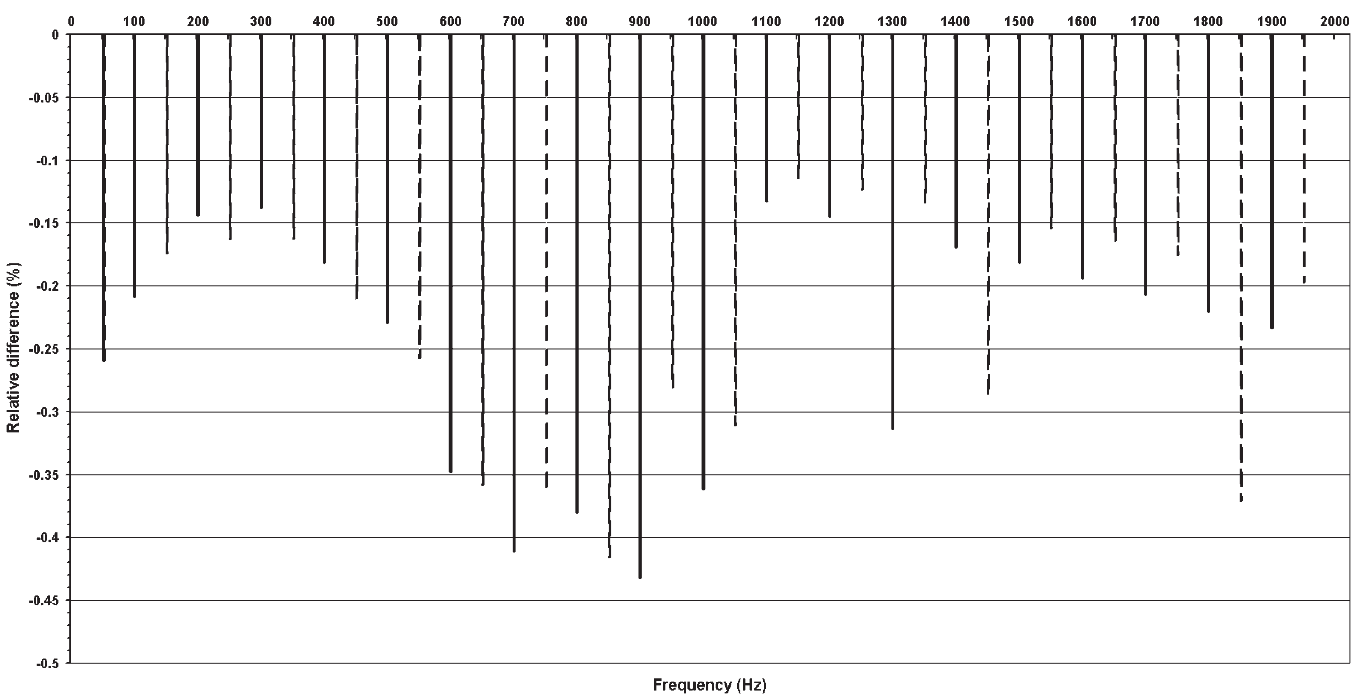

Fig. 9. Relative differences in current spectrum values for the NPL waveform mix in the harmonic range, when $|Z|$ at 50 Hz is 10% higher. (—) Even harmonics. (– –) Odd harmonics.

IV. Study of the Harmonic Power

The effect that the same harmonic distortion sources connected to the network may have on the spectral distribution of power was also investigated simulating the setup shown in Fig. 12.

In analyzing the effects that the change in the magnitude of the network impedance may have on the spectral distribution of power, the distortion generator was represented by the same simulated distortion sources. Both the active power and the apparent power were taken into account, calculating in each case the absolute, as well as the relative, differences occurring when each of the distortion generators was considered to be connected to the network model.

Significant differences resulted in the harmonic power spectra when the magnitude of the network impedance at 50 Hz was increased or decreased with 10%. While, in the case of

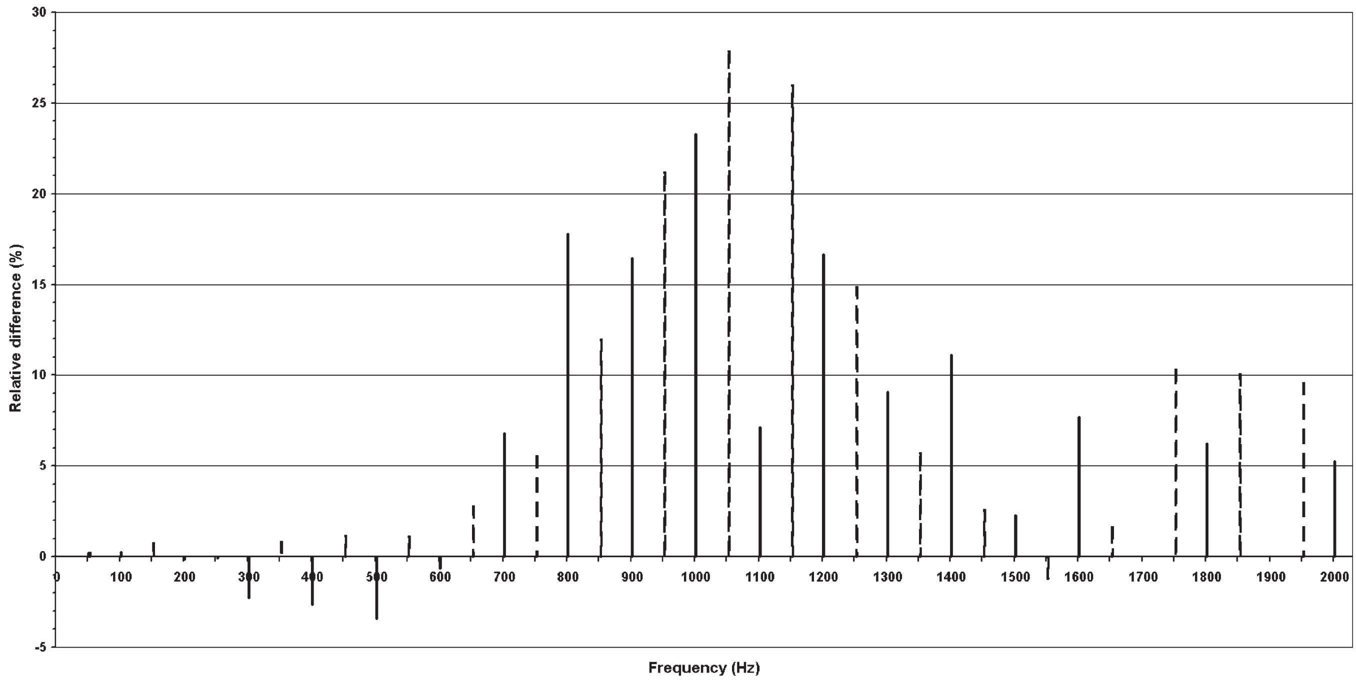

Fig. 10. Relative differences in current spectrum values for the SMPS in the harmonic range, when $|Z|$ at 50 Hz is 10% lower. (—) Even harmonics. (– –) Odd harmonics.

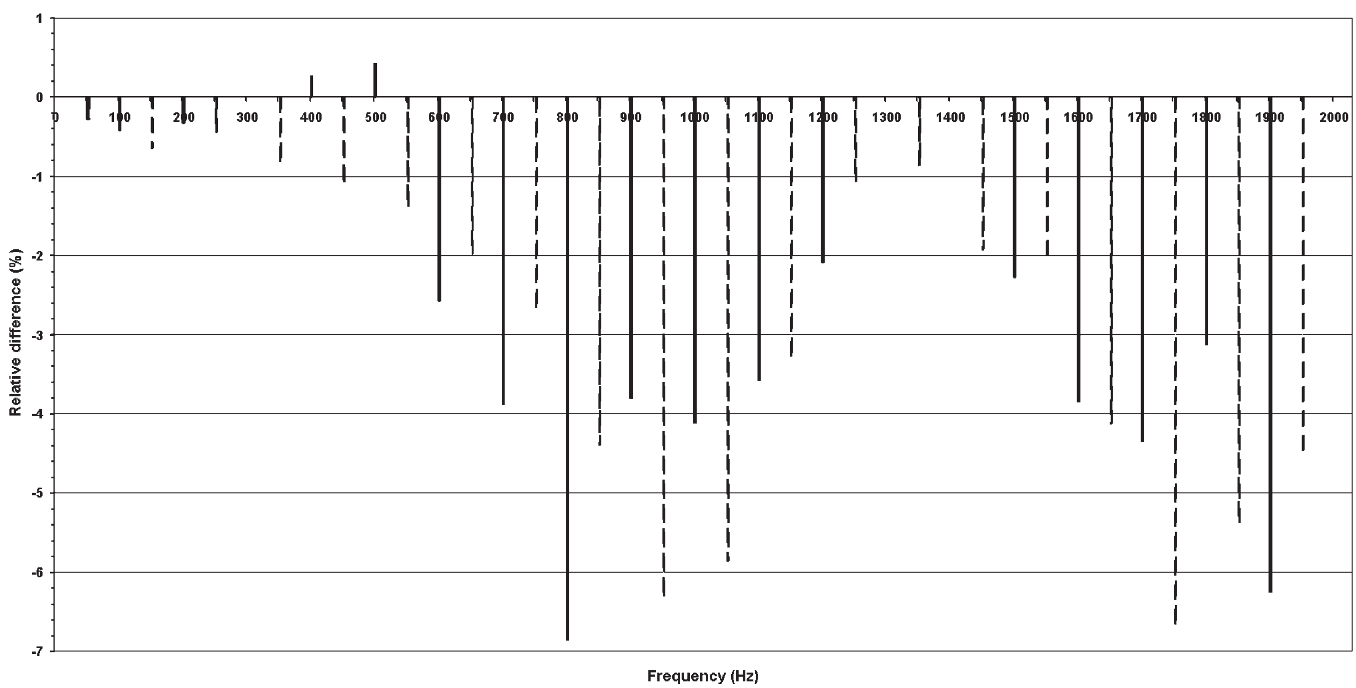

Fig. 11. Relative differences in current spectrum values for the SMPS in the harmonic range, when $|Z|$ at 50 Hz is 10% higher. (—) Even harmonics. (– –) Odd harmonics.

the NPL waveform mix, the relative differences in active power did not exceed +16% and −18%, with relatively high values at 100 Hz, in the case of the rectifier circuit and the SMPS, the relative differences were found to have significantly different patterns, with isolated high values of +155% at 950 Hz, when $|Z|$ at 50 Hz was 10% lower, and +164% at 100 Hz, when $|Z|$ at 50 Hz was 10% higher.

Another significant result of the study was the fact that, when the distortion generator was represented by a circuit and not by a waveform mix, the resulting relative differences, induced by the change of $|Z|$ at 50 Hz with either +10% or −10%, were both positive and negative, and the change of the impedance was reflected differently in even and odd harmonics.

V. Study of Flicker

Since the flickermeters are calibrated in the laboratory using a reference value for the network impedance, as stipulated in

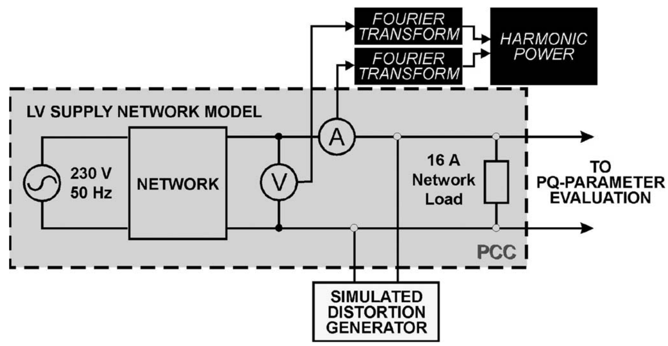

Fig. 12. Representation of the simulated setup used for the analysis of harmonic power distortions.

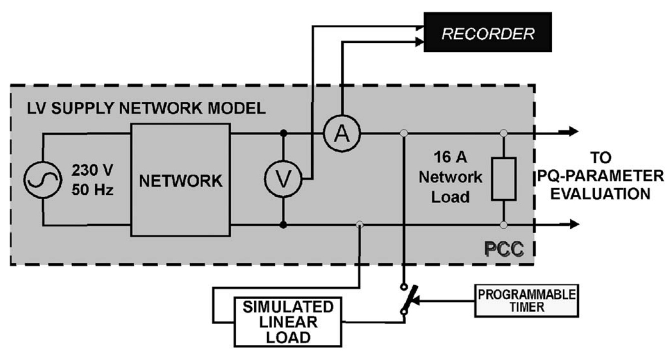

Fig. 13. Representation of the simulated setup used for the analysis of the influence that a change of the magnitude of the network impedance may have on the measurement of flicker.

the IEC 61000-3-3 standard, and the *in situ* PQ parameter measurements are performed under the specific conditions of that particular electricity supply network, to question whether changes in the supply network impedance occurring during the measurement of the short- and long-term flicker effects may influence the accuracy of the measurement results appears to be justified.

The voltage variations that induce the flicker sensation were simulated using the square modulation waveforms currently used in the NPL calibration service for flickermeters [13], as these provide the compliance with the provisions of the IEC 61000-4-15/A1 standard [14]. Applying these waveforms to a flickermeter should result in a value $P_{\mathrm{st}} = 1.0 \pm 0.05$ indicated by the instrument.

However, due to the limitations of the computer used for the simulation work, it was not possible to simulate all the square modulation waveforms, due to the very large amount of data acquired while attempting to simulate the square modulation waveforms for 1, 2, and 7 changes/min. Still, the authors are confident that the results obtained can describe very well the influence that small variations of the network impedance may have on the flicker measurements, with the number of changes per minute used in the simulation work being alternative means to induce the same flicker sensation, corresponding to a short-term flicker power $P_{\mathrm{st}} = 1$.

The general setup for these simulations is shown in Fig. 13.

The square modulation waveforms used in the NPL calibration service for flickermeters were simulated using the representation of a switch, controlled by a programmable timer, which simulated the connection or disconnection of a series of four loads in parallel to the network model. The modulation depths corresponding to the various rates of change were accurately simulated by adjusting the values of the elements in the four loads connected or disconnected to the network model. Using the programmable timer to control the switch, the modulation frequencies corresponding to the various rates of change for the network voltage were simulated.

The programmable timer controlling the switch and the values of the circuit elements in the four loads were appropriately adjusted in order to obtain the corresponding values for DV/V for each of the three values of the rate of change used in the simulation work, i.e., 39, 110, and 1620 changes/min. Thus, the compliance with the square modulation waveforms used in the NPL calibration service for flickermeters and, implicitly, with the values prescribed in the IEC 61000-4-15/A1 standard was assured, as shown in Fig. 14.

Changes of both the real and imaginary components of the network impedance were simulated so that changes in the magnitude of the network impedance at 50 Hz of -10% and $+10\%$ were obtained for each of the three rates of change of the network voltage.

The results of the simulation of a change in the magnitude of the network impedance at 50 Hz with -10% are shown in Fig. 15.

The results of the simulation of a change in the magnitude of the network impedance at 50 Hz with $+10\%$ are shown in Fig. 16.

One may notice that the change of the magnitude of the network impedance at 50 Hz with $\pm10\%$ induces changes of the values of DV/V, which are different for each of the three rates of change used in the simulation work. Moreover, the changes of DV/V induced by the change of $|Z|_{50\,\mathrm{Hz}}$ with $\pm10\%$ are clearly higher for lower values of the rate of change used in the simulation work and decrease when the rate of change used increases.

VI. Conclusion

The simulation work performed clearly indicates that changes in the network impedance may induce alterations of the spectral distribution of current, of the spectral distribution of active and apparent power, and on the flicker measurements. Since, in some cases, these alterations appear to be quite significant, it is possible to have significant errors when in-field measurements of the harmonic distortions or in-field flicker measurements are performed, using harmonic analyzers or flickermeters, which were calibrated in laboratory conditions using reference standardized values for the network impedance.

Since the topology of a real public urban low-voltage network is an individual characteristic of each network, with its own internal dynamics, depending on the required accuracy and on the harmonic interval in which the measurements are performed, gathering information regarding the network impedance at the point of connection and on the limits within which it may vary could be considered as a prerequisite for reliable in-field measurements of PQ parameters.

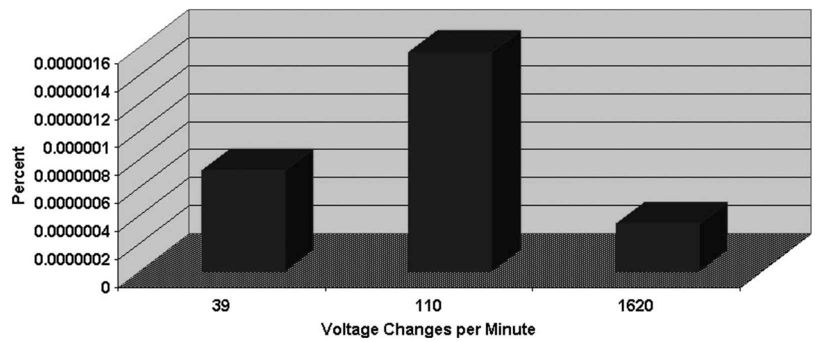

Fig. 14. Illustration of the accuracy with which the square modulation waveforms used at NPL for flickermeters were simulated.

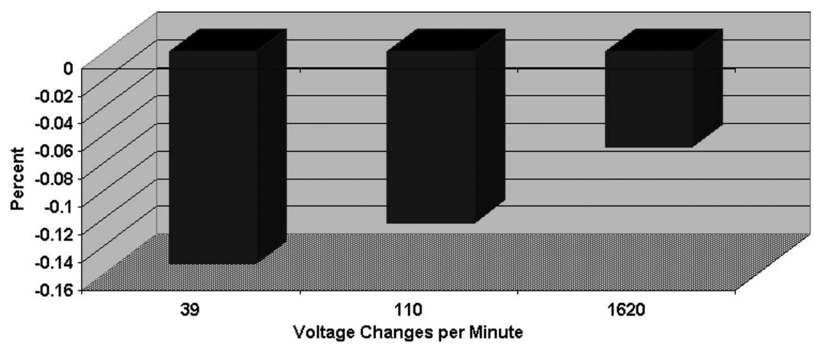

Fig. 15. Effect of a change in $|Z|_{50\ \mathrm{Hz}}$ with -10% on the voltage rates of change that should result in a value $P_{\mathrm{st}} = 1.0 \pm 0.05$.

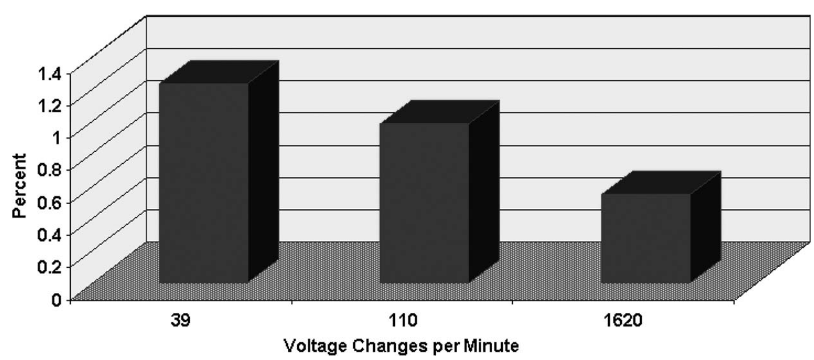

Fig. 16. Effect of a change in $|Z|_{50\ \mathrm{Hz}}$ with -10% on the voltage rates of change that should result in a value $P_{\mathrm{st}} = 1.0 \pm 0.05$.

This paper has addressed for the first time the possible influence of the network impedance on the calculated flicker parameters, such as P_{st}, $d_{\max}$, dt, and dc, and the analysis clearly shows that this influence cannot be neglected.

These conclusions are based on a representation of the low-voltage network in a computer simulation, assuming a change of the magnitude of the network impedance of $\pm 10\%$. In order to obtain a quantitative evaluation of the contribution to the measurement uncertainty resulting from the change of the magnitude of the network impedance when harmonic analyzers and flickermeters, which were calibrated in laboratory conditions, using the reference value of the network impedance according to the specialized standards, are used for in-field measurements, experimental results must be obtained regarding the interval within which the magnitude of a real low-voltage urban network may vary. The network impedance at the point of connection should be measured using one of the methods described in the literature [15], [16].

Even though the individual values of the differences in the current and power spectra, which are induced by the change of the magnitude of the network impedance, may be influenced by the way the change of the impedance is simulated, due to the special attention paid to complying with the constraints in the standard and also to the mimicking of a real network, the results of the study clearly indicate that, in the absence of any information regarding the network impedance at the point of connection, in-field measurements of harmonic distortion and flicker may lead, in some cases, to inaccurate results.

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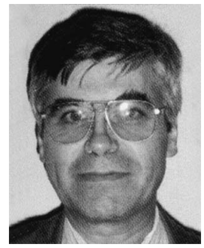

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Mr. Clarkson is a Chartered Engineer and a member of the Institution of Engineering and Technology.