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ON THE INFLUENCE OF NETWORK IMPEDANCE ON FLICKER MEASUREMENTS

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Se prezintă rezultatele studiului referitor la influenţa pe care variaţii relativ mici ale impedanţei reţelei electrice o poate avea asupra măsurărilor de flicker efectuate in-situ, cu instrumente pentru măsurarea severităţii flicker-ului (flickermetre) etalonate în laborator, în condiţii de referinţă. S-a realizat simularea variaţiei cu ± 10 % a impedanţei reţelei faţă de valoarea de referinţă, utilizând un model de reţea de joasă frecvenţă de tip urban şi forme de undă modulate rectangular, care simulează variaţii de tensiune în reţea corespunzătoare unui indice de severitate a flicker-ului $P_{ST} = 1$.

The results of the study on the influence that relatively small changes in the network impedance may have on in-field flicker measurements, performed using measuring instruments for the flicker severity (flickermeters), which were calibrated in laboratory, under reference conditions. Changes of the network impedance with ± 10 % of the reference value were simulated, using a network model, emulating a typical low voltage, urban network, and rectangular modulation waveforms, emulating changes in the network voltage corresponding to a flicker severity index $P_{ST} = 1$.

Keywords: flicker, flicker severity, network impedance, modelling, calibration.

1. Introduction

Voltage fluctuations in a low voltage distribution network are cyclical variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not exceed the range of permissible operational voltage changes, which are mentioned in IEC 38, meaning that they do not exceed ±10% of the nominal value. [1]

The flicker phenomenon represents a particular case of voltage fluctuations in a network, which is associated with the sensation of instability of

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the visual perception induced by a light source, as a result of rapid, recurrent changes in time of its luminous flux, or of its spectral distribution, produced by repeated voltage sags occurring in the network which powers that light source. It has been shown that the response on the chain eye-brain in humans is the highest when the fluctuations of the luminous flux are produced by voltage changes with a rate of about 1000 changes per minute, in the case of vulnerable persons, this rate of change representing a risk of triggering epileptic fits.

Since this flickering of the light source produces a significant discomfort for the human being, leading to physical and physiological tiredness, and even producing some pathological effects or causing work accidents in certain industrial environments, the systematic study of this phenomenon and performing repeatable and reproducible measurements are an important part of the power quality control issue.

The most frequent cause of such voltage changes (concerning its RMS value), which might result in the occurrence of flicker, is represented by large electrical loads connected to the network, which draw a fluctuating current, e.g., large motor drives and arc furnaces. The voltage changes referred here describe transitions in RMS voltage from one steady state to another, and therefore are a distinct case of voltage fluctuations from those described as transient phenomena.

2. The basic principle

The basic principle for the mechanism of this phenomenon may be illustrated using the circuit in Fig. 1.

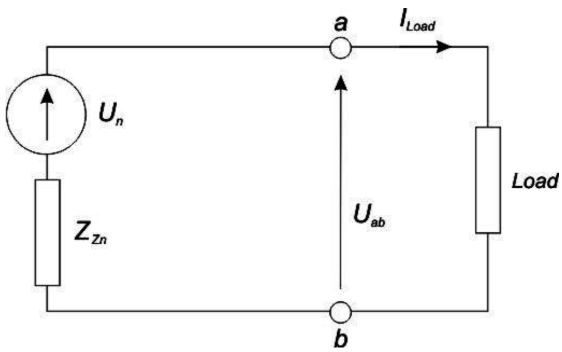

Fig. 1 Illustration of the influence of a load on a network [2]

The voltage at the point of connection of the load is lower than the voltage generated by the source due to the voltage drop on the network impedance:

$$U_{Z_n} = I_{Load} \cdot Z_{Z_n} \qquad (1)$$

where: I_{Load} = the current flowing through the network load

Z_{Zn} = the network impedance as seen from the point of connection (*a*, *b*).

The voltage at the point of connection (*a*, *b*) will, therefore, be:

$$U_{ab} = U_n - U_{Z_n} \quad (2)$$

One may notice that any change occurring in the load current I_{Load}, particularly in the reactive component, will result in an unwanted change of the voltage U_{ab} at the point of connection.

It is worth mentioning that even though the conditions that lead to the occurrence of flicker in a network are much more complex, the basic mechanism depicted above is essentially the same.

In practice, whenever a relatively large load is connected to the distribution network, two question arise, i.e., whether this load will determine the occurrence of flicker in the network and whether this flicker will exceed the accepted limits specified in the appropriate applicable standards. It is nevertheless true that the unwanted or even dangerous effects that connecting a large load to a network may induce depend very much on the specific parameters of that particular network, as well as on the type of loads which are also connected to the same load.

A method commonly used in practice to determine the severity of the flicker phenomenon is the one based on measuring the fluctuation of the luminous flux coming from an incandescent lamp powered by the current supplied by the assessed network. In this case, the relationship existing between the luminous flux of the lamp and the changes in the supply voltage are illustrated in Fig. 2. [2]

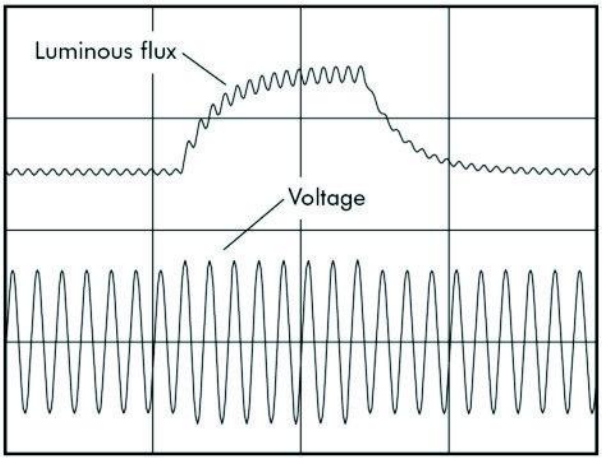

Fig. 2 The mechanism of the change in luminous flux of an incandescent lamp as a result of a temporary change in the supply voltage

The assessment of this effect may be achieved in two steps: [3]

- The measurement of the instantaneous flicker sensation, as the human eye perceives it;
- The statistical evaluation of the flicker severity index.

The flicker phenomenon raises serious problems when it comes to being quantitatively evaluated, because it involves measuring a physiological phenomenon with a high degree of subjectivity.

3. Measurement of flicker severity

The first instruments developed for the measurement of the flicker severity were based on the simple observation of luminous flux, then further developed in an attempt to model the human sensation of discomfort produced by the fluctuation of the luminous flux of a 60 W, 230 V tungsten bulb, which was commonly used as light source in Europe at that time.

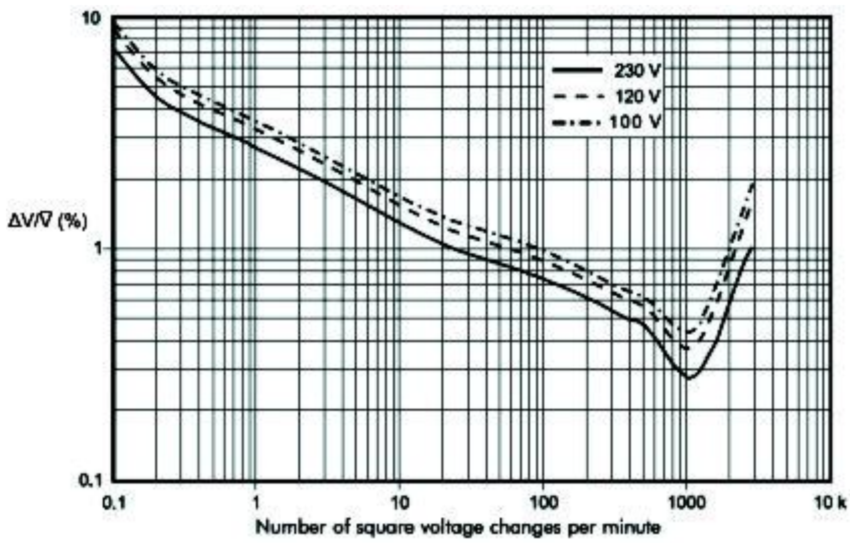

Fig. 3 Flicker perception characteristic for square-shaped voltage changes applied to 60 W bulbs

According to the model of the human sensation of discomfort produced by the fluctuation of the luminous flux of a 60 W, 230 V tungsten bulb a threshold of perception of the flicker sensation is determined as shown in Fig. 3, where this threshold of perception is represented in terms of percentage voltage change on the y axis and rate of square voltage changes per minute on the x axis [2]. The effect is likely to be disturbing to a human observer whenever the magnitude and frequency of the voltage changes lie above the curve, and it is considered to be imperceptible for the human eye, when the magnitude and rate of the voltage changes lie below the curve.

The dashed lines correspond to 60 W tungsten bulbs designed for other nominal voltages.

At present, the main problems concerning the quantitative evaluation of flicker may be considered to be to a large extent solved, since there is already a standardised method for the quantitative evaluation of the flicker sensation produced by the fluctuation of the supply voltage in the distribution network, as well as a standardised structure for the flickermeters, based on the flickermeter developed by UIE/IEC, structure defined in the IEC 61000-4-15 standard [4], which provides a good comparability of results.

In order to quantitatively evaluate the flicker sensation, two flicker severity indexes were adopted, i.e., short term flicker severity, P_{ST}, and long term flicker severity index P_{LT}. [5]

The short term flicker severity index P_{ST} is calculated based on the instantaneous flicker observation, using the cumulative probability function, over a period of 10 minutes:

$$P_{ST} = \sqrt{0.0314 P_{0.1} + 0.0525 P_{1S} + 0.0657 P_{3S} + 0.28 P_{10S} + 0.08 P_{50S}} \qquad (3)$$

where the percentages $P_{0.1}$, P_{1s}, P_{3s}, P_{10s}, P_{50s} are derived form the cumulative probability function and represent the flicker levels, which are exceeded in 0.1 %, 1.0 %, 3.0 %, 10.0 % and 50.0 % of the observation time.

The index ‘s’ in the probabilities P_{1s}, P_{3s}, P_{10s}, and P_{50s} signifies that these estimations are statistically derived by means of an averaging process.

The value of the short term flicker index P_{ST} = 1.0 corresponds to a flicker that is considered to be irritable for the human being.

This has been proven to be the level at which the corresponding fluctuations of the luminous flux of a 60 W incandescent bulb are perceived as flicker by 50 % of people.

The long term flicker severity index, P_{LT}, is also evaluated by means of a statistical process, as an average of the 3^{rd} power of P_{ST}, for a sequence of N evaluations of P_{ST}, the value of N being determined by the operation cycle of the load which induces the flicker disturbance in the network.

When the duration of the operation cycle is unknown, it is recommended to use a sequence of N = 12 evaluations of P_{ST}, each for a standard observation time of 10 minutes, which corresponds to the evaluation of P_{LT} over a period of 2 hours, using the expression:

$$P_{LT} = \sqrt[3]{\sum_{i=1}^{N} \frac{P_{STi}^3}{N}} \quad (4)$$

Since people's tolerance to flicker over longer periods is less than for the short term flicker, the upper limit for P_{LT} was set at 0.8 units.

As shown above, the fluctuation of the voltage at the point of connection depends on the network impedance as seen from that point. It would, therefore, be useful to study the influence that relatively small changes in the network impedance might have on the flicker measurements, performed in-field, using a flickermeter connected to the network.

4. The setup used in the study

Since the flickermeters are calibrated in laboratory conditions, against a reference value for the network impedance, according to the provisions in the IEC 61000-3-3 standard, while the in-field measurements of the parameters describing the power quality, including flicker, are performed in the specific conditions of that particular network, to question whether relatively small changes in the network impedance may have an influence on the measurement of flicker severity index is justified.

In order to be able to examine the influence that changes in the network impedance may have on flicker measurements, an original network model, previously developed for the study of the influence of the network impedance on the measurement of harmonic distortions, as part of the research project carried out within the framework of the PhD Programme with the Graduate School for Electrical Engineering of the University Politehnica of Bucharest.

The use of this model was considered to be appropriate for the flicker study, because it reproduces very accurately the magnitude of the impedance of a low voltage urban network at the nominal frequency of 50 Hz and allows the change of this magnitude, while maintaining the behaviour of the impedance in a typical real network, as defined in Annex B of the Amendment 1/FDIS to the IEC 61000-4-7 standard. [5]

Moreover, the use of the same model for the flicker related study provides a coherent and consistent approach for the whole study of the influence of changes in the network impedance on the measurement results of power quality parameters in a real, low voltage, residential network.

In order to simulate the voltage fluctuations which induce the flicker sensation, the square modulation waveforms developed and used in the calibration service for flickermeters, at the National Physical Laboratory (NPL), in the United Kingdom, were used by permission from NPL. These square modulation waveforms, whose principle is illustrated in Fig. 4, provide conformity with the provisions in the IEC 61000-4-15 / A1 standard.

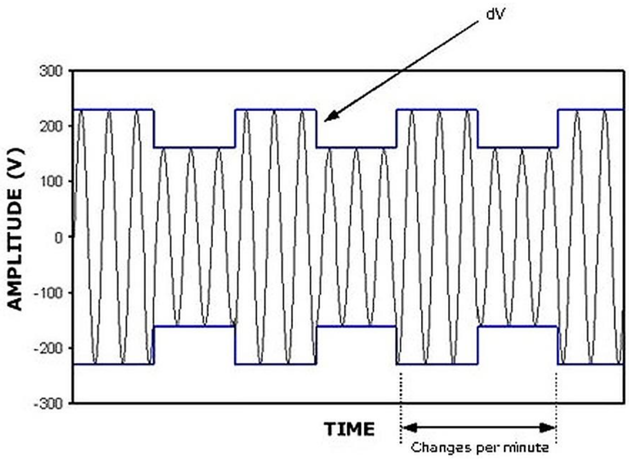

Fig. 4 square modulation waveforms used in the calibration service for flickermeters, at the National Physical Laboratory (NPL), UK

In order to study the influence that changes in the network impedance might have on flicker severity index measurements, the general setup illustrated in Fig. 5 was used.

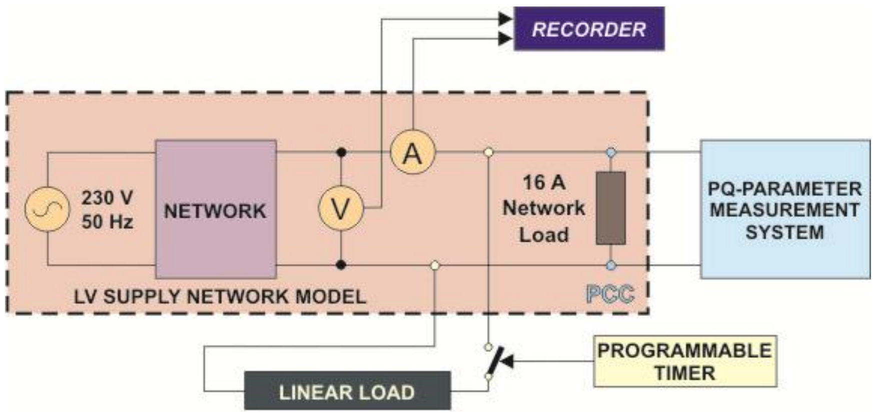

Fig. 5 Schematic representation of the setup used to study the influence of small changes in the network impedance on the measurement of flicker severity index

The square modulation waveforms used in the NPL calibration service for flickermeters were obtained by using a switch, controlled by a programmable timer, which connects or disconnects a linear load connected to the network model.

The network model used in the study was an original equivalent circuit, whose impedance may be changed by altering the values of both its resistive and reactive components, while maintaining the compliance with the behaviour of a typical low voltage residential network, as described in the standard, and the linear load was a group of four loads connected in parallel to the network model through a programmable switch, as shown in Fig 6.

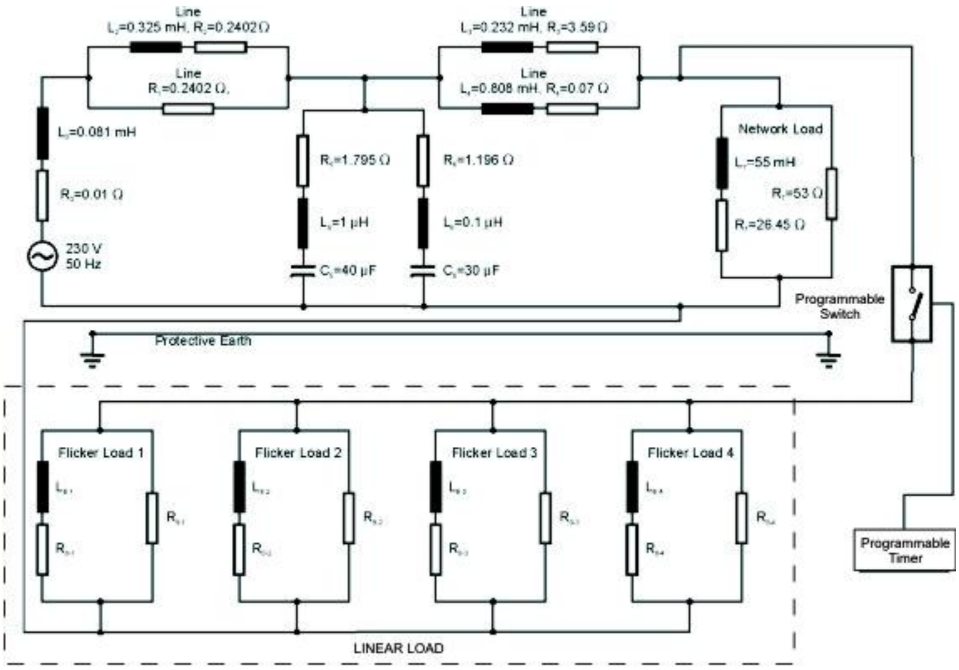

Fig. 6 Circuit used in the study of the influence that changes in the network impedance might have on the measurement of flicker severity index

The modulation depths corresponding to the various rates of change were accurately simulated by adjusting the values of the elements in the four loads which make the linear load.

Using the programmable timer to control the switch, the modulation frequencies corresponding to the various rates of change for the network voltage were realised, by connecting or disconnecting the group of four loads to the network model as illustrated in Fig. 6.

The flicker voltage thus induced into the network has the form:

$$S(t) = V_{\max}\left(1 + \frac{D}{200}\, sign\left(\sin\left(2\pi f_F t + \varphi_F\right)\right)\right) \times \sin\left(2\pi f t + \varphi\right) \qquad (5)$$

where: - D is the modulation depth, expressed in percents,
- f_F is the flicker frequency,
- f is a power line frequency,
- φ_F is the phase of the modulation waveform,
- φ is the phase of the carrier waveform
- sign(x) = + 1, for $x >= 0$ and – 1 for $x < 0$.

The typical modulation depths and frequencies for the square waveforms used to calibrate flickermeters at NPL are given in Table 1 and are in compliance with the data in Table 5 of the IEC 61000-4-15 standard.

Table 1

The modulation depths and frequencies for the square waveforms used by the calibration service for flickermeters at NPL

Modulation depth (%)	Modulation frequency (mHz)
2.724	8.333
2.211	16.667
1.459	58.333
0.906	325
0.725	916.667
0.402	13 500
2.4	33 333

The programmable timer allowed a very accurate reproduction of the modulation frequencies prescribed in Table 1 so that very accurate reproductions of the square waveform modulation depths and rates of change prescribed by NPL were achieved.

By applying such a waveform to the input of a flickermeter to be calibrated, the display of the instrument should indicate a value for the short term flicker severity index $P_{ST} = 1.0 \pm 0.05$.

It should be mentioned that, even though the setup described above allows a very accurate reproduction of all the square modulation waveforms developed and used by the calibration service for flickermeters at NPL, it was not possible to perform simulations for all the square waveforms due to the technical limitations of the computer used in the study. Thus, the attempts to perform a simulation of a flicker corresponding to the voltage rates of change of 1, 2 and 7 changes per minute failed due to the fact that the acquired data was so large that it exceeded both the storage memory and the data processing capability of the computer used in the study, even after extending the RAM up to the maximum supported by the hardware and the operating system

Nevertheless, it is justified to consider that the flicker simulations, which could be performed, using the voltage rates of change of 39, 110 and 1620 changes per minute, are representative for the study of flicker, since all the rates of change are alternative ways of inducing disturbances into the network, which produce the same flicker sensation, corresponding to a flicker severity index $P_{ST} = 1.0 \pm 0.05$, as indicated above.

It is therefore justified to consider that the simulations of the flicker generating disturbances corresponding to those voltage rates of change which were supported by the computer are relevant, since the square modulation waveforms developed and used at NPL are reproduced with high accuracy, as illustrated in Fig. 7.

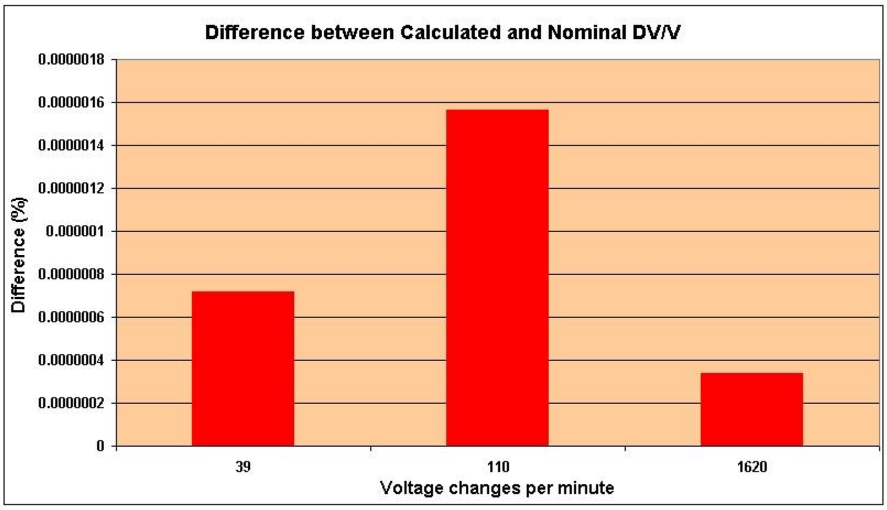

Fig. 7 The accuracy with which the square modulation waveforms from NPL are reproduced, for the three voltage rates of change used in the flicker simulations

Under these circumstances, it is justified to consider that the simulations performed using the setup presented above describe very well the influence that relatively small changes in the network impedance may have on the in-field flicker measurements.

5. Results of the study

In order to study the influence that relatively small changes in the network impedance may have on the measurements of flicker severity, and in order to maintain a realistic representation of a real low voltage residential network, where the changes in the network impedance are the result of changes occurring in the resistive component as well as in the reactive component of the impedance, within the study, both the resistive and the reactive components of the impedance of the network model were adjusted, so that the magnitude of the impedance, at the nominal frequency f = 50 Hz, is, in the first case, diminished with 10 % and, in the second case, increased with 10 % of its reference value at the nominal frequency, i.e., $|Z|_{50\,Hz} = 0.4717\ \Omega$.

This operation was repeated for each of the three voltage rates of change for which the data acquisition and processing was possible with the computer available for this study.

The results obtained when the magnitude of the network impedance at the nominal frequency f = 50 Hz was changed with – 10 % of the reference value $|Z|_{50\,Hz}$ are given in Annex 1.

In order to get an intuitive image of the results, the differences between the modulation depth when the network impedance is changed with – 10 % and when the network impedance has the reference value were calculated for each of the three values of the voltage rates of change used in the study. These differences in the values of DV/V, expressed in percentages, are represented in Fig. 8.

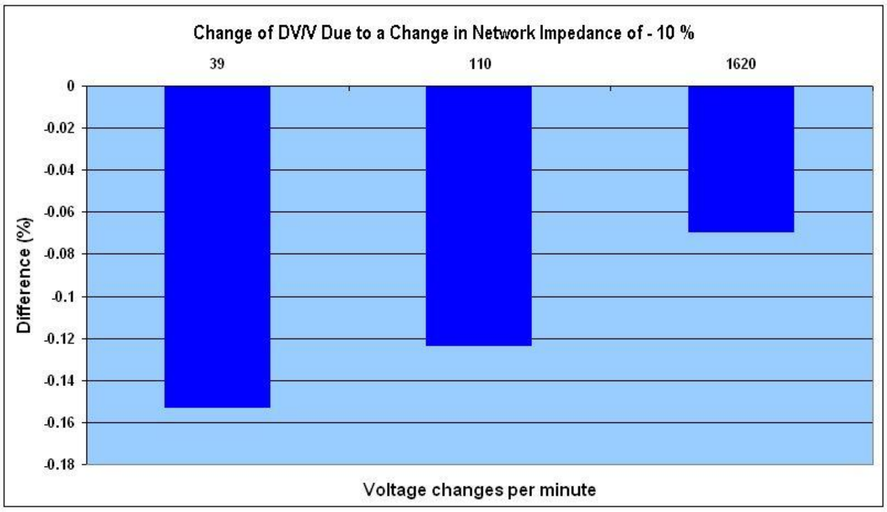

Fig. 8 The effect of the change in the magnitude of the network impedance $|Z|_{50\,Hz}$ with –10 % of the reference value on the modulation depth, for each of the voltage rates of change used in the study

As one may see from Fig. 8, the resulting differences in the values of DV/V, expressed in percentages, are all negative and relatively small, e.g., – 0.07% for the voltage rate of change of 1620 voltage changes per minute, but there is a clear tendency to increase as the voltage rate of change decreases, so that it reaches – 0.15 %, for the voltage rate of change of 39 voltage changes per minute.

The results obtained when the magnitude of the network impedance at the nominal frequency $f = 50$ Hz was changed with + 10 % of the reference value $|Z|_{50\ Hz}$ are given in Annex 2.

The differences between the modulation depth when the network impedance is changed with + 10 % and when the network impedance has the reference value were also calculated in this case, for each of the three values of the voltage rates of change used in the study. The resulting differences in the values of DV/V, expressed in percentages, are represented in Fig. 9.

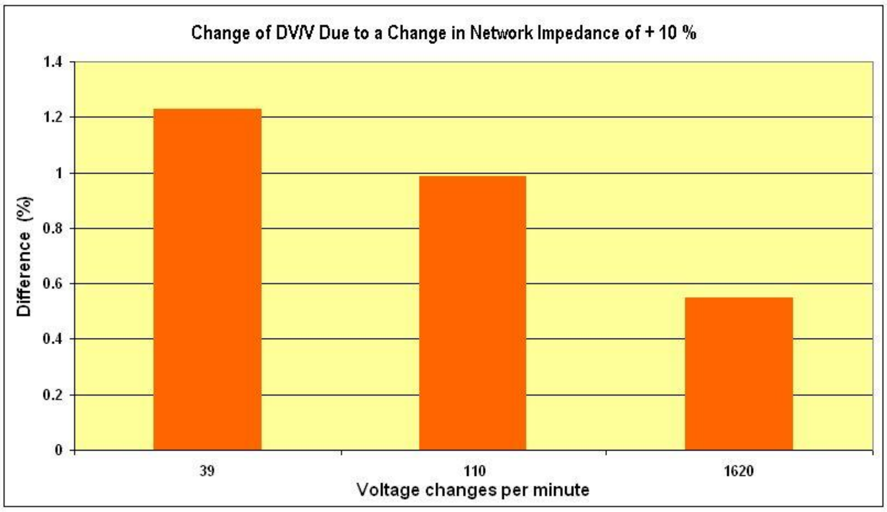

Fig. 9 The effect of the change in the magnitude of the network impedance $|Z|_{50\ Hz}$ with + 10 % of the reference value on the modulation depth, for each of the voltage rates of change used in the study

In this case, as one may see from Fig. 9, the resulting differences in the values of DV/V, expressed in percentages, are all positive, but significantly larger than in the previous case.

It is quite clear that the tendency of the differences in the values of DV/V, expressed in percentages, to increase as the voltage rate of change decreases is also present when the magnitude of the network impedance is changed with + 10 % of the reference value $|Z|_{50\ Hz}$.

Thus while the difference in the values DV/V, corresponding to the voltage rate of change of 1620 voltage changes per minute, is + 0.55 %, the value of DV/V increases to + 1.23 % for the voltage rate of change of 39 voltage changes per minute.

In order to have a better sense of the discrepancy between the differences in the values of DV/V when the magnitude of the network impedance changes with - 10 % of the reference value $|Z|_{50\ Hz}$, and when it changes with + 10 % of the reference value $|Z|_{50\ Hz}$, both situations are represented in the same graph, in Fig. 10.

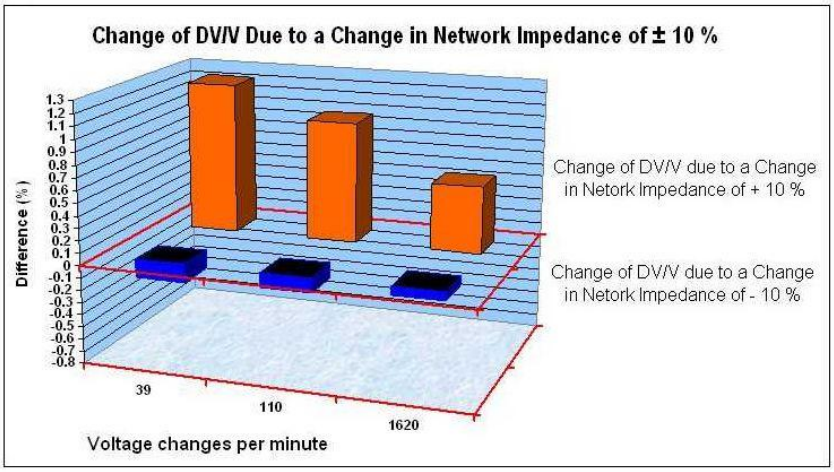

Fig. 10 Illustration of the different effect that the change in the magnitude of the network impedance has on the modulation depth when the magnitude of the network impedance changes with – 10 % of the reference value $|Z|_{50\ Hz}$ and when it changes with + 10 % of the same reference value, for each of the voltage rates of change used in the study

5. Conclusions

The study made use of and original network model and tackled the influence of the electrical network impedance on power quality, an aspect of power quality assessment less studied until very recently.

Regarding the particular influence that relatively small changes in the magnitude of the network impedance may have on the flicker severity, the results of the study performed demonstrate that the change in the magnitude of the network impedance at f = 50 Hz, $|Z|_{50\ Hz}$, with ± 10 % of the reference value, i.e., $|Z|_{50\ Hz} = 0.4717\ \Omega$, may indeed influence the in-field measurements of the flicker severity, performed with flickermeters that are calibrated in the laboratory, in reference conditions, which include the reference value of the magnitude of the network impedance.

The study showed that both the decrease and the increase of the magnitude of the network impedance with 10 % compared with the reference value, but the influence is different for the different voltage rates of change tested, being lower for higher rates and tending to increase as the voltage rate of change decreases. In particular circumstances, this dependence of the influence of the change in the magnitude of the impedance on the voltage rate of change may be likely to alter flicker measurements since all the voltage rates of change used in the study should result in the same flicker severity index $P_{ST} = 1.0 \pm 0.05$.

The study also showed that the influence of the change in the magnitude of the network impedance with + 10 % of the reference value on the modulation depth is significantly greater than the influence of the change in the magnitude of the network impedance with – 10 % of the reference value, in fact about one order of magnitude greater. That would seem to indicate that networks with higher impedance would be more likely to be affected by flicker induced by large loads connected to the network.

The study performed indicates that in determining the likelihood of inducing flicker in a network by connecting a large load to that network, among other characteristics of the network, a good knowledge of the network impedance is also important.

Acknoledgement

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ANNEX 1

THE INFLUENCE ON FLICKER MEASUREMENT OF A CHANGE IN NETWORK IMPEDANCE OF -10 %

Modulated signal (Carrier)		Reference network impedance at 50 Hz					Network impedance at 50 Hz down 10 %					
Voltage changes per minute	Voltage changes per second	V_{Peak1}	V_{RMS1}	V_{Peak2}	V_{RMS2}	Calculated DV/V	V_{Peak1}	V_{RMS1}	V_{Peak2}	V_{RMS2}	Calculated DV/ V	Absolute change of DV/ V
		V	V	V	V	%	V	V	V	V	%	%
39	0.65	319.5811	225.97796	316.6988	223.9398	0.9060007	320.3423	226.5162	317.9388	224.8167	0.7531165	-0.1528843
110	1.833333	319.5812	225.97803	317.2726	224.3456	0.7250016	320.3423	226.5162	318.4202	225.1571	0.6018199	-0.1231816
1620	27	319.5811	225.97796	318.2990	225.0714	0.4020003	320.3423	226.5162	319.2775	225.7633	0.3329478	-0.0690525

ANNEX 2

THE INFLUENCE ON FLICKER MEASUREMENT OF A CHANGE IN NETWORK IMPEDANCE OF +10 %

Modulated signal (Carrier)		Reference network impedance at 50 Hz					Network impedance at 50 Hz up 10 %					
Voltage changes per minute	Voltage changes per second	V_{Peak1}	V_{RMS1}	V_{Peak2}	V_{RMS2}	Calculated DV/V	V_{Peak1}	V_{RMS1}	V_{Peak2}	V_{RMS2}	Calculated DV/ V	Absolute change of DV/ V
		V	V	V	V	%	V	V	V	V	%	%
39	0.65	319.5811	225.97796	316.6988	223.9398	0.9060007	318.7112	225.3629	315.3013	222.9517	1.0756570	1.2285413
110	1.833333	319.5812	225.97803	317.2726	224.3456	0.7250016	318.7112	225.3629	315.9759	223.4287	0.8619365	0.9851182
1620	27	319.5811	225.97796	318.2990	225.0714	0.4020003	318.7112	225.3629	317.188	224.2858	0.4790696	0.5481222