# TESTS, RECORDINGS AND NUMERICAL PROCESSINGS OF DISTORTING AND UNBALANCED OPERATING REGIMES OF A SYNCHRONOUS GENERATOR

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*Abstract* – **The paper deals with the recording and analysis of electric quantities waveforms from the components of a synchronous generator. The quality parameters of powers are determined in distorting and unbalanced regimes. Based on the relations used for the determination of the quality factors of electric quantities and respectively for the determination of the active and reactive powers, an analysis is made. It is concerned with the waveforms from: the main generator stator, the auxiliary generator stator before the fully controlled rectifier with thyristors and from the main generator rotor. Possible interdependencies between these quantities are determined.**

***Keywords:*** *data acquisition, energy measurement, harmonic analysis, power quality.*

## 1. INTRODUCTION

The electric power supplying sources from a power system (synchronous generators from electric power plants) supply energy that obeys the quality norms in what is concerning electric energy supplying continuity and quality parameters. In the past years, simultaneously with the development of applications based on power electronics, new technical problems appeared [6], [9]. They turned into new challenges for those engineers that design and exploit the electric energy supplying sources from the electric power plants.

Even though the voltage delivered by a synchronous generator obeys the electric energy quality norms, in many other practical situations, owing to the interactions between the distorting consumers and the power sources from the power system, significant harmonic currents can occur. They should flow through the main or auxiliary generator windings. Often these quantities are amplified due to some resonance phenomena that can occur. This results into a more significant distorting of the voltage delivered to consumers [8]. Under these conditions the measuring of electric quantities (voltages and currents) and of powers imposes the use of better classes of precision to all test apparatus, in order to have a correct evaluation of the delivered energy [1], [10], [13], [14].

The results provided by modern acquisition system, along with faster soft packages for data analysis and processing can provide very useful real time information. Despite of all these still there are problems related to the theoretical support (different algorithms) applied during the test procedures and respectively to the fast decisions that one must take in very distinct situations [5].

The correct analysis and interpretation of the recorded data may be used, for the electro-energetic group as a whole, as a possible diagnosis method, based on the analysis of distorting and unbalanced regimes. The determination of the powers that correspond to the fundamental harmonic and respectively to the superior harmonics could provide precious indications both for the correct taxing of power flows from the electro-energetic group toward the power system and respectively for a possible erroneous operation of some components from the power system.

## 2. WAVEFORMS RECORDINGS

In order to detect the steady state operation and the interdependencies between various components of an electro-energetic group, we performed experimental determinations in an electro-energetic group whose rated installed power is 330 MW.

The experimental determinatios focused on:

- the recording of voltages and currents waveforms from the main generator's stator;
- the recording of voltages and currents waveforms from the main generator's excitation winding (after fully controlled rectifier);
- the recording of voltages and currents waveforms from the auxiliary generator's stator.

The currents and voltages waveforms recording was done using two data acquisition systems, with sample frequency as high as 4,000 Hz. In this way it was possible to record the first 40 harmonics. The first data acquisition system was used to record data from the secondary windings of the current and voltage transformers for the main generator (Fig.1). This system was specially designed for this application. Its calibration was made so as to enable it to record the voltages and currents from the secondary windings of the current and voltage transformers for the main generator.

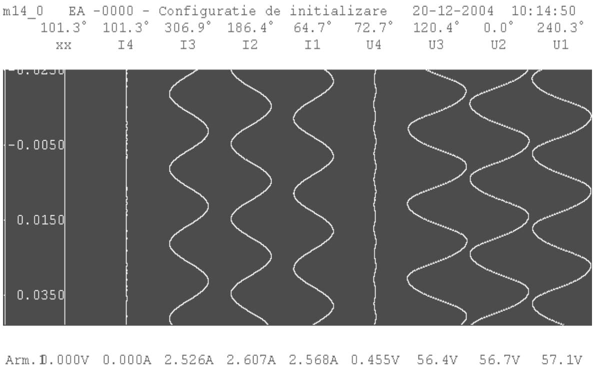


Fig. 1. The currents and the voltages at synchronous generator terminals

The second data acquisition system was used to record data corresponding to the time – variation of the currents ($i_1$, $i_2$, $i_3$) from the secondary windings of the current transformers and the data corresponding to voltages ($u_3$, $u_4$, $u_5$) were directly recorded from the auxiliary generator terminals. All these determinations are depicted by Fig. 2.

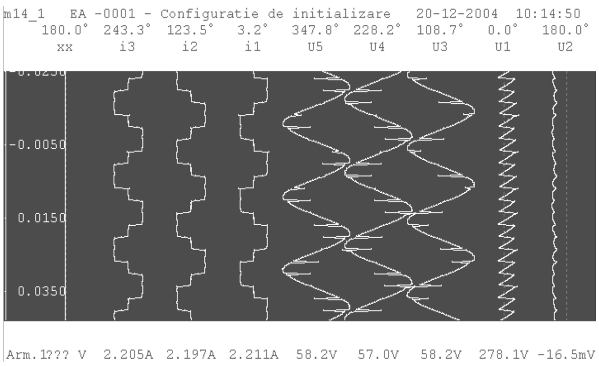


Fig. 2. The currents and the voltages at auxiliary synchronous generator terminals and d.c. voltage and current

The second data acquisition system was also used to record the waveforms after the fully-controlled rectifier with thyristors. The current after the rectifier was recorded using a 60 mV shunt ($u_2$ – from Fig.2) and the voltage after rectifier was directly recorded ($u_1$ – from Fig.2). The second data acquisition system was also specially designed for the presented application.

In order to detect the interdependencies between the various components of the electro-energetic group, a synchonization equipment was placed between the data acquisition systems. So the steady states recordings at both generators were made simultaneously.

## 3. ANALYZED QUALITY PARAMETERS

Based on the recorded waveforms there were performed harmonic decompositions of the voltages and currents up to the *40*-th harmonic order (according to the European norms). An original soft package was used, that relies on Fourier decomposition for any number of harmonics. In order to perform a verification of the accuracy of results provided by soft, the signals decomposed in harmonics were consequently recomposed. Every time we calculated the error detected through the comparison between the original signal composition and its counterpart, computed after recomposition using the 40 computed harmonics.

The performed decomposition relies on the possibility to decompose a periodic steady signal in Fourier series with the formula:

$$y(t) = Y_0 + \sum_{k=1}^{n} \sqrt{2} Y_k \sin(k\omega t + \gamma_k) \qquad (1)$$

Here continuous components are present ($Y_0$) and "n" is the finite number of harmonics, including the fundamental harmonic (corresponding to k=1) [2], [12]. Based on the decomposition from (1) one could determine quality factors for the recorded waveforms:

- Peak factor:

$$k_V = \frac{Y_{\max}}{Y} = \frac{Y_{\max}}{\sqrt{\sum_{k=0}^{n} Y_k^2}} \qquad (2)$$

- Shape factor:

$$k_f = \frac{Y}{\frac{2}{T}\int_{t_0}^{t_0+\frac{T}{2}} y(t)dt} \qquad (3)$$

- Distorting factor:

$$k_d = \frac{Y_d}{Y_1} = \frac{\sqrt{\sum_{k=2}^{n} Y_k^2}}{Y_1} = THD \qquad (4)$$

The harmonic decompositions made possible a subsequent determination of the active and reactive powers based on Budeanu's theory [2], extended for a unbalanced and distorting regime [3], [4]. The powers were determined with the following relations.

- Single phase fundamental active power:

$$P_{11} = U_1 I_1 \cos\varphi_1 \qquad (5)$$

- Single phase active power:

$$P_1 = U_0 I_0 + \sum_{k=1}^{n} U_k I_k \cos\varphi_k \qquad (6)$$

- Single phase fundamental reactive power:

$$Q_{11} = U_1 I_1 \sin\varphi_1 \qquad (7)$$

- Single phase reactive power:

$$Q_1 = \sum_{k=1}^{n} U_k I_k \sin\varphi_k \qquad (8)$$

- Three-phase active power:

$$P = P_1 + P_2 + P_3 \tag{9}$$

- Three-phase reactive power:

$$Q = Q_1 + Q_2 + Q_3 \tag{10}$$

## 4. DECOMPOSITION AND ANALYSIS OF VOLTAGES AND CURRENTS WAVEFORMS

### 4.1. Decomposition and analysis of stator waveforms

The waveforms corresponding to voltages and currents from the stator phases were decomposed into 40 harmonics. Fig. 3 depicts the harmonic content of the voltage from phase no. 1 and Fig. 4 depicts the harmonic content of the current through the same phase.

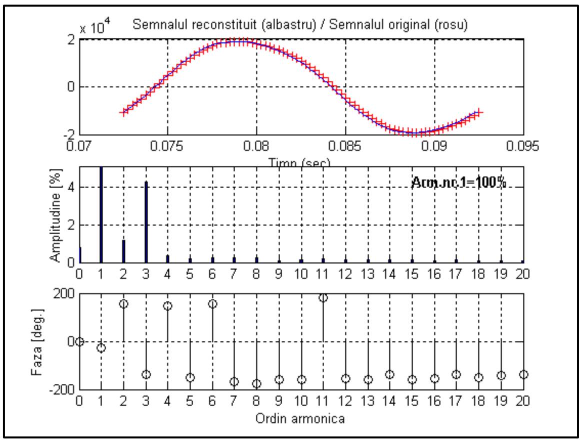


Fig. 3. Harmonic content of voltage $u_1$

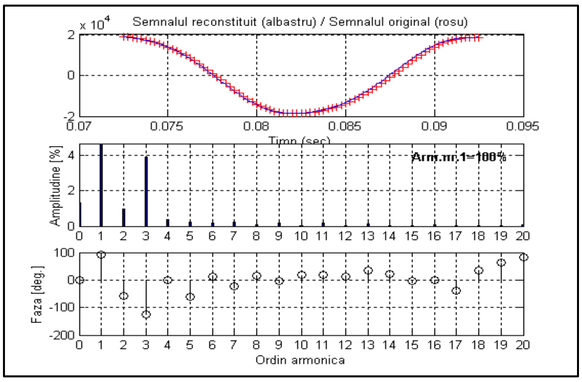


Fig. 4. Harmonic content of current $i_1$

In both cases the initially decomposed signal was reconstructed using its harmonics up to the 40-*th* order. Each time there were revealed small differences between the initial values and those obtained after the reconstruction. The quality parameters of the phase quantities are reproduced by Table 1 and Table 2.

| Quality parameter | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| RMS value [V] | 13 854 | 13 627 | 13 853 |
| Peak factor | 1.39 | 1.38 | 1.39 |
| Shape factor | 1.087 | 1.086 | 1.088 |
| UTHD | 4.61 | 4.63 | 4.31 |

Table 1: Quality parameters for phase voltages of main generator stator

| Quality parameter | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| RMS value [A] | 5 122 | 5 033 | 5 264 |
| Peak factor | 1.42 | 1.42 | 1.42 |
| Shape factor | 1.096 | 1.095 | 1.096 |
| ITHD | 2.50 | 2.93 | 2.32 |

Table 2: Quality parameters for phase currents of main generator stator

Based on the 40 harmonics decomposition, using the equations (2), (3), (4) we determined the quality parameters for the voltages and currents waveforms. The analysis of these quantities proves that the currents distorting is less visible than that corresponding to voltages (the total harmonic distortions for voltages had a minimum value $U_{THD3}$ = 4.31% and respectively a maximum value $U_{THD2}$ = 4.63%). In the case of currents, the total harmonic distortions vary from a minimum value of 2.32% ($I_{THD3}$) to a maximum value of 2.93% ($I_{THD2}$). The deviation from 1.41 (corresponding to the peak factor in the sine case) for every phase voltage peak factor is lower than the same set of deviations corresponding to phase currents. The shape factors for phase voltages present higher deviations from the ideal value of 1.1 (sine case) as compared to the shape factors corresponding to currents.

All these clearly prove the fact that the power system has a strong influence over the main generator from the electro-energetic group. Even though the voltages at generator terminals present higher distortions, owing to the power system, the currents flying through the stator phases present a lower distorting degree. This means that actually the main cause of the phase voltages distortions is an internal problem of the main generator.

The analysis of powers (computed with the relations (5)…(10)) reveals that:

- the phases total active power was $P_c$=212.25 MW, whereas its directly determined experimental counterpart was $P_m$=212.21 MW;
- the phases total reactive power was $Q_c$=5.731 MVAr, whereas its experimental counterpart (directly determined) was $Q_m$= 0 MVAr.

The revealed differences (although not significant) between the computed powers and the experimental ones prove that there are flows of reactive powers from the generator toward the power system along the superior harmonics. The surplus of the power delivered by the generator in this case along the superior harmonics is not properly taxed.

### 4.2. Decomposition and analysis of waveforms for rotor

**a) Decomposition and analysis of waveforms at the auxiliary generator**

The waveforms corresponding to voltages and currents from the stator phases at the auxiliary generator were decomposed into 40 harmonics. Fig. 5 depicts the harmonic content of the voltage from phase no. 1 and Fig. 6 depicts the harmonic content of the current through the same phase. In both cases the initially decomposed signal was reconstructed using its harmonics up to the 40-*th* order. Each time there were revealed small differences between the initial values and those obtained after reconstruction.

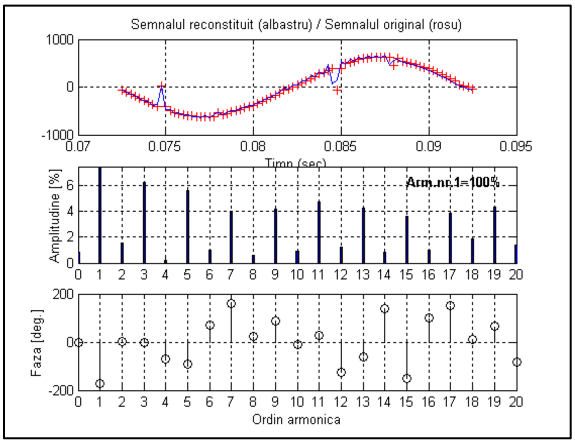


Fig. 5. Harmonic content of voltage $u_1$ for auxilliary generator

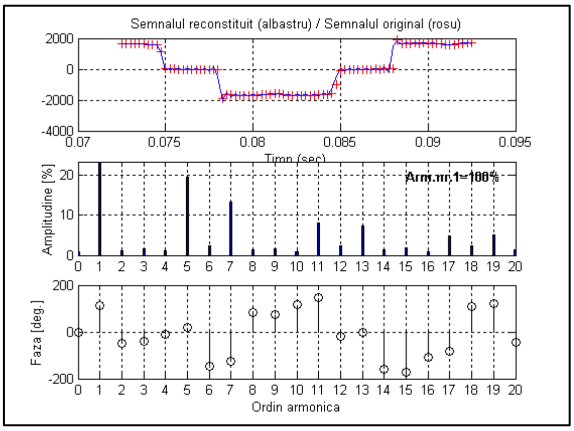


Fig. 6. Harmonic content of current $i_1$ for auxilliary generator

The quality parameters of the phase quantities, computed with the equations (2)-(4) are in Table 3 and Table 4.

| Quality parameter | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| RMS value [V] | 419 | 416 | 418 |
| Peak factor | 1.51 | 1.52 | 1.54 |
| Shape factor | 1.126 | 1.112 | 1.133 |
| UTHD | 18.69 | 18.53 | 25.49 |

Table 3: Quality parameters for phase voltages of auxiliary generator stator

| Quality parameter | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| RMS value [A] | 1 356 | 1 360 | 1 320 |
| Peak factor | 1.38 | 1.28 | 1.28 |
| Shape factor | 1.196 | 1.192 | 1.207 |
| ITHD | 28.23 | 28.22 | 27.43 |

Table 4: Quality parameters for phase currents of auxiliary generator stator

The analysis of the quality parameters of the phase quantities revealed the following:

- the voltages shape factors present small deviations from the ideal case (the shape factor is minumum for the phases 2 (1.112, being as high as 1.12, whilst for the 3-rd phase has a value of 1.133). In the same time, these factors present more significant deviations from the ideal value (that is 1.11) in the case of currents absorbed from the auxiliary generator by the rectifier fully controlled with thyristors (the shape factor is minimum for the 2-nd phase (1.192), whilst for the 3-rd phase it has a maximum value of 1.207;
- the voltages peak factors are generally higher than 1.41 (between 1.51 – for the first phase and 1.54 – for the third phase), whilst the currents peak factors are lower (a minimum is detected for the 2-nd and 3-rd phase, that is 1.28 and a maximum is detected for the 1-st phase, that is 1.38), fact that proves that the voltages are closer to the sine shape, even though some glitches can be noticed;
- the total distortions of the phase voltages and respectively of the phases currents are similar, but, if the voltages present a wider harmonic spectrum, the harmonic spectrum in the currents case presents significant weights for the following harmonics: 5,7,11,13,17,19. The significant weights of current harmonics corresponding to low orders (those of order 5 and 7 presents together weights of over 10% from the fundamental harmonic) has a certain influence over the operation of the entire electro-energetic group.

The voltages wider harmonic spectrum can be caused by a non-symmetrical operation within the main generator stator, that should be transmitted to the auxiliary generator through the reaction magnetic flow from the air-gap.

**b) Decomposition and analysis of waveforms after the fully-controlled rectifier with thyristors**

The harmonic decompositions of the excitation voltage and current (on the d.c. side) are depicted by

Figures 7 and 8. These figures depict both the recorded signals and respectively the harmonic decompositions of voltage and curly current – after the fully-controlled rectifier with thyristors.

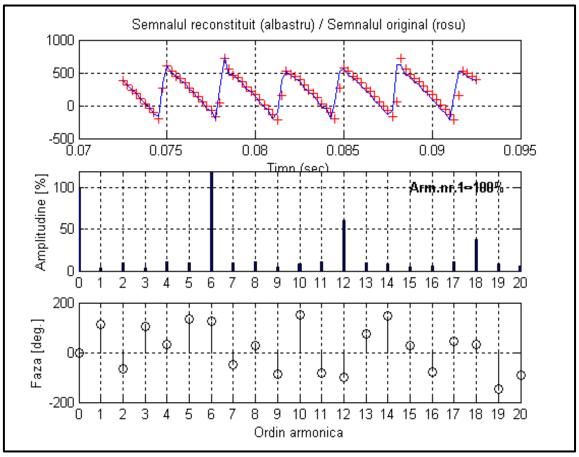


Fig. 7. Harmonic content of excitation voltage

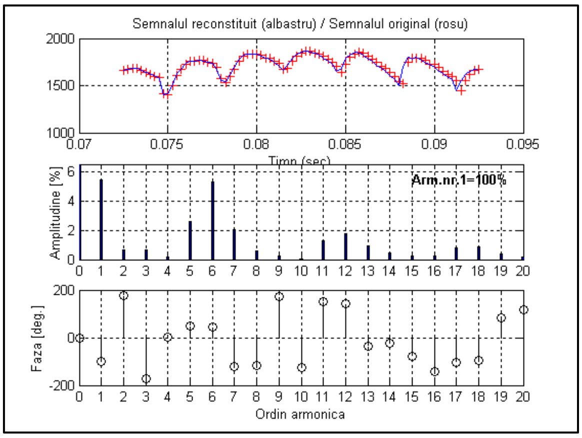


Fig. 8. Harmonic content of excitation current

The values of the d.c. components after the rectifier were: $U_{ex0}$=213.82V; $I_{ex0}$=1704A. In exchange, the RMS values of excitation voltage and current (considering the d.c. components too) were: $U_{exRMS}$=319V; $I_{exRMS}$=1707A.

The presence of some pulses in the auxiliary generator phase voltages and currents, probably caused by the non-synchronous control of thyristors from the fully controlled rectifier, leads to the apparition of some even harmonics, multiple of 6 in the rectified voltage waveforms. Therefore the difference between the d.c. value of the excitation voltage and its RMS value is significant. Moreover, the total active power of the d.c. components after the fully controlled rectifier was $P_{ex0}$=371kW, whereas the total value of the active power after the rectifier was $P_{extotal}$=363kW.

This difference proves an inverse flow of active power from the main generator toward the auxiliary generator.

## 5. CONCLUSIONS

The analysis of recordings and of subsequent numerical processing for the electric nature quantities (voltages, currents, powers) revealed some significant conclusions.

A. The connecting of the generator from the electro-energetic group to the European power system have the following effect: at system level, the voltages (considering the energetic consumptions for this period) approach the sine shape.

For significant loads of the synchronous generator (as the case presented by the paper), within the main generator stator can flow currents with significant harmonic weights. These harmonic currents can be caused by a non-symmetric operation of the generator, due to the excitation winding of the main generator (a possible fault between its loops) [7], [11].

B. The useful absorbed active power, transmitted from the auxiliary generator toward the main generator rotor is lower than the total active power of the d.c. component. This leads to the conclusion that, under harmonic regime, there is an inverse circulation of powers from the main generator toward the auxiliary one. Practically the fully-controlled rectifier behaves like a power converter: receives active power along the d.c. component and returns a part of it toward the auxiliary generator (along the harmonics). This power circulation (that is inverse from the power flow) can also explain the high harmonic content from the auxiliary generator stator [12].

C. Even though outside the electro-energetic group there aren't any problems, the internal distorting problems (local to the electro-energetic group) and the power flows from inside the group can lead to windings insulations faster ageing processes as well as to the fully-controlled rectifier reliability decrease.

D. The analysis of waveforms together with the correct determination of the power flows over the fundamental harmonic and respectively over all harmonics, along with other experimental determinations might provide indications on the operation of the electro-energetic group as a whole and respectively on each component, separately. It can also be used as a diagnosis method for some components from the electro-energetic group.

## References

[1] T. Zheng, E. Makram, A. Girgis, "*Evaluating Power System Unbalance in the Presence of Harmonic Distortion*", IEEE Trans. on Power Delivery, vol. 18, no. 2, pp. 393-397, Apr. 2003

[2] D. Shmilovitz, „*On the Definition of Total Harmonic Distortion and Its Effect on Measurement Interpretation*", IEEE Trans. on Power Delivery, vol. 20, no. 1, pp. 526-528, Jan. 2005

[3] A. Ţugulea, "*Criteria for the Definitions of the Electric Power Quality and its Measurement Systems*" ETEP, vol.6, no.5/'96, p.357-363

[4] J. Rico, M. Madrigal, E. Arha, „*Dynamic Harmonic Evolution Using the Extended Harmonic Domain*", IEEE Trans. on Power Delivery, vol. 18, no. 2, pp. 587-594, Apr. 2003

[5] A. Ramirez, A. Semlyen, R. Iravani, "*Harmonic Domain Characterization of the Resonant Interaction Between Generator and Transmission Line*", IEEE Trans. on Power Delivery, vol. 20, no. 2, pp. 1753-1762, Apr. 2005

[6] M. Depenbrock, "*The FDB-Method a Generally Applicable Tool for Analyzing Power Relations*," IEEE Trans. on Power Systems, vol.8, no.2/93, p.380-386

[7] A. Ţugulea, "*Consideraţii privind efectele energetice în regimuri deformante*", Energetica, no. 1/'86, p.27-31

[8] P. M. Nicolae., "*Instantaneous Real and Imaginary Powers at Three-Phase Networks with Balanced Loads that Function under Distorting Regime*" RRST Serie Electr. Et Energ., no. 3/`95, p. 311-319

[9] Task Force on Harmonics Modeling and Simulation, IEEE PES Harmonic Working Group, "*Characteristics and Modeling of Harmonic Sources – Power Electronic Devices*," IEEE Trans. on Power Delivery, vol. 16, pp. 791-800, Oct. 2001.

[10] P.M. Nicolae, "*Calitatea energiei electrice în sisteme electroenergetice de putere limitată*" Printed at Ed. Tehnică, Bucharest, 1998, p. 253.

[11] A. Mansoor, W. M. Grady and A. H. Chowdhury, "*An Investigation of Harmonics Attenuation and Diversity Among Distributed Single-Phase Power Electronic Loads*," IEEE Trans. on Power Delivery, vol. 10, pp. 467-473, Jan. 1995.

[12] A. McEachern, W. M. Grady and W. A. Moncrief, "*An evaluation of Some Proposed Rate Structures*," IEEE Trans. on Power Delivery, vol. 10, pp. 474-482, Oct. 2001.

[13] G.T. Heydt, Y. Liu, "*Second Harmonic Components in Power System Voltages and Currents*", IEEE Trans. on Power Delivery, vol. 20, no. 1, pp. 521-523, Jan. 2005

[14] S. H. Jaramillo, G. T. Heydt and E. O`Neill-Carrillo, "*Power Quality Indices for Aperiodic Voltages and Currents*," IEEE Trans. on Power Delivery, vol. 2, pp. 784-790, Apr. 2000