Integral mathematical model of power quality disturbances

Raúl Igual, Carlos Medrano, Francisco Javier Arcega
EduQTech group, Electrical Engineering Department
EUPT/EINA/IIS, Universidad de Zaragoza
Teruel, Spain
{rigual, ctmedra, arcegafj}@unizar.es

Gabriela Mantescu
Energy Environment Research Department
Valahia University of Targoviste
Targoviste, Romania
gabriela.mantescu@valahia.ro

***Abstract*— Power quality (PQ) disturbances lead to severe problems in industries and electrical grids. To mitigate PQ problems, the accurate detection and classification of the possible disturbances are essential. A large number of studies exists in this field. The first research step in these studies is to obtain several distorted signals to test the classification systems. In this regard, the most common trend is the generation of signals from mathematical models. In the literature, we can find several models with significant differences among them. However, to the best of our knowledge, there is no integral model that considers all types of distortions. This work presents an integral mathematical model based on the models found in the literature. The model also includes new types of combined disturbances. Twenty-nine disturbances are considered. Additionally, this work includes a software version of this integral model that is publicly available to be used by any interested researcher. In this way, PQ disturbances can be generated in a fast and automatic way. This software aims to facilitate future studies, supporting researchers in the modelling stage.**

***Index Terms*— Free software, Mathematical model, Power quality, Public.**

I. INTRODUCTION

Power quality (PQ) disturbances can be usually found in electrical grids. This is motivated by the massive use of non-linear loads in industrial environments such as adjustable speed drives, transformers, power supplies or photovoltaic inverters, among many others [1]-[3].

The term ‘power quality’ refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system [4]. Several phenomena are considered as PQ problems: impulsive transients, oscillatory transients, interruptions, sags, swells, harmonics, notching, flicker, among others [4]-[5].

PQ problems in the power delivery lead to economic losses. They might cause damage or incorrect operation of equipment installed in the grid as well as of end user equipment [6]. In end user systems they can lead to computer data loss and memory malfunction of sensitive loads such as computers, programmable logic controls, protection and relaying equipment; and erratic operation of electronic controls [7]-[8]. Thus, if PQ problems are not correctly detected, classified and mitigated, they can cause failures or malfunctions of many sensitive loads connected to the system, which may result very expensive. PQ disturbances also affect transmission grids. This is particularly severe in power systems that include renewable sources such as photovoltaic generation, which requires non-linear devices. Thus, in order to integrate renewable energies into the grid or to identify the source of distortion and adopt mitigation actions in industrial networks, it is firstly required to detect and classify PQ disturbances [7]. The first step in the studies centered on automatic detection and classification of PQ disturbances is to obtain several distorted signals to test the systems. Regarding this point, several trends appear in existing studies: generation of waves from mathematical models [8]-[11], use of databases containing real-world signals affected by PQ problems [12] and registration of real-world disturbances using a data acquisition system [13]. Regarding the first trend, several mathematical models have been proposed in existing studies. However, to the best of our knowledge, there is no integral model that considers all types of distortions. In this work, an integral mathematical model of PQ disturbances is proposed based on the models found in the literature. Additionally, this model is made publicly available to be downloaded by any interested researcher in such a way that PQ disturbances can be generated in a fully automatic way. The parameters of the disturbances are selected by the software randomly.

The rest of this paper is organized as follows: Section 2 presents the existing models taken as a reference to build the integral model, Section 3 describes the procedure to build the integral model, Section 4 presents the integral model and includes a link to download it, and finally Section 5 draws some conclusions.

978-1-5386-0517-2/18/$31.00

II. RELATED WORK

Several studies including mathematical models to generate PQ disturbances can be found in the literature. In general, those disturbances are generated considering IEEE recommendations [4], international standards [5] or on the basis of the experience gained in this field. The work of Deokar and Waghmare [8] modeled five disturbances: sags, swells, harmonics, fluctuations and transients (low and high frequency). The same disturbances were considered by Decanini et al. [9], Manimala et al. [10], Naderian and Salemnia [11], Borges et al. [14], Abdoos et al. [15], Li et al. [16], Huang et al. [17] and Moravej et al. [18], but this time with interruptions, harmonics with sag and harmonics with swell. Similar models with small differences can be found in the works of Khokar et al. [19] (flicker and combined disturbances not considered), Pahasa and Ngamroo [20], Milchevski et al. [21] (flicker and transients not included) and Lopez-Ramirez et al. [22] (flicker excluded). The works of Liu et al. [23] and Lee and Shen [24] added transients and notching to the set of PQ disturbances. In this regard, these disturbances were also considered by Kumar et al. [25] and Granados-Lieberman et al. [26], building a model with nine disturbances. Hooshmand and Enshaee [27] considered sixteen different disturbances that include, apart from the previously mentioned ones, fluctuations with swell, fluctuations with sag, sags with oscillatory transient and swells with oscillatory transient, among others. Kanirajan and Kumar [28] presented twenty disturbances while Kubendran and Loganathan [29] included twenty-four PQ problems, although the equations were not provided in both cases. All these studies also modeled the normal waves in order to conduct a fair comparison. Additionally, important differences have been identified regarding the mathematical models proposed in different papers to describe PQ issues. As an example, it is possible to mention the different approaches adopted to model the harmonics distortion. Abdoos et al. [15], Decanini et al. [9], Khokar et al.[19], Kumar et al. [25], Lee and Shen [24], Moravej et al. [18] and Pahasa and Ngamroo [20] considered the third, fifth and seventh harmonics with a multiplying factor of the amplitude in the range of 0.05-0.15. Li et al. [16], Liu et al. [23], Lopez-Ramirez et al. [22], Manimala et al. [10] and Naderian and Salemnia [11] considered the same harmonics but with different multiplying factors, which were not coincident with each other. Deokar and Waghmare [8] only considered the third and fifth harmonics with different multiplying factors. Granados-Lieberman et al. [26] considered many more harmonics. Hooshmand and Enshaee [27] took into consideration ten harmonics with different ranges of the amplitude and multiplying factors for the odd and even harmonics. Similar differences can be seen in the proposed models for other disturbances.

A common point of all these studies is that, to the best of our knowledge, the code to automatically generate the disturbances is not publicly available. In this paper, we publish that code in order to be used by any interested researcher.

III. METHODS

As part of this state of the art, we have examined how each distortion has been modeled by different authors. Considering all these models, the new integral model has been built. Each distortion has been examined in detail. For each distortion, those models with the highest level of consensus have been selected. For the distortions that were not clearly defined, we have considered the descriptions provided in the IEEE recommendations [4], adapting the model to that recommendation. Additionally, as large differences were found in the number of different types of distortions included, several additional distortions have been modeled in order to obtain a model as complete as possible.

The specific works taken as a reference for each type of distortion are listed in Table I (next to the name of the distortion).

IV. RESULTS

The integral mathematical model is presented in Table I. This model includes twenty-nine different types of disturbances, comprising both unique distortions (eight) and combined distortions (twenty-one). Each distortion is characterized by a set of parameters, whose possible values are given in Table I. For instance, for a PQ problem due to an oscillatory transient, the starting and ending time of the disturbance, the amplitude of the oscillation and the decreasing slope of the oscillation have to be defined.

A specific sample of each disturbance is represented in Fig. 1.

This integral model has been implemented in the numerical computing environments *Matlab* (not free software) and *Octave* (free software). The software model to be used in these environments is available to be downloaded by any interested researcher. It can be obtained from [30]. This software representation of the model comprises a function to generate PQ disturbances automatically. Researchers have the option to configure several parameters:

- The number of samples of each class to be generated (N_s). By default, 10 samples per class.
- The sampling frequency (f_s) in the range 200 Hz-30 kHz. The default value of this parameter is 16 kHz.
- The fundamental frequency (f) in the range 40 Hz-100 Hz. The default value is 50 Hz.
- The number of cycles of the fundamental frequency to be included in each disturbance (N). Possible values are in the range 3-100. By default, each signal comprise 10 cycles.
- The normal amplitude of the signals (A) in the range 0.1 V-400 kV. By default the function generates the amplitude of the PQ distortions per unit (p.u.).

The parameters of the PQ issues are generated randomly by the software (uniform distribution), among the possible values included in Table I. In this way, as many training and validation datasets as desired can be generated.

TABLE I. INTEGRAL MATHEMATICAL MODEL OF PQ DISTURBANCES

Equations			
Pure signal: [8]-[11], [14]-[29]	$v(t) = A\sin(wt-\varphi)$	Interruption: [9]-[11], [14]-[29]	$v(t) = A(1-\rho(u(t-t_1)-u(t-t_2)))\sin(wt-\varphi)$
Sag: [8]-[11], [14]-[29]	$v(t) = A(1-\alpha(u(t-t_1)-u(t-t_2)))\sin(wt-\varphi)$	Swell: [8]-[11], [14]-[29]	$v(t) = A(1+\beta(u(t-t_1)-u(t-t_2)))\sin(wt-\varphi)$
Transient/Impulse/Spike: [23]-[29]	$v(t) = A[\sin(wt-\varphi)-\psi(e^{-750(t-t_a)}-e^{-344(t-t_a)})((u(t-t_a)-u(t-t_b)))]$		
Oscillatory transient: [8]-[11], [14]-[19],[22]-[29]	$v(t) = A[\sin(wt-\varphi)+\beta e^{-(t-t_I)/\tau}\sin(w_n(t-t_I)-\vartheta)((u(t-t_{II})-u(t-t_I)))]$		
Harmonics: [8]-[11], [14]-[29]	$v(t) = A[\sin(wt-\varphi)+\sum_{n=3}^{7}\alpha_n\sin(nwt-\vartheta_n)]$	Flicker: [8]-[11], [14]-[18],[23]-[28]	$v(t) = A[1+\lambda\sin(w_f t)]\sin(wt-\varphi)$
Harmonics with sag: [9]-[11],[15]-[18],[20]-[24],[27]-[29]	$v(t) = A(1-\alpha(u(t-t_1)-u(t-t_2)))[\sin(wt-\varphi)+\sum_{n'=3}^{5}\alpha_{n'}\sin(n'wt-\vartheta_{n'})]$		
Harmonics with swell: [9]-[11],[15]-[18],[20]-[24],[27]-[29]	$v(t) = A(1+\beta(u(t-t_1)-u(t-t_2)))[\sin(wt-\varphi)+\sum_{n'=3}^{5}\alpha_{n'}\sin(n'wt-\vartheta_{n'})]$		
Flicker with sag: [27]-[28]	$v(t) = A[1+\lambda\sin(w_f t)-\alpha(u(t-t_1)-u(t-t_2))]\sin(wt-\varphi)$	Flicker with swell: [27]-[28]	$v(t) = A[1+\lambda\sin(w_f t)+\beta(u(t-t_1)-u(t-t_2))]\sin(wt-\varphi)$
Sag with oscillatory transient: [27]	$v(t) = A[\sin(wt-\varphi)(1-\alpha(u(t-t_1)-u(t-t_2)))+\beta e^{-(t-t_{I'})/\tau}\sin(w_n(t-t_{I'})-\vartheta)((u(t-t_{II'})-u(t-t_{I'})))]$		
Swell with oscillatory transient: [27]	$v(t) = A[\sin(wt-\varphi)(1+\beta(u(t-t_1)-u(t-t_2)))+\beta e^{-(t-t_{I'})/\tau}\sin(w_n(t-t_{I'})-\vartheta)((u(t-t_{II'})-u(t-t_{I'})))]$		
Sag with harmonics: [14],[27]	$v(t) = A[\sin(wt-\vartheta_1)+(-\alpha(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})]$		
Swell with harmonics: [14],[27]	$v(t) = A[\sin(wt-\vartheta_1)+(\beta(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})]$		
Notch: [23]-[27],[29]	$v(t) = A[\sin(wt-\varphi)-sign(\sin(wt-\varphi)\sum_{n=0}^{N\cdot c-1}k(u(t-(t_c+s\cdot n))-u(t-(t_d+s\cdot n)))]$		
Harmonics with sag with flicker:	$v(t) = A(1+\lambda\sin(w_f t))[\sin(wt-\varphi)+\sum_{n'=3}^{5}\alpha_{n'}\sin(n'wt-\vartheta_{n'})](1-\alpha(u(t-t_1)-u(t-t_2)))$		
Harmonics with swell with flicker:	$v(t) = A(1+\lambda\sin(w_f t))[\sin(wt-\varphi)+\sum_{n'=3}^{5}\alpha_{n'}\sin(n'wt-\vartheta_{n'})](1+\beta(u(t-t_1)-u(t-t_2)))$		
Sag with harmonics with flicker:	$v(t) = A[\sin(wt-\vartheta_1)+(1+\lambda\sin(w_f t))(-\alpha(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})]$		
Swell with harmonics with flicker:	$v(t) = A[\sin(wt-\vartheta_1)+(1+\lambda\sin(w_f t))(\beta(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})]$		
Sag with harmonics with oscillatory transient:	$v(t) = A[\sin(wt-\vartheta_1)+(-\alpha(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_{I'})/\tau}\sin(w_n(t-t_{I'})-\vartheta)((u(t-t_{II''})-u(t-t_{I'})))]$		
Swell with harmonics with oscillatory transient:	$v(t) = A[\sin(wt-\vartheta_1)+(\beta(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_{I'})/\tau}\sin(w_n(t-t_{I'})-\vartheta)((u(t-t_{II''})-u(t-t_{I'})))]$		

<table>
<tr><td>Harmonics with sag with oscillatory transient: [29]</td><td colspan="4">$v(t) = A[(1-\alpha(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_I)/\tau}\sin(w_n(t-t_I)-\vartheta)((u(t-t_{II})-u(t-t_I)))]$</td></tr>
<tr><td>Harmonics with swell with oscillatory transient: [29]</td><td colspan="4">$v(t) = A[(1+\beta(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_I)/\tau}\sin(w_n(t-t_I)-\vartheta)((u(t-t_{II})-u(t-t_I)))]$</td></tr>
<tr><td>Harmonics with sag with flicker with oscillatory transient:</td><td colspan="4">$v(t) = A[(1-\alpha(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_I)/\tau}\sin(w_n(t-t_I)-\vartheta)((u(t-t_{II})-u(t-t_I)))](1+\lambda\sin(w_f t))$</td></tr>
<tr><td>Harmonics with swell with flicker with oscillatory transient:</td><td colspan="4">$v(t) = A[(1+\beta(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_I)/\tau}\sin(w_n(t-t_I)-\vartheta)((u(t-t_{II})-u(t-t_I)))](1+\lambda\sin(w_f t))$</td></tr>
<tr><td colspan="5">Sag with harmonics with flicker with oscillatory transient:</td></tr>
<tr><td colspan="5">$v(t) = A[\sin(wt-\vartheta_1)+((-\alpha(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_{I'})/\tau}\sin(w_n(t-t_{I'})-\vartheta)((u(t-t_{II'})-u(t-t_{I'}))))(1+\lambda\sin(w_f t))]$</td></tr>
<tr><td colspan="5">Swell with harmonics with flicker with oscillatory transient:</td></tr>
<tr><td colspan="5">$v(t) = A[\sin(wt-\vartheta_1)+((\beta(u(t-t_1)-u(t-t_2)))\sum_{n''=1}^{5}\alpha_{n''}\sin(n''wt-\vartheta_{n''})+\beta e^{-(t-t_{I'})/\tau}\sin(w_n(t-t_{I'})-\vartheta)((u(t-t_{II'})-u(t-t_{I'}))))(1+\lambda\sin(w_f t))]$</td></tr>
<tr><th colspan="5">Parameters of the model</th></tr>
<tr><td>To be defined by the researcher (described in Section IV):
N , A , f_s
f -> $T = \frac{1}{f}$</td><td>General:
$w = 2\pi f$
$-\pi \le \varphi \le \pi$
$u(t) = \begin{cases} 0 & t < 0 \\ 1 & t \ge 0 \end{cases}$</td><td>Sag/Swell/Interruption related distortions:
$T \le t_2 - t_1 \le (N-1)T$
$0.1 \le \alpha \le 0.9$
$0.1 \le \beta \le 0.8$
$0.9 \le \rho \le 1.0$</td><td>Transient related distortions:
$0.222 \le \psi \le 1.11$
$T \le t_a \le (N-1)T$
$t_b = t_a + 1ms$</td><td>Flicker related distortions:
$0.05 \le \lambda \le 0.1$
$8 \le f_f \le 25Hz$; $w_f = 2\pi f_f$</td></tr>
<tr><td colspan="3">Oscillatory transient related distortions:
$300 \le f_n \le 900Hz$; $w_n = 2\pi f_n$; $8ms \le \tau \le 40ms$; $-\pi \le \vartheta \le \pi$;
$0.5T \le t_{II} - t_I \le \frac{N}{3.33}T$

$\frac{T}{5} \le t_{II'} - t_{I'} \le t_2 - t_1$; $t_{I'} \ge t_1$; $t_{II'} \le t_2$</td><td colspan="2">Harmonics related distortions:
$n = \{3,5,7\}$; $0.05 \le \alpha_n \le 0.15$; $-\pi \le \vartheta_n, \vartheta_{n'}, \vartheta_{n''} \le \pi$
$n' = \{3,5\}$; $0.05 \le \alpha_{n'} \le 0.15$
$n'' = \{1,3,5\}$; $\alpha_{n''} = 1 \mid n'' = 1$; $0.05 \le \alpha_{n''} \le 0.15 \mid n'' = \{3,5\}$</td></tr>
<tr><td colspan="5">Notch related distortions: $0.01T \le t_d - t_c \le 0.05T$; $t_d \le s$; $t_c \ge 0$; $0.1 \le k \le 0.4$; $c = \{1,2,4,6\}$; $s = \frac{T}{c}$</td></tr>
</table>

Once executed, the function provides a matrix of dimension N_S x N_T x N_D, where N_s is the number of samples of each class, N_D is the number of different classes (disturbances) and N_T is the number of discrete time points making up the signals (equation 1).

$$N_T = \frac{T * N}{T_S} \tag{1}$$

where T is the period of the fundamental wave and T_S is the sampling period.

The information contained in this matrix can be exported to a file to be used as best suits each researcher. Additionally, if only a specific set of distortions is needed, it is possible to use the distortions of interest exclusively. The heading of the function includes explanations about its use. It is distributed under the free software GNU General Public (GPL) license.

V. CONCLUSION

The integral mathematical model proposed in this paper may be useful in the field of automatic detection and classification of PQ events. Researchers in this field can use it to generate training and validation datasets in order to test their detection and classification algorithms. This allows checking the feasibility of their proposals rapidly, which represents an important advantage. This is especially interesting in the early stages of a research, given the reduction in the time spent that can be obtained.

Additionally, as the software model allows setting different parameters, signals in different conditions (sampling frequency, cycles captured, basic amplitude, etc.) can be easily generated. These disturbances may be used to test the classification systems under different operation conditions. Besides, any researcher can adapt the models to his/her needs since the code is distributed under the GNU GPL license. It would also be possible to easily implement any other combined disturbance not considered in this model, such as the notch-based ones presented in [29]. Furthermore, different levels of noise could be added easily.

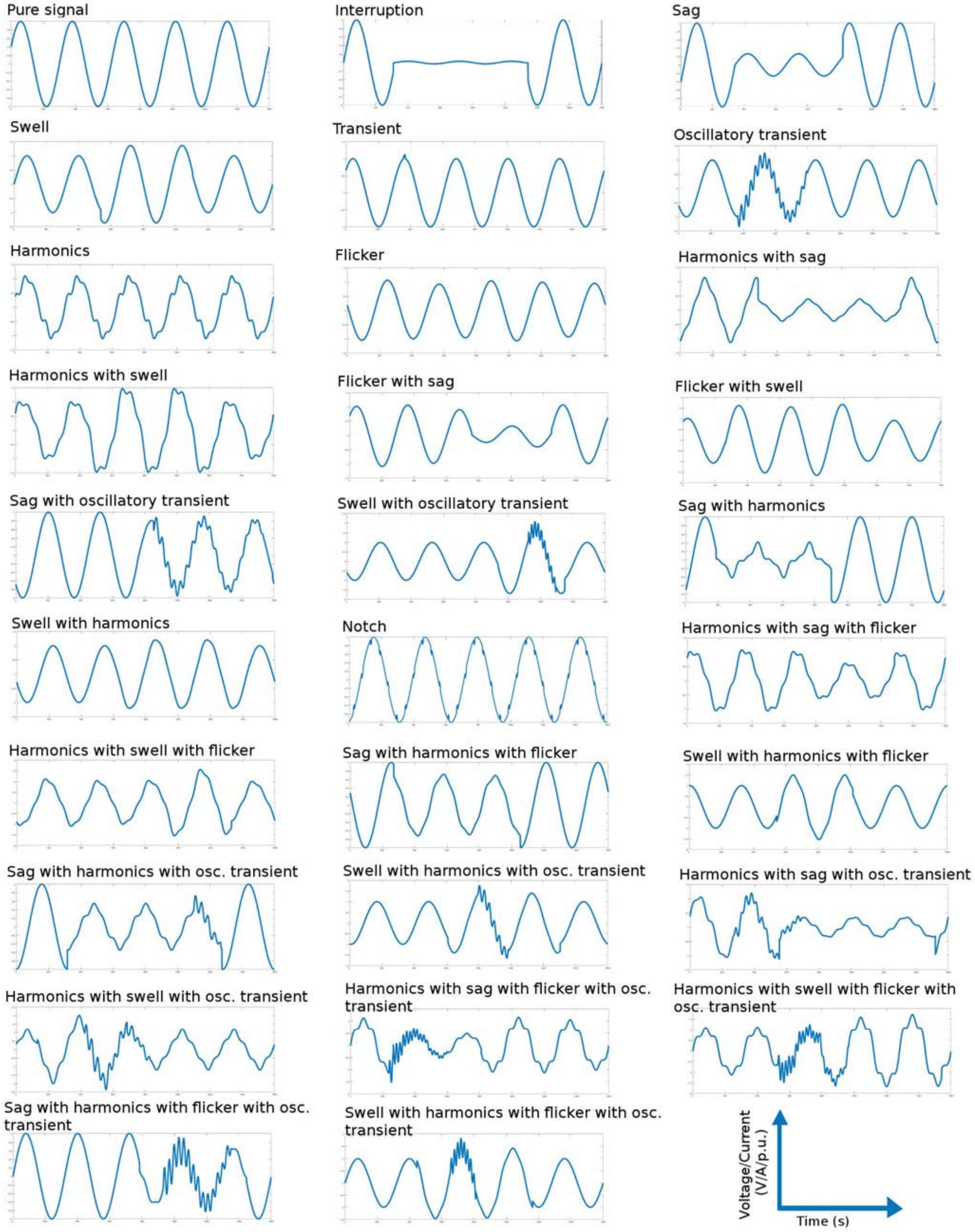

Figure 1. Samples of the distortions.

It is also worth highlighting that signals generated by this model can be exported to other working environments (apart from *Matlab* and *Octave*) such as, for example, *Python*. Another possible application could be the implementation of the integral model in a hardware platform in order to test the real-world operation of a particular approach, which is a live research line currently [6]. It could also serve to test the accuracy of any existing equipment or hardware implementation that performs automatic classification.

Summing up, this paper presents an integral mathematical model comprising the highest number of different types of PQ distortions that we could find in the literature. To the best of our knowledge, it is the first model whose software representation is freely available to be downloaded and modified by any interested researcher. This may be very useful for a rapid development of automatic detectors and classifiers of PQ events.

ACKNOWLEDGMENTS

We would like to acknowledge the "Vicerrectorado de Política Académica de la Universidad de Zaragoza - PRAUZ_17_190" the "Gobierno de Aragón - T81" and the "European Social Fund" for their support.

REFERENCES

[1] N. Patel, K. Gandhi, D. Mahida, P. Chudasama, "A review on power quality issues and standards", *International Research Journal of Engineering and Technology*, vol. 4, pp. 247-250, 2017.

[2] M.I. Muhamad, N. Mariun, M.A.M Radzi, "The effects of power quality to the industries", in *Proc. 5th Student Conf. Research and Development*, pp. 1-4, 2007.

[3] R. Igual et al., "Herramienta libre para el aprendizaje del efecto de los armónicos en los sistemas de potencia", in *Proc. XXIV Seminario Anual de Automática, Electrónica Industrial e Instrumentación*, Valencia, pp. 43, 2017.

[4] IEEE. (2009). Recommended practice for monitoring electric power quality. [Online]. Available: http://ieeexplore.ieee.org/document/5154067/

[5] Cenelec. (2011) EN 50160. Voltage characteristics of electricity supplied by public distribution systems.

[6] O.P. Mahela, A.G. Shaik, N. Gupta, "A critical review of detection and classification of power quality events", *Renewable and Sustainable Energy Review*, vol. 41, pp. 495-505, 2015.

[7] M.K. Saini, R. Kapoor, "Classification of power quality events – A review", *International Journal of Electrical Power & Energy Systems*, vol. 43(1), pp. 11-19, 2012.

[8] S.A. Deokar, L.M. Waghmare, "Integrated DWT–FFT approach for detection and classification of power quality disturbances", *Electrical Power and Energy Systems*, vol. 61, pp. 594–605, 2014.

[9] J.G.M.S. Decanini, M.S. Tonelli-Neto, F.C.V. Malange, C.R. Minussi, "Detection and classification of voltage disturbances using a fuzzy-ARTMAP-wavelet network", *Electric Power Systems Research*, vol. 81, pp. 2057– 2065, Dec. 2011.

[10] K. Manimala, K. Selvi, R. Ahila, "Optimization techniques for improving power quality data mining using wavelet packet based support vector machine", *Neurocomputing*, vol. 77, pp. 36–47, 2012.

[11] S. Naderian, A. Salemnia, "An implementation of type-2 fuzzy kernel based support vector machine algorithm for power quality events classification", *International Transactions on Electrical Energy Systems*, vol. 27(5), 2016.

[12] A.E. Lazzaretti, V.H., Ferreira, H. Vieira, "New trends in power quality event analysis: novelty detection and unsupervised classification", *Journal of Control, Automation and Electrical Systems*, vol. 27(6), pp. 718–727, 2016.

[13] H. Eristi, Ö. Yıldırım, B. Eristi, Y. Demir, "Optimal feature selection for classification of the power quality events using wavelet transform and least squares support vector machines", *Electrical Power and Energy Systems*, vol. 49, pp. 95–103, 2013.

[14] F.A.S. Borges, R.A.S. Fernandes, I.N. Silva, C.B.S. Silva, "Feature extraction and power quality disturbances classification using smart meters signals", *IEEE Transactions on Industrial Informatics*, vol. 12(2), April 2016.

[15] A.A. Abdoos, P.K. Mianaei, M.R. Ghadikolaei, "Combined VMD-SVM based feature selection method for classification of power quality events", *Appl. Soft Comput.*, vol. 38(C), pp. 637-646, January 2016.

[16] J. Li, Z. Teng, Q. Tang, J. Song, "Detection and Classification of Power Quality Disturbances Using Double Resolution S-Transform and DAG-SVMs", *IEEE Transactions on Instrumentation and Measurement*, Vol. 65(10), October 2016.

[17] N. Huang, D. Xu, X. Liu, L. Lin, "Power quality disturbances classification based on S-transform and probabilistic neural network", *Neurocomputing*, vol. 98, pp. 12–23, 2012.

[18] Z. Moravej, M. Pazoki, A.A. Abdoos, "Wavelet transform and multi-class relevance vector machines based recognition and classification of power quality disturbances", *Euro. Trans. Electr. Power*, vol. 21, pp. 212–222, 2011.

[19] S. Khokhar, A.A.M. Zin, A.S. Mokhtar, N. Ismail, "MATLAB/Simulink based modeling and simulation of power quality disturbances," in *Proc. IEEE Conf. on Energy Conversion (CENCON), Johor Bahru*, pp. 445-450, 2014.

[20] J. Pahasa, I. Ngamroo, "PSO based kernel principal component analysis and multi-class support vector machine for power quality problem classification", *International Journal of Innovative, Computing, Information and Control*, vol. 8(3A), March 2012.

[21] A. Milchevski, D. Kostadinov, D. Taskovski, "Classification of power quality disturbances using wavelets and support vector machine", Elektronika ir Elektrotechnika, vol. 19(2), pp.25-30, 2013.

[22] M. Lopez-Ramirez, L. Ledesma-Carrillo, E. Cabal-Yepez, C. Rodriguez-Donate, H. Miranda-Vidales, A. Garcia-Perez, "EMD-based feature extraction for power quality disturbance classification using moments", *Energies*, vol. 9(7), 565, 2016.

[23] X.S. Liu, B. Liu, D.G. Xu, "Recognition and Classification of Power Quality Disturbances on the basis of Pattern Linguistic Values", *J. Electr. Eng. Technol.*, vol. 11(2), pp. 309-319, 2016.

[24] C.Y. Lee, Y.X. Shen, "Optimal Feature Selection for Power-Quality Disturbances Classification", *IEEE Transactions on Power Delivery*, vol. 26(4), October 2011.

[25] R. Kumar, B. Singh, D.T. Shahani, "Symmetrical components-based modified technique for power-quality disturbances detection and classification", *IEEE Transactions on Industry Applications*, vol. 52(4), pp. 3443 – 3450, July/August 2016.

[26] D. Granados-Lieberman, M. Valtierra-Rodriguez, L.A. Morales-Hernandez, R.J. Romero-Troncoso, R. A. Osornio-Rios, "A Hilbert transform-based smart sensor for detection, classification, and quantification of power quality disturbances", *Sensors*, vol. 13(5), pp. 5507-5527, 2013.

[27] R. Hooshmand, A. Enshaee, "Detection and classification of single and combined power quality disturbances using fuzzy systems oriented by particle swarm optimization algorithm", *Electric Power Systems Research*, vol. 80, pp. 1552-1561, 2010.

[28] P. Kanirajan, V.S. Kumar, "Power quality disturbance detection and classification using wavelet and RBFNN", *Applied Soft Computing*, vol. 35, pp.470-481, 2015.

[29] A.K.P. Kubendran, A.K. Loganathan, "Detection and classification of complex power quality disturbances using S-transform amplitude matrix–based decision tree for different noise levels", *Int. Trans. Electr. Energ. Syst.*, 27:e2286, 2017.

[30] R. Igual, C. Medrano, F.J. Arcega, G. Mantescu, "Mathematical model of power quality disturbances", Mendeley Data, v1, http://dx.doi.org/10.17632/6kmkk9bjdx.1, 2017.