Random Generation of Arbitrary Waveforms for Emulating Three-Phase Systems

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***Abstract*—This paper describes an apparatus for generating a signal representative of steady-state and transient disturbances in three-phase waveforms of an ac electrical system as described in IEEE Std 1159-09. It can be configured as a synthesizer of randomly distorted signals for different applications: for testing the effects of disturbed grid on equipment and to generate patterns of electrical disturbances for the training of artificial neural networks, which are used for measuring power quality tasks. For the first purpose, voltage and current amplifiers are added in the output stage, which allows the generation of disturbed signals at grid level.**

***Index Terms*—AC generators, artificial neural network (ANN), education, load modeling, power hardware in the loop (PHIL), power quality (PQ), power system simulation, signal synthesis, test equipment.**

I. Introduction

MOST of today's instrumentation for three-phase systems used in the industry is focused and designed for testing and measuring power supply systems and equipment connected thereto [1]. Emerging methods for advanced experimentation exist, such as the power hardware-in-the-loop (PHIL) simulation [2], [3] whereby a piece of power hardware, for example, an energy-power meter or a power electronic drive, is operated from a virtual grid, simulated in real time with the necessary power capabilities through precision power amplifiers. PHIL simulation method can be applied too for researching the real-time behavior of controller and protection equipment. All of these applications have a positive and economic impact on industry.

In another context, it is well known that an effective way of testing equipment seems to be that of supplying their voltage and current input channels with prior unknown signals randomly generated [4], [5]. If the test is repeated a given number of times and a new set of test signals is randomly generated at each repetition, each new test shows different randomly generated test waveforms, and therefore, the behavior of equipment under test is likely to be verified in real conditions or very close to the real ones.

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In this paper, we developed an apparatus capable of generating realistic waveforms representative of many industrial power applications. Control and configuration of the unit is very intuitive owing to the use of self-explanatory graphical interface. Instead of competing with commercial systems, it is designed to provide a very low cost alternative for real-time hardware-in-the-loop applications while maintaining acceptable specifications.

In the literature, there are some examples of equipment similar to the random generator described in this paper, but in some cases only is it possible to generate a limited number of disturbances [6] or the graphical interface is not user-friendly and has low configuration possibilities [7].

The following sections will discuss the proposed procedure and provide the details of a laboratory prototype specifically developed:

1) without output amplifiers: a) arbitrary and random generation of training patterns for optimal design of artificial neural networks (ANNs) [8] and b) arbitrary generation of low-voltage and low-current levels (scaling-down version of three-phase power systems) in separated channels for training or teaching;
2) with output amplifiers: c) arbitrary and random generation of electrical patterns at high-power levels for testing the effects of power-line disturbances on equipment [5] and d) arbitrary generation of high-voltage and high-current levels in separated channels for representing dynamic behaviors of a power system.

II. AWG

According to the considerations in the previous section, the proposed solution for testing equipment under common *working* conditions or for training ANNs is based on the generation of randomly distorted waveforms for the voltage and current signals. This can be done in a relatively simple way employing a digital-to-analog conversion (DAC) board connected to a programmable device, such as a digital signal processor or PC.

A. Software

Based on this concept, LabVIEW and TestStand software (National Instrument) were used to program an automatic signal generator that allows complete configuration of the patterns required. First, a virtual instrument (VI), that we called Pandora, was implemented in LabVIEW [9]. This VI mainly generates a pattern based on the parameters defined by the user; thus,

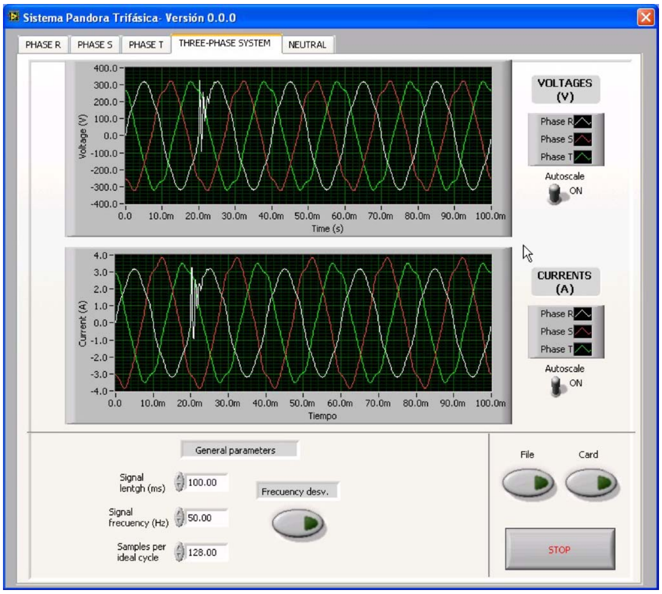


Fig. 1. Front panel of Pandora 3ph.

steady-state or transient-state disturbances were modeled as described hereinafter. In a first stage, the system was designed to be used manually, so the user needed to specify the parameters of the pattern for every simulation. Then, TestStand was included in order to provide automation. This software tool can help the user to develop automated test and validation systems, i.e., it can develop *test sequences* that integrate code modules written in any test programming language. Sequences also specify execution flow, reporting, database logging, and connectivity to other enterprise systems. Finally, test systems to production with easy-to-use operator interfaces can be organized [10].

Several algorithms were programmed in TestStand to launch the Pandora VI according to different goals (random harmonic contents patterns, noisy signals, transient disturbances, etc.). Generated patterns can be saved as text files to be used offline for ANN training for instance or sent to the DAC board in live experiments (as in test purposes).

The front panel of three-phase Pandora VI is shown in Fig. 1. A typical sequence consists basically of a setup operation, where all the variables reset to their default values, and the main operation where parameters and inputs that define the new experiment are modified and Pandora VI is executed. Then, with all these values, reports of the results are generated. Finally, the cleanup operation is executed, where the variables are reset again to default values. Therefore, the Pandora VI consists of the main processes of Fig. 2. First, inputs and parameters are collected from manual user or TestStand automatic sequences. Second, the signal is built according to these specifications, and third, the pattern is sent to a file or to the DAC board.

The main feature of the developed architecture is that it is a layer-based model. It distinguished three distinct parts or layers programmed in LabVIEW that carry out tasks that are essentially different.

1) Layer 3: This module is responsible for managing the user interface carrying out the display of the windows on each case. On the other hand, it allows the user to enter all the information necessary for the edition of the desired signal. Therefore, this layer is focused on gathering information that comes from the program's controls, grouped according to some data structure, and transfers it to layer 2.
2) Layer 2: It is the real engine of the application. From the data entered by the user and have previously been managed through layer 3, layer 2 performs all calculations necessary to generate the data signal to be edited. This is where the various models are implemented in each of the disturbances that we studied previously. The output of layer 2 is a set of numerical data corresponding to the edited signal. These values are transferred to layer 1.
3) Layer 1: This block performs all the communications with the screen, files, and data card. In this block, we properly take care of displaying the user interface. On the other hand, it condenses the implementation of all the functions necessary to export the data signal received from layer 2 to a data file that follows a standard format. Moreover, it performs all the communication with the hardware installed to perform the physical generation of the edited signal through the data card generation.

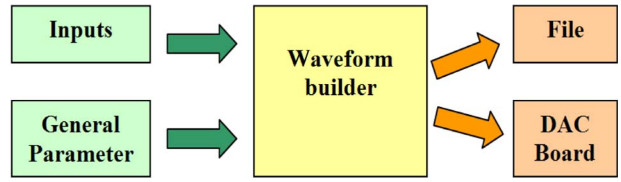


Fig. 2. General diagram of generation with Pandora.

The scheme of the layer-based model programmed in LabVIEW is shown in Fig. 3.

1) Constraints for Random Generation: Using this system, it is possible to synthesize any kind of waveforms in the frequency range of interest for the emulation of actual power systems.

Of course, a purely random generation of the distortion components is not likely to represent the real operating conditions of actual power systems. The system is designed to program disturbances as described in power quality (PQ) standards (i.e., IEEE Std 1159-09). Therefore, a number of constraints must be considered by the generation algorithm. In particular, the following constraints have been considered.

1) Highest harmonic order is given to the synthesizer as an input parameter so that the desired bandwidth is not exceeded.
2) Maximum allowed distortion is imposed as an input parameter in terms of maximum allowable total harmonic distortion (THD) factor, separately for the voltage and current signals.
3) Fundamental component of the voltage signal, U_1, can be set to any value in the range $[0.9U_1, 1.1U_1]$, where U_1 is the rated voltage [1].
4) Fundamental component of the current signal can be set to any desired percentage of the rated current, and its phase shift with respect to the fundamental component of

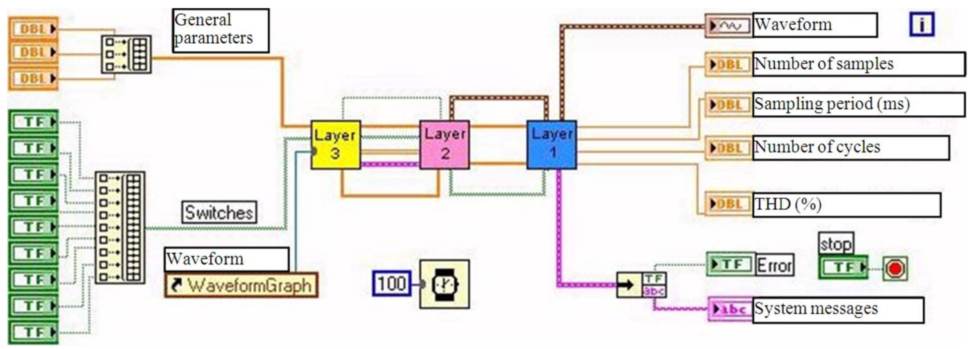


Fig. 3. LabVIEW architecture of Pandora.

the voltage signal can be set to any value, either leading or lagging.

5) Fundamental frequency can be set to any value in the range $[0.98f_n, 1.02f_n]$, where f_n is the rated frequency [1] (where $f_n = 50$ or 60 Hz).

Taking into account the aforementioned constraints, a random number of steady-state and transient-state disturbances can be emulated.

2) Steady-State Disturbances:

- Harmonics

Harmonic components, randomly distributed between the fundamental component and the maximum desired harmonic order, can be generated.

The current waveform always has the same harmonic components as the voltage waveform. It also has additional harmonic components that, when provided by the random generation, account for the presence of nonlinear loads.

Amplitude and phase shift are randomly generated for each of the harmonic components determined in the previous step. A check is performed so that the maximum desired THD factor is not exceeded.

If a suitable number of different randomly generated distorted signals are used to supply the unit under test (UUT), it is possible to assume that a significant number of possible working conditions have been reproduced so that the UUT can be hypothetically tested in its real working conditions.

The following mathematical model was implemented:

$$C(t) = A + \sum_{n=1}^{N} A_n \sin(2\pi n f_1 t + \varphi_n) \quad (1)$$

where A is the dc term (V or A), A_n is the amplitude of the nth harmonic of the signal (V or A), f_1 is the fundamental frequency (Hz), φ_n is the phase of the nth harmonic (rad), and n is the harmonic order $(n = 1, \ldots, N)$.

- Flicker

Flicker is considered an amplitude modulation of the carried signal $C(t)$, which changes in function of the modulating signal $F(t)$[11]. The modulating signal has sinusoidal form with prefixed random amplitude, frequency (usually around 30 Hz), and an initial phase. The equation which defines the mathematical model implemented by the emulator is

$$Z(t) = F(t)C(t) = [1 + A_{\mathrm{f}k} \sin(2\pi f_{\mathrm{fk}} t + \varphi_{\mathrm{fk}})]\, C(t) \quad (2)$$

where A_{fk}, f_{fk}, and φ_{fk} are the flicker amplitude, flicker frequency, and flicker phase, respectively.

- Unbalance: Steady-state symmetrical components

The method of symmetrical component analysis takes its origin from [12]. It presents a mathematical approach for the analysis of an asymmetrical polyphase system (under steady-state conditions) by transforming it into a set of symmetrical sequence networks called positive-, negative-, and zero-sequence networks.

If F_a, F_b, and F_c denote the corresponding original phasors of phases a, b, and c of a three-phase system, then

$$\begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} = \begin{bmatrix} F_a^+ \\ F_b^+ \\ F_c^+ \end{bmatrix} + \begin{bmatrix} F_a^- \\ F_b^- \\ F_c^- \end{bmatrix} + \begin{bmatrix} F_a^0 \\ F_b^0 \\ F_c^0 \end{bmatrix} \quad (3)$$

where $+$, $-$, and 0 denote positive-, negative-, and zero-sequence components, respectively. Since each set of sequence components is balanced, one can deduce [13]

$$\begin{bmatrix} F_a^0 \\ F_a^+ \\ F_a^- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \beta & \beta^2 \\ 1 & \beta^2 & \beta \end{bmatrix} \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} \quad (4)$$

where $\beta = \exp(\mathrm{j}2\pi/3)$.

3) Transient-State Disturbances:

- Overvoltage, swell, undervoltage, and sag

In these kinds of disturbances, the amplitude of the signal rises (overvoltage or swell) or falls (undervoltage and sag) a certain value along a time interval.

In the development of the disturbance generator, a trapezoidal model for the amplitude evolution (lineal slope) was considered. The model makes it possible to approximate the amplitude disturbances most frequently encountered in power systems. Fig. 4 shows a graphic of the model used for overvoltages or swells (inverse trapeze for undervoltages and sags); the following parameters are defined:

p initial sample of the disturbance;
pip slope of the initial ramp;
pfp slope of the final ramp;
$n1$ number of samples of the initial ramp;
$n2$ number of samples of the final ramp;
b number of samples at the bottom;
M total number of samples.

- Oscillatory transients

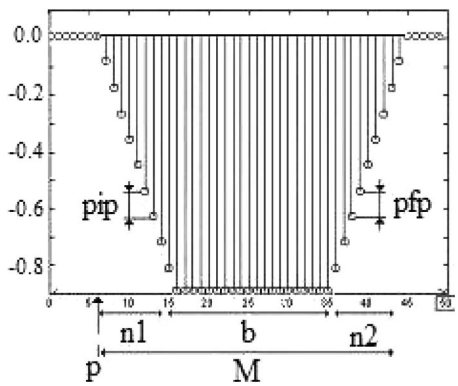


Fig. 4. Sag model.

The electrical pattern generator (EPG) models transient as a damped sine through a superposed exponential function, which is added to $C(t)$ at a certain point.

The implemented mathematical model is expressed as

$$T(t) = e^{-at} A_{\mathrm{r}} \sin(2\pi f_{\mathrm{r}} t + \varphi_{\mathrm{r}}) \tag{5}$$

where a is the oscillatory-transient exponent, A_{r} is the amplitude of the ripple (V or A), f_{r} is the frequency of the ripple (Hz), and φ_{r} is the initial phase of the ripple (rad).

- Noise

The generator makes it possible to add an additive white Gaussian noise in order to simulate more realistic signals of the power line.

B. Hardware

The emulator design is based on generating three-phase voltages and four line currents to emulate a low-voltage power system. Generated data sets are obtained from a host PC in the form of data files with American Standard Code for Information Interchange format compatible with the most popular data-analysis tools (Matlab, Mathcad, etc.).

The host PC is equipped with a NI PXI 6733 board with eight analog outputs at up to 1 MS/s, 16-b resolution, and ±10-V output range. Seven voltage signals are available: three proportional to the three phase-neutral voltages (V_a, V_b, and V_c) and four proportional to the three line currents (I_a, I_b, and I_c) and neutral current (I_n).

At the final stage, the amplifier section brings the voltage signals to the grid level. The number and type of amplifiers depend on the application of the system. The voltage across the load and/or the current flowing through the load or UUT can be simulated. Fig. 5 shows the simplified three-phase power emulation circuit.

1) Amplifier Section: A very critical issue in the design of the test system is the amplifier section since it must ensure accurate and constant gain and phase shift on the whole bandwidth required.

On the other hand, the amplifier type depends on the selected application. Two options have been considered.

Option 1. A power amplifier to test voltages at grid level

In this type of application, disturbed voltage signals at grid level are generated for testing equipment under real conditions

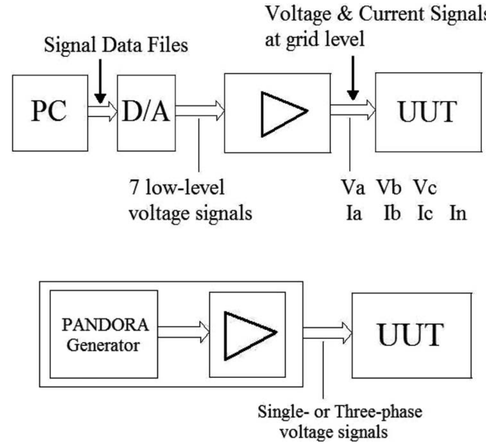


Fig. 5. Simulation of an actual voltage source (Option 1): Voltage generator with programmed disturbances and power amplifier.

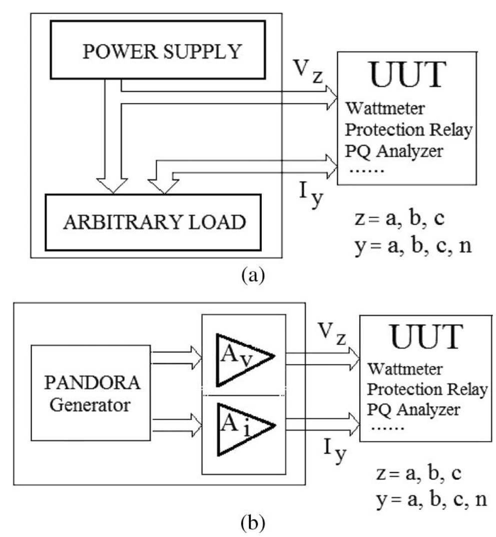


Fig. 6. Simulation of a complete system (Option 2): (a) Power source with programmable disturbances applied to an arbitrary load and (b) voltage and current generator with programmable disturbances and amplified outputs.

(see Fig. 5). In this case, generated voltage signals can be configured for single-phase or three-phase systems. The amplifier section consists of one or three voltage amplifiers with the power capability necessary to supply the UUT.

A laboratory prototype has been implemented for testing single-phase systems. The Pacific Power Source Model 320 was used as a power amplifier to fulfill all the proposed requirements:

1) output voltage up to ±600 peak volts;
2) maximum output power: 1.2 kVA;
3) bandwidth (30–5 kHz) at full power;
4) THD $< 0.2\%$.

Option 2. A high-voltage amplifier and a high-current transconductance amplifier to test voltages and load currents at grid level (see Fig. 6) .

In this second type of applications, it is necessary to generate both voltages and currents at grid levels to simulate a complete system with high-voltage sinusoidal supply source with added disturbances and arbitrary load. In these applications, common UUT (power meters, power analyzers, protection relays, etc.)

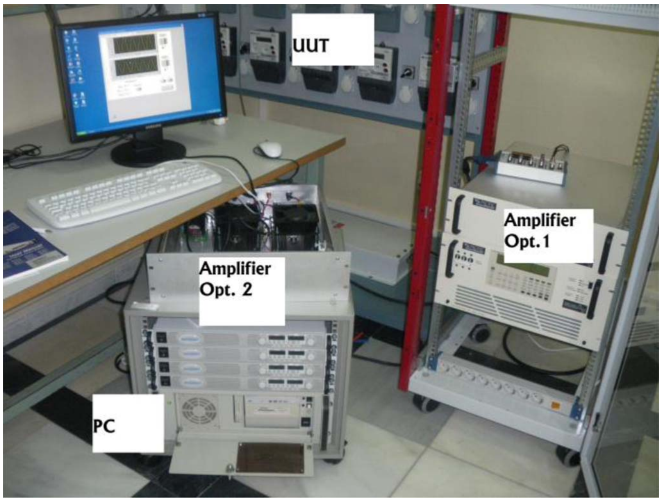


Fig. 7. Laboratory prototype of the proposed test system with voltage and current amplifiers.

measures the voltages and/or currents through independent inputs.

These inputs typically have high-input impedance for voltage measurements and low-input impedance for current measurements, so it is not necessary to amplify the output signals with high-power capabilities.

Voltage amplifiers (A_{v}) have been designed using Apex PA05 high-voltage low-power operational amplifiers with some important specifications:

1) output voltage up to ± 600 peak volts;
2) maximum output current $= 5$ mA;
3) bandwidth (dc to 50 kHz);
4) THD $< 0.1\%$.

Current amplifiers (A_{i}) have been designed using operational amplifiers and discrete transistors as high-current low-power transconductance amplifiers. Their main characteristics are as follows:

1) output current up to ± 50-A peak;
2) maximum output voltage $= \pm 8$ V;
3) bandwidth (dc to 50 kHz);
4) THD $< 0.2\%$.

Fig. 7 shows the implemented laboratory prototype of the proposed test system, with the two types of amplifiers.

III. Applications

The single-phase or three-phase power arbitrary waveform generator (AWG), without or with the amplifier stage configured according to Option 1 or Option 2, allows a set of applications requiring the use of high-power or low-power sources.

A. Training Patterns for Optimal Design of ANNs

The AWG has been developed as an auxiliary tool to generate electric patterns for ANNs, i.e., we have configured the AWG as an EPG. Pattern recognition in ANNs generally requires preprocessing of data, feature extraction, and final classification [16]–[19]. One of the most important tasks in the design and development process of an ANN is to generate an adequate number of training patterns in order to approximate future inputs. Sometimes, an optimal design of the ANN is found, but the limited number of training patterns does not give good results. In particular, in PQ measurement, a great number of electrical patterns is necessary due to the multiple combinations of different disturbances which can coincide in one or various samples.

Thus, in order to extract the signal features, ANNs are usually combined with mathematical analysis, such as Fourier and wavelet transforms, for the generation of signal features which serve as inputs of the network [8]. Thus, with the help of these mathematic tools, the detection of the electrical disturbances has tended to be easy, but their classification is still a difficult task in which ANNs play an important role [14]–[16].

Another additional problem with ANNs applied to PQ is the impossibility of obtaining real useful training patterns directly from the power grid due to the irregular apparition of these disturbances and the difficulty to capture them. In turn, it is very difficult to get access to databases of electrical disturbances and, once achieved, to adjust the features of the obtained electrical patterns to the requirements of the system to be designed (in parameters such as sample time and voltage range defined for each type of disturbance).

Thus, for the task of training ANNs for the detection and classification of electrical disturbances, the EPG generates an unlimited number of patterns to be used by a classification system. The types of disturbances include overvoltage, swell, undervoltage, sag, oscillatory transients, harmonics, flicker, unbalance, frequency variations, and interruptions.

For the application described in [8], over 27 000 signal files have been generated, including one-disturbance signals and two-disturbance signals, and tried to sweep all the types of disturbances.

B. Training or Teaching Tool

Another important application of the emulator system is as teaching and/or training tool. Three-phase power can be taught in a safe laboratory environment using the three-phase power emulator without exposing the student to dangerous high voltages and currents. Another important consideration of the emulation system is the low cost to build and maintain. An affordable low-cost emulation system can be very helpful to schools wanting to improve their laboratory equipment and teaching techniques. The students can learn about phase-angle relationships by editing the output waveforms, which are displayed on the screen via the monitoring program.

C. Testing Equipment

Using Option 1, it is possible to test different types of systems in the presence of supply voltage disturbances at grid level. The output voltages should be used to drive the UUT within the power limits of the power amplifier [14], [15]. In this kind of applications, it is possible to test the equipment under voltage disturbances [20], [21], researching the real-time behavior of controller and protection equipment [4], [22] or testing and

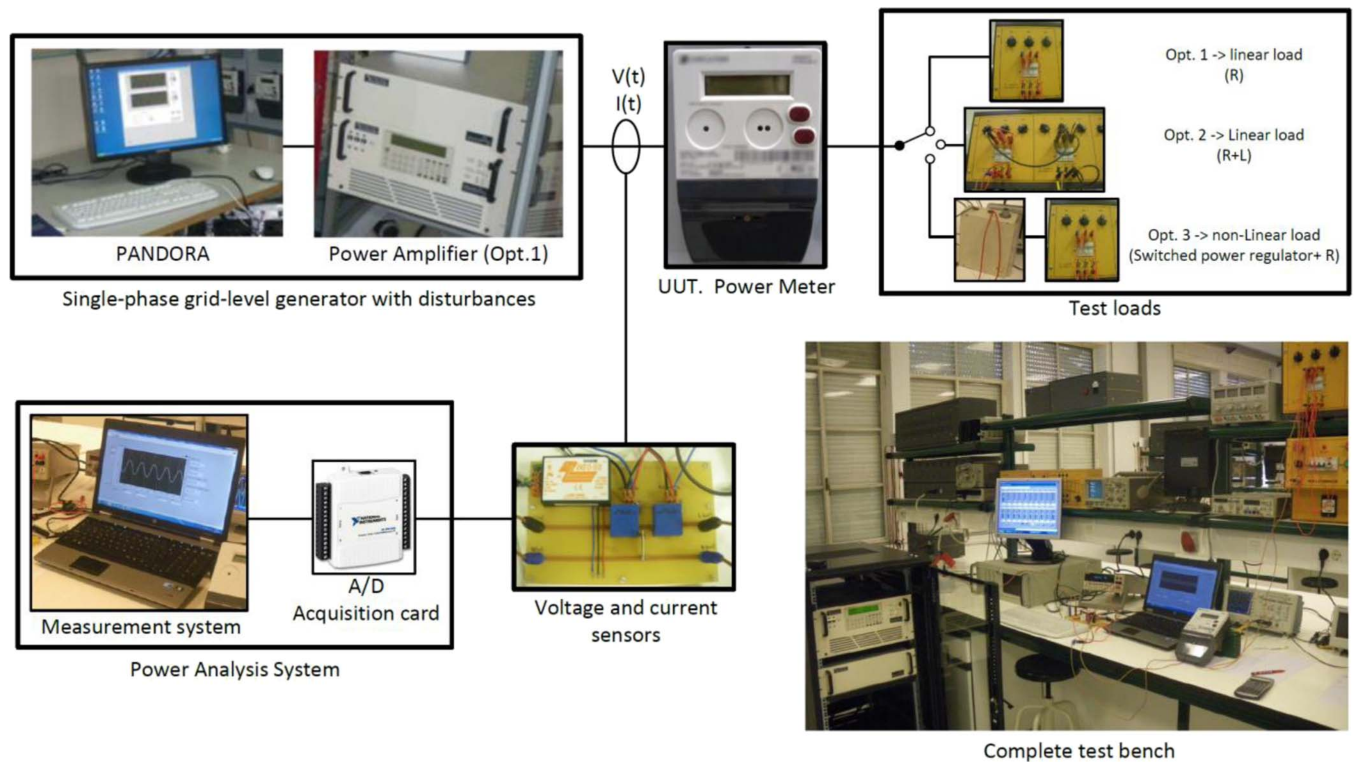


Fig. 8. Laboratory setup for testing a power meter.

comparing systems and/or techniques for disturbance analysis [23]–[26]. This type of application has been implemented in the case study described in Section IV of this paper.

D. Scaling-Down Version of Three-Phase Power Systems

Finally, system designers and manufacturers can use the three-phase power emulator to build and test a scaled-down version of the system being considered. Studying scaled-down versions of the proposed equipment can greatly aid the designer in testing and performing system alterations by saving time and cost. Troubleshooting can be controlled and easy to perform with smaller manageable systems. Once the small-scale model is fully functional, the system is ready for full-scale assembly.

IV. Example of Real Application

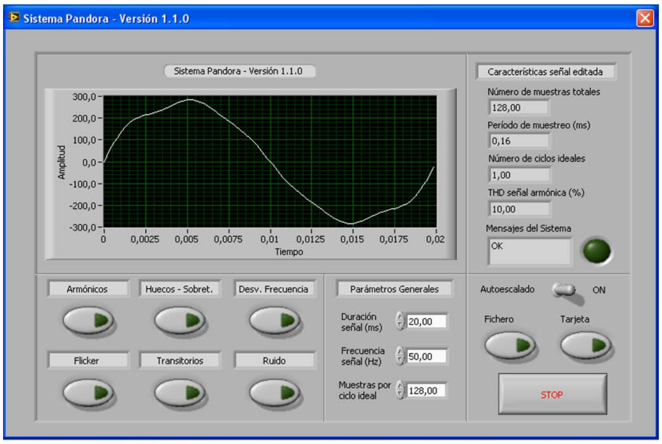
Fig. 8 shows an example of a real experimental setup for testing an energy-power meter (power line communication) under conditions of grid disturbances. The accuracy in the measurement of voltage, current, active and reactive power, and power factor, with different kinds of load (linear R or RL and nonlinear) and periodical disturbances (flicker, harmonics, combined, transient, etc.), has been analyzed.

Pandora system combined with a commercial power voltage amplifier has been used to generate a single-phase voltage signal at grid level with an added set of common disturbances. This signal had been applied to a digital energy/power meter (UUT) with different loads: linear (real or complex) and nonlinear (switched power regulator). The output data values of the UUT have been compared, for different loads and disturbances, to a reference power-analysis system consisting in a calibrated sensor card equipped with voltage and current sensors (both based on Hall effect) and a PC equipped with an analog-to-digital acquisition board and controlled by data-analysis software developed in LabVIEW.

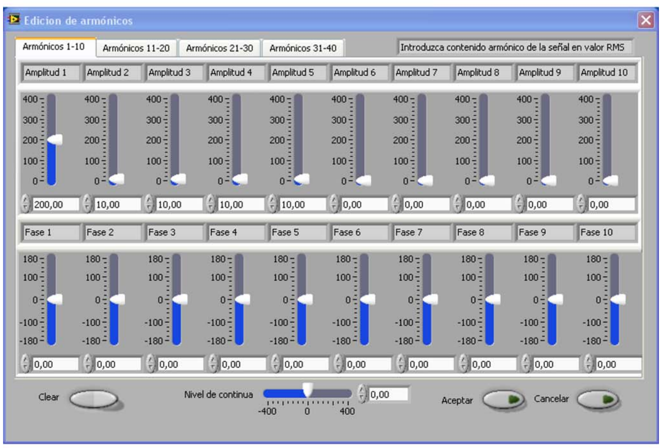
TABLE I
Experimental Results

Test ID	Test description	Load	Active Power (kW) (Reference)	Active Power (kW) (UUT)	Max Deviation (%)
1	Undisturbed	R	1.03	1.03	U.R.*
2		R+L	0.43	0.43	U.R.*
3		Nl	0.57	0.57	U.R.*
4	Flicker disturbance (10Hz)	R	0.68	0.68	U.R.*
5		R+L	0.33	0.33	U.R.*
6		Nl	0.39	0.39	U.R.*
7	Flicker disturbance (5Hz)	R	0.67	0.68	U.R.*
8		R+L	0.33	0.33	U.R.*
9		Nl	0.39	0.39	U.R.*
10	Harmonic disturbance Even harmonics (2nd and 4th)	R	0.77	0.78	U.R.*
11		R+L	0.32	0.32	U.R.*
12		Nl	0.36	0.36	U.R.*
13	Harmonic disturbance Odd harmonics (3rd and 5th)	R	0.77	0.80	3.8
14		R+L	0.32	0.32	U.R.*
15		Nl	0.37	0.37	U.R.*
16	Harmonic disturbance (2nd, 3rd, 4th and 5th)	R	0.78	0.79	U.R.*
17		R+L	0.32	0.32	U.R.*
18		Nl	0.38	0.38	U.R.*
19	Flicker (10Hz) + Harmonic disturbance (2nd, 3rd, 4th and 5th)	R	0.80	0.82	2.4
20		R+L	0.34	0.33	U.R.*
21		Nl	0.40	0.40	U.R.*
22	Harmonic disturbance (10th)	R	1.01	1.03	1.9
23		R+L	0.33	0.32	U.R.*
24		Nl	0.36	0.36	U.R.*
25	Transient disturbance	R	0.77	0.78	U.R.*
26		R+L	0.32	0.32	U.R.*
27		Nl	0.36	0.36	U.R.*

*This difference is lower or equal than output resolution.
**Nl = Non-linear load



(a)



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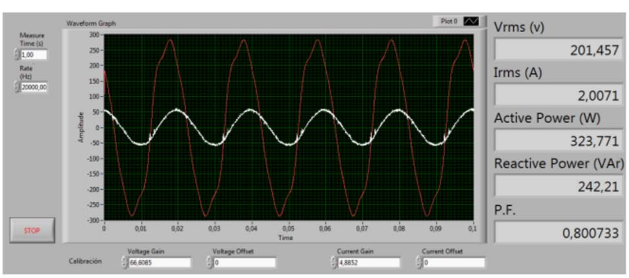


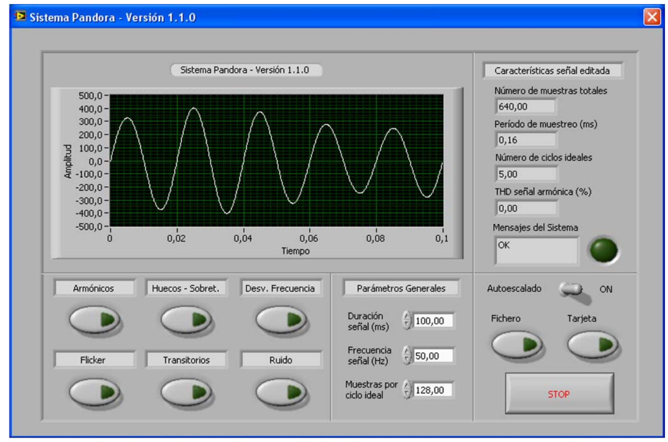
(c)

Fig. 9. Example 1—Harmonic disturbance (Test ID 17). (a) Pandora's front panel. (b) Pandora's harmonic setup. (c) Measures from the reference power-analysis system (the measured current, white signal, is scaled by 20).

Table I summarizes the results of tests in active power measurements. Because the measures are located in the lower range of the UUT (< 1 kW), the practical output resolution is limited to two digits. With these precision limits, we conclude that the UUT is practically not affected, in the measure of the active power, by the disturbances tested. However, there are significant differences in the reactive power, and power factor, measured when the current has high-frequency harmonics.

This may be caused by a switching load or by the presence of high-frequency harmonics in voltage applied on a resistive load.

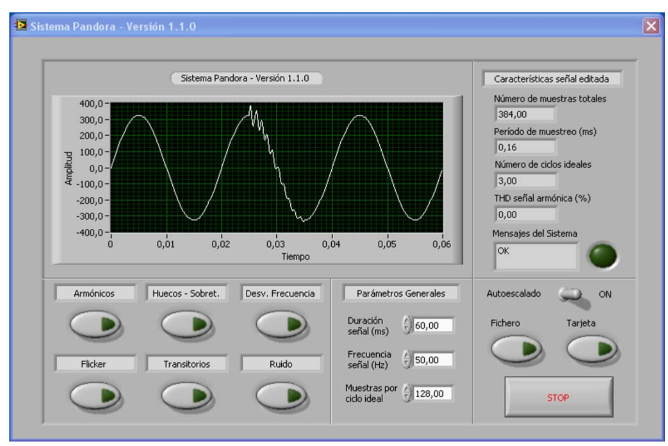
Figs. 9–11 show the front panel of Pandora and the corresponding screen of the power-analysis system for three types of disturbance: harmonics, flicker, and transient.



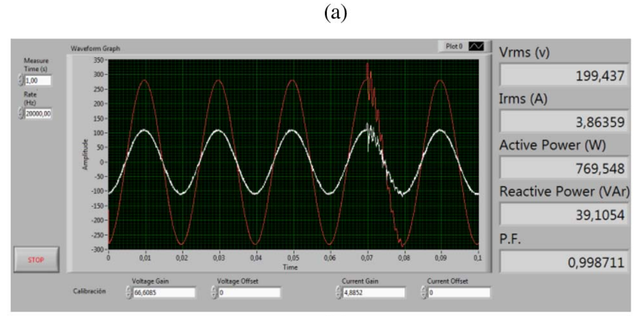
(a)

(b)

Fig. 10. Example 1—Flicker disturbance (Test ID 6). (a) Pandora's front panel. (b) Measures from the reference power-analysis system (the measured current, white signal, is scaled by 20).



(a)



(b)

Fig. 11. Example 3—Generation of a transient disturbance (Test ID 25). (a) Pandora's front panel. (b) Measures from the reference power-analysis system (the measured current, white signal, is scaled by 20).

This real application demonstrates the flexibility and ease of use that the system Pandora involved in this type of application.

V. Conclusion

This paper has described an AWG for signals representative of steady-state and transient disturbances in single- or three-phase waveforms of electrical systems, as described in IEEE Std 1159-09.

The system has different potential applications: training pattern generation for ANN design, training or teaching tool, equipment testing, or scaling-down version of three-phase power systems.

Depending on the application, it is possible to use the system with or without an output amplifier. In that case, there are two possible options. The first one consists in a power amplifier to test at grid-voltage level. The second option combines a low-power high-voltage amplifier and a high-current transconductance amplifier to test grid-voltage and load-current levels.

An example of a real equipment testing application is described in order to demonstrate the system flexibility and ease of use.

The system is a valuable alternative to commercial arbitrary generators in terms of user-friendly interface, low cost, and flexibility to disturbance combination and configuration.

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