Integrated Modeling, Simulation and Signal Processing for Power Quality Analysis in the Context of Smart Grids

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***Abstract* – Power systems have been increasing its complexity in the latest years, due to the penetration of renewable energy, bringing the concept of Smart Grids. The presence of a great amount of renewable sources implies in a significant number of inverters, which increases the harmonics in the system. This paper presents an example of a microgrid modeling and simulation integrated with a signal processing interface using Wavelets. The objective of the proposed integration is to facilitate the system analysis in real time during steady state or transient conditions. The system used was a modified IEEE 13 bus distribution system in Simulink. The interface developed proved to be simple and effective in order to evaluate the power quality of the system in real-time.**

***Index Terms* – Harmonics, wavelets, wind turbine.**

I. INTRODUCTION

The introduction of renewable sources in power systems brought a new concept called Smart Grids. This concept arose due to a series of factors, such as the population growth and the search for cleaner sources [1]. The growth of nonlinear loads and inverters that connect renewable sources to the grid leads to a distortion in the waveform of both voltage and current, which makes power systems more complex nowadays [2]-[3].

In order to analyze those distortions, Fourier's series is used to represent the nonsinusoidal wave as the sum of infinite periodical signals, that have frequencies multiple of the fundamental [4]. The sinusoid signals with frequency multiple of the fundamental are called harmonics, which can bring a lot of unfortunate events like equipments failures and error in metering devices [5].

In order to maintain the system operating under reasonable conditions, a set of studies must be addressed about harmonics, such as monitoring [6], suppression [7] and compensation [8].

This paper proposes a tool for monitoring the fundamental frequency and the harmonics using wavelets transform. The main objective of this work is to identify the harmonics of higher order by obtaining the power spectrum density of a window of 12 cycles. Afterwards, the fundamental and the three higher harmonics are then decomposed from signal in order to have their behavior observed in the meantime.

The system used for this purpose was a modified IEEE 13 bus distribution system. Simulations have been carried out using the Simulink tool, from the software MATLAB. A wind turbine of 2 MW is placed in bus 692 of the system. This model of wind turbine is present in MATLAB by default, is called Type 4 Wind Turbine. This is composed by a synchronous generator connected to a diode rectifier, a DC-DC IGBT-based PWM boost converter and a DC/AC IGBT based PWM converter. Maximum energy extraction is also possible, since this model has a control system for the DC-DC converter, in order to maintain the shaft speed at 1 pu and the reactive power generated at zero [9]. Despite the fact that the turbine reduces the losses of the system and raises the voltage level of the buses around, it also injects a significant amount of harmonics in the system, due to its nonlinear power electronics devices [10].

It was also added a 300 [kW] load connected to the system through a 6 pulse rectifier in bus 675.

The main contribution of this paper is to provide a tool to observe the harmonics of higher order in a period of 12 cycles.

The simulations were carried out with the system in steady state condition. Then, voltage sag was applied, in bus 671, for 12 cycles and the results provided were then evaluated in order to conclude if the method proposed is reliable for real-time monitoring.

II. SYSTEM MODEL

The wind turbine used in this paper, was the Type 4 Wind Turbine, represented as a block in MATLAB's Simulink library. This block takes as input the wind speed, the reactive power of reference (How much reactive power is desired to be injected in the grid) and the three-phase voltage lines.

As for the output, it can be chosen the ones of interest, through the block "Bus Selector".

The model represents both mechanical and electrical parts of the turbine. The mechanical part consists of wind turbine and a drive train, responsible for coupling the wind turbine to the synchronous machine. As for the electrical part, the synchronous machine is followed by a diode rectifier, a DC-DC IGBT-based PWM boost converter and a DC/AC IGBT-based PWM converter, finally, being connected to the grid.

For this study, the system used for the modeling and ssimulation was a modified IEEE 13 bus distribution system, shown in Fig. 1. The main elements of the system are:

Bus 632: Swing bus

Bus 692: DG Wind Turbine
Bus 675: Rectifier Load
As for the rest of the buses, their loads are linear.

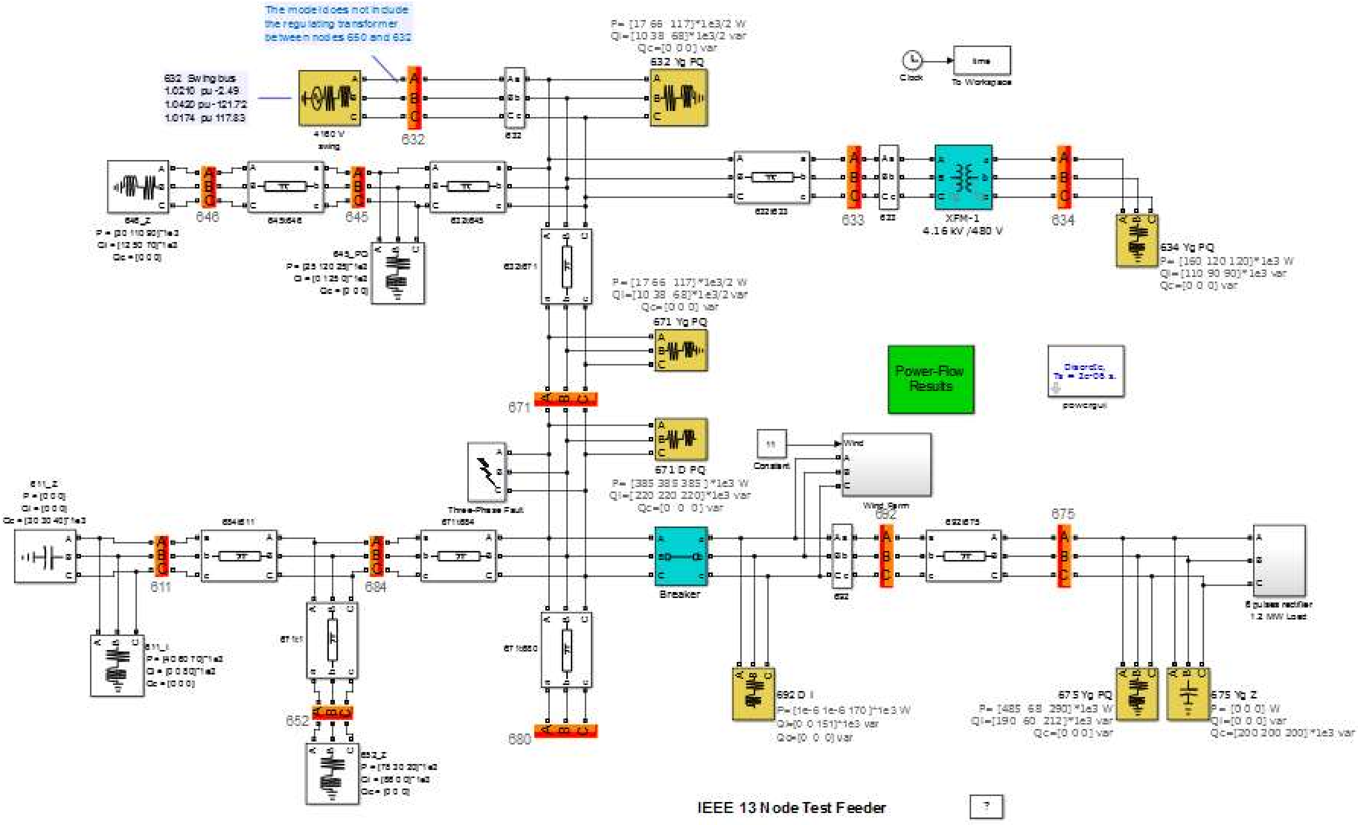

Fig. 1 – System Schematics

The voltage lines are represented by the "Three-Phase PI Section Line", all loads were modified to be three-phase loads, the Swing bus is Bus 632, with a voltage level of 4.16 kV, short-circuit level of 10 MVA and a X/R ratio of 10. Wind Turbine Type 4 of 2 MW was placed at Bus 692. Additionally, a 1.2 MW load was connected to the system through a 6 pulses rectifier at Bus 675, which injects harmonics in the order of [11]:

$$h = 6 \cdot n \pm 1$$

Finally, the block "Three-Phase Fault" is considered at Bus 671 to apply sags during the simulation. This enables one to evaluate the performance of the monitoring tool.

III. SIGNAL PROCESSING TOOL

In order to a waveform be considered a wavelet, it must obey two main properties [12]. The first is the finite energy:

$$E = \int_{-\infty}^{\infty} |\psi(t)|^2 dt \quad (1)$$

And the second is the admissibility condition (Mean equals to zero):

$$\int_{-\infty}^{\infty} \psi(t) dt = 0 \quad (2)$$

In power systems, wavelets can be used as a tool of diagnostics for power quality, such as the identification of harmonics or contingencies.

Wavelet analysis, from a historical point of view, is based on Fourier series which states that a signal can be represented as an infinite sum of periodical signals with frequencies multiple of the fundamental. The continuous wavelet transform, decomposes the signal in a sum series of a 'wavelet mother', with different dilations and translations [13], as shown in (3):

$$X_{CWT}(\tau, s) = \int_{-\infty}^{\infty} x(t) \cdot \psi_{\tau,s}^{*}(t) dt \quad (3)$$

where τ is the translation factor and s is the dilation factor.

There is a set of wavelets that proven to be useful for signal processing, called 'Wavelet Families'. The main ones are '*Haar*', '*Daubechies*', '*Biorthogonal*', '*Coiflets*', '*Symlets*', '*Morlet*', '*Mexican Hat*' and '*Meyer*' [13].

For this work the '*Daubechies 45*' (db45), was used to decompose the signal of interest. Fig. 2 illustrates the db45 wavelet

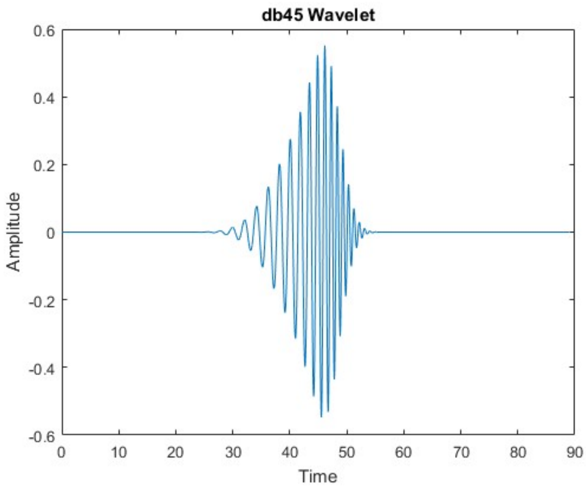

Fig. 2 - Daubechies 45

IV. INTEGRATED MODELING AND SIGNAL PROCESSING ANALYSIS

The simulations were carried out in the time-domain for an equivalent to 72 cycles for the fundamental frequency of 60 Hz, with a sampling frequency of 500 kHz due to the Type 4 turbine, and a constant wind speed of 11 m/s. In the interval of 1/3 and 8/15 seconds, which is equivalent to 12 cycles in 60 Hz, a voltage sag of 30% is applied at Phase A in Bus 671. Afterwards, the system returns to it's normal operation conditions.

Once the simulation is over and the data is saved, the waveform of interest is loaded in a MATLAB graphical interface program, being resampled to a frequency of 15360 Hz.

The interface proposed is composed of four rows and three columns. The first column is for phase A, the second for phase B and the third for phase C. The first row shows the full signals over time, the units in the y-axis are in kV. As for the second, third and fourth rows, are meant to show the three harmonics of higher order for each phase over time, during a specific 'window' of 12 cycles over time, with the y-axis units in Volts. Those harmonics are identified through the Fast-Fourier Transform (FFT). The interface is shown in Fig. 4.

This 'window', described in the paragraph above, is chosen by selecting the interval of interest in the pop-up menu, shown in the upper left of the interface. These intervals are '0 to 0.2 seconds', '0.2 to 0.4 seconds', '0.4 to 0.6 seconds', until '1 to 1.2 seconds'. Once this interval is selected, the interface is updated automatically, by highlighting the interval of interest in red of the plots of the first row and filling the three last rows with the harmonics of higher order.

There are also two buttons present in the interface, those are the 'Fundamental' and the 'Frequency spectrum'. The 'Fundamental' opens a window with 3 plots, one for each phase, showing the decomposed fundamental frequency versus the original signal. As for the 'Frequency spectrum', it also opens a window with 3 plots, one for each phase, that shows the frequency spectrum in dB/Hz, with a range of 0 until the 15th harmonic. Both of these buttons responses are referent to the interval chosen in the pop-up menu.

As for the wavelet decomposition, it was used the wavelet packet, it was chosen 'Daubechies 45' (db45) as the wavelet mother and 8 levels of decomposition, through the MATLAB command line:

```
wpt = wpdec(x,8,'db45','shannon');
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Which x represents the signal to be decomposed, the number 8 represents the levels of decomposition, 'db45' referent to 'Daubechies 45', 'shannon' is the type of entropy and 'wpt' is a wavelet packet tree corresponded to the decomposed signal. The wavelet tree that results from an eight level decomposition is shown in Fig. 3:

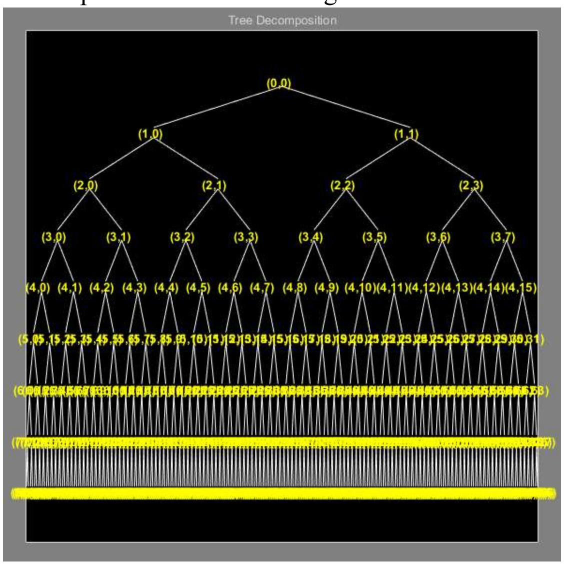

Fig. 3 – Wavelet packet decomposition tree

As can be seen, its composed of 8 rows and the number of columns present in each level is the double of the previous one.

Summing up, once an interval is settled in the pop-up menu, the interval of interest is highlighted in the first row, a FFT is executed in order to identify the three harmonics of higher order for each phase and they are plotted through the decomposition described above.

The results shown in the following section, are related to Bus 692.

V. RESULTS

The first results obtained are in the interval of '0 to 0.2 seconds', shown in Fig. 4, according to the proposed interface:

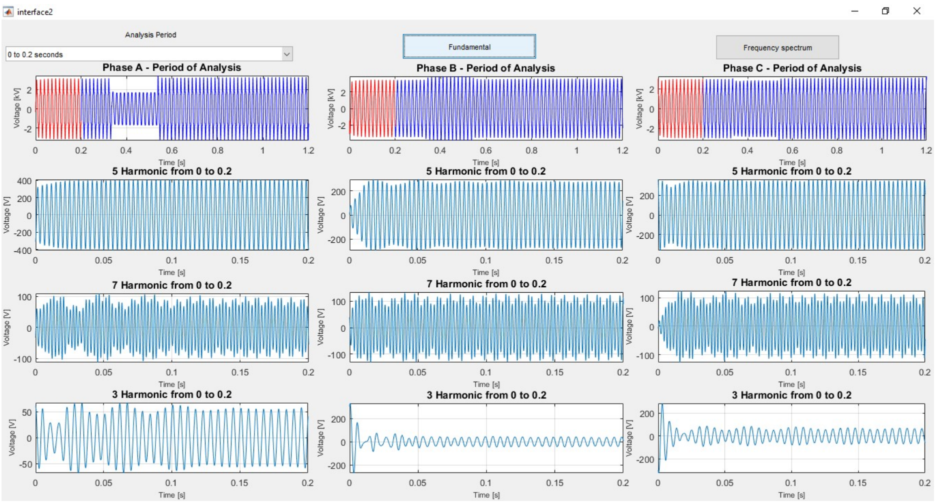

Fig. 4 - Analysis from 0 to 0.2 seconds

The interface shows that for all phases the harmonics of higher amplitude are the 5th, 7th and 3rd respectively. In order to observe the fundamental frequency, the button ‘Fundamental’ is pressed and the results are shown in Fig. 5:

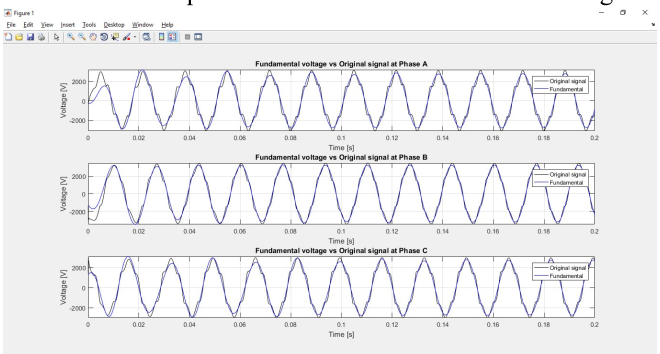

Fig. 5 - Fundamental frequency from 0 to 0.2 seconds

And to check the magnitude of the harmonics until the 15th, the button ‘Frequency spectrum’ is pressed and the result is in Fig. 6:

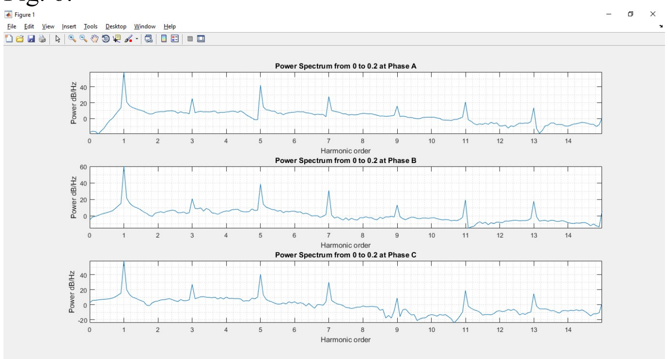

Fig. 6 - Frequency spectrum from 0 to 0.2 seconds

Now choosing the interval of ‘0.2 to 0.4 seconds’, where the sag starts at 0.333 seconds, there is a change in the amplitude of the harmonics, as shown in Fig. 7:

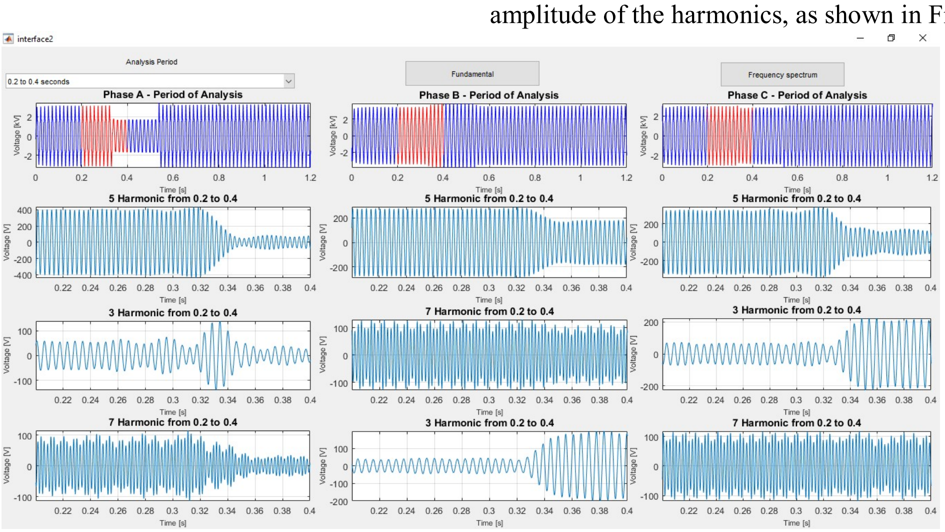

Fig. 7 – Analysis from 0.2 to 0.4 seconds

From Fig. 4 to Fig. 7 the only change that happened was the third harmonic from phases A and C, where the 3rd harmonic presents a higher energy than the 7th.

By pressing the ‘Fundamental’, opens the window shown in Fig. 8, is possible to observe that a sag occurs in phase A, a slight overvoltage is present in phase B and phase C practically does not change.

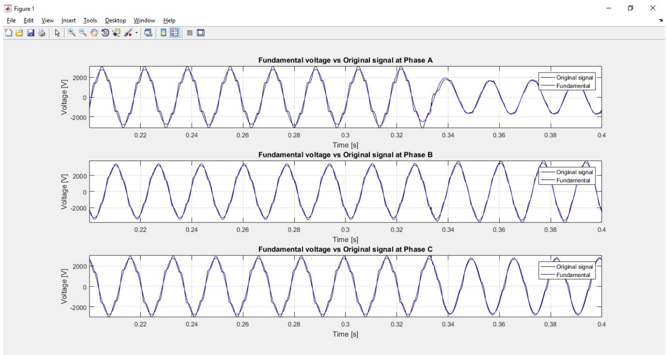

Fig. 8 – Fundamental frequency from 0.2 to 0.4 seconds

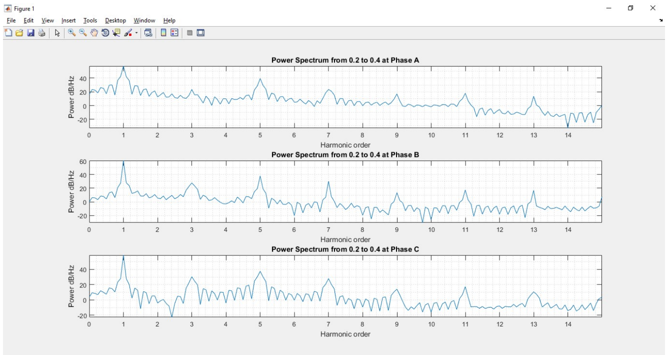

Fig. 9 – Frequency spectrum from 0.2 to 0.4 seconds

And by pressing ‘Frequency spectrum’, Fig. 9 is obtained, where can be observed significant increase in the amplitude of harmonics that were very low in Fig. 6:

Now repeating the process used to obtain Fig. 7 - Fig. 9, for the interval of ‘0.4 to 0.6 seconds’, where happens the end of the sag and the system returns to normal, Fig. 10 - Fig. 12 are obtained.

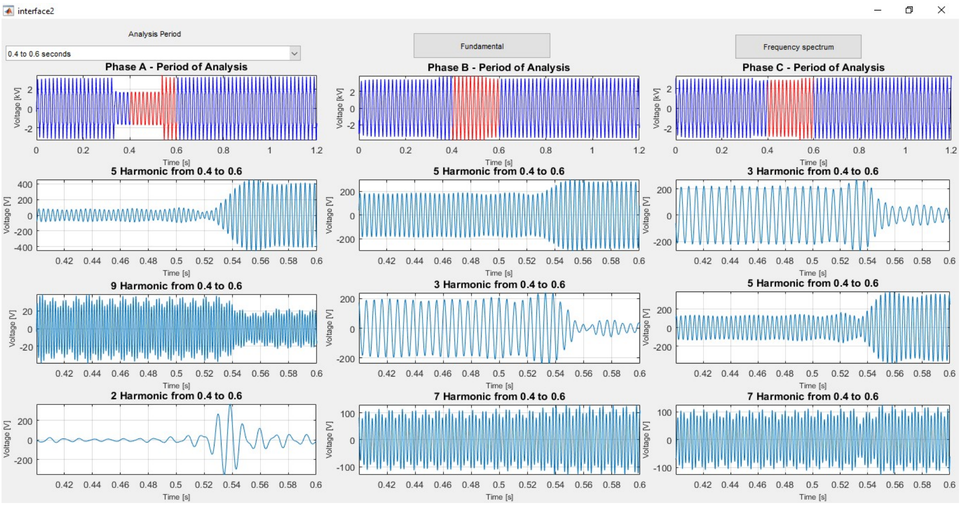

Fig. 10 - Analysis from 0.4 to 0.6 seconds

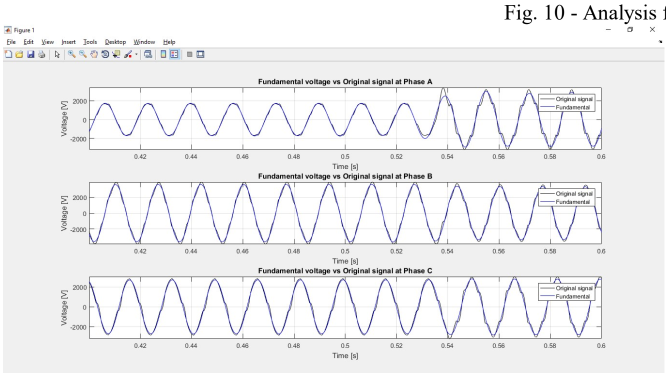

Fig. 11 – Fundamental frequency from 0.4 to 0.6 seconds

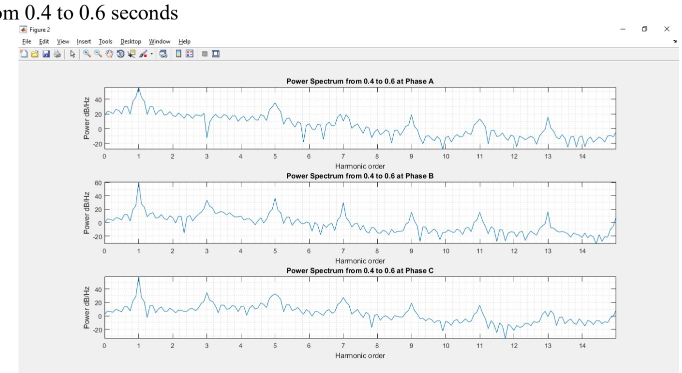

Fig. 12 – Frequency spectrum from 0.4 to 0.6 seconds

By observing Fig. 10, it can be seen that the harmonics with higher amplitude are: 5^{th} , 9^{th} and 2^{nd} for phase A, 5^{th} , 3^{rd} and 7^{th} for phase B and 3^{rd}, 5^{th} and 7^{th} for phase C.

In Fig. 11 it can be observed that the sag at phase A and the overvoltage present in phase B ends at 0.533 seconds. Phase C remains unaltered mostly. Finally, for Fig. 12, shows that a few harmonics still show a significant amplitude just like Fig. 9.

As for the rest of the options present in the pop-up menu, the results obtained are the same presented in Fig. 4 to Fig. 6, once the system returns to it’s normal operational conditions.

VI. CONCLUSION

This paper proposed the use of a MATLAB graphical user interface integrated to a Simulink / simpowersystems toolbox, in order to provide a tool that allows the power quality monitoring and in particular of time-varying harmonics.

There is also the possibility of monitoring the fundamental frequency and viewing the frequency spectrum in the specified time, by pressing the 'Fundamental' and 'Frequency spectrum' respectively.

The results obtained showed that the interface is simple to operate, and the methodology applied in order to evaluate the harmonics of higher amplitude and to decompose the signals were very effective, providing a very useful tool to monitor power quality.

For future projects, the work developed for this paper may be extended to real-time monitoring and diagnostics.

VII. ACKNOWLEDGEMENTS

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REFERENCES

[1] V. C. Gungor *et al.*, "Smart Grid Technologies: Communication Technologies and Standards," in *IEEE Transactions on Industrial Informatics*, vol. 7, no. 4, pp. 529-539, Nov. 2011.

[2] A. Eigeles Emanuel, "Harmonics in the early years of electrical engineering: a brief review of events, people and documents," *Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441)*, Orlando, FL, 2000, pp. 1-7 vol.1.

[3] A. Khan, M. A. Alkali, S. Parasuraman, I. Elamvazuthi, M. Amudha and N. Debnath, "Harmonics analysis in a DC-DC converter based line frequency inverter for domestic lighting loads," *2016 2nd IEEE International Symposium on Robotics and Manufacturing Automation (ROMA)*, Ipoh, 2016, pp. 1-6.

[4] M. F. Zambroni de Souza, M. L. Pereira, P. M. Silveira and P. Ribeiro, "A MATLAB tool to study harmonics penetration in grid unbalanced conditions," *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*, Belo Horizonte, 2016, pp. 715-720.

[5] R. C. Dungan, 1988, "Harmonic Considerations for Electrical Distribution Feeders".

[6] T. L. de Oliveira, L. F. Moreira, T. C. O. Carvalho, W. D. M. Xavier and P. F. Ribeiro, "Microcontroller implementation for monitoring time-varying harmonics from non-linear loads," *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*, Belo Horizonte, 2016, pp. 896-902.

[7] A. Ali, M. A. Khan and Z. Hu, "Applying Negative Permittivity Media to Microstrip Patch Antennas for Harmonic Supression," *2007 Loughborough Antennas and Propagation Conference*, Loughborough, 2007, pp. 245-248.

[8] C. Zhang, Y. Li, J. Li, Q. Yang and J. Zhu, "Measurement of Three-Dimensional Magnetic Properties With Feedback Control and Harmonic Compensation," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 3, pp. 2476-2485, March 2017.

[9] Richard Gagnon and Jacques Brochu (Hydro-Quebec). 2016. *Mathworks*. [ONLINE] Available at: https://www.mathworks.com/help/physmod/sps/examples/wind-farm-synchronous-generator-and-full-scale-converter-type-4-detailed-model.html. [Accessed 7 March 2017].

[10] B. Chen, G. Pin, W. M. Ng, T. Parisini and S. Y. R. Hui, "A Fast-Convergent Modulation Integral Observer for Online Detection of the Fundamental and Harmonics in Grid-Connected Power Electronics Systems," in *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 2596-2607, April 2017.

[11] Ahmed, A. (1999) *Power Electronics for Technology*. PEARSON

[12] Ribeiro, P. F.; Augusto, C. A.; Silveira, P. M. and Cerqueira, A. S. (2014) *Power Systems Signal Processing for Smart Grids.* WILEY.

[13] Misiti, M.; Misiti, Y.; Oppenheim, G. and Poggi, J. M. (2005) *Wavelet Toolbox For Use With MATLAB.* Version 3. The Mathworks.