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MATLAB-Simulink-Based Power Quality Simulator for Educational and Research Purposes*

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This paper describes an efficient method of teaching power quality, to senior undergraduate and postgraduate students of power system groups in electrical engineering departments, as a part of a power quality course. The paper shows a MATLAB-Simulink based simulator in order to teach students the power quality and to practice analysing the simulation results. In this paper, first the theoretical aspect of simulation and simulator are described, and then the results are presented. Evaluation of the simulations using more than 40 students is very positive in terms of their developing confidence in and understanding of simulations.

Keywords: MATLAB-Simulink; power quality; simulator; impulse; wavelet

1. INTRODUCTION

COMPUTER SIMULATION plays an important role in engineering course teaching. Nowadays, a variety of software tools are available to simulate electrical circuits; one is MATLAB. Many simulations performing power system analysis for educational purpose have been presented by different researchers [1–8].

The term quality is sometimes used as synonymous with supply reliability to indicate the existence of an adequate and secure supply. A broader definition has described service quality, encompassing the three aspects of reliability, supply and quality of power offered. Judging by the content of the innumerable contributions to the topic in recent years, power quality is generally used to express the quality of the voltage. With the expansion of electronic control in the transmission and utilization of electrical energy, there is increasing acceptability of the latter interpretation [9–10].

The following phenomena are used for power quality.

1. Harmonics
2. Flicker
3. Power frequency phenomena
4. Transients.

Power quality research and recommended practices have taken on a growing importance over recent years [11–19].

Voltage fluctuation or flicker can be described as a cyclical variation of voltage changes. The main flicker sources are industrial loads such as arc furnaces, arc welding plants, rolling mills and large motors with varying loads [9–11]. Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate. Harmonic disturbances are generally caused by equipment characterized by non-linear loads like converters, induction furnaces and arc furnaces [9–11]. Power frequency phenomena are a temporary deviation from the steady-state waveform caused by faults of brief duration or by sudden changes in the power system. Voltage sag, voltage interruption and voltage swell belong to this category [9], [10], [14]. Voltage disturbances shorter than sags or swells are classified as transients [9–10]. Table 1 shows characteristics of these phenomena [17].

2. SIMULATOR PRESENTATION

2.1 Power quality module

What is power quality?

- Power quality = voltage quality
  - Frequency, amplitude, distortion
- Temporary voltage quality issues
  - Faults, switching, lightning
- Continuous voltage quality issues
  - Nonlinear loads, use of power conductors for data transmission
  - System design problems

This module consists of 15 weeks of a theoretical course. In this course the principles of power quality are taught and the student will be made familiar with examples in this field.

The aim of this paper is to introduce a helpful method to the instructor for teaching the examples of power quality. The authors chose MATLAB-

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Table 1. Categories and typical characteristics of power system electromagnetic phenomena [17]

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 μs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 μs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μs	0–4 pu
2 Short-duration root-mean square (rms) variation			
2.1 Instantaneous		0.5–30 cycles	0.1–0.9 pu
2.1.1 Sag		0.5–30 cycles	1.1–1.8 pu
2.1.2 Swell			
2.2 Momentary		0.5 cycles–3 s	< 0.1 pu
2.2.1 Interruption		30 cycles–3s	0.1–0.9 pu
2.2.2 Sag		30 cycles–3 s	1.1–1.4 pu
2.2.3 Swell			
2.3 Temporary		> 3 s–1 min	< 0.1 pu
2.3.1 Interruption		> 3 s–1 min	0.1–0.9 pu
2.3.2 Sag		> 3 s–1 min	1.1–1.2 pu
2.3.3 Swell			
3 Long duration rms variations			
3.1 interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8–0.9 pu
3.3 Overvoltages		> 1 min	1.1–1.2 pu
3.4 Current overload		> 1 min	
4 Imbalance			
4.1 Voltage		steady state	0.5–2%
4.2 Current		steady state	1–30%
5 Waveform distortion			
5.1 DC offset		steady state	0–0.1%
5.2 Harmonics	0–9 kHz	steady state	0–20%
5.3 Interharmonics	0–9 kHz	steady state	0–2%
5.4 Notching		steady state	
5.5 Noise	broadband	steady state	0–1%
6 Voltage fluctuationT	< 25 Hz	intermittent	0.1–7%
7 Power frequency variation		< 10 s	

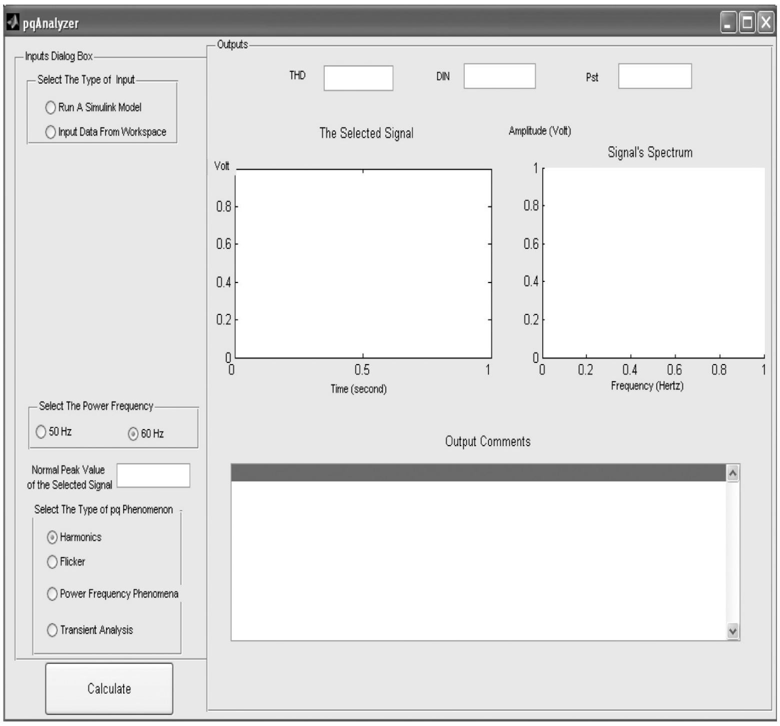


Fig. 1. Main menu of simulator.

SIMULINK as the instructional tool. This method of instruction has enabled students to understand the power quality subject. Their success rate in understanding the subject shows the usefulness of this method.

2.2 Simulator feature

An essential feature of the simulator is to incorporate the visualization and control of results in a graphical form on a computer screen. This is particularly important in the analysis or simulation of power networks because of their large size and wide geographical distribution.

A GUI-based power quality simulator is designed for analysis of flicker, harmonics, power frequency phenomena and transients in power system. Figure 1 shows the main menu of a simulator.

Input data can be entered in two ways (main menu). Figure 2 shows the first method of getting input data from the workspace. The selected vector (input) can be updated by pressing the update input signals key and choosing the signal that should be updated, and getting the input form measured signals.

The second way of getting input data is selecting the Run A Simulink Model key. By pressing this key the following menu appears (Fig. 3). It is possible to run a Simulink-simulated network and use the resulting signal as input to the simulator.

2.3 Calculation procedure

2.3.1 Harmonics

Distortion factor or total harmonic distortion (*THD*) is the square root of the sum of the squares of the rms values of all harmonics divided by the fundamental expressed as:

$$THD = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \tag{1}$$

In some cases (such as: capacitive load or some kind of inverter) instead of *THD* computation the distortion index (*DIN*) is computed as follow.

$$DIN = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{\sqrt{\sum_{n=1}^{N} V_n^2}} \tag{2}$$

$$DIN = \frac{THD}{\sqrt{1 + (THD)^2}} \tag{3}$$

$$THD = \frac{DIN}{\sqrt{1 - (DIN)^2}} \tag{4}$$

In this paper the Fourier transform of the wave is computed, and then from equations (2–4) the *THD* and *DIN* are computed.

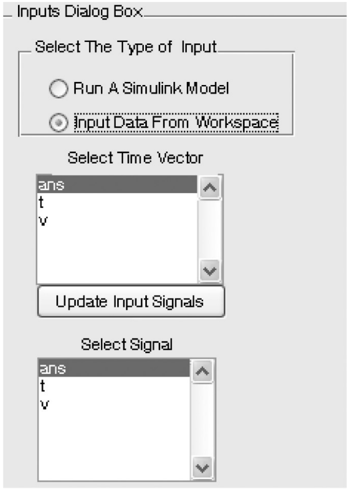


Fig. 2. Input data from workspace.

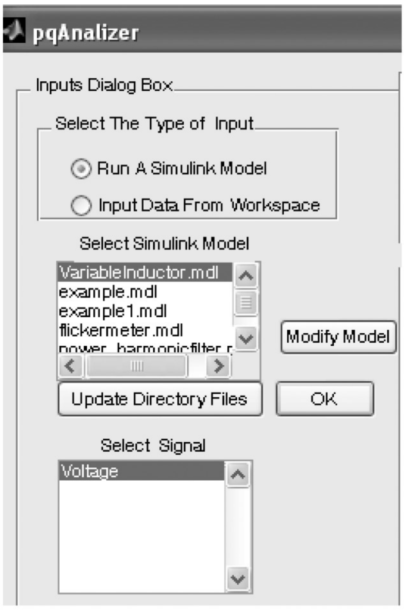


Fig. 3. Run A Simulink Model menu for getting input.

2.3.2 Flicker

In the flicker the analysis is performed by the IEC flicker meter [20]. This flicker meter contains five blocks.

1. Block 1: input voltage adaptor and calibration checking circuit
2. Block 2: square law demodulator
3. Block 3 and Block 4: weighting filters, squaring and smoothing
4. Block 5: online statistical analysis.

A Simulink model is used for modelling blocks 1, 2, 3 and 4. The output of the fourth block is the instantaneous flicker level (IFL). In this paper the statistical analysis is done on IFL in block 5 and the output is short-term flicker severity index (Pst).

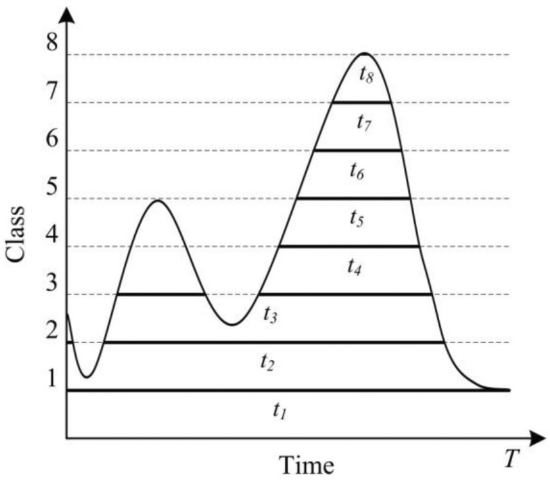


Fig. 4. Linear classification of time series, each t_k ($k = 1.\,.\,.\,.\,.\,.8$) indicates the duration the signal exceeds the lower limit of the corresponding class k.

2.3.3 *IFL and Pst calculation*

The amplitude of the flicker sensation is subdivided into a suitable number of classes. Every time that the appropriate value occurs, the counter of the corresponding class is incremented by one [9] and the frequency distribution function of the flicker sensation is obtained. If a sampling frequency of at least twice the maximum flicker frequency is chosen, at the end of the measuring interval the result represents the distribution of flicker level duration at each class. The probability density function of the flicker is obtained by adding the contents of all counters of all classes and expressing the count of each class relative to the total. The cumulative probability, $p(l)$ that IFL exceeds l is defined as:

$$p(l) = \frac{t_l}{T} \tag{5}$$

T is total observation time and t_l is time duration that the signal remains above l. Figure 4 shows the classification of the signal.

Figure 5 shows the resulting discrete cumulative probability function (CPF) for the observation time. Clearly, increase in the number of classes will result in a more accurate distribution but at the expense of more computation. For increasing the accuracy of classification methods and limit the computation, several interpolation techniques are proposed by IEC [9], [24]. Two severity indices are proposed for flicker evaluation: short-term flicker severity (P_{st}) and long-term flicker severity (P_{lt}). P_{st} is generally computed over 10 min and is derived from the time-at-level statistics obtained from the cumulative probability function.

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \tag{6}$$

Where the percentiles $P_{0.1}$, P_1, P_3, P_{10}, and P_{50} are the flicker sensation levels exceeded for 0.1%; 1%; 3%; 10% and 50% of the time during the observation period [9]. The suffix s in the formula indicates that the smoothed value must be used [9].

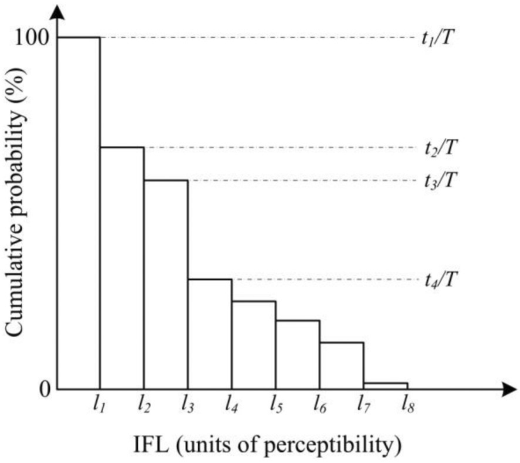


Fig. 5. CPF of the signal of Fig. 4 for observation time T.

$$\begin{aligned} P_{50s} &= (P_{30} + P_{50} + P_{80})/3 \\ P_{10s} &= (P_6 + P_8 + P_{10} + P_{13} + P_{17})/5 \\ P_{3s} &= (P_{2.2} + P_3 + P_4)/3 \\ P_{1s} &= (P_{0.7} + P_1 + P_{1.5})/3 \end{aligned} \tag{7}$$

The 0.3s memory time constant in the flickermeter ensures that $P_{0.1}$ cannot change abruptly and no smoothing is needed for this percentile. The long-term flicker severity P_{lt} is derived from following formula [9]:

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{sti}^3}{N}} \tag{8}$$

Where P_{sti} ($i = 1, 2, 3.\,.\,.\,.$) are consecutive readings of the short-term severity P_{st}.

2.3.4 *Power frequency phenomena and transient analysis*

Wavelet transform is used for analysis and calculation of power frequency and transient phenomena. The wavelet transform (WT), originally derived to process seismic signals, provides a fast and effective way of analysing non-stationary voltage and current waveforms. As in the Fourier case, the WT decomposes a signal into its frequency components. Unlike the Fourier transform, the wavelet can tailor the frequency resolution, a useful property in the characterisation of the source of a transient.

The ability of wavelets to focus on short-time intervals for high-frequency components and long intervals for low-frequency components improves the analysis of signals with localised impulses and oscillations [9], [21], [22].

If the used scaling function and the wavelets form an orthonormal basis, then the parseval's theorem relates the energy in each of the expansion components and related wavelet coefficients [23]. This means that the norm or the energy of the signal can be portioned in terms of the expansion coefficients.

$$\int |f(t)|^2 dt = \sum_{k=-\infty} |c(k)|^2 + \sum_{j=0}^{\infty} \sum_{k=-\infty}^{\infty} |d_j(k)|^2 \quad (9)$$

The energy of the distorted signal will be divided in different resolution levels in different ways depending on the power quality at hand. The standard deviation can be considered as a measure of the energy for a signal with zero mean.

A variety of wavelets originating from a mother wavelet can be used to approximate any given function. In this paper wavelet db10 is used for power frequency and transient phenomena analysis. Any changes in the pattern of signal can be detected and localized at the finer resolution levels.

The power frequency and transient phenomena categories presented in this paper are according to Table 1. One of the main reasons for developing the different categories of electromagnetic phenomena is that there are different ways to solve power quality problems depending on the particular variation that is of concern (Table 1).

2.4 Flowchart simulator operation

Flowchart of simulator operation is as Fig. 6. This flowchart shows the methods of inputting data, and calculation method for the simulator. The methods for input data are described above (Figs 2 and 3) and the harmonics analysis, flicker analysis, power frequency phenomena (PFP) analysis and transient analysis are performed.

2.5 Simulation results

2.5.1 Results of harmonics simulation

In order to show the ability of harmonics analysis of the simulator, a circuit of Fig. 7 is

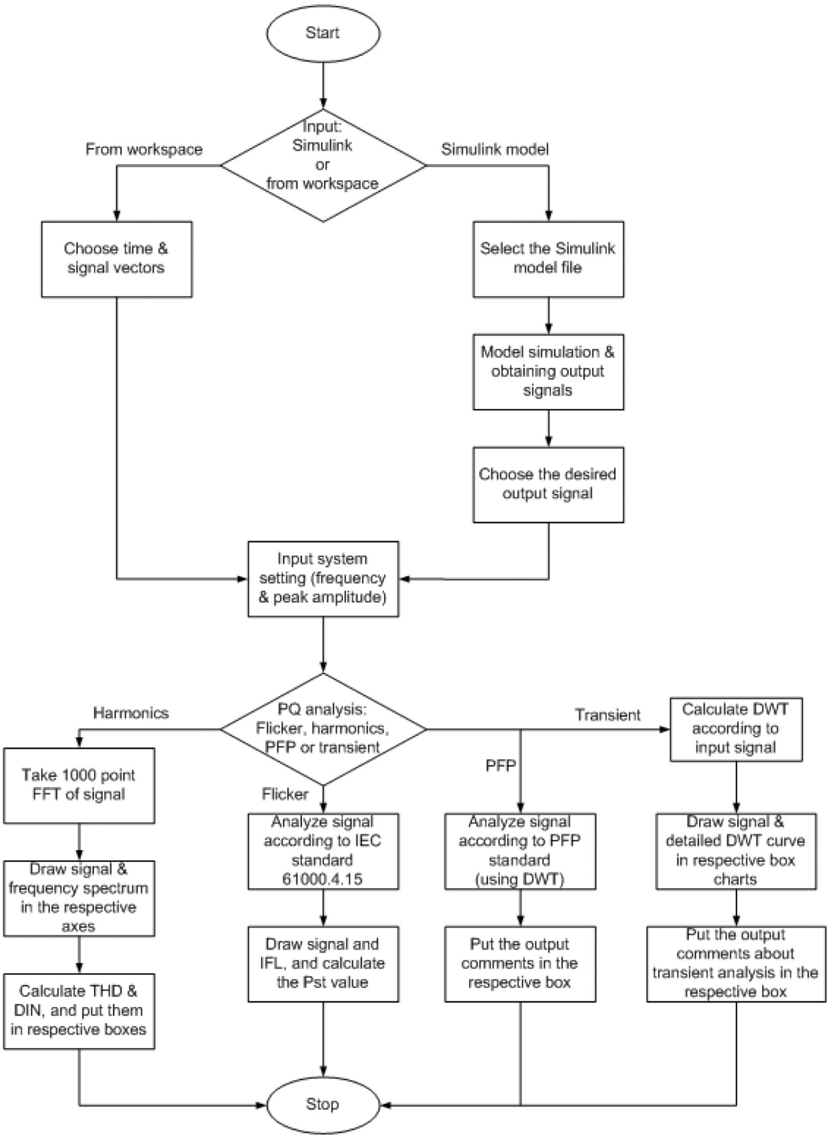
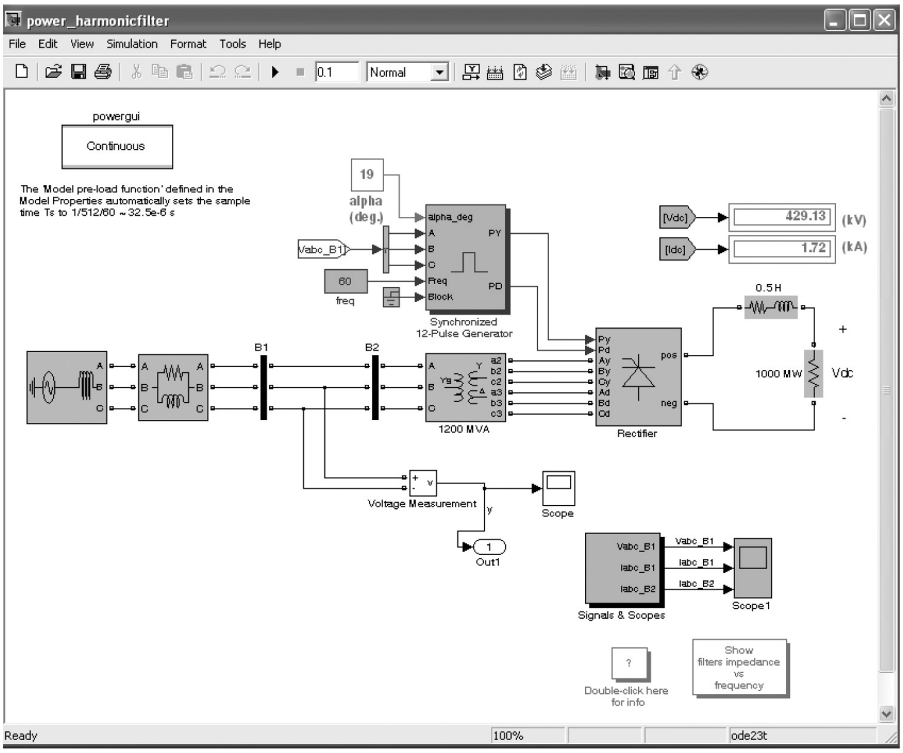
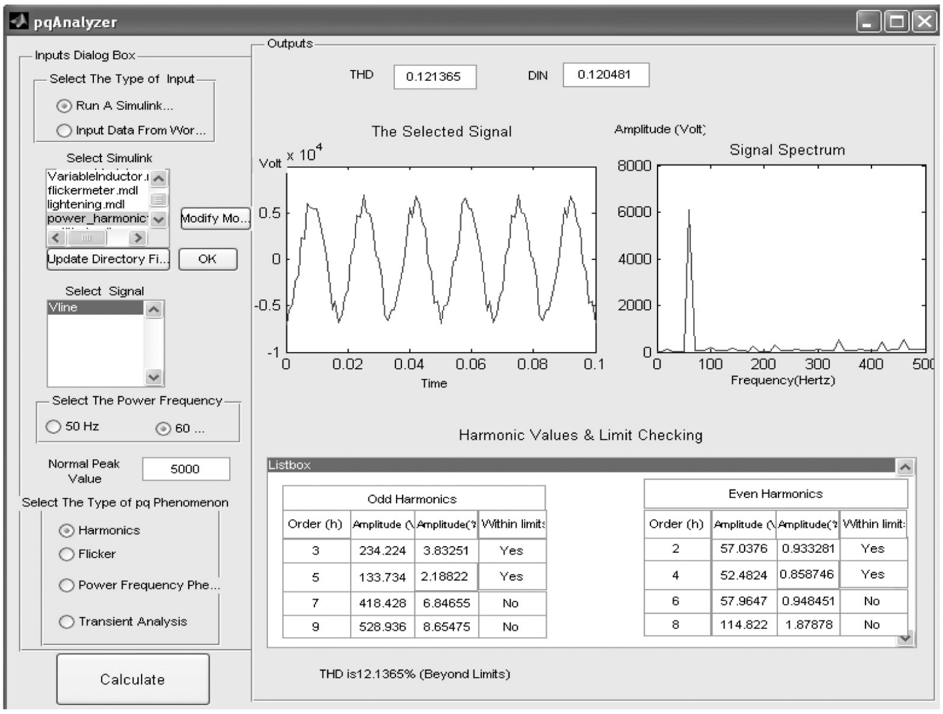


Fig. 6. Flowchart of simulator operation.



The Model pre-load function' defined in the Model Properties automatically sets the sample time Ts to 1/512/60 ~32.5e-6 s

Fig. 7. Simulated circuit for harmonics analysis.



● Run A Simulink...
○ Input Data From Wor...

○ 50 Hz ● 60 ...

Normal Peak Value: 5000

● Harmonics
○ Flicker
○ Power Frequency Phe...
○ Transient Analysis

THD: 0.121365
DIN: 0.120481

Odd Harmonics

Order (h)	Amplitude (\	Amplitude(?	Within limits
3	234.224	3.83251	Yes
5	133.734	2.18822	Yes
7	418.428	6.84655	No
9	528.936	8.65475	No

Even Harmonics

Order (h)	Amplitude (\	Amplitude(?	Within limit
2	57.0376	0.933281	Yes
4	52.4824	0.858746	Yes
6	57.9647	0.948451	No
8	114.822	1.87878	No

THD is12.1365% (Beyond Limits)

Fig. 8. Harmonics analysis result.

simulated on MATLAB-Simulink and a voltage signal is captured and analysed according to flowchart sequence. Harmonics analysing is shown in Fig. 8.

The THD and DIN are calculated, the odd and even harmonics are checked with the standard limits and are shown (Fig. 8). From this results can conclude that the harmonics and THD are in limits or not.

2.5.2 Results of flicker simulation

In order to show the ability of flicker analysis of the simulator, a circuit of Fig. 9 is simulated on MATLAB-Simulink and a voltage signal is used

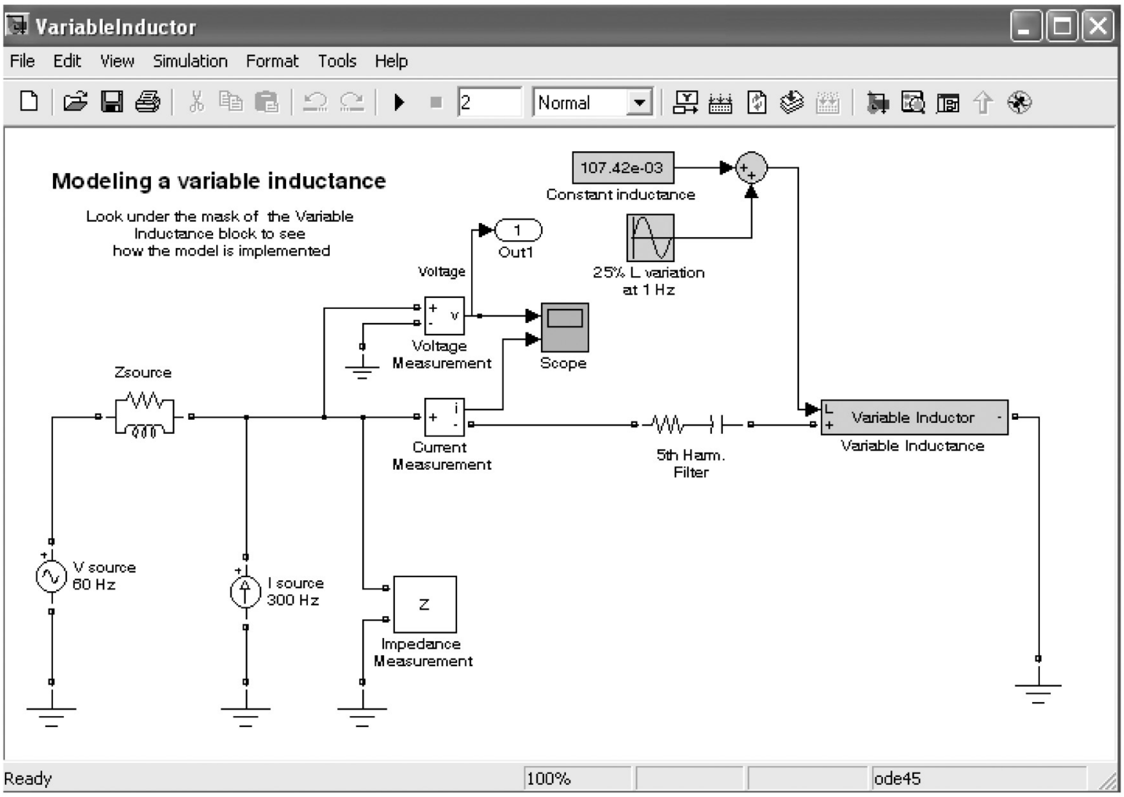
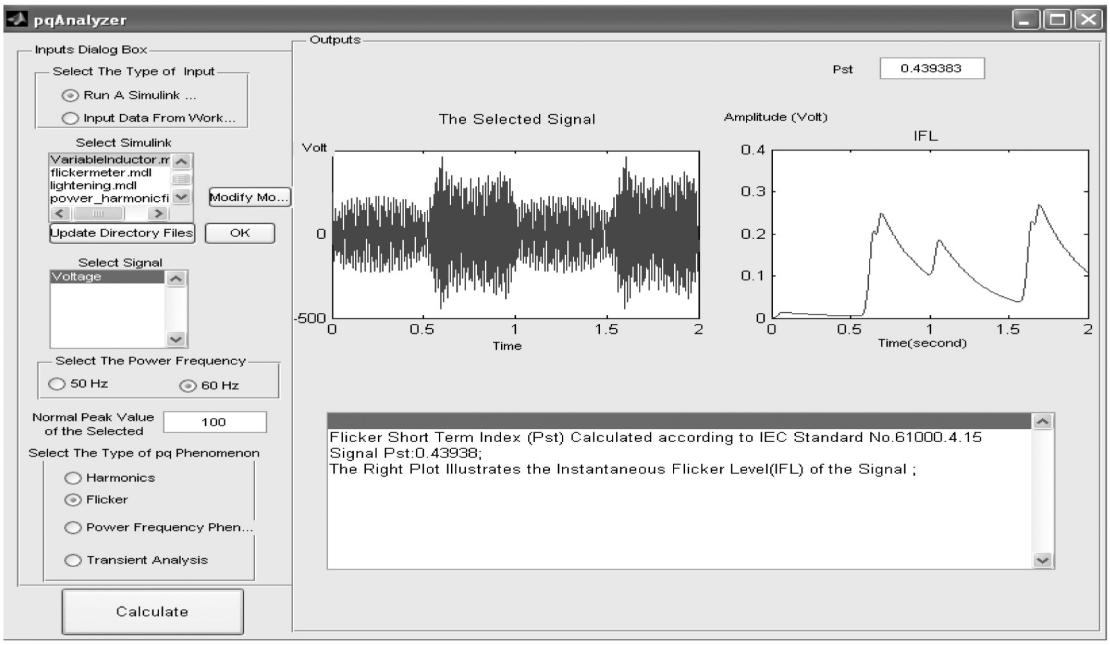


Fig. 9. Simulated circuit for flicker analysis.



Pst 0.439383

Normal Peak Value of the Selected 100

```
Flicker Short Term Index (Pst) Calculated according to IEC Standard No.61000.4.15
Signal Pst:0.43938;
The Right Plot Illustrates the Instantaneous Flicker Level(IFL) of the Signal ;
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Fig. 10. Flicker analysis result.

for flicker analysing (the formulas are as before). This analysing result is shown in Fig. 10 (IFL and P_{st}).

2.5.3 *Results of power frequency phenomena simulation*

In order to show the ability of power frequency phenomena analysis of the simulator, a circuit of Fig. 11 is simulated on MATLAB-Simulink and power frequency phenomena analysing is shown in Fig. 12 with comments.

2.5.4 *Results of transient analysis simulation*

In order to show the ability of transient analysis

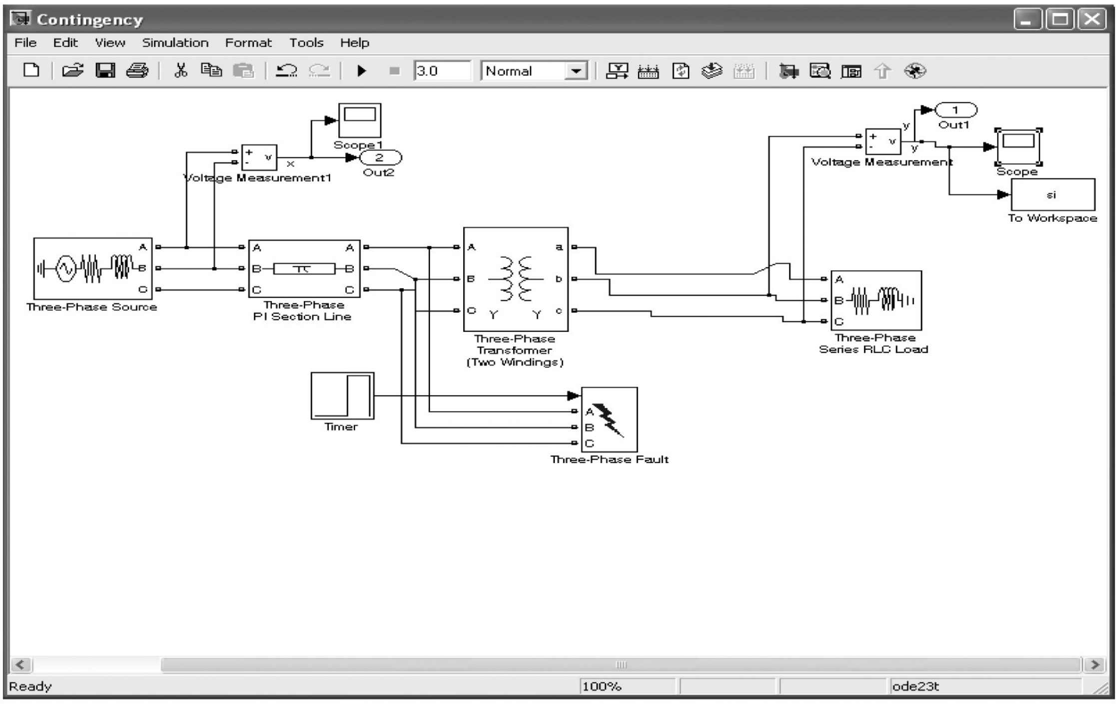
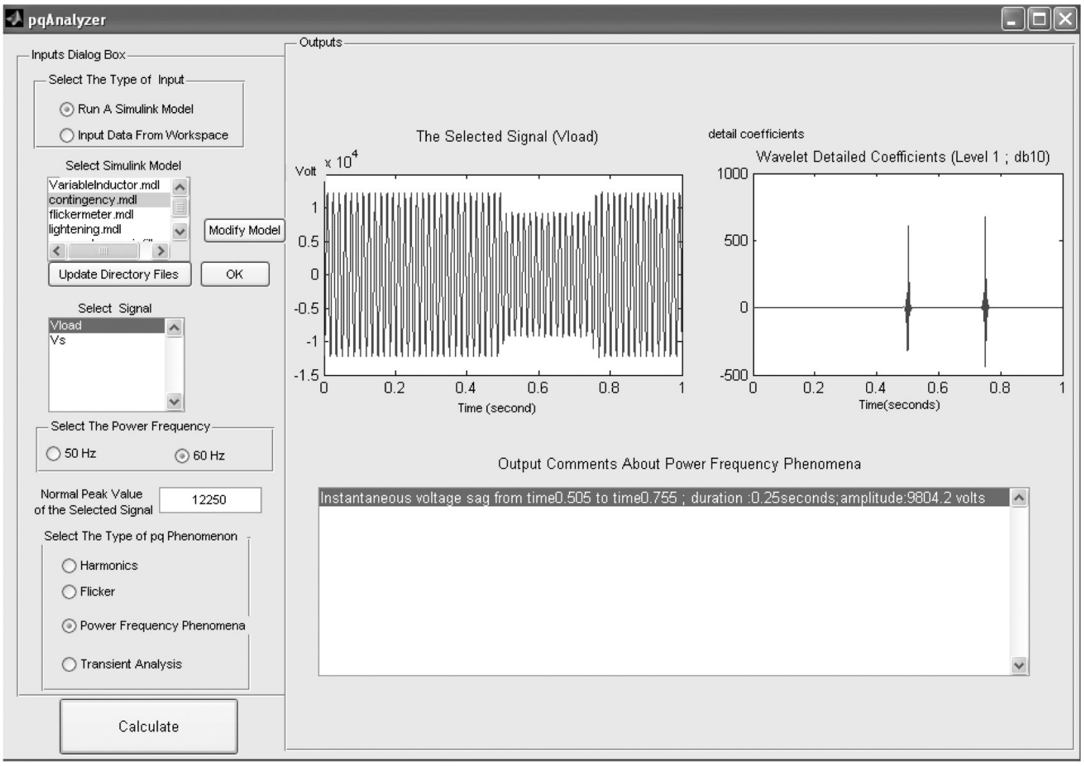


Fig. 11. Simulated circuit for power frequency phenomena analysis.



Select The Type of Input
● Run A Simulink Model
○ Input Data From Workspace

Select Simulink Model
VariableInductor.mdl
contingency.mdl
flickermeter.mdl
lightening.mdl

Select Signal
Vload
Vs

Select The Power Frequency
○ 50 Hz
● 60 Hz

Normal Peak Value of the Selected Signal: 12250

Select The Type of pq Phenomenon
○ Harmonics
○ Flicker
● Power Frequency Phenomena
○ Transient Analysis

Output Comments About Power Frequency Phenomena

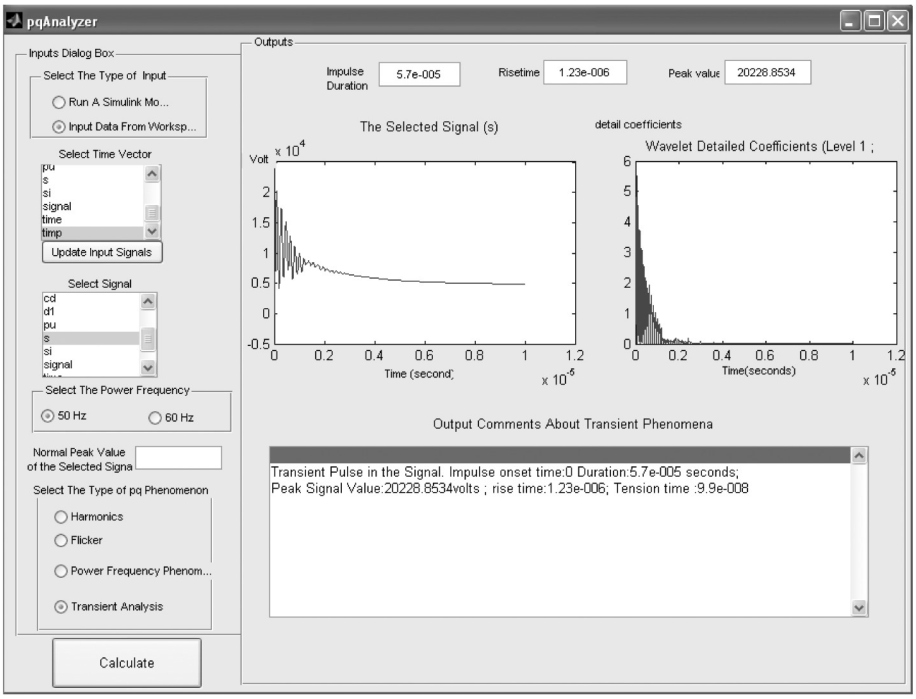
Instantaneous voltage sag from time0.505 to time0.755 ; duration :0.25seconds;amplitude:9804.2 volts

Fig. 12. Power frequency analysis result.

of the simulator a transient wave is got from network by computer as input of the simulator. Fig. 13 shows the result of analysis. The wave characteristics and comments are shown on the simulator (Fig. 13).

3. DISCUSSION

Assessment of learning outcomes refers to specific processes through which learners demonstrate the attainment of learning outcomes. In a course,



● Input Data From Worksp...

● 50 Hz

● Transient Analysis

Impulse Duration 5.7e-005

Risetime 1.23e-006

Peak value 20228.8534

Transient Pulse in the Signal. Impulse onset time:0 Duration:5.7e-005 seconds;
Peak Signal Value:20228.8534volts ; rise time:1.23e-006; Tension time :9.9e-008

Fig. 13. Transient analysis result.

Table 2. Questionnaire answered by the students

Questions	Score
1- I had previous knowledge of MATLAB-SIMULINK	
2- The content of this practical is valuable for an engineer	
3- Are you understanding the concept of power quality better after using this utility	
4- Are you more familiar with the power quality after using this utility	

the instructor has the obligation to require learners to demonstrate that they have attained the learning outcomes. The methodology described in the present paper has been used for 40 students in a power system group (20 senior undergraduate students and 20 MSc students). They used the methodology and filled a questionnaire form. The questionnaire consisted of four questions shown in Table 2. The students graded them as 1 (poor), 2 (not much), 3 (good) and 4 (very good). Figure 14 shows the global results obtained from the students' questionnaire. Table 3 shows the average scores for each question out of students' feedback.

Table 3. Average score obtained from students' answers

	Average score
Question 1	3.5
Question 2	3.7
Question 3	3.47
Question 4	3.55
Total	3.55

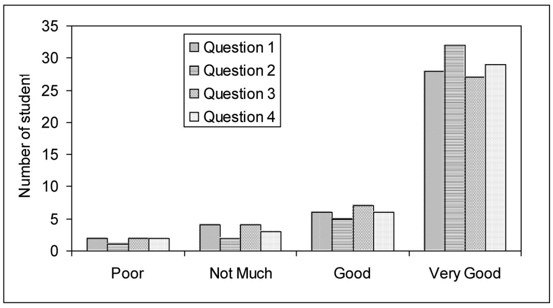


Fig. 14. Global results obtained from students' questionnaire.

4. CONCLUSIONS

Introducing power quality problems in several power system courses to students has been a unique educational source. The presence of harmonics, flicker, transient and power frequency phenomena in power systems, has raised many questions; simulation of these phenomena and analysis of results can help the students to better understand them.

The widespread use of the program Simulink in the MATLAB environment has encouraged the authors to develop a study for simulating the power quality phenomena in this software tool. The paper presents this simulation and analyses the results, showing the parameters with reference to international standards. The simulator has the ability to get inputs from a simulating circuit in

Simulink or from files that contain a recorded wave from an electric network.

Results of simulation are analysed using common parameters according to international standards; they are shown on the main page of simulator. Different ability is shown on the pq analyser page; also after analysis comments are shown. This simulator can be used for both educational and research purposes.

5. GLOSSARY OF ABBREVIATIONS

THD	Total harmonic distortion
DIN	Distortion index
V_n	nth harmonic value of voltage
IFL	Instantaneous flicker level
Pst	Short-term flicker severity index
$p(l)$	The cumulative probability, $p(l)$ that IFL exceeds l
T	Total observation time
t_l	Time duration that the signal remains above l.
P_{lt}	The long-term flicker severity
$c(k)$	Approximation coefficient
$d_j(k)$	Detailed coefficient
k	Number of coefficient at the decomposition level j

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