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A Comparative Modeling and Analysis of Voltage Variation by Using Spectrogram

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Abstract

In this paper, the power quality (PQ) disturbance which is the voltage variations consist of voltage swell, sag and interruption are model and analyze. Different types of voltage variations PQ disturbances models are developed and created by using MATLAB/Simulink as well as mathematical models. The mathematical and Simulink model are used to compare in terms of time-frequency representation (TFR). The Simulink models include shutting down enormouscapacities from system to resemble voltage swell, large loads energizing and three-phase fault to simulate voltage sag as well as implementing permanent three-phase fault to simulate voltage interruption. The signals generated are analyzed by using linear time-frequency distribution (TFD). The signal parameters such as root mean square voltage (Vrms), total harmonic distortion (THD) and power value are estimated from the TFR to identify the characteristics of the voltage variation. The results of analysis on the PQ disturbance waveforms generated are identical to the actual real-time PQ signals and the models can be modified to any desired situation respectively. The PQ waveforms obtained are suitable to be further analyzed.

***Keywords**: power quality, power quality disturbances, simulation model, matlab simulation, time-frequency distribution, spectrogram*

1. Introduction

Power Quality (PQ) of power system has become a critical concern to consumers in all levels of usage since the impacts and losses caused by power quality cannot be neglected. The term of power quality is the mixture of voltage and current quality, but the point of convergence is now focused to the quality of the supply voltage as only voltage quality can be controlled by the power system itself [1], [2]. Various types of faults, improved nonlinear loads and operations of power system often create power quality disturbances. Any voltage, current or frequency deviations manifested case which lead to equipment failure or disoperation is power quality problem [3]–[5]. Poor power quality can cause problems such as reduce the lifetime of the load, instabilities and interruptions in production as well as fatal costs due to downtime of the equipment as indicated by IEEE Std. 1159-2009 [6], [7]. It is important to remove or reduce the disturbances occurred within the power system. To perform the procedure of power quality signals analysis, it is needed to get a clear vision regarding the basic characteristics of power quality and the parameters of each occurred event [8], [9]. In this paper, voltage variation which include voltage sag, swell and interruption in the content of power quality disturbances are studied and their parameters are summarized. Voltage sag can be generated by short-circuits happened in the transference network, starting of huge motor parcels or switching action conjuntion with short disconnection of supply. Similar to that, voltage swell can be evoked by system fault, exchanging state on a huge capacitor bank or turning off a big load in a power system. Voltage interruption is usually caused by permanent fault occurred within the power system [8]-[12].

The power quality disturbances waveforms can be artificially generated by parametric models together with the real-time system models [13], [14]. The power quality commotions created by mathematical equations are convenience which ease the analysis jobs, yet justification is needed to verify the validity of the voltage variations produced. So, a proper

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simulation models based on software is needed as well. Many types of simulation software are available for modeling the events of voltage variation. The most widely used are ATP/EMTP, MATLAB/Simulink and PSCAD/EMTDC. In [13]–[16], the authors practiced PSCAD/EMTDC software for replicating the actual signals of the variations. However, transfering data into MATLAB software is needed for undergoing moreanalysis process. MATLAB/Simulink is one of the simulation devices for designing and interpreting the real-time systems [17], [18]. The Simulink toolbox can be used to model thepower quality disturbances in actual distribution system in sufficient manner [19]. This paper presents simulation models in MATLAB/Simulink used to generate various types of voltage variation.

Numbers of techniques were discussed by research workers for analyzing power quality problems [20]–[22]. In this paper, spectrogram technique is implemented to analyze the disturbances by representing the signals acquired in the form of time frequency representation (TFR). Then, the parameters obtained from both mathematical model and Simulink model such as power value, root-mean-square voltage (Vrms), and total harmonic distortion (THD) are estimated from the TFR and then tabulated.

2. Power Quality Disturbances

Power Quality disturbances in a power system can be obviously differ in their characteristics. According to IEEE Std. 1159-2009 [23], [24] a number of categories of PQ disturbances and their features were introduced. In this paper, the type of disturbances researched is voltage variation which includes the voltage sag, swell and interruption included with Simulink simulation models respectively.

2.1. Voltage Sag

The voltage sag is a abridged period decline of the Root-Mean-Square (RMS) voltage between 10% to 90% usually lasting from 0.5 to 10 cycles [24]. Voltage sags are caused by short circuit miscues [8]. Switching events of huge motors, thunderbolt stroke and transmission omissions can result to this problem as well. These events can severely bring to a shutdown of power plants and bring losses to the plants [25], [26].

2.2. Voltage Swell

The voltage swell is a growth of RMS voltage from 1.1 per unit to 1.8 per unit which maintains for 0.5 to 1 minute period [24], [27]. The voltage swells are associated with the short circuit faults on power system as well. Voltage swell can be created by turning off an excessive load and so on [11], [28].

2.3. Voltage Interruption

Voltage interruption of a total loss of supply voltage for a short time not more than 1 minute. Interruptions are caused by transient fault [23]–[25]. Voltage magnitude is approximately close to 0 when interruption occurs. The causes can be a broken fuse, or breaker gap that inflicting large loss the power system. The power system faults and equipment failures are the consequences of the interruptions [29].

3. Spectrogram

The spectrogram involves a compromise between time resolution and frequency resolution. It is time-frequency distributions (TFD) that portrays the signal in time and frequency representations [22], [30]-[32]. It computes and shows square magnitude of STFT [10]. The equation can be expressed as:

$$S_v(t, f) = \left| \int_{-\infty}^{\infty} v(\tau)\, w(\tau - t) e^{-j2\pi f}\, dt \right| \tag{1}$$

where $v(\tau)$ is the input signal, $w(t)$ is the observation window.

4. Power Quality Parameters

The parameters of the PQ disturbances signals can be estimated to identify their characteristics from the TFR [10], [33], [34], [35].

4.1. Voltage Measurement

The RMS voltage, Vrms can be derived from TFR and the equation can be expressed as:

$$V_{rms}(t) = \sqrt{\int_0^{f_{\max}} P_x(t, f)df} \quad (2)$$

where $P_x(t, f)$ is the TFD, $f_{\max}$ is the maximum interest frequency.

4.2. Total Harmonic Distortion

Total Harmonic distortion (THD) is defined as the behaviour of signal intensity present at non-fundamental frequencies. The equation can be written as [33]:

$$THD = \frac{\sqrt{\sum_{h=2}^{H} V_{h,rms}{}^2}}{V_{1rms}} \quad (3)$$

where $V_{h,rms}$ is the RMS harmonic voltage, V_{1rms} is the RMS voltage, *H* is the highest measured harmonic integral.

4.3. Power Measurement

The power equation can be expressed as:

$$P = \frac{1}{T}\int_{t=0}^{T} v(t)i(t)dt \quad (4)$$

5. Simulation Models

Simulation models include mathematical model and voltage variation models to represent the occurrence of power quality disturbances [13], [36], [37].

5.1. Parametric Equations Model

In the research of voltage variations, the signals are usually simulated in software to get a view of the actual condition. In this paper, 4 types of voltage variations are built by using the mathematical models as shown in Table 1.

Table 1. Mathematical Model of PQ Disturbances

Disturbances	Quantity	Controlling Parameter
Pure sine	y(t) = Asin(wt)	w= 2πf
Sag	y(t) =A(1 - $\propto$(u(t - t_1) - u(t - t_2)))sin(wt)	0.1 ≤ α ≤ 0.9; T ≤ $t_2 - t_1$ ≤ 9T;
Swell	y(t) =A(1 + $\propto$(u(t - t_1) - u(t - t_2)))sin(wt)	0.1 ≤ α ≤ 0.9; T ≤ $t_2 - t_1$ ≤ 9T;
Interruption	y(t) =A(1 - $\propto$(u(t - t_1) - u(t - t_2)))sin(wt)	0.9 ≤ α ≤ 1; T ≤ $t_2 - t_1$ ≤ 9T;

y(t)=PQ signal, A=Amplitude (constant), w=angular frequency, t=time,
$\propto$=time duration of event occurrence (constant), T=time duration

5.2. Pure Sine Voltage Simulink Model

The pure sine voltage waveforms are produced by designing a power distribution system model in Figure 1. This model consists of 25kV, 50Hz 3-phase source block connected to a 25kV/0.6kV, 10MVA star/delta transformer. There are loads connected to the transformer.

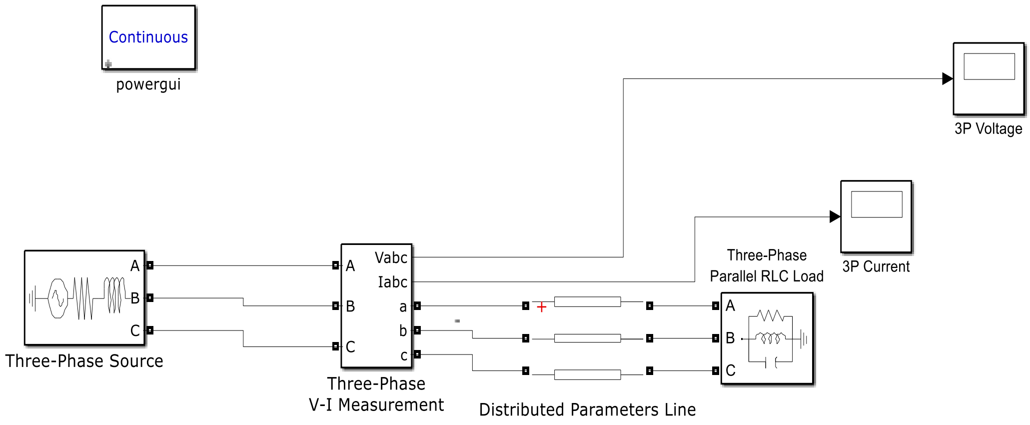


Figure 1. Model of power distribution system

5.3. Voltage Swell Simulink Model

The developed huge load shutdown Simulink model is shown in Figure 2 below. The huge load closedown model is used to simulate the voltage swell situation by eliminating the load. This model consists of 25kV, 50Hz 3-phase source block connected to a 25kV/0.6kV, 10MVA star/delta transformer. There is a 3-phase external load clossure upon clearance of three-phase breaker at 0.6kV feeder line which brings the occurrence of voltage swell.

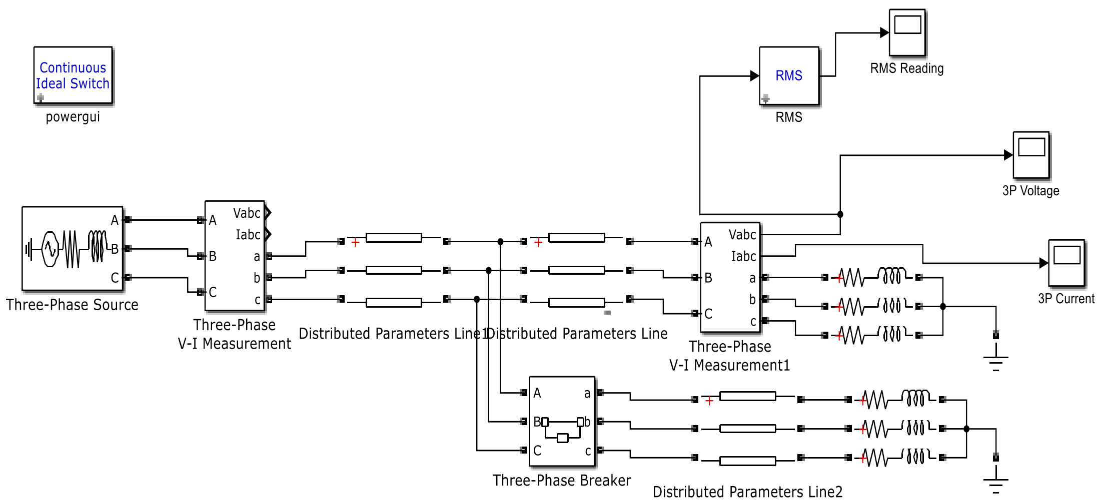


Figure 2. Simulation model of voltage swell

5.4. Voltage Sag Simulink Model

The Simulink model of restorative of huge load is used to simulate the voltage sag situation is shown as in Figure 3 below. This model consists of 25kV, 50Hz 3-phase source block connected to a 25kV/0.6kV, 10MVA star/delta transformer. A fault block is applied at the load and energizing large load occurs.

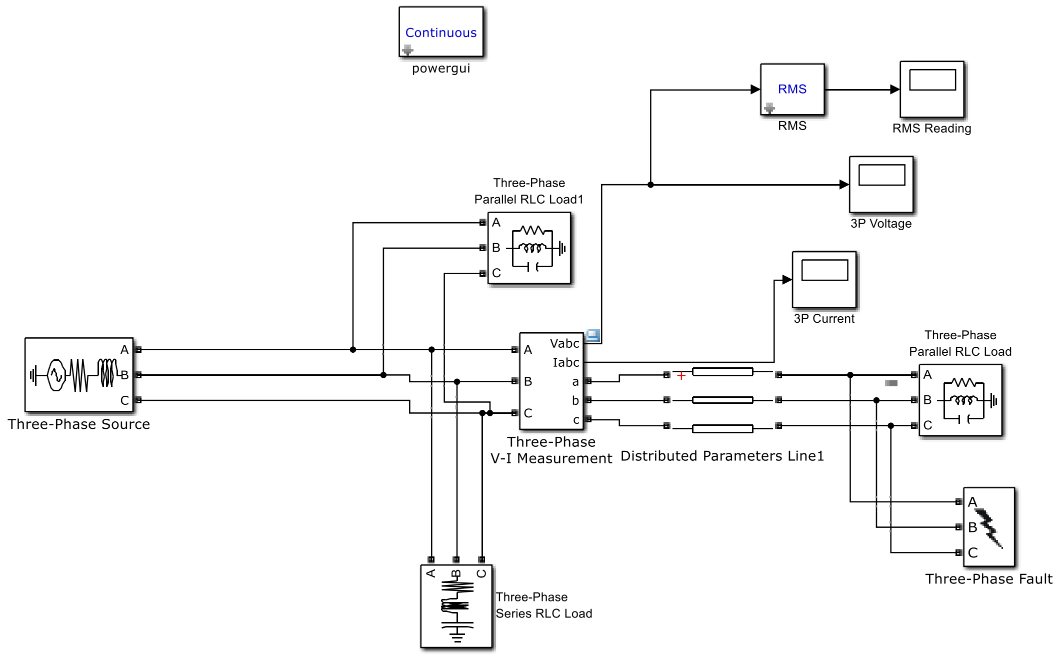


Figure 3. Simulation Model of Voltage Sag

5.5. Voltage Interruption Simulink Model

The model for voltage interruption is developed in Figure 4. This model is used to represent the actual condition of interruption due to fault. It consists of 25kV, 50Hz 3-phase source block connected to a 25kV/0.6kV, 10MVA star/delta transformer. A fault block is applied at the load which acts as permanent fault to interrupt the voltage magnitude within the system for interruption simulation.

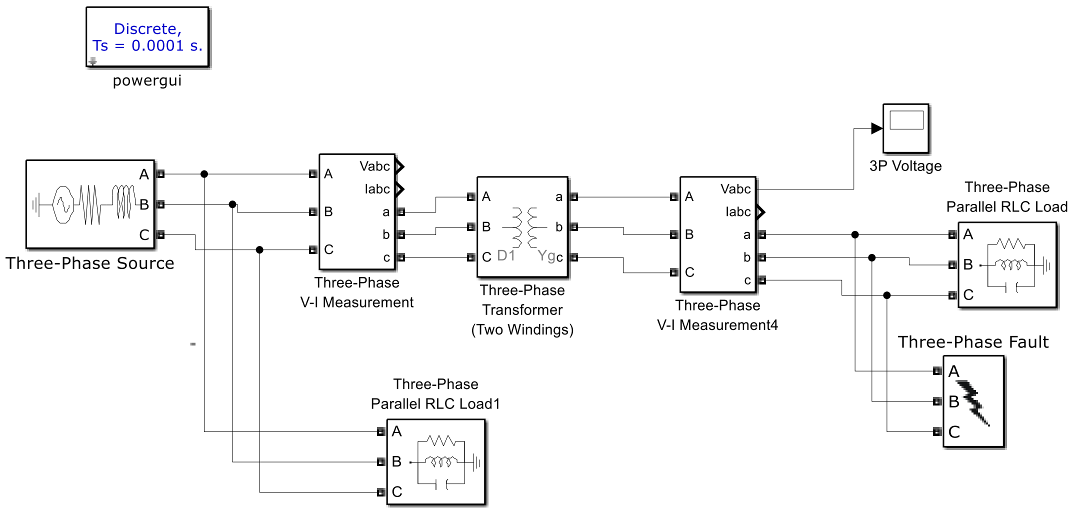


Figure 4. Simulation model of Voltage Interruption

6. Simulation Results and Discussion

The voltage variations power quality disturbances are obtained by implementing the parametric equations and Simulink models. The fundamental frequency set is 50Hz while the sampling frequency is 12kHz. The signals generated by both mathematical and Simulink models are then analyzed by using spectrogram.

6.1. Mathematical Models

The power quality disturbances are generated by using parametric equations in MATLAB software. Figure 5 shows the voltage variations waveforms produced by using the equations stated.

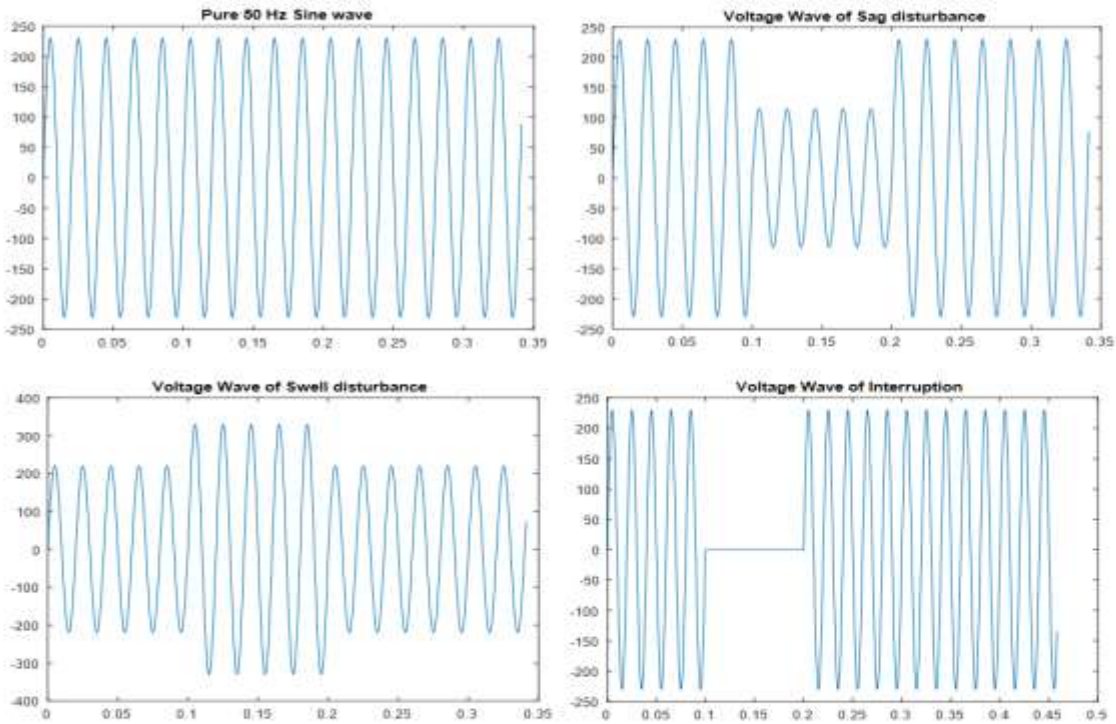


Figure 5. PQ disturbances waveforms

There are a lot of advantages of voltage variation signals modeling by using the mathematical equation in MATLAB.The signal waveforms and parameter are almost identical to the realpower quality signals occur in power system. The voltage variation signals simulated by this model can be easily applied in analysis to extract their distinctive features and characteristics.

6.2. Simulink Models

The power quality disturbances signals are produced by using the Simulink introduced by using sampling frequency of 12kHz. Each PQ waveforms are captured at the scope block. The 3-phase normal voltage sine waveforms graph is shown in Figure 6(a). Voltage swell are usually caused by surges, restorative of capacitor banks, unbalanced faults, transients, and clowndown of large loads. In the voltage swell model, load is removed to simulate the swell situation. The 3-phase voltage swell waveforms obtained is shown in Figure 6(b). The load closedown occurs at 0.05s and switched on at 0.15s (5 cycles) with the help of three-phase circuit breaker. When the circuit breaker is switched on, the circuit is then connected back to large load, thus the voltage in all phases return to original waveforms. Fault is one of the causes to cause voltage and the 3-phase waveforms simulated are shown as in Figure 6(c). The fault occurs at 0.05s and cleared at 0.15s (5 cycles) after the fault is removed at 0.15s, the voltage in all phases return to original form. The voltage interruption is created due to permanent fault and the waveforms are shown in Figure 6(d). The permanent fault is applied at 0.05s and cleared as

0.15s (5 cycles). The voltage is unable to be referred by the scope during the 5 cycles fault until the fault is cleared.

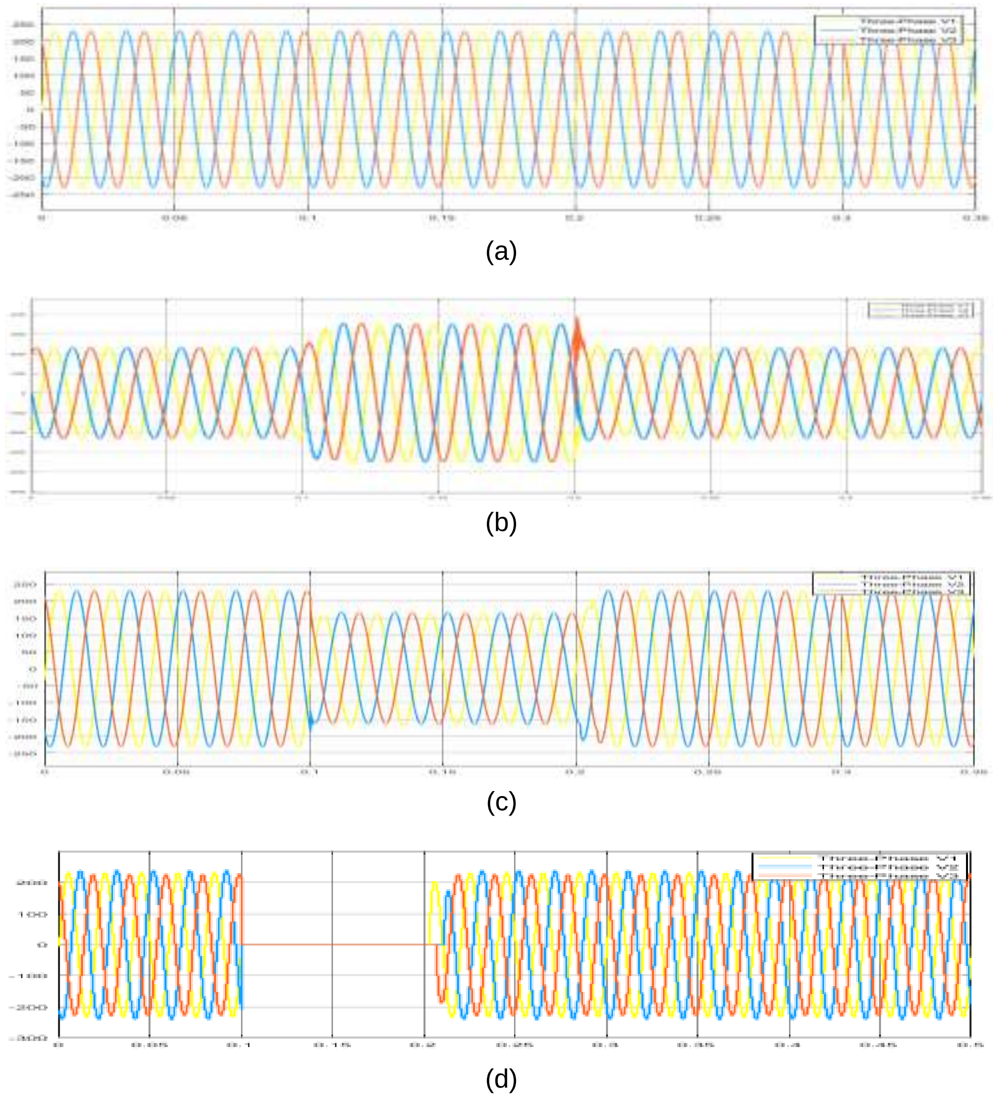
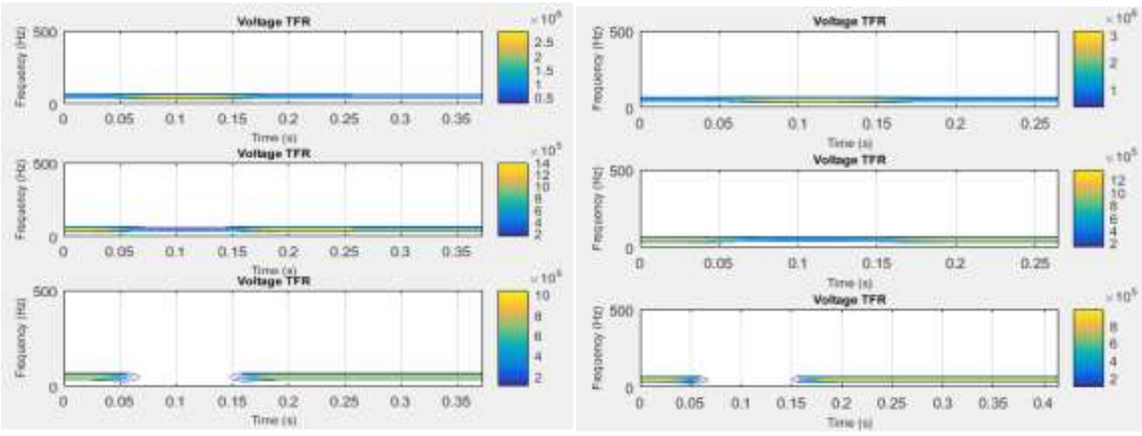


Figure 6. (a) Normal Voltage Sine Waveforms, (b) Voltage Swell Waveforms, (c) Voltage Sag Waveforms, (d) Voltage Interruption Waveforms

6.3. Spectrogram

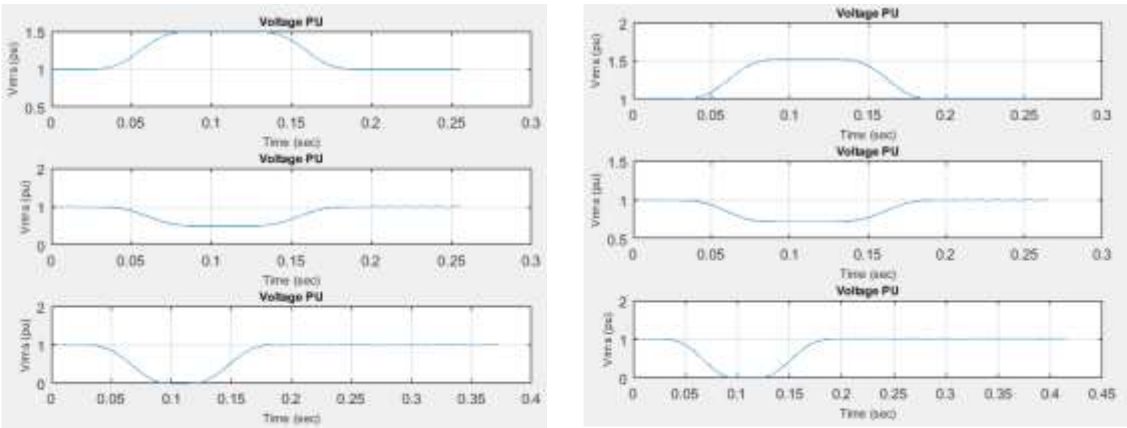
The signals simulate from both mathematical models and Simulink models are analyzed in spectrogram to identify their characteristics. The TFR of both mathematical and Simulink models of power disturbances are obtained using Hanning window with size 1024 are presented in Figure 10(a) and (b). The yellow color of the contour represents the highest power of the signal whereas blue one indicates the lowest power. The Vrms p.u. graphs of each model are presented in Figure 11(a) and (b).

A voltage swell whose duration is 17 cycles is analyzed with spectrogram. Under an assumption of 50Hz and a 25kV system, the TFR graph is obtained. Based on the TFR and Vpu graph obtained, the signals are detected at 50Hz. The voltage variation occurs at 0.05s to 0.15s with an increase of magnitude, 1.0pu to 1.5pu, indicating the occurrence of voltage swell. A voltage sag with a duration of 17 cycles is analyzed in spectrogram. The variation happens with decrease of magnitude, 1.0pu to 0.75pu at duration 0.05s to 0.15s showing the occurrence of voltage sag. When the magnitude is no longer can be presented at 0.05s to 0.15s, a dropping of 1.0pu to 0pu, indicating the occurrence of voltage interruption. The Vrms and power values are estimated and calculated from each of the TFR presented in each variation. The THD values are being extracted at fundamental frequency of the signals which is 50Hz. The parameters obtained and extracted from the spectrogram of each variation are as tabulated in Table 2.



(a) (b)

Figure 10. (a) TFR of mathematical models, (b) TFR of Simulink models



(a) (b)

Figure 11. (a) Vpu graph of mathematical models, (b) Vpu graph of Simulink models

The power quality disturbances of the voltage variation signals are produced in MATLAB Simulink. The voltage variation signals are created with different amplitudes in voltage supply, frequency supply, time duration and instant on waveforms. The sampling frequencies in both models are considered as 12kHz. Both models gave similar output waveforms which are correlative with the real-time situation. Simulation techniques presented in this paper enable research workers the affability to build power system model to produce power quality disturbances of voltage variation by accumulatingseveralpower system blocks provided in the MATLAB Simulink. It gives perception on how power quality disturbances occur and behave within the models designed.

The limitation of the simulation method of both mathematical and Simulink models are their dependency on the parameters used and the building of blocks in MATLAB Simulink to reproduce the wanted output of the power quality situation. The signals simulated of both models are analyzed by using spectrogram. The TFR and parameters obtained of both models enable researchers to understand more regarding the power quality signals presented in time and frequency form. The Vpu graphs obtained allow the researchers to compare the simulation reading with the typical voltage magnitude of actual situation.

Table 2. Parameters Obtained

Models	PQ Disturbances	Measured Parameters
Mathematical	Swell	V_{rms} = 265.45V
		THD = 10.75%
		Power = 2477.23W
	Sag	V_{rms} = 253.92V
		THD = 13.51%
		Power = 2266.5W
		V_{rms} = 229.08V
	Interruption	THD = 34.48%
		Power = 1844.94W
Simulink	Swell	V_{rms} = 262.03V
		THD = 10.75%
		Power = 2413.83W
	Sag	V_{rms} = 262.08V
		THD = 13.70%
		Power = 2414.9W
	Interruption	V_{rms} = 222.63V
		THD = 35.71%
		Power = 1742.42W

V_{rms} = root mean square voltage, THD = total harmonic distortion

7. Conclusion

The voltage variations simulation have beenperformed by using both mathematical models and Simulink models with the help of MATLAB software. The simulation results and TFD analysis show that the power quality disturbances created by these 2 methods are almost identical as well as close to the actual situation. The voltage variation signals constructed by Simulink models are flexible to be altered by manipulating the blocks in Simulink according to any situation desired. The signals simulated can be then applied for further analysis.

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