MATLAB/Simulink Based Modeling and Simulation of Power Quality Disturbances

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***Abstract*— The continuous monitoring of power quality (PQ) disturbances in electrical power distribution system has become an important issue for utilities and customers. The power system operation can be improved and maintained by analyzing the PQ disturbances systematically. In this paper, an attempt has been made to review the modeling and simulation of the PQ disturbances due to the exploitation of various types of loads. The PQ disturbances are created by using parametric equations as well as electrical power distribution system models in MATLAB/SIMULINK environment. The PQ disturbances of voltage magnitude variation such as sag, swell and interruption are created by applying different types of faults and heavy load in the power distribution model. The frequency variation types of PQ disturbances like harmonics are generated by applying power electronic converter. The non-stationary or transient PQ disturbances are produced by applying a capacitor switching bank in distribution model. The results of PQ disturbance waveforms obtained by both techniques are very similar to real-time PQ signals. The PQ waveforms obtained are suitable for checking the performance of the new automatic classification algorithms.**

Keywords—power quality; simulation; detection; feature extraction; wavelet transform;

I. INTRODUCTION

In an electrical power system, various types of faults, the dynamic operation of power equipment and augmented exploitation of nonlinear loads often create power quality disturbances. The term PQ is actually the combination of voltage quality and current quality [1, 2], but mostly it is concerned to the quality of the supply voltage owing to the fact that the power supply system can only control the voltage quality. Since the quality of current is dependent on the particular load which draws current from the power supply system [3]. Thus, the norms in the PQ area are employed to maintain the supply voltage within the permissible limits. The AC power supply system is designed to operate at a sinusoidal voltage with a constant frequency (usually 50 or 60 Hz). The PQ disturbances are created whenever there is a significant change in the supply voltage magnitude, supply frequency, and/or waveform deviation due to various types of faults, non-linear loads, switching of heavy loads, power electronics converters etc [4].

The PQ disturbances cause a huge financial loss to electric utilities, their customers (especially industrial customers) and electrical equipment suppliers [5]. The majority of electricity consumers are not familiar with the types of the PQ disturbances that usually happen in the power system. The PQ problems may create harmful effects to affected loads such as malfunctions, instabilities and short lifetime [6]. Therefore, it is important to detect and classify PQ disturbances in order to increase PQ and avoid any accident in power system. The research on the automatic classification of PQ disturbances is carried out by using the waveforms and data of the disturbances and events. The modeling and simulation approach of PQ disturbances in power system is one of the most widely applicable research method. A variety of PQ disturbances waveforms and data are created by varying the simulation parameters and hence can be useful for PQ disturbances detection and classification algorithms.

The PQ disturbances waveforms are synthetically obtained by mathematical models [7-9] as well as real-time distribution system models [10-12]. Although the PQ disturbances created by parametric equations have many advantages yet the application of real time disturbances is necessary to justify the validity of the pattern recognition algorithms. However, few researchers have used real-time simulation models for the automatic classification of PQ disturbances.

There are various types of simulation tools available for the modeling and analysis of various power system events. The most widely used tools in academic research are PSCAD/EMTDC, ATP/EMTP and MATLAB/Simulink with SimPowerSystem Blockset. In [13-15], authors employed PSCAD/EMTDC software for simulating actual signals in order to validate the classification algorithms. In [16, 17], authors have used ATP/EMTP software for the simulation of PQ disturbances. However, it is required to transfer the data in MATLAB software for further analysis of the disturbed signals.

MATLAB/Simulink [18] is one of the powerful simulation tools for modeling and analyzing the real-time systems in an efficient manner. The SimPowerSystem toolbox is used to simulate PQ disturbances for a real-time distribution system

This research work was financially supported by Universiti Teknologi Malaysia under vote number 03H45.

model. In this paper, a comprehensive model of real-time power distribution system is created by using SimPowerSystem toolboxes in MATLAB/Simulink. The PQ disturbances are generated by the application of various types of faults, energization of capacitor banks, and nonlinear loads.

II. POWER QUALITY DISTURBANCES

The PQ disturbances are usually characterized in terms of the effect upon the system voltage and supply frequency. They can be broadly classified according to voltage magnitude variations, frequency variations and transients.

A. Voltage sag

The voltage sag is the most common type of PQ disturbances which is usually lasting from 0.5 to 10 cycles within the consumers' premises. The sag is usually associated with the short circuit faults such as single-line to ground (LG), line to line (LL), double-line to ground (LLG), three-phase (LLL), and three-phase to ground (LLLG) faults. The voltage sag can also be created owing to the energization of heavy loads such as starting of large motors [3, 4].

B. Voltage swell

The voltage swells are also associated with the short circuit faults on power system. In a single line to ground fault, the sag is created on the phase in which fault is occurred while the swell is produced on the non-fault phases. The swell can also be created by switching-off a heavy load or energizing a large capacitor bank [3, 4].

C. Interruption

The complete loss of the supply voltage for a period of time not exceeding 1 minute is known as an interruption. The supply voltage is decreased to 10% of the nominal value. The power system faults, equipment failure, and control functions are the consequences of the interruption [3, 4].

D. Harmonics

The harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency (50 or 60Hz). The harmonics are mainly caused by the nonlinear loads such as rectifiers and inverters and other static power conversion equipment [3, 4].

E. Transients / Surge

An undesirable and momentary event in power system is known as transients. The transients may be classified as oscillatory and impulsive. The transient produced due to switching off/on a heavy load, capacitor bank energization, transformer energization is known as oscillatory transient. The transient usually caused by the lightning strokes is known as impulsive transient or surge [3, 4].

F. Voltage fluctuations/ flickers

Voltage fluctuations or flickers are systematic variations of the supply voltage envelope or a series of random voltage variations, the magnitude of which does not exceed by 0.9 to 1.1 pu. The voltage deviations caused by the continuous and rapid variations in the load are termed as flickers. The voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage fluctuation in some loads. Both terms have same meaning in standards. The arc furnace is the most common cause of the voltage fluctuations on utility transmission and distribution systems [3, 4].

TABLE 1 Mathematical Model of PQ Disturbances

Disturbances	**Equation**	**Controlling Parameter**
Pure sine	$y(t) = Asin(\omega t)$	$w = 2\pi f$
Sag	$y(t) = A(1 - \alpha(u(t - t_1) - u(t - t_2)))sin(\omega t)$	$0.1 \leq \alpha \leq 0.9$; $T \leq t_2 - t_1 \leq 9T$
Swell	$y(t) = A(1 + \alpha(u(t - t_1) - u(t - t_2)))sin(\omega t)$	$0.1 \leq \alpha \leq 0.9$; $T \leq t_2 - t_1 \leq 9T$
Interruption	$y(t) = A(1 - \alpha(u(t - t_1) - u(t - t_2)))sin(\omega t)$	$0.9 \leq \alpha \leq 1$; $T \leq t_2 - t_1 \leq 9T$
Harmonics	$y(t) = \alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)$	$0.05 \leq \alpha_3 \leq 0.15$; $0.05 \leq \alpha_5 \leq 0.15$; $0.05 \leq \alpha_7 \leq 0.15$; $\sum \alpha_i^2 = 1$
Oscillatory Transients	$y(t) = A[sin(\omega t) + \alpha^{-(t-t_1)/\tau} sin\omega_n(t - t_1)\,(u(t_2) - u(t_1)]$	$0.1 \leq \alpha \leq 0.8$; $0.5T \leq t_2 - t_1 \leq 3T$; $8ms \leq \tau \leq 40ms$; $300 \leq f_n \leq 900Hz$

G. Power Frequency Variations

The deviation in the fundamental frequency from its specified nominal value (50 or 60 Hz) is known as power frequency variations. The power system frequency (*f*) is directly related to the rotational speed (N_s) of the synchronous generators at fixed number of poles (*P*) i.e. ($N_s=120*f/P$). There is slight variation in frequency due to mismatch between load and generation. The power frequency variations are caused by faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line [3, 4]..

III. POWER QUALITY DISTURBANCES MODELS

A. Parametric Equations Model

Real-time PQ disturbances signals are difficult to capture. In the research of PQ disturbances, usually disturbance signals are produced by simulation for further analyzing them. In this paper, six types of PQ disturbances are produced by using mathematical models as shown in Table 1 [7, 9, 13]. The PQ disturbances are easily generated and appear very similar to actual situation. There are some advantages of using parametric equation such as it is possible to vary signal parameters in a wide range and in a controlled manner. It is easier to obtain the samples in an enormous quantity. The signals generated by mathematical models can be easily used in the classification of PQ disturbances to extract their distinctive features.

B. Electrical Power Distribution Model

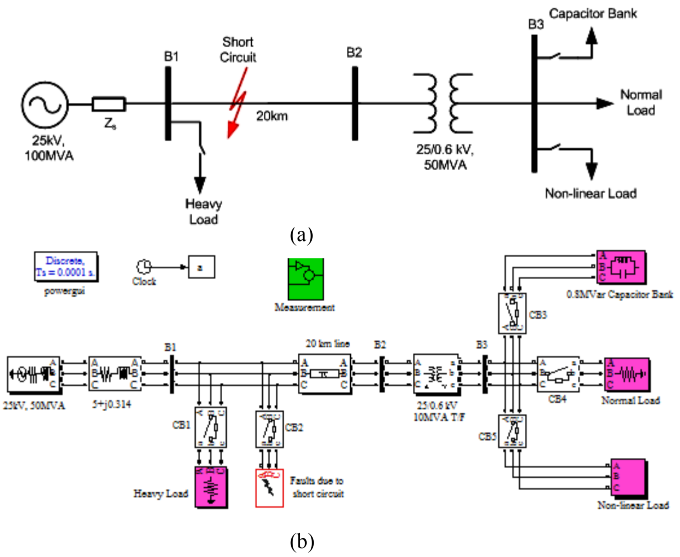


Fig. 1 (a) Electrical power distribution model (b) its Simulink diagram

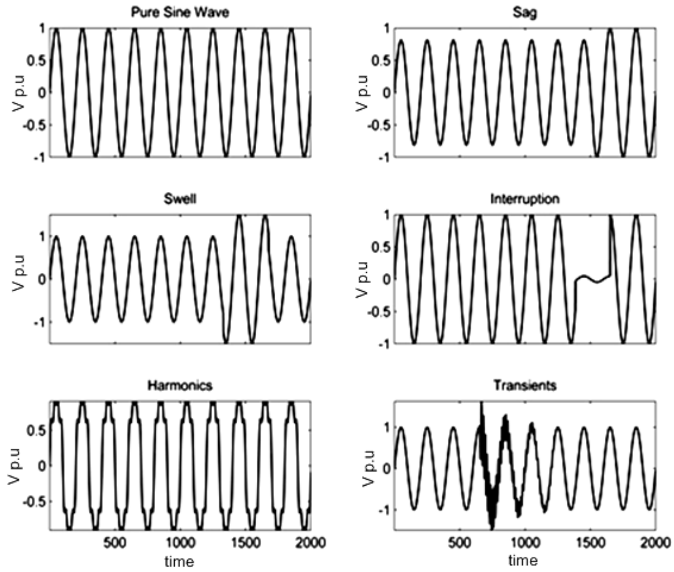


Fig. 2 PQ disturbances waveforms

The PQ disturbances are simulated by considering a test model of the electrical power distribution system as specified in Fig. 1(a). The test model is found very close to actual power distribution system. Many practical assumptions are considered in this simulation process. The power distribution system model consists of a 25kV, 50MVA generator with an impedance of Z_s, a 20km distribution line, a delta/star step-down transformer and a normal load. The transformer of 25/0.6 kV, 10MVA supplies a power to normal (1MVA, RL load) and non-linear (130V, controlled rectifier) loads at the point of common coupling i.e., bus B3. The load bus B3 is also equipped with a capacitor bank (0.8MVA) for reactive power compensation in order to simulate a fixed switching of a bank of capacitors which causes oscillatory transients, as in real-time case. A heavy load is connected at the distribution line. The faults created at the 20km distribution line cause voltage sag in faulty phase and voltage swell in non fault phase.

The test model of the distribution system is simulated in SimPowerSystem and Simulink Blockset of MATLAB which is shown in Fig. 1 (b). The model is used to study various PQ disturbances in power system due to system faults, heavy loads, switching and non-linear loads.

IV. Simulation Results

The PQ disturbances waveforms are obtained by using mathematical models as well as power distribution test model in MATLAB/Simulink software. The sampling frequency and fundamental frequency in both cases are considered as 10 kHz and 50 Hz, respectively.

A. Mathematical Models

The PQ disturbances are generated in MATLAB software by using parametric equations. Each waveform has a normalized magnitude of 1.0 pu and fundamental frequency of 50Hz. The sampling frequency is 10kHz, i.e., 200 points for each cycle which is suitable for practical implementation. The overall duration of the signals considered is of 10 cycles (2000 points). Figure 2 shows various types of the PQ disturbances waveforms generated by parametric equations.

Various samples of voltage sag between 1 to 10 cycles with 0.1 to 0.9 pu magnitudes can be generated as the training and testing patterns for applying automatic classification algorithm. Similarly, voltage swell samples can be created with magnitude between 1.1 to 1.8 p.u. The interruption can be created when the magnitude of voltage falls below 0.1 at any instant. For the simulation of the pure harmonics, the harmonic components of 2^{nd}, 3^{rd}, 5^{th} and 7^{th} order are varying from 5% to 15% of the fundamental frequency in a variety of possible combinations. The low frequency transients are simulated with a transient frequency range of 300 Hz to 900Hz.

There are various advantages of PQ signals modeling by using parametric equations in some aspects [19]. It is possible to change training and testing signal parameters in a wide range and in a controlled manner. The waveforms and parameter variation range are very similar to actual PQ signals.

B. Simulink Models

In this part, the PQ disturbances are simulated using simulink models by applying various types of loads and faults such as short circuit faults, heavy load, capacitor bank switching and non-linear loads as shown in Fig. 1.

Each PQ waveform consists of 10 cycles and a sampling frequency of 10 kHz. A distribution equivalent circuit with 25kV voltage source and 50 Hz frequency is shown in Fig. 1. The transmission line is of 20km length and π-equivalent model. The PQ disturbances are captured at the end of load i.e., at bus B3. A single line-to-ground fault is created at bus B1 which causes voltage sag and interruption in the fault phase

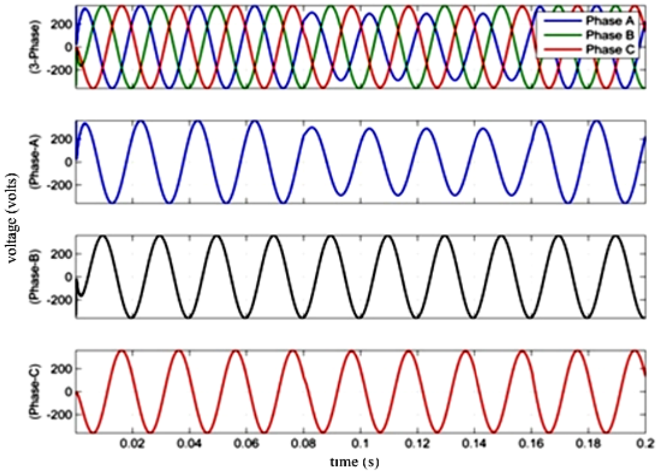


Fig. 3 Voltage sag due to single line to ground fault

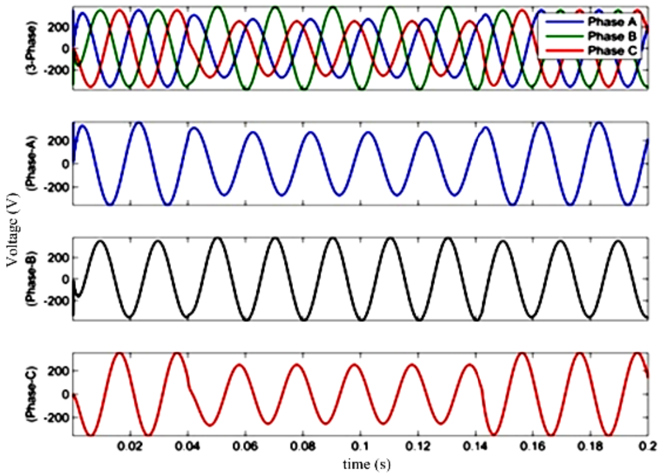


Fig. 4 Voltage sag and swell due to line to line fault

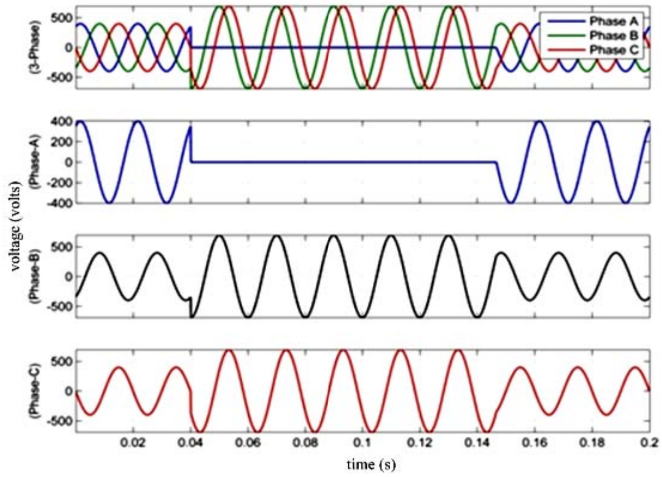


Fig. 5 Voltage swell and interruption due to heavy load

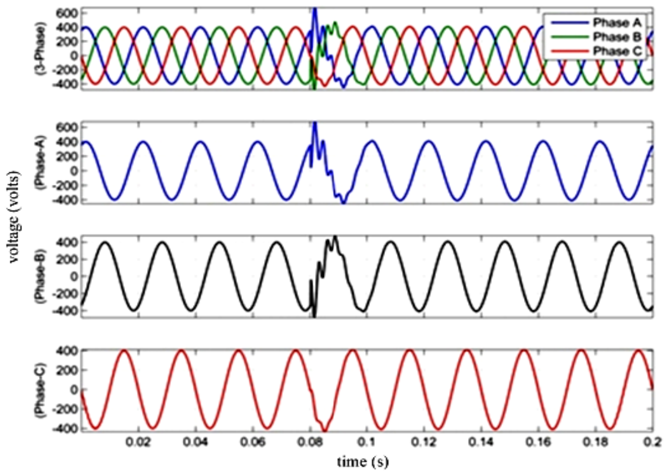


Fig. 6 Oscillatory Transiets due to capacitor switching

and swell in the non-fault phase. A variable normal load, non-linear load and capacitor bank are connected at bus B3. A variable load causes voltage flicker and fluctuation. The non-linear load creates steady-state distortions such as harmonics. The capacitor bank creates transients types of PQ disturbances. The simulation time for all disturbances is selected as 0.2s (10 cycles).

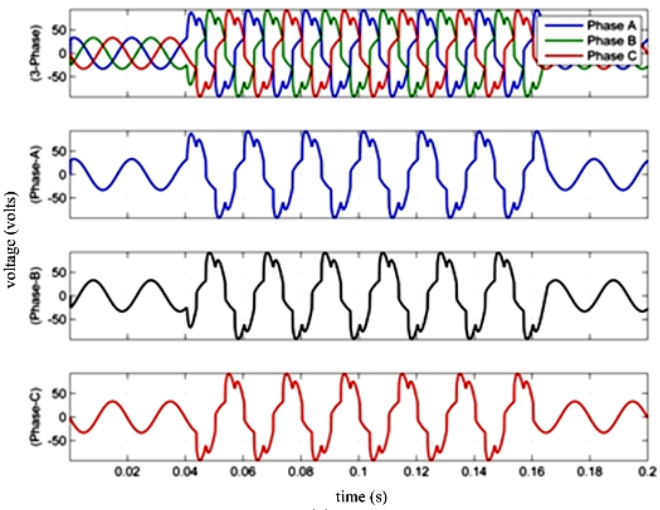
The voltage sag, swell and interruption types of PQ disturbances are created in the power distribution supply system due to short circuit faults, switching on a heavy load, or starting of large induction motors. Fig. 3 shows a three phase

voltage waveform at bus B3. The voltage sag is created in phase-A due to single-phase to ground fault in phase A. The fault occurred at 0.08s and cleared at 0.16 (4 cycles). When the fault is cleared at 0.16s, the voltage in all phases is normal. In Fig. 4, line to line fault is created in phases A and C for a period of 0.04s to 0.14s (5 cycles). Therefore, sag is produced in phases A and C where as swell in phase B. Fig. 5 shows interruption in phase A and swell in phases B and C between 0.04s and 0.14s due to heavy load on phase A.

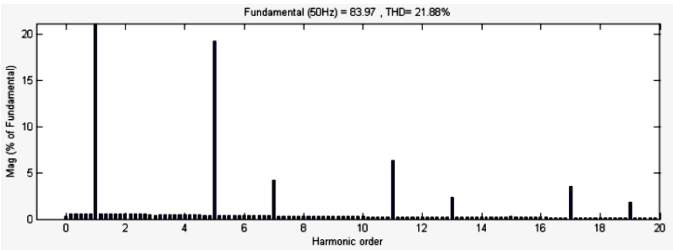
The capacitor bank is energized when circuit breaker CB4 in Simulink model is switched on. As shown in Fig. 6, a transient is produced in supply voltage due to operation of a capacitor bank. The transient frequency depends upon the size of the capacitor bank. The large size capacitor has lower transient frequency.

The harmonics are caused by the switching on the non-linear loads. A three-phase bridge rectifier connected at bus 3 (Fig. 1) is used as a three phase nonlinear load. The current waveform and its Fourier analysis are shown in Fig. 7.

The harmonic contents of a distorted waveform are indicated by the common harmonic index known as total harmonic distortion (THD). The THD is a measure of the effective value of the harmonic components of the distorted voltage or current waveform. The THD is defined as the ratio of the harmonics expressed in percentage of the fundamental (e.g., voltage, current) component [20],



(a)



(b)

Fig. 7 (a) current waveform (b) its Fourier Analysis

$$THD = \sqrt{\sum_{h=2}^{\infty} (V^{(h)})^2} \Big/ V^{(1)} \qquad (1)$$

where $V^{(h)}$ is the amplitude of the h harmonic component.

The THD of phase A in Fig. 7 is calculated as 21.88% with the harmonics orders *(h)* of 1^{st}, 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, and 19^{th} in accordance with (2),

$$h = 6k \pm 1 \qquad where\ k=1,2,3,\ldots \qquad (2)$$

V. Discussion

The PQ disturbances signals are generated by MATLAB/Simulink software. The disturbances can be generated with different magnitudes in per unit, time durations, and instant on waveform. The sampling frequency in both cases is considered is 10 kHz. Simulation techniques provide researchers the flexibility to create power system model to simulate PQ disturbances by assembling various power system block sets in the MATLAB/Simulink environment. It gives an insight on how PQ disturbance propagates and behaves within the simulated power system model. The limitation of simulation method is its dependency on the capability of the chosen simulation software and the availability of power system building blocks to simulate the desired PQ disturbances.

VI. Conclusion

The PQ disturbances have been produced by using mathematical models and actual electrical power distribution model built in MATLAB/Simulink environment. The simulation results show that the PQ disturbances created by two methods are very similar and also both are very similar to actual PQ disturbances. The PQ disturbances created either by mathematical models or by Simulink models can be applied for the automatic classification algorithms.

Acknowledgement

The authors would like to thank to the Faculty of Electrical Engineering of Universiti Teknologi Malaysia (UTM), Malaysia for providing the facilities to carry out this research, and Ministry of Education (MoE) of Malaysia for their financial support under vote number 03H45. Suhail Khokhar is also thankful to Quaid-e-Awam University of Engineering, Science & Technology (QUEST) Pakistan, for their financial support.

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