CLASSIFICATION AND CHARACTERIZATION OF POWER QUALITY PROBLEMS IN THREE PHASE SYSTEM

S. ASHA KIRANMAI
Research Scholar, Department of Electrical Engineering, UCE, Osmania University, Hyderabad, India
Email: asha_ks2006@yahoo.co.in

Dr. A. JAYA LAXMI
Professor, EEE Department, Co-ordinator, Centre for Energy Studies, JNTUH College of Engineering, Hyderabad, India
Email: ajl1994@yahoo.co.in

Abstract: *The concern for good power quality is increasing day by day due to the great damage caused by power quality problems in terms of scrambling of data, malfunctioning and failure of the equipment of public or industrial facilities. Hence, to improve the power quality, the detection and monitoring of power quality problems are necessary before taking appropriate mitigating action. To achieve this, the paper presents an algorithm used for the classification and characterization of various categories of voltage sag, swell, interruption, unbalance, under voltage and over voltage problems. The detection is based on the three phase RMS voltages calculated over a window of the half cycle. The RMS voltage samples are given to the program written in MATLAB to classify and characterize the problems. The program outputs are shown for different cases of power quality problems.*

Key words: *Characterization, classification, detection, half cycle RMS voltages, power quality problems.*

1. Introduction

Nowadays, consumers not only require reliability of the power supply, but also need quality power. With the increased use of highly sophisticated electronics, microelectronic processors in various types of equipment such as computer terminals, programmable logic controllers and diagnostic systems; power electronics and other nonlinear, time-variant loads in the power distribution network; the demand for clean power has been increasing in the past several years.

The growing interest in Power Quality (PQ) issues should be viewed in a context of wider developments in power delivery engineering. Increased importance of PQ problems in industry and scientific community has many reasons [1-3]. The deregulation of the electricity market has caused growing need for standardization and performance criteria. Electronic and power electronic equipment has become more sensitive to voltage disturbances than its counterparts in the past. Modern power electronic equipment as well as other non-linear devices are not only sensitive to voltage disturbances, but also cause disturbances for other customers. According to the survey by IEEE Transactions on Industrial Applications (IAS) for 210 large commercial and industrial customers, the average cost for a 4-h outage and a momentary outage are $74,835 and $11,027, respectively [4]. Also, according to the data investigated by the Electrical Power Research Institute (EPRI), the US economy is losing between $104 billion and $164 billion a year to outages, and another $15 billion to $24 billion for PQ phenomena [5]. For instance, the power outage in North America in August 14, 2003 influenced the vast area from east of New York, north to Toronto and west to Detroit, Michigan – an area that is home to about 50 million people. It leads to losses of $4 billion to $10 billion in the USA alone [6]. Therefore, the research of power quality issues has captured ever increasing attention in the power engineering society.

Due to the usage of sensitive load, the efficiency, energy saving and high controllability can be increased. But, this increment can cause the electric power disturbances to occur. Not only customers, but also internal phenomena in the supply system, can lead to PQ deterioration. The disturbances can stimulate the sensitive equipment damage and costly to repair. The cost to repair causes severe financial losses.

All these impacts of poor power quality have called for focus on detection of them [7, 8]. In order to reduce the effects of power quality problems, it is essential to understand how and why they occur and to be able to characterize them. While in quantification of power quality problems, the most important parameters are magnitude and duration. The characteristics of the disturbances identify the type of power quality problem.

Power quality monitors in the occasion of a disturbance can either save the actual voltage waveform that contains the event or the corresponding RMS. The latter option reduces significantly the memory that is needed for saving the event. Using RMS voltages, classification of events such as Energizing, Non-fault and fault interruptions, Transformer saturation etc., are carried out [9]. In [10], it is proved that the characterization of voltage dips by using RMS voltages is a good measure of the severity of a dip, even though more sophisticated methods exist. The RMS voltage values are used to get the sag characteristics [11-12]. The detailed classification of various categories of power quality problems using RMS voltages is presented in [13]. In [14], it is observed that the half cycle RMS method takes least detection time among RMS, peak, fourier transform and missing voltage methods for offline and online detection of voltage sag and swell.

So, the present work utilizes half cycle RMS method to develop an algorithm to classify and characterize in detail all the categories of voltage sags, swells, interruptions, unbalance, under voltage, over voltage problems and to give the number of occurrences of similar kind of problems. The algorithm provides the characteristics of power quality problems such as magnitude and duration individually for each phase and also cumulatively for all the three phases. This algorithm is implemented and tested using MATLAB software.

The paper is organized as follows: Section II discusses about the characteristics of power quality problems such as sag, swell, interruption, unbalance, under voltage and over voltage along with the formula used for RMS calculations. Section III deals with the algorithm developed for classification and characterization of power quality problems. Section IV shows the MATLAB simulation model used for generating the data for various power quality problems. The test results and discussions of the program written in MATLAB are given in Section V and Section VI gives the conclusions of the work.

2. Characteristics of power quality problems

In order to find any solution for the power quality problems, it is necessary to know its characteristics. The power quality problems are mainly characterized by its magnitude and duration. The magnitude is defined as the voltage during the event and the duration is defined as the time between the commencement and the clearance of the event [15].

A. Voltage sag characteristics

Voltage sag is defined as a decrease in RMS voltage between 0.1 p.u. to 0.9 p.u. at the power frequency for durations of 0.5 cycles to 1 minute, reported as the remaining voltage [16]. Voltage sags are caused by ground faults, lightning strikes, energizing heavy loads; start-up of elevators, heating and air-conditioning equipment, compressors and copy machines. The sag magnitude in case of a three-phase system is the minimum RMS voltage during the sag, if the sag is symmetrical and for unsymmetrical sag, the phase with the lowest remaining voltage is used to characterize the sag. The duration of voltage sag is the amount of time during which the voltage magnitude is below threshold and is typically chosen as 90 % of the nominal voltage magnitude. For measurements in the three-phase systems, the three RMS voltages have to be considered to determine the duration of the sag. The sag starts when at least one of the RMS voltages drops below the sag-starting threshold. The sag ends when all three voltages have recovered above the sag ending threshold [17].

B. Voltage swell characteristics

Voltage swell is defined as an increase in RMS voltage between 1.1 p.u. and 1.8 p.u. at the power frequency for durations from 0.5 cycles to 1 minute. Voltage sags and swells are usually associated with system fault conditions, but voltage swells are not as common as voltage sags. One way that a swell can occur is from the temporary voltage raise on the unfaulted phases during an SLG fault. Swells can also be caused by switching off a large load, energizing a large capacitor bank and poorly regulated transformers. Swells are characterized by their magnitude (RMS value) and duration. The swell magnitude in case of a three-phase system is the maximum RMS voltage during the swell if the swell is symmetrical and for unsymmetrical swell, the phase with the highest voltage is used to characterize the swell. The duration of voltage swell is the amount of time during which the voltage magnitude is above threshold and is typically chosen as 110 % of the nominal voltage magnitude. For measurements in the three-phase systems, the three RMS voltages have to be considered to determine the duration of the swell. The swell starts when at least one of the RMS voltages raise above the swell-starting threshold. The swell ends when all three voltages have recovered below the swell-ending threshold.

C. Interruption characteristics

An interruption occurs when the supply voltage decreases to less than 0.1 p.u. for a period of time not exceeding 1 min. Interruptions can be the result of power system faults, equipment failures and control malfunctions. The interruptions are usually measured by their duration since the voltage magnitude is always less than 10 % of nominal. The duration of interruption is the amount of time during which the voltage magnitude is below the threshold limit of 10 % of the nominal voltage magnitude. For measurements in the three-phase systems, the three RMS voltages have to be considered to determine the duration of the interruption. The interruption starts when at least one of the RMS voltages drops below the interruption-starting threshold. The interruption ends when all three voltages have recovered above the interruption-ending threshold.

D. Voltage Unbalance Characteristics

Voltage Unbalance is sometimes defined as the maximum deviation from the average of the three phase voltages, divided by the average of the three phase voltages, expressed in percent. The primary source of voltage unbalances of less than 2 % is unbalanced single-phase loads on a three-phase circuit. Voltage unbalance can also be the result of blown fuses in one phase of a three-phase capacitor bank or use of single-phase line regulators. Severe voltage unbalance of greater than 5 % can result from single-phasing conditions such as an open protective device upstream of the monitoring point. Voltage unbalance is characterized by Percentage Voltage Unbalance Rate (PVUR) and the time duration. The duration of voltage unbalance is the amount of time during which PVUR is greater than 2 % of the limit [16]. The formula for PVUR is given in (1).

$$PVUR = \frac{\text{Maximum voltage deviation from average voltage}}{\text{Average voltage}} \times 100 \quad (1)$$

E. Under voltage characteristics

An under voltage is a decrease in the RMS AC voltage from 0.8 to 0.9 p.u. at the power frequency for a duration longer than 1 min. Switching on a load or switching off a capacitor bank can cause an under voltage, until voltage regulation equipment on the system can bring the voltage back to within tolerance limits. The magnitude and duration of an under voltage is determined similar to that of a voltage sag.

F. Over voltage characteristics

An over voltage is an increase in the RMS AC voltage from 1.1 to 1.2 p.u. at the power frequency for a duration longer than 1 min. They are usually the result of load switching (e.g., switching off a large load or energizing a capacitor back). Incorrect tap settings on transformers can also result in the system over voltages. The magnitude and duration of an over voltage is determined similar to that of a voltage swell.

The magnitudes of the 3-phase voltages can be determined in a number of ways. The most common method is to obtain the magnitudes from RMS voltages by monitoring the data. There are several alternative ways of quantifying the voltage level. Two obvious are the magnitude of the fundamental component of the voltage and the peak voltage over each cycle or half cycle. But the RMS voltage is a quantity commonly used in power systems as an easy way of accessing and describing power system phenomena. The RMS value can be computed each time a new sample is obtained but generally these values are updated each cycle or half cycle. If the RMS values are updated every time a new sample is obtained, then the calculated RMS series is called continuous [9]. In this paper, RMS values are continuously calculated for a window of half cycle for more accuracy [14, 18]. Equation (2) is used for the calculation of RMS values.

$$\begin{aligned} V_{rms}(k) &= \sqrt{\frac{\sum_{i=k-N+1}^{i=k} v(i)^2}{N}} \quad for\ k \geq N \\ &= V_{rms}(N) \quad for\ k < N \end{aligned} \quad (2)$$

'*N*' is the window length of one half cycle and '*k*' is the time stamp which is restricted to be an integer that is equal to or greater than 1. Each k^{th} value of RMS voltage is obtained from N-1 previous samples and the current k^{th} sample. Here, the first (N-1) RMS voltage values have been made equal to the value for sample N. It is due to data window limitation and data truncation and couldn't be avoided.

3. Algorithm for classification and characterization of power quality problems

The following are the steps of proposed algorithm which are implemented for the classification and characterization of power quality problems:

1. The three phase RMS voltages (V_{arms}, V_{brms}, V_{crms}) at PCC are measured and sampled.
2. For ($V_{arms} = V_{brms} = V_{crms}$), go to step 3 else go to step 6.
3. For ($0.1\times V_{ref} \leq V_{arms}/V_{brms}/V_{crms} < 0.9\times V_{ref}$), obtain sag time duration & voltage magnitude for 3-phases differently and cumulatively to determine the type of sag. Count the number of occurrences of a similar type.
4. For ($1.1\times V_{ref} < V_{arms}/V_{brms}/V_{crms} \leq 1.8\times V_{ref}$), obtain swell time duration & voltage magnitude for 3-phases differently and cumulatively to determine the type of swell. Count the number of occurrences of a similar type.
5. For ($V_{arms}/V_{brms}/V_{crms} < 0.1\times V_{ref}$), obtain interruption time duration & voltage magnitude for 3-phases differently and cumulatively to determine the type of interruption. Count the number of occurrences of a similar type.
6. For ($V_{arms} \neq V_{brms} \neq V_{crms}$), determine the value of PVUR and if PVUR > 2 %, obtain unbalance time duration and voltage magnitudes of 3-phases. For sag or swell in any phase, obtain time duration and magnitude to determine its type. Count the number of occurrences of voltage unbalance.
7. Repeat steps 2 to 6 till all the samples are completed.
8. Display the type of power quality problems occurring along with the magnitudes, time durations and number of occurrences.

The algorithm checks the magnitudes of the three phase voltage signals. If any power quality problem occurs, depending on the magnitude level and time duration, the algorithm outputs the information about the type of power quality problem/s, the number of times they are occurring in the given period and their characteristics. This algorithm is constructed using simple logic based on standard definitions [2] and is easily coded and executed using MATLAB programming. The proposed algorithm can be used for the classification and characterization of all the categories of the major power quality problems such as sag, swell, interruption, unbalance, under voltage and over voltage.

4. Simulation model

A simulation model as shown in Fig. 1 is used for the analysis of power quality problems. The circuit consists of a 33/11 kV distribution substation connected to a 2 km distribution line having a 11/0.433 kV distribution transformer supplying to a load of 190 kW, 140 kVAr [12]. The system is modelled using Simulink and SimPower System utilities of MATLAB. It is simulated to get the data for voltage sag, swell, interruption, unbalance, under voltage and over voltage problems. The 3-phase RMS voltages calculated at the Point of Common Coupling (PCC) are used as the data for classification of the power quality problems. The data is sampled at a frequency of 2 kHz. Voltage sags are created by balanced 3-phase to ground faults with varying fault impedance and duration for different categories of sags. Voltage swells are created by switching capacitors of different capacitances connecting to the line for varied durations to get different categories of swells. Interruptions are introduced by opening circuit breaker 1 (CB 1) for different time durations, thereby disconnecting the supply. The voltage unbalance is created by a 3-phase unbalance fault.

5. Results and discussion

For testing the algorithm written, circuit shown in Fig. 1 is simulated for different categories of power quality problems of sags, swells, interruptions, unbalance, under voltage and over voltage. Three sets of data of 3-phase RMS voltages with various combinations of power quality problems are generated and the program is tested for these data samples.

Data for the first case includes under voltage of 0.85 p.u. for 62 s, instantaneous swell of 1.43 p.u. for 0.1 s, momentary interruption for 1.05 s and temporary interruption for 3.5 s. The 3-phase RMS voltages in this case are shown in Fig. 2. The output of the program is shown in Fig. 3, which clearly indicates the type of problems occurred along with its characteristics for each individual phase and cumulatively for three phases.

The data for second case includes temporary sag of 0.74 p.u. for 10 s, momentary swell of 1.35 p.u. for 2 s, instantaneous interruption for 0.4 s and unbalance with 0.8 p.u., 0.75 p.u., 0.91 p.u. of voltages in the three phases having PVUR of 10.982 % for 5 s. The corresponding 3-phase RMS voltages and the output are shown in Fig. 4 and Fig. 5 respectively.

Data for third case includes two instantaneous sags of 0.4 p.u. for 0.5 s and 0.54 p.u. for 0.25 s, temporary swell of 1.15 p.u. for 6 s and over voltage of 1.15 p.u. for 70 s. The 3-phase RMS voltages for this case are shown in Fig. 6. The output of the program is shown in Fig. 7, which shows the type of power quality problems occurred, it's occurrence number and characteristics.

The test results of the algorithm for the three cases are summarized in Table 1. It shows the actual values of voltage magnitudes and time durations of the power quality problems, along with the values obtained from the algorithm for 3-phases differently and cumulatively. The accuracies in voltage magnitudes and time durations are indicated. It is observed that the overall accuracies are 99.595 % and 98.890 % respectively.

The program checks the extracted voltage samples for balanced or unbalanced conditions. If it is balanced case, the 3-phase RMS voltages will be same and this value is compared with the voltage ranges of sag, swell, interruption, under voltage and over voltage. If the voltage sample matches with any of these ranges, the magnitude of the voltage is

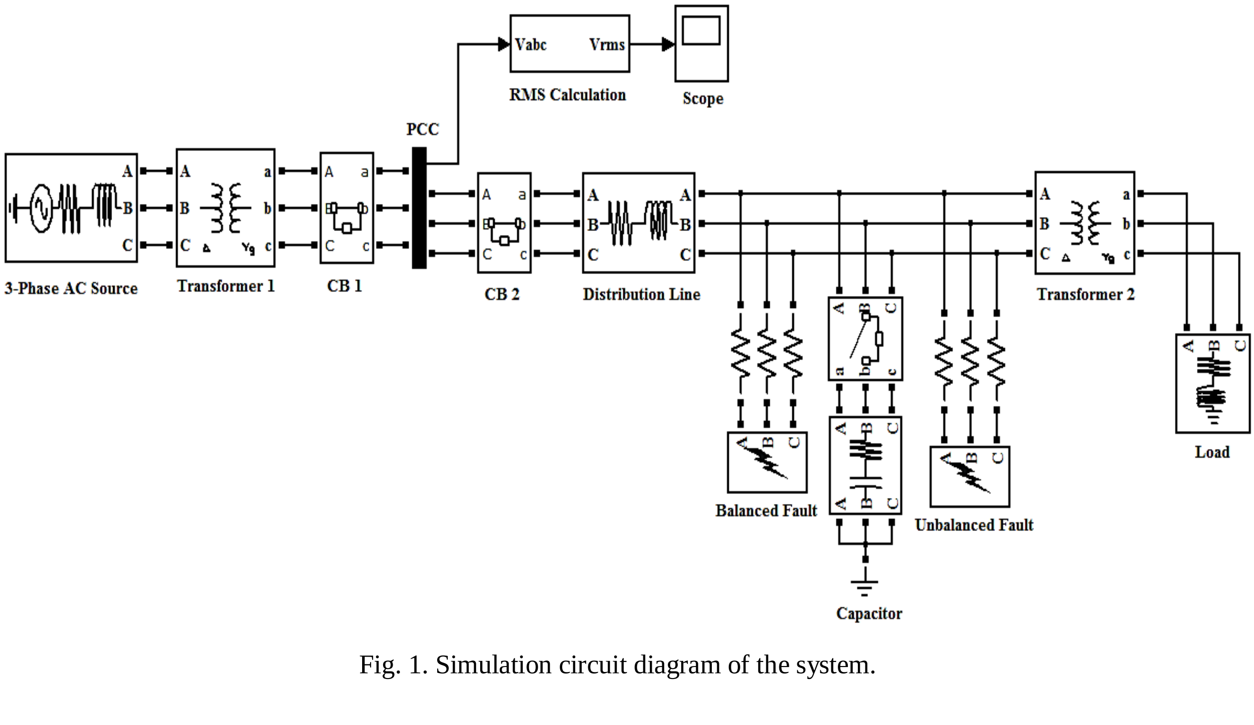

Fig. 1. Simulation circuit diagram of the system.

noted and such samples are counted to obtain the duration of the disturbance. The time duration obtained is used to determine whether the problem occurred is of instantaneous, momentary, temporary or sustained type. During unbalance conditions, the 3-phase RMS voltages will be different and the voltage unbalance percentage is calculated. If this value exceeds 2 %, the 3-phase voltage magnitudes are noted along with unbalance percentage. Then the sample counting starts and continues till the unbalance condition is satisfied. If the same type of problem occurs for the next time, along with magnitudes and time period calculation, the count of occurrences is also incremented. This process continues till all the samples are completed.

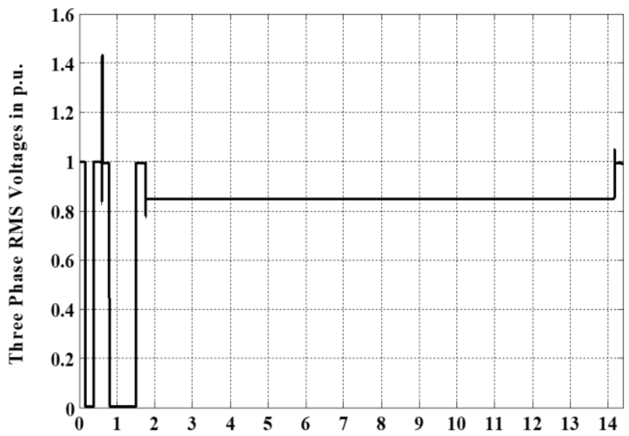

Fig. 2. Three phase RMS voltages at PCC for case 1.

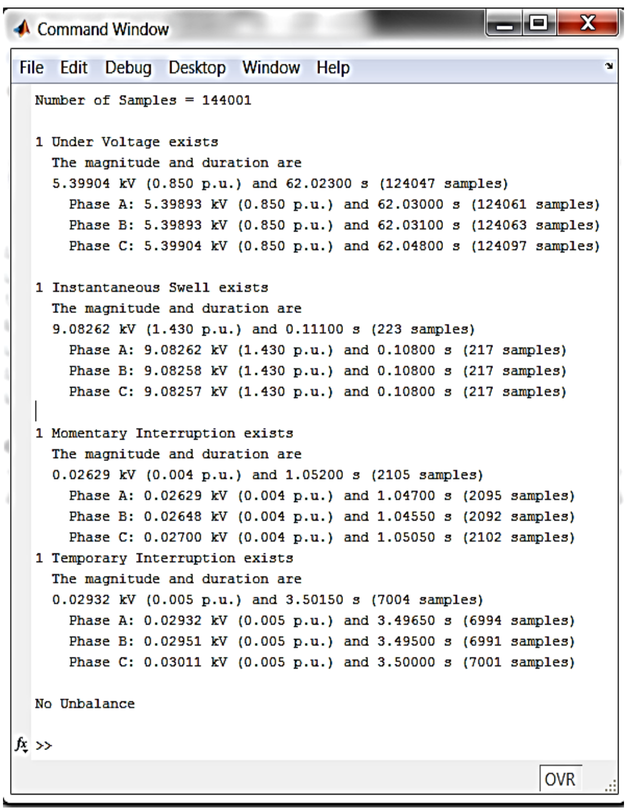

Fig. 3. Output of the program for case 1.

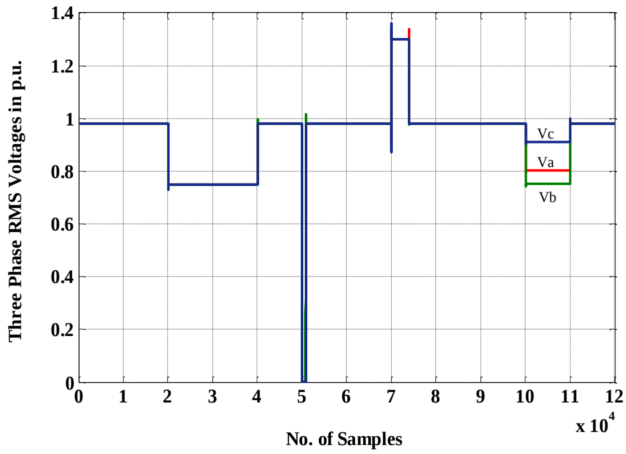

Fig. 4. Three phase RMS voltages at PCC for case 2.

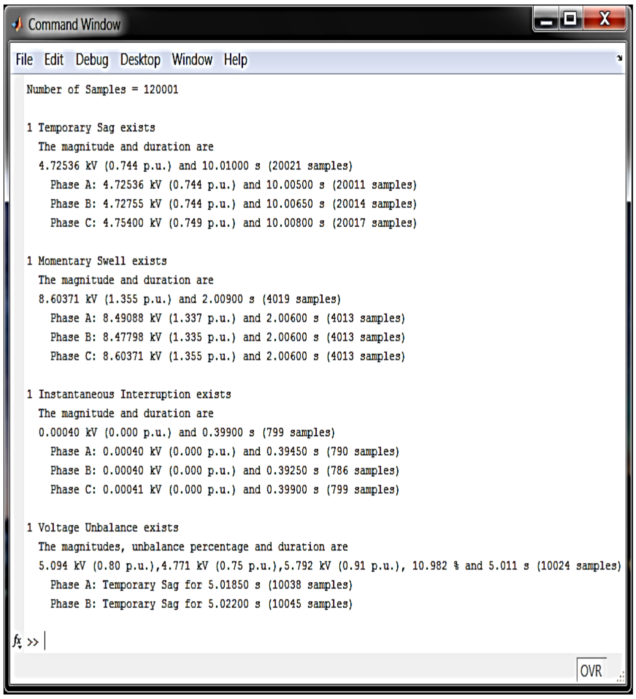

Fig. 5. Output of the program for case 2.

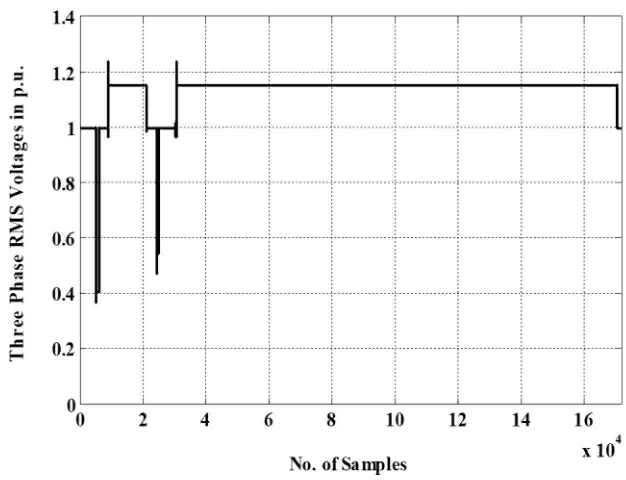

Fig. 6. Three phase RMS voltages at PCC for case 3.

Table 1. Test results of the algorithm in comparison with the actual values

Case	PQ Problems	Actual Values		Values from Algorithm		Accuracy in Voltage Magnitudes (%)	Accuracy in Time Durations (%)
		3-Phase Voltage Magnitude/s (p.u.)	Time Duration in 3-Phases (s)	Individual and Cumulative 3-Phase Voltage Magnitudes (p.u.)	Individual and Cumulative Time Durations in 3-Phases (s)		
1	Under Voltage	0.85	62	0.850	62.0300	100	99.952
				0.850	62.0310	100	99.95
				0.850	62.0480	100	99.923
				0.850	62.0230	100	99.963
	Instantaneous Swell	1.43	0.1	1.430	0.1080	100	92
				1.430	0.1080	100	92
				1.430	0.1080	100	92
				1.430	0.1110	100	89
	Momentary Interruption	0	1.05	0.004	1.0470	99.6	99.714
				0.004	1.0455	99.6	99.571
				0.004	1.0505	99.6	99.952
				0.004	1.0520	99.6	99.81
	Temporary Interruption	0	3.5	0.005	3.4965	99.5	99.9
				0.005	3.4950	99.5	99.857
				0.005	3.5000	99.5	100
				0.005	3.5015	99.5	99.957
2	Temporary Sag	0.74	10	0.744	10.0050	99.459	99.95
				0.744	10.0065	99.459	99.935
				0.749	10.0080	98.783	99.92
				0.744	10.0100	99.459	99.9
	Momentary Swell	1.35	2	1.337	2.0060	99.037	99.7
				1.335	2.0060	98.888	99.7
				1.335	2.0060	98.888	99.7
				1.335	2.0090	98.888	99.55
	Instantaneous Interruption	0	0.4	0.000	0.3945	100	98.625
				0.000	0.3925	100	98.125
				0.000	0.3990	100	99.75
				0.000	0.3990	100	99.75
	Unbalance	0.8	5	0.80	5.0185	100	99.63
		0.75		0.75	5.0220	100	99.56
		0.91		0.91	-	100	-
		PVUR = 10.982 %		PVUR = 10.982 %	5.011	100	99.78
3	Instantaneous Sag-1	0.4	0.5	0.405	0.4995	98.75	99.9
				0.405	0.4985	98.75	99.7
				0.405	0.5070	98.75	98.6
				0.405	0.5070	98.75	98.6
	Instantaneous Sag-2	0.54	0.25	0.545	0.2495	99.074	99.8
				0.545	0.2485	99.074	99.4
				0.545	0.2560	99.074	97.6
				0.545	0.2570	99.074	97.2
	Temporary Swell	1.15	6	1.150	5.9995	100	99.992
				1.150	5.9995	100	99.992
				1.150	5.9995	100	99.992
				1.150	6.0035	100	99.942
	Over Voltage	1.15	70	1.150	69.9995	100	99.999
				1.150	69.9995	100	99.999
				1.150	69.9995	100	99.999
				1.150	70.0035	100	99.995
Overall Accuracies						**99.595**	**98.890**

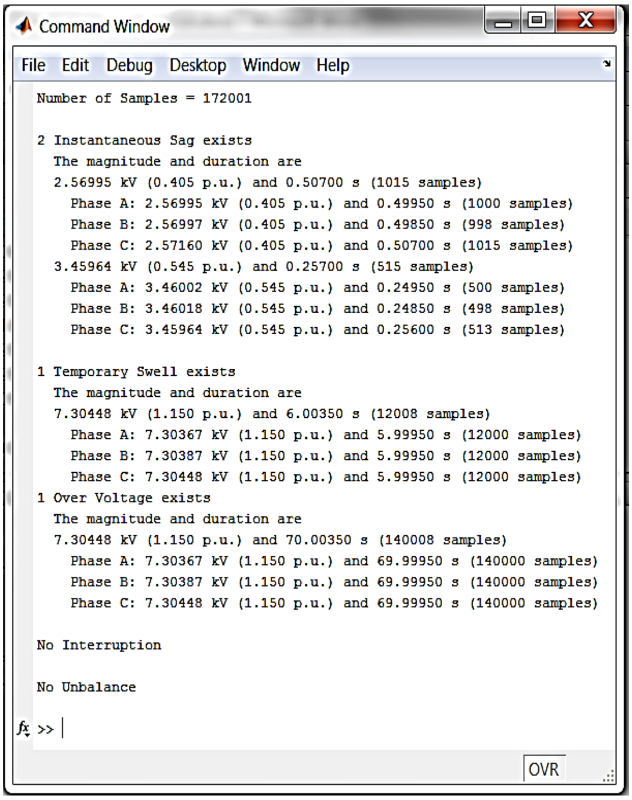

Fig. 7. Output of the program for case 3.

The program output clearly indicates which type of problems has occurred and how many times with the indication of magnitudes and time durations. The program outputs for different cases demonstrate the effectiveness of the proposed algorithm in detection, classification and characterization of all the categories of power quality problems considered.

5. Conclusion

This paper presents a program for classification and characterization of various categories of power quality problems. Sag, swell, interruption, unbalance, under voltage and over voltage conditions are applied to the distribution system considered which is modeled in MATLAB Simulink. Data samples in terms of 3-phase RMS voltages at PCC are measured and are analyzed using the algorithm written in MATLAB m-file. The algorithm identified the different types of power quality problems considered and presented the output in terms of type and category of the problem, its magnitude, duration and number of occurrences of that problem. The classification program outputs for various cases show the ability of the proposed algorithm in identifying, classifying and characterizing all the categories of considered power quality problems for three phase system. This broader characterization of power quality problems is intended to improve the estimation of load tolerance and reduce investments on power quality problems mitigation.

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