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Assesment of Power Quality Disturbances For Grid Integration of PV Power Plants

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ABSTRACT

Power Quality problems, which have become an important consumer issue in recent years, are defined as changes in voltage, current, or frequency in the power system. Among the factors affecting energy quality in grid-connected PV systems are island mode operation, current and voltage harmonics, transients, flicker, interruption, DC offset, notches, frequency changes, voltage sag/swell, voltage imbalances in the system and power factor. Several transmission and distribution losses consist of both the consumers and the generators sides because of the power quality problems. The integration of PV power plants to the main grid will cause several power quality problems so a reliable operation of the grid with PV power plants is a significant issue for a distributed generation. Thus, the first step in preparing a reliable algorithm for detecting power quality events occurring in the current grid is to model a power system in which power quality impairments can be analyzed. In this study, the power quality disturbances that occur in the low-voltage grid that is fed through both the main grid and the grid-connected PV system are modeled and investigated. Developed electric power distribution model includes simulation of voltage sags caused by the three-phase fault, transformer energization and asynchronous motor switching, voltage swells caused by the three-phase fault, transients due to large capacitor bank switching, harmonics and notches caused by the load connected via the power converter. Examination of the power quality disturbances with simulation clearly revealed the resulting waveforms, the response of the electrical power system to the fault conditions. Another advantage of the realized study is that the developed model can be used to measure the performance of the PV connected distributed generation system in fault detection and classification studies.

Keywords: Distributed Generation, Power Quality Disturbances, Grid-Connected PV Systems

1. INTRODUCTION

The ever-increasing involvement of new consumers in the electricity grid, changes in user needs, electricity market expectations, and extreme dependence on today's society's advanced technological services are triggering more reliable and more flexible electrical infrastructure work. For this reason, integration of renewable energy sources into the existing electricity network and the identification and prevention of power quality (PQ) problems have become a priority issue [1].

PQ parameters are a set of limits that allow an equipment to operate as intended without significant performance and life expectancy loss [2]. Any PQ problem that causes voltage, current and frequency deviations can lead to failure of consumer equipment or improper operation of

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equipment. Among the factors for power quality are island mode operation, harmonics, transients, flicker, interruption, DC current injection, noise, notches, frequency changes, voltage sag/swell, voltage imbalances in the system and power factor.

Distributed energy sources, which are increasing in popularity each year in the electrical energy market, play an important role in overcoming the global energy crisis. The rapid decline in the production costs of photovoltaic (PV) power plants over the last few years has led to the rapid development in PV energy systems. The integration of a grid-connected PV system with the existing grid and the identification of PQ problems and the establishment of conditions for identifying these problems have become an important issue.

The first step in preparing a reliable algorithm for detecting and mitigation PQ events occurring in the current grid is to model a power system in which PQ disturbances can be analyzed [3]. Classification based fault detection methods (artificial neural networks [4], decision trees, support vector machines [5], feature extraction) and field alternating fault methods (Fourier and Wavelet transform) utilize the fault signals obtained by modeling the electrical grid [6-8].

Waveforms of power quality impairments can be obtained by mathematical methods, simulation studies and real-time data obtained through the power system. It is proposed by a mathematical method for the analysis of waveforms resulting from PQ problems [9]. A Labview-based power quality signal generator has been proposed that can reproduce PQ disturbances that overlap with actual system data in another study [10]. One of the studies carried out, detection and classification of islanding and PQ disturbances were performed in a distributed generation (DG) based hybrid power system connected to the main grid [11]. In [12], PQ disturbances were identified and classified using real data collected from the system.

In this paper, the PQ disturbances that occur in the low-voltage grid that is fed through both the main grid and the 1 MWp grid-connected PV plant are modeled in MATLAB / Simulink environment. Developed electric power distribution model includes different types of PQ disturbances simulation such as voltage sags, voltage swells, transients, harmonics and notches.

2. POWER QUALITY DISTURBANCES IN GRID-CONNECTED PV PLANTS

Different international standards for regulating power quality have been established. For example, IEEE 1547 standards set limits for total demand distortion (TDD) and amplitude of harmonic currents delivered to the main grid by grid-connected PV systems [13, 21]. Another important standard for research is the IEEE Std. 519, which specifies voltage and current harmonic limits [14]. Apart from these, IEEE Std. 1159 offers some suggestions for monitoring the quality of power events [15]. In this study, the fundamentals of the power quality events and the restrictions that are defined for the reliable grid operation are investigated.

2.1. Voltage Fluctuation

When PV power plants enter and exit the circuit, it may cause a voltage drop or rise. These values are limited to ± 3.3% V according to IEC 61000-3-3 standards [16]. In addition, the effective value of the voltage provided by the PV plant may deviate by ± 10% of the nominal value at 95% of the year, according to the standards. When voltage analysis is performed, the limit values that the system can tolerate should be analyzed.

2.2. Long and Short-time Voltage Variations

Variations in the effective value of the nominal voltage that occurs over a period of more than one minute are called long-term voltage variations, while short-term changes in the nominal voltage of the grid are called short-term voltage variations. Depending on the magnitude of the voltage change, long-term voltage variations can be classified as under-voltage, over-voltage, and continuous interruption.

Voltage sag/dip is defined as a 10% to 90% reduction in effective voltage, limited to a time interval of 10 ms to 60 s on a system operating under nominal conditions (IEEE Std. 1159). This disturbance is caused by the switching of high power motors, overloads and short circuit faults along the line.

Voltage swell is defined as a 110% to 180% increase in voltage, limited to a time interval of 10 ms to 60 s on a system operating under nominal conditions (IEEE Std. 1159). Along with being a type of malfunction that is not often seen in the electrical system, the maneuvers in the power system, such as the disconnection of large inductive loads or the actuation of large capacitor banks, result in voltage swells. Depending on the fault location and power system conditions, a fault or PQ problem may cause a voltage drop, swelling or interruption. Waveforms of voltage sag, voltage swell, and voltage interruption are shown in Fig. 1.

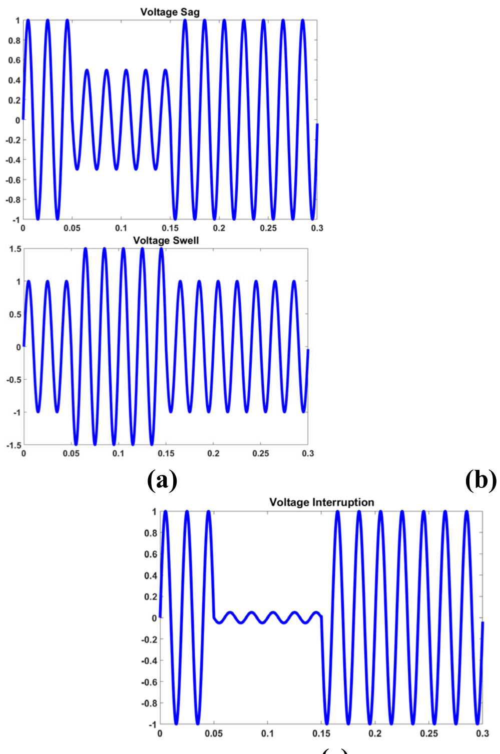


Figure 1. Signal samples of **(a)** Voltage Sag, **(b)** Voltage swell, **(c)** Voltage interruption

2.3. Voltage Imbalance

For the low-voltage (LV) system, the imbalance should not exceed 2% in 95% of the measurement time according to the EN 50160 standards, which are based on only the negative component of the voltage. In order to prevent voltage imbalance, the power of the PV plant must be distributed equally.

2.4. Harmonics

The ratio of the total effective value of the harmonics outside the fundamental harmonic in the voltage and current waveform to the effective value of the fundamental harmonic is defined as the total harmonic distortion (THD).

$$\text{THD} = \sqrt{\sum_{n=2}^{\infty} V_n^2} \Big/ V_1 \qquad (1)$$

where V_n is the amplitude of the n-th harmonic components, V_1 is fundamental componenet.

Depending on the IEEE 519 standards, the total harmonic distortion for voltage in the power system is limited to a maximum of 8% in low voltage grids. In addition, each harmonic value is limited to be less than 5%. The most commonly used power quality standards for low voltage systems are IEC 61000-2-2, IEC 61000-3-2, and 61000-3-4 respectively. According to these standards, the THD amount must be less than 8% up to the 40th harmonic value. Fig. 2 shows harmonics caused by the universal bridge connection.

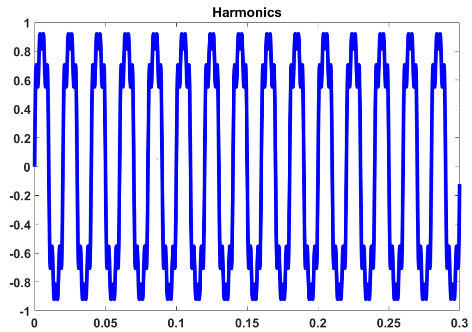


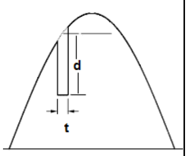
Figure 2. Harmonics caused by universal bridge connection

2.5. Notches

The notch is a voltage waveform distortion of the converter in a period of the voltage in a system operating at the grid frequency, which is proportional to the number of pulses of the converter [17]. This distortion is shorter than half a period. Since the frequency components generated by the notch effect are too high, they cannot be identified with conventional harmonic measuring devices. According to the IEEE 519-

2014 standard, the notch area and the depth-dependent limit values are as shown in Table 1.

Table 1. Notch area and depth definition (IEEE 519-2014)

System	Special Applications	General System	Systems with Converters
Notch Depth	%10	%20	%50
Notch Area (A_N)	16400	22800	36500
Notch area and depth definition (IEEE 519-2014)		% notch depth =d/V×100 A_N = td = u sec × volt	

2.6. Transients

Transients that can be examined in two classes, oscillatory and impulsive, are undesirable momentary events in power systems. These events occurred in less than half a period [18]. Impulsive transients are usually sudden and unidirectional distortions caused by lightning strokes. In oscillatory transients, the resultant change in polarity of the current or voltage occurs very quickly, resulting in bi-directional distortions. Oscillatory transitions are caused by switching off/on large loads, energization of the capacitor banks or the energization of the transformers. The voltage signal waveform containing the transient is given in Fig. 3.

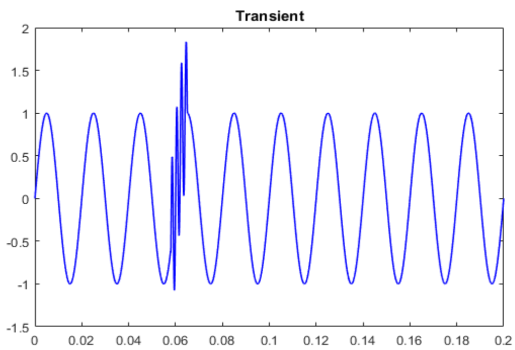


Figure 3. Transient disturbances waveform

3. DEVELOPED ELECTRICAL POWER DISTRIBUTION MODEL

This study includes simulation of voltage sags and swells, transients, harmonics, voltage fluctuations, and notches. In this paper, effective value conversion was used to observe the effect of power quality disturbances on the voltage.

$$U_{RMS}=\sqrt{\frac{1}{M}\sum_{i=1}^{M}u(i)^2} \quad (2)$$

where M is window size and $u(i)$ is the voltage waveform is the i-th sample.

3.1. PV Plant Modeling

Fig 4 shows the developed grid-connected PV system [19, 20] has sub-models consisting of a PV plant, H-bridge converter, MPPT controller module, load and the grid connection modules. The 1 MWp PV power plant is connected to the DC line via the three-phase inverter and the three-phase inverter output is connected to the 10.5 kV Bus1 via the LCL filter.

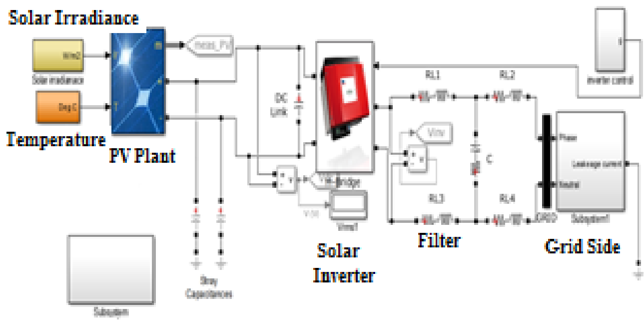


Figure 4. Developed a grid-connected PV system for residential power plants [17]

3.2. Electrical Power Distribution Model

In order to detect PQ problems, the response of the power system should be observed first in case of a fault. The simulation model was developed using MATLAB / Simulink which is shown in Fig. 5. The simulation model realized include phase-to-phase and phase-to-ground short circuit faults, starting with a large powerful asynchronous motor, transformer energizing, capacitor bank switching and system behavior under nonlinear load.

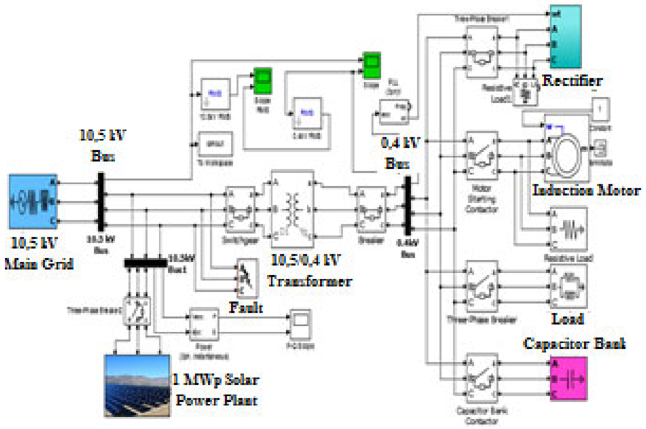


Figure 5. Matlab/Simulink model of the developed electrical power distribution system

The power distribution system model consists of 10.5 kV main grid, 10 MVA generator, 1 MWp grid-connected PV plant, a delta/star connected step down two windings transformer, inductive and resistive loads, induction motor, capacitor bank and three phase nonlinear load. The transformer of 10.5 kV/0.4 kV supplies three-phase nonlinear (20 kVA RL load) and normal (150 kVA RL load) loads, squirrel-cage 160 kW induction motor at the point of common coupling (PCC). 0.4 kV load bus also equipped with 50 kVA capacitor bank.

4. ASSESSMENT OF POWER QUALITY ISSUES

In this section, several grid conditions are investigated to indicate the power quality effects of the PV power plant to the main grid and the other electrical equipment. In three-phase systems, faults between phases and between phases and ground can be examined in two groups, symmetric and asymmetric. Fig. 6 shows the effective values of the voltages resulting from the fault occurring as a result of the short-circuiting of the three phases between 0.15 and 0.25 seconds. The resulting fault is symmetrical because it creates similar effects on all three phases.

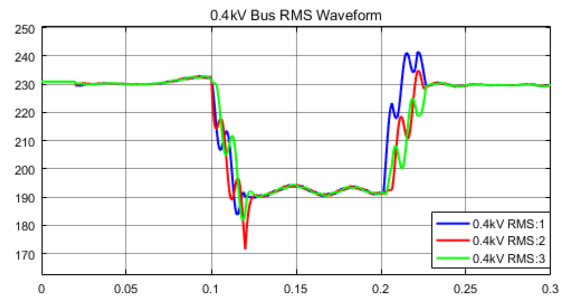


Figure 6. Effective values of voltages that occur as a result of three-phase short circuit fault

Fig. 7 shows the changes in the effective values of the voltages of the phases during faults between A and B phases between 0.1 and 0.2 seconds. The short circuit fault resistance on the model is selected as 7 ohms.

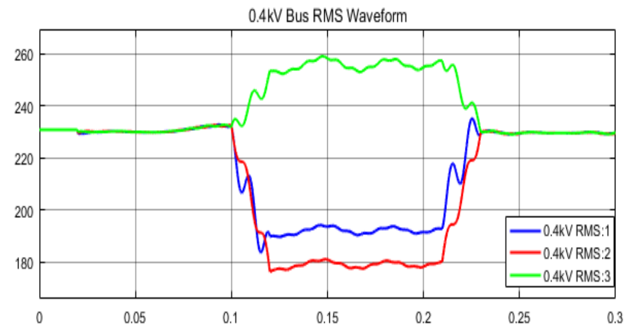
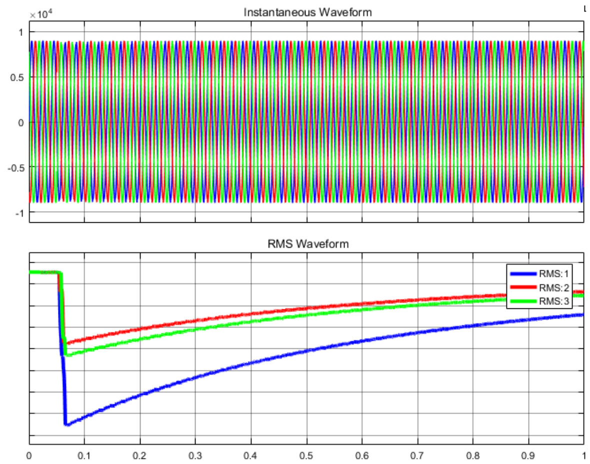


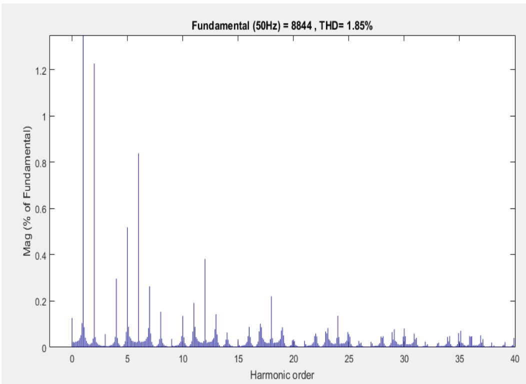
Figure 7. Effective values of phase-to-phase voltage resulting from faults

As a result of the simulation, voltage swell occurs in phase C, while voltage sag is observed in phases A and B. As seen in the Fig. 7, two-phase faults, single phase-to-ground, and two phase-to-ground faults show asymmetrical characteristics.

The breaker of the transformer was closed at 0.05 second on the model for the analysis of the voltage sag that occurred as a result of transformer energization. As a result of transformer energization, the change in instantaneous and effective values of phases A, B and C is given in Fig 8. FFT analysis used in determining the harmonic distortion is shown in Fig. 8(b). Because of the different phase angles, there is also a difference in the size of the voltage sag of each phase. The collapse of the voltage resulting from the impulse current and the saturation of the core caused a sudden drop in the system voltage and a long period of stabilization began. Simulation studies have shown that the voltage sag is larger when transformer power or line power is increased. In the FFT analysis, it was observed that the n-th harmonic components were most affected by transformer energization of 2nd, 6th, 12th and 18th harmonics.



(a)



(b)

Figure 8. The transformer energization results in **(a)** the change in the instantaneous and effective values of phases A, B and C, **(b)** FFT analysis

The voltage waveforms of phases A, B, and C at the 400 V low voltage bus as a result of the asynchronous motor start-up are shown in Fig 9. Simulation duration is 0.3 seconds and 0.02nd seconds the asynchronous motor is activated by closing the circuit breaker. As a result of the voltage sag event, a voltage drop of about 15% in the voltage effective values of the 400 V bus has been observed. Simulation studies have shown that the amount of sag depends on the power of the motor. The resulting fault showed a balanced distribution unlike the transformer energization and each phase voltage showed similar behavior.

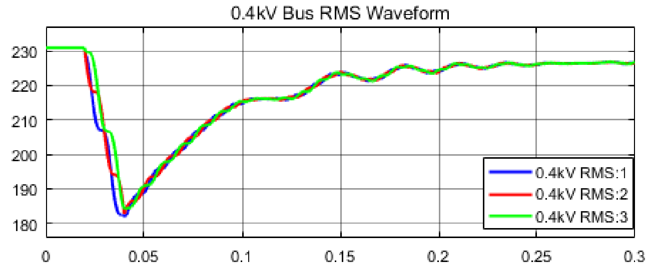


Figure 9. Voltages in the result of induction motor start-up

In order to investigate the power quality disturbance caused by the switching of the capacitor bank, 0.4 kV 50 kVA capacitor bank connected to the 400 V bar on the model was switched on with the help of a phase breaker (Fig. 4). Fig. 10 shows capacitor bank switching upon closing of the breaker at 400 V feeder line causes transient in voltage at low voltage bus at 0.03 seconds. In this short-time event, the effective value of the voltage increased about twice, especially in phase B, and the system frequency changed. After the time of the first uprising, this oscillation continued to increase and decrease in voltage and settled at the latest nominal value. Size of capacitor bank affects the voltage transient frequency. The low voltage transient frequency is caused by very large capacitor banks. Increasing the amount of load causes a higher damping factor.

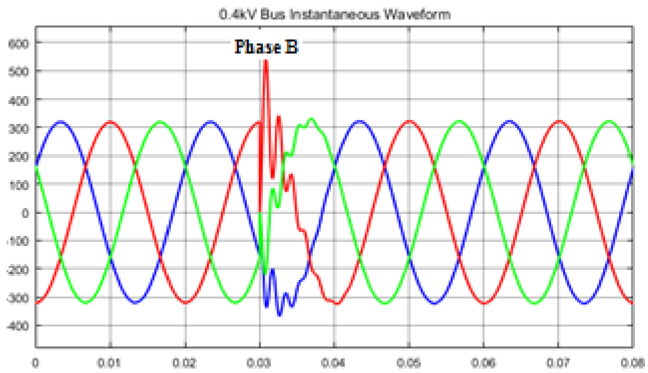


Figure 10. The voltage waveforms resulting from the switching of the capacitor bank

A nonlinear load is also fed through a switched converter to observe the notch formation. Figure 11 shows that each notch has a depth and a duration similar to those of the other. It is seen that the harmonic values of 5th, 7th, 11th and 13th components are high in the FFT obtained as a result of notch formation. The location and depth of the voltage notch depend on the ignition angle control of the converter. The notch width depends on the amount of inductive load and increases as the number of load increases.

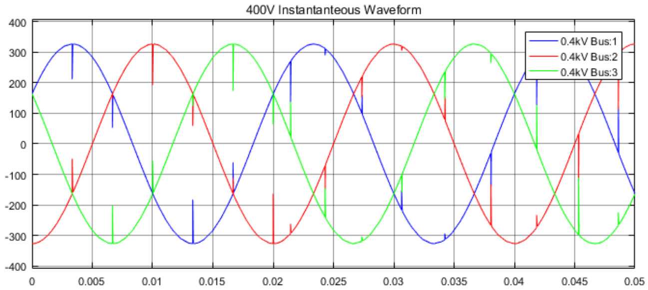


Figure 11. Voltage notch waveforms at low voltage bus

5. DISCUSSION AND CONCLUSION

In this study, the power quality (PQ) disturbances that occur in the low-voltage grid that is fed through both the main grid and the 1 MWp grid-connected PV plant are produced by using developed electrical distribution model in MATLAB/ Simulink environment. Examination of the PQ disturbances with simulation clearly revealed the resulting waveforms, the response of the electrical power system to the PQ disturbances conditions.

The advantage of the realized study is also that the developed model can be used to measure the performance of the PV connected distributed generation system in fault detection and classification studies.

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