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RESEARCH ARTICLE

Power Quality Evaluation of Distributed Generation Systems

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ABSTRACT

Effective and efficient use of power systems is directly related to the quality of the distributed power. Power quality should be monitored, and various analyses should be made to provide full control over the network. The importance of the power quality is clearly understood when the number of consumers in distribution systems is considered. When handling the distribution systems, it is seen that the distributed generation resources (DGS) may have positive and negative impacts on power quality. Increasing the presence of DGSs in power systems requires evaluation of their effects on the network. In this study, we aimed to examine the effects of DGSs on power quality through indices. The response of the power quality before and after the integration of distributed generation into the distribution system was evaluated using voltage variation and total harmonic distortion (THD) indices. Various simulation studies have been carried out on a real test system at different harmonic levels for THD, voltage variation, related power quality variation indices, and system indices for THD to be calculated. It has been observed that the indices considered are important to analyze the power quality of a distribution network in the presence of DGSs. The results show that the impact of harmonics and voltage drop can be reduced with properly located and increased rated power of DGSs.

Keywords: Distributed generation, voltage variation, power quality, power quality indices, total harmonic distortion

Introduction

With the rapid development of the industrial sector, there is an increase in power consumption, which will continue to rise. This development might lead to an increase in power quality problems. Therefore, it is very important to identify and deal with these problems.

Today, reasons such as decrease in fossil energy sources, increase in the number of consumers, and negative effects of traditional energy sources on the environment have increased the interest in alternative energy sources. With an increasing interest in these resources, the concept of distributed generation has emerged. The term "distributed generation" is used for generation resources below 10 MVA connected to the power system from the distribution network [1].

Distributed generation shows both positive and negative effects on power systems, which are widely found in the networks. Distributed generation can cause power quality problems that can have significant effects. These problems include voltage fluctuations caused by the change in the output power of the generator in distribution networks, imbalances caused by single-phase generators, and temporary impacts such as the activation and disconnection of generators [2]. However, distributed generation contributes to strengthening the network and reducing losses. Thanks to the strengthened network structure, it is easier to overcome waveform distortions and voltage drops, which are among the power quality problems that may occur. To observe the effects of distributed generation on power systems, it is necessary to analyze power quality levels for situations before and after installation. An indicator is needed for this analysis.

Power quality indices are indicators that are used to quantify the degree of power quality deterioration that occurs in power systems for any reason [3]. Measuring the extent of power quality disturbances and their adverse effects on power systems can be performed using power quality indices. These indices are numerical representatives characterizing the nature of a power quality event on the basis of time or frequency information. There are studies in the literature evaluating the effects of distributed generation on power quality over indices. In 2009, appropriate probabilistic indices were used for distribution networks to evaluate power quality levels in the presence of distributed generation [4]. Bracale et al. [2] have taken into account the problem of assessing power quality levels in the presence of distributed generation. Therefore, they used probabilistic indices suitable for distribution networks. Nourollah and Moallem [5] aimed to obtain two global power quality

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indices to evaluate the power quality levels of several distribution regions according to the type of load and its location in the distribution system. Dash et al. [6] proposed the modified recursive Gaussian-Newton (MRGN) method for estimating power quality indices in distributed generation systems in both island mode and non-island mode states. In another study, they proposed a unified power quality index for the distribution network using a two-level analytical hierarchy process for possible, ideal, and real situations [7]. Alfieri et al. [8] developed new power quality indices to evaluate waveform distortions from 0 to 150 kHz in power systems where distributed generation is available. Elbasuony et al. [9] used the unified power quality index to evaluate the power quality in different distributed generation systems using the analytical hierarchy process. As a result of the study, it was observed that the suggested index makes it easier to evaluate the power quality. They also found that a hybrid system showed better power quality performance than other systems. Jasinski et al. [10] analyzed long-term power quality data using cluster analysis and a hybrid technique based on global power quality indices proposed by them. Moghaddam et al. [11] aimed to minimize losses and improve power quality indices by using the antlion optimization algorithm.

In this study, power quality indices were used to investigate the effects of distributed generation units on power quality. Various simulations were carried out on a real test system through DigSilent Power Factory, which is a power system analysis program. Power quality indices were computed for each case. Improvements in the voltage profile and THD were observed with the integration of distributed generation units into the system.

The remainder of this paper is structured as follows: the second section explains the power quality indices; the later section discusses the simulation study and results; and the conclusion section represents a summary of main findings of the study.

Methods

Power Quality Indices

Power quality addresses different aspects of the behavior of a power system. Its main function is to provide an uninterrupted voltage with sinus wave form at a fixed frequency to the end user.

Power quality variation indices are used to evaluate service quality. Variation indices are grouped under two headings. The first of these is single indices that address each power quality distortions we calculate using traditional indices. The second is global variation indices that simultaneously handle multiple power quality distortions. When evaluating a general power quality index for both types, the mentioned index presented with X, X_V and the power quality variation index (X_V), which allows to quantify the increase or decrease in power quality resulting from the integration of distributed generation units into the system, which is calculated as follows:

$$X\_V = \frac{X_O - X_N}{X_0} \tag{1}$$

X_N in equation 1 is the value of the single/global index X with the existence of distributed generation. X_0 is the value of the single/global index X without distributed generation. All these indices can be calculated for each bus regionally as well as for the whole system under the name of system indices.

Single Variation Indices

Individual variation indices for all power quality disturbances can be obtained; however, in this study, only indices related to harmonic distortions and voltage changes will be evaluated.

Harmonic Variation Index

Equations for THD for voltage and current used commonly in the standards are given as follows:

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \tag{2}$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{3}$$

The harmonic variation index is an indicator that helps to compare the situation before and after the integration of the distributed generation unit into the system. Equation (4) is used to calculate the harmonic variation index for a region, that is, for a specific bus.

$$THD_{Vj} = \frac{THD_{Oj} - THD_{Nj}}{THD_{Oj}} 100 \tag{4}$$

where THD_{Vj} represents the THD variation index in the busbar j owing to the integration of a new distributed generation unit into the system, THD_{Oj} represents the total harmonic distortion value before integration of the distributed generation unit into the system, and THD_{Nj} represents the total harmonic distortion value after integration of the distributed generation unit into the system. If the value of this change index is positive, it indicates that there is an improvement in THD owing to distributed generation.

Voltage Variation

Calculation of voltage variation indices as well as harmonic variation index for a particular bus is very important in terms of in-

Main Points

- Power quality indices are used to evaluate the power quality in distribution networks.
- Distributed generation units are evaluated with power quality indices depending on their position in power systems.
- Distributed generation units are evaluated with power quality indices depending on their power.
- The cases of distributed generation sources being synchronous generators or wind farms are discussed.

creasing the quality performance of the power system. The regional voltage variation index is calculated as follows:

$$VDA_{Vj} = \frac{VDA_{Oj} - VDA_{Nj}}{VDA_{Oj}} 100 \quad [5]$$

where VDA_{Oj} represents the voltage variation value before integration of the distributed generation unit into the system and VDA_{Nj} represents voltage variation value after integration of the distributed generation unit into the system. If the VDA_{Vj} value is negative, it means that there is an improvement in the system in terms of voltage variation.

System Indices and System Variation Indices
The indices obtained as a result of calculating a specific power quality index for the whole system are called system indices. System indices are calculated using equation (6),

$$STHD = \frac{\sum_{k=1}^{M} w_k \, THD_k}{\sum_{k=1}^{M} w_k} \quad [6]$$

where w_k is the weight factor of the busbar k, M is the total number of busbars observed in the system, and THD_k refers to the total harmonic distortion index in the busbar k.

To determine the effect of distributed generation on system indices, system change indices calculated per equation (7) is used.

$$STHD_V = \frac{STHD_O - STHD_N}{STHD_O} 100 \quad [7]$$

A decrease in system indices indicates an improvement in power quality.

Global Variation Indices
Global indices allow general characterization of the voltage quality. The unified power quality index (UPQI), which is a global index, accurately represents the overall voltage quality in the presence of various disturbances. As in other indices, the change in UPQI should be calculated to have information about the effects of distributed generation on power quality. Equation (8) is used to calculate the variation in the UPQI.

$$UPQI_{Vj} = \frac{UPQI_{O,j} - UPQI_{N,j}}{UPQI_{O,j}} 100 \quad [8]$$

where $UPQI_{Vj}$ represents the UPQI variation index in the busbar j because of the integration of a new distributed generation unit into the system, $UPQI_{Oj}$ represents the unified power quality value before integration of the distributed generation unit into the system, and $UPQI_{Nj}$ represents the unified power quality value after integration of the distributed generation unit into the system. A positive UPQI variation index indicates an improvement in power quality in the power system.

Results

Simulation Study
The most common disturbances in power systems are voltage variation and harmonics. Voltage variation is defined as a decrease in voltage magnitude that occurs within the period specified by the standards. Harmonics can be defined as unwanted components of a distorted periodic waveform whose frequencies are integer multiples of the fundamental frequency [12]. As both power quality problems must be addressed, in this study, the aforementioned impairments were analyzed with the DigSilent Power Factory program, using power quality indices, on the basis of the presence or absence of distributed generation in the system.

In this study, the list of situations that were analyzed is given below:

- Calculation of THD variation indices for the situation where synchronous generators with different power levels are connected to the bus closest to the network and comparison of indices calculated at each power level.
- Calculation of THD change indices for the situation where synchronous generators with different power levels are connected to the bus, which is the furthest to the network and comparison of indices calculated at each power level.
- Calculation of voltage variation indices for synchronous generators with different power levels connected to the bus closest to the network and comparison of indices calculated at each power level.
- Calculation of voltage change indices for synchronous generators with different power levels connected to the bus, which is the furthest to the network and comparison of indices calculated at each power level.
- Calculation of system indices for synchronous generators with different power levels connected to the bus, which is the closest to the network and comparison of indices calculated at each power level.
- Calculation of system indices for synchronous generators with different power levels connected to the bus, which is the furthest to the network and comparison of indices calculated at each power level.

Test Setup
A feeder of Izmit 2 substation was selected for the implementation setup. The short circuit capacity of the system to which this feeder was connected was 418 MVA. The single line diagram of a 37 buses feeder is given in Figure 1 with its load values. The number of buses observed was 25 in total, 12 of which were load buses, and power factor for all loads was assumed to be 0.98 (inductive) [14].

The summary of busbars and loads are given in Table 1.

All mentioned loads are selected as harmonic sources, and the fifth harmonic value of the loads was 20%, the seventh harmonic value was 14.28%, the 11^{th} harmonic value was 9.09%, the 13^{th} harmonic value was 2.7%, and the 17^{th} harmonic value was 2.48%.

Simulation Results
Synchronous generators are considered as DGSs and modeled in the sample test system to improve the voltage profile and har-

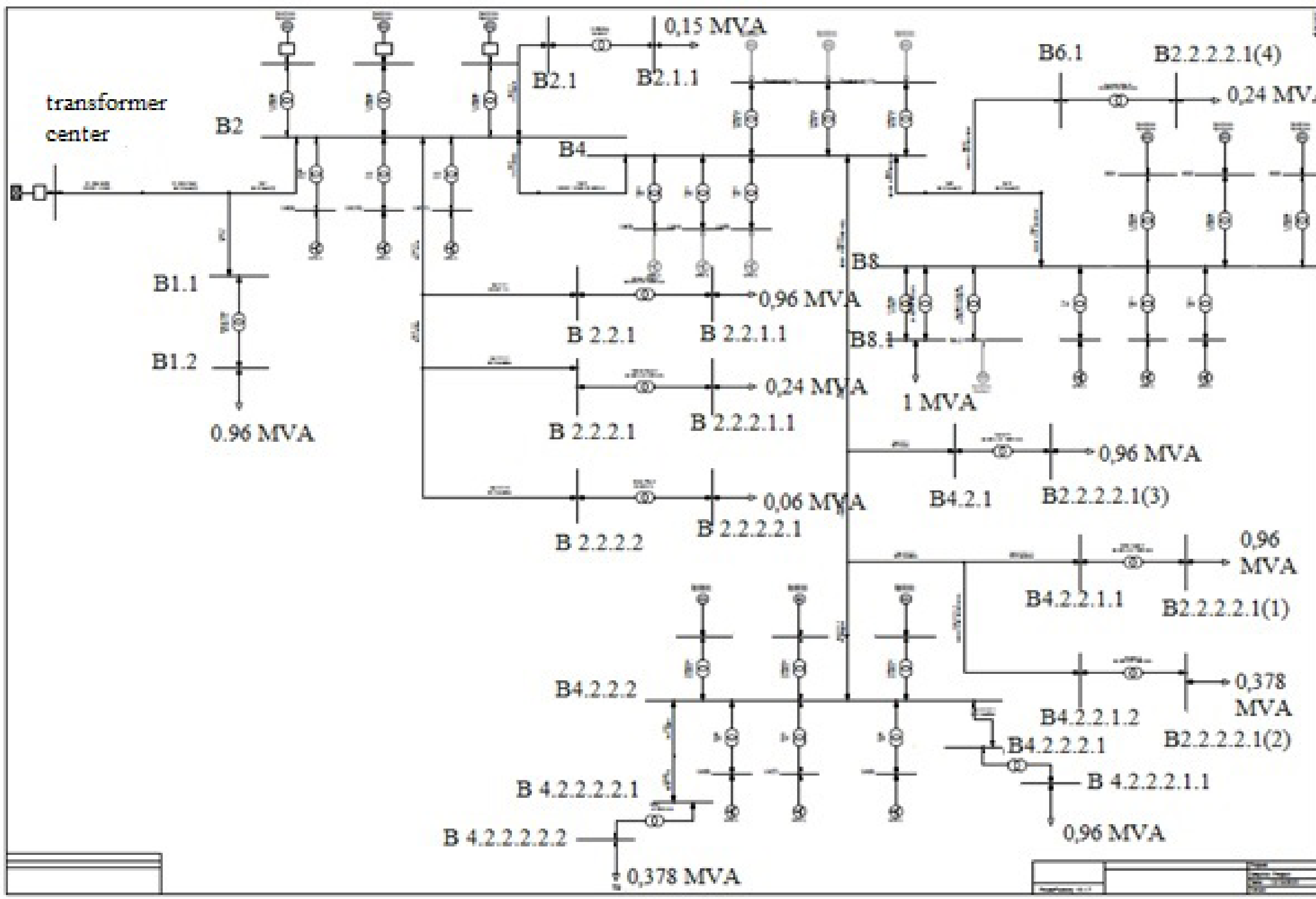

Figure 1. Single line scheme

Table 1. Summary of busbars

Busbar Name	Busbar Load ([1]MVA)	Weighting Factor (w_j)
B2.1.1	0.15	0.020548
B2.2.1.1	0.96	0.131507
B2.2.2.1.1	0.24	0.032877
B1.2	0.96	0.131507
B2.2.2.2.1	0.06	0.008219
B2.2.2.2.1[1]	0.96	0.131507
B2.2.2.2.1[2]	0.378	0.051781
B2.2.2.2.1[3]	0.96	0.131507
B2.2.2.2.1[4]	0.24	0.032877
B4.2.2.2.1.1	0.96	0.131507
B4.2.2.2.2.2	0.378	0.051781
B8.1	1	0.136986
Total Load: 7.3 MVA		

monics. Simulation studies are carried out over the closest (B2) and the farthest (B4.2.2.2) busbars.

Three synchronous generators, each rated 1.9MVA were added to the test system. Analyses having one, two, and three synchronous generators were performed separately for THD and voltage change. THD change variation indices are compared in Figures 2 and 3, where DGSs are connected at the closest and farthest busbars, respectively.

As a result of the analysis, a decrease in THD values is observed with the integration of synchronous generators into the system. This decrease in THD values indicates an improvement in THD in the system. As can be seen, THD variation indices take positive values, which is a desired situation. In addition, the more rated power of DGSs, the more improvement for low THD. Another observation is that reduced harmonic levels are achieved as DGSs move away from the network.

The changes in voltage owing to the use of DGs connected at the closest and furthest busbars are given in Figures 4 and 5, respectively.

When analyzed in terms of voltage, an increase in voltage values with the integration of DGSs into system was observed. Because

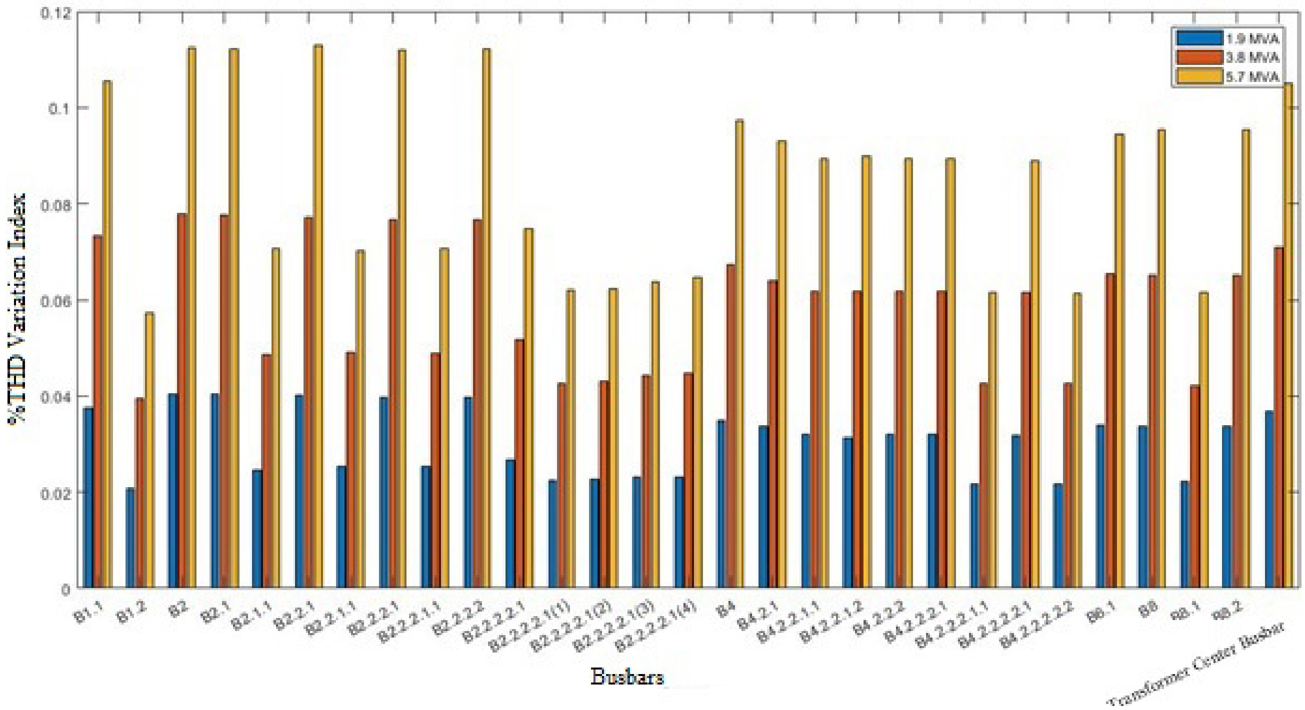

Figure 2. Total harmonic distortion variation index for the closest busbar (B2)

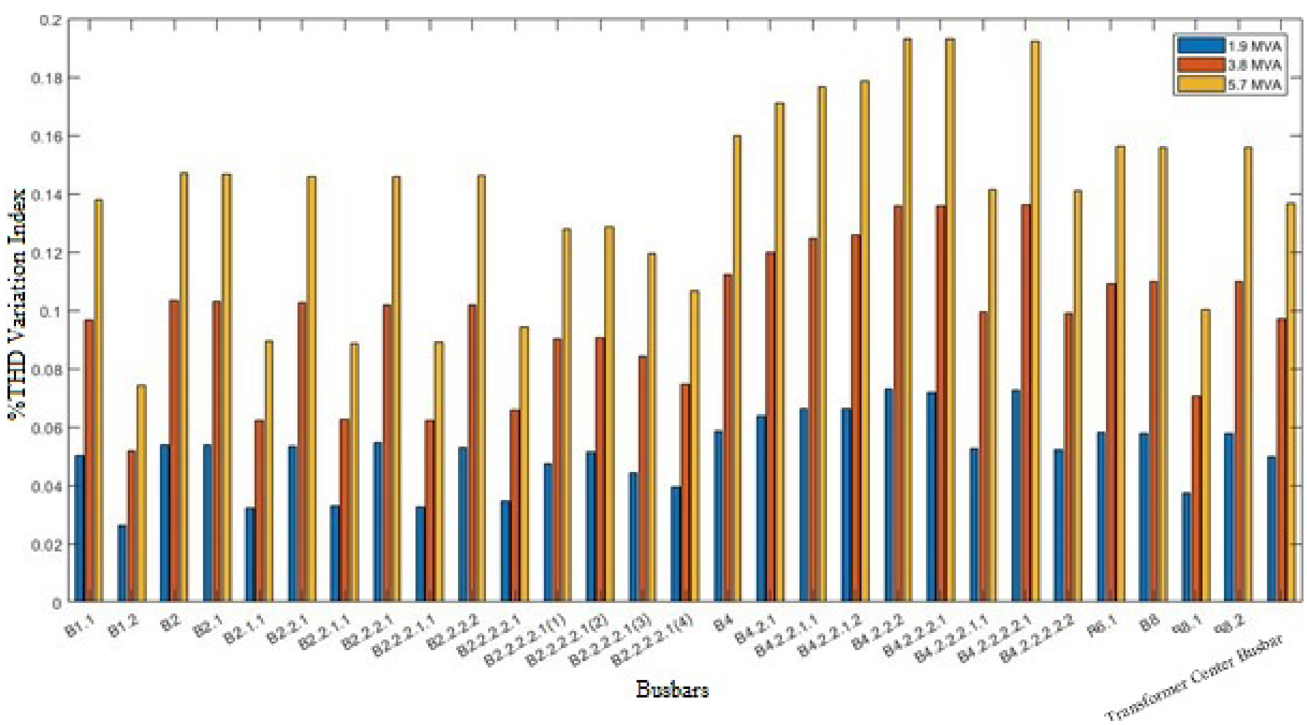

Figure 3. Total harmonic distortion variation index for the furthest busbar (B4.2.2.2)

of the increase in the voltage values, the voltage variation indices take negative values as should be. This indicates that the test system is enhanced in terms of power quality.

Knowing the general status of the system is important in terms of having information about the distribution system [13]. Therefore, the system indices for synchronous generators with different

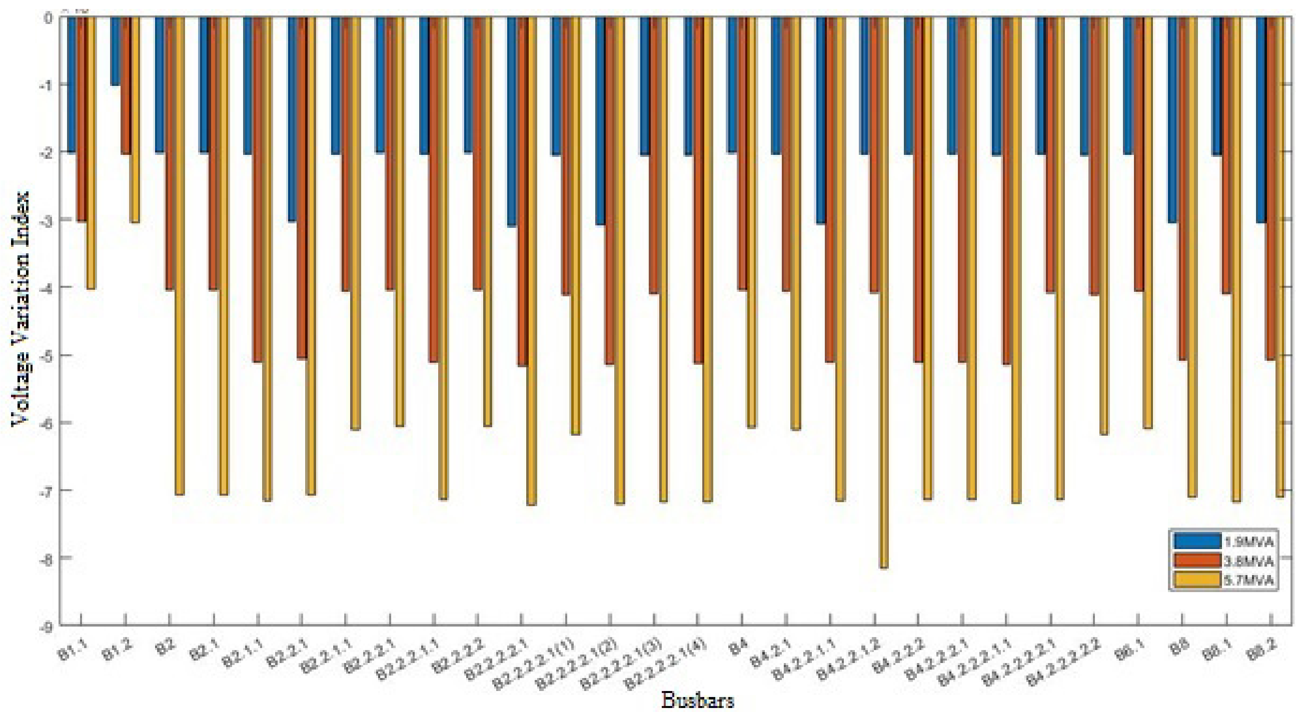

Figure 4. Voltage variation index for the closest busbar (B2)

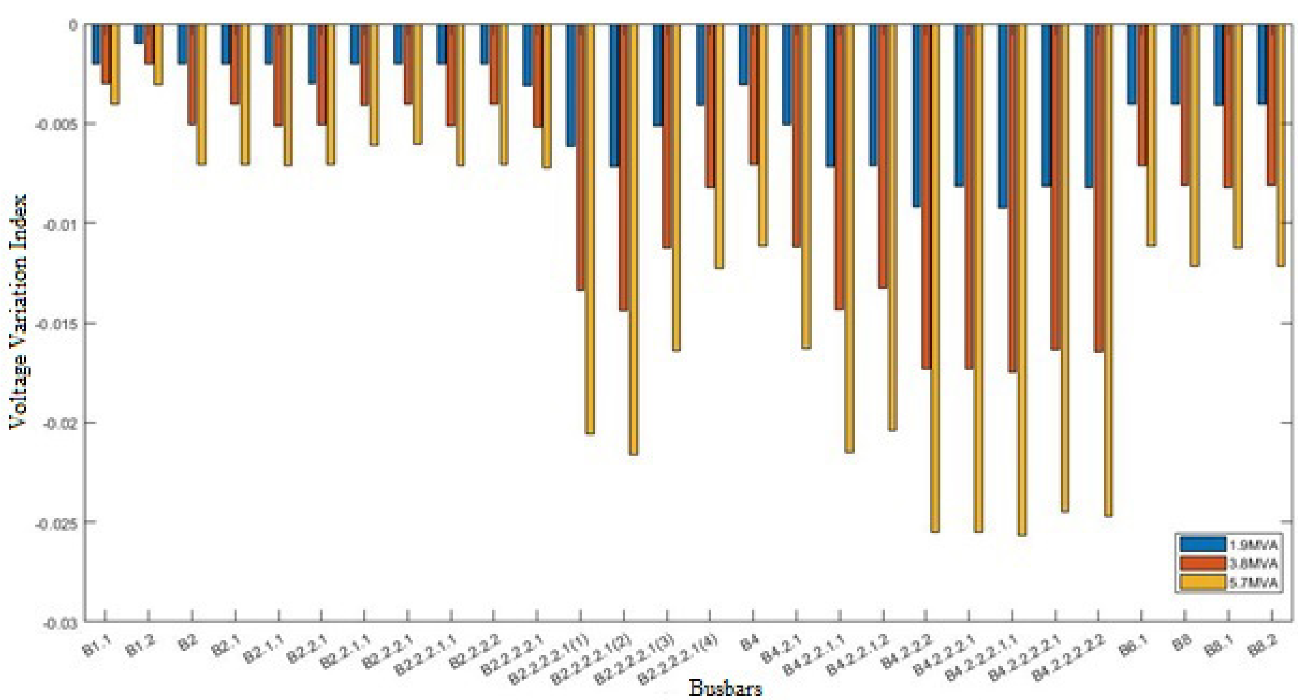

Figure 5. Voltage variation index for the furthest busbar (B4.2.2.2)

power levels connected to the buses, which are the closest and furthest to the network are calculated. Comparison results are given in Table 2.

It was observed that the values of the system indices for THD decreased as the power increased. According to these results, it was determined that there was an improvement in power quality with

Table 2. Comparison of system indices for closest and furthest buses

Power Levels	Closest Bus (B2)	Furthest Bus (B4.2.2.2)
1.9 MVA	0.133861	0.130658
3.8 MVA	0.130994	0.125273
5.7 MVA	0.128344	0.120333

MVA: Megavolt Ampere

increasing power. Again, when we make a comparison in terms of the closest and the furthest bus, it can be said that there is an improvement in terms of system indices as we move away from the network.

When all results are evaluated together, the obtained results are specific to the system and the scenario (system topology). At this point, the difference in the distribution of the loads in the system rather than the different sources or the distance situation are effective in the results obtained.

Discussion

Distributed generation is a reality today and may have positive and negative impact on a power system. In this study, its positive impact in terms of power quality has been investigated. For this purpose, the power rating and the position of distributed generation has been varied, and the performance of the system has been measured with power quality indices related to voltage harmonics and voltage profile. A feeder belonging to Izmit 2 Transformer Station had been used to carry out analyses. The results showed that with the integration of distributed generation units into the system, improvements were demonstrated in THD and voltage profile as the power rating of DGSs increased, and their location was further away from the network.

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