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Power Quality Impact of Renewable Energy Based Generators and Electric Vehicles on Distribution Systems

Masoud Farhoodnea*, Azah Mohamed, Hussain Shareef, Hadi Zayandehroodi

Department of Electrical, Electronic, and Systems Engineering, University Kebangsaan Malaysia, 43650 Bangi, Selangor, Malaysia

Abstract

This paper presents a power quality analysis on the effects of high penetration of electric vehicle charging stations (EVCSs) and renewable energy based generators (REGs) which include wind turbines, grid-connected photovoltaic and fuel cell power generation units on the 16-bus test distribution system. All data on EVCS, wind farm, photovoltaic and fuel cell units as well as weather conditions were collected from various manufacturers and the Malaysian Meteorological Department. The system is modeled and simulated using the MATLAB/Simulink software and the effects of the REGs and EVCS technologies on system performances were investigated for various penetration levels and at different loading and weather conditions. Simulation results indicated that the presence of high penetration EVCS and REGs can cause severe power quality problems such as frequency and voltage fluctuations, voltage drop, harmonic distortion and power factor reduction.

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Keywords: Electric vehicle stations, fuel cell, photovoltaic, power quality, renewable energy, renewable energy generator, wind farm

1. Introduction

Power systems have been conventionally designed for unidirectional power flows from the main source, distributed downstream at lower voltage levels. The increasing number of customers willing to install distributed generation (DG) to provide part of their power consumption indicates that DG has gained more interest in the

* Corresponding author. Tel.: +6-03-89216590; fax: +6-03-89216146.
E-mail address: farhoodnea_masoud@yahoo.com

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electricity market. Considering the environmental issues related to conventional power plants, especially CO_2 emission, utilities and customers have widely accepted the use of pollution-free renewable energy based generators (REGs), which include photovoltaic (PV) system, wind turbine (WT) and fuel cells (FC), among others, as alternative sources of electricity. Utility-scale hybrid REGs consisting of two or more energy conversion mechanisms are widely developed to overcome the limitations and improve the security and reliability levels of REGs as well as their interconnected networks. The power plant in Zhangbei, China is an example of a utility-scale hybrid REG with a 100 MW wind turbine, a 40 MW PV, and 20 MW to 36 MW battery storage [1].

Economic and operational advantages provided by REGs for distribution systems include the following: power balance during peak demand, decreased occurrence of power interruptions and system outages, reduction in investment and operational costs due to flexible capacity and installation, as well as decreased dependence on imported fossil fuel [2]. Despite these advantages, the increasing use of scattered and time-varying hybrid REGs can result in a bidirectional power flow, which may either improve or worsen power quality, protection and stability. These effects, especially with high penetration of REGs heavily rely on the characteristics of each installation and specifications of the distribution system. Therefore, a distribution system must be continually monitored for satisfactory levels of power quality [3]. Electric vehicle (EV) technology and electric vehicle charging stations (EVCS) are rapidly being developed to reduce oil dependence and minimize greenhouse gas emissions. The influence of EV and future EVCS on system performance highly depends on the charging scenario and the ability of power utilities to deliver the required power to EVCS regardless of loading conditions. This dependence is due to the time variability of electricity use by EVs [4].

Accurate assessment of the possible impacts of large grid-connected REGs and EVCSs on network performance before installation is crucial. Performing such analysis is important so as to allow power utilities to become efficiently equipped to solve potential operational issues caused by REGs and EVCSs. Numerous studies have focused on steady-state modelling as well as the analysis of a single REG and its impacts on the system [5]. However, studies on the effects of high penetration REGs on dynamic operation and control of the system before real-time implementation have scarcely been reported. This paper aims to analyze accurately the dynamic effects of high penetration hybrid REGs and EVCSs on the power quality performance of distribution systems. To address the practical aspects, the required data on weather conditions, EVCS loading conditions, and REG modelling were obtained from the Malaysian Meteorological Department [6]. The REG data were obtained from various power system manufacturers such as SunPower, Sanyo, General Electric, and FuelCell Energy. Simulations using the MATLAB/Simulink software were conducted on a modified radial 16-bus test system installed with distributed EVS, WT, PV, and FC units to study the effects of hybrid REGs and EVSs on system performance under various weather and loading conditions.

2. Power quality problems associated with renewable energy based generators and electric vehicle stations

REGs have recently been considered efficient sources of power that can provide sustainable and clean energy. Despite the efficiency of these generators, the connection of large hybrid REG systems to utility grids can cause several operational problems for distribution networks. The severity of these problems directly depends on the applied REG technology, penetration level, and geography of the installation. The negative effects of EVCS as a vital part of future transportation systems must also be considered. Hence, studying the possible impacts of large hybrid REGs and EVSs on the performance of a distribution network and its components can provide feasible solutions to meet engineering requirements for voltage, frequency, waveform purity, and others prior to implementation. This section aims to introduce possible technical problems caused by high penetration hybrid REGs and EVCSs to distribution systems.

2.1. Inrush Current

The small inevitable difference between REG voltage and grid voltage can produce transient inrush current that flows between the REG and the distribution system at the time of connection. The current decays to zero at an exponential rate. Inrush current can cause a temporary voltage sag at the neighboring buses, thermal stress of the power components, or nuisance trips of the protection systems. The severity and duration of the produced inrush current depends on the system impedance, magnitude and sign of the flux linkage of the coupling transformer, and nonlinear magnetic saturation characteristic of the coupling transformer [7].

2.2. Safety and Protection

Safety problems in REGs may arise at the time of fault occurrence and unintended islanding in specific parts of utility grids. Under the islanding condition, REGs may sense the loads or part of the system even after the network has been disconnected from the utility grid. The installed REGs can also increase fault levels and problems related to protection coordination and isolation [8].

2.3. Undervoltage / Overvoltage

Some REGs such as PV systems are usually intended to operate near unity power factor to optimize solar energy use. Therefore, these systems only inject active power into the utility side of the grid, which may change the rate of reactive power flow in the system, and the nearby buses may experience under/overvoltage problems because of the lack of reactive power.

2.4. Output Power Fluctuation

Output power fluctuations of REGs can present severe operational problems. Example of power fluctuations in the interconnected WT and PV systems are caused by minute-to-minute variations in wind speed or solar irradiance. The severity of such phenomenon depends on weather conditions, installation, geographical condition and topology of the system. Power fluctuations may increase overloading or underloading, unacceptable voltage fluctuations, and voltage flicker [9].

2.5. Harmonic Distortion

Harmonic distortion which is known as a critical power quality can occur because of the power inverters used in REG systems without the application of proper filters. Harmonic distortion can increase the risk of parallel and series resonances, overheating in capacitor banks and transformers, neutral overcurrent, and false operation of protective devices.

2.6. Frequency Fluctuation

Frequency fluctuation is one of the more important factors influencing power quality. Any imbalance between power production and power consumption can result in frequency fluctuation. Small REG systems cause negligible frequency fluctuations compared with large REG systems. However, at increased penetration levels, REG systems can increase the severity of this problem. Frequency fluctuations can change electromotor winding speed and damage generators [10].

3. Simulation results

A modified IEEE 16-bus test system [11] shown in Fig. 1 is modelled using the MATLAB/Simulink software to investigate the various effects of hybrid REGs and EVCSs on distribution systems. The system is fed through 380 and 230 kV utility grids. It also consists of 9 loads with a total power of 10 MVA, a power factor between 0.65 and 0.8, 3 inter-tie circuit breakers, and 2 capacitor banks to improve the power factor on buses 5 and 6. An 8 MW wind farm, a 1.4 MW FC, and a 2.4 MW grid-connected PV system are placed on buses 4, 7, and 11, respectively, to supply the required power for local loads and exchange the rest with the system. A 2.3 MW EVCS that can simultaneously charge 230 EVs with an average power of 10 kW was also placed on bus 9.

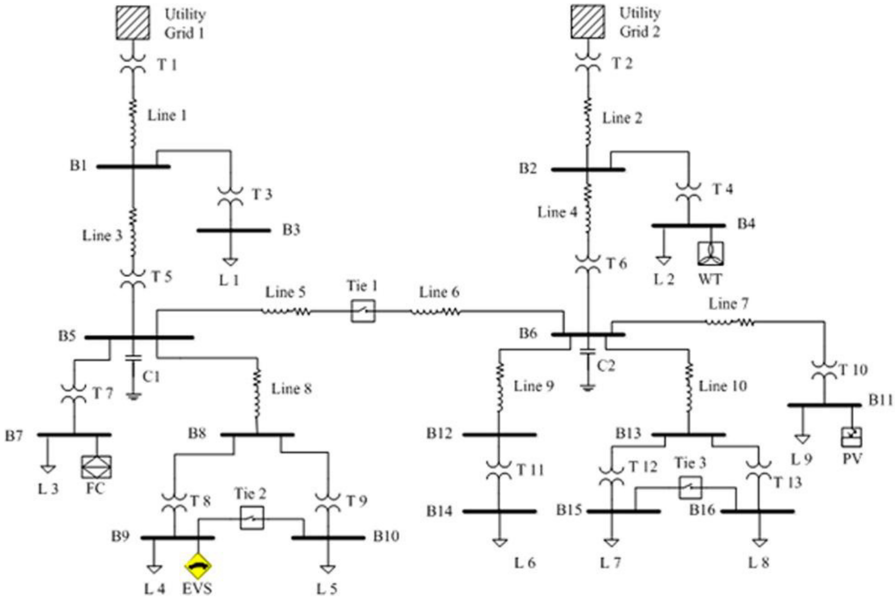

Fig. 1. Single-line diagram of the IEEE 16-bus test system

The commercial specifications of the PV arrays, WT, and FC were collected from SunPower SPR-305 [11], Sanyo HIP-225 [12], General Electric 2.5-100 WT [13], and FuelCell Energy DFC3000 [14]. The required data related to solar irradiance and wind speed under different weather conditions within a year were collected from the Malaysian Meteorological Department [6]. The data were combined to create different patterns for slow and fast weather variations, as shown in Fig. 2.

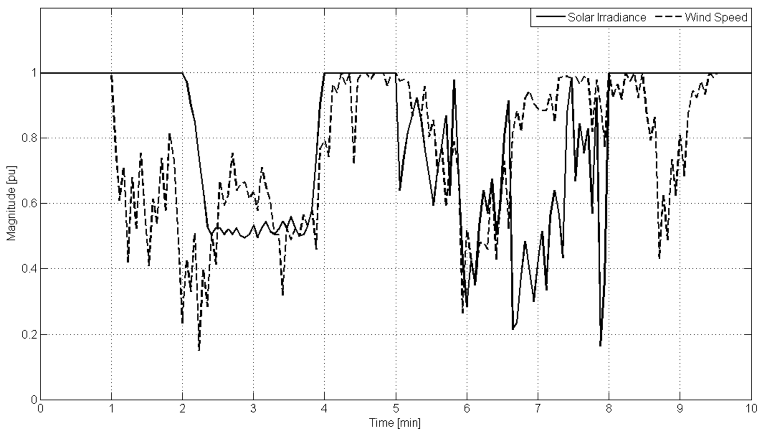

Fig. 2. Solar irradiance and wind speed pattern

The REGs and EVSs in the system are designed to operate at three penetration levels. At the first penetration level, all REGs operate at 33.3% of their nominal power and EVS also operates at 33.3% of its charging capacity. The penetration level escalates to the second and third levels when the REGs operate at 66.6% and 99.9% of their nominal powers, respectively.

The measured frequency on buses 1 and 2 are shown in Fig. 3 to show the effects of REGs and EVS on the system frequency at different penetration levels. Fig. 3 shows the frequency fluctuations on buses 1 and 2. These variations escalate and exceed the frequency limits of ±1% at higher penetration levels because of the active power fluctuations at the PV and WT terminals under different weather conditions. Fluctuations also occur more frequently on bus 2, which is closer to PV and WT buses.

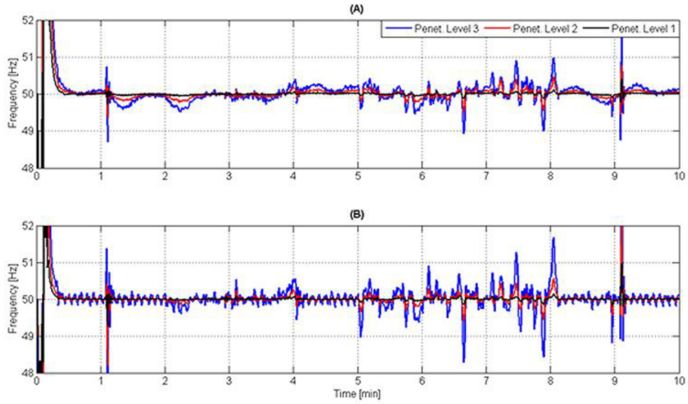

Fig. 3. Measured frequencies, (A) Bus 1, (B) Bus 2

In addition to frequency issues, the sudden active power absorption caused by EVCSs and the unmanaged power produced by FCs can interrupt the active and reactive power equilibrium of the system. Such absorption also causes a voltage drop, as shown in Fig. 4 for buses 6 and 8. The figure indicates that bus 8 experiences a deeper voltage drop because of its proximity to EVCS compared to bus 6. Voltage fluctuations caused by different weather conditions are observed on both buses.

Power exchanges between REGs and EVCSs with the utility system influence the amount of utility-injected active and reactive powers. These power exchanges can negatively influence the pre-designed power factor of the system, as shown in Figs. 5 and 6. The figures indicate that variations in WT power generation and EVCS power consumption cause power factor variations on buses 5 and 6 and that the installed capacitor banks on these buses cannot maintain the power factor at the desired level.

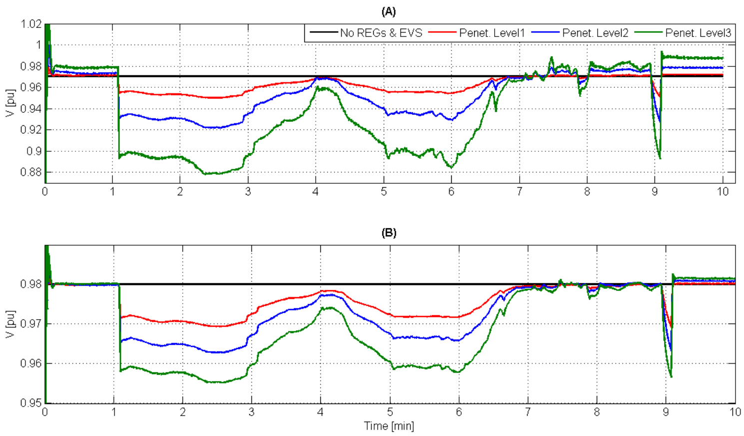

Fig. 4. Voltage profile (a) Bus 8 (b) Bus 6

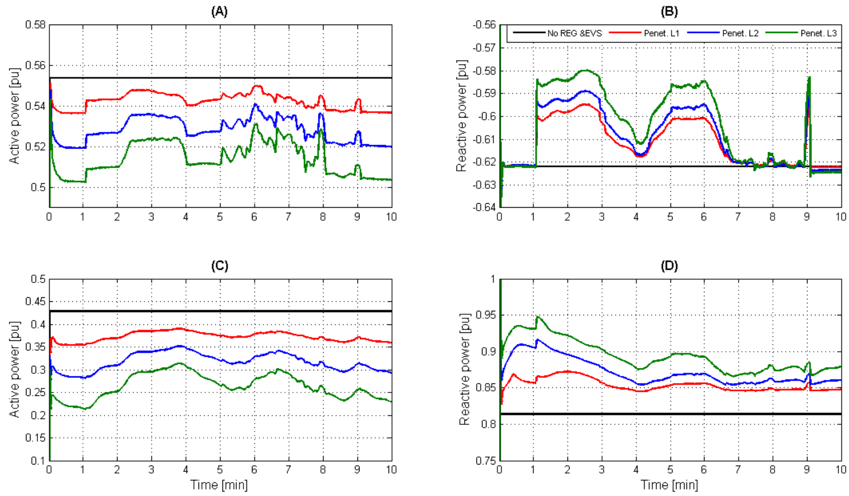

Fig. 5. Injected active and reactive powers, (a) Active power on bus 1; (b) Reactive power on bus 1; (c) Active power on bus 2; (d) Reactive power on bus 2

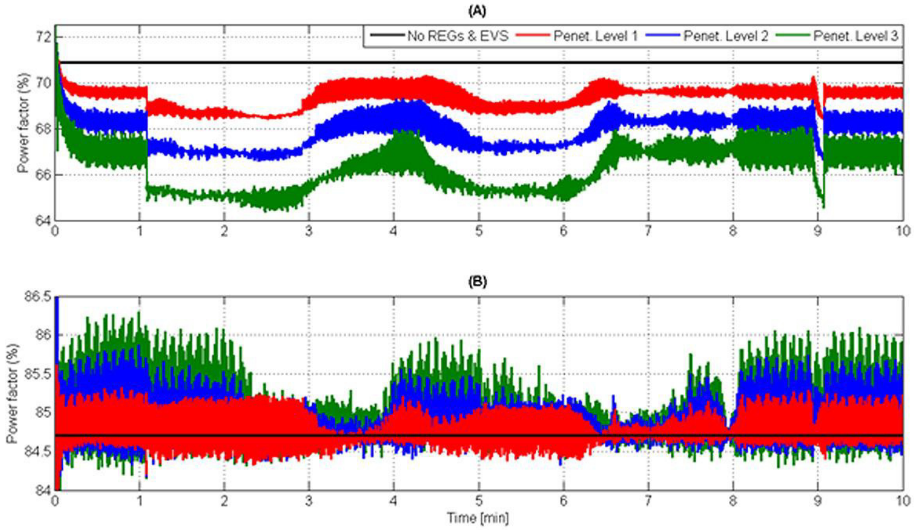

Fig. 6. Measured power factor (a) Bus 5; (b) Bus 6

The voltage and current total harmonic distortion (THD) of the system buses were measured to assess the harmonics generated by the REG and EVCS inverters. The measurements are indicated the worst current THD values 24% at bus 5 in third penetration level which exceed the IEEE Std. 519 limits of 12%; the same current harmonic distortion also occurs at most of the system buses. Meanwhile, the voltage THD values exceed its limits of 5% at most parts of the system in the third penetration level [15] due to the absence of proper harmonic filter in the inverters or at the connection points.

Simulation results indicate that frequency and voltage fluctuations are the most critical effects of PV and WT systems. These fluctuations occur because of solar irradiance and wind speed variations as well as excessive real power produced by the PV unit, which can severely harm system components. EVCSs and FCs can also result in a severe voltage drop at the neighbouring buses because of high power consumption and unmanaged power production, respectively. The power production and consumption of the installed REGs and EVCSs reduce the system power factor, as well as increase the voltage and current THD on most system buses in which these problems are aggravated at a higher penetration level. Therefore, adjustable capacitor banks or active power conditioning devices in close electrical proximity with REG and EVCS units must be used to manage the exchanged powers and the control voltage magnitude of the system. Proper harmonic filters in the inverter terminals of REG and EVCS systems may reduce the voltage, current THD, and resonance probabilities especially in distribution systems with low X/R ratio.

4. Conclusions

This study investigates the possible effects of high-penetration REG and EVCS systems on PQ in distribution systems under varying weather and loading conditions. All information related to modelling of EVCS, WF, PV, and FC systems as well as weather conditions were obtained from different power companies and the Malaysian Meteorological Department, respectively. A radial 16-bus test system with distributed EVCS, WF, PV, and FC units was simulated using MATLAB/Simulink software under various weather conditions. The results indicated that the installed hybrid REG and EVCS systems cause frequency and voltage variations, voltage drop, power factor reduction and harmonic distortion, thus creating severe PQ problems in the system components.

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