Emerging Power Quality Challenges Due to Integration of Solar and Wind Energy Sources

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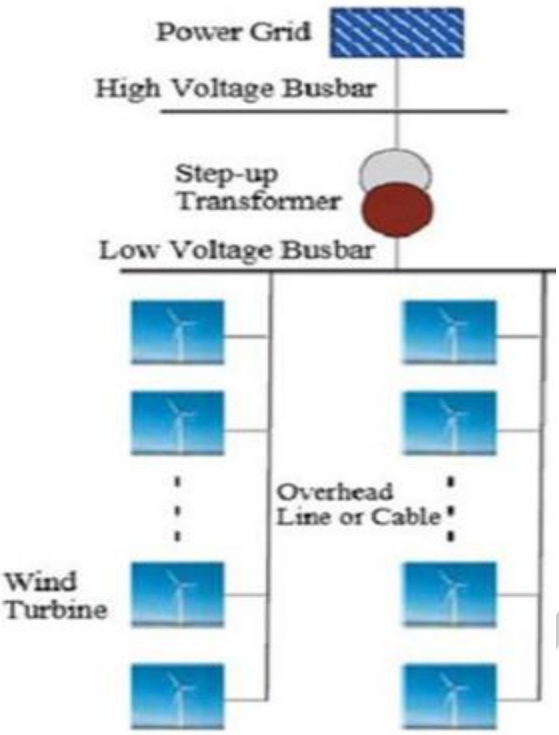
Abstract—**Renewable energy becomes a key contributor to our modern society, but their integration to power grid poses significant technical challenges. Power quality is an important aspect of renewable energy integration. The major power quality concerns are: 1) Voltage and frequency fluctuations, which are caused by non controllable variability of renewable energy resources. The intermittent nature of renewable energy resources due to ever-changing weather conditions leads to voltage and frequency fluctuations at the interconnected power grid. 2) Harmonics, which are introduced by power electronic devices utilized in renewable energy generation. When penetration level of renewable energy is high, the influence of harmonics could be significant. In this paper, an extensive literature view is conducted on emerging power quality challenges due to renewable energy integration. This paper consists of two sections: 1) Power quality problem definition. Wind turbines and solar photovoltaic systems and their power quality issues are summarized. 2) Existing approaches to improve power quality. Various methods are reviewed, and the control-technology based power quality improvement is the major focus of this paper. The future research directions for emerging power quality challenges for renewable energy integration are recommended.**

Index Terms— Electric energy storage, frequency control, harmonics mitigation, power quality, renewable energy integration, voltage control.

I. INTRODUCTION

RENEWABLE energy such as wind turbines and solar photovoltaic (PV) systems use natural resources and provide desirable green energy. The penetration of renewable energy is increasing worldwide. It was reported in 2014 that wind, solar, and biomass power plants provided 60% electricity generation in Denmark; about 30% of electricity demand in Portugal was supplied by non hydropower renewable; Spain had 29% renewable energy generation. The Advancement in renewable energy is exciting but also creates significant technical challenges to power industry [1], [2]. Renewable energy, however, is distributed, independently controlled, and intermittent. Therefore, adapting power grids to operate reliably with renewable energy sources can be very complicated. It was recognized that grid-connected renewable power generation would introduce power quality issues to power grid. From renewable energy side, renewable generation is non dispatchable and intermittent with high fluctuations due to varying nature of renewable energy resources. As penetration level of renewable generation increases over time, such high fluctuations create serious power quality concerns. From power grid side, the grid-side disturbances, such as voltage sags caused by short-circuit faults and frequency variations due to load and generation change would interact with the inter connected renewable energy sources, which create more complicated and uncertain operating conditions. Power quality, among many other factors, appears to be one of the most important aspects that could affect the overall stability and reliability of tomorrow's power grid [3]. Many research results about different power quality challenges and solutions due to renewable energy integration have been reported. As smart grid attracts more attention from academia and industry, there is an urgent need to summarize existing approaches and technologies in order to better guide future research and engineering effort in this important area. This paper aims to offer an extensive literature review on emerging power quality challenges due to integration of renewable energy sources into power grid. This paper focuses on the control-technology-based power quality improvement including the virtual synchronous machine (VSM) method (also known as virtual synchronous generator method) and the virtual impedance-control method. The future research directions are also recommended in this paper, which highlight major areas with significant research potential.



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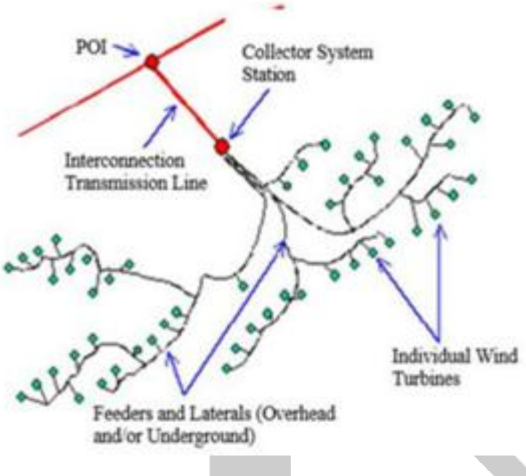

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Fig.1: Wind power plant: (a) general configuration [5]; and (b) more detailed typical topology [6].

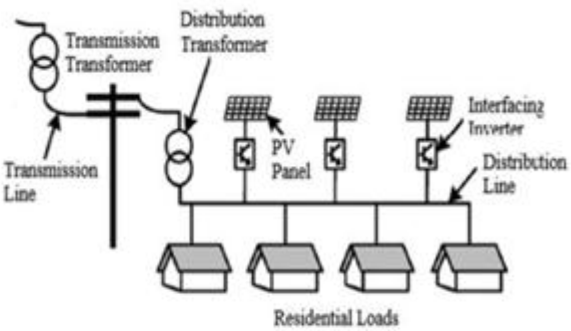
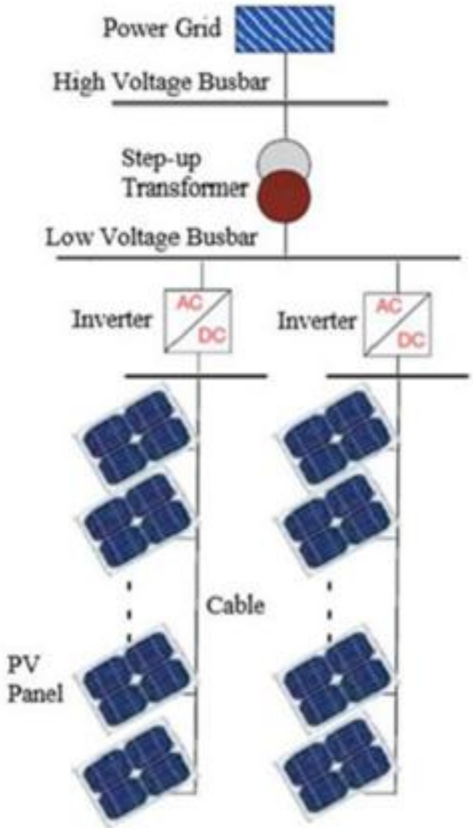


Fig.2: Typical topology for a residential solar PV system.



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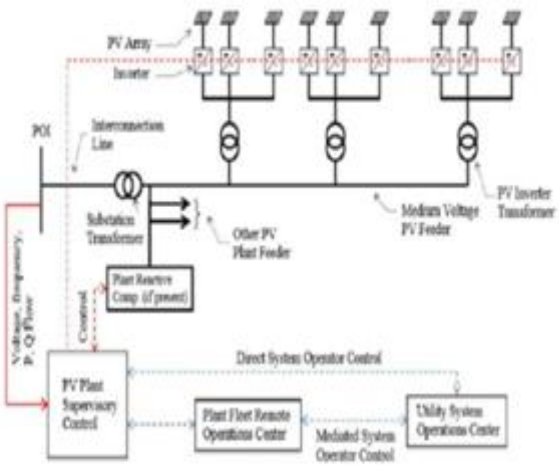

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Fig. 3: Solar PV power plant: (a) general configuration [5]; and (b) typical topology with control systems [7].

II. POWER QUALITY ISSUES DUE TO INTEGRATION OF WIND AND SOLAR PV POWER GENERATION

A. Wind Power

Wind power is produced by wind power plants. In the beginning of wind energy development, the size of a wind power plant was small ranging from under one megawatt to tens megawatts. In the past 40 years, its size has increased significantly [4]. Wind power plants around the world had an estimated installed capacity of 159 GW and produced 273 TWh of electricity in 2009. This number includes both onshore and offshore wind. The integration challenges presented may differ between onshore and offshore wind power, specifically for special transmission technologies for offshore plants. The offshore segment mostly located in Europe. Europe's offshore wind capacity was 4 GW at the end of 2011[5]. The general configuration of a wind power plant is shown in Fig. 1(a) [5]; a more detailed topology of a wind power plant is shown in Fig. 1(b) [6].

B. Solar PV

Power Grid-connected solar PV power can be generated by either solar PV power plants or residential or commercial PV systems. Solar PV power plants are large-generation facilities, and some of them exceeding 100 MW. These large-power plants are connected to transmission systems. However, most PV systems are residential (up to several kilowatts) and commercial scale (up to several megawatts) connected to distribution networks. Solar PV system had 22GW of global capacity and generated 20 TWh of electricity in 2009 [5]. It is stated in [5] that though solar PV generation capacity is much smaller than wind power capacity, it is expected to grow at a faster pace than wind over the next several decades. By 2013, 138.9 GW of PV had been installed globally, and the growth between 2009 and 2013 was significant [8]. The general configuration of a solar PV power plant is shown in Fig.2 (a) [5], and a more detailed topology of a solar PV power plant is shown in Fig. 2(b) [7]. The topology for a residential solar PV system is shown in Fig. 3.

C. Power Quality Issues

Power quality issues for renewable energy integration refer to: 1) voltage and frequency fluctuations, which are caused by non controllable variability of renewable energy resources and also by power grid-side disturbances, and 2) harmonics, which are introduced by power electronic converters used in renewable energy generation. As defined by the IEEE Standard 929-2000, voltage, voltage flicker, frequency, and distortion are four major parameters used to evaluate the power quality in PV systems.

1) Renewable Energy Side: Wind and solar PV power generation both experience intermittency due to a combination of non controllable variability and partial unpredictability features of wind and solar resources. A wind turbine needs wind to generate electricity, and a solar PV system requires sunlight to operate. When wind speeds and available sunlight vary, the output of wind and solar power generation varies accordingly. The non controllable variability could result in voltage and frequency fluctuations on the transmission system. Such power output fluctuation requires additional energy to balance supply and demand of the power grid on an instantaneous basis and requires frequency regulation and voltage support [5].

2) Power Grid Side: Another power quality issue that affects renewable energy integration is due to power grid-side disturbances. The power grid-code requirements for grid-connected renewable power plants have experienced a continuous evolution in different countries to ensure a reliable power system operation. According to several European grid codes, PV power plants must be able to ride through specific disturbances without disconnections. One PV power plant had dual-axis trackers with 1-MW capacity; two fixed array PV power plants had 4-MW and 5-MW capacities. Voltage sags were monitored using a commercial power quality analyzer, and collected at the 20-kV high-voltage side of the POI of the three PV power plants. The field measurements took place from July 2008 to December 2011.Only PV power plants and their ancillary loads are connected to the POI during field measurements. It is found that 59% of the total recorded voltage sags resulted in 0.8–0.9-p.u. residual voltages; another 20% led to0.7–0.8-p.u. residual voltage; while the rest more severe voltage sags were distributed at various small percentages forming the total case. The control system for the PV inverter and energy storage system can be designed to improve voltage level during voltage sags due to power grid-side disturbances, and, thus, improve PV power plants ride through capability. This can be one of promising future research directions for renewable energy integration.

III.VOLTAGE AND FREQUENCY FLUCTUATIONS

In a power system, voltage variation is related to reactive power flow, while frequency variation is determined by the rate of change in real power flow [4]. The smoothing of voltage and frequency fluctuations can, thus, be achieved through the control of reactive power and real power, respectively.

A. Voltage Control

The solar PV systems connected to the utility power grid do not regulate voltage, but inject current into the power grid. The voltage operating range for PV inverters is chosen for power system protection that responds to abnormal utility conditions, not for voltage regulation. When the current injection from PV systems into the power grid has large quantity, they could impact utility voltage: 1) if the PV current injection on a utility line remains less than the load on that line, the utility's voltage regulation devices will continue to operate normally; 2) if the PV current injection exceeds the load, the corrective action is required, because voltage regulation devices do not normally have directional current sensing capability. The appropriate operating interconnection voltage range for solar PV system can be set between 88% and 110% of the nominal voltage. For a wind power plant power system, the IEC Standard 61400-21 recommends that the 10-min average of voltage fluctuations should be within ±5% of its nominal value.

1) Conventional Methods: The reactive power compensation is one effective method for voltage control. Based on advanced power electronic technologies and innovative designs, the flexible alternating current transmission system equipment can be applied to improve the capacity, stability, and flexibility of ac transmission, making it more capable of transmitting large-capacity renewable generation. Thyristor-controlled series compensators can be installed in transmission lines to reduce electrical distance, increase damping, and mitigate system oscillation; a SVC, a STATCOM, or a controllable shunt reactor can be shunt installed on substation buses to solve the reactive power compensation and voltage control problems in renewable energy integration [4], [5].

2) VSM Method: Conventional generation power plants can maintain and regulate voltage and frequency during disturbances because a synchronous generator stores large amount of kinetic energy due to inertia and this kinetic energy can be released or absorbed to compensate imbalance in electrical and mechanical power of the generator. In a power grid, large rotational masses of synchronous generators can provide significant amount of inertia. When a frequency variation occurs in the system, the inertial reserve of the power system counteracts the initial frequency deviation before the primary reserve brings the frequency back to a steady-state value. Power electronic inverters as interface between renewable energy and utility power grid are static without any rotational energy, which leads to negligible inertia. Therefore, extensive usage of these devices can reduce the equivalent rotational inertia of power grid. The fundamental concept of the VSM, real power, and reactive power flow between the renewable energy source and power grid through VSM is shown in Fig.4.

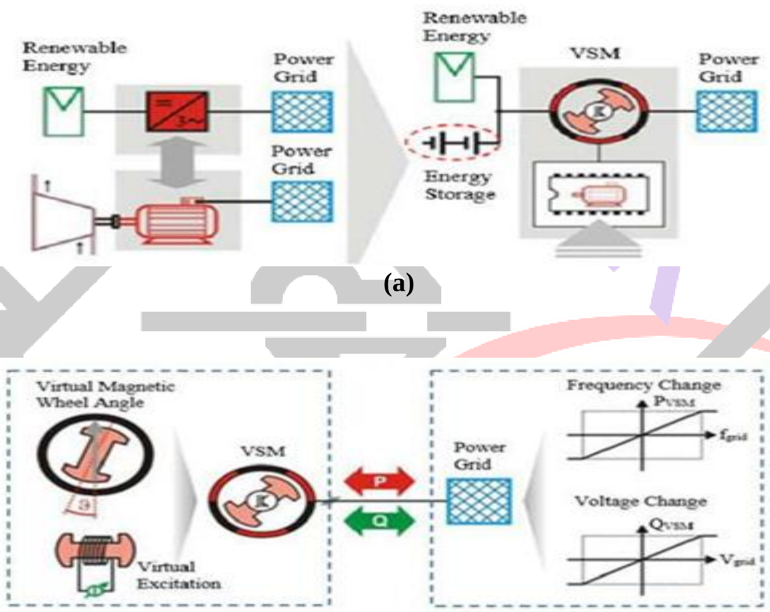

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Fig. 4: VSM method: (a) Fundamental concept. (b) Active power and reactive power flow due to variations on local induced renewable generation side (left) and voltage and frequency variation on the grid side (right).

B. Frequency Control

The VSM method is mostly utilized for frequency control due to its ability to add virtual inertia to control power-electronic device-based systems. Arco and Suul demonstrate the equivalence between VSM-based control and frequency-droop controllers. The demonstrated equivalence links a single theoretical frame into these two well established concepts, which have been developed in separate contexts. Droop-based schemes have become the preferred solution for control of voltage-source converters (VSCs), which can ensure stand-alone operation and load sharing among parallel connected VSC units during steady state and transients, similarly to traditional synchronous machines. The principle of the frequency-droop controller is demonstrated by a block diagram in Fig.5. The active power Pel measured at the grid interface of the power electronic converter is low-pass filtered before it is used as the measurement feedback signals Pm. These filters are necessary to stabilize the control loops. Similar to the VSM method, the instantaneous voltage phase-angle reference resulting from the droop controllers is given by the integral of the frequency reference.

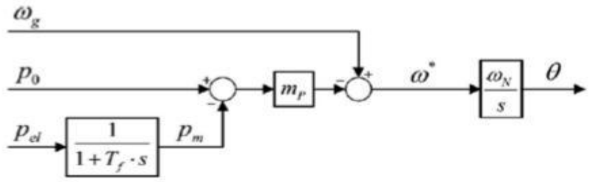


Fig.5. Frequency-droop controller for micro grids

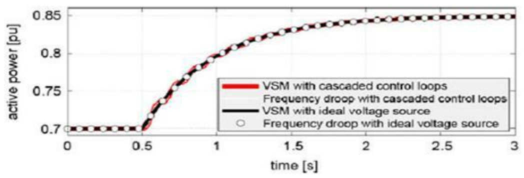
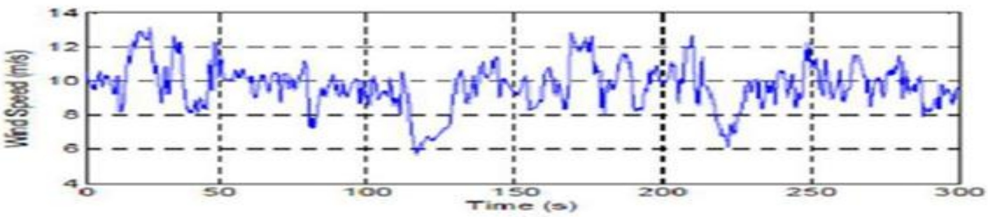


Fig.6. Comparison of various concepts for VSM and droop controllers

The self-tuning algorithms are developed and used to continuously search for optimal parameters during the operation of the VSM control to minimize the amplitude and rate of change of frequency variations and the power flow through the energy storage. Other frequency-control methods without involving the VSM are also developed. For example, an application of superconducting magnetic energy storage (SMES) is utilized in to minimize output frequency fluctuations of a wind farm for an isolated power system. The SMES is a superconducting coil that stores energy in the magnetic field generated by the dc current flowing through it. The SMES system can acquire a rapid response to the fluctuations of the wind power by absorbing and releasing the energy. Due to this feature Plus high efficiency, high power density, and long life time, the SMES system becomes a preferable energy storage solution for wind power generation. The applications of SMES for wind farms include: 1) improve stability; 2) regulate the output power and voltage; and 3) minimize the system frequency fluctuations.

IV. HARMONICS

Due to application of power electronic converters/inverters, harmonics are produced by renewable energy generation. Various harmonics mitigation and compensation methods have been investigated and proposed. Active power filters form a commonly used research stream in harmonic reduction. Another main research stream is to design and implement innovative-control methods for grid interfacing converters to compensate harmonics, which is the main focus in this section. There are three control methods for harmonic compensation: the current-control method (CCM), the voltage control method (VCM), and the hybrid-control method (HCM). The harmonic compensation can be either for local loads or at the PCC. The virtual-impedance based control scheme provides an attractive way to shape dynamic profiles of converters. Over last few years, the virtual impedance method was increasingly employed mainly driven by the fast-growing renewable power generation and energy efficient loads inpowergrid.



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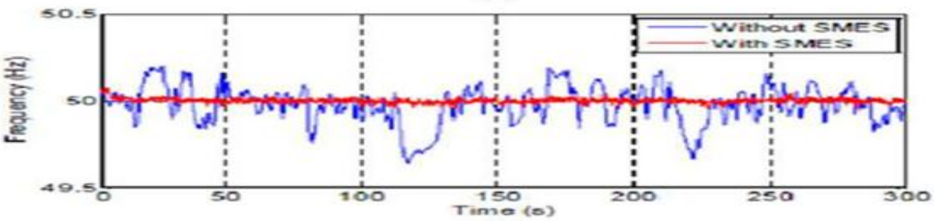

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Fig.7. Response of system frequency with variable wind speed: (a) wind speed and

(b) Frequency response without and with the SMES system

V. ELECTRICAL ENERGY STORAGE

Electrical energy storage can be utilized in power grid for the following purpose: 1) reduce electricity costs by storing electricity obtained at off-peak hours when its price is lower, and using it at peak hours instead of using the electricity bought at higher prices; 2) support customers when power grid failures occur to improve the reliability of the power supply; and 3) maintain and improve power quality. A basic service requirement for power utilities is to supply power to customers with the voltage and frequency within tolerance. On the other hand, the renewable energy output is undependable because of changing weather conditions. The fluctuations in the renewable generation output makes system frequency control difficult and electric energy storage can provide frequency control functions to achieve effective frequency control. Although the voltage is generally controlled by transformer tap changers and reactive power with phase modifiers in power grid, electric energy storage can also help with voltage adjustment. The energy storage located at the end of a heavily loaded line can help us to improve voltage drops by discharging electricity and reduce voltage rises by charging electricity .For a small isolated power network ,such as an island ,electric energy storage enables utility to supply stable power to consumers, where diesel generators and renewable energy sources are usually used together .Electrical energy storage can be combined with advanced control systems to achieve the improved stability, reliability, and power quality for renewable energy integration.

VI. CONCLUSION

In this paper, an extensive literature review is conducted for emerging power quality challenges due to integration of renewable energy sources to power grid. The major quality issues (voltage and frequency fluctuations, harmonics) are reviewed; existing state-of-art technologies related to them are summarized. The electric energy storage and its role in power quality due to renewable energy source integration are also covered in this review. The future research directions are recommended as follows. 1) It appears the VSM method is a very promising future research direction for voltage and frequency control. It can be utilized by itself or combined with other functions, such as reactive power compensation. 2) the virtual impedance method is an important method for harmonic compensation based on the converter control. This method also shows significant future potential to improve the system stability. 3) More efforts should be put in obtaining field measurements on harmonic spectrums for wind and PV power plants, and residential PV systems in order to investigate their harmonic characteristics. 4) The innovative control schemes for inverters should be developed to cope with the grid-side disturbances for improving renewable energy sources ride-through capability.

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