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Present Understanding of the Impact of Distributed Generation on Power Quality

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Abstract—One of the solutions to meet the growing load demand in rural and remote areas is to introduce Distributed Generation (DG) within the existing network. With different types of power generation available at present, it is believed that some designs contribute significantly to a network's Power Quality (PQ). Standards and guidelines pertaining to PQ are one of the criteria that limits the level of DG penetration in a network. This paper provides an overview of some of the known PQ issues related to the introduction of different types of DG systems into a power network. The analysis is based on common types of DG system designs and associated technologies. Based on the available literature, common PQ problems arising from DG systems impacting on power network as well as common existing network based PQ issues impacting on DG systems have been identified. As a result of these common PQ problems, some types of networks can be identified as requiring immediate attention.

Index Terms—Distributed Generation, Power Quality, Distribution Network, Sustainable Energy Systems

I. INTRODUCTION

With the growth of power demand, finding alternative arrangements to support this increase is vital. One possible solution, especially in rural and remote areas, is the introduction of Distributed Generation (DG) within the network. Although DG is not a new concept, the application of DG is continuously changing. Initially, DG systems were mostly utilised for shaving peak power or providing power where electrical networks could not reach. At present, DG systems (in addition to initial applications) are used for voltage support, providing load relief for transmission lines, supporting consumers under conditions of mains failure and toward the improvement of networks PQ issues. DG also provide means of utilising renewable energy resources. However, DG systems tend to have some disadvantages in regards to Power Quality (PQ), especially when utilising renewable energy such as wind, hydro and solar power to support rural networks.

It is understood that in some cases the distribution network shows significant levels of PQ problems, such as voltage sags and/or voltage distortion regardless of where DG systems are connected in the network or not. The causes of network based PQ problems arise from both utility and customer equipment [1]. Some examples are capacitor switching and power electronic (PE) equipment based speed control of large motors drives. PQ problems within the network may exist

even before implementing DG and thus need to be included as 'background' disturbances.

This paper discusses common types of DG systems used by utilities and their interaction with the electrical network from the PQ perspective. The DG types discussed in this paper are based on wind, small-hydro, solar and diesel generation. This paper also discusses critical PQ problems that require immediate attention in typical networks with embedded DG systems.

II. PQ PROBLEMS IN DISTRIBUTION NETWORKS

In modern distribution networks PQ problems are common, though individual PQ problems within networks may differ. Some networks may experience significant voltage sags (eg rural networks) while others may experience voltage harmonic distortion (eg city networks). Therefore, it is possible to assume that even before the DG is installed, we have so-called "background" PQ problems. With this understanding, identifying a combination of PQ problems in distribution systems is crucial prior to the planning and implementation of DG systems.

From the perspective of background PQ problems, distribution networks can be categorised into three types: networks that do not exhibit significant levels PQ problems to be considered as PQ prone network (Type 1), networks that lie on the border where PQ problems have almost reached suggested standard/guideline limits (Type 2) and networks experiencing PQ problems that lie beyond suggested limits most of the time and require an immediate solution (Type 3).

Since, most MV and LV networks are predominantly radial in design with customer types of rural, commercial and industrial, then voltage sags, voltage harmonic distortion and voltage unbalance seems to dominate these networks [2]. The reasons for this are attributed to long feeders supplying rural customers, large office buildings with distortive equipment and long feeders with uneven load distribution.

Introducing DG systems into distribution networks may signify some of these problems based on the network's PQ condition [2]. The impact of DG on distribution networks is discussed in the following sections.

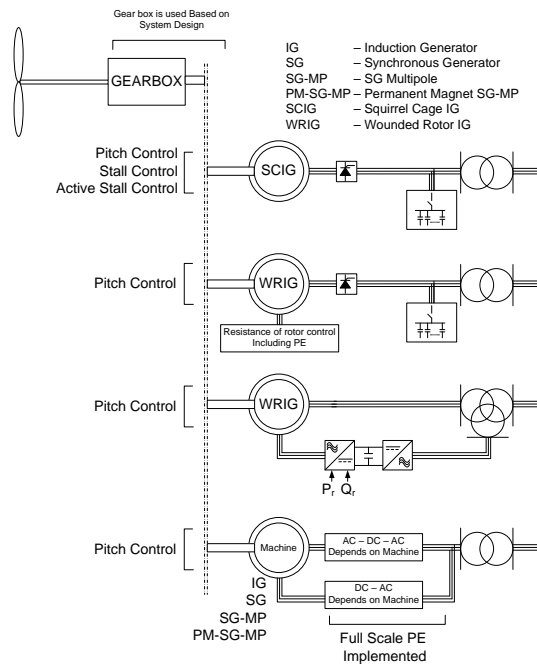


Fig. 1. Present day wind energy system designs

III. DG IMPACTS ON DISTRIBUTION NETWORK

The technologies associated with DG are becoming more sophisticated [3], hence widening applications DG systems. The discussion in this section is based on four types of DG systems: (1) wind turbines, (2) small-hydro turbines, (3) photovoltaic power generation and (4) diesel generation. From a grid connection perspective, there exists two major types, machine connection (synchronous and induction types) and power electronic front-end.

A. Wind Energy Systems

The prime-mover or the drive system of wind turbines is mainly categorised into two parts: 1) variable speed drives and 2) fixed speed drive systems. The most common types of machines presently associated with variable-speed systems incorporate synchronous generators. An emerging design in the market is based on permanent magnet synchronous generators [4]. The induction generators seem to be common for both fixed and variable speed systems. The types of induction generators used in wind turbines employ squirrel cage rotor machines, wound rotor machines (with controllable rotor resistance to change the slip) and doubly-fed induction generators. From the design perspective some generators are directly connected to the grid (through dedicated transformers) while others incorporate power electronics (based on the design the rating of power electronic systems vary). Many designs, however, include some level of power electronics to improve controllability. A simplified diagram representing some common types of wind energy systems are shown in Fig. 1.

The impact of increasing distributed wind generation could reduce the number of sags [5], [6]. This reduction depends strongly on where the generator is connected, loading conditions and the cause of sag. Nonetheless, wind turbines can themselves be the cause of the voltage sags within the network. A wind turbine start-up procedure (depending on the type of starter), which lasts a period of approximately 0.2–3 seconds [7] where the inrush current can be extremely high. Hence, a voltage sag is experienced at other feeders in the system. A comparison test between induction and synchronous machine types for wind applications [8] suggests that based on a voltage sag perspective, a constant voltage synchronous machine is desirable. Testing criteria includes keeping the machine dynamics as generic as possible and having different loading conditions (all combinations of maximum and minimum for loading and generation). However, the intensity of the sag and the network configuration would determine the customers affected in a given region of the network.

Regardless of the control (pitch or stall) and mechanical setup (with or without gear box) implemented, the mechanical speed fluctuates during wind turbulence and tower reflection, hence flicker is a problem in wind turbine systems [7]. A wind speed variation of approximately $\pm 1 \text{ ms}^{-1}$ causes approximately $\pm 20\%$ fluctuation of the mean value of power for pitch controlled wind turbines [7]. This is significantly large compared to stall-regulated wind turbines. The short term flicker compared with fixed speed and variable speed are 0.136 and 0.051, respectively [7] [9] [10]. A note on the fixed speed type wind turbines is that approximately 30% of the total flicker is due to the tower turbulence, effect of 3p frequency at 2.15Hz [7]. The fundamental difference (in terms of flicker analysis) between the variable and fixed speed turbines, which is that the flicker level increases as the wind speed increases with fixed speed turbines while with variable speed turbines the flicker level decreased [7].

Wind energy systems may contribute to the distribution network voltage distortion because of its rotating machine characteristics [11] and the design of its power electronic interface [12]. If the machine is subjected to non-sinusoidal distribution of stator and rotor windings, this could lead to harmonics in the air-gap and as a result stator and rotor will contribute to current harmonics. Other harmonic sources that may arise are the slot harmonics, which are due to the main field passing over the stator slot increasing the rotor and stator voltages in steps [11]. This is an inherent characteristic of the machine, hence harmonics are unavoidable [11]. As presented in Fig. 1, wind energy system designs incorporate a wide range of power electronic interfaces with different ratings. These power electronic interfaces are rated as a percentage of the machine power, hence larger systems are accountable for higher distortions. A recent investigation [13] based on a wind energy system suggests that frequency converters (with a typical pulse width modulated, switching frequency of 2.5kHz) can in fact cause harmonics in the line current, leading to harmonic voltages in the network. The study incorporates various appropriate harmonic load models, representation of

harmonic network elements and harmonic sources with the application and guidance of the IEC 61000-3-6 [14] and IEC 61400-21 [15].

B. Photovoltaic Systems

The analysis of major PQ problems from photovoltaic systems are based on aggregated systems perspective (subsystems include PV modules, smoothing block, inverter block, filter block), collected in a residential block.

Voltage fluctuations due to PV systems are not problematic in most networks, because probably the network is stronger or “stiffer” to power changes in PV systems. In considerably weaker grids, in some cases during islanding operation and when vast amounts of PV systems are connected sparsely, voltage fluctuation has been recorded as problematic [16]. One of the solutions to mitigate the voltage fluctuation produced by PV systems (in these scenarios) requires “bridging power” from stored energy systems. With many different types of storage solutions available, super-capacitors and inductors (SMES-Superconducting Magnetic Energy Storage) to support this period can be considered as an emerging technology. As batteries may be insufficient to withstand a high number of charge cycles. Voltage fluctuations have been reported in [16] to last from minutes to 1 hour. Factors characterizing voltage fluctuation based on measurement data as suggested in [16] are:

- Magnitude of voltage
- Duration of transition between “cloudy” and “clear” sky
- Speed of transition (based on the ratio of magnitude and duration).

For densely populated PV systems in the network, the use of a fluctuation index and a fluctuation energy index serves the assessment of persistence and severity due the impact of PV systems on voltage fluctuation in the network. The most significant fluctuations occur under overcast sky conditions persisting for 5–12 minutes, but depending on the overcast records show that it could last from several seconds to 1 hour [16]. At present mitigation techniques could support fluctuations of a magnitude of 6.4% to 9.9% of the rated voltage, but this comes with a considerable cost. Overall, voltage fluctuations depend on the density of the PV system and its characteristics.

The project [17] undertaken in Holland, to analyse network voltage distortion caused by photovoltaic systems, was based on 60MW maximum demand with a feedback of 36MW from photovoltaic generators. The photovoltaic systems were self-commutated, single phase, voltage source converters with ratings between 1–3kW, and a combination of designs including transformer and transformerless types. Inverters were based on a PWM switching scheme with a practical switching frequency range of 20–500kHz [17] with different power levels. Two of the significant problems associated with high penetration of PV systems was the undesirable switching-off of PV units or increased harmonic current emission in individual PV modules. Some related causes could be the existing distortion in the network, voltage decrease at the PCC or manufacturing

fault. The dominant harmonic in the network voltage spectrum was found to be at a frequency of 1062Hz (approximately) around the 21st harmonic. The result from [17] also agrees with a subsequent study presented for a typical Australian LV distribution network where acceptable penetration levels of PV systems is limited by frequencies around the 21st harmonic [18].

C. Small Hydro Systems

Small hydroelectric power generation systems can be considered as being similar to small wind energy systems from the generator types used in the production of power. The differences in these two systems lie in the design of the overall system and the condition of the input power. Since the input power of hydro systems is more stagnant and controllable compared to wind energy systems the output power quality is considerably better. Hence the PQ problems arising from small hydro are far less than wind energy systems.

The results of a small hydro system with an induction machine presented in [19], revealed an improvement on the distribution network distortion when the hydro systems were connected. The distortion rose by 50% after all five hydro systems were disconnected. Though the author did not mention the guidelines followed by their industry, total voltage harmonic distortions limits of the network were within the IEC [14] and IEEE guidelines [20],[21]. The machines in this study are believed to be acting as harmonic sink.

D. Small Diesel Systems

When diesel systems are used as distributed generators running in parallel with the power network, PQ issues are believed to be insignificant to cause any problems. In order to understand the PQ issues due to interaction of diesel systems with other network elements, a “hybrid network” condition is considered. A typical diesel-hybrid network can be a combination of wind-diesel, photovoltaic-diesel and hydro-diesel, supplying power to rural or remote areas.

As an example, consider a small network [22] consisting of wind (induction generator) and diesel generations units supplying a collection of miscellaneous load types. In this case the purpose of the diesel unit is not only to supply power, but to also be responsible for maintaining the network frequency and voltage within appropriate levels. If the responsibilities of the diesel generator are disrupted due to unpredictable wind and load conditions, then frequency and voltage based problems may occur within the network.

In a small hybrid network of wind-diesel generation, the voltage sags due to wind turbine startup can be approximately 13% at the diesel generator terminal (lasting approximately 0.5 sec) with a frequency dip of 5% [22] before recovering to nominal values. Experimental investigations reveal that a frequency excursion can in fact last up to 1 minute, with a wind speed of 21 m/s of a 800kW hybrid wind diesel system [23]. One of the problems associated with small diesel generator sets established with wind energy systems is the slow response of the governors. As a result, a stable frequency may not be

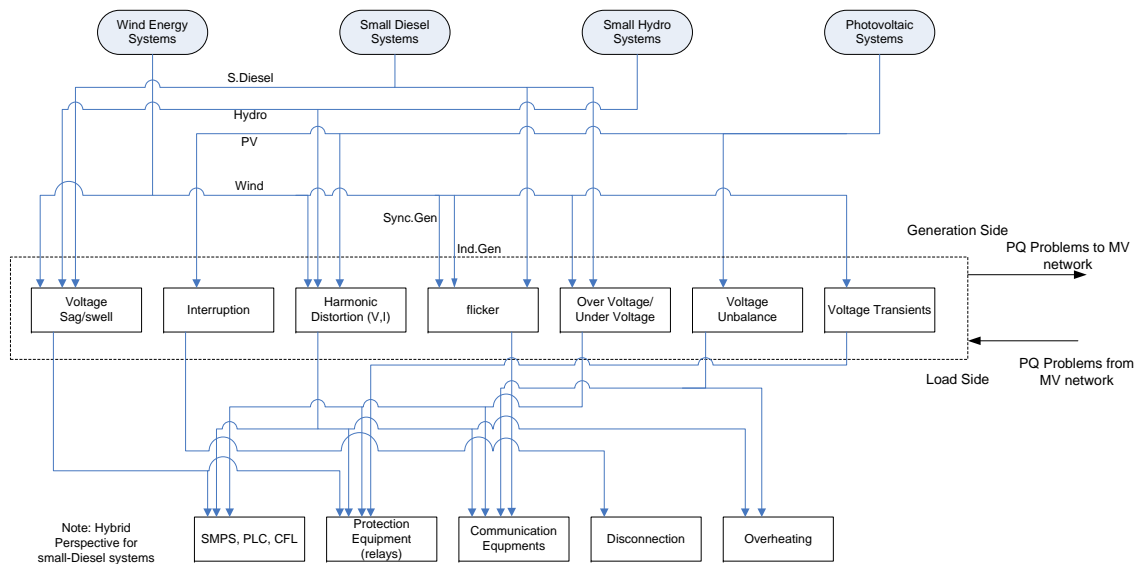


Fig. 2. PQ problems originating from DG systems

maintained and voltage regulation of the network may degrade. Hence, one solution may be in the area of governor control and voltage regulation.

In summary, PQ issues originating from DG systems impacting on the distribution network is shown in Figure 2.

IV. DISTRIBUTION NETWORK IMPACTS ON DG

There are many network-to-network PQ problems, including voltage sags/swells, voltage harmonic distortion and voltage unbalance [2].

A. Network Distortion

As mentioned before, harmonic voltage distortion is not severe in most networks, however, many researchers predict otherwise because of load growth [2]. The most sensitive DG system of those previously discussed in this paper are PV systems. Fig. 3 shows the fifth harmonic current distortion profile for a 30kW PV inverter system [24]. Power electronic devices may be the cause of network distortion, while they themselves are vulnerable to multiple frequencies in the network voltage.

B. Voltage Unbalance in the Network

Some common causes of networks voltage unbalance in distribution network are:

- 1) Uneven distribution of single phase loads or with random usage of single phase loads in an evenly distributed network.
- 2) An unsymmetrical system from either network loads or faults.
- 3) Open delta or star connected transformers.

One of the systems with a wide range of applications in DG networks is the back-to-back inverter consisting of a synchronous front-end. A significant characteristic of this inverter system is its ability to control bidirectional power

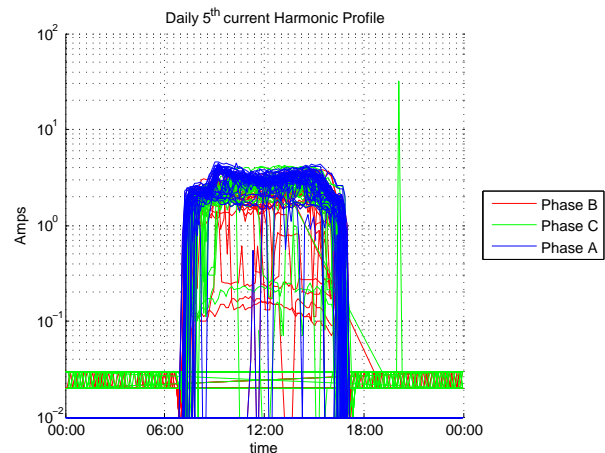


Fig. 3. Fifth harmonic current distortion profile of a 30kW PV inverter system

flow. If the equipment is exposed to grid unbalance, the dc-link sees multiples of even harmonics. These harmonics are of concern as they are low order and of significant magnitude, increasing the ripple in the dc-link and hence influencing the level of capacitance required. The main consequence of voltage unbalance was found to be the high dc component in the output of this back-to-back inverter system, as small dc components will significantly affect transformers and motors. An unbalance of 5% can subject the inverter to produce dc, second and third harmonics at the output [25].

Voltage unbalance can lead to abnormal operation of rotating machines, especially in DG networks. In order to minimise the impact of unbalance, provide protection and to gain better control over the rotating machine, recent designs employ PE. As is similar to the previous case with inverters, an

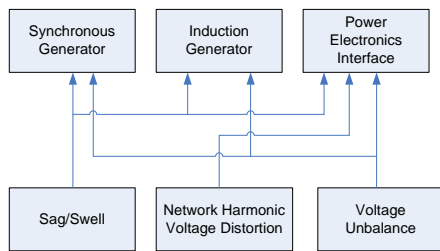


Fig. 4. Represents network originated PQ problems impacting on different DG interfaces

unbalance of 5% in the network can subject rotating machines to initiate thermal overload, torque pulsation (twice the grid frequency), shaft vibration and hence causing physical damage to generator [26], [27].

C. Voltage Sags

Voltage sags mostly occur in the network due to faults, utility based actions and sudden starts of large loads. During this period voltage decreases between 0.1 and 0.9 pu for a period of 1 minute. With many classifications of voltage sags in a distribution network [28], the impact on DG systems are of concern.

Nodal voltage recovery was observed when several machines serving in wind applications (including some types of induction and synchronous generators) were exposed to voltage sags originating from system faults [8]. Among the investigated machines in [8], the constant voltage synchronous generator was found to be the most appropriate type of machine to recover the voltage after a sag incident. If the voltage sag was due to a monotonically increasing load the chance of voltage collapse is high.

The study presented in [29] discusses the sensitivity of commercially available PV inverters to voltage sags. Nine different inverters (from different manufacturers) of a nominal power rating between 0.5–4.5kW were exposed to sags at the terminal. These inverters were tested based on IEC 61000-4-11 [30]. The outcome of the study revealed that only one inverter was not very sensitive to voltage sags and phase changes (for a 5 degree change). With a pre-sag power feed-in level, the MPPT (maximum power point tracking) showed sensitivity to voltage sags. It is important to note since these are single phase inverters, such tripping is likely to create high level of voltage unbalance in the system.

In summary, the impact of network originated PQ problems impacting on DG systems are given in Figure 4

V. DISCUSSION

The Interaction between DG systems and the distribution network types discussed in this paper, can lead to PQ issues requiring immediate attention. A Type 1 network (background PQ issues well below suggested levels) can be considered as being most able to support a greater level of DG. Type 2 (background PQ issues at the boundary of suggested levels)

TABLE I
POSSIBILITY OF CONNECTING DG TO SOME DISCUSSED NETWORK TYPES

Network	Wind Sys	S.Hydro Sys	Photovoltaic Sys
Type 1	Possible	Possible	Possible
Type 2	Possible (special measures)	Possible (special measures)	Possible (special measures)
Type 3	Significant Mitigation (Possible)	Significant Mitigation (Possible)	Significant Mitigation (Possible)

networks can support some wind and small hydro systems with minor voltage distortion and unbalance. Type 2 networks supporting these types of DG systems, however, can be considered as presenting a risk of flicker and voltage sags. A Type 2 network with background distortion could quickly lead to a violation of network distortion limits if PV systems were to be connected. Type 3 (background PQ issues above suggested levels) networks are not suited for accommodating any of the DG systems discussed unless special measures are taken to improve PQ. The analysis is summarised in Table I.

Any difficulties in connecting DG to power networks that have existing PQ issues will largely depend on the type of PQ issues arising from the introduction of DG and the severity of background disturbances. Since DG systems themselves produce PQ problems, in a case where network and DG related PQ issues are additive the overall state of PQ may reach limits suggested by standards and guidelines. In a distribution network with background voltage sags, attention to these could be considered necessary if the introduction of DG systems were to exacerbate the problem.

VI. CONCLUSION

Common grid connected DG systems used at present are represented by wind energy, photovoltaic power and diesel power. Common PQ problems that arise due to the interaction of DG systems with the network have been presented in this paper.

Some power quality problems arising from different DG systems could be regarded as “common”. In some cases network based power quality problems can have a significant impact on the DG systems discussed. PQ problems associated with DG systems as well as background network issues could coincide to produce a significant PQ issue that may violate any local standards or guidelines. If this is the case, such PQ problems can be considered as requiring immediate attention. To meet the growing demand for DG systems, additional methods and technologies are needed to mitigate common power quality problems.

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