THE IMPACT OF LARGE-SCALE PV ON DISTRIBUTION GRID OPERATION AND PROTECTION; AND APPROPRIATE TESTING

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ABSTRACT

The paper focuses on the impact grid-connected, large-scale photovoltaic (PV) has on the power system operation (stability, availability, reliability) and protection philosophy. It assesses qualification methods and standards of particularly the utility-interactive equipment (grid inverters), which directly influences the security of supply and power quality of the grid. Advanced emulation of grid conditions, including hardware in the loop testing scenarios, are proposed for the testing and validation of such grid equipment under realistic conditions (including worst-case). This to ensure suitability of the equipment for grid application and stable and safe grid operation.

INTRODUCTION

The contribution of distributed generation (DG) into the electrical generation energy mix is increasing rapidly and will continue to do so in the foreseeable future, as shown in Figure 1.

Renewable energy sources (RES) and distributed energy resources (DER) are diverse, ranging from geothermal, solar (thermal and photovoltaics (PV)), wind, biomass, hydro-electric, but also including combined heat and power (CHP) systems, heat pumps and fuels cells. Wind and thereafter solar being the technologies already mature enough for large-scale integration into electrical power grids in the short term.

Power electronic interfaced DG

Grid connection of renewable and distributed energy resources is performed for the largest part by static converters, or grid inverters [2]. This is either because the primary energy source is otherwise incompatible with the grid (i.e. DC or deviating AC frequency), or because of the added benefits provided in terms of control and functionality.

Nevertheless, it is clear that the amount of subsequent power electronic grid interfaces will therefore increase significantly as the penetration levels of DG into electricity grids increase.

This has a profound impact on the characteristics of the distribution grid, its operation and required protection.

Apart from the inherent challenges of DG, such as:

• the intermittent character of renewable sources,
• feeder control (voltage control and reverse power flow), and
• impact on assets (loss of life due to increased regulator and capacitor bank switching),

which should all be addressed by interconnection studies, the electrical system will face electrical challenges in terms of:

• frequency stability,
• frequency control;
• power quality, and
• transient stability,

due to a.o. the lack of inertia from power electronic interfaced DG, challenging generation predictions (cloud coverage across part of a PV array, for example) and high power ramp rates.

Power ramp rate concerns

The high rate of change of solar irradiation is already raising concerns inter alia in Germany, where PV systems are both rising in number and in size [3]. Should a cloud move over a large PV power plant (> 50 MW), the ramp rate of power change could affect the primary control loop of the grid itself.

As the size of PV plants increase, the amount of primary control reserves required increase. At the same time the total installed PV competes with conventional power generation. This in turn reduces the amount of primary control reserves, as PV does not provide it. Potentially this can lead to variations in the voltage and, the frequency. In
the worst case the stability of the grid is affected.

However, DG helps to reduce the primary control problems in two ways:

1. By distributing the PV over a larger area, the ramp rate of power decreases. The effect of the cloud moving over the array is diluted by the fact that the PV generators are distributed over a larger area. Therefore, the moment at which each generator's output ramps down is different.

2. Monitoring the distributed PV generators provides information that allows more accurate prediction for the ramping down of the other PV generators. The primary control loop can anticipate on this ramp, if the grid control and reserve power components are designed for this function.

**Protection concerns**

Furthermore, the reduction of short-circuit current contribution from power electronic interfaced DG will require a revision of the grid protection philosophies, which are today primarily based on the detection and isolation of over-current situations.

**Wind vs. PV**

Similar issues have already arisen with the large scale integration of wind into distribution and transmission grids. The PV industry can therefore learn a lot from the experience gained already in the slightly more advanced wind industry. However, with wind not all DG is interfaced with power electronic converters, as some types of wind generators (i.e., doubly-fed induction generators (DFIG)) are only partially interfaced using power electronics (Figure 2).

![Figure 2 Doubly-fed induction generator partially interfaced to the grid by means of power electronics](image)

In the case of PV this is different. PV DG is inherently a DC-source and therefore interfaced by fully rated power electronic inverters to the grid (Figure 3).

![Figure 3 PV plant fully interfaced to the grid by means of power electronics](image)

From a grid perspective both the location of the DG from its substation and the DG penetration level play critical roles in the associated grid performance.

Recent PV integration studies have shown that PV output curves tend to match up better with commercial circuit load profiles than with residential circuits (Figure 4). This is advantageous as the chance of reverse power flow is thereby reduced without having to curtail unnecessary power. This also favours large scale PV integration above scattered residential integration.

![Figure 4 Residential circuit load profile with and without PV](image)

**TESTING OF INVERTER INTERFACED SYSTEMS**

Ensuring grid stability and power quality in a high power electronic interfaced grid in essence boils down to adequate and appropriate testing of the grid inverters individually and thereafter as part of the intended integrated power system. The behaviour of these components and their synergy needs to be verified for all foreseeable operational circumstances, therefore also under fault and short circuit conditions (worst-case).

Grid-inverters are currently tested along a large variety of guidelines that exist per region [5] - [10], with the German and Danish codes being the most stringent. It provides details for issues such as:

- allowable voltage drop,
- short-circuit currents,
interface protection,
galvanic separation and means of grid disconnection,
DC-injection,
active power control
voltage regulation
voltage flicker,
harmonics; and
other power quality requirements.

The lack of international standardisation currently leads to a challenge for both the manufacturers, which need to comply with all different guidelines, as well as the testing bodies that need to perform these tests and certify the grid-inverters.

Moreover, the prevailing standards and codes do not require small size grid inverters (<500 W) to be tested, implying that their effect on the grid is deemed negligible. However, in larger quantities their combined contribution might be significant and their effect should not be ignored.

From the perspective of asset management, the influence of the effects of large scale integration of intermittent renewables on both the new and existing grid equipment is of great concern. Similarly, for obtaining an in-depth understanding of these effects and their impact on the grid equipment, realistic performance evaluation and model validation is required. This is especially difficult to obtain under severe grid conditions and particularly risky during field trials.

ADVANCED EMULATION AND HARDWARE-IN-THE-LOOP TECHNIQUES

It is clear that the testing and validation of individual components will no longer be sufficient on its own. For the purpose of de-risking equipment in complex grids under dynamic situations, the testing should include the entire system.

Adequate testing therefore requires advanced emulation of realistic system conditions, thus including a.o. grid impedances (representative of the distance of a PV plant from its substation), feeder characteristics (impedance to resistance ratio of cables), power profiles (day patterns and cloud cover effects) and adequate bandwidth to validate all control interaction.

For large scale plants this implies that testing facilities are required to provide both the required control bandwidth and high power provisions to validate the static and dynamic response of at least one central grid inverter in combination with the grid.

To accomplish this combining simulation with hardware experimentation will be inevitable to allow the validation of the system at the required complexity including the highly dynamic and transient power system behaviour under real-time constraints.

The approach of combining simulation with hardware experimentation is known as hardware-in-the-loop (HIL), and distinguishes control HIL – the testing of protection relays, power converter controllers and power quality regulators – and power HIL – the testing of actual power devices such as PV-inverters.

Power-hardware-in-the-loop testing allows equipment to be validated in a virtual power system under a wide range of realistic conditions, repeatedly, safely and economically. It combines the power of real-time simulation with the actual response of real power and control hardware components.

In response to particularly these developments, KEMA is operating the Flex Power Grid Laboratory (FPGLab, Figure 5). The FPGLab [11], [12] offers unique services for validating grid inverters and its control system by offering a predefined and programmable grid in the medium-voltage range under complex, realistic conditions in terms of voltage level (400V-24kV), power level (1MVA), fundamental frequency range (DC-75Hz) and harmonic frequency range (2400Hz bandwidth).

Figure 5 Impression of the Flex Power Grid Lab

Advanced emulation allows severe stress testing of both the control system and the power hardware and contributes to the process of de-risking technologies for application in distribution grids. During prolonged stress testing one can identify the reliability and stability of the system, even under adverse conditions. This provides the valuable information required for the operation and protection of (distribution) grids with a high penetration of power electronic converter interfaced DG, such as large scale PV.

FINAL REMARKS

There is significant attention from the main driving forces
identified herein to ensure that renewable energy will constitute a larger share in the global energy mix in the near future. Grid inverters are to a large extent the key enabling technology to make this possible. The high penetration of grid inverters will however have a significant impact on the electrical grid’s stability, availability, reliability, and control and protection philosophy. The high security and quality of supply of energy via future electrical grids can only be guaranteed if harmonised standards exist for grid inverters, in combination with capable means for testing and certification thereof. Adequate testing is deemed to include at least feeder characteristics, power profile dependencies and adequate bandwidth to validate all control interaction.

It is the author’s opinion that advanced emulation of grids using a combination of control and power hardware in the loop techniques will become the industry standard for the validation and testing of (large-scale) integrated DG systems into distribution grids.

REFERENCES


[10] Danish Technical Regulations TF 3.2.6 - Wind turbines connected to grids with voltages below 100 kV, 19 May 2004
