PERFORMANCE EVALUATION OF EQUIPMENT UNDER SEVERE GRID CONDITIONS

Erik C.W. DE JONG
KEMA – the Netherlands
Erik.deJong@kema.com

Peter T.M. VAESSEN
KEMA – the Netherlands
Peter.Vaessen@kema.com

Jan BOZELIE
Alliander – the Netherlands
Jan.Bozelie@Alliander.com

ABSTRACT

The introduction of widespread, grid-connected distributed energy resources into distribution grids, including their localised control changes the way in which distribution grids are comprised and ultimately will be managed. To allow for continued, or even improved, reliability of such grids the manner in which the associated equipment's performance is evaluated, tested and validated also needs to change likewise. The performance evaluation of distribution grid equipment under severe grid conditions is presented on three equipment types with mutual interaction and a vision for the future of testing presented.

INTRODUCTION

The contribution of renewable energy sources (RES) and distributed energy resources (DER) into the electrical generation energy mix is increasing rapidly and will continue to do so in the foreseeable future, as can be seen in Figure 1.

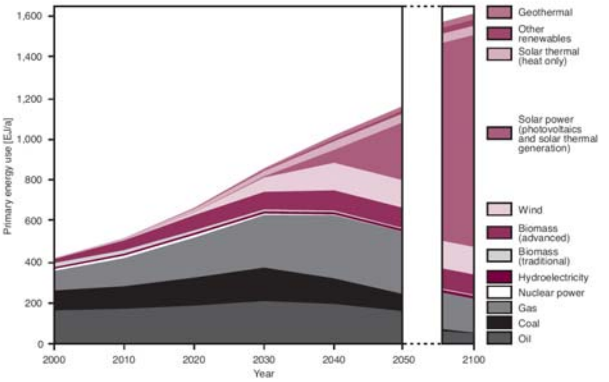

Figure 1 Changes in the global energy mix, from 2000 until 2050/2100. Source:WBGU

This change is driven by dwindling fossil-fuel supplies as well as low-emmission directives and is promoted by large-scale incentives. Grid connection of these resources is commonly performed by static converters, called grid inverters. Upscaling from single-user, domestic equipment (upto 3 kW) to large-scale, aggregated plants (100 MW+) implies that the grid connection needs to feed-in at higher voltage levels to efficiently accept and transmit the level of energy generated, having consequences for power quality, availability and reliability at different levels of the distribution grid and its equipment.

The influence of these effects on both the new, but also the existing distribution equipment is of great concern from an asset management point of view. Having an in-depth understanding of the power quality effects on the distribution equipment however, requires realistic performance evaluation and model validation. This is especially difficult to obtain under severe grid conditions and particularly risky during field trials.

In this regard, the progress that has been made in the performance evaluation of full-scale distribution equipment, performed within a specialised MV laboratory (the Flex Power Grid Lab in Arnhem, the Netherlands, see Figure 2 and [1],[2]) is presented in this paper.

Special attention is given to the qualification (research, testing and where possible certification) of medium-voltage distribution equipment under severe grid conditions, in particular power quality, associated with a high level of DG penetration in a MV/LV distribution grid.

Figure 2 The Flex Power Grid Lab, Arnhem, NL

Case studies, based on the following three grid equipment types, are presented and critically evaluated:

- *DER equipment:* utility-interactive, grid inverters intended for large-scale PV applications,
- *Conventional equipment:* MV/LV distribution transformers, and
- *Countermeasures:* a newly developed fault current limiter (FCL).

Thereafter a view on the future of testing is presented with particular focus on the role of power hardware-in-the-loop testing on DER units.

TESTING OF MV GRID EQUIPMENT

Utility-interactive, or grid inverters form one of the main areas of interest for KEMA with its Flex Power Grid Lab (FPGLab), both in terms of research and in testing, as it is deemed the enabling technology for the large-scale integration of DER and RES, including storage.

Testing of MV grid equipment therefore focusses strongly on the validation of the grid-connection requirements of such power electronic converter systems.

Grid-connection requirements, as described in LV standards such as the EN 50438[3], dictate the physical prototype validation and include aspects such as:

- Interface protection
  - Over voltage
  - Under voltage
  - Over frequency
  - Under frequency
  - Loss of mains / anti-islanding
  - Automatic reconnection/synchronisation after network outage
- EMC and Power Quality
  - Harmonic current emission
  - Electrostatic discharge immunity
  - Radiated EM field immunity
  - Electrical fast transient immunity
  - Surge transient immunity
  - RF conducted immunity
  - DC-injection
  - Voltage fluctuations and flicker
- Efficiency
- Power factor
- Fault level contribution
  - Fault ride-through (FRT)
  - Low-voltage ride-through (LVRT)

International trends predict that similar requirements will be set for MV connection of similar generators.

Beyond the physical prototype validation, yet another validation requirement is slowly but surely emerging, one of (simulation) model verification.
Germany is currently leading as far as requirements in terms of model validation/verification of distributed energy resources (DER) are concerned, having already included requirements since the 1st of January 2009. However, it is expected that other countries are soon to follow the German example, ultimately leading to inclusion hereof in international standards.
The BDEW guideline [4] describes a utility-interactive grid inverter (the physical protoype) to be validated by an independent testing body to obtain a so called 'unit certificate' for the equipment type. Thereafter it requires the (simulation) model of the utility-interactive grid inverter to be validated alongside the physical prototype by an independent testing body to obtain a so called 'plant certificate' for the same equipment. A plant certificate entitles the holder to integrate the connected DER equipment into the actual grid [5].

These advances in standardisation and legislation strengthens the ties between digital simulation (PC based) and physical emulation (laboratory based) as both are now required to safely integrate the increasingly more intelligent components required to facilitate the envisaged low-carbon (electrical) energy supply chain.

Testing laboratories, therefore, need to embrace the world of (digital) simulation together with (traditional) power testing in order to deliver the services required of them.
The experience of the Flex Power Grid Lab will be discussed using some case studies as examples.

CASE STUDIES FOR DIFFERENT TESTING ASPECTS

A) DER equipment: Utility-interactive grid inverters intended for large-scale PV applications

For emerging DER applications such as photovoltaic (PV) panels and energy storage systems (batteries), for example, the grid interface for the exchange of power is realised by an utility-interactive grid inverter.
The testing of grid-inverters is typically performed without the actual energy generator (PV solar panels) or energy storage device. This is due to restrictions in available laboratory floorspace and off-course the unpredictable behaviour of the sun not being suitable for stringent PV testing. This implies that the laboratory infrastructure must provide adequate emulation, in terms of power and bandwidth, of both the DC source behaviour as well as the AC grid behaviour. This dictates to a large extent the requirements of the laboratory. For example, for AC grid emulator laboratories, such as the FPGLab, the amount of total harmonic distortion generated by the emulator should be controlled very precisely as it should be significantly low as not to influence harmonic measurements during harmonic emission testing, but also be adjustable to a user-defined level during harmonic immunity testing and for research purposes.

Figure 3 A range of utility-interactive PV-inverters undergoing testing in the FPGLab

A range of utility interactive grid inverters, upto 500kW have already been tested in the Flex Power Grid laboratory (FPGLab) facility (Figure 3).
Apart from harmonic measurements at the AC-connection interface between the inverter and the grid, to validate compliance with the EN-IEC 61000-3-4, NEN-EN 50160 EMC standards, Low Voltage Ride Through (LVRT) and Fault Ride Through (FRT) capability amongst others, are tested by emulating the full-scale grid conditions required for these severe grid events and closely measuring, monitoring and recording the behaviour of the system (both the distribution grid and the inverter control system).

B) Conventional equipment: MV/LV distribution transformer

Distribution grid equipment such as MV/LV transformers could be exposed to power quality phenomena such as increased THD levels in grids when a high penetration of grid-converter connected DER with sub-standard emissions arise. The remaining grid equipment is then exposed to extra losses due to the extra harmonic content, which will result in increased temperatures, sound production and vibrations during normal operation of the transformer.

Research in the form of laboratory testing has been performed to quantify the thermal effect of an individual harmonic on specific parts of a MV/LV distribution transformer (Figure 4).

Figure 4 A 250kVA MV/LV transformer (right) in combination with a fault-current limiter (left) undergoing thermal testing under severe harmonic conditions in the FPGLab

The temperature rise of a 250kVA, 10/0.4kV distribution transformer (right in photo) being submitted to a large amount of harmonic distortion (all odd harmonics upto the 15th with amplitudes according to the European standard EN50160) in both its MV and LV winding systems, respectively, during full load conditions have been measured by emulating a harmonically distorted MV and LV grid using the FPGLab facility. This resulted in the power loss contribution of the most significant harmonics as shown in Table 1.

Table 1 Individual harmonics' contribution towards power loss within the transformer (measured)

Harmonic order	Power losses [kW]
3rd	13.5
5th	3.9
7th	5.4
9th	27.8
11th	5.0

The temperature distribution throughout the transformer structure (windings, core and oil) have been measured by temperature sensors (fibre-optic as well as PT100) specially installed for this measurement throughout the transformer. From the individual temperature measurements the losses due to each harmonic, as shown in Table 1, can be used to quantify the specific harmonic losses as well as identify the location within the transformer (windings, core, etc.) where the extra losses could result in a hot-spot.

It can be seen that this particular transformer design is particularly sensitive to 9th harmonic (11% of total power). Typically, grid inverters (six-pulse rectifiers for example), produce 5th and 7th harmonic. The combined power loss in the transformer due to only these two harmonics totals approximately 10kW, accounting for almost 4% of the transformer power rating.

These results are used together with other transformer data to verify a model for use in grid-planning and asset management.

Alternatively, MV/LV distribution transformers can be equipped with power quality improvement equipment (active filters) to counteract these phenomena. An example of such a system is the smart substation [6].

C) Countermeasures: a newly developed fault current limiter (FCL)

Although grid-inverters do not contribute to short-circuit levels of distribution grids, a need still exists to counteract large short-circuit currents in parts of networks during a fault condition.

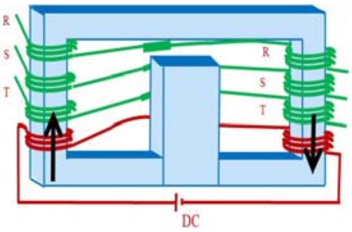

Figure 5 Diagram of 3-phase FCL magnetic circuit

A fault current limiter [7] has been developed at the Delft University of Technology and is currently being tested at full-scale in cooperation with the Dutch utility company Alliander and KEMA (Figure 7). The concept revolves around a satured series reactor on 10kV level, which desaturates during a short-circuit fault condition in the grid and limits the dynamic peak of the short-circuit by increasing its impedance during the fault [8] (Figure 5). Its electrical and thermal performance during assymetrical grid conditions, including harmonics, are studied in the FPGLab by emulating the assymetrical grid conditions as well as the harmonic grid conditions.

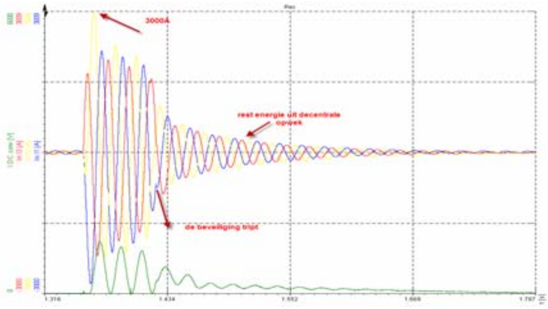

Figure 6 Small scale laboratory 3-phase fault test Peak value (yellow) 3000 A; green is current through DC-windings

Thereafter, at the KEMA High-Power Laboratory, a 10 kV/10 kA 3-phase power source has been short-circuited by the FCL and proved to be able to reduce the single phase fault from 25 kA_{peak} to 4.7 kA_{peak}, while multi-phase fault currents have been reduced to 22 kA_{peak} only (Figure 6).

The results from such testing provides the confidence that the mechanical design is sound, the device will function during the timeperiod it is intended for as well as what the behaviour of the device is within a specific distribution grid during normal operation (insertion losses, asymmetric behaviour, contribution to harmonic damping, etc.).

Figure 7 A fault-current limiter (FCL) with common core and trifilar windings undergoing asymmetric behaviour characterisation in the FPGLab

THE FUTURE OF VALIDATION & TESTING

The availability and stability of a distribution grid is becoming more relient on the correct functioning of the DER units being integrated into it as well as their support during fault conditions.

This places a large responsibility on the testing and validation of the system response of the equipment to de-risk the diverse technologies and their interaction. The diversity in the manner in which components and systems are tested can already be seen from the case studies presented herein. Apart from the new components and systems that need to be tested in a more interactive way to validate its complex behaviour (Case A), the testing of conventional equipment also needs to change to include the effects of the neighbouring DER units (Case B) as well as suitable countermeasures developed and tested for suitability and interoperability (Case C).

Testing laboratories will need to focus on a combination of:

- Hardware simulators (grid) for setting defined boundary conditions and facilitate system integration
- Communication and thermal interfaces
- Control and Protection validation

The increased complexity of testing and the need to validate solutions for realistic grid conditions, especially with the increasing complexity and interaction within an evolving distribution grid, is already leading to laboratories incorporating hardware-in-the-loop type testing (Figure 8). This type of testing combines network information (within real-time models) with the addition of the physical hardware.

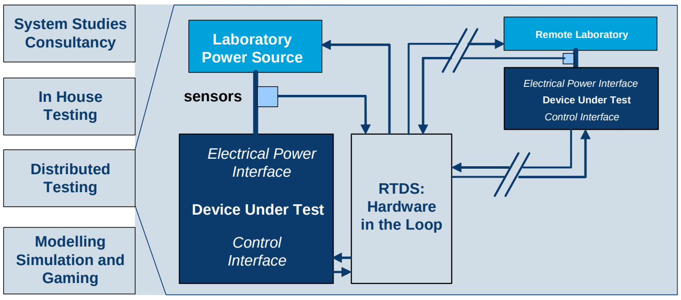

Figure 8 Hardware in loop testing [9]

It is foreseen that integrated testing will become the main stream of testing to ensure reliable operation of distribution grids, despite increasing complexity, decentralised control and decentralised generation.

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