VALIDATION AND TESTING FOR GRID ACCEPTANCE USING HARDWARE-IN-THE-LOOP

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ABSTRACT

As the influence of power electronic converter controls, required to connect distributed energy resources, increases proportionally together with the integration of DER into power grids and smart grid initiatives to balance local instantaneous supply & demand are introduced, the characteristic of the grid will change significantly. The suitability of power hardware in the loop methods for the validation of grid acceptance of such active equipment to capture the interaction between newly developed equipment and ever-changing power grids, under realistic grid conditions is critically evaluated on applicability. Such testing techniques are seen as front-runners for future, independent, third-party, certification regimes of DER.

INTRODUCTION

Dwindling fossil-fuel supplies as well as low-emission directives are driving some significant changes within electrical power systems around the globe. In Europe, for example, the share of energy from renewable sources has already exceeded 14.1% of the gross final energy consumption in 2012, as reported by Eurostat[1] [1], shown in Figure 1 as the distribution amongst all 28 member states, and targets are set for achieving 20% in 2020.

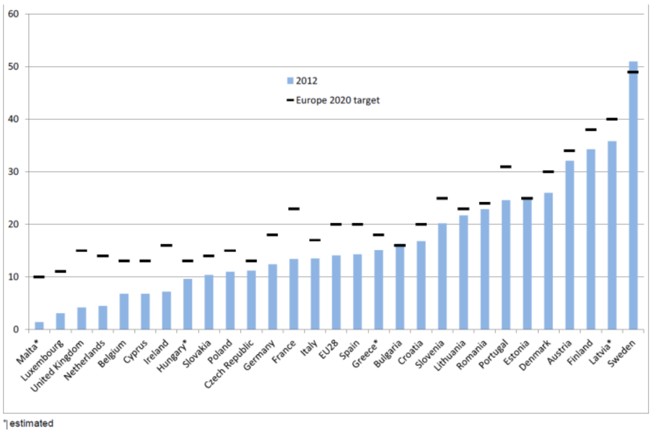
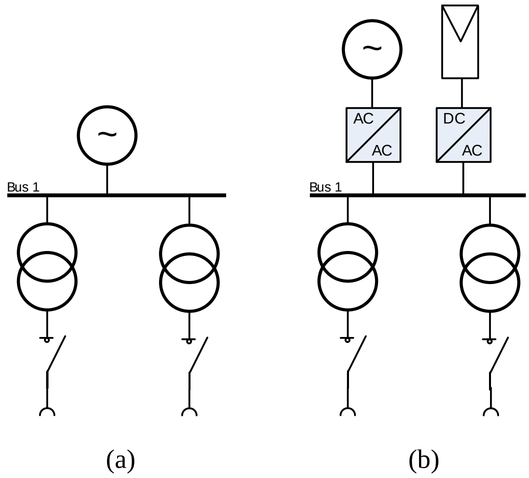


Figure 1 Renewable energy penetration in the 28 EU member states, as of 2012

The integration of large-scale (>500kW) distributed energy resources (DER) to offset carbon emissions by renewable sources is one such important change. Connection of such volatile and intermittent resources to the otherwise rigid power system is commonly performed by power electronic converter systems, the control and protection of which will have an increasingly more profound impact on the quality, reliability and availability of supply of the power system. For example, as the penetration of DER, and thereby also the penetration of power electronic converters, into the power system increases with time the levels of natural inertia - typically provided by the rotating mass from synchronous generators – the availability of short-circuit power (Figure 2), especially at extremities of the grids, and the level of power quality – especially total harmonic distortion - will most likely diminish. If this is not addressed appropriately by the power electronic or supervisory control systems or by another means – storage systems are being investigated to provide virtual inertia for example [2][3] – all these levels could fall below critical values forcing grid operators to take drastic measures in their grid operation and protection philosophies [4][7].



Electrical parameters at Bus 1	(a)	(b)
Inertia, expressed as RoCoF[2] $\left[\frac{\partial f}{\partial t}\right]$	Low	High
Available short circuit current [i_{sc}]	High	Σi_n
Total harmonic distortion [THD]	Low	High

Figure 2 Electrical parameter changes from (a) classical -, and (b) power electronics dominated, power systems

At the same time the power system itself, and the way it is structured and operated is evolving as a diverse range of smart grid initiatives to balance local supply & demand, such as active distribution system management [5] or (EV) storage systems [6], for example (schematically shown in Figure 3), are deployed system wide.

1 the statistical office of the European Union

2 Rate of change of frequency

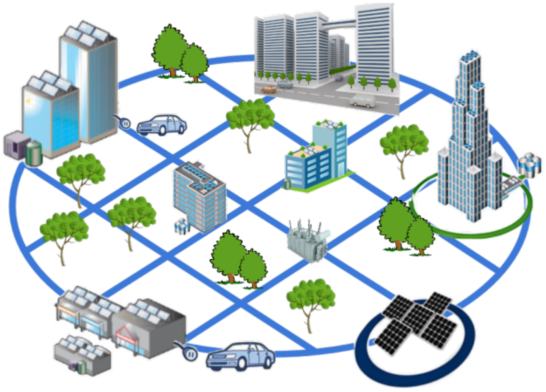


Figure 3 Typical smart grid initiatives being deployed

Therefore, for the overall power system to remain reliable, operation to be stable and the risk associated with the introduction of vastly new technologies and equipment to the power system minimized, it is worthwhile to focus attention on that specific point in this evolution where the impact of the change is the greatest but the risk reducing process is still manageable (financially and practically). For utility-interactive power converters being integrated into the power system – applicable for a large part of the available DER technologies – this particular point is when the grid acceptance testing and validation on the equipment itself is performed.

Knowing this, it is evident that the approach on how to test and validate equipment also needs to adapt accordingly. It is foreseen that the test and validation of individual components for grid acceptance will no longer suffice on its own. To de-risk equipment in complex power systems under dynamic situations, the validation tests – performed in suitable laboratories – should take into account the entire power system in all of its facets, including steady-state, dynamic and transient operation as well as take into account embedded higher-level control actions (appropriate for hierarchical, agent based control [8][9]).

This is a feat not easily achieved, considering the scale of power grids in relation to the equipment being tested.

Therefore, to capture all the dynamic interactions realistically it is foreseen that the combination of (digital) simulation together with physical 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, whilst keeping the economics of performing the actual test realistic. A promising technique for testing and validation in which both simulation models and hardware prototypes are combined - referred to as closed loop testing, and more specifically for power converters: hardware in the loop (HIL) – could prove to do exactly that.

This paper explores on a conceptual level what closed loop testing techniques are; what it could do for both control (CHIL) and power (PHIL) aspects within the existing and future testing and validation practices of large-scale power systems, with special attention for the grid acceptance of power electronics connected DER; and finally the challenges that remain in this area to be able to provide closed-loop testing services as part of standardised, independent, third-party testing and certification activities.

TESTING: TODAY & TOMORROW

Today the testing for grid acceptance of most grid components is performed on single components and in an open-loop manner. This implies that all boundary conditions required for the test are presented to the equipment under test (EUT) by a suitable laboratory facility and its sophisticated range of sources and all activities recorded by suitable measurement equipment. During the actual testing appropriate stimuli are introduced to or on the EUT (external voltage for dielectric testing; or increased short-circuit currents for mechanical integrity testing, for example) in order to excite specific component responses typically according to standardised methods[3], which in turn can be checked and validated against known values (a benchmark or predetermined behaviour). For the larger part of classical distribution and transmission components, the inner workings of the equipment (cables, switchgear and transformers, for example) are well known to the test engineers and testing procedures tuned to validate a number of vital parameters applicable to that type of equipment. Furthermore, as these components are predominantly passive components the dynamic response of the system it is connected to is not pivotal in its functioning nor a barrier to comply with (type-) test certification requirements. In this case open-loop testing – testing that does not take into account the dynamic interaction between the EUT and the specific power system it is intended for – is sufficient to de-risk the equipment and declare it fit for purpose.

However, for active components, such as utility-interactive power electronic converters for DER, often comprising of an intricate system of systems, the dynamic interaction between the EUT and the specific power system it is intended for is crucial, whilst the inner workings of the EUT are often not known to the test engineers. This is due to the fact that the behaviour of such EUTs are largely independent of the hardware but rather heavily dependent on the control software behaviour.

In this case open-loop testing will not adequately capture the level of detail, especially the dynamic interaction, required to be able to validate its behaviour, let alone certify compliance for grid acceptance in complex power systems. Introducing closed-loop techniques that do capture the required level of detailed as regards dynamic interaction, would bring the certification and grid acceptance of such systems a step closer.

Furthermore, due to the complex system behaviour dictated by the control software it is a challenging task to perform benchmark comparisons of different systems and create standardised test protocols.

The different closed-loop techniques available and their specific application areas are explored next.

3 international standards such as ISO, IEC or IEEE

CLOSED-LOOP TESTING TECHNIQUES

Closed-loop testing in general is deemed one of the most thorough means of testing physical electrical devices such as protective relay systems and control systems. Closed-loop testing, as schematically illustrated in Figure 4, is characterized by taking signals output from a simulation, running on a suitable real-time hardware platform, and using them as input for the equipment under test. The output from the device being tested is then properly scaled and fed back into the simulation, thereby affecting it under actual service conditions. A distinction can be made in the testing technique based on whether hardware is included in the test set-up (hardware in the loop), or the testing is completely simulation based – model in the loop. Thereafter for the HIL testing a further distinction can be made whether control signals (low voltage, low power) only are exchanged (control HIL) or power (higher voltage, higher power) is exchanged (power HIL, Figure 5).

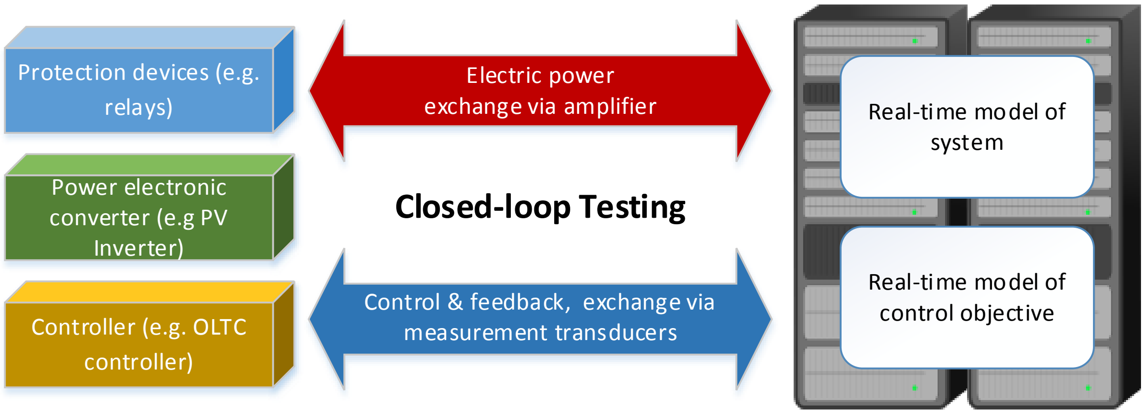


Figure 4 Schematic representation of closed-loop testing technique applicable to power system testing and validation

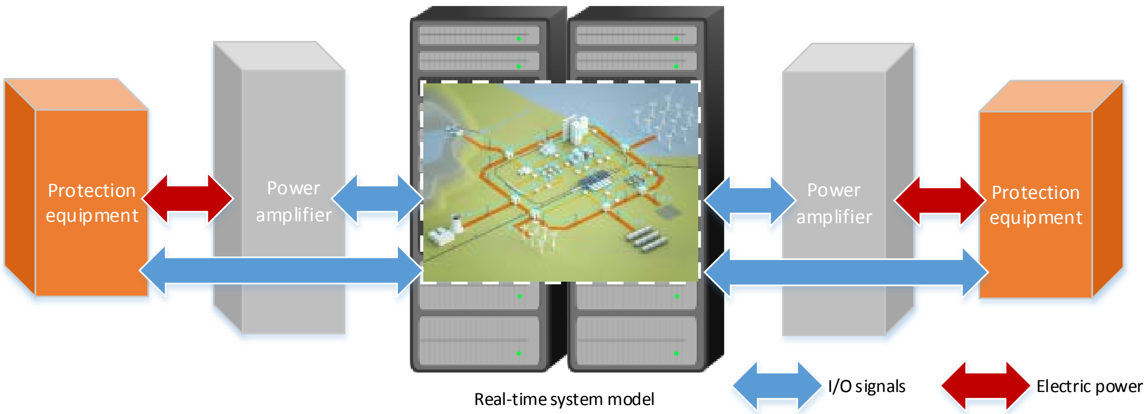


Figure 5 Schematic representation of power HIL testing of protection equipment

In general, a clear advantage of the closed-loop testing technique is that the results obtained most closely resembles the actual performance of the device under test. It not only tests the functionality and setting of a particular device, but also tests the system's reaction to that device's operation. This provides for a realistic environment for testing the system, the device, and the interaction between the two. However, as a disadvantage it often requires the exchange of large number of input and output signals. The simulator's hardware architecture must facilitate handling large amounts of input and output signals on a synchronised time basis. In turn, especially for power HIL, each signal exchange will also require its own suitable power amplifier and suitable measurement transducer(s) to allow for the simulation environment to be properly interfaced with the hardware environment (EUT).

TESTING AND VALIDATION ASPECTS FOR GRID ACCEPTANCE OF POWER ELECTRONICS CONNECTED DER

The art of testing itself - performed to de-risk a component, system or technology for its intended purpose in a controlled-risk environment before commissioning it in the real world - is, in essence, all about creating appropriate boundary conditions and system impulses to trigger a (known or unknown) response from the equipment under test that can be validated against known or expected values and responses. Should the individual equipment's response be influenced by the connected system and its upstream network, for example, these influences should then also be incorporated into the testing method to bestow credibility on the validation and grid acceptance of that component, including its controls and protections, into the system.

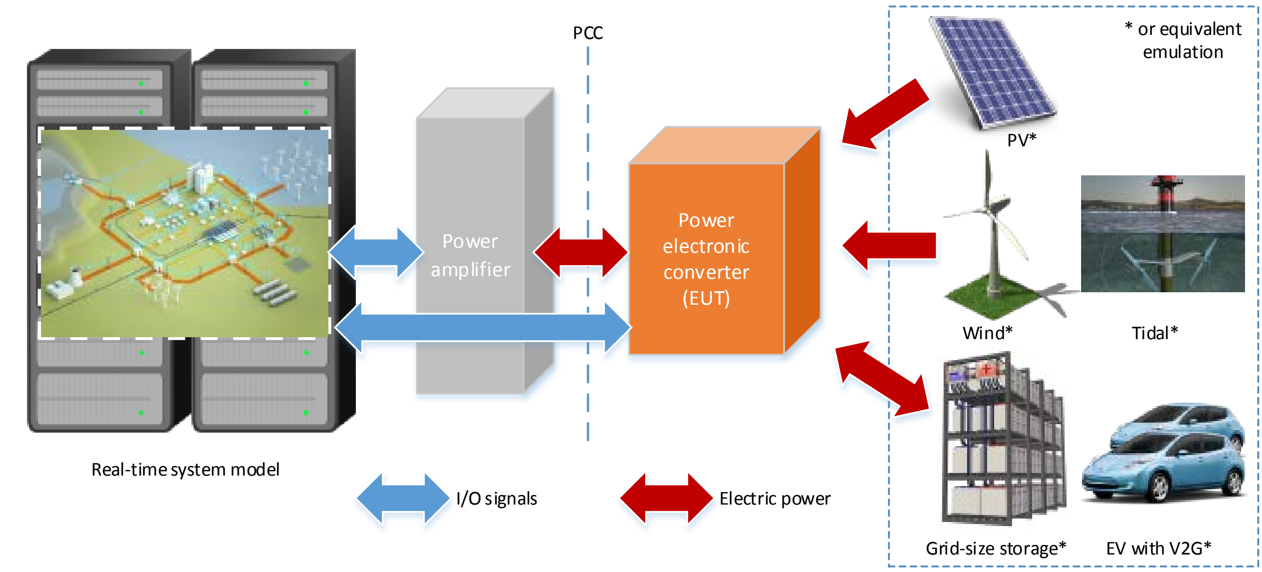


Figure 6 Schematic representation of proposed grid acceptance test & validation of DER inverters at the grid PCC

Validation of the system behaviour during testing of the physical prototypes, however, requires a large portion of flexibility, innovation and ingenuity from the laboratory, which needs to cope with omnipresent practical and physical limitations. Think for example of the vast amount of impedances required to emulate a certain grid characteristic, or the necessity of one or more suitably powerful and high bandwidth programmable AC sources to emulate the voltage profiles of the respective nodes within the associated grid scenario.

For practical and economic reasons, this part of the validation process is then usually deferred completely to (digital) software simulation, using validated component models together with extensive power system network models, in which the system aspects can be incorporated to a larger extent. There is however an inherent risk associated with validation by simulation alone, as this type of validation is only as good as the (validated) models are.

HIL test and validation techniques, as introduced earlier in this paper and illustrated in Figure 6, aim to bridge this gap in validation by incorporating the dynamic behaviour of the physical prototype, including its controls and protections, with the system response obtained from the extensive power system modelled in (digital) software models, running on a suitably fast simulation platform. Validation of the realistic behaviour at the point of common coupling (PCC) then becomes possible. Although HIL has drawbacks of its own[4], it offers the prospect of increasing the accuracy of validation by triggering more realistic responses from the equipment under test as part of a realistic larger system. It could even reveal system related aspects such as identify natural limits for the penetration of DER into particular distribution areas. This can't be achieved by the testing of individual components alone.

From a testing laboratory point-of-view, the simulation aspect offers great flexibility in designing and performing test scenarios. It can be changed easily and quickly without the need for hardware adaptations, (rewiring, etc.). Various experiments can be performed repeatedly with increased consistency and improved repeatability. Extreme conditions can be studied with minimum cost and risk, while hidden issues of the equipment can be revealed allowing in depth understanding of the behaviour of the device under test.

The next step is to develop standardised and industry accepted certification procedures based on the outcome of HIL testing techniques. However, for certification a standardised testing method, which is repeatable as well as internationally traceable, is a prerequisite. This is not yet available, but initial efforts undertaken by the European Distributed Energy Resources laboratories (DERLab) [10] as well as internationally within the ISGAN/SIRFN [11] implementation agreement, are already underway.

4 Drawbacks include: High cost of the real-time simulator platform; related training and technical support. Time consumed by establishing and validating real-time system/device model. Extra effort required in the training of test engineers in real-time modelling and HIL testing methods.

Consider the grid acceptance test of a utility-interactive battery storage system as an example. A grid-size battery storage system in the range of 250kW, 100-500kWh, could easily reach investment costs in the order of millions of euros, whilst inappropriate control signals from the battery management system can cause serious damage to both the battery and its utility-interactive inverter. Furthermore, as more and more ancillary service responsibilities from the grid are bestowed on the inverter, inappropriate functioning of the inverter control could directly impact grid stability. This multi-objective testing requirement to validate that the battery management system correctly operates and protects its battery under all (dynamic) circumstances, whilst simultaneously validating that the advanced inverter functions (frequency and/or voltage support [12]) are provided to the power grid; all protection equipment engaged in a sufficiently fast manner; and higher order grid operation (peak shaving [13], for example) achieved simultaneously; can only be realistically validated using control as well as power hardware in the loop techniques from within sophisticated laboratory infrastructure [14]. Otherwise, the risk for material and financial damages for the storage- and grid operator will become unacceptable.

CURRENT CHALLENGES

The current challenges facing the technical implementation of HIL techniques for the testing and validation of large scale DER testing include the following:

- Stability of closed-loop test circuits: Stable operation of a test is dependent on the electrical parameters of both the EUT in combination with those of the test equipment (more specific the power and measurement interfaces). To allow for a 'black-box' testing approach – to ensure repeatability of testing without compromising the manufacturers' IP – suitable stability criteria that can ensure operational safety at all times without restricting EUT functionality are still required.
- The interface: in order for the test circuit not to influence the functionality and performance of the EUT, an oblivious interface with adequate bandwidth, acceptable latency, and effective protection of test equipment (for both the hardware and software components) and the EUT is required. Power amplifiers with suitable characteristics are either limited in power (linear amplifiers), or limited in bandwidth (PWM based power converters).

The non-technical challenges for the implementation of HIL techniques for the testing, (model) validation and certification of large scale DER testing include:

- System model dependency: For repeatability and wide adoption of this testing method it is advantageous that the test itself is not dependent on case-specific criteria. This discrepancy needs to be addressed for acceptance of the test method.
- Interoperability of system modelling software: Models built in different software tools need to be interoperable to allow for testing in third-party testing laboratories.
- Standardisation: International traceability of testing methods is missing to come to an industry accepted certification regime.

FINAL REMARKS

Implementing closed loop testing techniques to validate sophisticated equipment operation in complex power grids will become unavoidable in order to ensure stable and reliable grid operation in future power electronic dominated grids. However, numerous challenges still need to be solved first and international procedures aligned before testing and certification - based on HIL - will become common place as type certification is today.

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