# Measurement Infrastructure to Support the Reliable Operation of Smart Electrical Grids

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***Abstract*— Grid operators are facing a significant challenge in ensuring continuity and quality of electricity supply, while more and more renewable energy sources are connected to the grid. The resulting evolvement of so-called smart grids strongly relies on the availability of reliable measurement data for monitoring and control of these grids. This paper presents an overview of the results achieved in recent smart grid metrology research in Europe, aiming to realize the required metrology infrastructure for ensuring security and quality of supply in future smart electrical grids. A consortium of 22 metrology and research institutes has made significant steps in modeling of smart grids, enhancement of the revenue metering infrastructure, performance and evaluation of onsite power quality campaigns, and the development of a metrological framework for traceability of smart grid phasor measurements.**

***Index Terms*— Electrical grids, grid modeling, metrology, phasor measurement unit, power quality (PQ), revenue metering, smart grid, synchrophasor.**

## I. Introduction

THE addition of intelligence to the present electrical grids is crucial for ensuring a smooth uptake of renewable energy sources and for minimizing grid investments through lowering of peak demand via demand side management programs. These developments challenge grid stability due to increased power flows and more nonlinear loads connected to the grid. Furthermore, the addition of intelligence to the grids does not automatically improve the situation, since this may not only make the grids smart but also more vulnerable to instabilities caused by inadequate control and feedback routines. This calls for improved measurement instrumentation for monitoring and control of the smart grid system state [1], [2].

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In this paper, we describe recent results achieved in the realization of a metrology infrastructure in Europe to support the reliable operation of smart electrical grids. After a description of the progress achieved in synchrophasor testing and calibration, the results of five onsite power quality (PQ) campaigns in a variety of electricity grids are presented. This is followed by a description of two reference high-voltage (HV) revenue energy metering systems for onsite calibration and verification of grid metering systems. The final part of this paper concerns the results of an extensive study on a nodal load observer (NLO) dynamic state estimation (SE) method to estimate the grid state in medium-voltage (MV) distribution grids, followed by considerations concerning smart grid data reliability and security.

## II. Phasor Measurement Units

Phasor measurement units (PMUs) are crucial tools for the monitoring of large transmission networks and are likely be used in the future in MV and low-voltage (LV) distribution grids as well. Thus, research was initiated with the aim to establish a metrological framework capable of dealing with all aspects of PMU traceability. This framework encompassed the development of a simulation platform for PMU algorithms, a reference PMU, and a metrology-grade calibrator. Together, these tools permit to develop and evaluate PMU algorithms, calibrate PMUs, and compare PMUs in laboratory and field conditions.

The simulation platform was designed to facilitate the design and testing of PMU algorithms. It comprises a waveform generator, a standardized algorithm interface, and an error computer that are controlled through a graphical user interface. The waveform generator is capable to create all signals outlined in [3] as well as special tests. The generator computes the theoretical phasor values, frequency, and rate of change of frequency of the generated data sample. These theoretical values are compared with those generated by the PMU algorithms in the error computer [4].

The simulation platform was subsequently used to test a series of PMU algorithms. Early tests concentrated on evaluating the P class and M class algorithms described in [3, Annex C], but it was quickly realized that these algorithms are not suitable for high accuracy applications or for highly distorted waveforms. Therefore, new algorithms were investigated and tested, e.g., using phase sensitive frequency estimation [5]. Fig. 1 shows the susceptibility of the relative frequency error of some of the algorithms investigated to the presence of harmonics.

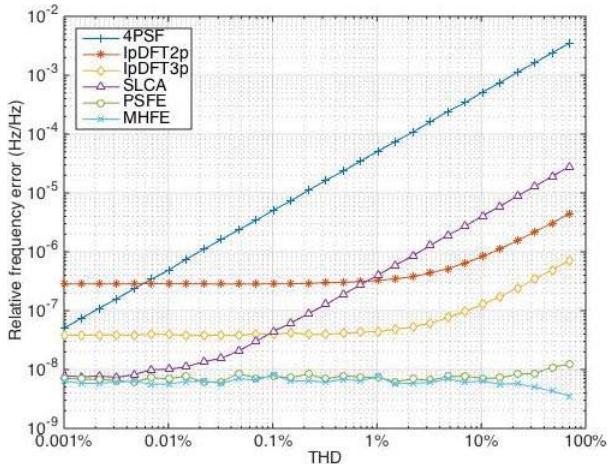


Fig. 1. Relative frequency error of a series of PMU algorithms as a function of total harmonic distortion of the test signal.

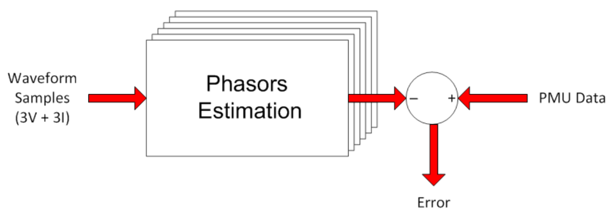


Fig. 2. Waveform processing taking place in the PMU calibrator.

Once tested, PMU algorithms can be loaded in the reference PMU and evaluated with real electrical signals generated by the reference grade calibrator [6]. Using this calibrator, the algorithms can be tested in real time, as all the test signals are now aligned to universal coordinated time (UTC).

This same calibrator can also be used for commercial PMUs with voltages up to 230 V and currents up to 10 A. The calibrator is able to provide all the static and dynamic test signals described in [3]. The uncertainty of the calibrator is around 300 parts in $10^6$ in magnitude and better than $0.01°$ in absolute phase for 50-Hz signals. The latter corresponds to a time uncertainty of 555 ns, which includes the 50-ns uncertainty of the reference UTC signal applied to the calibrator. The $0.01°$ phase uncertainty also includes a known phase error in the setup that can be compensated for in the data evaluation software. The present work concentrates on reducing the phase uncertainty to below $0.002°$.

The UTC synchronized waveforms applied to the reference PMU are resampled and analyzed so as to extract the reference values which are then compared with the data provided by the PMU algorithm. Fig. 2 shows the process.

The phasor estimation in the reference system is made through fitting of the waveform model to the reacquired waveforms. This method is preferred to a direct comparison with a reference PMU algorithm. In effect, PMU algorithms must satisfy many conflicting requirements outlined in [3], while a specific fitting can be tailored to a specific test and thus results in much more accurate results. Figs. 3–5 show some of the test results that were obtained with the calibrator on a commercial PMU [7]. Fig. 3 shows the results of the susceptibility of the PMU

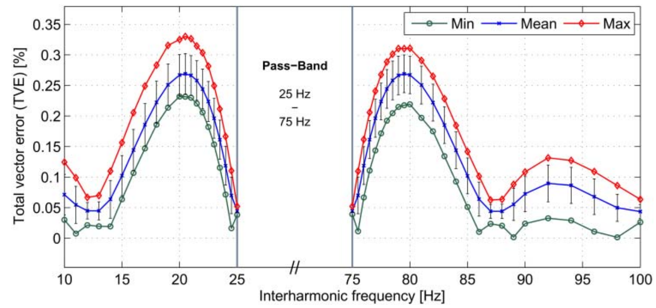


Fig. 3. Test of the susceptibility of a PMU to interharmonics with 10% magnitude of the fundamental signal.

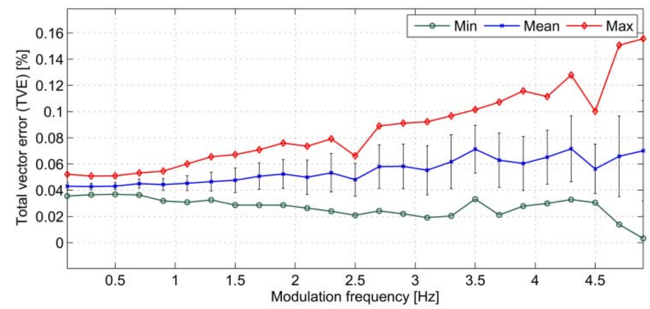


Fig. 4. TVE during a 0.1 rad phase modulation test, as a function of the modulation frequency of the phase.

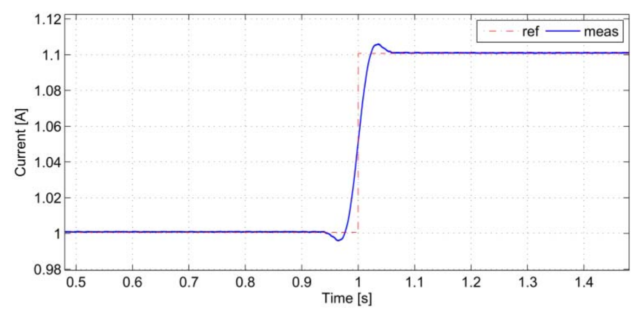


Fig. 5. Step response of a PMU for a 10% step in current amplitude at $t = 1.0$ s.

to interharmonics outside the 25-Hz widepassband. Following the requirements, in [3], an interharmonic signal with 10% amplitude of the fundamental 50-Hz signal has been applied, with frequencies between 10 and 100 Hz. The results of the test are expressed as a total vector error (TVE) which is the combination of the magnitude and phase error of the PMU [3]. The test results show that this particular PMU has a significant TVE for out of band interference signals, but still is well within the 1% limit of the IEEE C37.118.1 standard [3].

Fig. 4 shows the result of a phase modulation test, where the phase of the fundamental is modulated with 0.1 rad at a frequency between 0.1 and 4.7 Hz. The results show an excellent behavior of the PMU for this test. As a final example, Fig. 5 shows the PMU response to a 10% step in current. The PMU response apparently starts before the applied current step. This is due to the internal averaging of the PMU phasor algorithm over several cycles of the mains frequency, combined with the convention chosen for the position of the time tag of the measurement. To facilitate interoperability between different PMUs, the IEEE C37.118.1 standard requires placing the time tag of a single measurement well before the end of the record used for the calculations [3]; for a symmetric finite impulse response estimator the time stamp nominally is in the center of the averaging period. Note that a measurement will not appear at the PMU output until after the last data point used in the phasor estimate window, which is well after the time indicated by the time tag. For the particular PMU tested here, the number of cycles used in the averaging can be set by the user [7], and was set to six cycles for the tests in Figs. 3–5. An important parameter derived from this test is the delay of the time where the PMU response is 50% of the amplitude step, with respect to the time where the applied current step is 50% of its final value.

Over the next few years, the work on PMU algorithms, reference PMU, and PMU calibrator will be continued with the aim to increase accuracy and robustness. In the future, PMUs are likely to be used in distribution networks, where phase angles are much smaller, whereas at the same time the content of PQ disturbance is significantly higher compared with HV networks. This puts more stringent requirements on the phase accuracy of PMU algorithms and PMU calibrators.

## III. Revenue Metering

Liberalization of the energy market has increased the importance of accurate measurement of energy flows in the grid, where small measurement errors have large financial consequences. As an example, for a 500-MW electrical power plant, the typical 0.5% uncertainty in the measurement of the electricity power output using standard commercial instrumentation corresponds to a financial uncertainty of around 1 M€ per year. This significant financial impact makes it worthwhile to not only calibrate the components of the commercial instrumentation in the field but also calibrate and validate the complete grid energy measurement setup. To be able to do such a system calibration and validation, two reference setups have been developed for onsite calibration of HV grid energy measurement systems with aimed total expanded uncertainties of less than 0.1%, at least a factor 5 better than present grid metering systems [8].

The two reference HV energy measurement systems, developed by Van Swinden Laboratorium (VSL) and Central Official Laboratory of Electrotechnic (LCOE), respectively, slightly differ in their approach. The LCOE reference system is a single-phase system suitable for offline calibration of the grid metering systems (part of the grid is taken offline during the complete time of the calibration). This approach has the significant advantage that the calibration can cover a large range of voltages and currents, for example, those mentioned in [9], but does require taking the grid offline for a prolonged period of at least one day. The VSL reference system is a three-phase system designed for online calibration of the grid metering system (part of the grid only needs to be taken offline for connecting the reference system, which is of the order of a few hours). This approach thus has the advantage that it requires a shorter grid offline time, but as a down side, the calibration is only done under the conditions prevailing in the grid during the period of calibration (which extends to at least one week).

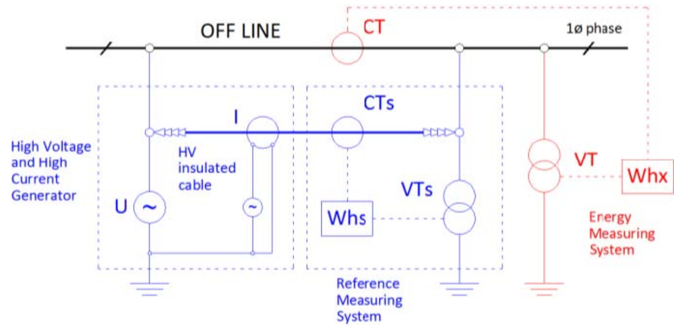


Fig. 6. Reference revenue metering setup (in blue, bottom left) for traceable onsite offline calibration of a grid energy measurement system (in red).

Both HV reference metering systems consist of the same basic components, namely, high-quality current transformer (CT) and voltage transformer (VT) and an accurate power meter, which all have to be suitable for onsite use. Fig. 6 shows the layout and components of the LCOE single-phase offline system. Since the measurements are performed offline, the LCOE system also contains facilities for generating the calibration HV and high current signals.

The first characterization of the setups consisted of calibrating the components against higher quality reference standards. The results of these calibrations proved that all selected equipment were suitable for reaching the finally required system uncertainty: typically, the relative deviations from nominal value were less than $1 \cdot 10^{-4}$, and in the cases where they were slightly higher, they could be determined with at least $1 \cdot 10^{-4}$ relative uncertainty and subsequently corrected for.

Since the calibrations of the components were performed under laboratory conditions, whereas the setups are aimed for onsite use, an extensive program was set up to characterize the possible effects of the nonideal circumstances prevailing in electricity grid substations. This among others concerned the following tests.

1) *Temperature Effects* on the CTs, VTs, and power meter. These effects appeared to be reasonable small, mostly below five parts in $10^5$ over a temperature range typical for onsite conditions. In the case of the VSL setup, the temperature effect on the power meter was further limited by placing it in a temperature controlled measurement rack.
2) *Effect of Electromagnetic Interference:* This included testing of the effect of interference and ground currents on the secondary wiring of the reference setup as well as, in the case of the LCOE setup, the influence of the generation of the HVs and high currents on the accuracy of the reference CTs and VTs. The latter appeared to be a nonnegligible uncertainty source in the LCOE setup of a few hundred $\mu$W/VA. In the VSL setup, double shields were used in the secondary wiring of the CTs and VTs, following [10]. In this configuration, the effect of intentionally induced ground currents up to 1 A in the outer shield had no effect within the 20-$\mu$W/VA noise level of the power meter.
3) *Effect of Harmonics:* The power meter was submitted to an extensive program of tests with harmonic currents, ranging from the third to twenty-fifth harmonic

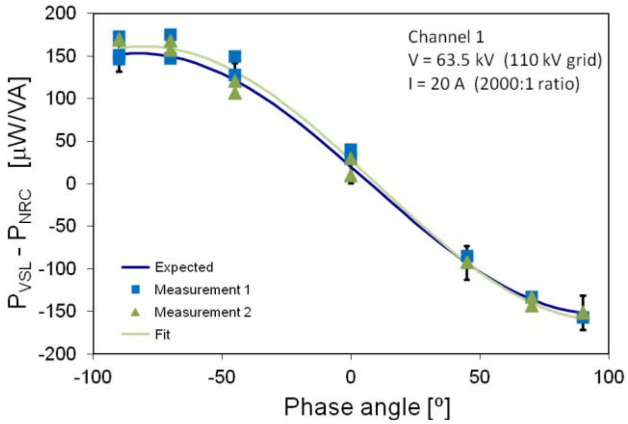


Fig. 7. Difference in power measured by the VSL and NRC reference setups at 63.5-kV line to ground voltage and 20-A primary current as a function of phase angle between voltage and current. The solid blue line is the expected difference based on the calibration results of the components of the VSL setup, the points indicate the results of two measurement runs, and the green line is a fit through the measurement data.

frequency and harmonic current levels ranging from 0.1% up to 10%. In the case of the VSL power meter, the effect of harmonic current was not visible within the 20 $\mu$W/VA noise level of the test, except for one current range where at 10% of third harmonic current an effect of 30 $\mu$W/VA was seen.

As a final test of the overall uncertainty of the reference system, VSL performed a comparison of its new HV grid metering reference system against the load loss system of National Research Council (NRC). This NRC system has a negligible deviation from nominal value, with a typical uncertainty of 10 parts in $10^6$ in both magnitude and phase [11]. The voltage and current channels of the VSL and NRC systems were connected in parallel and series, respectively, and subsequently the systems were compared at 64-kV (line to ground) voltage and currents ranging from 20 to 1000 A.

Fig. 7 shows the result of the comparison performed at low current as a function of phase angle between current and voltage. At 0° and 90° phase angle, this reveals the magnitude and phase angle difference, respectively, between the two setups. The results show an excellent agreement of the VSL and NRC systems, with the measurement data differing less than 15 $\mu$W/VA from each other over the complete phase angle range.

Based on this excellent result achieved under laboratory conditions and the small effects of possible onsite effects, it is estimated that the total uncertainty of the VSL reference energy measurement system is 300 $\mu$W/VA (0.03%) for onsite measurements. For the LCOE system, the estimated overall uncertainty is slightly worse, 700 $\mu$W/VA, due to the interference effects of the generated HV and current on the reference instrument transformers of the setup. Both overall uncertainties are well below the aimed 1000-$\mu$W/VA (0.1%) uncertainty aimed for.

## IV. Onsite Power Quality

Adequate PQ is important to the reliable and stable operation of the electricity network, and indeed the level of PQ can be used as an indication of the condition of a network and its vulnerability to stability issues. Governmental targets for the integration of renewable generation, such as wind turbines and photovoltaics (PV), will increasingly affect the operation of the grid as the proportion of this sporadic generation increases. One possible consequence is an increase in PQ events, such as voltage dips and swells, and changes in harmonics levels related to the inverters and voltage-control-circuits used by renewable generators. The extent to which this proposition is true, is dependent on the type and topology of the network, the proportion of renewable energy supply, and the prevailing load and generation balance.

This research aimed to investigate the PQ consequences of connected renewables in a variety of distribution networks. This was achieved by undertaking six prolonged measurement campaigns, and correlating the detected events to renewable activity. These campaigns were conducted over periods of sufficient length to encompass variations in weather conditions and seasonal load changes, such that comparisons of the network behavior with and without the given type of renewable generation could be compared. A summary of five of these campaigns is given below, followed by a description of some common findings in these campaigns.

### A. Roof-Fitted PV in a LV Distribution Grid

*Location:* Anglesey, North Wales, U.K.
*Network Type:* LV Distribution.
*Smart Grid Elements:* 49 × 1.5 kW roof-fitted PV.
*Participants:* Scottish Power plc and NPL.
*Instrumentation:* NPL eight-channel digitizer [12], Rogowski coils for current measurement.
*Campaign Length:* nine months (May–October).

*1) Summary of Findings:* The effect of the PV cluster generation on local PQ was assessed and PQ parameters, including current and voltage harmonics, flicker, active and reactive power, voltage unbalance were all measured, and compared during periods of PV generation and no PV generation (linked to solar radiance). The most significant effect seen during the study was a rise in voltage associated with PV generation. The analysis of the results presented shows that the voltage at the substation transformer increased by about 1 V during periods of generation. The rise in the middle of the feeder was more significant, showing a voltage change of about 4 V during PV generation. Although the rise in voltage was relatively small, less than 2% of the mains voltage, still the result was of particular importance to the utility, since the increase brought the mains voltage level very close to the high end of the U.K. statutory limits. There was no detectable evidence of significant harmonic, interharmonics, or flicker disturbance from the type of inverter used in this installation [13].

### B. Renewable Energy Sources in an Industrial Park

*Location:* Walqa Technology Park, Aragón, Spain.
*Network Type:* Research network, LV Distribution.
*Smart Grid Elements:* Wind, PV, and $H_2$ production.
*Participants:* Fundación del Hidrógeno and Centro Español de Metrología (CEM).

*Instrumentation:* CEM Global positioning system synchronized digitizer.
*Campaign Length:* nine months.

*1) Summary of Findings:* The auto-disconnection (trip) of various wind turbines on the network was found to be common at weekends; results from the PQ study indicated that these trips corresponded to increased overvoltage events due to the relative light grid loading at weekends. Understanding the cause of these trips will allow the use of MV auto-reclosers to quickly reconnect the turbine.

Wind-turbines must conform to international limits on flicker [14], an important PQ parameter related to public health and the annoyance of electric lighting disturbance. During this measurement campaign, excessive levels of flicker were observed at the customers' buildings. The renewables had been suspected as the source of flicker, however, detailed analysis of the recorded data revealed the source to be the high level of nonlinear loads (i.e., computers and lighting) installed inside the buildings. Conversely, the flicker levels of the renewable sources were always below the statutory limits.

### *C. PV in an LV Distribution Grid*

*Location:* Western Slovakia.
*Network Type:* LV Distribution.
*Smart Grid Elements:* PV (before and after installation).
*Participants:* Západoslovenská energetika Distribucia a.s. and SMU.
*Instrumentation:* Commercial PQ analyzer (Fluke 1760 PQ1) with 50 A/5 A clamps.
*Campaign Length:* two parts; June prior to installation, July–September after installation.

*1) Summary of Findings:* A four-to-five-times increase in over-voltage and voltage-dip PQ events was observed following the installation of the PV panels. This is consistent with the trend in the Anglesey campaign, where PV generation was seen to cause voltage regulation difficulties, although the results of this Slovakian study were much more significant and beyond the statutory limits. In the July and August period, these events were augmented by nine long-term supply interruptions. The total events reduced in September which could be related to reduced sunshine, and alternatively the high July/August event count could be explained by the general degradation of the quality of the network due to summer period system maintenance outages and changed load types. In a follow-up study, these events should ideally be correlated to solar radiation to strengthen the conclusions of this paper.

### *D. Large PV Park in an MV Distribution Grid*

*Location:* Northern Italy.
*Network Type:* MV (15 kV) Distribution Network.
*Smart Grid Elements:* Large PV Park (800 kW).
*Participants:* Istituto Nazionale di Ricerca Metrologica (INRiM).
*Instrumentation:* Commercial digitizer based on ADC cards, Rogowski coils and INRiM built MV resistive voltage dividers.
*Campaign Length:* two parts; autumn (2012) and late spring/early summer (2013).

*1) Summary of Findings:* No significant PQ problems were detected that could be attributed to the large PV plant. Several overvoltage events were found (no more than one over a week) and significant current harmonics typical of nonlinear loads were measured. No harmonic component at the PV invertor switching frequency was detected and no obvious voltage fluctuations were correlated to solar irradiance.

### *E. Wind Turbine*

*Location:* Western Denmark.
*Network Type:* Test center for large wind turbines owned by five manufacturers.
*Smart Grid Elements:* Wind turbine.
*Participants:* Trescal, NPL, and a wind-turbine manufacturer.
*Instrumentation:* NPL built digitizer with Rogowski coils for current measurement.
*Campaign Length:* six months, December–May.

*1) Summary of Findings:* A prototype large wind turbine was assessed for its flicker emissions (voltage fluctuations). This involved making measurements over the full operational range of wind speeds. This was achieved by automatically triggering and categorizing each measurement (sampling channels for 10 min) based on anemometer readings. Digital filtering and asynchronous sampling corrections were applied to condition the data from each channel before determining the phase and amplitude components. These components served as inputs to the so-called fictitious grid [14], which is used to decouple the natural voltage fluctuation of the host network. The results from the measurement demonstrated the validity of this technique and furthermore showed that the prototype wind turbine met the limit requirements of the IEC standard [14].

There were two main common findings of the campaigns. First of all, the required preparations for the different campaigns were very similar. Therefore, a common check list was developed that identified a large series of issues to be discussed with the utility before a campaign was started. These included details of the measurement site, the available instrument transformers, the safety requirements, and the availability of auxiliary services (for example, mains supply and Internet access for PQ data transmission).

A second important common finding was that the overall uncertainty of the PQ measurements was mainly limited by the available VT and (especially) CT, and not by the PQ digitizer/analyzer that was used. In cases where existing transformers mounted in the grid can be used, they often are of protection quality (CTs, 5% accuracy) or at best of 0.5% or 1% accuracy. In most campaigns, the current sensor of the PQ measurement system was used. This current sensor typically is Rogowski-coil or current-clamp type since these can be applied without breaking the existing grid current circuit. Although these sensors in principle can be calibrated with better than 1% uncertainty, in the practical situation of the onsite measurement this uncertainty is difficult to achieve due to electromagnetic interference and due to space limitations that, e.g., do not allow a symmetric positioning of the current sensing ring with respect to the current conductor. Therefore, future research should aim to develop current sensors with adequate wideband properties and good uncertainty under onsite conditions [20].

## V. Smart Grid Measurement Strategy

The increasing number of decentralized generation units at the distribution level of power grids causes new dynamics in the electric grid. These need to be observed through measurements or by estimation to ensure safe and secure grid operating conditions. Therefore, a dynamic SE method called NLO has been developed. The NLO method estimates the grid state in MV distribution grids, i.e., power flow in the lines and voltages magnitudes and phases at nodal points, especially for the case of an incomplete measurement infrastructure. It is based on measurements of voltage phasors at grid buses and forecasts of load and generation data. Simulation studies on MV distribution networks and validation on the laboratory test grid showed the efficiency of the method. The NLO algorithm proved to be highly successful in limiting the effect of pseudomeasurements (estimates of quantities based on past usage data) on the accuracy of the SE. In the following, Section V-A describes the Strathclyde laboratory test grid, and Section V-B the testing of the NLO method using this test grid.

### A. Strathclyde Microgrid Measurement System

A full description of the microgrid at Strathclyde University can be found in [15]. The sensors installed on the grid are configured to be representative of those found in real grids. The uncertainty of measurement data available for SE is generally assumed to be around a few percent. For example, in [16], three cases are presented in which the uncertainty of real measurements is assumed to be between 1% and 3%. For PMUs, the accuracy requirements are more demanding and in [17], the necessary accuracy for voltage magnitude is indicated to be between 0.5% (with phase angle error equal to zero) and 0.2% (with phase angle error equal to 0.09°) to achieve an overall 1% uncertainty in power flow. The sensors installed on the microgrid and the data acquisition system have a precision of 2.14% in the measurement of voltage and current magnitude and a precision of 4.5% the power flow measurement. This level of precision is considered enough to simulate the real operating conditions of an energy management system at the LV level.

The microgrid was setup, as shown in Fig. 8. Busbar 0 is connected to the main power supply and acts as the slack bus. Variable load banks are connected to busbars 1 (load B) and 3 (load C). An induction machine acting as a generator is connected at busbar 1 (generator B). Busbars 2 and 4 are not connected to loads or generators. The grid is operated at a base voltage of 400 V (230 V per phase).

### B. Testing of the NLO Algorithm

The actual testing of the NLO algorithm was done via application of the algorithm to a set of real measurement data obtained at the Strathclyde microgrid. The version of the algorithm used here is based on the algorithm reported in [18].

To simulate realistic grid behavior over time, load and generation curves were chosen for a time period of 10 min and applied to generator B and loads B and C. Measurements of the

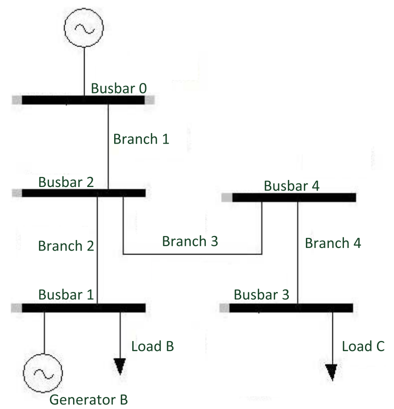


Fig. 8. Schematic of the Strathclyde microgrid used for testing of the NLO algorithm.

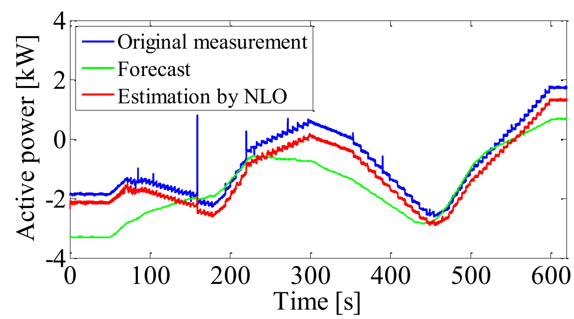


Fig. 9. Results for active power at busbar 1 in setup 1.

positive sequence voltage magnitude and phase (global, with respect to slack node) were performed at every busbar, and active and reactive power were taken simultaneously every 0.05 s at generator C, and loads B and C.

The NLO algorithm requires sufficient measurements of power flow and voltage, depending on the size and complexity of the network, and a forecast of the power drawn from the system. For MV grids, this forecast can usually be taken from load curves provided by the network operator. However, this is more difficult for LV grids, where such information may not be available. Improved forecasting for LV grids and improving the performance of the algorithm with lower quality or absent forecasts is the subject of a future paper. For the results presented here, forecast data are approximately based on the chosen load curves, with some errors introduced as can be seen in Fig. 9, for example.

Since two busbars are internal in the sense that no power is injected or drawn from the grid at these busbars, the order of the measurement system can be reduced to four by introducing perfect measurements of active and reactive power at busbars 2 and 4, which means setting the active and reactive power of these busbars to zero. No other measurements of active or reactive power are used for the NLO calculations. Grid observability is then obtained if the number of voltage measurements is equal to or greater than two.

Three measurement setups were investigated, comparing different choices of placements for voltage measurements.

*Setup 1:* voltage measurement at busbars 1 and 3.

*Setup 2:* voltage measurement at busbars 2 and 4.

*Setup 3:* voltage measurement at busbar 3 (unobservable network).

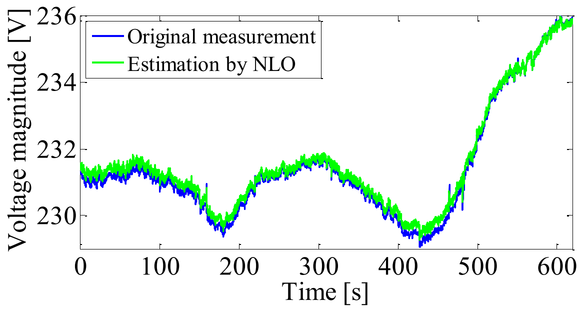


Fig. 10. Results for voltage magnitude at busbar 2 in setup 1.

As a typical example, the results of active and reactive power for setup 1 are presented here in more detail. Fig. 9 shows the measured and forecast active power and active power provided or drawn from the grid at busbar 1 as estimated by the NLO. For convenience, the power which has been injected to the grid is shown with positive sign, power drawn from the grid with negative sign.

It can be observed that the algorithm completely reconstructs the qualitative behavior of active and reactive power over time. However, an offset of maximum 0.5 kW (0.25 kVAR) can be seen between the original measurement and estimation. There are several possible reasons for this. The original measurements may be inconsistent themselves (as can be shown by running a power flow calculation based on measured active and reactive power). In addition, the uncertainties in the line impedances have not been considered so far.

It can also be seen that the incorrect forecasts do not have a significant effect on the estimation of the NLO. Large deviations in power estimates only have a very small effect on the voltage estimates. To demonstrate this, Fig. 10 shows the results for estimation of voltage magnitude at busbar 2 compared with the original measurements (which have not been used for calculations by the NLO). Deviations here are less than 1 V, so the estimation is very close to the original measurement. The results for setup 2 show a similar performance for the NLO: the qualitative behavior of the active and reactive power over time is reconstructed, and the deviation of the estimated voltage from the original measurements is less than 2 V.

For setup 3, the algorithm only reconstructs the qualitative behavior of active and reactive power over time more or less accurately at busbar 3, where a direct voltage phasor measurement is available. Not enough information is available for a complete reconstruction, and at busbar 1 the estimates are forced to follow the (incorrect) forecast. A small correction occurs, based on the minor influence of voltage phasor measurements taken at busbar 3. The deviations are still small at busbar 4, which is a direct neighbor of busbar 3, but larger deviations and a qualitatively different behavior over time was observed at busbars 1 and 2. The results for setup 3 clearly show that in the unobservable case the results almost only depend on the quality of the given forecasts.

## VI. Smart Grid Security

Smart grids are highly critical systems which need to be protected against manipulations and threats. More and more utilities and governments realize that cyber attacks on their grid infrastructure are a very serious threat with immense consequences for society [19]. At the same time, basic precautions such as EU-wide guidelines to ensure secure end-to-end smart grid data communication and control are presently missing. Therefore, research was performed on the design of such a smart grid data security infrastructure.

A security concept for smart grid measurement and control systems first of all needs to determine the critical components and data flows of the grid. Critical elements are all sensors and actors which show the grid state, or influence them, such as measurement devices, switches, controllers, energy management systems, or persons. A main feature of the developed generic security concept is end-to-end security in the data flows between these critical elements, reached on a functional level via a combination of symmetric and asymmetric cryptography. End-to-end security first of all requires that each grid element has a unique identity at the same trusted level. An important further requirement is protection of the security key inside the internal memory of the elements. The authenticity of the exchanged process data has to be testable by the opposite process and reliable measures should be available to verify data integrity, independent of the actual communication channel used to exchange the data. Nowadays, such bidirectional authentication is not used in electricity grids.

Each grid application has to have a signature key and cryptographic algorithm on the same high-protection level. Since a system is so strong as its weakest link, all components must have the same cryptographic strength. Each application furthermore should be able to verify signed data elements using the key of the other application either using a Public key infrastructure (PKI) based on trusted certification authorities or an individual key management system in case of symmetric algorithms. In the design of a secure system, the physical and technical resources have to be considered (timing of the whole processes, execution time, and data transfer time). The advantage of the proposed model is that the security of the communication channel is independent from the data exchange. For the realization of the security concept, different preconditions are needed, such as system-wide unique data elements for the authenticated data exchange between processes.

Appropriate encryption algorithms that can be used are Advanced Encryption Standard (AES), e.g., AES-128, and elliptic curve digital signature algorithm (ECDSA), e.g., ECDSA-256. Signatures have to be generated by a smart card or a crypto controller. The keys generally have to be generated inside the crypto controller if no other special requirements are set. For key management of the asymmetric crypto functions, a well-defined PKI has to be set up. When data encryption is needed, elliptic curve Diffie–Hellman should be used for sharing the AES key. If this approach is followed, the security depends on crypto measures only.

Following the general requirements and findings, all most important functions of a smart grid security infrastructure have been developed in a laboratory test system. ECDSA signatures are used, and the certificates of the measurement and control components are generated by an intermediate certificate, such as used by commercial certification authorities. The first results achieved in this test environment show the complexity in finding operational concepts for trusted measurement systems based on strong cryptography. Especially, the integration of other needed parties and functions, like service, parameterization, or field inspection, appears to be a challenge.

The present work concentrates on the development of special monitoring and verification tools, and the use of other security platforms than the present smart card system. One of the main future challenges is to design a protocol-independent data model, considering the needs of dynamic processes in smart grid measurement and control systems. The final aim is to realize a complete and system-wide smart grid security concept that considers both existing systems and new system requirements, at an acceptable cost.

## VII. Conclusion

Excellent results have been achieved in a European joint research project that tackled several metrological challenges related to the successful development and implementation of smart electrical grids. Significant steps have been made in designing optimal instrumentation of smart grids, dynamic SE using a new NLO algorithm, extension of the revenue metering infrastructure, performance and evaluation of onsite PQ campaigns, and development of a metrological infrastructure for reliable phasor measurements.

Future work will involve expanding PQ campaigns to multiple sites in the same grid to explore PQ propagation through the grid, and research related to application of PMUs in distribution grids, where very small phase angles need to be accurately measured under significant levels of distortion of the grid voltage and current [20]. In addition, work on dynamic SE and optimal sensor placement in distribution grids will be continued, together with the further development of a smart grid security infrastructure.

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## References

[1] G. Rietveld *et al.*, "Measurement infrastructure for observing and controlling smart electrical grids," in *Proc. 3rd IEEE PES Int. Conf. Exhibit. ISGT Eur.*, Berlin, Germany, Oct. 2012, pp. 1–8.

[2] G. Rietveld, J.-P. Braun, P. S. Wright, P. Clarkson, and N. Zisky, "Smart grid metrology to support reliable electricity supply," in *Proc. Conf. Precis. Electromagn. Meas.*, Aug. 2014, pp. 680–681.

[3] *IEEE Standard for Synchrophasors for Power Systems*, IEEE Standard C37.118.1-2011, 2011.

[4] U. Pogliano, J.-P. Braun, B. Voljc, and R. Lapuh, "Software platform for PMU algorithms testing," *IEEE Trans. Instrum. Meas.*, vol. 62, no. 6, pp. 1400–1406, Jun. 2013.

[5] R. Lapuh, "Estimating the fundamental component of harmonically distorted signals from non-coherently sampled data," *IEEE Trans. Instrum. Meas.*, to be published.

[6] J.-P. Braun and C. Mester, "Reference grade calibrator for the testing of the dynamic behavior of phasor measurement units," in *Proc. Conf. Precis. Electromagn. Meas.*, 2012, pp. 410–411.

[7] *Arbiter Model 1133A Power Sentinel User Manual*. [Online]. Available: http://www.arbiter.com/, accessed Aug. 26, 2014.

[8] G. Rietveld, F. Diouf, X. Guo, and E. So, "The establishment of a reference system at VSL for on-site calibration of HV revenue metering systems," in *Proc. Conf. Precis. Electromagn. Meas.*, 2012, pp. 130–131.

[9] *Instrument Transformers—Part 1: Current Transformers, Instrument Transformers—Part 2: Voltage Transformers*, IEC Standard 60044-1 and IEC Standard 60044-2, 2003.

[10] A. Bergman, "*In situ* calibration of voltage transformers on the Swedish national grid," Ph.D. dissertation, Inst. High Voltage Res., Uppsala Univ., Uppsala, Sweden, 1994.

[11] E. So, P. N. Miljanic, and D. J. Angelo, "A computer-controlled load loss standard for calibrating high-voltage power measurement systems," *IEEE Trans. Instrum. Meas.*, vol. 44, no. 2, pp. 425–428, Apr. 1995.

[12] P. S. Wright and P. Clarkson, "Development of an ethernet-enabled digitizer for on-site AC measurements," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 7, pp. 2229–2234, Jul. 2011.

[13] P. S. Wright, G. Murphy, K. Lennon, and P. Clarkson, "Measurements of power quality and voltage level effects associated with a photo voltaic cluster on a domestic housing estate," in *Proc. 22nd Int. Conf. Exhibit. Electricity Distrib.*, Stockholm, Sweden, 2013, pp. 1–5.

[14] *Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines*, IEC Standard 61400-21, 2008.

[15] A. J. Roscoe, A. Mackay, G. M. Burt, and J. R. McDonald, "Architecture of a network-in-the-loop environment for characterizing AC power-system behavior," *IEEE Trans. Ind. Electron.*, vol. 57, no. 4, pp. 1245–1253, Apr. 2010.

[16] A. Venturi *et al.*, "The role of accurate measurements within smartgrids," in *Proc. 2nd IEEE PES Int. Conf. Exhibit. Innov. Smart Grid Technol. Eur.*, Manchester, U.K., Dec. 2001, pp. 1–6.

[17] R. Singh, B. C. Pal, and R. A. Jabr, "Choice of estimator for distribution system state estimation," *IET Generat., Transmiss., Distrib.*, vol. 3, no. 7, pp. 666–678, Jul. 2009.

[18] W. Heins, N. Ell, H.-P. Beck, and C. Bohn, "State observation in medium-voltage grids with incomplete measurement infrastructure through online correction of power forecasts," in *Proc. Eur. Control Conf. (ECC)*, Strasbourg, France, 2014, pp. 1306–1312.

[19] Energy Sector Control Systems Working Group. (Sep. 2011). *Roadmap to Achieve Energy Delivery Systems Cybersecurity*. [Online]. Available: https://smartgrid.gov/node/58256

[20] P. S. Wright, J. P. Braun, G. Rietveld, H. E. van den Brom, and G. Crotti, "Smart grid power quality and stability measurements in Europe," in *Proc. Conf. Precis. Electromagn. Meas.*, 2014, pp. 70–71.

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