APPLICATION OF PMUS FOR MONITORING A 50 KV DISTRIBUTION GRID

Gert RIETVELD
VSL – The Netherlands
grietveld@vsl.nl

Arjen JONGEPIER
DNWG – The Netherlands
ajongepier@dnwg.nl

Joeri VAN SETERS
DNWG – The Netherlands
jvanseters@dnwg.nl

Marco VISSER
DNWG – The Netherlands
mvisser@dnwg.nl

Pei LIU
TU Delft – The Netherlands
P.Liu-2@student.tudelft.nl

Milos ACANSKI
VSL – The Netherlands
macanski@vsl.nl

Dennis HOOGENBOOM
VSL – The Netherlands
dhoogenboom@vsl.nl

Helko E. VAN DEN BROM
VSL – The Netherlands
hvdbrom@vsl.nl

ABSTRACT

The strong variability of energy produced by renewable energy sources is challenging the stability of distribution grids. This calls for improvement of the grid monitoring and control infrastructure with faster and more accurate measurement equipment. In a joint effort of the Delta Network Group (DNWG) and VSL, the national metrology institute of the Netherlands, a project is started for monitoring a heavily loaded 50 kV ring of the DNWG network with phasor measurement units (PMUs). A set of six PMUs is installed in five substations of the ring with the aim to gain more insight in the grid behaviour, especially in dynamic events caused by the large amount of RES connected to the 50 kV ring. Before installation, the PMUs have been tested in order to verify their ability to measure the small phase angle differences occurring in the distribution grid. The main initial PMU applications will be the detection of oscillations and other dynamic events in the DNWG 50 kV grid, and the monitoring of power flows and power/voltage stability. The first measurement results are expected to become available in early 2015.

INTRODUCTION

Renewable energy sources (RES) such as wind or solar power greatly affect distribution networks. Increased energy flows and especially their rapid variation due to the variable nature of the feed in from RES may lead to static, dynamic, or transient overload phenomena. For the DELTA Network Group (DNWG), one of the distribution network operators (DNOs) of the Netherlands, this specifically becomes a problem in one of its 50 kV distribution grids. Here, a significant amount of electricity is produced by wind farms, solar panels, and combined heat and power (CHP). Especially greenhouses with large CHP installations may either be a source or a load depending on the load situation, energy market, and weather conditions. Combined with grid switching operations and the behaviour of other sources and loads, the number of fast, dynamic events and transients is rapidly increasing in this heavily loaded grid.

The present monitoring and maintenance of the DNWG 50 kV grid is based on offline models and calculations for dynamic grid phenomena, combined with real-time current and voltage measurements for the static grid behaviour. At present, these measurements are performed relatively infrequently, only once every 1 – 10 seconds. It is expected that better measurements, that is more frequent and also more accurate measurements, in combination with near real-time processing of the data will provide the opportunity for more effective monitoring and control of the energy flows, and for early warning of possible grid instabilities. Phasor measurement units (PMUs) are a promising technology for realising such an improved grid measurement infrastructure [1].

In a joint effort of DNWG and VSL, the national metrology institute of the Netherlands, a “Proof of Concept” project has been started to apply PMU technology in the heavily loaded DNWG 50 kV distribution grid. The paper first describes the aim of the project, followed by a short description of the 50 kV DNWG distribution grid and the relevant possible PMU applications. The second part of the paper describes the selection, testing, and actual installation of the PMUs in the DNWG 50 kV grid. In the conclusions and outlook, the results achieved so far are summarised together with an indication of the ongoing and future work.

AIM OF THE PROJECT

The overall aim of the joint DNWG–VSL project is to realise more efficient and more effective management and operation in a highly-utilized 50 kV distribution grid. This should improve the reliability and availability of the grid and provide insight on the impact of renewable energy sources on grid stability, which should eventually result in cost savings via delaying or even preventing expensive grid expansions.

The project aim will be realised via the development of several applications based on PMU technology installed in the grid. Since at present not many PMUs are actually available in distribution grids, the DNWG–VSL project is considered as a “proof of concept” project which should provide useful knowledge and insight in the added value of PMU technology for distribution grids.

An additional project aim for DNWG is to gain experience with integration of new technologies into the DNWG infrastructure (both hardware and ICT), as well as with the sharing of large amounts of data with external parties in a safe and reliable way.

DNWG 50 KV RING

The Delta Network Group (DNWG) is one of the DNOs in the Netherlands with over 10.000 km of network length, providing electricity and gas to more than 200.000 customers. The DNWG grid is located in the south-west of the Netherlands, near the North Sea. This makes the area ideally suited for significant RES generation using wind parks. The additional significant feed in from CHP greenhouse installations results in an overall system generation that is roughly double the 300 MW system load.

Figure 1 shows a geographic picture of the DNWG 50 kV distribution ring. It consists of a northern and southern part, with the end points connected to the 150 kV transmission grid. The northern part of the ring has a length of around 57 km, all cable except for 2 km, with several water crossings. It contains 5 substations with 50/10 kV power transformers feeding the local 10 kV distribution grids. Apart from significant RES generation, additional power flows are caused by the fact that the 50 kV north ring is in parallel with a main 150 kV overhead line. The nuclear power plant of Borssele, west of the 50 kV ring, is providing a significant amount of energy to the rest of the Netherlands via this 150 kV line. This energy partly flows via the 50 kV ring, leading to additional loading of the ring.

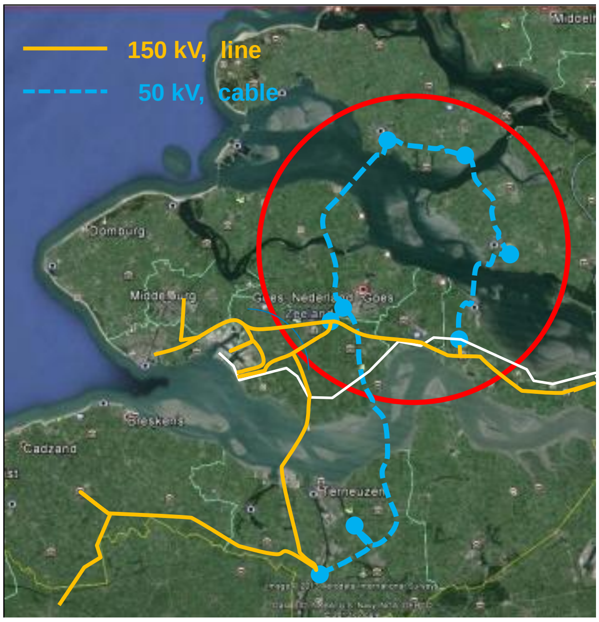

Figure 1. Geographic layout of the DNWG 50 kV grid (blue dashed line), with the northern part marked by a (red) circle. The 50 kV substations are marked with dots.

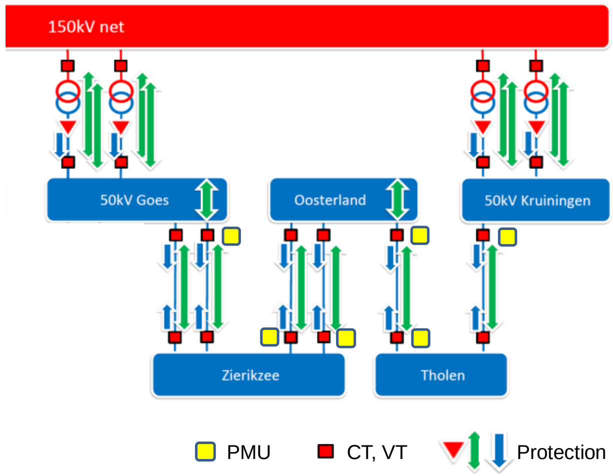

Figure 2. Schematic of the DNWB 50 kV north ring indicating the substations and the six PMU measurement locations.

Figure 2 gives a schematic of the 50 kV north ring indicating among others the final PMU measurement locations. The decision was to install at least one PMU in each substation of the ring in order to have maximum observability with information on the voltage phasors of all five substations. An envisaged outcome of the project will be the determination of the minimum number of PMUs required to have sufficient monitoring of the grid.

Since DNWG is particularly interested in monitoring all power flows through the 50 kV grid, an extra PMU was installed in the Zierikzee substation. The two cables between Zierikzee and Oosterland have different impedances which requires to measure the current in both cables in order to have the complete power flow between these stations. The two cables between Goes and Zierikzee have essentially equal impedances so that a measurement in only of the cables is sufficient.

PMU APPLICATIONS

Several authors have discussed possible applications of PMUs in distribution grids, see for example [2]-[5]. In this section we shortly review the applications that we consider for implementation in the present project.

Power flow

First of all, PMUs can be used to monitor the power flow in the grid substations. Changes of loads and of RES generation connected to the grid can be easily detected through variations in power flow. Their fast reporting rate give PMUs a significant advantage with respect to energy meters already installed in the grid. It makes PMUs much more suitable for analysis of fast changes in energy consumption or generation and for timely detection of imminent overloads in the grid.

State Estimation

PMUs can greatly contribute to improvement of state estimation techniques since they perform a direct measurement of the state vector, made up of bus voltages' magnitudes and phase angles. This direct measurement greatly reduces the required computational time in the state estimation process, while the fact the PMUs produce truly synchronised data significantly enhances its accuracy. Even though state estimation of distribution networks is not widely spread, PMUs can give significant benefits in among others the estimation of dynamic grid behaviour [2],[3].

Dynamic Monitoring & Oscillation Detection

Grid oscillations can be triggered by a disturbance, such as a generator trip or fast change in RES energy supply. It is important that the grid is stable and well-damped so that it quickly settles back to normal operating values after such an event. The high sampling speeds of PMUs, up to 50 readings per second, make them ideal for detecting grid oscillations and to facilitate damping actions taken by the grid operator [4],[6],[7].

Dynamic Line Rating (DLR)

PMUs have particular advantages with respect to other grid impedance measurement techniques [8] and dynamic line rating (DLR) based on impedance measurements [9]. DLR allows for temporarily larger power flows than the static design values, and thus facilities the incorporation of a large amount of volatile RES without the need of grid expansions.

Power Quality (PQ)

Non-linear loads cause disturbances in the grid voltage waveform. Solar panels and wind farms are known to be significant sources of bad power quality (PQ). Since PMUs make GPS-time stamped samples of the voltage and current waveforms, they can also be used for synchronous PQ measurements [10], which is advantageous for analysis of propagation of PQ phenomena [11].

PMU TESTING AND INSTALLATION

The quality of the measurement data resulting from the PMUs is very important for the successful realisation of reliable grid operator applications. Therefore, careful attention was paid to the selection, testing, and installation of the PMUs.

PMU requirements

An important criterion for the selection of the PMUs is compliance with the IEEE C37.118.1 standard [12]. This standard defines a large series of tests with static and dynamic signals for which PMUs should generally not have a total vector error of more than 1 %. This 1 % error can be caused by a magnitude error, a phase error, or an arbitrary combination of the two. For application in distribution grids it is important that the PMU has low noise since the phasor differences in these grids are smaller than those in transmission grids.

Since the focus in the DNWG–VSL project is on the application of PMUs in distribution grids, and on demonstrating their added value, a strong preference existed to use proven PMU measurement technology including a central phasor data concentrator (PDC) with software for real-time data analysis. The final choice was to use Arbiter 1133A PMUs with Elpros WAProtector software[1]. An important feature of this software platform is that it allows for development of custom user applications. One of the advantages of the Arbiter 1133A PMU is that it also performs truly synchronous PQ measurements [10]. This will significantly extend the present limited PQ-measurement scheme in the DNWG grid.

PMU testing

For any electronic measurement device, it is important to calibrate and verify its performance before its use in critical applications. This is particularly relevant for application of PMUs in distribution grids. Here, even the extensive tests of the IEEE C37.118.1 standard [12] not fully cover all requirements of these grids. For example, better phase accuracy is required in distribution grids as well as better accuracy at low current levels.

Therefore, before installation in the DNWG grid, VSL tested the PMUs using a series of static test signals. The tests covered a range of voltage, current, frequency, and phase angle values. The nominal voltage, current, and frequency were 63.5 V, 5 A, and 50 Hz respectively. Figure 3 shows the VSL reference setup used during the test. DACs with power amplifiers generate the 3-phase test signals and ADCs with reference voltage dividers and current shunts are used to measure the applied signals.

Figure 3. VSL system for PMU testing.

[1]The manufacturers and instrumentation mentioned in this paper do not indicate any preference by the authors, nor does it indicate that these are the best available for the application discussed.

As an example to the results achieved in the tests, Figure 4 gives the results of the current tests at different current levels for 4 of the PMUs. For clarity, the result of only one channel per PMU is shown; the other channels show similar results. The IEEE C37.118.1 standard requires an accuracy of 1 % in magnitude and 0.57° in phase down to 10 % of nominal current. The PMUs clearly are well within these limits, even down to 1 % of nominal current. Further examination, taking into account application requirements and other system parts will show if the larger error at low current levels is acceptable or not.

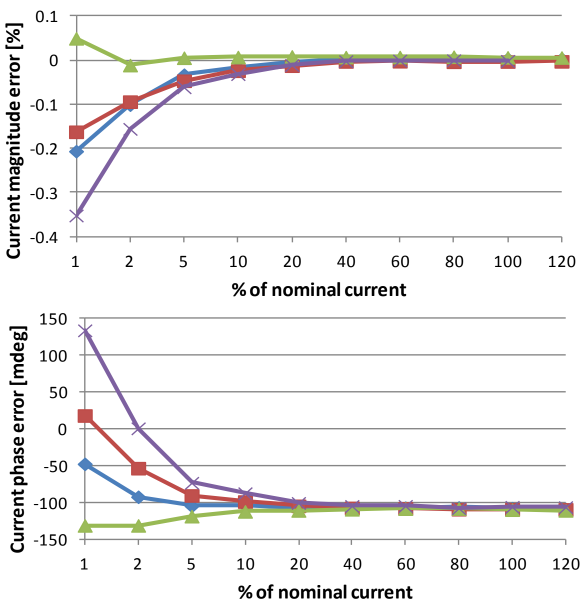

Figure 4.Current magnitude and phase errors of 4 PMUs as a function of current levels. Nominal current is 5 A.

For some PMU applications consistency between PMUs is more important than absolute accuracy. Dynamic line rating applications, for example, are very sensitive to inconsistencies in voltage magnitude and phase measurements. Therefore the PMUs were also tested for voltage at different voltage levels. Figure 5 shows the results of these tests for the same 4 PMUs as above. It can be seen that all PMUs give very consistent and repeatable results, within 0.01 % in magnitude and 10 m° in phase. This is far beyond the standard requirements [12], but still very useful in DLR applications.

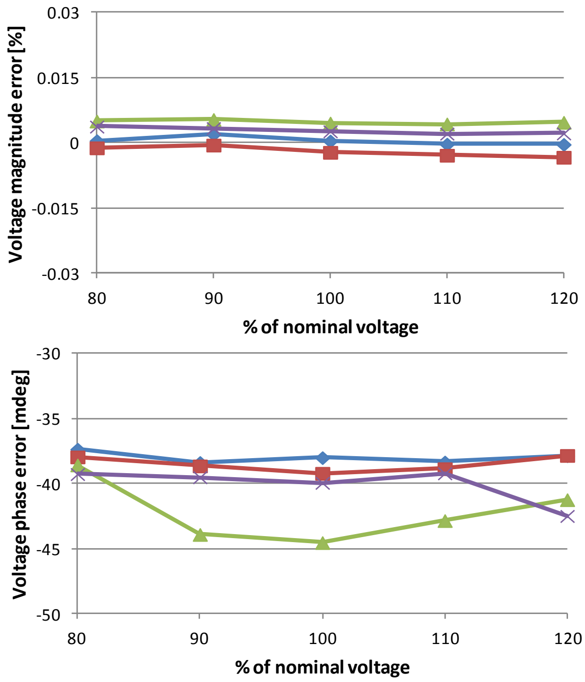

Figure 5. Voltage magnitude and phase errors of 4 PMUs as a function of voltage level. Nominal voltage is 63.5 V.

PMU installation

The preparation and actual installation of the PMUs in the five substations of the DNWG 50 kV ring was very similar to the installation of for example energy meters. The main difference was that in addition GPS antenna's had to be installed and a higher bandwidth communication channel to the regional control server is required.

The PMUs were connected to the secondary outputs of the current transformers (CTs) and voltage transformers (VT) of the primary installation. Each substation has two VTs, installed in the two central rail bus bars of the substation. Switches in the secondary wiring of the VTs ensure that the PMU input is always connected to the VT in the rail feeding the line bay where the phasor measurement is to be performed. The CTs in the line bays have both protection and measurement cores. In order to achieve sufficient accuracy in the current and power phasor measurements, the PMUs are connected to the metering cores. Selecting the measurement cores protects the PMU input circuitry during short circuits in the grid, but limits the application of the PMU for detection of large grid disturbances such as faults. Both the VTs and metering CTs typically have class 1 accuracy. Only the Oosterland substation, that was added later to the 50 kV ring, has VTs and CTs of better accuracy class, namely class 0.5 and 0.1 respectively.

The GPS antennas were installed at the outside of the substation buildings. It never appeared to be a problem to continuously have at least 5 GPS satellites in view. At most 20 meters of cable was required to connect the GPS antenna's to the PMUs. In order to prevent small phasor differences due to differences in cable lengths, all GPS cables were selected to have the same 20 m length.

For sending the PMU data to the PDC in the regional control centre, the already available DNWG communication infrastructure is used. The PMUs were connected to the local network switch in each of the 5 substations. For connection with the PDC a virtual network was defined, separate from the other network services (metering, protection, control) using the same glass fibre ring infrastructure.

After installation, all PMUs were tested on their correct configuration and installation. Figure 6 shows a typical result of the tests. In the first part of the test, the PMUs were not yet connected to the VTs and CTs and an external voltage and current source was used to verify the polarity of the PMU connections and the applied scaling factors. The PMUs subsequently were connected to their respective VTs and CTs, and their voltage, current, and power readings were compared with those of a fault recorder connected to the same line bay.

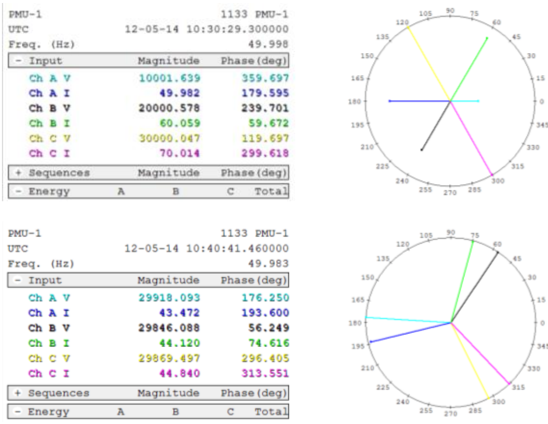

Figure 6. Installation test results of a PMU in the 50 kV DNWG ring, using an external voltage and current source (top) and when connected to the VTs and CTs in the grid (bottom).

CONCLUSION AND OUTLOOK

A joint DNWG-VSL project is started on the application of PMUs in a heavily-utilised 50 kV distribution grid in the Netherlands, with a significant amount RES generation. The aim of the project is to realise more efficient and more effective grid management and operation, and to gain insight on the impact of RES on grid stability and dynamic behaviour.

A series of 6 PMUs have been installed in the substations of the 50 kV grid. Extensive laboratory tests before the installation show that for the static tests performed, the PMUs give very consistent and reproducible results, well within the 1 % magnitude and 0.57° phase limits posed by the IEEE C37.118.1 standard [12]. This is especially important for the present application in the DNWG distribution grid, where the phasor differences between substations are expected to be of the order of only 0.25 % and 0.14 m° at 10 % of nominal current.

The CTs and VTs where the PMUs are connected to typically are of accuracy class 1, and thus are a major limiting factor in the overall accuracy of the grid phasor measurement. Present work includes the evaluation of the CT and VT test reports, so that their magnitude and phase displacement errors can be corrected for in PMU applications requiring high accuracy.

Early 2015, all PMUs will be connected to the PDC and work will start on the implementation of PMU applications. These will include the monitoring of power flows, detection of oscillations, and a trial on dynamic line rating (DLR) using PMUs. At the conference, further details will be presented on the design and implementation of the PMU monitoring system, together with first measurement results.

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