EXPERIENCE WITH FIRST SMART, AUTONOMOUS LV-GRIDS IN GERMANY

Christian OERTER
Wuppertal University – Germany
christian.oerter@uni-wuppertal.de

Nils NEUSEL-LANGE*
Wuppertal University – Germany
neusel-lange@uni-wuppertal.de

Philipp SAHM
Wuppertal University – Germany

Markus ZDRALLEK
Wuppertal University – Germany
zdrallek@uni-wuppertal.de

Wolfgang FRIEDRICH
Bilfinger Mauell GmbH – Germany
wfr@mauell.com

Martin STIEGLER
SAG GmbH – Germany
martin.stiegler@sag.eu

ABSTRACT

The ongoing shift towards a more decentralized and renewable energy system in Germany requires extensive modifications to existing grids and their operating principles – especially at the distribution level. Furthermore, the integration of e-mobility will have a significant effect on distribution grids.
Smart distribution systems are one way of handling these new supply scenarios. Hence, a self-sustaining monitoring and control system for LV-grids has been developed. It monitors the power flow situation and is able to control the grid if necessary. The system has been implemented in four LV-grids in Germany. The present paper describes the automation system and our initial experience with this smart grid approach.

INTRODUCTION

During the past decade, utilization of power systems in Germany has changed considerably due to a fundamental shift in the variety of power generation. Never before have so many decentralized generation units been integrated into distribution grids. In the near future, e-mobility will also exert significant influence on distribution grids – again, especially at the LV-level. As a result, violations of the permitted voltage range and exhaustion of the grid components' capacity will push distribution grids to their limits. While these critical grid states already occur for several hours today, they are expected to be a frequent problem tomorrow.
In general, there are two possible solutions to these problems. The first solution is the extensive enhancement of grid structures, which means strengthening or replacing transformers and cables with new components offering more capacity. This solution might be useful for single grids, or, in some cases, inevitable, if the grid faces off-limit-conditions most of the time. Then again, it is impossible to renew every grid structure completely, primarily for cost reasons.
The second solution is therefore the enhancement of existing grids in the direction of smart grids, which means integration of automation devices and surveillance technologies. Power-system experts agree that these smart distribution systems will be a crucial element in tomorrow's power systems. Research and development is focusing on this topic and several different approaches have been elaborated to establish smart distribution systems.
The change in grid operating methods permits handling of the critical grid states described above while also offering new ways of operating and maintaining. This paper presents an automation system for LV-grids, consisting of a state-identification module and a grid control method based hereon. Moreover, experience from ongoing field tests will be depicted.

MONITORING LOW VOLTAGE GRIDS

A first step towards smart distribution grids – monitoring of a grid – provides necessary information related to power quality, capacity utilization etc. Today, there might be particular measurement points within LV-grids in some cases but usually there is no monitoring system to cover the entire LV-grid.

Grid-State Identification

With respect to the increasing utilization ratio of distribution grids, capacity shortages and decreased voltage stability may appear at any point in the grid. By using state-identification methods, it is possible to determine the location of the problem. Moreover, grid-state identification is the primary requirement for any continuative surveillance or control method.
As stated above, necessary measurement and surveillance equipment is usually not installed at the LV-level, neither for single grid components nor for the entire grid itself. Considering the numerous distribution grids in Germany, it is impossible to fully equip them with measurement technology from a financial point of view. Hence, a monitoring system for LV-grids has to meet two obviously contrary requirements: a minimum number of measurement devices (denoted as sensors) and a maximum of supervision, i.e. of the entire grid. Power-flow calculation for LV-grids with a sparse sensor environment is a new challenge involving online monitoring of the grid state with scarce measurement data, resulting in an under-determined system of equations [1]. Moreover, power flows at the LV-level cannot be assumed to be symmetric like at the MV-level and above but are asymmetric and require phase-selective treatment.
However, a grid-state identification algorithm which meets

those requirements has been developed and implemented [2, 3]. The algorithm permits online calculation of the grid's state represented by nodal voltages and branch currents for each phase within the entire LV-grid. The algorithm consists of two main components:

- a power-flow algorithm, adapted and optimized for phase-selective calculation of power flows in LV-grids with respect to possible unbalance of the voltages and currents on each phase
- a predictive algorithm for estimating load and feed currents based on sparse measurement data to compensate for the lack of information caused by the sparse sensor environment.

Thus, it is possible to evaluate power quality and grid utilization. The monitoring system supervises the grid state periodically, such as every 30 seconds.

As the number of sensors within the grid should be minimized, there is a distinction between two types of sensors. There are a number of mandatory sensors which are crucial for the monitoring system to work properly. This is the minimum number of sensors. Every additional sensor is facultative and will improve the system's accuracy. The number of mandatory sensors depends on the grid's topology.

The monitoring system is also the foundation of the control algorithm described in the next chapter.

Automatic Recognition of Grid Topology Changes after Switching Operations

Switching operations within the grid can become necessary due to planned or unplanned events and will result in a change of the grid's topology. As grid-state identification depends on accurate topology data, the change in the grid's topology will result in more or less serious calculation errors in the state-identification process, if the data is not updated. Fortunately, it is possible to determine different grid topology data sets in advance in most cases as the number of switches or switching possibilities is limited.

In order to make distribution grids as smart as possible and to support the operator, such changes in topology should be recognized automatically. For this reason, an algorithm has been developed to detect the current topology state [4, 5]. With respect to the limited number of switching points, all possible switching states are determined in advance. The topology pre-sets are then stored within a topology catalogue and are transferred to the topology recognition algorithm. Fig. 1 illustrates the concept.

The topology recognition algorithm is summoned periodically after a specific period of time, such as every 60 minutes. Within the recognition algorithm, the state of the grid is calculated using only the mandatory measurement units. The calculation is executed consecutively for each element of the topology catalogue. The facultative elements of the grid's measurement topology do not enter into these calculations: they are reserved for the next step of the technique.

Now, after a unique grid-state estimate has been attributed to all elements of the topology catalogue, the deviation of the reserved facultative measurements from the values provided by the estimated grid state is calculated and pushed into an error vector for each element of the topology catalogue.

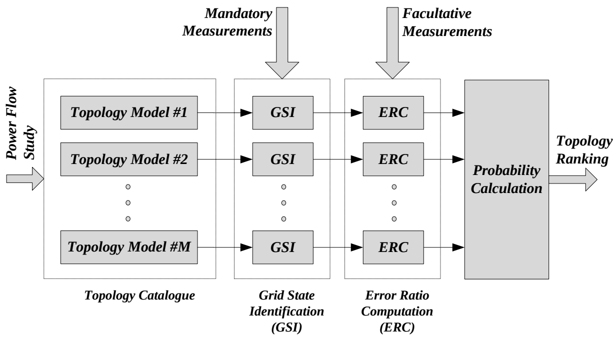

Fig. 1: Concept of the topology-recognition algorithm

The described technique is based on the following axiom: at a given point in time, one of the elements within the topology catalogue will cause significant minor deviations of the estimated values from the real values, as this element is the most correct configuration within the topology catalogue, compared to the real grid topology. Hence, the probability that this particular topology pre-set will be larger than the probability of the other pre-sets. To eliminate measurement errors, this procedure is executed five times within a short period of time. If one of the elements of the topology catalogue can sustain its position at the top of the probability ranking, this element will replace the current active topology pre-set.

Test and Verification of the Identification Methods

Both techniques described above have been the subject of several extensive functionality tests within a simulation and test environment. Fig. 2 shows the test environment for the state identification algorithm. Randomly generated realistic load and generation profiles were used to compute reference power-flow scenarios. Then, virtual values were derived from these reference scenarios and were calculated using the newly developed algorithms. The deviation from the exact power flow was determined afterwards.

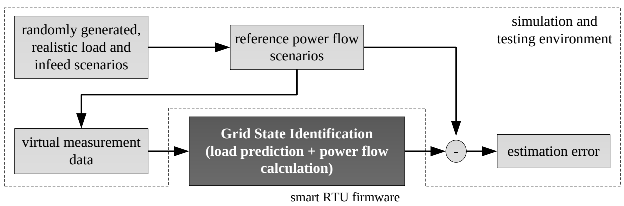

Fig. 2: Simulation and test environment

The proof of concept of both methods, especially relating cost-effectiveness, robustness and performance, has been demonstrated in previous work [2, 3, 5].

CONTROL OF LOW VOLTAGE GRIDS

The second step towards smart distribution grids is thus the possibility of controlling the grid, especially as a remedy for critical grid states. Based on the monitoring system described above, a control system for LV-grids has been developed. One main requirement of this control system is autonomous operability: critical grid states should be corrected without the grid operator's interaction. With respect to the numerous LV-grids, autonomous operation is crucial for efficient operation.

Overview of the Control Process

There are three control methods to respond to violations of the permitted voltage range:

1. Voltage control for the entire low voltage grid or single lines by use of a controllable transformer or voltage regulator (if available and feasible)
2. Power-factor control of individual generation, load and storage units at or near the location of the interference point
3. Active power curtailment of individual generation, load and storage units if inevitable.

These three control methods have been combined into a 3-stage control model, illustrated in Fig. 3.

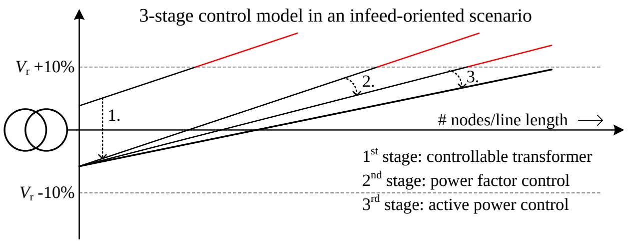

Fig. 3: 3-stage control model (infeed-oriented scenario)

If the grid's capacity is exceeded, active power curtailment is the only method to handle this overload situation. The first two stages will thus be skipped in this case.

The 3-stage control model has been integrated into the firmware of the automation system. By controlling available controllable devices (denoted as actuators) within the grid, it will be possible to correct the critical grid state.

Closed Loop Control

The control system acts in similar fashion to a closed loop controller. The monitoring system compares measurement values gathered periodically at the set points for the grid. If a critical grid state is detected, such as a violation of the permitted voltage range, the control process will be activated. After analysis of the current grid state and determination of the most critical nodes or branches within the grid, the control algorithm selects the most suitable actuator to solve this off-limit-condition. Eligibility criteria for selection of an actuator are the current stage of the control process, the individual capabilities of the actuator such as control ranges, response times, availability etc., and the electrical distance (i.e. the impedance) between the most critical point and the position of the actuator within the grid. After selection of the most suitable actuator, a control command will be triggered for this device. In the next cycle of the monitoring process, for example, after 30 seconds, the effects of the control command will become visible and renewed analysis of the grid state will show whether the critical grid state has been corrected. If the critical grid state persists, the control process will be reactivated, the most suitable actuator will be selected and the next control command will be triggered.

Like any other closed loop controller, a few cycles are necessary to compensate for disturbances and to get the grid back to a safe operating state. The time required for solving the off-limit-condition depends on the cycle interval time set in the monitoring and control system.

Forecasting Control-Command Effects

In order to optimize the entire control process, a second operation mode for the control system has been implemented. This mode provides a forecasting module which can evaluate the effect of control commands in advance before a command is triggered to the actuator. In case a single command is not sufficient to solve the off-limit-condition, further control commands are computed until the forecasting module confirms that the off-limit-conditions are corrected. Afterwards, the control commands are triggered to multiple actuators, if necessary.

This operation mode has the advantage of compensating for disturbances within only one cycle of the monitoring and control process (referring to cycle interval times from 10 to 30 seconds and cycle times in the lower hundred-millisecond range). Fig. 4 illustrates the differences between the two operation modes. In the direct mode, the control module is summoned consecutively after grid-state identification, if a critical grid state is identified. In the optimized control mode, a link between the different modules ensures that (one or more) optimal control commands are triggered.

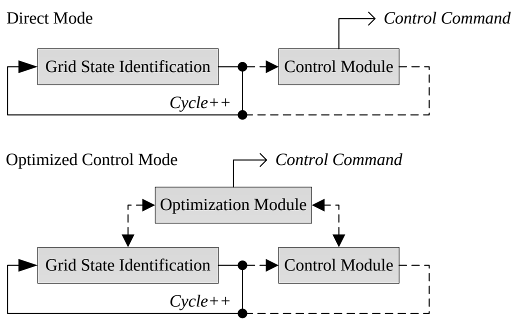

Fig. 4: Comparison of the two control system operation modes

Active power curtailment should be avoided as long as possible. If this step is inevitable, it should be as minimal as possible. The forecasting module can support this requirement by optimizing control commands.

An example depicts the forecasting model for active power control:

The active power output of distributed generators often can be controlled in predefined steps, e.g. 100%, 60%, 30% or 0% of the nominal power output. In order to forecast the effect of a power feed-in-reduction of such a device, e.g. from 100% to 60%, the difference of 40% power output will be modelled as a virtual load. The load current will be approximated by equation (1):

$$I_{diff} = -\frac{P_{diff}}{(3 \cdot U_Y)} \text{ with } P_{Diff} = \frac{(P_{actual} - P_{set})}{100} \cdot P_n \qquad (1)$$

A power-flow calculation is then executed where every load/in-feed current except this particular virtual load and the slack bus voltage is adjusted to zero. The results of this power-flow calculation (2) directly represent the influence of power reduction to the node voltages of the grid:

$$\boldsymbol{Y} \cdot \boldsymbol{u}_{Diff} = \boldsymbol{i}_{Diff} \qquad (2)$$

By superposing (3) this virtual differential voltage vector to the currently valid voltage vector for the grid, the resulting voltage of every node can be calculated:

$$\boldsymbol{u}_{(s+1)} = \boldsymbol{u}_s + \boldsymbol{u}_{Diff,s} \qquad (3)$$

It will then be possible to calculate the resulting branch currents.
This method makes it easy to forecast the effect of active power control within the grid.

FIELD EXPERIENCE

As proof of concept of the developed algorithms, their functionalities have been tested extensively in a virtual environment. Nevertheless, the developed approach has to stand the test of real operating conditions. Therefore, a series of real field tests has commenced. The automation devices have already been installed and set up running on four LV-grids in Germany.

Initial Results from Field Tests

The first field tests focused on the monitoring system. The prediction algorithm for missing measurement data in particular, whose functionalities had already been verified in a virtual test environment, had to be tested under real conditions where measuring errors would have an influence on accuracy.
A way to validate the functionality of the state-identification technique is to compare calculated state variables to measured values that were excluded from the power-flow calculation. To keep calculation results at the requested accuracy level, the measurement topology of the automation system was overdesigned for testing purposes. This allowed the exclusion of particular sensors from the power-flow calculation for use as reference measurements. The analyses were performed for an extensive period of time. The deviations between the state identification method, including calculation and measurement errors, and the reference measurements were ±1.49% at maximum. It has been proven that the developed approach and the installed sensors offer adequate accuracy related to the requirements at the LV-level [5].

Field-Test Road Map

The functionalities of the control algorithm will be verified under real conditions, optimized and extended in upcoming tests. For this purpose, some backup generators will be connected to the grid which can simulate the behaviour of different distributed generators like photovoltaic generators or combined heat and power (CHP) units. These generators will be equipped with automation devices so that the system can control them as an actuator. These test methods make it possible to test the control system without affecting customers connected to the grid.

CONCLUSION

The present paper describes a smart grid approach with a self-sufficient automation system for LV-grids. There are to main components in the system's firmware: the grid-state identification module is responsible for calculating an accurate power flow, based on few sensors and an estimation algorithm, whilst the control module is activated if a critical grid state is identified. The system is designed to work autonomously; only if there are severe problems the grid operator's control centre will be notified. Nevertheless, the operator is able to get real-time information on the current status of the system at any time. The system enables the grid operator to better use existing grid capacity and to delay grid enhancements. The system will be used for an e-mobility research project and is supposed to be adapted for MV-grids as well.

REFERENCES

[1] N. Neusel-Lange, C. Oerter, M. Zdrallek, W. Friedrich, M. Stiegler, T. Wodtcke, P. Birkner "Sichere Betriebsführung von Niederspannungsnetzen durch dezentrale Netzautomatisierung" (International ETG conference, Würzburg 2011)

[2] N. Neusel-Lange, C. Oerter, M. Zdrallek "State Identification and Automatic Control of Smart Low Voltage Grids" (3rd IEEE PES ISGT Europe, Berlin 2012)

[3] C. Oerter, N. Neusel-Lange, M. Zdrallek, P. Kloeker, W. Friedrich, J. Antoni, P. Birkner "Practical Experience with Smart Low Voltage Grids" (VDE congress, Stuttgart 2012)

[4] N. Neusel-Lange, C. Oerter, M. Zdrallek "First Practical Experience with Smart Low Voltage Grids" (1st IEEE SG-TEP, Nuremberg 2012)

[5] C. Oerter, N. Neusel-Lange, C. Zbros, M. Zdrallek, P. Kloeker, U. Dietzler: "Smart Control of Low Voltage Grids – Application Results" (CIGRE/CIRED Symposium on Smart Grids, Lisbon 2013)

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