The Strijp-S living lab for embedded microgrid studies

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ABSTRACT

Some existing challenges with the integration of distributed energy resources (DER) and embedded microgrids are: congestion and voltage management, and fault protection issues. Until now, a limited amount of field experiments have been performed with embedded microgrids. This paper presents the Strijp-S living lab for embedded microgrid studies. The living lab consists of an urban distribution network with over 1000 consumers. For experimentation, advanced measurement equipment, automated switchgear and a high penetration of DER are installed in the living lab. Over the coming years the important challenges with the integration of DER and embedded microgrids will be addressed by universities and industrial partners.

INTRODUCTION

The integration of DER (e.g. photovoltaics, electric vehicles, and energy storage) in distribution networks poses a variety of challenges, such as: overloading of network components, voltage violations, and fault protection issues [1]. These problems impact the reliability and security of the network, and conventional solutions (e.g. network reinforcements) are typically expensive to implement, or non-existent.

Network operators investigate alternative, cost-effective solutions to mitigate these challenges. Enabling embedded microgrids with the integration of advanced measurement devices, automated switchgear and DER is identified as an effective solution [2]. Microgrids can coordinate DER to manage congestion in normal operating conditions by exploiting flexibility. While in fault conditions microgrids utilize automated switchgear to enable islanded operation [3].

Congestion and voltage management in distribution networks can be ensured by applying flexibility. This however poses new challenges to the network operator. The network operator has to forecast the load profile and implement a method to translate the forecasted load profile into a decision to utilize flexibility at a given location, time, and duration [4]. The uncertainty of the available flexibility has to be taken into account, which is dependent on the flexibility mechanism (e.g. price-based, direct control, market-based) in place [5].

Islanded operation of embedded microgrids requires effective control of DER. A hierarchical control architecture is commonly proposed in literature to provide local voltage and frequency control, and to resynchronize with the main grid [6]. Although islanded microgrid operation is a popular research area, challenges such as stability and power sharing between DER have yet to be solved, and tested with field experiments [7].

The dynamic behavior of embedded microgrids differs from conventional distribution grids. Embedded microgrids have fast changing bidirectional power flow and voltages in grid-connected operation. When switching to islanded operation can make the power flow and voltage in the network even more dynamic, while also the frequency can deviate from nominal [8]. To determine the network states (e.g. voltage, power flow and frequency) during the fast dynamics of embedded microgrids, dynamic state estimation (DSE) can be utilized.

Conventional fault protection devices such as fuses and overcurrent relays are inadequate to protect embedded microgrids due to the bidirectional power flows, varying fault currents and changing topology of microgrids [9]. Several novel protection systems have been proposed in literature to mitigate these issues [10]. However, no real-life testing and validation of these systems has been performed.

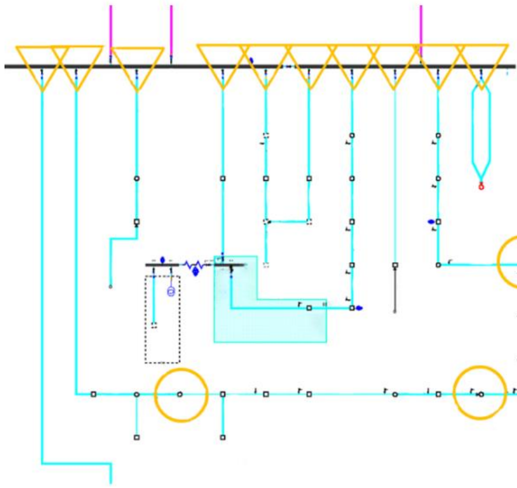

Figure 1. Strijp-S network topology. The yellow triangles and circles indicate the location of automated switchgear. The blue box indicates the connection point of BESS and PV systems.

Congestion and voltage management, islanded operation and novel protection systems within the embedded microgrid concept should be tested in a large-scale testing and experimentation site. Such a site should contain advanced measurement devices, automated switchgear and a high DER penetration. This paper presents the Strijp-S living lab to enable these experiments with embedded microgrids in a real-life scenario. An overview of the equipment and measurement data is given, followed by a description of DSE and the experiments which can be performed in the living lab. To conclude, an outlook of future research directions is given.

THE LIVING LAB

A living lab with state-of-the-art equipment is being developed in Strijp-S, Eindhoven, the Netherlands. The distribution network consists of a medium voltage (MV) station to which ten MV cable feeders are connected. These feeders connect 34 medium to low voltage (MV/LV) stations. Figure 1 shows the MV network topology. Over 1000 consumers (commercial and residential) are connected to the network, typically at LV level.
To enable the operation of embedded microgrids in the network, advanced measurement solutions, automated switchgear and DER are integrated into the network.
The DER are connected to two LV networks located in the blue box shown in Figure 1. The two LV networks are located close to each other and are connected to the same MV ring. This enables direct interaction between the networks and islanded operation with both networks in the same island.
The connection of DER in the low voltage networks is shown in Figure 2. In the first network, photovoltaics are connected to two feeders and 14 charging points are connected to a single feeder. In the second network, a battery energy storage system is connected to a feeder and 12 more charging points are connected. Measurement devices are present in all feeders. The next section describes the equipment in more detail.

EQUIPMENT AND DATA

In an embedded microgrid, measurement devices allow the network operator to determine the states (e.g. current and voltage) in the network. The network operator can control automated switchgear and DER to change the states and mitigate problems in the microgrid.

Advanced measurement devices

Measurement devices are crucial for embedded microgrids to provide information about and respond to the network states. Three types of remote measurement systems are installed in the living lab. The distribution automation (DA) measurement systems are located at all the outgoing feeders of the MV station and the MV/LV stations with automated switchgear (see Figure 1). The distribution automation light (DALI) measurement systems are located at every feeder of the MV station and all MV/LV stations. The smart measurement devices (SMD)

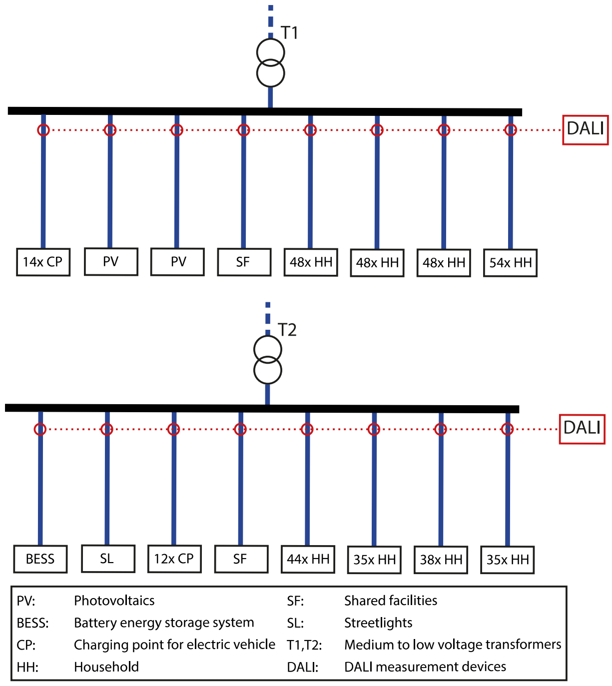

Figure 2. DER integration in the two low voltage networks. Smart measurement devices are not shown.

Table 1. Measurement data of DA, DALI and SMD. The maximum reporting rate of DA, DALI and SMD are 1 second, 15 minutes and 128kHz respectively.

Data	DA (1 sec)	DALI (15 min)	SMD (128kHz)
Voltage	Single phase to neutral	All phases to neutral	All phases to neutral
Current	All phases	All phases	All phases
Frequency	No	No	Yes
Power	Total active and reactive power	Active and reactive per phase	N.A.
Energy	Bi-directional	Bi-directional	N.A.
THD	N.A.	Per phase current	N.A.

are located within several feeders of the LV networks. DA systems provide real-time data with a reporting rate of 1 second averaged data. DALI systems provide 15-minute averaged data, while SMD provide synchronized measurement data with a reporting rate up to 128kHz.
The measured data of both systems is shown in Table 1. With these measurement systems the voltage, current, power flow and THD at the MV/LV station can be monitored in near real-time. In the LV network the voltage, current and frequency can be monitored in real-time. All households are equipped with smart meters for data. SMD are based on an open source platform, which enables the addition of data outputs at a later stage.

Automated switchgear

Embedded microgrids require automated switchgear to reconfigure the network and isolate from the main grid in case of a contingency. The location of automated switchgear in the living lab is indicated in Figure 1 as yellow triangles and circles. Automated switchgear is available at all outgoing feeders of the MV station and three MV/LV stations. This provides several reconfiguration and islanding options, and allows microgrids consisting of a single or multiple LV networks.

Distributed energy resources

Distributed energy resources enable embedded microgrids to control and react to the current state of the network e.g. network loading and voltage. The living lab has a high penetration of different types of DER including generation, storage and flexible demand. In the living lab a photovoltaic installation of 268kWp is installed as intermittent generation source. A battery energy storage unit with a power rating of 255kVA and an energy rating of 315kWh is installed as energy storage. As flexible demand, 26 electric vehicle charging stations of 22kW each are installed. These charging stations are smart-charging enabled, which means charging schedules can be sent to the charge points, managing the charging power.
With the DER present in the network, a vast number of actuators are available for different types of experiments.

DYNAMIC STATE ESTIMATION

To determine all the states in an embedded microgrid, the synchronized measurements of SMD can be used for DSE. The process of DSE can be divided into three stages: parameter identification, state prediction and state filtering [11]. The stages are performed at every time instant $k+1$ to determine the estimated network states $\hat{x}_{k+1}$ from the measured values z_k and the states of the last timestep k.
The network states at time instant $k+1$ can be described by equation 1.

$$x_{k+1} = F_k x_k + G_k + w_k \quad (1)$$

Where column vector w_k is white noise vector, and the nonzero parameter matrix F_k and column vector G_k describe the dynamic behavior of the system. These parameters can be identified by using on-line prediction techniques such as linear exponential smoothing [12], [13].
To predict the network states at time instant $k+1$, several forecasting methods such as regression, time series, fuzzy theory or artificial intelligence based methods can be used [14]. The predicted network states $\tilde{x}_{k+1}$ can be determined with equation 2.

$$\tilde{x}_{k+1} = F_k \hat{x}_k + G_k \quad (2)$$

The estimated states $\hat{x}_{k+1}$ at time instant $k+1$ can be determined by state filtering. Kalman filters such as the extended Kalman filter are often used to perform state filtering [13].

$$\hat{x}_{k+1} = \tilde{x}_{k+1} + K_{k+1}(Z_{k+1} - h(\tilde{x}_{k+1})) \quad (3)$$

Where K_{k+1} is the Kalman gain, Z_{k+1} is the measurement vector and $h(\tilde{x}_{k+1})$ is the calculated measurement vector.
During operation, the estimated network states (i.e. voltage, network loading and frequency) can be controlled used for effective DER and switchgear control actions.

POSSIBLE EXPERIMENTS

The low-level measurement data provided by DALI, SMD and DSE can be utilized to provide high-level information to the network operator. This information can be utilized to control the network states (e.g. network loading and voltage) and react to contingences.
This section describes topics which will be researched in the living lab for the Horizon 2020 projects UNITED-GRID [15] and InterFlex [16]. However, many other field experiments are possible in the living lab.

Congestion and voltage management

For efficient congestion and voltage management, accurate forecasts and (near) real-time measurements of network loading and voltage are required [4]. The measurement data of DALI and SMD enable the development of loading and voltage forecasting models, and enables the monitoring of system states in (near) real time.
The THD measurements of DALI can be utilized to identify and localize power quality issues in the network. The high reporting rate of SMD enables the development of highly detailed models of generation and demand for congestion management.
When congestion or voltage problems have been identified in the network, the network operator can obtain flexibility by curtailing PV generation, influencing the BESS power output, or altering the charge rate of the electric vehicle charging stations. Alternatively, the network operator can utilize automated switchgear to reroute power flow or utilize the battery energy storage unit to solve the problems in the network .
Main challenges addressed:

- Obtaining local flexibility for congestion management
- Obtaining local flexibility for long-term voltage management
- Reconfiguring distribution networks for congestion management

Islanded operation

When a fault occurs in a distribution network, embedded microgrids can isolate from the main grid utilizing the automated switchgear. During and after the transient period from grid-connected to islanded operation, DER should ride through the fault and remain stable. When the microgrid is in islanded operation, voltage and frequency should be controlled by DER.
The estimated states by DSE can be utilized for secondary control. The voltage and current measurement data of DALI can be utilized for tertiary control. Before reconnecting the islanded microgrid to the main grid, the phase angle and frequency should be synchronized. The synchronized measurements of SMD can be utilized to determine phase angle differences for resynchronization.
During islanded operation generation and demand can be balanced by controlling photovoltaic generation and the

power output of the battery energy storage unit. Additionally, the charging power of electric vehicles can be controlled to control the demand in the microgrid.
Main challenges addressed:

- Enhance the fault ride-through and transient stability of DER.
- Resynchronizing islanded microgrids with the main grid.
- Controlling DER to maintain generation and demand balance during islanded operation.

Fault locating

The bidirectional power flows, varying fault currents and changing topology of embedded microgrids pose challenges for traditional protection systems. A novel protection system which can mitigate these challenges is dynamic state estimation-based protection. In this protection system the estimated and measured states in the network are compared. If the probability of the difference between the estimated and measured states is smaller than a predefined threshold, a fault is detected in the network. Other novel protection systems such as traveling wave-based protection can utilize the synchronized measurement data of SMD to locate the fault.
Main challenges addressed:

- Accurate and selective protection of grid-connected reconfigurable networks.
- Protection of islanded microgrids with limited fault current.

CONCLUSIONS AND FUTURE RESEARCH

The living lab will be the testing ground of many innovative embedded microgrid systems. Over the coming years the demonstrator will be used for field experiments in (amongst others) the Horizon 2020 projects UNITED-GRID and InterFlex. Several key challenges for the integration of DER and microgrids will be addressed within the living lab in this future research. Examples are the coordinated control of DER using direct and market-based congestion management, assessment of flexibility which can be provided by DER, protection of reconfigurable networks and islanded microgrids, and enhancing ride-through and power-sharing capabilities of DER to continue operation in fault conditions. Research and experimentation will be performed by universities and industrial parties for joint advances in science and practice.

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