A Virtual Power Plant Demonstration Platform for Multiple Optimization and Control Systems

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Abstract

The Demonstration Project Virtual Power Plant Neckar-Alb is constructing a Virtual Power Plant (VPP) demonstration site at the Reutlingen University campus. The VPP demonstrator integrates a heterogeneous set of distributed energy resources (DERs) which are connected to control infrastructure and an energy management system. This paper describes the components and the architecture of the demonstrator and presents strategies for demonstration of multiple optimization and control systems with different control paradigms.

1 Introduction

The increasing number of Distributed Energy Resources (DER) including power, heat, and cooling trigeneration as well as volatile renewable energy sources brings new challenges for the electrical power grids and the energy market. To leverage flexibilities for matching energy demand and supply, DERs can be controlled by an energy management and control system (EMCS). This way multiple small DERs are aggregated and can participate at the energy market as a larger entity called Virtual Power Plant (VPP).
The *Demonstration Project Virtual Power Plant Neckar-Alb* (Demonstrationsprojekt Virtuelles Kraftwerk Neckar-Alb) [1, 8] aims at building a demonstration platform involving a heterogeneous set of DERs* and multiple different approaches for operation, optimization, and control.
This work is structured as follows. Section 2 provides an overview of related projects and publications. In Section 3 we present the DERs integrated into the VPP demonstrator. Section 4 introduces the different DER controllers used for the demonstrator. We show the overall architecture of the demonstrator in Section 5 and present the approaches for coexistence of multiple optimization and control paradigms in Section 6. Section 7 concludes the paper.

2 Related Work

In this section, we provide an overview of related projects, including microgrid and VPP demonstrators and testbeds.
The PowerMatcher framework [15] aims at providing a communication and trading infrastructure for VPPs at distribution system operator scale. PowerMatcher is implemented as a hierarchical multi-agent system. The agents are connected over the MQTT message bus middleware. A demonstration of Powermatcher was performed in multiple field tests in the Netherlands [14, 22].
Jiang et. al. [12] describe the Power Mix Manager (PMM). PMM is an energy management system that is currently under development and will be used in two research microgrids in Singapore – the Eco Campus, and the Renewable Energy Integration Demonstrator Singapore (REIDS) [24].
The Smart Polygeneration Microgrid (SPM) [2] is a testbed and demonstrator for microgrid and VPP technology at the Savona campus of the University of Genoa in Italy. DERs include combined heat and power plants (CHP), photovoltaic (PV) systems, wind turbines, battery and thermal storage as well as absorption chillers and charging stations for electrical vehicles (EV). The DERs are managed using a control architecture based on IEC 61850 [10].
The Intelligent Microgrid Demonstrator [7] is a research microgrid at the Center for Electromechanics at the University of Texas, Austin. The microgrid is used for research on power systems for ships and comprises diesel engine and gas turbine powered generators with an overall power rating of 2 MW. The control infrastructure for the microgrid is based on *NI LabView*.
The Nice Grid Demonstrator [17, 18] is a project integrating PV systems, distributed battery storage and controllable loads in residential buildings in the region of Nice, France. Its goal is to maximize the use of renewable energy by means of demand-response and optimized use of storage technology. The control infrastructure is based on *GE Grid Solutions Network Energy Manager* and uses XMPP [23] as communication protocol.
The project Regenerative Modellregion Harz (RegModHarz) [9] is a VPP demonstrator in the Harz region in Germany. RegModHarz combines PV systems, wind turbines, bio gas fueled CHPs and pumped hydroelectric storage to a combined virtual power plant. The control infrastructure is based on web services using IEC 61850 data models [11].

*In this paper we use the term *DER* in accordance with the CIGRÉ Microgrid Evolution Roadmap [16], comprising energy generators, energy storage, and controllable loads.

The project Kombikraftwerk 2 [13] demonstrates a VPP for ancillary services like frequency and voltage control using renewable energy sources. DERs include wind turbines, PV systems, and bio gas engines. Communication and control infrastructure is based on OPC-XML-DA, Modbus TCP [20], and IEC 61850 [10].
MikroVKK [19] is a VPP demonstration project in Baden-Württemberg, Germany. It aims at proving that cogeneration using small CHPs with a power output of less than 100 kW each can be integrated into a VPP in a profitable way.
The projects mentioned above demonstrate microgrids and VPPs with various goals and usage scenarios. While optimization strategies can be exchanged in some of the architectures, operating a VPP with multiple EMCSs and different control paradigms has not been investigated.

3 DER Portfolio

The VPP demonstrator comprises both on-campus DERs and off-campus DERs. The on-campus DERs are installed by consortium member Ruoff Energietechnik and are located in a project lab or in buildings at the Reutlingen University campus. They are owned by the Reutlingen University or the project consortium. Off-campus DERs are owned by external partners of the project and are located at the premises of their respective owners. While the on-campus DERs can be actively influenced by the EMCS, the off-campus DERs are initially limited to measurement and monitoring. In the following, we provide an overview of the on-campus DERs.

3.1 Electrical Generators

At the project lab, a *g-box 20* gas-fueled combined heat and power plant (CHP) with 20 kW electrical output is installed. The roof of the project lab is covered by four *SOLAERA* photovoltaic/thermic (PVT) hybrid collectors with 1.36 kW peak electrical output. On a different building nearby, a photovoltaic (PV) system with 180 kW peak electrical output will be installed.

3.2 Electrical Loads

As a consumer of electrical energy and producer of thermal energy, the project lab contains a *SOLAERA* heat pump. Next to the lab, four AC charging stations for electrical vehicles (EV) with 22 kW each and a charging station for up to 20 e-bikes and electric scooters will be installed.

3.3 Storage Systems

A *Mack Electronic Systems* battery storage system with a capacity of 12 kWh and 12 kW electrical output is available for storage of electrical energy produced by the CHP and PV systems. For temporal decoupling of heat generation and consumption, the project lab contains a *PR 2000* thermal storage unit for the CHP and a *SOLUS II* thermal storage unit for the PVT system.

3.4 Other Devices

An *HTC 18 plus* adsorption chiller at the project lab serves as sink for excess heat and can be used for air conditioning. Building automation systems of several campus buildings and a weather station provide sensor data.

4 DER Controllers

Three different DER controllers are provided by members of the project consortium. In the following, we present the key features of the solutions that are used for the demonstrator.

4.1 AVAT Automation Controller

The DER controller provided by AVAT Automation performs local optimizations on any combination of CHPs, heat pumps, and backup boilers. It can also operate with production schedules received from the central EMCS. Additionally, the controller incorporates decentralized prediction based on weather forecasts and historical data.

4.2 GridSystronic Energy Controller

The controller solution produced by GridSystronic Energy (GSE) consists of a central server or cloud service and communication gateways installed at the DERs. DER-specific protocols, data formats, and control logic are implemented in a central server only. The gateways provide a secure tunnel to the server. Status messages from the DERs are encapsulated by the gateways and forwarded to the server. Control messages sent by the server are decapsulated by the gateways and forwarded to the DERs.

4.3 Enisyst Controller

The DER controller provided by enisyst can operate both autonomously and in cooperation with an EMCS. Autonomous operation can target use cases like optimization of self-consumption. In cooperation with an EMCS, schedules or external optimization objectives can be used.

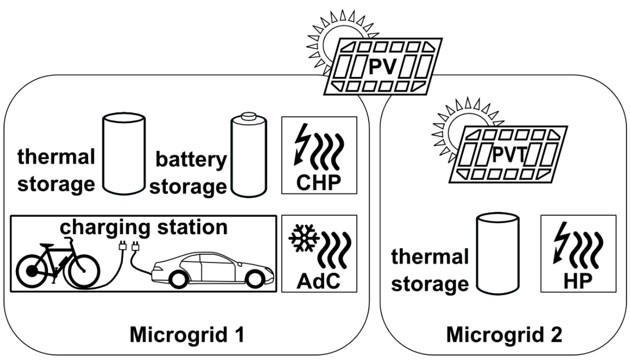

Figure 1 On-campus DERs structured in two virtual micgrogrids.

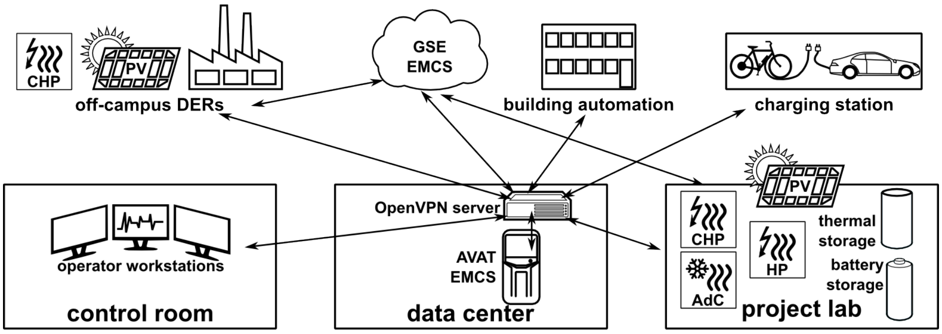

Figure 2 Overview of the communication relationships in the VPP demonstrator.

5 Demonstrator Architecture

In this section we describe the management and control infrastructure of the VPP demonstrator, the organization of the on-campus DERs into virtual microgrids, the integration of off-campus devices installed at external partners, and the communication infrastructure.

5.1 Energy Management and Control Systems

A central EMCS is provided by AVAT Automation. It is based on the WinCC Open Architecture [5] framework and runs on a server at the Reutlingen University datacenter. A second EMCS provided by GridSystronic Energy (GSE) runs as cloud service at an external datacenter. Both systems can perform optimizations for usage scenarios like, e.g., self-comsumption of renewable energy, direct marketing of electricity, co-optimization of heat and power, and providing ancillary services, as described in [8].

A VPP control room is established at the Reutlingen University campus. The control room contains an operator workstation and displays for monitoring and visualization of the VPP state. The operator workstations serve as remote console for the AVAT EMCS and provide access to the GSE EMCS via its Web management interface.

5.2 Virtual Microgrids

The on-campus DERs listed in Section 3 are structured into two virtual microgrids as shown in **Figure 1**. These microgrids are not electrically separate distribution grids and do not support islanding operation. Hence, they do not satisfy the definition of physical microgrid [16]. However, they can be treated like microgrids by the central EMCS using energy balances calculated from energy meter data. Therefore, we use the term *virtual* microgrids.

The CHP, the adsorption chiller, the *PR 2000* thermal storage unit, the battery storage, and the charging stations are assigned to Microgrid 1. The heat pump, the PVT collectors, and the *SOLUS II* thermal storage unit are assigned to Microgrid 2. Power inverters of the PV system are assigned to both microgrids.

5.3 Off-campus Devices

Live production data of an off-campus PV system in Reutlingen will be supplied to the EMCS.

DER controllers will be added to manufacturing plants, CHPs, PV systems, and other types of DERs for monitoring and measurement at external participants in the Neckar-Alb area. For the demonstrator, this partnership provides a larger set of data for evaluating optimization strategies. The cooperation partners benefit from energy analysis and consulting by consortium members PATAVO and energiefrey and can see potential value of participating in a VPP.

5.4 Communication Infrastructure

Figure 2 shows the communication infrastructure of the demonstrator. Network connectivity for the DER controllers in the campus microgrids is provided via the campus Ethernet. Off-campus DER controllers are connected via mobile cellular data services or by using the Internet connectivity of external partners.

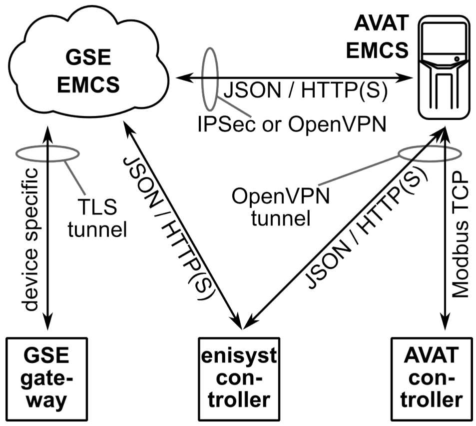

Figure 3 Communication technologies and protocols.

All communication between DER controllers and the EMCS is based on IP networking. The connections between AVAT EMCS and the DER controllers are secured using OpenVPN [25] tunnels. Additionally, OpenVPN serves as mechanism for traversal of network address translation (NAT) devices or for reaching controllers at dynamic network addresses. This is of particular importance for integrating DER controllers connected by dial-up lines or mobile cellular data services. The OpenVPN server is colocated with the EMCS at the Reutlingen University data center. The AVAT DER controller includes an OpenVPN client, for other types of DER controllers, separate OpenVPN routers can be used.

The communication protocols and tunnel technologies used in the demonstrator are depicted in **Figure 3**. The communication between the AVAT EMCS and the AVAT DER controllers is based on Modbus-TCP [21, 20]. Enisyst DER controllers communicate using an HTTP-based REST [6] interface using a JSON [3] data format. The GSE EMCS and the GSE gateways communicate over a TLS [4] based tunnel with certificate authentication. Connections between the GSE EMCS and the AVAT EMCS are secured using IPsec or OpenVPN tunnels.

6 Demonstration Approaches for Multiple Optimization and Control Systems

The project aims at demonstrating various optimization, operation, and control strategies with different control components on the same set of DERs. To demonstrate the full capability range of all DER controller solutions, approaches for coexistence are required in the project. In the following, three coexistence schemes, a sequential, a parallel, and a hierarchical approach are presented.

6.1 Sequential Demonstration

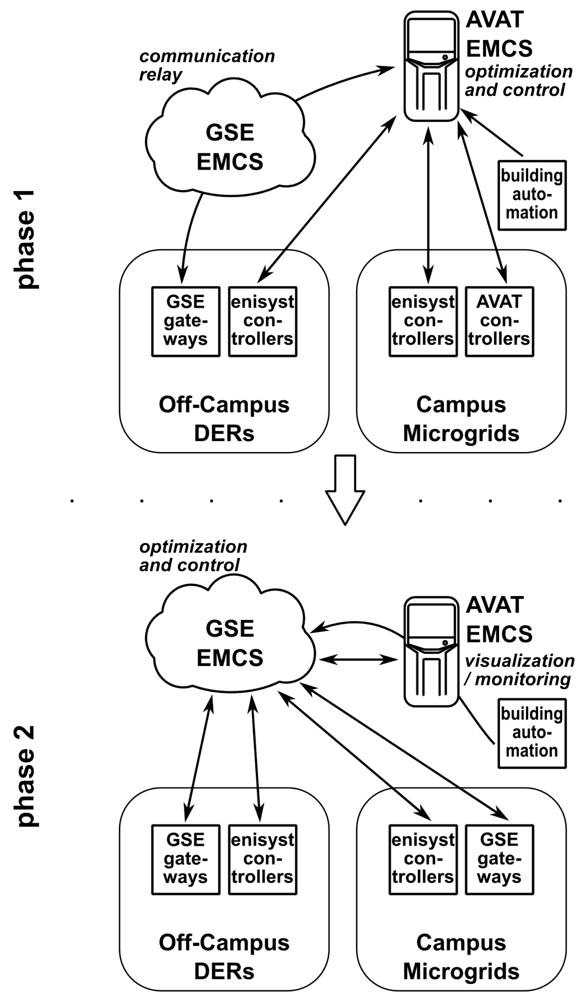

Figure 4 Sequential demonstration.

Both AVAT and GSE can provide central control and optimization functionality for the VPP. One approach for demonstrating the feature set of both implementations is coexistence in time. For a sequential demonstration of both optimization an control systems, the demonstration time is split in two phases.

In Phase 1 the AVAT EMCS manages the VPP and performs the optimizations. Weather information, market data, and measurement data from building automation is supplied directly to the AVAT EMCS. Enisyst and AVAT DER controllers receive schedules from the AVAT EMCS and supply status information to the EMCS. Some off-campus DERs are equipped with GSE gateway boxes that require the GSE server component for operation. As DER controllers at the premises of external partners cannot be replaced easily, the GSE server can be used as a relay between the AVAT EMCS and the GSE gateway boxes. Schedules issued by the AVAT EMCS are interpreted by the GSE server, and the respective commands are sent to the DERs via the gateways.

In Phase 2 the GSE server takes the responsibility for management and optimization of the VPP. Weather information and market data, is supplied directly to the GSE EMCS. Measurement data from building automation is forwarded by the AVAT EMCS. Apart from that, the AVAT EMCS provides only visualization, monitoring, and logging functionality in Phase 2. All DERs equipped with GSE gateways or IP interfaces are directly controlled by the GSE server. The enisyst DER controller can also be connected to the GSE server. An operator terminal for the GSE server will be available at the control room.

Sequential demonstration appears to be the most straightforward strategy. However, it comes with the effort for reconfiguring the VPP. Additionally, due to the limited set of DERs that can actually be controlled, it requires changing DER controllers on-site between Phase 1 and Phase 2 for meaningful results.

6.2 Parallel Demonstration

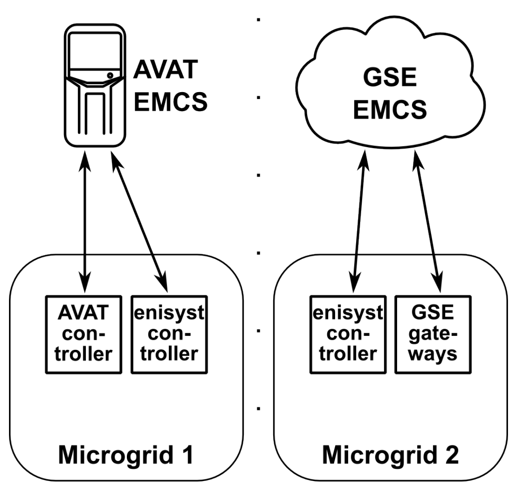

Figure 5 Parallel demonstration.

A second strategy is the parallel demonstration of different controller implementations for different sets of DERs. As mentioned in Section 5.2, the on-campus DERs are divided into two virtual microgrids. Thus, for coexistence in space, different DER controllers can be installed in each of the microgrids. Additionally, the demonstrator can be split into two separate VPPs as shown in **Figure 5**. This way, the AVAT EMCS and the GSE server can both independently manage and optimize a subset of the DERs.

6.3 Distributed Optimization

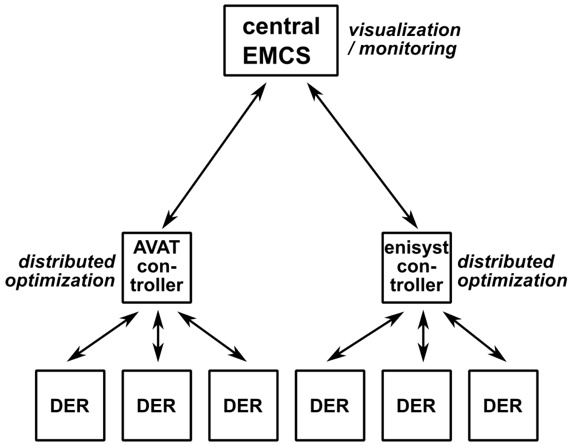

Figure 6 Distributed optimization.

Both the AVAT and enisyst DER controllers can perform local optimizations. Therefore, as a third demonstration strategy, we propose distributed optimization. This scenario is shown in **Figure 6**. The EMCS supplies weather and market information to the DER controllers. The optimization and scheduling of DERs is performed at the local DER controllers. The central EMS provides monitoring and visualization of all DERs. In contrast to the parallel demonstration, all DERs are connected to a single EMCS. The GSE EMCS performs all optimization and scheduling centrally at the server component, so it cannot be used for this approach.

7 Conclusion

In this paper we have presented the VPP demonstrator at the Reutlingen University campus. The demonstrator consists of DERs in two on-campus microgrids and at external partners. All DERs are connected to a management and control infrastructure.

We have shown multiple strategies to operate the VPP demonstrator using different energy management and control systems and a heterogeneous set of DER controllers with the same set of DERs. The proposed strategies will be evaluated in the project and one of them or a combination thereof will be selected for the operation of the demonstrator.

The demonstrator will be used as a platform for research projects and teaching at Reutlingen University. Additionally, the demonstrator's premises will be open for interested companies to increase acceptance for and improve understanding of VPP technology.

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References

[1] Virtuelles Kraftwerk Neckar-Alb: Demonstrator. http://www.virtuelles-kraftwerk-neckar-alb.de/demonstrator/, last retrieved June 2017.

[2] S. Bracco, F. Delfino, F. Pampararo, M. Robba, and M. Rossi. The University of Genoa Smart Polygeneration Microgrid Test-Bed Facility: The Overall System, the Technologies and the Research Challenges. *Renewable and Sustainable Energy Reviews*, 18:442–459, 2013.

[3] T. Bray. The JavaScript Object Notation (JSON) Data Interchange Format. RFC 7159 https://www.ietf.org/rfc/rfc7159.txt, Mar. 2014.

[4] T. Dierks and E. Rescorla. The Transport Layer Security (TLS) Protocol Version 1.2. RFC 5246 https://www.ietf.org/rfc/rfc5246.txt, Aug. 2008.

[5] ETM Professional Control. Simatic WinCC Open Architecture. http://siemens.de/wincc-open-architecture, last retrieved June 2017.

[6] R. T. Fielding. *Architectural Styles and the Design of Network-based Software Architectures*. Dissertation, University of California, 2000.

[7] R. E. Hebner, J. D. Herbst, and A. L. Gattozzi. Intelligent Microgrid Demonstrator. In *Electric Machines Technology Symposium 2010 (EMTS2010)*, May 2010.

[8] F. Heimgaertner, M. Hoefling, M. Menth, E. Schur, F. Truckenmueller, H. Hagenlocher, J. Zunke, A. Frey, D. Ebinger, S. Jaegers, L. Duerr, T. Roeger, K. Lindner, and C. Kahlert. The Demonstration Project Virtual Power Plant Neckar-Alb. In *VDE Kongress 2016: Internet der Dinge*, Nov. 2016.

[9] P. Hochloff, D. Filzek, G. Heusel, K. Lesch, A. Liebelt, L. Nicklaus, P. Ritter, K. Rohrig, C. Roehrig, F. Schloegl, C. Volkert, M. Wickert, and M. Winter. Regenerative Modellregion Harz – RegModHarz. In *Kasseler Symposium Energie-Systemtechnik*, Oct. 2011.

[10] IEC. IEC 61850: Power Utility Automation, 2003.

[11] IEC. IEC 61400-25-4: Communications for Monitoring and Control of Wind Power Plants - Mapping to Communication Profile, 2008.

[12] T. Jiang, L. Costa, P. Tordjman, S. S. Venkata, N. Siebert, J. Kumar, H. B. Puttgen, A. Venkataraman, S. Dutta, Y. Li, and T. Tang. A Microgrid Test Bed in Singapore: An Electrification Project for Affordable Access to Electricity With Optimal Asset Management. *IEEE Electrification Magazine*, 5(2):74–82, June 2017.

[13] K. Knorr et al. Kombikraftwerk 2. Abschlussbericht, Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES), Aug. 2014.

[14] J. Kok, B. Roossien, P. MacDougall, O. Pruissen, G. Venekamp, I. Kamphuis, J. Laarakkers, and C. Warmer. Dynamic Pricing by Scalable Energy Management Systems - Field Experiences and Simulation Results using PowerMatcher. In *IEEE Power and Energy Society General Meeting*, July 2012.

[15] K. Kok, C. Warmer, and R. Kamphuis. PowerMatcher: Multiagent Control in the Electricity Infrastructure. In *International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, July 2005.

[16] C. Marnay, S. Chatzivasileiadis, C. Abbey, R. Iravani, G. Joos, P. Lombardi, P. Mancarella, and J. von Appen. Microgrid Evolution Roadmap. In *International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, 2015.

[17] A. Michiorri, R. Girard, G. Kariniotakis, C. Lebossé, and S. Albou. A Local Energy Management System for Solar Integration and Improved Security of Supply: The Nice Grid Project. In *IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*, 2012.

[18] A. Michiorri, G. Kariniotakis, and F. Foucault. An Aggregator for Distributed Energy Storage Units Under Multiple Constraints in the Nice Grid Demonstrator. In *CIRED Workshop 2014: Grid Operation and Congestion Management*, June 2014.

[19] mikroVKK Consortium. Demonstration der Machbarkeit, Wirtschaftlichkeit und der Smart Grid-Potentiale von Virtuellen Kraftwerken mit Mikro- und Mini-BHKW. http://new.hs-offenburg.de/mikrovkk/, last retrieved June 2017.

[20] Modbus IDA. Modbus Messaging on TCP/IP Implementation Guide V1.0b, 2006.

[21] Modbus IDA. Modbus Application Protocol Specification v1.1b3, 2012.

[22] B. Roossien. Field-Test Upscaling of Multi-Agent Coordination in the Electricity Grid. In *CIRED International Conference on Electricity Distribution*, 2009.

[23] P. Saint-Andre. Extensible messaging and presence protocol (XMPP): Core. RFC 7159 https://www.ietf.org/rfc/rfc6120.txt, Mar. 2011.

[24] A. Venkataraman, S. Dutta, Y. Li, S. Kayal, L. M. Costa, T. Jiang, R. Plana, P. Tordjman, D. Tang, F. H. Choo, and C. F. Foo. REIDS Microgrid: Development and demonstration of a Power Mix Management System. In *Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, Oct. 2016.

[25] J. Yonan. OpenVPN – An Open Source SSL VPN Solution. http://openvpn.net, 2008.