

Reactive Power Coordination Strategies with Distributed Generators in Distribution Networks

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Abstract— In this paper, latest results of the industrial project “Q-Study” are presented, which is carried out by “Fraunhofer IWES” together with the German distribution system operator “Bayernwerk Netz GmbH”. The proposed project focuses on reactive power management in distribution systems using distributed generators and covers comprehensive research activities such as concept development, potential assessment, cost-benefit analysis and test in laboratory and in a real distribution grid. In addition, the applied real-time test- and simulation environment is also presented in detail, which allows the user to test an operative control approach in the smart grid domain by emulating a large power system with multiple voltage levels and substantial amounts of generators, storages and loads in real time.

Reactive Power Control; Distribution system; Real-Time Simulations

I. MOTIVATION

Changing reactive power behavior of distribution systems (e.g., due to higher degrees of cabling and local reactive power provision through DGs) [1], together with the loss of generator-based reactive power sources at transmission system level could require the exploitation of novel reactive power sources by the transmission system operator (TSO) in the future [2] [3]. TSOs are therefore interested in using the aggregated reactive power capabilities of the downstream distribution system for their own voltage control purposes. The question is, how can distribution system operators (DSOs) utilize the reactive power control capabilities of their local reactive power sources (e.g., dispersed generators, capacitor stacks) in order to provide a certain amount of controlled reactive power at their interface to the transmission system level but still keeping its own grid in a safe operation mode?

In order to answer this question, different research and industrial projects are carried out by Fraunhofer IWES together with German distribution and transmission system operators regarding reactive power coordination strategies in distribution networks. This paper presents the latest outcomes of the industrial project “Q-Study”, which focuses on reactive power management and voltage limitation using distributed generators in the distribution network.

II. REACTIVE POWER CONTROL CONCEPTS

There are several strategies how reactive power from DGs can be coordinated and utilized to compensate the missing part from the central power plants. The study assumes that sufficient controllable reactive power from DGs is online during the simulation periods. This corresponds to a situation increasingly observed in systems with high DG penetration. The challenge consists of coordinating the available resources. In this paper, three strategies are presented and compared with each other in different application contexts. Figure 1 gives a schematic overview of these strategies.

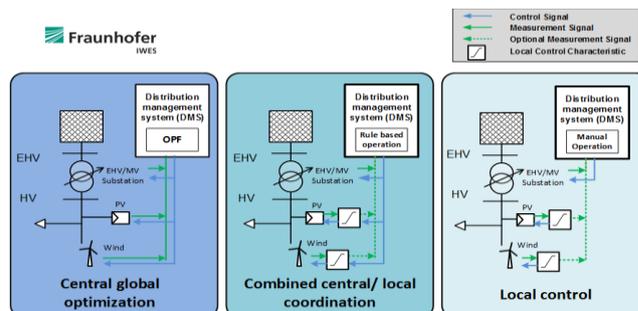


Figure 1: Schematic overview of different reactive power control strategies in distribution system

- i. Central global coordination using optimization algorithms and full knowledge of network information (left in Fig. 1).
- ii. Central control strategies using the local control of DGs and only little to no knowledge of network information (middle in Fig. 1).
- iii. Local voltage control using (optimized and variable) droop curves (right in Fig. 1).

The scope of this paper is mainly the combined central rule-based with local control (middle in Fig. 1).

III. CASE STUDY: REACTIVE POWER MANAGEMENT IN GERMAN DISTRIBUTION SYSTEM

1. INTRODUCTION :

As a case study, the latest project results of Fraunhofer IWES together German distribution system operator “Bayernwerk Netz GmbH” regarding reactive power management in distribution system are reported in this section. The investigated grid area is an HV grid section of Bayernwerk Netz GmbH and a down-streamed MV grid “Seebach”. Both selected grid sections are situated in an area which achieves within the highest PV penetration rates in Germany. A major objective of reactive power management in distribution systems is to keep the reactive power flow at the network connection points with the upstreamed grid operator (here TSO/DSO-NCPs) within specified limits. Figure 2 shows the annual active (P) and reactive (Q) power exchange at the TSO/ DSO-NCPs for the investigated grid section and the requirements according to the new ENTSO-E Demand Connection Code (DCC) regulation [4].

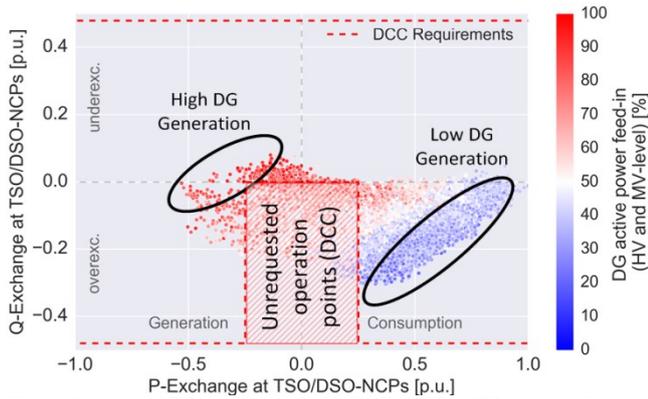


Figure 2: Annual PQ exchange at the TSO/ DSO-NCPs (normalized to the annual peak demand of the distribution grid section)

It can be seen that currently not all operation points at the TSO/DSO-NCPs are within the requested operational area, hence reactive power management with DGs might improve the reactive power exchange at the TSO/DSO-NCPs. The color of the operation points indicates the active power feed-in of DG systems at the HV and MV-level. Since the Q provision capability of DG systems strongly depends on the current active power feed-in, the color of the operation points also indicates the Q-potential (underexc.) from DG systems. For operation points with an unrequested Q-exchange (Figure 2 hatched area) a low (light blue points) to high (red points) Q-flexibility potential by DG systems is identified. It should also be highlighted, that these requirements are not the current requirements at the TSO/DSO-NCPs and that the detailed national implementation of the DCC is under discussion.

2. Case Study Area:

The investigated German distribution grid section covers 9 EHV/HV substations (9 TSO/ DSO-NCPs) and 87 HV/MV substations and is situated in an area which achieves within the highest PV penetration rates in Germany. Figure 3 shows the installed generation capacity at different voltage levels for the selected distribution grid section.

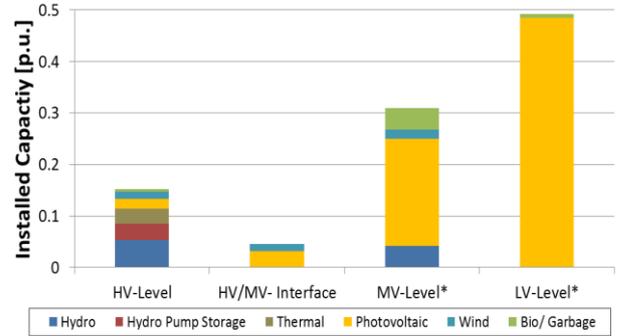


Figure 3: Installed generation capacity in the investigated grid section (normalized to total installed DG capacity in the investigated distribution grid section)

The values in Figure 3 are normalized according to the total generation capacity in the investigated distribution grid section. The total generation capacity exceeds the maximum peak demand by a factor of 1.9 and significant reverse power flows are already measured at the EHV/HV interfaces (compare Figure 2). Approximately 50% of the total DG capacity is installed in the LV level with mainly PV installations. In the MV level approximately 30% of the total DG capacity is installed, with mainly PV systems, hydro power, bioenergy plants and wind turbines. At the HV/MV interfaces 17 PV and 5 wind parks are installed. And in the HV-level 6 hydro power plants, 2 hydro pump storage plants, 2 thermal power plant (gas and waste), 2 PV parks and 2 wind parks are installed.

3. Assessment of Reactive Power Potential:

In this case study, a statistical analysis of the reactive power flexibility by DGs is presented. Figure 4 shows the methodology for the theoretical Q flexibility assessment. In the theoretical analysis, comprehensive time series analyses of DG generation data is performed. The DG Q-flexibility is only limited the by the Q(P)-capability of the generators, hence no grid simulations are required and grid constraints (e.g. overvoltage, over-loading) are not considered.

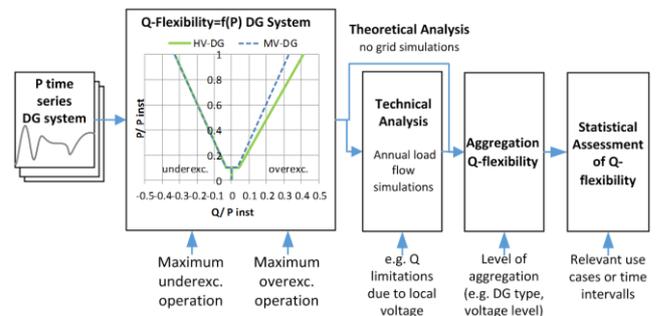


Figure 4: Applied methodology for the reactive power flexibility assessment by distributed generators

The theoretical analysis of the Q-flexibility potential is performed for DG at HV to MV-level. The considered Q(P)-capability of the DGs is shown in Figure 4 (2nd block). The aggregation of the Q-flexibility potential (4th block) is performed in the time domain, therefore simultaneity effects between the DG systems are considered. The statistical assessment (5th block) can be performed for different time intervals (e.g. time of the day,

time of the year) or for relevant use cases (e.g. high load condition, high generation condition). In this case study report the statistical assessment is performed for solely points in time with an unrequested Q exchange at the TSO/DSO-interfaces according to the DCC requirements (use case DCC, compare Figure 2, hatched area).

As results of the theoretical analysis, Figure 5 gives an overview on DG Q flexibility potential at different voltage levels. The color bars indicate different availability values for the DG Q flexibility in the use case (DCC):

- **Very high availability (e.g. 95% and 98% percentile):** this DG Q flexibility is at least available for 98% or 95% of the analyzed operation points.
- **High availability (e.g. 80% and 90% percentile):** this DG Q flexibility is at least available for 80% or 90% of the analyzed operation points.
- **Median availability (50% percentile):** this DG Q flexibility is at least available for 50% of the analyzed operation points.
- **Maximum Q flexibility (0% percentile):** the maximum determined DG Q flexibility for the analyzed operation points (very low availability).

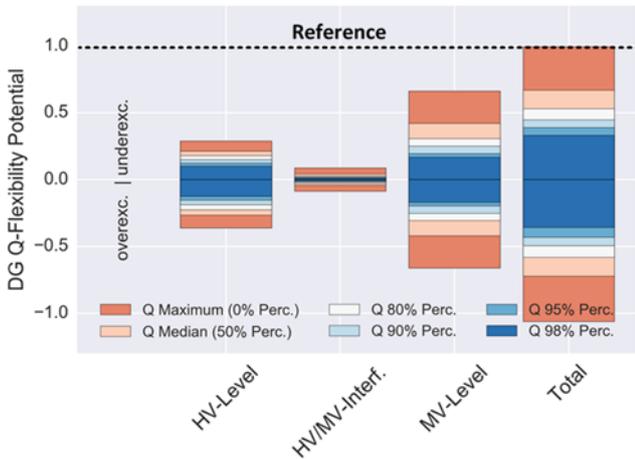


Figure 5: Overview on Q flexibility at different voltage levels for the applied use case (The values are normalized to the maximum underexcited DG Q provision in the investigated grid section)

The DG Q flexibility potential in Figure 5 is normalized by the maximum DG Q flexibility (underexc.) in the HV- and MV-level for the analyzed use case (DCC). Therefore, in the voltage levels HV, HV/MV-interface and MV-level a maximum DG Q-flexibility potential (underexc.) of 1 p.u. is determined (dashed line). The DG Q-flexibility (Figure 6, total) with median availability accounts for 0.67 p.u. (50% perc.), with high availability (90% perc.) accounts 0.39 p.u. and with very high availability (98% perc.) accounts 0.33 p.u. of the maximum DG Q-flexibility potential. Therefore, only 33% of the maximum DG Q-flexibility shows a very high availability for the analyzed operation points and is hence largely independent from weather conditions and other external impact factors. The comparison of the

voltage levels shows a high Q flexibility potential especially at the MV-level and at the HV-level.

Furthermore, Figure 6 shows the Q-flexibility potential for different types of DG at MV level in detail. A Q potential with a very high availability (dark blue bars, 98% percentile) is only determined for hydro power plants and biomass power plants in the MV level. However, PV systems can provide a relevant Q flexibility already with a high availability (white bars, 80% percentile) for the defined use case. And with a median availability, PV systems can provide the highest Q-flexibility potential within the MV-level and for the defined use case.

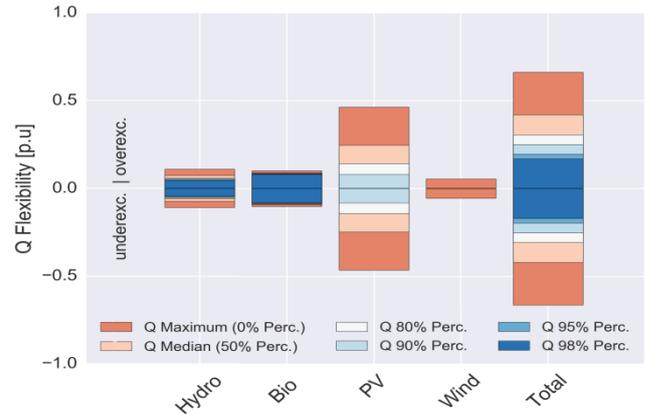


Figure 6: Q flexibility per DG type at the MV-Level for the applied use case (The values are normalized to the maximum underexcited DG Q provision in the investigated grid section)

4. Developed Reactive Management Concept:

It is also the aim of this case study to develop a suitable reactive power management approach for the DSO, which allows the DSO to provide a certain amount of controllable reactive power flexibilities at network interfaces between two voltage levels (e.g. HV/MV level) by utilizing the local reactive power capabilities of DGs in the distribution system. Since using the characteristic based local Q(V)-control in distribution grid could efficiently support the local voltage limitation without causing redundant reactive power provision from DG, the local Q(V)-control is already required in the grid connection guideline of Bayernwerk Netz GmbH. Considering the properties of the distribution grid (e.g. lack of online information at MV level), the following points are given by Bayernwerk Netz GmbH at the beginning of the project as requirements for the new reactive power management approach:

- Reliable and stable control behaviour
- Compatible with the existing local Q(V)-control
- Requiring as few online information as possible from the network
- Using the reactive power provision capability of DGs at MV level
- Simple implementation in a real distribution grid

Based on the requirements above, an application-oriented reactive power management approach is developed and applied in the selected MV grid “Seebach” case study [5].

The proposed Q-Management concept aims at controlling the reactive power exchange at one 110 kV-NCP using the quasi-linear relationship between local reactive provision from DGs and the reactive power change at the 110 kV-NCP caused by it. Figure 7 gives a general overview of the introduced reactive power control approach. The proposed Q-Management concept can be mainly divided in central and local parts. At a first step, the DSO centrally determines the reactive power set point values for all associated DGs at MV level and sends them to the respective DGs. At a next step, the local DG controller checks the received set point values according to its local voltage and limits it - if necessary - to comply with the predefined operation area in order to support the local voltage limitation. The proposed Q-Management concept consists of the following 6 control processes:

1. Determine the target value of Q-exchange
2. Determine the actual deviation of Q-exchange
3. Determine the Q-setpoint deviation for controllable MV-DGs
4. Send Q-setpoint deviation to controllable MV-DGs
5. Local limitation according to the extended Q(V) characteristic
6. Set the Q provision of controllable MV-DGs

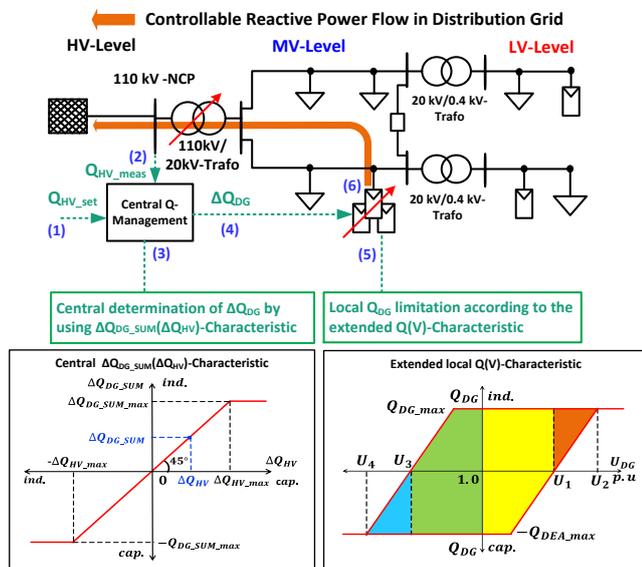


Figure 7: Developed reactive power management concept

Compared to other central control approaches (e.g. Optimal Power Flow), the developed Q-Management concept is very application-oriented and requires only the actual Q-exchange at the 110 kV-NCP as its online measurement. The concept hence can be simply implemented in a real distribution grid without requiring complex ICT-infrastructure. In addition, the proposed approach is compatible with local Q(V)-control, which efficiently supports the local voltage limitation. The first description of the concept may be found in [5].

However, since the developed Q-Management approach does not gather any online measurements, it cannot provide a detailed overview on the actual state of distribution grid.

The line loading therefore is not considered by the proposed Q-Management concept and the local voltage limitation cannot always be guaranteed.

5. Simulation and Test in laboratory and field:

The proposed central Q-Management concept was analyzed at first in a simulation environment. The technical feasibility and potential of the proposed approach were investigated by applying it in different MV grids of Bayernwerk Netz GmbH and performing time series simulation using open source simulation tool "Pandapower"¹, provided by Fraunhofer IWES and University of Kassel [6]. As results, applying the proposed approach by centrally regulating the local reactive power provision of multiple DGs at MV level could enable a controlled Q-exchange at the 110 kV-NCP with satisfactory control accuracy.

At a next step, the central Q-Management is investigated in laboratory environment under more realistic conditions using the "OpSim"² real-time Controller-in-the-Loop simulation platform (s. Section V) [7]. The goal of this investigation is to test the functionality and stability of the proposed Q-Management. Figure 8 shows the test infrastructure in laboratory of Fraunhofer IWES. The test infrastructure can be mainly divided into two parts: the distribution network "Seebach" and an external PC, which is the central controller in this investigation. The first part "distribution network Seebach" consists of the network model "Seebach" with its MV DGs and local DG controllers implemented. This part is realized on the real-time-simulator "ePHASORSim" from Opal-RT in order to emulate the behavior of distribution system in real-time. The central Q-Management, on the other hand, is implemented on the external PC, which is responsible for computing reactive power set points for all controllable DGs. Measurement and control signals between external pc and real-time simulator are interchanged during the simulation via the proxies, clients and message bus provided by the "OpSim" platform.

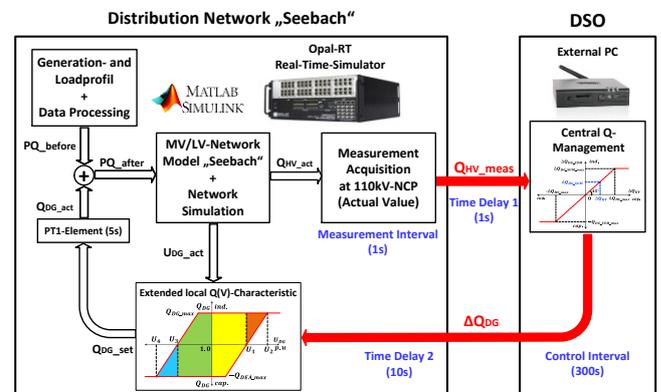


Figure 8: Test infrastructure for real-time Controller in the Loop Test

¹ <http://pandapower.readthedocs.io/en/v1.4.0/index.html>

² <http://www.opsim.net/en>

The real-time Controller-in-the-Loop test is performed for a critical time period (9:00-17:00) of a clear sunny summer day with high solar irradiation and the reactive power exchange at 110 kV-NCP should be minimized by applying the proposed Q-Management approach. As can be seen in Figure 8, 300 s and 1 s are used during the simulation for Q-Management as control interval and measurement interval. In addition, time delays were added in the simulation platform between two components in order to emulate the time delay during measurement and signal transmission using real-life ICT-infrastructure.

Figure 9 shows the achieved results of the real-time Controller-in-the-Loop simulation. The red line represents the original reactive power exchange at the 110 kV-NCP without using Q-Management. The blue line shows the controlled reactive power exchange. It can be recognized, due to the increased PV generation and the changes of network component loading, that the original Q-exchange at 110 kV-NCP (red line) changes continuously during the investigated time period. Using the central reactive power control approach could minimize the reactive power exchange significantly and efficiently (blue line).

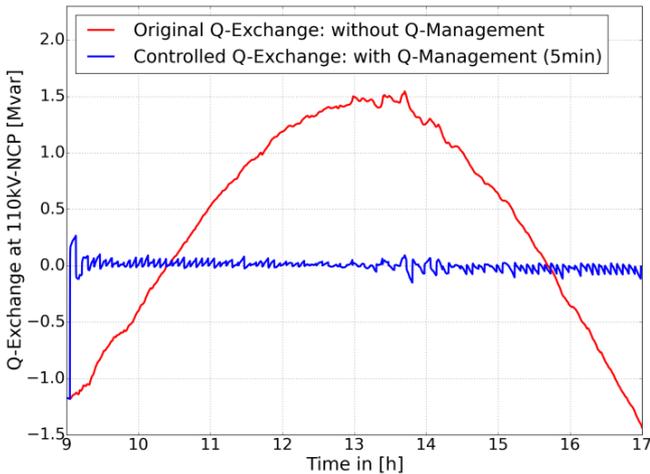


Figure 9: Exemplary results of real-time Controller-in-the-Loop test (9:00 - 17:00)

Since the proposed Q-Management approach utilizes the quasi-linear relationship between reactive power provision from DGs and the changes of reactive power exchange at 110 kV-NCP, small control deviations can be observed in the first control period. However, this deviation can be significantly reduced after two control periods. Hence, even the relationship between Q provision from DG and the induced Q changes at 110 kV-NCP is greatly simplified and the central controller requires only one online measurement to achieve satisfactory control accuracy and stable control behavior.

The proposed Q-Management approach is further investigated in a real German distribution grid with two centrally controlled large PV systems. This investigation aims at gathering first practical experiences to evaluate the feasibility, performance as well as the stability of the proposed central Q-Management approach by performing a field test for a few months [8].

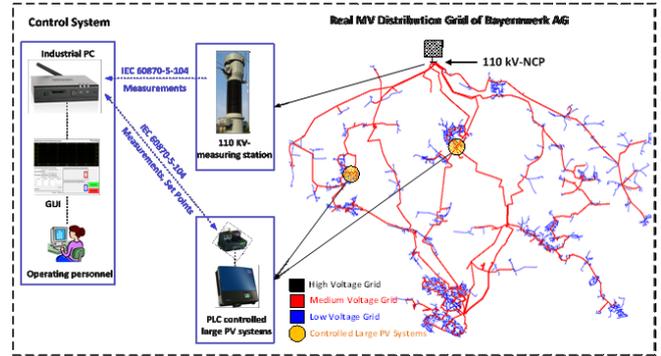


Figure 10: System infrastructure for the field test

Figure 10 shows the system infrastructure for the planned field test. Two large PV systems in the investigated distribution system are chosen for the field test and equipped locally with conventional remote terminal units (RTU), which enables the communication with the central control system as well as the implementation of the local Q(V) limitation characteristic. The control system consists of an industrial PC, in which the introduced Q-Management algorithm and a graphical user interface (GUI) are implemented. Based on the actual measurements and the target values given by operating personnel, reactive power set points for the controllable MV DGs are automatically calculated in the industrial PC and sent to the PV controller iteratively. Measurements and set point values are exchanged between measuring station, RTU and control system by using standard transmission protocol IEC 60870-5-104.

IV. DMS FUNCTION DEMONSTRATOR

In Figure 11, an overview of the field test pilot system from the national research project SysDL2.0³ is shown (see [9]). This system follows the global central approach from Section II. In order to use the full functionality of this approach, it is necessary to integrate network asset data and online measurements. These data is imported via a CIM (Common Information Model) interface and the online measurements are cyclically updated.

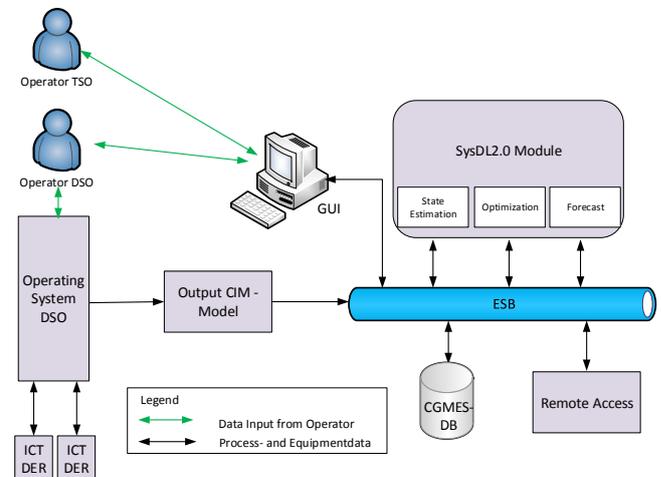


Figure 11: Overview of DMS function demonstrator

³ <http://www.sysdl20.de>

The system consists of a state-estimation, an optimization and a forecast processing module. With the full knowledge of the network state, it is possible to determine the optimal set of input vectors for DGs under network constraints. These constraints can be for example asset operational limits or certain values at points of common coupling. The system is also capable of considering contingencies and finds n-1 secure solutions. With the help of forecast data, reactive power flexibility ranges for the next four hours are computed and provided via a graphical user interface. It is also possible to detect network congestions beforehand. Eventually, this pilot system will be installed and working at two German distribution grid operators in an experimental field test.

V. CO-SIMULATION AND TESTING WITH OPSIM

The proposed central Q-Management approach is investigated in laboratory environment using the “OpSim” real-time Controller-in-the-Loop simulation platform. The OpSim platform is a test- and simulation-environment with applications ranging from developing prototype controllers to testing operative control software in the smart grid domain. OpSim enables users to connect their software to simulated power systems, or test it in conjunction with other software. The power grid simulator of OpSim is capable of emulating large power systems with multiple voltage levels and substantial amounts of generators, storages and loads. Figure 12 gives an overview of the OpSim test environment. The core of OpSim is a flexible message bus architecture, which allows arbitrary co-simulations in which power system simulators, controllers and operative control software can be coupled together.

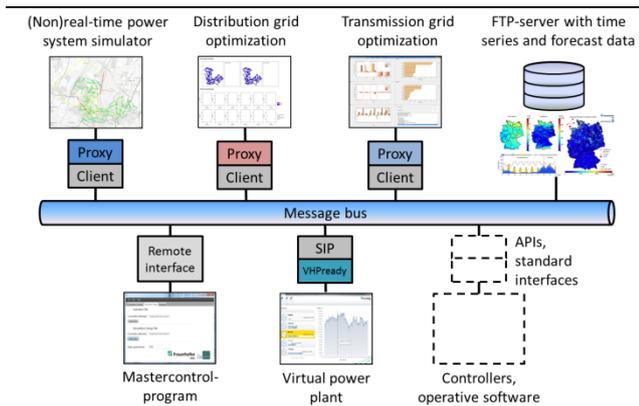


Figure 12: Overview of OpSim test environment developed by Fraunhofer IWES [www.opsim.net/en]

VI. CONCLUSIONS

In this paper, latest results of the industrial project “Q-Study” are presented, which is carried out by Fraunhofer IWES together with German distribution system operator Bayernwerk Netz GmbH. The presented project focuses on

reactive power management in distribution systems using distributed generators and covers comprehensive research activities such as concept development, potential assessment, laboratory and field test. In addition, the applied real-time test- and simulation environment OpSim is also presented. OpSim allows users to test operative control approaches in the smart grid domain by emulating large power systems with multiple voltage levels and substantial amounts of generators, storages and load in real time.

VII. REFERENCES

- [1] M. Kraiczy, T. Stetz, H. Wang, S. Schmidt, M. Braun, “Entwicklung des Blindleistungsbedarfs eines Verteilnetzes bei lokaler Blindleistungsregelung der Photovoltaikanlagen im Niederspannungsnetz”, VDE ETG Congress, Kassel, 2015.
- [2] E. Kämpf, S. Schmidt, B. Walther, S. Wildenhues, J. Brantl, M. Braun, “Reactive Power Provisioning from MV to HV by use of Reactive Power Capabilities of Decentralized Generators”, ETG-Congress, Berlin, 2013.
- [3] E. Kämpf, M. Braun, T. Stetz, H. Abele, S. Stepanescu, “Reliable Controllable Reactive Power for the Extra High Voltage System by High Voltage Distributed Energy Resources”, CSE Journal, 2015.
- [4] European Commission Regulation 2016/1388: Establishing a Network Code on Demand Connection, Article 15, Reactive Power Requirements, 2016.
- [5] H. Wang, T. Stetz, M. Kraiczy, K. Diwold, S. Schmidt, M. Braun, “Blindleistung für den Netzübergabepunkt Hochspannung/ Mittelspannung durch Nutzung eines zentralen Regelungsverfahrens”, VDE ETG Congress, Kassel, 2015.
- [6] L. Thurner, A. Scheidler, J. Dollichon, F. Schäfer, J.-H. Menke, F. Meier, S. Meinecke, and et. al., “pandapower: Convenient Power System Modelling and Analysis based on PYPOWER and pandas,” 2016. [Online] Available: http://pandapower.readthedocs.io/en/v1.2.2/_downloads/pandapower.pdf, Accessed on: Aug. 17 2017.
- [7] H. Wang, T. Stetz, F. Marten, M. Kraiczy, S. Schmidt, C. Bock, M. Braun, “Controlled Reactive Power Provision at the Interface of Medium- and High Voltage Level: First Laboratory Experiences for a Bayernwerk Distribution Grid using Real-Time-Hardware-in-the-Loop-Simulation”, VDE ETG Congress, Bonn, 2015.
- [8] H. Wang, M. Kraiczy, S. Schmidt, B. Requardt, J. –C. Töbermann, M. Braun: “Blindleistungsmanagement im Verteilnetz durch zentrale Regelung großer PV-Anlagen: Pilottest in einem Mittelspannungsnetz der Bayernwerk AG”, 4th. Conference, Zukünftige Stromnetze für Erneuerbare Energie, Berlin, 2017.
- [9] S. W. – v. Berg, N. Bornhorst, S. Gehler, “SYSDL 2.0 - Systemdienstleistungen aus Flächenverteilnetzen: Methoden und Anwendungen”, 14. Symposium Energieinnovation 2016, Graz, 2016.