Journal of Energy Challenges
and Mechanics
http://www.nscj.co.uk/JECM/

ISSN 2056-9386
Volume 3 (2016) issue 3, article 3

Optimized reactive power management across different voltage levels on the example of medium-voltage grids

中壓電網示例中跨不同電壓電平之優化無功功率管理

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Accepted for publication on 3rd September 2016

Abstract - **The secure supply of ancillary services in the future electrical energy supply system is an important question of both distribution and transmission system. Decentralized generation units provide an increasing share of the electrical power generation. Thus, these units are an important factor within the overall grid state. The latest grid code requirements for generation units, depending on voltage level and nominal power, include the ability of reactive power provision, in the distribution grid mainly for voltage band optimization. This required reactive power provision and in addition, the current grid expansion as well as the grid integration of new consumers, e.g. electric mobility, leads to ongoing changes within the reactive power exchange between all voltage levels. In future grid states an optimized reactive power exchange will be needed for a secure grid operation. In this paper, the results of the interdisciplinary research project "iQ" for optimized reactive power management of medium-voltage grids regarding the high-voltage level are described as well as the outlook for further research questions in the field of reactive power exchange across all voltage levels.**

Keywords - **power system management; reactive power control; distributed power generation; wind power generation, smart grids**

I. INTRODUCTION

The provision of reactive power is an important ancillary service for as well the transmission system as the distribution system of the electric power grid. Because the transmission of reactive power over long distances leads to massive voltage drops, it has to be solved as a local problem and the reactive power demand of all grid components and consumers has to be provided for all points in time within varying grid states. Traditionally the synchronous generators of conventional power plants provided with different field ratios in addition to static VAR compensators or flexible alternating current transmission systems (FACTS) the reactive power demand in the transmission system. To optimize the compliance with the tolerable voltage bands in the transmission system a three-level concept comparable to the control power reserve has been established [1]. First the transformer tap-changers are set automatically to secure predefined voltage set-points. Secondly the set-points of the voltage regulators of the synchronous generators are optimized or reactive power compensators are switched on. Afterwards optimal power flow (OPF) methods are used to monitor and optimize all control variables.

The reactive power demand of distribution grids has been depending on the active power demand of the loads. Low load states in (medium-voltage) grids with high shares of cables lead to reactive power provision[I] for the higher voltage levels, peak load states to a high reactive power demand (see Fig. 1) [2]. Within the ongoing transformation of the energy supply system the share of distributed generation (DG) units mainly using renewable energy sources (RES) is increasing. The primary energy sources of the DG are thereby fluctuating with time. Because the DG units are mainly connected in the distribution grid and hence to the low-voltage (LV), medium-voltage (MV) or high-voltage (HV) grid, the load flow direction between all voltage levels as well as the amount of reactive power exchange is changing. Furthermore the correlation between active and reactive power is getting more and more unpredictable and independent of the current load situation, but more dependent on the current feed-in of the distributed generation and ratio of DG and loading. This leads on the one

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[I] In this paper current and voltage are assumed the same direction in a passive load ("*Verbraucherzählpfeilsystem*") hand to points in time where distribution grids start to provide reactive power to the ultra-high-voltage (UHV) level and on the other hand to increasing reactive power demand in all voltage levels.

In future grid states with high shares of DG synchronous generators of conventional power plants may no longer be evenly distributed in the transmission system and active in all points in time. Hence the future reactive power supply in the highest system level will presumably have to be reassigned and the reactive power exchange within all voltage levels rearranged (see Fig. 1).

A classic characteristic load state is a low load state without active or reactive power supply of DG units. In this grid state power lines with high nominal voltages with low loading provide reactive power (blue arrows in Fig. 1) because of their capacitive characteristics and the load state below the natural operational. The low reactive power demand (red arrows in Fig. 1) of normally high demanding loads, as e.g. industrial loads, could in this case be supplied by the capacitances of power lines and the synchronous generators, which in some cases could also operate underexcited (see Fig. 1). Within such load cases in some extent the MV level especially in rural regions could provide reactive power to the HV level.

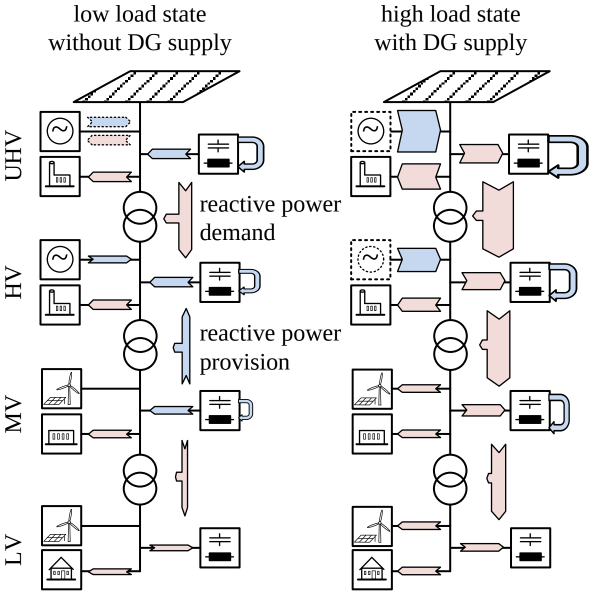


Fig. 1, Change of reactive power demand and exchange within all voltage levels

One future problematic grid state could be a high load state with active and reactive power supply of DG units with e.g. a fixed inductive power factor cos(φ) to handle the problem of voltage increase at high feed-in of active power [3], [4]. In load cases like this the reactive power exchange throughout all voltage levels would be clearly different. All power lines (including the cables) would demand reactive power because the inductive share exceeds the capacitive characteristic because of the load state above the natural operation. Also the loads and transformers demand reactive power. The demand of the DG units is dependent on their active power supply, thus fluctuating with time. Without a high-level coordination and a possible loss of the synchronous generators in the UHV level the reactive power supply within all voltage levels could be demanding, because first a high demand and second a high exchange of reactive power has to be supplied and controlled.

Several solutions for this problem are discussed. Under reserve of the future grid expansion plans, the integration of high-voltage direct current (HVDC) power lines with the according voltage source converters (VSC) could provide additional reactive power sources in the transmission system. This could lead to more control variables in a hybrid grid operation with high-voltage alternating current (HVAC) and HVDC systems [5]. Also classic solutions with expansion of static VAR compensators or other FACTS are a possible solution with well-known modeling and simulation approaches [6], [7]. Because one driver of the reactive power exchange variations are the DG in the distribution system, an optimized reactive power management with the use of DG units and an optimized reactive power exchange within all voltage levels is also a common solution [2], [8], [9].

II. REACTIVE POWER MANAGEMENT OF DISTRIBUTION AND TRANSMISSION GRIDS

As a consequence of the high generation of DG in the lower voltage levels, voltage band problems can occur if the power supply is not handled correctly [10]. Therefor the grid codes and requirements for generation units in the medium or low-voltage grids demand detailed outlined reactive power provision of generation units. This has been progressively increased with the growing share of DG in the energy supply system. The grid codes are specified depending on nominal voltage and power of the generation units [3], [4]. In this way voltage band problems and the need of grid expansion can be minimized. In addition with the beginning of the year 2016 the European Commission in cooperation with the European Network of Transmission System Operators (ENTSO-E) published comparable binding grid codes for all voltage levels [11]. The national grid codes will be complemented with the new requirements and define open issues.

One challenge within the analyses and standardization of distribution grids is the high diversity of these grids, especially in the lower voltage levels. The relevant grid parameters as e.g. load density, length of lines, share of cables and saturation with DG vary extensively between e.g. rural and urban grids as well as between different regions. Hence every distribution grid is considered to be very individual. The German forum network technology / network operation (VDE FNN) has published a guideline for the evaluation of the reactive power ability of distribution grids [8]. These guidelines are considered in the scenario definition (see 3.2) and stationary simulations of this study (see 3.3).

The reactive power provision is one important aspect in the evaluation of the possibilities as well as the boundaries of a future energy supply system mainly based on DG using RES. Because this is an integrated matter of both system levels (transmission and distribution system) a coherent overall system model is needed to analyze the interactions across all voltage levels [12], [13], [14]. The research project *Smart Nord* developed several interdisciplinary methods and approaches for research questions in the fields of decentralized coordination procedures, integrated markets, micro grids, capability and environment as well as the power grid and European market [12]. One aspect in the working package 4.1 was the development of a voltage level comprehensive system model (see Fig. 2) to evaluate the integration of DG units in addition to an existing grid and market model of the ENTSO-E transmission system [13], [15], [16]. This model was used to analyze both stationary as well as dynamic processes [17].

The project *Smart Nord* covered the analyses of active power supply of DG within all voltage levels, frequency stability analyses with control power reserve of DG units and voltage band optimization in the transmission system [17]. Within the analyses of stationary processes the reactive power provision was briefly simulated with synthetic high-voltage grids and several scenarios [18] for adapted versions of a medium-voltage benchmark grid [19]. The research question covered the pan European integrated grid and market simulation, thus an effective large-scale approach was used.

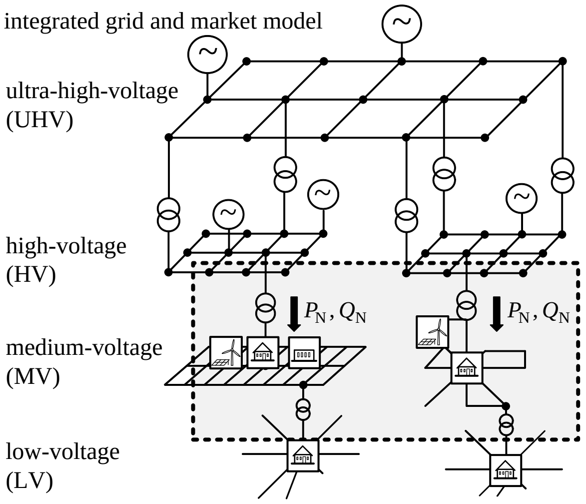


Fig. 2, Adapted cohesive grid and load model [18]

Considering the high divergence of medium-voltage grids and the increasing interconnection of the transmission and distribution system, a more detailed approach for analyses of an optimized reactive power exchange between different voltage levels was needed. Thus within the follow-up project to *Smart Nord* the research project "iQ" – intelligent reactive power management – stationary analyses of several medium-voltage grids in different scenarios have been realized to identify the reactive power ability of characteristic distribution grids [20]. In this way possible reactive power provision concepts between medium and high-voltage grids could be elaborated. The cohesive grid and load model was reduced to the MV and HV level and the total aggregated grid power consumption (P_N, Q_N) at the high-voltage side of the main transformer of the single MV grids including all loads, generation units and losses are used as main resulting variables (see Fig. 2 and Fig. 4 to Fig. 7).

III. RESEARCH PROJECT IQ

The interdisciplinary research project "iQ – intelligent reactive power management" was a one year lasting cooperation between research institutes of information technology, power supply and control theory with industrial partners of grid operators and IT consulting [20]. The main research question of the project was to analyze and optimize the control and stability of reactive power provision of DG units regarding requirements for the reactive power exchange at the main HV/MV-transformer for specific set-points.. Different approaches and methodologies have been evaluated by the use of both software analyses and a co-simulation set-up. An industrial control-hardware was used to be evaluated for the different control tasks within the project. First the interconnection of the simulation models was established via software interfaces. Second a real-time simulator was used in order to establish the communication with the hardware-based control strategy (realized with an industrial controller). The main task for the software set-up was the incremental development of both the co-simulation and hardware setup with the use of an industrial computer [21].

The input parameters of the research project, in this project the grid models and load data, have been analyzed in characteristic distribution grids in different scenario setups of the reactive power provision of the DG units in stationary time-series simulations (see chapt. III). These results have been the basis of the evaluation of optimized reactive power exchange of the rural grid regarding the HV level and the co-simulation approach and evaluation of control strategies (see chapt. IV and [20]).

3.1. IMPLEMENTATION OF TYPICAL GRID DATA

To cover the high divergence of medium-voltage grids four typical MV grids (see TABLE 1 and TABLE 2) have been selected and modeled with the power system modeling and simulation tool DIgSILENT PowerFactory [22]. In the first project stage a common rural grid from a literature source was used to have a quick set-up [8], [9]. Additionally the project partners (an urban and a rural grid operator) provided all needed grid specifications (see TABLE 1) for one rural 20-kV-grid, one urban 10-kV-grid and one suburban 20-kV-grid. The data included measured data at the HV/MV-transformer. All data had been transferred and implemented in PowerFactory to enable a manageable data exchange between all research partners.

TABLE 1, STRUCTURAL PARAMETERS OF THE ANALYZED MV GRIDS

grid	power lines	local substations
urban 10 kV	41.5 km	67
urban 20 kV	95.2 km	113
rural 20 kV	134.5 km	113
literature [8], [9]	199 km	121

All grids show different characteristics for as well the topological data (see TABLE 1) as well as the installed power of DG and the particular peak load (see TABLE 2). In the rural grid one wind farm close to the HV/MV-transformer with eleven wind turbine generators (WTG) with 22 MVA installed power in total is notable. Whilst in the grid of previous works [9] a mix of WTG and photovoltaic (PV) units was used, the urban grids have only a few DG units including combined heat and power units (CHP) installed in the current state.

TABLE 2, INSTALLED POWER OF DISTRIBUTED GENERATION UNITS IN THE ANALYZED MV GRIDS IN MVA

grid	WTG	PV	CHP	loads
urban 10 kV	0	0	0	17.64
urban 20 kV	3.7	1.74	5.37	39.44
rural 20 kV	22.15	3.2	0.23	35.22
literature [8], [9]	6	19.1	0	25

Because the research focus of the project was the control of DG units, the urban 10-kV-grid without any DG was not analyzed in detail. The grid operators provided the measured data of active and reactive power at the high-voltage side of the main HV/MV-transformer at the substation. Hence different configurations of the DG units should be analyzed in time series simulations, all loads and generation units needed data for one year. The source of the normalized time series of the loads was the parent project *Smart Nord* [12], the normalized generation data was determined from public data of a transmission system operator [23], [24].

With these synthetic load and generation data in combination with the nominal data in the grid models the original grid behavior has been reproduced [21]. However the simulated grid behavior at the main transformer differs from the measured data, because of a higher simultaneousness of the loads and DG as well as missing information of further influencing factors.

The maximum values of active power have been used to determine the need of scaling factors analog to the simultaneity factor in standard grid analyses. The implemented time series leads to specific grid characteristics shown in TABLE 3. With the combination of the normalized time series the dates for typical high and low load states could be determined.

TABLE 3, CHARACTERISTIC POINTS IN TIME OF HIGH AND LOW LOAD

date dd.mm.yyyy	time hh:mm	wind in %	solar in %	loading in %
21.03.2015	13:00	55	99	68
20.12.2015	19:00	89	0	72
18.07.2015	13:00	0	87	81
30.10.2015	20:00	0	0	67
11.05.2015	11:00	70	59	39
23.12.2015	04:00	95	0	15
07.06.2015	09:00	0	72	29
01.10.2015	05:00	0	0	12

These points are not the maximum/minimum load states or maximum/minimum feed-in of the DG, but typical points within the correlation of all load and generation data. The time points are useful to compare different scenarios or grid analyses, thus the shown color classification is used to highlight these specific load states in the results (cf. Fig. 4 to Fig. 7).

3.2. SCENARIO DEFINITION

Time series simulations within different scenarios have been used to evaluate the reactive power capability of distribution grids. The aim is to determine the operational area of these grids and thus the possible adjusting range for a potential control of reactive power provision [8]. According to the latest grid codes four scenarios were defined for the simulations (see TABLE 4).

TABLE 4, SCENARIOS FOR DG UNITS AND LOADS IN THE STATIONARY GRID ANALYSES

scenario	WTG	PV	loads
1	1	0.95 ind.	0.98 ind.
2	0.95 ind.	0.95 ind.	0.98 ind.
3	0.95 cap.	0.95 ind.	0.98 ind.
4	$\cos(\varphi)(P)$	0.95 ind.	0.98 ind.

To reduce the problem on the comparison of control of reactive power through a single control unit in different set-ups the photovoltaic units have been simulated with fixed power factors according to the current grid codes [3], [4], irrespective of nominal power or date of installation. The different reactive power provision of the wind turbines is therefore the main research task, because for the rural grid the control hardware was set up to optimize the wind farm at the main busbar and the results shall be comparable [20], [21].

The scenario 4 with the function $\cos(\varphi)(P)$ describes a reactive power supply proportional to the active power P with two boundaries for low and high power provision according to the current grid codes for generation units in medium-voltage grids [4].

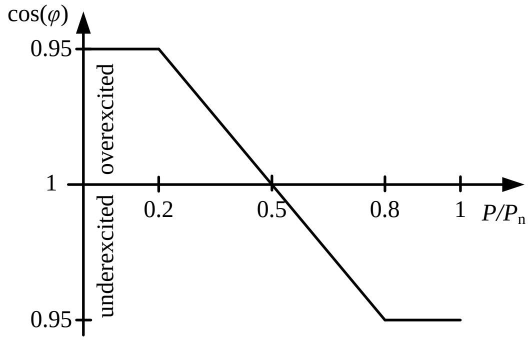


Fig. 3, $\cos(\varphi)(P)$-characteristic for scenario 4 according to [4]

In this paper the characteristic is defined with limits of 0.2 and 0.8 for the ratio of P/P_n (ratio of active power P to nominal power P_n) and 0.95 as limitation for the inductive or capacitive load factors.

3.3. Reactive Power Management of typical Medium-Voltage Grids in different Scenarios

For the modelled medium-voltage grids all scenarios were simulated in time series of one year in one-hour steps. The results are shown for all grids (except the urban 10-kV-grid) with the characteristic points of high and low load highlighted in the diagrams. For the reactive power capability analyses the shown diagrams provide a good indication [8]. The results of the time series simulations are plotted with each reactive power Q_N to the corresponding active power P_N at the main transformer for every single point in time. In this way *PQ*-clouds or -curves can be determined from the load flow calculations, which describe the stationary grid behavior for the different grids over one year precisely and allow a comparison of different input parameters [8].

20-kV-rural grid (literature)

At points in time with high load and only little generation the reactive power follows the active power demand proportionally (see Fig. 4 – high load case 4). The high share of PV units in this grid leads to a constant reactive power provision within all scenarios. Hence the grid behavior is not varying significantly between all analyses. Low loading of lines brings out the capacitive characteristic of the power cables, especially for a rural grid with long circuit lines (see Fig. 4 – low load case 4). The results show primarily for scenario 1 and scenario 2 a typical grid behavior of medium-voltage grids with a high share and balanced mixture of DG units [8], [9].

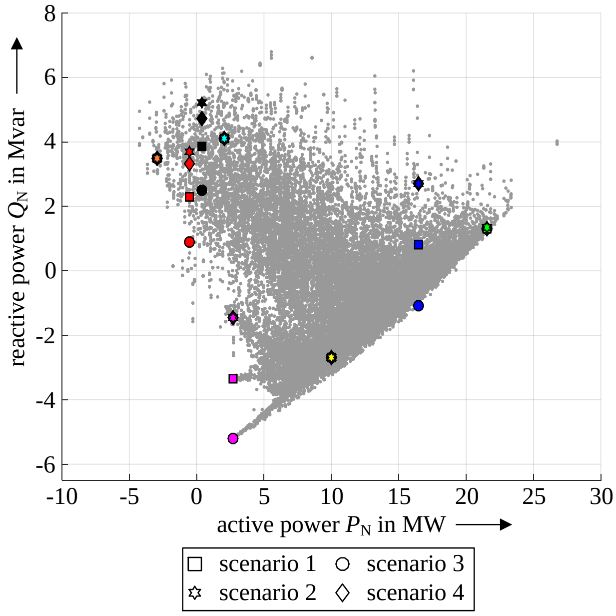


Fig. 4, Results for the 20-kV-rural grid in the scenario analyses

The unusual capacitive power factor in scenario 3 (the wind turbines provide reactive power and increase the nodal voltages) leads to the most negative operational points for the reactive power exchange at the main transformer (see Fig. 4 – low load case 2). Due to possible voltage band problems this scenario is not practically reasonable in all points in time, but works as negative boundary for the capability analyses. The scenario 4 with the $\cos(\varphi)(P)$ characteristic is always between the limitations of 0.95 underexcited and 0.95 overexcited (see Fig. 3) and thus between scenario 2 and scenario 3 (see e.g. Fig. 4 – high load case 1).

For this grid model detailed analyses have been published in several studies [8], [9], hence it was used as benchmark for the simulation set-up.

20-kV-urban grid

The urban grid with 20 kV nominal voltage has only very few DG units installed. Thus in all scenarios a very proportional behavior of active and reactive power to the load states was obvious. Additionally, because of the shorter length of lines and higher load density, the minimum value of Q_N is only about -3.5 Mvar (see Fig. 5 – low load case 2).

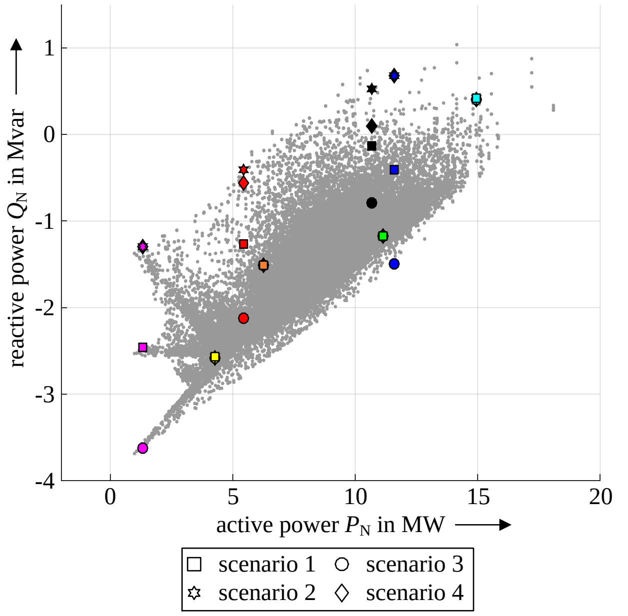


Fig. 5, Results for the 20-kV-urban grid in the scenario analyses

To match the measured data of the grid operator a scaling factor of 0.6 had to be used for all loads, because the simultaneousness of the used load time series did not exactly recreate the original data. The results show a typical overall grid behavior for nearly all points in time with a negative reactive power balance to the upper voltage level. Potential scenarios for reactive power optimization could be a more optimized grid behavior or a minimization of the impact on the upper voltage levels, if more DG units are installed with a future expansion of RES in urban grids like this.

20-kV-rural grid

The rural grid including the measured data from the grid operator was the main simulation subject of the research project "iQ". With a 22 MVA wind farm installed at the main busbar a good practice-oriented set-up could be build up, especially for the co-simulation approach with the control-hardware. The results of the stationary grid analyses (see Fig. 6) show a different characteristic of active to reactive power behavior as the other observed grids (cf. Fig. 4 and Fig. 5).

Contrary to the other grid simulations, the measured data and the results did first not match either qualitative or quantitative. This can be explained with different input parameters in the load flow calculation, the aggregation of some subgrids (as e.g. the cables of the wind farm and a few bigger industrial loads), different voltage set-points at the main transformer and of course a much more individual behavior of all loads within the real grid in comparison to the simulation. As a solution a base load of 5 Mvar had to be installed to match the measured data quantitative.

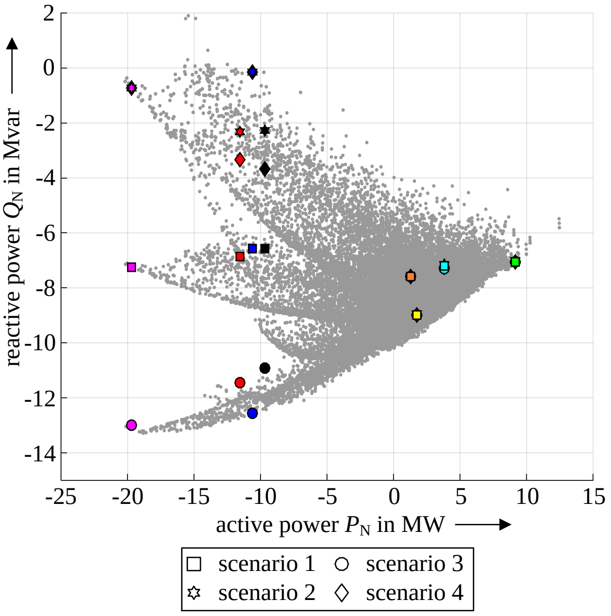


Fig. 6, Results for the 20-kV-rural grid in the scenario analyses

The qualitative behavior could not be matched satisfactorily. The exact operation for active and reactive power of the wind farm in the time span of the measured data could not be elaborated. However independent from the actual operation of the wind turbines in the comparison between the measured data and the results of the four scenarios (see Fig. 6) the best match has been most likely an operation between either scenario 2 ($\cos(\varphi) = 0.95$ ind.) or scenario 4 ($\cos(\varphi)(P)$) to reproduce a most matching overall grid behavior.

An improved methodology of recreating measured grid data and the influence of further possible improvements for emulating the original grid behavior as e.g. different grid switching states and more individual loads is still a missing task (see chapt. VI). Furthermore the grid model was supplemented with 400 mm² AL cables with a standard two-string-topology for the wind farm to consider the influence of the connecting cables to the reactive power exchange. This was also an important parameter of the control hardware.

In comparison of all scenarios the results show the high influence of all DG units and especially the wind farm (see Fig. 6):

- the original grid as well as the simulation results show a high negative behavior of the reactive power for most points in time (compensators have not been considered in the simulations)
- all scenarios have a big influence on the overall grid behavior (power exchange and voltage bands)
- scenario 1 differs from the results of the literature grid because of different WTG/PV and load ratio
- scenario 2 and 3 are primarily proportional of wind-farm active power to reactive power (the influence of the PV units is diminished)
- scenario 4 differs as in Fig. 4 between scenario 2 and 3 because of the used $\cos(\varphi)(P)$-characteristic
- the reactive power ability differs significantly with the available active power of the DG units
- the difference between the characteristic points in time varies from only a few Mvar up to 14 Mvar at weak load and high wind generation

The 14 Mvar difference at the peak generation approximate the overall reactive power ability of the wind farm. In the optimization of the reactive power exchange (see 4.1 and 4.2) a typical operation diagram of wind turbines was used to determine this characteristic more detailed. Within the project this results were used as framework for the further studies with the control hardware, complemented also with analyses of control values and system stability [20].

3.4. COMPARISON OF THE STATIONARY GRID ANALYSES

All results combined with a synthetic simulation of the urban 10-kV-grid, which was supplemented with a WTG for comparison purposes, give a good overview of the high divergence of the stationary grid behavior (see Fig. 7).

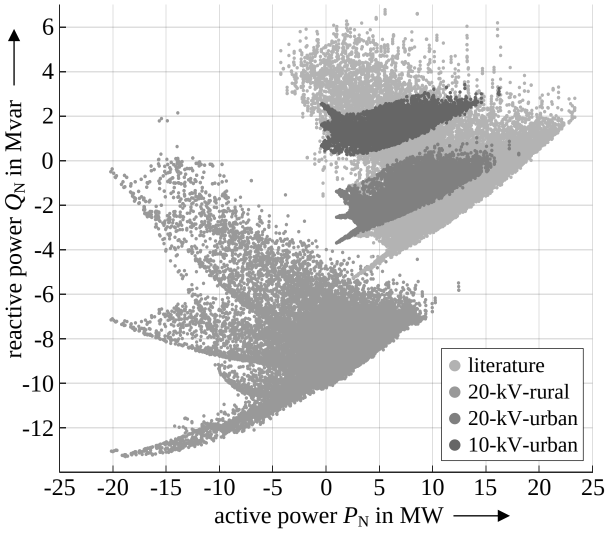
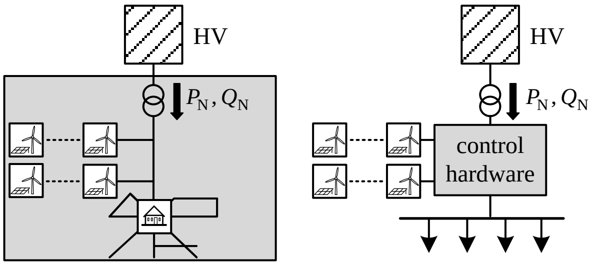


Fig. 7, Results of all medium-voltage grids combined

Especially the 20-kV-rural-grid is deviating from the average grid behavior. The specific points in time of high and low load allow a good and quick approximation of the active to reactive power characteristic, but only the simulation for one year, even with time characteristics with a higher simultaneousness than real loads and generation units, describe the grid behavior sufficiently. Additional approaches as e.g. the variation of photovoltaic units, alternating voltages at the 110-kV-busbar, automatic tap-changing of the main transformer or different load characteristics have also been simulated for selected grids, but will be content of future work (see chapt. VI).

IV. REACTIVE POWER EXCHANGE OPTIMIZATION

After the stationary analyses of all presented medium-voltage grids, the optimization of reactive power exchange between the high-voltage grid and one single medium-voltage grid (the rural 20-kV-grid) has been analyzed. Two different approaches have been realized. First a simulative analyses was implemented in PowerFactory, to give a theoretical basis of comparison to the experimental approach. Second, a co-simulation with the integration of a control-hardware was set up (see Fig. 8).



complete MV grid aggregated MV level

Fig. 8, Set-up for the reactive power exchange optimization approaches in section 4.1 and 4.2

The aim of both approaches was to fulfil definite set-points at the high-voltage side of the main transformer for the reactive power Q_N , which is equal to the reactive power exchange between these two voltage levels as well as the overall medium-voltage reactive power consumption of the considered MV grid model. The differences of both approaches are within the details of the grid model (see Fig. 8) and different optimization methods.

4.1. THEORETICAL REACTIVE POWER ABILITY

Three different set-points at the main transformer have been simulated in 15-minutes steps to evaluate first the reactive power ability on the basis of the maximum and minimum reactive power exchange values of the overall grid behavior and second the ability of the wind farm to achieve one single set-point.

- set-point 1: $Q_N = Q_{max}$
  (maximum demand of the MV grid to the HV grid)
- set-point 2: $Q_N = Q_{min}$
  (maximum provision of the MV grid to the HV grid)
- set-point 3: $Q_N = 0$
  (a neutral grid behavior to the HV grid is desired)

The results show the ability of the wind farm within typical operational limitations of the wind turbines to fulfil these set-points (see Fig. 9). In PowerFactory the maximum, minimum or exact needed reactive power provisions for all wind turbines are calculated automatically in several iterations with knowledge of all the complete grid data with the use of a control method for all wind turbines.

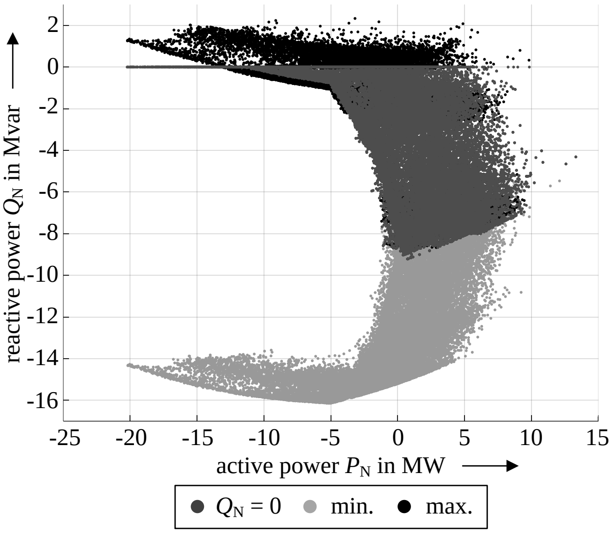


Fig. 9, Results for the 20-kV-rural grid for specific set-points

With the use of the complete grid model in the points in time with high wind generation and thus high reactive power reserve the set-point $Q_N = 0$ could be fulfilled exactly. This is divergent to the results of the co-simulations with the control hardware, which was using an aggregated grid model and had limitations in accurateness because of closed source libraries (see 4.2 and [20]).

Nevertheless, for most points in time the reactive power reserve of all wind turbines was too small to exceed the overall grid behavior (capacitive character of the power lines) so it was not possible to fulfil the set-point of zero reactive power exchange for every grid state. Additionally the PV units have been considered in the same optimization, but provided no significant effect on the general relations of the results. To improve the reactive power ability more control variables would be needed within the optimization (see chapt. VI).

4.2. CO-SIMULATION SET-UP WITH A CONTROL-HARDWARE

Co-simulation is defined as the interconnection of two or more models in a coordinated fashion. The set-up can be comprised of software, hardware models or a combination of both. The iQ project utilizes a software co-simulation set-up [25] that integrates three distinctive models as virtual machines (VM) to evaluate the practical operation of control units in combination with a wind farm for reactive power optimization [21]. The first is the distribution grid modeled in PowerFactory (as discussed in the previous sections). The second is a time series that contains the power production of the entire wind farm within the grid model. The final model is an industrial controller overseeing the reactive power provision for grid stabilization. Fig. 10 portrays a graphical representation of the interconnection of the three models described.

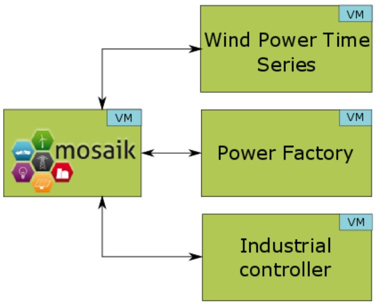


Fig. 10, Software in the loop architecture

The scenarios, grid models and results from the previous analyses are used as input parameters. This means that the previously defined PowerFactory models are reused and connected together with the industrial controller. In addition, the simulation model of the control strategy uses an internal load flow calculator for the set-point calculation. This requires a description of the grid topology within the model of the industrial controller. However a reduced grid topology is employed in order to reduce the complexity of the grid (i.e. the current grid model contains over 700 nodes). Therefore, the grid model within the industrial controller is reduced to the wind farm, main busbar and main transformer.

The complete analysis of the results is shown in [20] and [21], from these two scenarios are selected. In the presented case 1 there is a predominantly high load contribution (approximately 68 % at its peak) and a moderately contribution from the wind farm (55 % of power provision). The case 2 studies the scenario of a low load contribution (29 % of loading) and low power provision (0 % at the lowest point in time). In addition, the set-point $Q_{\mathrm{N}} = 0$ (see 4.2) has been defined. This entails that the industrial controller is measuring the reactive power values at the distribution transformer busbar and controlling the wind farm to provide the required reactive power in order to reach 0 Mvar. The results of the co-simulation set-up are compared with the results from the scenario 4, which has been assumed as the most suitable to represent the original grid behavior from the measured load data supplied by the grid operator. The simulation time for the scenarios has been defined for 24 hours in steps of one hour.

Case 1: high load case 1 (21.03.):

For this specific load case the wind farm supplied 11.796 MW active power in average. Thus a reactive power reserve of ± 8.104 Mvar with the implemented capability curve was available on average. These values are varying within the simulated 24 hours (see Fig. 11).

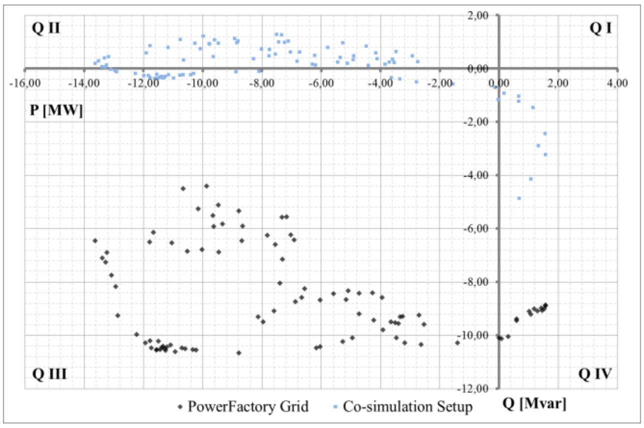


Fig. 11, Results for the 20-kV-rural grid in the high load case 1 with the control-hardware in comparison with the stationary analyses

The results show, that in points in time with high reactive power reserve as high load case 1 the industrial controller was able to configure all wind turbines in the farm in such way, that the set-point value ($Q_{\mathrm{N}} = 0$) was approximated in most of the time. Deviations are notable and for some points in time the set-points could not be achieved at all. This was also notable at the theoretical approach (see Fig. 9)

Case 2: low load case 3 (07.06.)

For this specific load case the wind farm supplied 0.842 MW active power in average. Thus a reactive power reserve of ± 2.247 Mvar with the implemented capability curve was available on average. These values are varying within the simulated 24 hours (see Fig. 12).

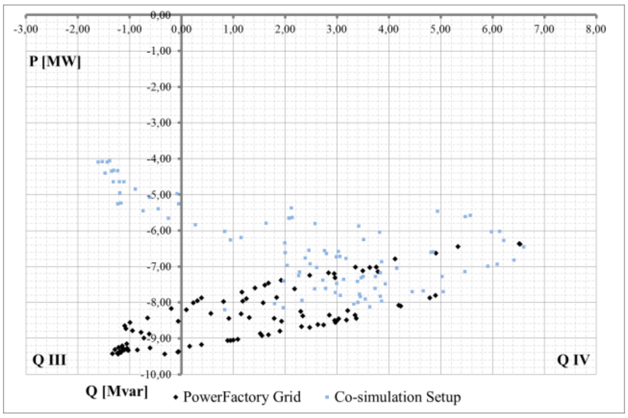


Fig. 12, Results for the 20-kV-rural grid in the low load case 3 with the control-hardware in comparison with the stationary analyses

In Fig. 12 it is observed that the industrial controller attempts to improve the reactive power demand as best as possible taking into consideration the required set-point. However, the set-point value is not reached. This occurs because there is a small amount of power reserve (0 % at its lowest point) coming from the wind farm.

4.3. COMPARISON OF REACTIVE POWER ABILITY RESULTS

The results of the theoretical approach with PowerFactory (see 4.1) and the software integration of the control-hardware (see 4.2) deviate in quality and quantity. The theoretical approach was calculated for one year, thus more values are available, also apart from the characteristic points in time. Furthermore the approach with PowerFactory in contrary to the control-hardware was able to fulfil the set-point $Q_{\mathrm{N}} = 0$ exactly. This deviation can be explained with several reasons:

- the control-hardware uses an aggregated grid model of the detailed grid model, thus deviations in the load flow calculations are naturally
- the theoretical approach had full knowledge of the grid model and was allowed to iterate as often as needed
- the control-hardware is a closed source industrial product, thus not all configurations could be changed as needed

The deviations in the results show some limitations in the used approach. This is the result of being unable to access the control algorithm of the industrial controller. On the other hand, the co-simulation set-up enables the interaction among interdisciplinary simulation models which paves the way for inexpensive testing of multiple scenarios involving several control strategies with different grid topologies.

V. CONCLUSION

Because reactive power provision is a correlated problem of all voltage levels both system levels (transmission and distribution system) have to be analyzed for future power system management concepts. The continuance of the research work after the interdisciplinary research project *Smart Nord* in the follow-up project “iQ” lead to promising results. With the successful collaboration of research and industrial partners within the project the evaluation of realistic and practical approaches has been realized. This paper describes the results of the research project “iQ” and the relation of reactive power supply of medium-voltage grids to the high-voltage level in the current research field of reactive power management.

The detailed analyses of the medium-voltage grids have been evaluated considering current grid codes and the VDE FNN guidelines for reactive power management. It is important to consider the diversity of distribution grids in the research of reactive power management, thus rural and urban grids have been considered in the study. The medium-voltage grids have been simulated with time series for loads and generation units in four defined scenarios for parametrization of the reactive power supply of generation units.

The grid models and simulation results were used as input parameters within the research project and for comparison of different approaches for the evaluation of the reactive power supply ability of a wind farm in a rural 20-kV-grid. With the use of DIgSILENT PowerFactory an optimized power supply of generation units for given set-points could be determined. This is used as theoretical best case scenario in comparison with the use of an industrial control-hardware in a co-simulation approach. The results show differences in the accuracy of fulfillments of the set-point. The dependence of reactive power supply of current load situation and active power reserve is significant in both approaches.

The grid models, simulation frameworks and results can be used in further analyses with different control tasks, continuing studies of reactive power exchange within all voltage levels and reactive power management of distribution and transmission system.

VI. OUTLOOK

With the ongoing transformation of the electrical energy supply system, the reactive power exchange will continue to vary in quantity and quality in future grid states with high shares of distributed generation units. Also the reactive power provision within all voltage levels and in the large-scale view within all system levels will have to be evaluated.

Hence voltage collaborating models and methodologies are needed to analyze not only the possibilities but also the boundaries of the use of DG units to supply ancillary services, as e.g. the reactive power provision. The approaches of this paper in the software simulation as well as in the co-simulation of the hardware component are proper methodologies to analyze different scenarios and requirements for control of several DG units, as e.g. a wind farm. Furthermore other hardware components or different control tasks could be analyzed in the co-simulation, which would allow several interdisciplinary research questions also in the field of control-strategies and system stability [20].

The simulative approach could be extended with the use of various different medium-voltage grids or different scenarios, respectively different reactive power behaviors of the grid components with more generic data as described in [8]. The current work in DIgSILENT PowerFactory has been validated with load flow studies in Matlab based on Newton-Raphson method and the same scenario data as described. With all data transferred to Matlab more flexibilities arise within the field of power supply. The further integration of the underlying voltage levels in the existing grid and market model of the ENTSO-E transmission model would allow large-scale analyses with the use of a broad data base [13], [16]. The regional data for characteristics of economy, market, population, industry or geography for different regions from this model could be used for an advanced approach for generic analyses of the reactive power exchange of different characteristic distribution grids.

An improved reproduction of the measured grid data as often provided from grid operators (15 minutes mean values of active and reactive power at the main transformer) with aggregated loads and DG units could enhance the performance and quality of the scenario analyses.

Furthermore the optimization of the reactive power provision as well as the exchange within all voltage levels has to be continued to analyses within the interconnection of distribution and transmission system and therefore between the HV and UHV level. This could be elaborated with e.g. the use of optimal power flow methodologies, to implement also the flexibilities of other grid components as FACTS, transformer tap-changers and static VAR compensators.

Acknowledgments The *Smart Nord Transferprojekt iQ Intelligente Blindleistungssteuerung für Verteilnetze* acknowledges the support of the Lower Saxony Ministry of Science and Culture (MWK) (Grant number VWZN3002).

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