Derivation of Recommendations for the Future Reactive Power Exchange at the Interface between Distribution and Transmission Grid

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ABSTRACT

Conventional power plants in the transmission network are increasingly replaced by distributed generation in power distribution networks. This leads to a lack of reactive power provision in the transmission network. At an ever increasing dimension, cost-intensive measures are taken, such as the installation of compensation elements. This paper aims to present and discuss alternative solutions for cost-efficient provision of reactive power considering reactive power control concepts including distribution networks. A methodology is derived which allows to calculate the potential of reactive power available from the distribution system and to calculate the use-case-dependent need of reactive power in the transmission network. A metaheuristic optimization approach has been developed to consider different comprehensive reactive power strategies. With the help of these investigations it is possible to derive basic recommendations for the organization of the future reactive power exchange at the interface between distribution and transmission networks and the contents of corresponding contracts.

INTRODUCTION

The substantial increase in installed capacity of distributed generation (DG) in power distribution networks (high-, medium- and low-voltage) leads to an increasing replacement of conventional power plants in the transmission network (extra high-voltage) which causes a lack of system service provided to the transmission network. As a consequence, there is a loss of reactive power (Q-)sources, resulting in increasing challenges in terms of voltage maintenance in the transmission network. A conventional countermeasure is the installation of static compensation elements like capacitors or inductors in the transmission network. Next to this cost-intensive measure, a reactive power support by the distribution networks is a conceivable solution. There are several possibilities to provide reactive power within distribution networks. In particular, the DG connected to the distribution networks could be used for this purpose, a reactive power provision of these facilities is prescribed in the corresponding connection regulations, e.g. in Germany.

For this kind of overall reactive power exchange concepts, guidelines are required for the future Q-exchange between distribution and transmission systems. The European "Demand Connection Code 2013" [1] developed by the ENTSO-E already contains first approaches. Due to requirements strongly differing between separate control areas, recommendations can only be made in a broad sense. Given by complex interactions between voltage levels, there is a risk of one-sided apportionment or technically inefficient solutions. Therefore, studies are required which examine reactive power control concepts for specific regions. These concepts can range from passive support by distribution networks such as limits for the reactive power transfer to system-state-dependent reactive power target values at the interfaces between distribution and transmission networks. It is also conceivable that conventional measures in the transmission network are cheaper in a macroeconomic view than a support by the distribution network. The following questions have to be answered:

- What is the reactive power potential available from the distribution networks?
- What is the future situational need of reactive power in the transmission system?
- Which conflicts in the distribution networks can result in a Q-provision for the transmission network?
- Which overall reactive power strategy might be reasonable and cost-efficient for specific regions?

ANALYSIS

Influences on reactive power behavior of distribution networks

Supporting the transmission network with reactive power from distribution networks can be realized by influencing the reactive power behavior (Q-Balance) of the connected distribution networks. Distribution network operators have several possibilities to influence the Q-balance of their grid. Table 1 shows possibilities which are directly available to distribution networks.

Table 1: Q-variables of distribution networks

Influencing the reactive power provision of DG
Changing the tap position of substation transformers
Switching compensation elements
Net topology measures

In the following, these possibilities are called Q-variables. In Germany the possibility of reactive power provision by DG is defined by the grid code for distribution networks. The directives prescribe reactive power provision dependent on the voltage level and partly on the actual voltage at the connection point.

For example, new connected DG in medium voltage networks must have the possibility to provide reactive power between cos(φ) = 0,95 inductive to capacitive [2]. The limits depending on active power seem to be useful from the perspective of an overall voltage control concept, especially at high DG infeed, as this may result in additional demand of reactive power by the distribution network. On the other hand, the reactive power of DG is essentially limited by current. In principle, plants could provide more reactive power at lower active power supply. This would set free further potential without creating significant additional costs.

Changing the tap position of substation transformers is another Q-variable which also influences the Q-balance significantly by varying the operating voltage in distribution networks. The stepping leads to changes in the reactive power assumption of equipment and connected customers.

In many distribution networks there are connected compensation elements which are owned or at least can be controlled by the network operator. Operating these elements can also substantially influence the Q-Balance. Topological measures in the distribution network, e.g. changing the position of disconnection points, hooking reserve lines etc., are rarely used to influence the Q-balance of the network due to low topology redundancy and will not be considered in this paper.

In the focus of interest arising from future developments in system management, there are different concepts of control and regulation of these Q-variables. Significant changes in the operation of networks, particularly in distribution levels, are discussed and being expected within a time horizon of 10 to 15 years. Vision is a network consisting of a great number of central coordinated network utilities and DG. A central controller instance (e.g. an Optimal Power Flow-method) operates these components based on the currently available use case and current topological conditions. For this purpose, adequate system observability and the integration of coordinated network utilities and DG in communication networks is required. On the one hand this centralized control allows high flexibility, on the other hand it leads to additional costs and high demands on network operations due to the great complexity of the control. Alternative concepts are based on decentralized, autonomous controls of the network utilities and DG or fixed default values for Q-provision. The subsequently introduced method to evaluate Q-strategies is able to consider both concepts. For a more detailed view, the concept with central control is considered exclusively.

Conflicts between distribution and transmission networks

The mentioned Q-variables are nowadays primarily used only for interests of distribution networks. Reactive power management is done for voltage maintenance reasons, for example if the active power infeed of DG leads to a voltage increase. For this reason, network operators often ask for an under-excited operation mode of DG to reduce the voltage in their network. This is, however, associated with a strong impact on the Q-balance of distribution networks, as the under-excited operating mode leads to a high demand of inductive reactive power. This demand has to be covered by the overlaid network. In addition, since there are high power flows in the transmission network due to the return feed from DG, overhead lines also have a high demand of inductive reactive power. The superposition of these two effects may lead to voltage maintenance problems in the transmission network. Thus, there is a conflict between the interests of distribution and transmission system operators which is shown by the use of Q-variables.

Another conflict arises from additional power losses by using Q-variables. Distribution system operators are interested to reduce costs by operating the network with minimum power loss. High reactive power flow causes additional apparent power transport in the distribution network. Consequently, specific target values for reactive power at the interface between the voltage levels lead to increasing losses in the distribution network.

METHODOLOGY

Interaction between voltage levels

For the derivation of overall reactive power control concepts, a network model is required which takes all voltage levels into account. A schematic overview of the network model is shown in Figure 1.

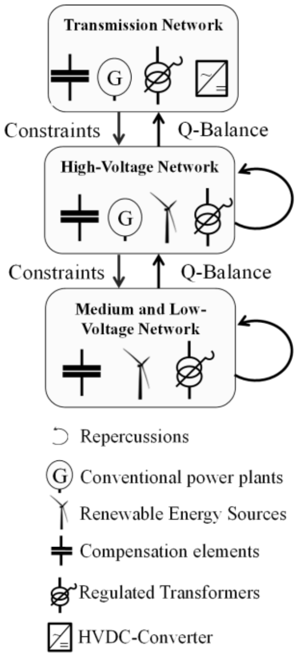

Figure 1: Schematic network model

Transmission and high-voltage networks can define corresponding constraints at each interface, such as limits, target values or even no restrictions which are fulfilled by the Q-variables of the subordinated grids. The result is a certain Q-balance appearing at the interfaces between the voltage levels. It is important to note that the fulfillment of constraints is always associated with repercussions in form of voltage, load and power loss changes in the subordinated grids.

Virtual prosumers

The transmission and high-voltage network is simulated in detail due to the high degree of intermeshing. Therefore, the model of the German Network Development Plan for 2023 is used. For a selected section of the transmission network the subordinated grids are modeled in detail. For the rest of the network underlying grids are represented as equivalent loads.

The medium- and low-voltage networks and their overlaid network are often connected at only one interface. Therefore, they can be reduced to active and reactive power flows at the interface to the high-voltage network.

To consider the flexibility potential of reactive power in the distribution system these networks are represented as so-called virtual prosumers. There Q-behavior is adjustable similar to a conventional generator with use-case-dependent reactive power limits and information about power loss correlation to the Q-variables. The reactive power limits are determined with the help of an optimization approach using the Q-variables as degree of freedom and regarding maximum load of utilities and voltage limits for distribution networks corresponding to the directive of EN 50160 [3] as constraints. The optimization approach considers continuous and discrete variables to simulate the Q-provision of DG as well as changing transformer tap positions or switching of compensation elements. A metaheuristic optimization method using a Particle Swarm approach is suitable to solve these problems. The determination of Q-limits for distribution networks has to be undertaken in plenty of use cases. Figure 2 shows the determined Q-limits for a rural distribution network with central control of all Q-variables.

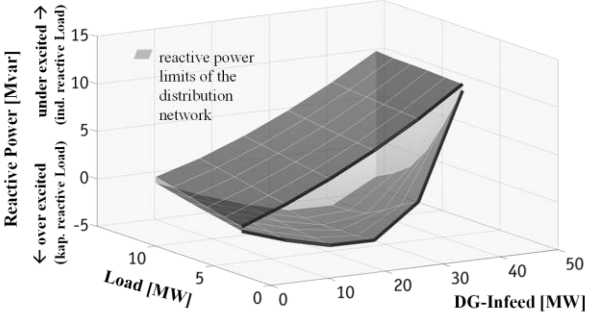

Figure 2: Reactive power limits of an exemplary rural distribution network

The upper shaded surface describes the distribution network's maximum under-excited limit and the lower surface its maximum over-excited limit from the perspective of the overlaid network. At low DG-infeed there is only a small reactive power potential, since the grid codes in Germany prescribe only active power dependent Q-limits of DG without Q-provision at no infeed. The left Q-potential comes from DG, with a type of energy allowing a continuous operation mode (e.g. biomass energy) or by stepping of substation transformers without violating the voltage limits.

At a low consumption and an increasing DG-infeed the Q-potential expands proportionally caused by the linear correlation between active and reactive power by prescribing a fixed cos(φ)-limit. In the exemplary network at an infeed of about 20 MW this relation in the minimum Q-balance (over-excited mode) is interrupted. The reason is given by the necessity of voltage maintenance in the distribution system. At high DG-infeed the voltage at the grid connection nodes of DG rises especially for DG which is electrically far from the regulated substation. To avoid violation of voltage limits, DG has to provide capacitive reactive power (under-excited mode). The result is a less over-excited, at high infeed only under-excited Q-balance limit of the distribution network. For the shown network the whole DG connection capacity is used from the perspective of voltage maintenance due to the merging of upper and lower limit at maximum DG-infeed. The characteristics of those limits also depend on the control concept of the Q-variables (centralized or decentralized control) [4]. The results at centralized control represent the maximum band of reactive power provision of the distribution network.

The subordinated distribution networks analyzed for this study are synthetically generated using standardized utilities. A procedure [5] is used which distinguishes between different spatial categories (rural, urban, suburban) and simulates active and reactive load with a developed consumer model.

Power loss curve

For every use case it is possible to calculate an individual power loss curve which describes the losses depending on the Q-balance (Figure 3). The figure shows a parabolic relationship. Additionally the parable is shifted in discrete steps against the transformer tap position, because the higher the voltage in the network, the lower the power losses. With regard to an operating mode with minimal power losses for a certain tap position, a trend can be evaluated: the lower the absolute value of Q-Balance, the lower the power losses. This is derived from the fact that in neutral condition the reactive power flows are normally small.

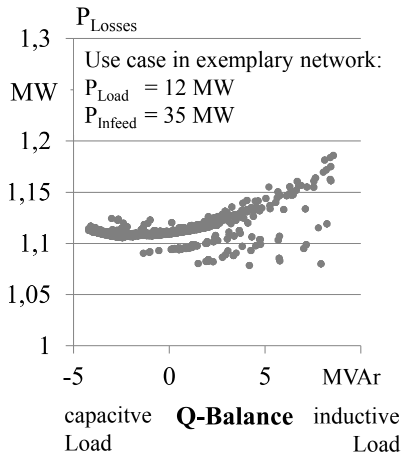

Figure 3: Power losses against Q-Balance for a use case

A power loss curve will be deposited for every use case and every virtual prosumer to allow representing the conflict of potentially increasing power losses when supporting the transmission network with reactive power.

Strategies for the reactive power exchange between voltage levels

There are several strategies conceivable for the reactive power exchange over all voltage levels. These can reach from no restrictions at the interfaces or specific constraints all the way to use-case-dependent target values for the reactive power exchange. In this paper, the former and the latter strategy will be analyzed in detail. Therefore, an optimization approach is developed. For the latter strategy, this approach derives the target values for the subordinated grids from the need of reactive power in the transmission network. For the former strategy, it calculates an operating mode with minimal power losses in the distribution networks. The absolute value of the horizontal reactive power exchange of the considered transmission network section is used as an evaluation parameter. Corresponding to the Continental Europe Operation Handbook for the transmission network, the reactive power exchange of control areas should be as low as possible. This specification is also anticipated for the considered section of the transmission network. The exchange is opposed to occurring power losses of the distribution network for each strategy.

Strategy 1: Operating with minimal power losses in the distribution networks

The optimization method is composed of a multi-level approach. In the first level only the reactive power operation mode of the distribution network is optimized with minimal power losses as objective function. The maximum load factors of utilities and the voltage limits in the distribution network are constraints for this optimization. In the next step the determined Q-variables of the distribution networks are fixed and the Q-variables of the transmission network are optimized with the objective of a minimal absolute value of the horizontal reactive power exchange. In this case the maximum load factors of utilities and the voltage limits of the transmission network are set as constraints. If it is not possible to comply with these conditions, a third optimization determines the position and the size of an additional compensation element in the transmission network. Afterwards, the optimization of the transmission network's Q-variables is repeated. Level 2 and 3 will be iterated until no further violations will occur. Result of the optimization is a minimal power loss operation mode of distribution networks without considering the demand of the transmission network.

Strategy 2: Use-case-dependent target values for the reactive power exchange

The other extreme for reactive power exchange strategy is the complete control of all Q-variables in the distribution network by the transmission network. Of course, it is still necessary to consider constraints in the distribution network such as thermal or voltage limits.

The optimization approach is similar to the minimal power loss method, but without considering the first level. Instead of this, the Q-variables of the distribution network will also be used to minimize the absolute value of the horizontal reactive power exchange of the transmission network.

RESEARCH PROGRAMME AND RESULTS

The focus of exemplary studies shown in this paper refers to a network section in Northern Germany (Figure 4).

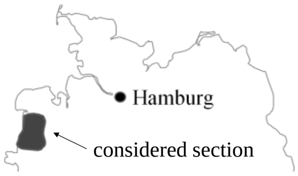

Figure 4: Considered network section

The predominantly rural character of the network section is characterized by high installed power from wind turbines and PV plants. A characteristic day with high wind- and PV-infeed is analyzed for a scenario in winter 2023 as shown in Figure 5.

The optimized inductive reactive power exchange of the considered transmission network section and the increase of losses in the distribution networks at strategy 2 compared to strategy 1 are presented in Figure 6. In situations without any or with low PV-infeed (01:00h – 09:00h) the reactive power exchange in strategy 1 is relatively low, but higher than in strategy 2. The Q-variables in the distribution networks are comparatively flexible, because node voltages are far from their limits.

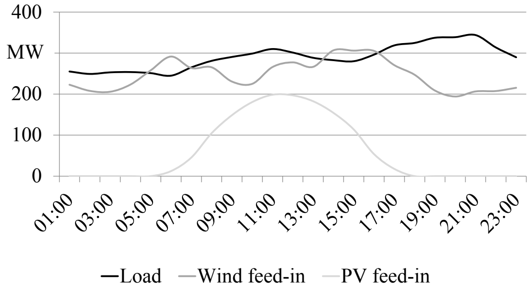

Figure 5: Characteristic day in winter 2023

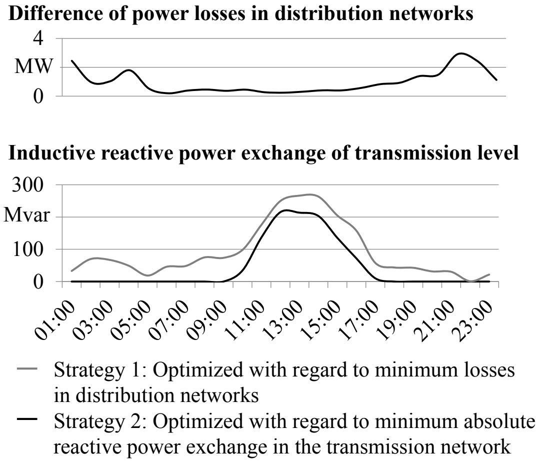

Figure 6: Power losses and horizontal reactive power exchange compared for the considered strategies

The high flexibility of Q-variables allows a neutral reactive power balance for the considered transmission network section in strategy 2 at the cost of higher power losses. High wind- and PV-infeed in the hours between 10:00h and 16:00h lead to a general increase of inductive reactive power need caused by increasing load factors of the lines. This also affects the Q-exchange of strategy 2. Simultaneously, the flexibility of Q-variables drops, because the reactive power is more and more needed for voltage maintenance reasons in the distribution networks itself. This is why the reactive power exchange of strategy 1 and 2 comes closer together and the difference in losses is smaller. At the end of the day the flexibility rises again and the Q-balance decreases in both strategies similar to the morning hours. Decision on efficient strategy has to be based on comparison in terms of economy (Figure 7). Therefore, the theoretical annuity cost of new compensation elements (10T€/Mvar and 1900T€ for a switch bay) to neutral the reactive power exchange is calculated for both strategies. Besides, the cost for additional power losses in strategy 2 dependent on the future prize per MWh is shown in the figure. It can be seen that a complete Q-support by the distribution networks is much more expensive as far as the cost is more than 10€/MWh. Consequently, measures in the transmission network appear to be economically more reasonable than a nearly unconditioned support by the distribution networks. Moreover, costs for central reactive power control have not been considered.

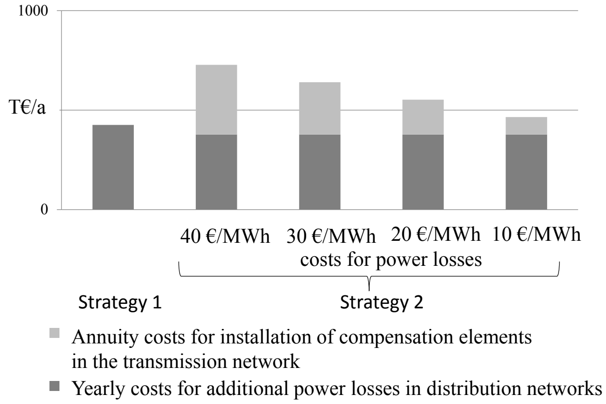

Figure 7: Costs for each strategy

SUMMARY AND OUTLOOK

In this paper current research results for a reactive power exchange concept over all voltage levels is presented. The results show that a reactive power support of the distribution to the transmission network in terms of use case dependent target values appears to be economically worse than measures in the transmission network. The developed methods are also able to focus on other reactive power strategies, such as limits for the reactive power at the interfaces between voltage levels which will be done in future research work.

ACKNOWLEDGMENTS

This work is supported by the Initiative and Networking Fund of the Helmholtz Association, in the frame of the Helmholtz Energy Alliance.

REFERENCES

[1] ENTSO-E, Network Code on Demand Connection, Brussels, 2012.

[2] BDEW, Erzeugungsanlagen am Mittelspannungsnetz, Juni 2008.

[3] Deutsches Institut für Normung e.V., DIN EN50160:2011-02 - Merkmale der Spannung in öffentlichen Elektrizitätsversorgungsnetzen; Deutsche Fassung EN50160:2010 + Cor.:2010.

[4] Schäfer, Krahl, Vennegeerts, Moser, FGH e.V., Spannungsebenenübergreifendes Regelungskonzept für Blindleistung, ETG Congress in Berlin, 05.-06.11.2013.

[5] Schäfer et al. "Flexibilisierung von Erzeugungs-anlagen im Verteilnetz zur Systemstabilisierung", Energiewirtschaftliche Tagesfragen, vol. 64, no. 5, pp. 78-81, 2014.