FLEXIBLE REACTIVE POWER EXCHANGE BETWEEN MEDIUM AND HIGH VOLTAGE NETWORKS: CASE STUDY

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ABSTRACT

This paper presents the results of a case study in which a concept to modify the power exchange between several MV-networks and the overlay HV-network is analysed.
This concept is based on a remote control of the MV-connected generators' power factors. The tap position of the HV/MV-transformers is also remotely regulated in order to minimise voltage deviations.
An algorithm based on successive optimal reactive power dispatches is used for the assessment of the reactive power flexibility. The simulations are carried out for a period of one year.
The aims of the study are to assess the maximum reactive power flexibility per hour, to find the reason for its limitation and to analyse the influence of the achieved flexibility on aspects of network operation like energy losses.

INTRODUCTION

Besides the reversal of active power flows, the penetration of Distributed Energy Resources (DER) in Distribution Networks (DNs) has also caused a high volatility of the reactive power flows between DN and Transmission Networks (TNs).

In order to host the increasing dispersed generation without violating voltage limits, it is a common practise in Germany that DER operate with inductive power factors during periods of high generation. This operation is in accordance with the technical guidelines both for MV- and for LV-connected generators and represents no additional costs for the Distribution System Operator (DSO) [1, 2]. The side effect of this practise is the increasing reactive power demand of DNs. When the penetration of DER is sufficiently high, the reactive power demand during high generation exceeds the reactive power demand during peak load. Measurements in a rural DN exemplifies, see Figure 1, this phenomenon. This figure also shows that one grid can have both a capacitive and an inductive behaviour during periods with the same active power reversal.

In this paper, reactive power consumption will be considered positive when there is absorption of inductive reactive power from the DN. Negative reactive power consumption will simply express inductive reactive power generation, like capacitors. Values of the DN's consumption are always at the HV-side of the HV/MV transformer.

If this reactive power consumption of DNs is controlled, the reactive power flows between DNs and TNs can be adapted to cover the reactive power demand of the latter. In other words, DNs could operate like flexible reactive power plants and replace the conventional power plants which are being rapidly disconnected from the TN [3].

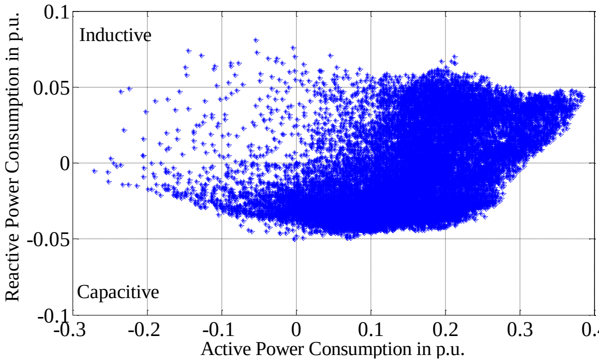

Figure 1: Hourly *PQ*-measurements over a year in a rural MV-network with high penetration of DER. Values referred to the rated power of the HV/MV-transformer and measured at the HV-side.

In this paper, the maximum band for the flexible reactive power exchange between a group of MV-networks and the overlay HV-network is calculated for every hour over a year. The main goals are to calculate the maximum and minimum reactive power consumption, to find the reason for the limitations and to evaluate the influence on losses.

The calculations are based on successive Optimal Reactive Power Dispatches (ORPD) controlled by an overlay algorithm. In the following section, the overlay algorithm and the assumptions used for the calculations are explained in detail.

DESCRIPTION OF THE ALGORITHM AND ASSUMPTIONS FOR THE SIMULATIONS

In order to calculate the maximum and minimum reactive power consumption of the MV-networks, the algorithm shown in Figure 2 has been used.

The first step of the algorithm is to import the values of demand and generation from given profiles into a power system analysis software. In this case study, the profiles are based on measured values of wind generation, PV-generation and power demand in the region where the analysed MV-networks are located. The total power of other types of DER like biomass-fired power stations is small compared with the installed power of PV- and wind generators. For the simulations, its generation has been assumed to be constant.

Once the values are imported, two processes are executed in parallel: a standard load flow and the calculation of the reactive power band of each active power generator at this point in time. The reactive power band used for this case study is based on the German guideline for the generators connected to the MV-network [1]. According to these guideline, MV-generators have to be able to operate within a range of power factors from 0,95 inductive to 0,95 capacitive. This range is independent of the operating point of the generator. In our case study, only the wind and PV-generators connected to the MV-network are considered active generators. The Overall Available Reactive Power of the Active Generators (OARPAG) is the sum of the maximum calculated reactive power absorption, or generation, of each active generator.

For the standard load flow, the power factors of the MV-generators are assumed to be 1. On the contrary, the generators connected to the LV-networks, most of them PV-generators, follow cos $\varphi(P)$-curves like the curve presented in [4]. These curves are common practise in Germany and are based on the application guideline of the German Association for Electrical, Electronic and Information Technologies [2]. One of the results of the load flow is the reactive power demand of the MV-network. This value is used as the reference reactive power for the ORPD.

Once the two first steps are executed, the first iteration of the algorithm starts. Its cornerstone is the execution of ORPD whose control variables are the reactive power provision of each active generator. Initially, the tap position of the HV/MV-transformer is set to the position calculated in the standard load flow and, therefore, represents no control variable for the ORPD.

The algorithm used to find a solution to the optimisation problem is described in [5]. The objective function for the optimization is always the minimisation of power losses. In addition, the solution has to fulfil all the following constraints:

- Thermal capacity of each transformer, cable and overhead line.
- Voltage limits of each MV- and LV-node.
- Reactive power band of each active generator.

The thermal capacity of lines and transformers is considered to be 100% of its rated current. The maximum voltage deviation of all the MV- and the underlay LV-nodes is set to be ±10% of its nominal voltage, as set out in the European Standard EN 50160 [6]. The upper and lower limit of the reactive power absorption/generation of the active generators has been calculated in the previous step using the limits of the power factors and actual active power generation.

Moreover, a constraint for the reactive power exchange with the HV-network is used. For the first ORPD, this reactive power exchange is limited to a narrow band around the value calculated with the standard load flow. This reference value is modified in every iteration by adding a sufficiently small portion of the OARPAG to the reference reactive power. By means of this constraint, the reactive power consumption of the DN can be modified. The maximum reactive power absorption from the MV-network is considered to be the value of the reference reactive power of the last iteration where the ORPD has converged.

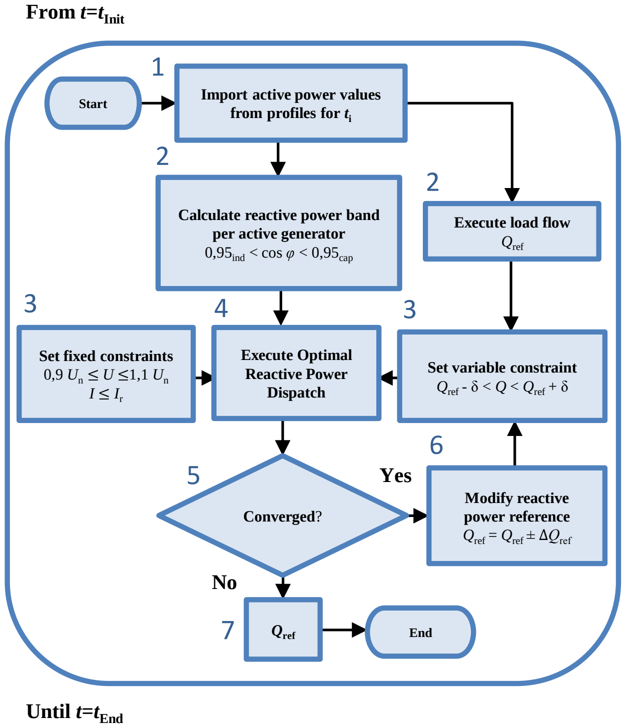

Figure 2: Simplified flow chart of the developed algorithm.

If the last convergent ORPD does not make full use of OARPAG, it means that either the voltage or the thermal limits of the MV-network are violated to reach the targeted reactive power consumption. In this case, it is checked if there is the possibility to solve the thermal or voltage problems by changing the tap position of the HV/MV-transformer. If so, the tap position is modified and the iteration process is restarted with the last reference value.

This outer loop is repeated until at least one of the following two requisites is fulfilled:

- The OARPAG is completely used.
- No modification of the tap position can increase the reactive power consumption.

All this process has to be executed twice per point in time: the first one by increasing the reference value of the reactive power in order to calculate the maximum reactive power consumption and the second one by decreasing the reference value in order to calculate the minimum reactive power consumption. This minimum reactive power consumption has to be understood as the maximisation of the capacitive behaviour of the DN. Furthermore, the results of the algorithm are only valid at a specific point in time t_i. Therefore, the algorithm has to be executed several times in order to get sufficient points within a defined period of time t_{Init}-t_{End}.

In this case study, the algorithm has been executed for a whole year every hour. In addition, it is recommendable to use this algorithm for each grid independently. The reason is that the simulation time increases rapidly with the network size, whereas the convergence of the ORPD worsens [5, 7]. Despite this precaution, the high number of necessary ORPD makes this algorithm very time-consuming from a computational point of view.

For this case study, it has been assumed that the DSO has 100% observability of both the MV-network and the underlay LV-networks. Moreover, another assumption is the remote controllability of all the active generators, in our case the MV-connected wind and PV-generators.

This algorithm can also be used for lower degrees of observability and controllability. In case of lower degrees of observability, only the voltage and thermal limits of the monitored equipment would be considered for the ORPD by means of fixed constraints. Similarly, the portfolio of active generators can be adapted in order to consider the reactive power of only those generators that can be remotely controlled by the DSO. Furthermore, the reactive power band per generator can be individually calculated to determine, with a better accuracy, the actual reactive power capability in case the legal framework do not oblige each MV-connected generator to operate within the same predefined range of power factors.

Consequently, this algorithm has a high degree of flexibility and can be adapted to the specific legal framework and the different degrees of observability and controllability of each DN.

CHARACTERISTICS AND MODEL OF THE NETWORK

The results presented in this paper are based on simulations of eight MV-networks located in southern Germany. These networks are connected to the same overlay, meshed 110-kV-network. The electric distances among the MV-networks are small. For this case study, the effects of the enhanced Reactive Power Flexibility (RPF) on the 110-kV-network are neglected and all the MV-networks are considered to be connected to the same HV-substation. The results of the simulations are the sum of the results of the eight simulated MV-networks. Further works will focus on the effect of the flexible reactive power flows in the overlay network.

The analysed MV-networks have a typical rural character with long feeders, low energy densities and the existence of overhead lines. The nominal voltage of all the analysed MV-networks is 20 kV. For the simulations, a detailed electrical model of the MV-networks has been used. The standard voltage regulation for both the MV- and the underlay LV-networks is carried out by the on-load tap changer of the HV/MV-transformers. The reference voltage for this regulation is 1,03 p.u. and the dead band around the reference voltage is ±0,02 p.u. Each MV-network consists of several MV-feeders and has a radial character. Optimisation of the switching status during the simulations is set out the scope of this paper.

LV-networks connected to the MV-networks are modelled in order to simulate the real voltage deviations along the MV/LV-transformer and LV-feeders. The modelling of the LV-networks has been made in a simplified manner by using common types of equipment and typical lengths of LV-feeders [8].

During the last years, a high amount of DER has been connected to the networks. The approximate power capacity installed in the eight networks is shown in Table 1. Wind generation accounts for around two thirds of the total installed power and it is exclusively connected to the MV-level. Around one quarter of the installed capacity is based on PV-generators. Almost 70% of the overall PV power capacity is connected to the LV-networks. This reduces the maximum controllable reactive power from active PV-generators.

Table 1: Installed power capacity of DER in the analysed networks.

	Installed Power Capacity (MW)		
	LV-network	MV-network	**Total**
Wind	0	232	**232**
PV	64	30	**94**
Other types	24	1	**25**
Total	**88**	**263**	**351**

The DN's active power consumption during peak load and no generation is around 130 MW and is well below the installed capacity of the wind power generators. That causes a reversal of the active power flow during windy situations that is especially high when the demand is simultaneously low.

RESULTS AND ANALYSIS

Figure 3 presents the consumption of active and reactive power of the eight MV-networks over the analysed year simulated through a standard load flow. The group of networks reaches its most capacitive behaviour at points in time where both the generation and demand are low.

This is mainly due to the strong capacitive behaviour of weak-loaded MV-cables. If either the generation or the demand increases, the networks begin to behave more inductive. There are three reasons for this behaviour:

- Higher loading of equipment and the corresponding rise of its inductive losses.
- Inductive power factor of the loads.
- Reactive power absorption of LV-connected generators to limit voltage rises.

The maximum reactive power consumption occurs when both demand and PV-generation, mainly located in the LV-networks, are simultaneously very high. The reason is the combination of the reactive power absorption of the underexcited LV-connected generators and of the loads.

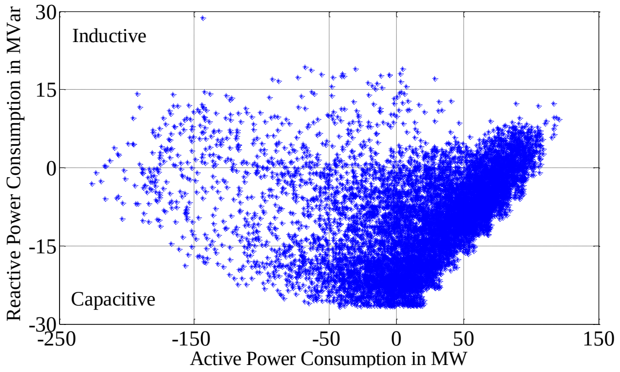

Figure 3: *PQ*-Diagram without reactive power control. Results of hourly standard load flows over an analysed year.

Figure 4 shows the RPF band over a sunny and not very windy day. In case thermal and voltage limits of the networks are not violated and the variation of reactive losses is negligible, the bandwidth is proportional to the active power generation. This generation is very volatile and therefore the RPF band has the same nature.

Since the German guidelines for MV-connected generators do not consider reactive power provision during times without active power generation [1], the RPF band accounts for zero in those situations. The simulation over the analysed year shows that these situations are common: more than 30% of the time the RPF is less than 1 MVAr.

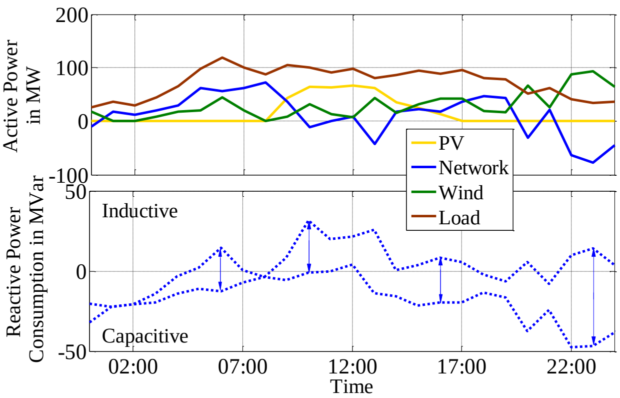

Figure 4: Active power demand and generation versus RPF band during a sunny day.

During situations of high active power generation, the RPF band can reach values up to 160 MVAr. In Figure 5, the RPF bandwidth versus the number of hours in year is plotted. This figure shows that the period of time where the bandwidth accounts for values higher than 50 MVAr is relatively small but increases rapidly for lower bandwidths.

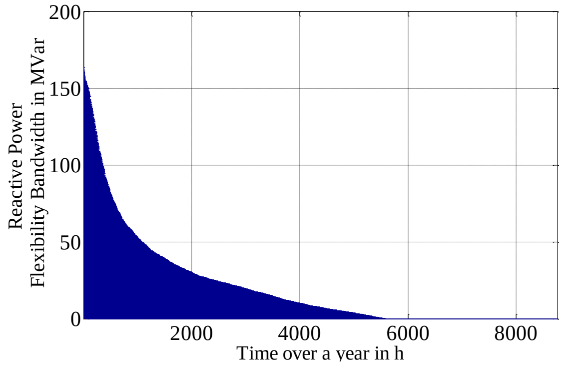

Figure 5: Bandwidth of RPF versus time.

Figure 6 presents the percentage of time in which each of the three types of restrictions hinders higher RPF. Voltage and thermal limits are only considered to act as restriction when less than 95% of the OARPAG is used. The results show that the restrictions of the RPF due to voltage and/or thermal problems do not occur often. In the rest of the time, over 99%, the RPF is restricted by the German guideline for MV-connected generators [1].

The low influence of the voltage limit on the RPF can be explained by the combination of Wide Area Voltage Control of the HV/MV-transformer and ORPD. The voltage regulation by both methods is extremely effective when the voltage homogeneity of the networks is sufficiently high [4].

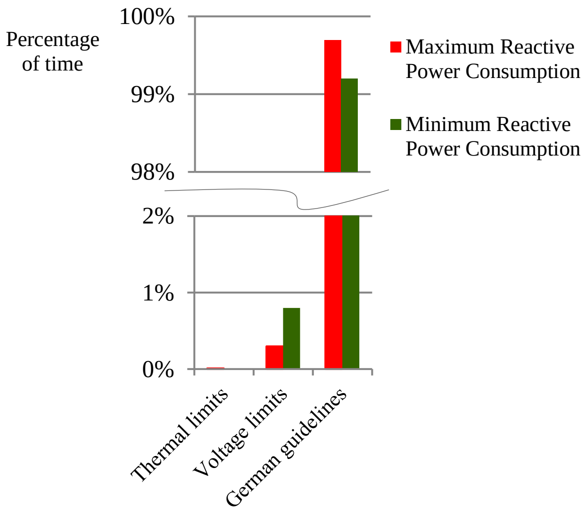

Figure 6: Reasons for the restriction of RPF in percentage of time over an analysed year.

The high potential for RPF during times of high active power generation suggests that DNs could be able to follow reactive power targets when the active power reverses. This would have notable effects on the planning and operation of the TN.

Another strategy enabled by the enhanced RPF is the minimisation of reactive power exchange between the group of MV-networks and the overlay HV-network. The results are presented in Figure 7.

Following this strategy, the maximum reactive power consumption falls from 29 MVAr to 12 MVAr. Moreover, the overall reactive energy exchange over the analysed year drops from 98 GVArh to 57 GVArh. Despite the fact that the maximal negative reactive power consumption cannot be reduced due to the lack of active power generation at this point in time, the number of hours when the reactive power consumption is under the limit of -20 MVAr is notably reduced.

From a qualitative point of view, another positive effect of this strategy is the reduction of power losses since power losses normally reach a minimum close to the operating point where the reactive power exchange is reduced to zero [9]. Nevertheless, the simulations show that the reduction of energy losses in the simulated year is around 1% and, therefore, quantitatively insignificant. The reasons for the low improvement are the following:

- No control of reactive power flows in either MV/LV-transformers or the LV-feeders.
- Long periods of time without controllable reactive power due to absence of active generation.
- Considerable number of MV-feeders without any MV-connected generator which makes any type of reactive power optimisation impossible.

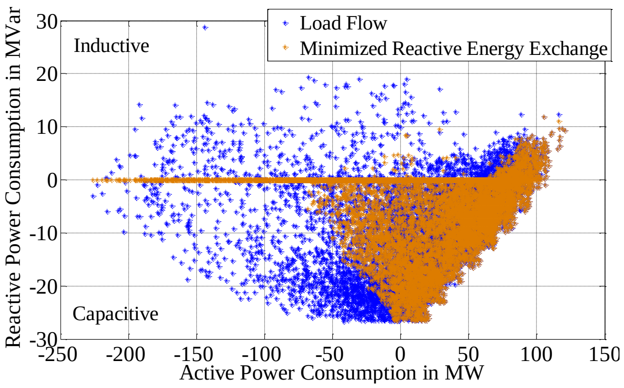

Figure 7: *PQ*-Diagram minimising reactive power exchange.

This low influence on power losses becomes an advantage when the goal of the RPF is to provide high amounts of reactive power to the overlay networks. The difference in power losses between the scenario of minimum reactive power consumption and standard load flow is roughly 1,5%. The difference between the scenario of maximum reactive power consumption and standard load flow is even smaller. The simulations of these eight MV-networks confirm the idea that the power losses will not surge in the MV voltage level if these networks actively participate in the reactive power management of the overall power system.

CONCLUSION

The algorithm based on ORPD is an effective method to calculate the RPF band that can be provided by a portfolio of generators connected to distribution networks. The disadvantage of this method is the great number of necessary ORPD which makes this algorithm very slow.

The results of the simulations of eight, real MV-networks show that, despite its high maximum value, the RPF bandwidth has a volatile nature due to its correlation with the dispersed generation. The problem could be notably reduced if the generators were able to increase the power factor range at partial load and to provide reactive power at no load.

However, these two requirements are not reflected in the current German guideline [1]. Therefore, this guideline is the exclusive restriction to the RPF in more than 99% of the time in the year.

Despite the abovementioned weak point, the potential of this concept to reduce both the reactive energy exchange over a year and the maximum reactive power consumption is notable. Moreover, distribution networks can follow reactive power reference values during times of high generation. This can have a high influence on the TN planning and operation.

Moreover, the effect of RPF on energy losses over a year has been proven to be negligible.

Acknowledgements

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