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Reactive power redispatch at the TSO-DSO interface: analysis of the challenges and differences for processual integration

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Abstract The increasing challenge of maintaining voltage due to reduced reliable reactive power potentials in the transmission grid requires a fast and economically optimal consideration of reactive power in the congestion management processes of transmission system operators. Established processes such as the German Redispatch 2.0 process adjust the dispatch of plants to avoid congestion but do not make use of available reactive power potentials to avoid voltage-related congestion. This work evaluates the suitability of existing processes for application to reactive power. Using a realistic distribution grid, the procedural Redispatch 2.0 specifications for clustering reactive power are applied. It can be shown that the determination of reliable reactive power capability is associated with more dependencies and influencing factors than with active power. This leads to the need for a separate cluster concept and, due to the operating point dependency, for a procedure coordinated with the grid situation.

Keywords Reactive power sensitivity · Redispatch · TSO-DSO coordination · Voltage stability

Blindleistungsredispatch an der TSO-DSO-Schnittstelle: Analyse der Herausforderungen und Unterschiede in der prozessualen Integration

Zusammenfassung Die zunehmende Herausforderung der Spannungshaltung infolge der Reduzierung zuverlässiger Blindleistungspotenziale im Übertragungsnetz erfordert eine schnell umsetzbare und wirtschaftlich optimale Berücksichtigung von Blindleistung in Engpassmanagementprozessen der Übertragungsnetzbetreiber. Etablierte Prozesse wie der deutsche Redispatch 2.0 passen zur Vermeidung von Engpässen den Dispatch von Anlagen an, greifen jedoch zur Vermeidung spannungsbedingter Engpässe nicht auf verfügbare Blindleistungspotenziale zurück. Diese Arbeit bewertet die Eignung des bestehenden prozessualen Vorgehens zur Anwendung auf Blindleistung. Unter Verwendung eines realistischen Verteilnetzes erfolgt die Anwendung der prozessualen Redispatch-2.0-Vorgaben zur Clusterbildung auf Blindleistung. Es kann gezeigt werden, dass die Bestimmung zuverlässiger Blindleistungskapazität mit mehr Abhängigkeiten und Einflussfaktoren einhergeht als für Wirkleistung. Dies führt zur Notwendigkeit eines gesonderten Clusterkonzepts und aufgrund der Arbeitspunktabhängigkeit zu einem auf die Netzsituation abgestimmten Vorgehen.

Schlüsselwörter Blindleistungssensitivität · Redispatch · TSO-DSO-Koordination · Spannungsstabilität

1 Introduction

Historically, conventional power plants at transmission grid level serve as reliable suppliers of reactive power and are responsible for balancing the reactive power of the transmission and distribution grid. With the German energy transition, a continuing reduction of these sources and shift to the distribution system can be observed. Additionally, with the geographically optimized connection of renewable energy sources (RES), the distance between load and generation is increasing and increases the reactive power demand. German transmission system operator (TSO) forecast

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a demand of *58.8 Gvar* to the year 2037 [1] of new reactive power sources.

Challenges in voltage maintenance are arising, which are intensified by the increasing number of volatile plants. Their volatile feed-in behavior leads to higher volatility in the grid voltage and therefore to a rising volatile reactive power demand, which can, with missing reactive power sources, lead to critical voltage events.

The Technical Requirements for the Connection (German: Technische Netzanschlussrichtlinien, TAR) define minimum requirements for the provision of reactive power by RES [2]. Due to their large number in the high voltage level, they gain importance [3] to provide reactive power at the Point of Common Coupling (PCC) between the transmission and distribution grid and thus support the voltage stability of the TSOs as an additional degree of freedom.

In addition to the urgent need to answer the question of how the required reactive power potential can be procured in the long term with simultaneously decreasing potential in the transmission grid, the TSOs as well as distribution system operators (DSOs) are confronted with the need to integrate reactive power into their congestion management. This requires solutions that can be implemented promptly and economically.

RES are already considered into existing congestion management processes e.g. the German Redispatch 2.0 [4] to achieve the control of active power and avoid bottlenecks. Not considered yet is the use of reactive power capabilities. Including RES in this process, it becomes clear that there are several challenges to determine and provide the amount of reactive power from RES as an ancillary service at the TSO-DSO interface. Several papers have discussed approaches for determining the potential capability [5, 6] and treating forecast uncertainties [7]. The integration into existing system management process is not considered in literature, which means that it is not yet integrated into operational planning and activation processes. In this respect, grid operation requires robust and reliable processes.

As timely solutions are needed to consider reactive power in congestion management, this paper focuses on how existing regulations and specifications defined in Redispatch 2.0 are transferable and suitable. This closes a gap in research, which is focused on the optimization of reactive power, but not on its processual integration.

This paper will focus on the challenges of integrating reactive power management at PCC in the system operation process based on German regulations. Therefore, it outlines the steps for building clusters and accumulating the reactive power capability at the PCC. Not considered is the implementation of the retrieval. Hypotheses are defined and evaluated using a testbed representing realistic conditions, offering transferability of results. The aim is to answer the question, to what extent existing German regulations focusing on active power are transferable for reactive power to achieve an easy and promptly implementation roadmap.

The paper is structured as follows: Chaper 2 describes the Redispatch 2.0 process, focusing on the general approach and given regulations. Chapter 3 presents hypotheses regarding the transferability of the procedure in Redispatch 2.0 from active power to reactive power. To investigate these hypotheses, a simulation-based method is presented, which aims at a realistic consideration and implements a corresponding case study. Chapter 4 presents the results and proves the hypotheses. Finally, Chaper 5 summarizes the most important findings.

2 State of the art—Redispatch 2.0 (DE)

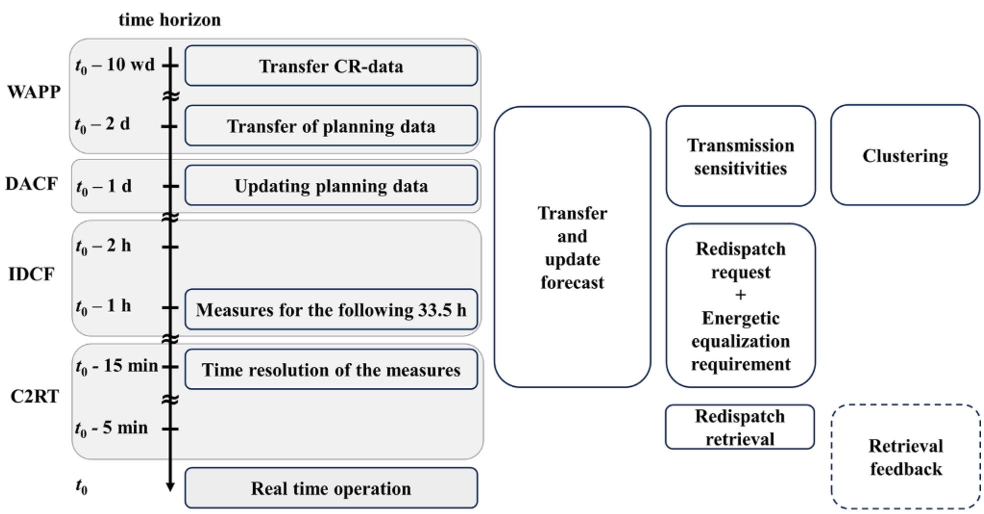
Determining the possible provision of reactive power in grids, both in planning and for use in operation and to support the voltage maintenance of the TSO, has already been investigated in several papers [5, 6] and [8]. propose methods to quantify the flexibility of distributed devices in term of active and reactive power at the TSO-DSO interface. As an extension optimal costs are considered in [7]. A control scheme is proposed in [9].

The valid national regulations and technical standards must be observed for general consideration of reactive power potentials of distribution grids. Paragraph 13 of the German Energy Industry Act (german: Energiewirtschaftsgesetz, EnWG) [10] assigns system responsibility to the TSO, allowing him to intervene in the market if system security is at risk. One instrument is Redispatch, whereby power plant generation is adjusted to avoid congestion. This balance-neutral measure reduces active power generation before and increases it after the congestion, either within or across control areas.

After Weak Ahead Planning Process (WAPP), which addresses the preventive assessment of system utilization, the TSO receive the scheduled dispatch for the following day and determine bottlenecks in their control area using a power flow calculation (grid security calculation), known as Day Ahead Congestion Forecast (DACF) process. This is followed by a continuous update of the planning data, considering forecast data, which becomes more accurate as it approaches real-time operation (so called Intra Day Congestion Forecast (IDCF)). In principle, measures are requested as late as possible but as early as necessary. The activation is made a few minutes prior to real-time (Close to Real Time (C2RT)). The timeline of the process is shown in Fig. 1.

With the Grid Expansion Acceleration Act 2.0 (NABEG 2.0) [11], the process has been extended to plants with a rated power of 100 kW or more and remote-controlled plants since October 2021. This leads to increased participation of RES and DSOs.

Fig. 1 Time schedule of Redispatch 2.0



Furthermore, larger amounts of data are generated. Section 3 EnWG requires a platform on which the corresponding Redispatch capabilities of the plant operators are reported. Reactive power is currently not considered in this process. Active power-based redispatch is also used for voltage-related bottlenecks.

For redispatch, DSOs cluster plants, including RES, according to similar calculated or actual costs and sensitivities [12]. This is associated with lower communication costs and promotes grid-friendly retrieval by adapting it to the current grid state. The larger the cluster, the lower the forecasting uncertainty. Clusters are formed bilaterally between the grid operators [12].

To ensure the reliability of the flexibility of specified active clusters, the deployment planning of participating plants (Flexibility Resource, FR) is continuously updated, and flexibility restrictions are determined concerning the maximum (positive and negative) active power potential of the cluster. The sum of the active power provision of the FR results in the active power potential of the Cluster Resource (CR). Several grid operators can access a CR at the same time, but not one and the same FR. The potential of the CR is determined for 15-minute intervals. Additionally the operators determine and provide information about the sensitivity of the CR to the PCC [12]. The grid operator coordination concept specifies that the sum of the sensitivities of an FR across all PCCs must be equal to one. Whether this requirement also applies to reactive power is discussed in Chap. 4. The active power sensitivities can generally be calculated using Power Transfer Distribution Factors (PTDF). This is done by performing an AC or DC load flow calculation using the Jacobi Matrix (Eq. 1). For the case study, the AC sensitivity is determined to have a better comparison between active and reactive power sensitivity.

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial U} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial U} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} \tag{1}$$

The PTDF is determined by the change in the active power of node j (e.g. PCC) when the active power of node i (e.g. at a FR) changes. The same applies for reactive power. Eqs. 2 and 3 define the PDTF and for reactive power the QTDF.

$$PTDF_{i,j} = \frac{\Delta P_j}{\Delta P_i} \tag{2}$$

$$QTDF_{i,j} = \frac{\Delta Q_j}{\Delta Q_i} \tag{3}$$

3 Process expansion to include reactive power

Integrating reactive power into existing TSO and DSO congestion management instruments such as Redispatch 2.0 raises the question of to what extent the existing processes are transferable. This section presents an approach starting from active power-based Redispatch 2.0 (Chapter 2) to determine the reactive power capability available in the distribution grid at the PCC to support the TSO's voltage stability. Costs are not considered here for the sake of simplicity.

Three hypotheses are to be proven in Chap. 4:

1. One and the same plant does not necessarily have the same sensitivity regarding reactive and active power.
2. There needs to be a separate clustering concept for reactive power besides the existing process for active power.
3. The determination of the reactive power capability differs from the active power capability determination and involves more uncertainties and interdependencies.

The following describes the testbed, assumptions, and the procedure for validating these hypotheses. The aim is to investigate and realistically estimate differences between the determination of active and reactive power capabilities at the PCC, considering the process structure of Redispatch 2.0.

Fig. 2 Grid image of the realistic 110kV distribution grid

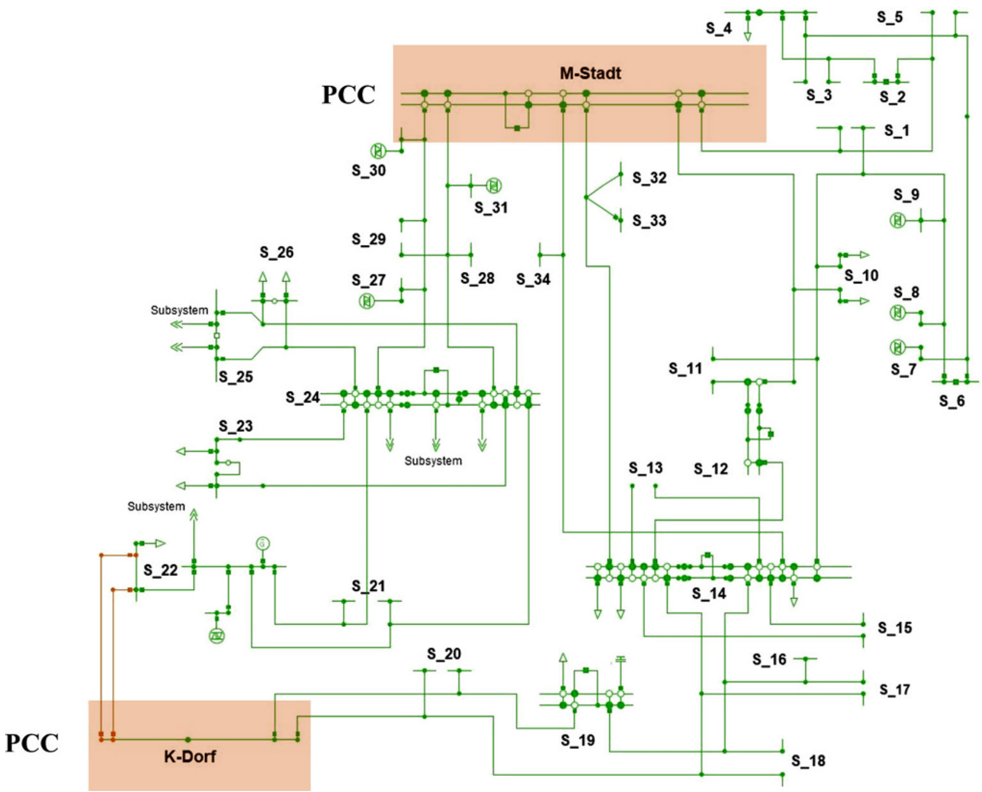


Table 1 Grid characteristics

Parameters	IEEE 39-bus Transmission Grid	Distribution Grid
Rated voltage [kV]	380	110
Number of nodes	39	105
Number of lines	34	102
Number of plants (of these RES)	10 (0)	74 (57)
Maximum active load [MW]	6278	239
Maximum reactive load (underexcited) [Mvar]	1478	55

Table 2 Scenario data (definition of triggers)

	Scenario: Low Load with high Generation (in % of maximum Generation/Load)
Feed-In Solar	50
Feed-In Wind	70
Feed-In other RES	100
Industrial Load (day)	10
Industrial Load (24/7)	80
Other Loads (general)	30
Proportion of e-vehicles	12

3.1 Testbed/investigation model

For the case study, a reduced version of the distribution grid described in [13], which is a realistic 110kV distribution grid, and the IEEE-39 bus system as 50 Hertz version [14] are selected. The simulation environment (testbed) is set up in DIgSILENT PowerFactory.

The distribution grid is reduced to two PCCs to the transmission grid. The data for both grids can be found in Table 1 for the case study under consideration. A simplified single line diagram of the distribution grid can be found in Fig. 2. Further details on the testbed can be found in [15]. The calculation of the sensitivity of available reactive power capability is carried out with a steady state load flow.

For validating the hypotheses, a reference scenario is used, as described in Table 2, and influencing the characteristics given in Table 1. It is characterized by low load and high generation of all plants. Therefore, high bus voltages can be observed.

To simplify matters, all generation plants and loads in the distribution grid are connected to the 110kV level. In addition, the loads are not voltage dependent. Only plants that would be involved in redispatch according to Chap. 2 due to their power rating above 100kW are considered. The PQ diagram assigned to the plants is based on the PQ-capability chart variant 2 of the TAR high voltage [2].

The reactive power control of the plant is oriented according to "reactive power with voltage limiting function" defined by TAR [2] and depicted in Fig. 3. This in the following named Q characteristic curve is a reactive power voltage characteristic curve with external specification of a reactive power setpoint as an offset for the function. It differs from the Q(V) characteristic curve in that it can be shifted horizontally by

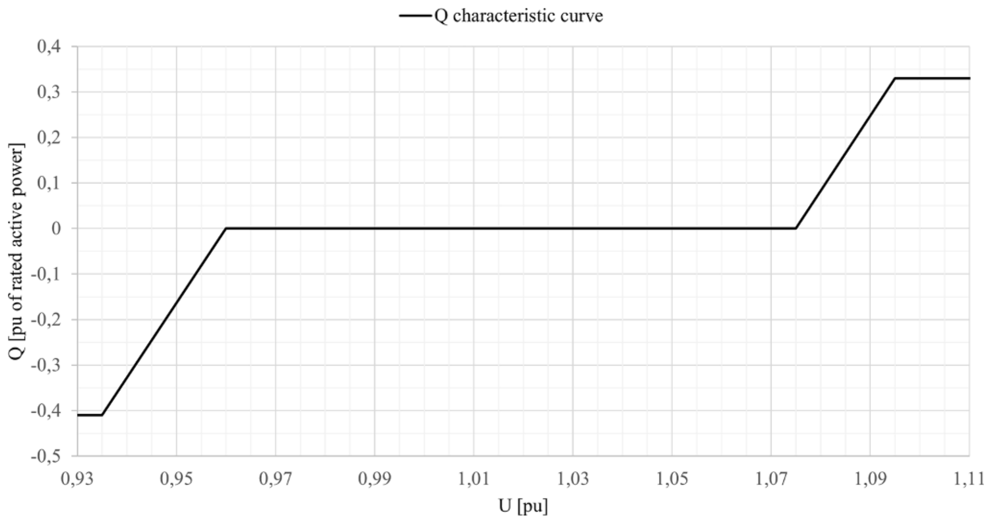


Fig. 3 Q characteristic curve

external specification and a voltage deadband can be set in which no change is made to the reactive power setpoint. It therefore has a voltage limiting function. The outer voltage limits deviate slightly from those given in the TAR and are set from *0.93* pu to *1.10* pu.

3.2 Procedure

Based on the existing Redispatch 2.0 process described in Chap. 2, the approach for a possible reactive power redispatch is described in the following. It is a two-stage process in which the clusters are firstly defined, and secondly the redispatch capability is determined.

As for active power, reactive power clusters are built in this research only considering sensitivities defined in Chap. 2 and using the AC load flow calculation. The QTDF of each plant is determined considering the grid topology, dispatch, forecast data, and whilst every other plant not providing reactive power (Q = 0). The limitation by the PQ diagram and Q characteristic curve for the plant under consideration are lifted, but not for the other plants. Starting from this, the reactive power capability at the PCCs substation, called *M-Stadt* and *K-Dorf*, as marked in Fig. 2, is determined considering a congestion-free, *n*-1 secure grid state, as it is after active power redispatch optimization.

4 Case study

The testbed and the approach developed enable an initial assessment and differentiation of the reactive power retrieval from the active power retrieval in terms of sensitivity and clustering. The most important findings are summarized below and aim to prove the hypotheses outlined in Chap. 3.

4.1 Determination of clusters

Hypothesis 1: One and the same plant does not necessarily have the same sensitivity regarding reactive and active power.

The active power sensitivity (PTDF) of the plants proves to be linear dependent on the operating point of the plant under consideration and of neighboring plants. The PTDF shows an almost linear trend across all operating points. In contrast, the reactive power sensitivity (QTDF) shows a dependency on the operating point of the plant and a non-linear trend, whereby an increased QTDF can be observed.

The investigations lead to the following findings for the comparison of active and reactive power sensitivity:

- The PTDF depends on the grid topology but less on the operating point of the plant.
- The QTDF depends on its own operating point, that of neighboring plants and other grid elements, when some or all the plants are operating in voltage dependent control modes.
- The further away a plant is from the PCC, the greater the impact of node voltages and changes in the grid state on the QTDF.

Figure 4 shows the resulting QTDF and PTDF values for the scenario described in Table 2. The plants are controlled using the Q characteristic curve specified by TAR [2]. The sensitivity for both overexcited and underexcited retrieval is close to each other for both cases, which makes the determination of only one value sufficient. Some of the plants do not achieve a sensitivity of *1.0* for both PCCs. The reason for this is that high node voltages make neighboring plants compensate for the reactive power provided (overexcited). This statement applies to plants that are voltage-dependent controlled. Further examination shows that the sensitivity for plants with fixed Q setpoint specification (Q control) is approximately *1.0* for both PCCs in total. Using only Q control can lead

Fig. 4 Resulting cluster

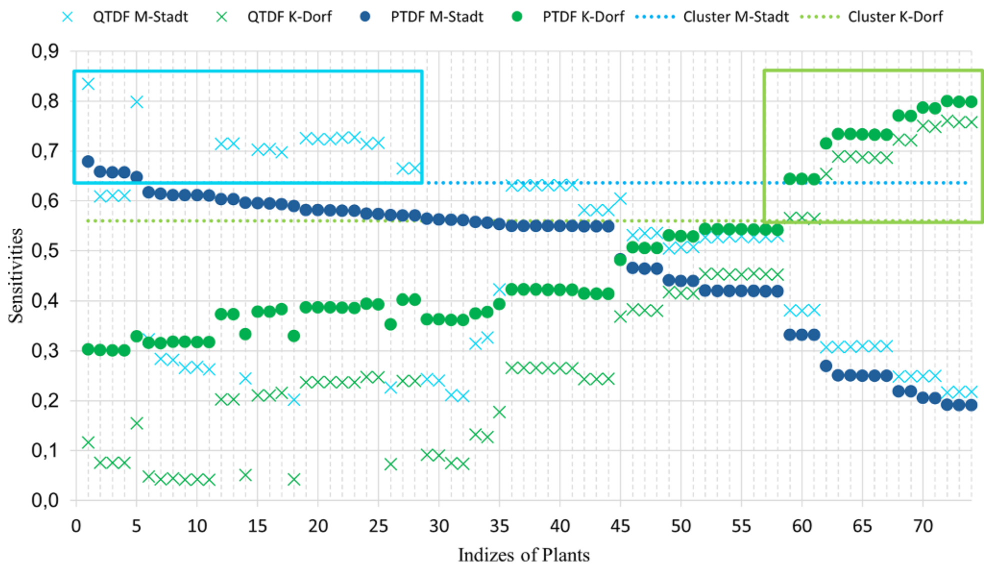


Table 3 Reactive power cluster specification

PCC	Number of plants participating	Max. Reactive Power overexcited [Mvar]	Max. Reactive Power underexcited [Mvar]
M-Stadt	16	–111	89
K-Dorf	15	–131	105

to exceeding the voltage limits and would require an additional voltage control concept.

From Fig. 4 it can be determined that plant *i* with a high PTDF do not necessarily have a significant high QTDF for PCC *j* (Eq. 3), e.g. plants 6 to 11 for *M-Stadt*. For *K-Dorf* this conclusion cannot be made. Plants with high PTDF have a high QTDF. The deviation for *M-Stadt* comes from high node voltages for the plants, while they are for *K-Dorf* not that high. The nearer the (electrical) distance of the plant to the PCC, the higher the sensitivity of the plant on the PCC due to lower compensation effects (both active and reactive power). Hypothesis 1 can, therefore, be confirmed for the case study under consideration and shows additionally, how grid state dependent the QTDF are for voltage-dependent controlled plants.

4.2 Adapted cluster concepts

Hypothesis 2: There needs to be a separate clustering concept for reactive power besides the existing formation specification for active power.

Redispatch 2.0 provides for the formation specifications of so-called active clusters, which are to be determined according to sensitivity and calculated costs. The latter is not considered in this case study. The sensitivity thresholds for the clusters, which specify which plants are included in the clusters, are defined individually. In Fig. 4, the threshold for each PCC for the resulting reactive power clusters of the case study are marked. For the reactive power cluster, plants with a sensitivity *20%* below the maximum QTDF are considered. This threshold is chosen to have enough plants involved in the clusters.

As proven for hypothesis 1, the sensitivity of a plant to the PCC can differ qualitatively between active and reactive power. This can lead to different cluster composition for active and reactive power (only considering sensitivity and depending on the threshold value which can be different for active and reactive power). In Fig. 4, the resulting reactive power clusters are marked green and blue. Active power clusters are not formed here.

Table 3 specifies the resulting reactive power clusters for the case study. The grid has for the case study under consideration a total active power of 1368 *MW*, and reactive power in an amount of 561 *Mvar* maximum overexcited and 451 *Mvar* maximum underexcited.

For cluster *M-Stadt*, just a few plants (number *1* and *5*) with both high PTDF and high QTDF are included, while for the resulting *K-Dorf* cluster all plants have both high PTDF and QTDF due to favorable grid state (lower node voltages).

As can be seen for *M-Stadt*, this procedure can lead to an availability problem. It makes sense to consider forming clusters for active power and reactive power in which the plants are not available for both and can therefore be requested independently of each other. For the *M-Stadt* cluster, plants *2* to *4* and *6* to *11* would be suitable for this concept, as they are not considered in the reactive power cluster but have high PTDF and are therefore suitable for active power based redispatchItalic However, the exclusive participation of plants in clusters can also lead to plants with both high PTDF and QTDF being blocked for one of the two clusters (example plant number *1*). Again, this conclusion applies to voltage dependent controlled plants, as they show deviation values for QTDF and PTDF.

Fig. 5 Alternative cluster concept

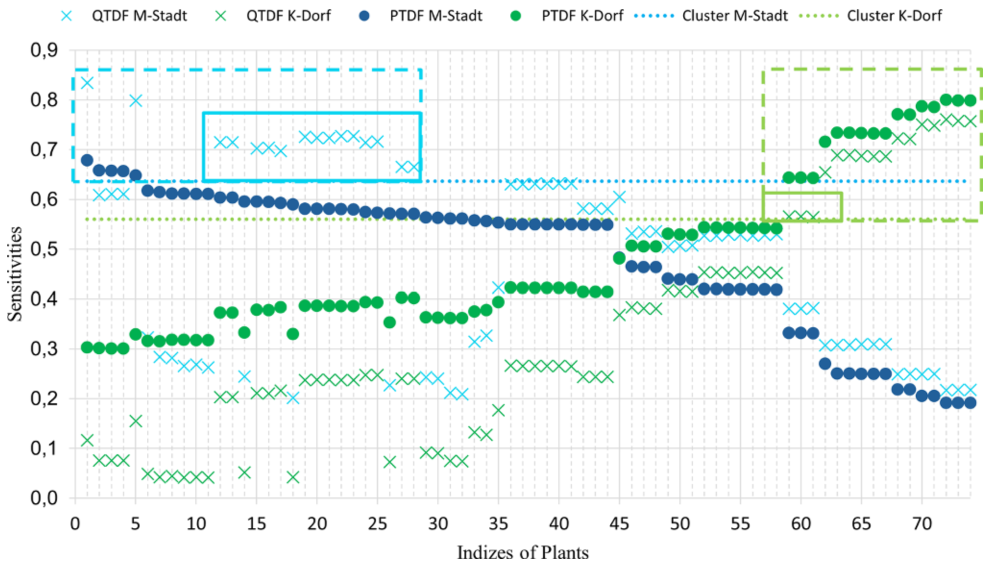


Table 4 Redispatch capability after weighting the sensitivity and consideration of grid and plant-side limitations

Active Power	*Positive Redispatch capability [MW]*		*Negative Redispatch capability [MW]*	
	M-Stadt	K-Dorf	M-Stadt	K-Dorf
	0	0	152	134
Reactive Power	*Overexcited Redispatch capability [Mvar]*		*Underexcited Redispatch capability [Mvar]*	
	M-Stadt	K-Dorf	M-Stadt	K-Dorf
	–41	–77	68	73

Figure 5 shows how the reactive power clusters are reduced by the number of participating plants if only those plants are considered that are assumed not to be eligible for active power clusters (for the given threshold). This effect is more serious for *K-Dorf*, as the plants here have both high PTDF and QTDF. If plants that are already intended for the active power cluster are not eligible for the reactive power cluster, a shift in the cluster threshold value must be considered in this case to achieve a significant cluster size (number of participating plants). As the height of the PDTF and QTDF differ for *M-Stadt*, a sufficient number of plants are available here for reactive power cluster. With shifting the active power cluster threshold value, more plants could participate in the active power redispatch without reducing the number of plants for reactive power redispatch.

In coming work, the robustness of cluster will be researched and relevant grid state changes identified, for which new cluster should be determined. It can be stated that a different, from active power independent cluster formation specification must be introduced for reactive power.

Hypothesis 3: The determination of the reactive power capability differs from the active power capability determination and involves more uncertainties and interdependencies.

The limited operating range of reactive power through the PQ diagram limits the retrievable reactive power in the cluster. For active power, the redispatch capability of the cluster can be determined using the average PTDF and operating point and is approximately linear dependent on the operating point (if there are no topology changes). Table 4 provides the resulting redispatch capabilities and shall prove hypothesis 3.

With a resulting operating point of 245 *MW* for *M-Stadt* and an average cluster PTDF of *0.62*, the negative redispatch capability for *M-Stadt* can be determined as seen in Table 4. The positive redispatch capability is zero, as in the case study conventional plants are already operated with the rated power, and RES are limited in this aspect.

For reactive power, the available potential band at the PCC must be calculated for the case study using power flow calculation, as the QTDFs do not allow a reliable determination of the capability and do not sufficiently consider limitations. A determined maximum overexcited reactive power of –111 *Mvar* for *M-Stadt* (Table 3) and an average QTDF of *0.75* results in a theoretical capability of –83,25 *Mvar* which is much higher than the actual capability of –41 *Mvar*. The QTDFs are, therefore, exclusively suitable for identifying plants with a sensitive effect on the PCC for cluster formation.

For Q controlled plants it can be stated that the theoretical and actual retrievable reactive power redispatch capability is approximately the same. Voltage dependent reactive power control leads to a reduction in the capability due to the operating point dependency and regulation against the provided reactive power through neighboring plants. Especially for the case study under consideration, as the bus voltages are already high, this effect can be observed. That also explains, why the underexcited retrieval is approximately equal to the potential determined from the sensitivities.

The operating point dependency underlines the need, that the reactive power redispatch capability should be determined close to the time of retrieval to be able to assume that the potential is secure. Regarding hypothesis 3 it can be concluded that the determination of the redispatch capability for reactive power is much more complex than for active power and may not be able to be derived from the sensitivities and changes between different grid states. Additionally, and due its dependency on the grid state, there may be a need for grid operator dependent procedures, to optimize the reactive power retrieval.

5 Conclusion

This paper examines the suitability of existing procedural requirements for active power-based redispatch in Germany for application to reactive power. The background is the need to integrate reactive power into existing congestion management processes of German TSOs and DSOs to ensure voltage stability despite increasing volatility and reduction of reactive power potential.

The examination under realistic conditions on a testbed, which takes current regulations into account, shows that reactive power clusters can be determined effectively based on the sensitivities. Core results regarding the sensitivity analysis-based clustering are:

- The sensitivity of a plant to the PCC can differ in terms of active and reactive power. Depending on the grid state and the electrical distance to the PCC, there are overlaps regarding suitable plants with high sensitivity for the formation of both active and reactive power clusters.
- A voltage-dependent plant control can have a major influence on the reactive power sensitivity (depending on the grid state).
- The resulting operating point dependence of the sensitivities should be redetermined when the grid state changes.
- It makes sense not to involve plants in both active and reactive power clusters to request capabilities independently of each other. This requires flexible clustering specifications.

Continuing, and considering the resulting redispatch capability, it can be stated that:

- The active power redispatch capability of the cluster is higher than the reactive power redispatch capability (if the same plants are involved).
- The redispatch capability for reactive power cannot be reliably derived from the sensitivities due to the operating point dependency.
- Voltage-dependent control of neighboring plants reduces the theoretically available reactive power capability of the plants in question in unfavorable grid states (e.g. high voltages).
- It is expedient to determine the capability close to the actual retrieval to ensure the reliability of the calculated capability.

From the results it can be concluded that a management concept is needed to optimize the involvement of plants for active and reactive power based redispatch. An active power based redispatch can affect the reactive power based redispatch capability and the other way around. This requires a more flexible cluster forming concept (depending on the grid state flexible cluster threshold) and the coordination of existing market-based concepts as well as voltage control concepts. These examinations are not considered here.

Integrating reactive power into processes such as Redispatch 2.0 is a procedure that involves many dependencies and interactions. This also requires automation of the process due to the proximity to real-time operation and calls for a separate concept for reactive power in parallel to existing active power-based processes.

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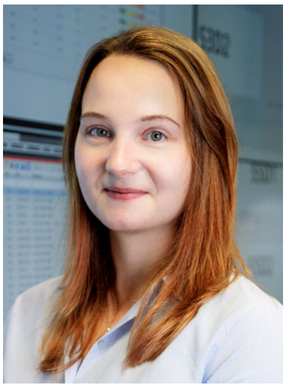

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