Dynamic distribution grid management through the coordination of decentralized power units

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***Abstract*—Coordination of ancillary services provided by decentralized power units has become one of the main grid operation challenges because system service responsibilities are increasingly being shifted to medium- and low-voltage networks. This paper describes an implementation method of considered control algorithms on real power units in German medium-voltage systems in order to maintain the distribution node voltages within the allowable range. The algorithms adjust active as well as reactive power set points, taking into account sensitivity matrices of critical nodes to ensure voltage stability at any time and in any system state. The remote control of the considered electrical system is designed according to the approved smart grid communication standards. Taking into account the electrical limitations of the considered power units selected cases are validated by load flow calculations in order to demonstrate the technical feasibility of the algorithms and their supporting effect on the distribution grid.**

***Index Terms*—Power system management, distribution grid, load flow, voltage control**

I. Introduction

Due to the growing number of renewable power units in German distribution networks at medium voltage levels, system operators are faced with new challenges in order to maintain the stability of the grid at all times. Nowadays, shifting the responsibilities for ancillary system services towards the medium and low voltage grid is one of the main topics that are being widely discussed in Germany [1]. In the future, even small power plants need to provide reactive power and voltage control mechanisms. Therefore, necessary requirements e.g. coupling requirements for decentralized power plants, loads and storage systems have been specified in several German energy policy acts, e.g. [2] or more specifically [3] for wind and [4] for solar power plants.

The project "REStabil" is aimed at the implementation of algorithms for voltage and power control for decentralized power units in order to support stable operation of medium voltage networks. The practical access to power units, e.g. bio mass plants, and measurements in substations offers the possibility to implement and test theoretical, developed algorithms regarding their efficiency and reliability in real field test environments. The project also focuses on suitable software and communication standards in order to provide optimal exchange of monitoring and control signals.

Against this background, the optimization of voltage maintenance is the focus of this paper. Considering the technical capability of selected power units, set points are recalculated by applying developed voltage control algorithms. The effects of different approaches are shown by software simulation in characteristically structured networks. Through pointing out the system deployment, taking into account data exchange mechanisms and suitable communication standards between all components of the system, their practical application in field test environments is arranged.

II. Comparison of Methods

With respect to the practical implementation of the developed control algorithms in the field test environment, technical capabilities of power units – additionally limited by their dedicated control devices and their ICT interfaces – have to be considered. For that reason theoretically possible high precision adjustments must be balanced against pragmatic solutions using commonly available control variables, like active and reactive power output. For that reason different methods for voltage control purposes are presented and compared in this section. Based on the results, a suitable algorithm has been developed.

A. Jacobian matrix

Voltage control in high voltage transmission networks is usually carried out by means of changes in reactive power. Typically the amount of reactive power needed to be applied to correct nodal voltage is calculated using (1).

$$\begin{bmatrix}\Delta \mathbf{P}\\ \Delta \mathbf{Q}\end{bmatrix}=\begin{bmatrix}\mathbf{J}_{P\theta} & \mathbf{J}_{PV}\\ \mathbf{J}_{Q\theta} & \mathbf{J}_{QV}\end{bmatrix}\begin{bmatrix}\Delta \boldsymbol{\theta}\\ \Delta \mathbf{V}\end{bmatrix} \quad (1)$$

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According to [5] there is a significant impact of reactive power changes to the node voltages. Assuming that active power is not used to control voltages (1) can be transformed into (2).

$$\mathbf{\Delta Q} = \left[\mathbf{J}_{\mathbf{QV}} - \mathbf{J}_{\mathbf{Q\theta}}\mathbf{J}_{\mathbf{P\theta}}^{-1}\mathbf{J}_{\mathbf{PV}}\right] \cdot \mathbf{\Delta V} = \mathbf{J}_{\mathbf{R}} \cdot \mathbf{\Delta V} \qquad (2)$$

Determination of reactive power adjustments to cause the required change in voltage can be done by solving (2) for $\mathbf{\Delta V}$. The inverted Jacobian matrix $\mathbf{J_R}^{-1}$ then includes factors describing the individual influence of each node. In this way, the required reactive power value can be calculated taking into account the voltage difference and the largest coefficient for a particular node.

Used matrices can be simplified by applying the Fast Decoupled Load Flow method (FDLF). The basic concept is quite similar to the NRLF, whereas the strong connection between reactive power and voltage as well as between active power and phase angle is utilized more consistently [6]. Corresponding elements in the Jacobian matrix and their derivatives can then be approximated to be zero. The simplified relation is described in (3).

$$\mathbf{\Delta Q} = \mathbf{J}_{\mathbf{QV}} \cdot \mathbf{\Delta V} \qquad (3)$$

B. *Sensitivity matrix*

For medium voltage radial networks, the sensitivity matrix approach presented in [7] can be used. Here, the matrix elements describe the dependency between node power injection changes and their voltage effects on other network nodes. Though Brenna et al. mainly focus on reactive power adjustments using (4), the influence of active power changes for node voltage control can be developed similarly, resulting in (5).

$$\mathbf{\Delta V} = \mathbf{s}_{\mathbf{Q}} \cdot \mathbf{\Delta Q} \qquad (4)$$

$$\mathbf{\Delta V} = \mathbf{s}_{\mathbf{P}} \cdot \mathbf{\Delta P} \qquad (5)$$

The sensitivity matrix for reactive power change $\mathbf{s_Q}$ is explicitly described in [7]-[8]. $\mathbf{s_P}$ for active power changes can be developed analogously.

C. *Evaluation*

The presented approaches are compared in Tab. 1. Their performance is analyzed using the proposed network in Fig. 1, where an overvoltage at node B was caused by increased generation at node A. In order to provide voltage control support, the requested voltage set point at node B was set to 1 per-unit.

TAB. 1: PERFORMANCE COMPARISON OF VOLTAGE CONTROL METHODS

Method	$V_{B,before}$ **[pu]**	$V_{B,after}$ **[pu]**	Q_B **[MVar]**	ΔV_B **[pu]**
Jacobian matrix	1.102	0.995	-4.359	0.005
Simplified Jacobian matrix		1.058	-1.934	0.058
Sensitivity matrix		0.993	-4.432	0.007

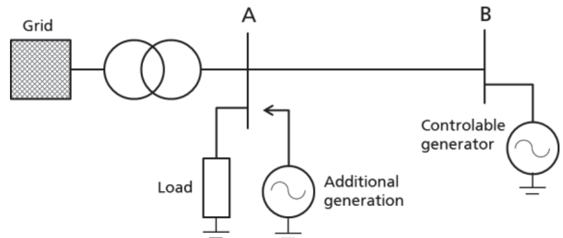

Fig. 1: Proposed system for voltage control method evaluation

The results show that the differences of the sensitivity matrix approach do not vary much from the unrestricted Jacobian matrix method, while the simplified Jacobian matrix provides low accuracy For this reason the sensitivity matrix method was chosen to be applied in the project since it provides satisfactory accuracy, simplicity and low input data requirements.

III. VOLTAGE CONTROL ALGORITHM

Fig. 2 shows the general algorithm for controlling node voltages by adjusting both active and reactive power using the proposed method.

First, the problem is classified. If over-voltage occurs, the possibility of reducing reactive power is investigated. Limits defining voltage violations can be set specifically in order to prevent the system from developing critical situations.

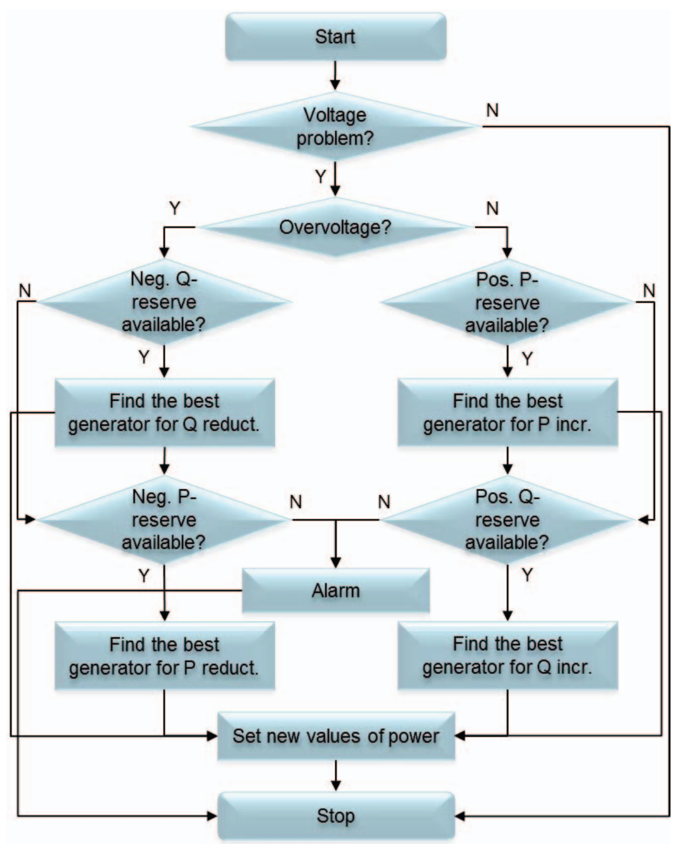

Fig. 2: Applied node voltage control algorithm

In the next step, if there are not any more generators that are able to adjust their reactive power, the same process is performed for active power. In contrast, under-voltage problems are directly handled by checking possible active power increase. During the process of power adjustment, *cos φ* is monitored constantly to ensure it remains in the allowed range.

In its actual configuration the algorithm searches for generators with a maximum effect on the network stability but that use minimum control interventions. As a result, one single generator is mostly chosen to provide active or reactive power adaption. This way interoperability effects, e.g. due to different time constants of the generators, are minimized and a coordinated use of voltage support capabilities in the field test environment can be guaranteed.

IV. Simulation Results – Case Study

To verify the application of the developed algorithm in the field test, a simulation model of a test system, based on a radial feeder structure, has been selected (Fig. 3).

A. Definition of test scenarios

Three different scenarios have been chosen to simulate the effects of different strategies for voltage control using:

1. Reactive power only
2. Active power only
3. Active and reactive power

The maximum power factor limitation as well as the maximum apparent power of each unit individually is taken into account in every case. Additionally, possible adaptions of reactive power capacities regarding the actual working point are considered. Combining both variables in order to cause voltage changes, the proper one is selected depending on whether a reduction or an increase of active power in the grid is necessary (see Fig. 2).

B. Description of the test system

The 20 kV test system consists of 24 nodes that are connected by a stub line with an overall length of about 29 km. A transformer links the superior 110 kV grid to node 1, where an aggregated generation unit (AG 1) and a load (L1) are also connected. At the other end a controllable biogas plant (BGP 24) is installed at node 24 and is used for voltage control. Its maximum apparent power is defined with 0.623 MVA. The other parameters of all considered power units are presented in Tab. 2. Because under normal conditions none of the permissible limits are violated, a disturbed operation state needs to be initiated.

Tab. 2: Power Unit Parameter

Node	$\underline{S}_{Generation}$ [MVA]	$\underline{S}_{Load}$ [MVA]	Voltage[a] [pu]
1	9.01 + j0	4.04 + j0	1.06
12	0 + j0	0 + j0	1.07
24	0.595 + j0	0 + j0	1.07

a. Simulation results from the reference scenario without voltage control

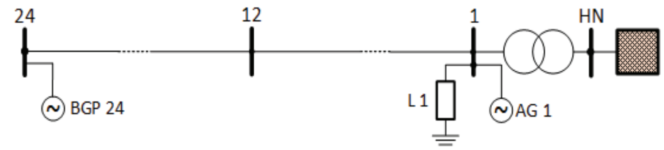

Fig. 3: Scheme of the radial test system

C. Simulation results

For each scenario two sub-scenarios have been analyzed, based on the maximum achievable power factor of the biogas plant in its actual working point with constant active power feed-in:

a) cos φ = 0.95

b) cos φ = 0.80

The simulation results are presented in Tab. 3 and Tab. 4.

1) Scenario 1: Reactive power only

The disturbed system state is caused by adding an extra generation of 30 MW at node 1 and 0.5 MW at node 12. The maximum allowable voltage deviation is 0.1 pu. By adjusting the reactive power feed-in at node 24 the voltage can be led back into a normal state after 3 iterations.

2) Scenario 2: Active power only

Scenario 2 uses the same assumptions as the first one, whereby the reactive power injection at node 24 remains zero. Because this voltage control method does not affect the reactive power values, simulation results are the same for sub-scenario a) and b). In both cases *cos φ* is equal to 1. It can be seen that the efficiency of scenario 2 is quite similar regarding the number of iterations that are necessary to recover a stable operation.

3) Scenario 3: Active and reactive power

Scenario 3 involves a fixed relation between active and reactive power at the biogas plant defined by the *cos φ* value. Here, the network disturbance is realized by an additional infeed of 3.5 MVAr (inductive) at node 12. This causes an even stronger violation of voltage limits compared to the first scenarios and consequently leads to an increased number of necessary iterations for recovering stable operation.

Tab. 3: Simulation results for cos Φ = 0.95

Sc.	V_{before} [pu]	$\underline{S}_{BGP\,24}$ [MVA]	Iterations [-]	V_{after} [pu]
1	1.105	0.595 - j0.195	3	1.100
2	1.105	0.244 + j0.000	4	1.098
3	1.111	0.000 + j0.000	8	1.100

Tab. 4: Simulation results for cos Φ = 0.80

Sc.	V_{before} [pu]	$\underline{S}_{BGP\,24}$ [MVA]	Iterations [-]	V_{after} [pu]
1	1.105	0.500 - j0.226	3	1.098
2	1.105	0.244 + j0.000	4	1.098
3	1.111	0.025 - j0.019	10	1.099

In general, all approaches lead the system back into permissible voltage limits. The individual efficiency of scenario 1 and 2 largely depends on the configuration of the network parameter. Scenario 1 seems to be the preferred method from the power unit operator's point of view (due to the non-lost profit for active power feed-in). However, regarding the maximum allowable power factor it can be assumed that reactive power capacity will not always be enough to keep nodal voltages within their acceptable limits.

Combining active and reactive power adjustment by a fixed ratio brings about the best results for maintaining voltage stability. Indeed, the number of iterations is higher than in Scenario 1 and 2 but so is the voltage transgression that has to be eliminated. Both sub-scenarios a) and b) show that the biogas plant has to be massively powered down in order to realize stable operation parameters of the medium voltage grid.

V. System Deployment

A. *Communication structure*

The coordination of decentralized energy units heavily depends on the proper reception and transmission of measurement data and control values. So the implementation of a powerful communication system is necessary. This is true for the low level data exchange mechanisms as well as for the high level communication protocols. Additionally, the interoperability between all components to be included must be ensured. This is why only approved smart grid standards should be applied. There are three main standards to be taken into consideration in the scope of the system described here.

1) IEC 61850

This standard series describes the concept of information exchange between decentralized units, remote terminal units, automated substation and other devices used in the electrical energy system and the connection to control centers. It describes the communication up to a semantic level, so that interoperability becomes easier, since no device specific address mapping is necessary. The communication stack described is based on other well-known protocols, like TCP/IP and MMS, but does not take into account mechanisms for security related issues [10][11].

2) IEC 61970/61968

These standards describe an abstract interface for information exchange in control centers and between different applications that are used by network operators [12][13].

3) IEC 62351

Mechanism for secure information exchange in electrical energy systems are described in the IEC 62351 standard series. This is done by defining profiles on how to apply security mechanisms for different communication protocols like MMS, TCP/IP and IEC 61850. Some of the measures described are encryption, PKI systems and using digital signatures [14].

An overview of the communication structure of the system is given in Fig. 4, which shows several components and their interconnection. The components contained in the control center are shown in the upper part. The graphical user interface gives the user the possibility to monitor measurement and set point values and modify configurations if necessary. The database keeps track of all data and provides it to the other components. The component containing optimization algorithms performs the necessary calculations based on the provided data. The data gateway is the interface to the field devices, sending and receiving data from the remote terminal units (RTU). Here only two connected RTUs are shown. The connection between all the components in the control center is realized according to the interface definition of the Common Information Model (CIM - IEC 61970). The data gateway as the bridge to the RTUs converts the data from IEC 61970 format to IEC 61850 protocol, so that a reliable communication to RTUs is possible.

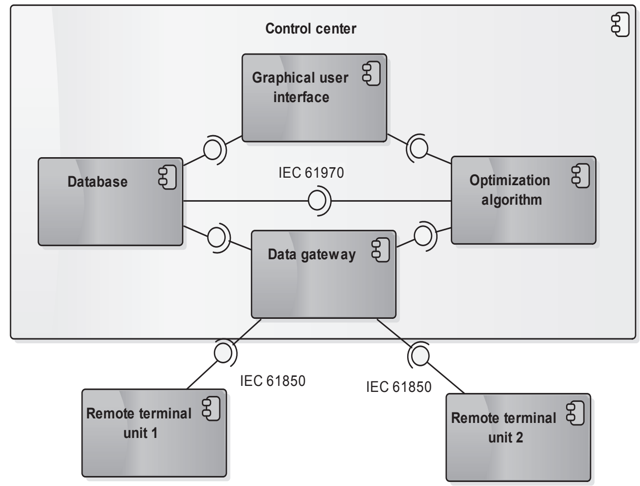

Fig. 4: Component overview of the communication structure

In addition to the structure shown in Fig. 4, the IEC 62351 standard is also applied. The main concept in this system is the application of a back-to-back asymmetric encryption and the usage of VPN tunnels. Therefore, the used RTUs are directly connected to VPN routers while the VPN back-end is located in the data gateway of the control center.

B. *Field test implementation*

The radial test system used for validating the control algorithms shown in Fig. 3 describes a similar network structure that is provided for practical test implementation. Field devices (RTUs presented in Fig. 4) are installed at the coupling point to the 110 kV transformer (node 1) and the biogas plant BGP 24 (node 24).

In a central control system, the algorithms used for monitoring and control (described above) have been implemented. The algorithms themselves are written in JAVA and provide an interface that allows for creating the appropriate methods while providing the necessary input data and output data. This proprietary interface is mapped to the CIM interface according to IEC 61970, so that the standardized communication throughout the control center – with its graphical user interface (Fig. 5) – is applied.

Fig. 5: Graphical User Interface of the Control Center

Considering the dynamic capability of the algorithm, very short calculation times in combination with high gradients of active and reactive power set points can be reached in practice. However, technical restrictions of power plants, such as start-up ramps (especially for biogas technology) or fixed *cos φ* ratios defined by the DSO, limit the possible dynamic effect on the stability of the grid. Moreover, with respect to the test system the number of available measurements for verification is limited to the monitoring functions of both RTUs. In that regard the installed unit in node 1 can serve as an indicator for superior voltage effects at the beginning of the strand.

A big challenge during system implementation is also the availability of a stabile physical communication connection. This challenge is caused by the fact that not all decentralized units have a sufficient connection to the internet. For this reason, in some cases, the usage of an LTE broadband mobile solution was chosen to realize the access. In general, this connection works quite reliably, although data may be lost depending on the weather conditions. To circumvent these difficulties appropriate software solutions were applied, e.g. storing a backup schedule locally at the RTU, so that operation can continue when the connection is interrupted. Additionally, intelligent algorithms for reestablishing the connection and the application of dual SIM solutions were applied, which allow a broader spectrum of the available frequency channels to be used.

VI. CONCLUSIONS

Different approaches for voltage stability maintenance were presented in this paper. Although the developed methods seemed to be very effective in theory, practical limitations involving the technical capability of power plants, accessibility for monitoring purposes and the low amount of power resource that is actually controllable reduce the possible dynamic impact. Never the less, an appropriate effect could be demonstrated by using customized algorithms and properly selected smart grid communication technologies that already meet the requirements for future distribution grid management systems.

ACKNOWLEDGMENT

This paper was developed as part of the research program "REStabil" funded by the German Ministry of Agriculture and Environment (Saxony-Anhalt).

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