This paper was presented at the 15th Wind Integration Workshop and published in the workshop's proceedings.

Voltage Control Support and Coordination between Renewable Generation Plants in MV Distribution Systems

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***Abstract*—This paper focusses on voltage control support and coordination between renewable generation plants in medium voltage distribution systems. An exemplary benchmark grid in Denmark, including a number of flexible ReGen plants providing voltage control functionality, is used as a base case. First, voltage sensitivity analysis is performed to quantify node voltage variations due to injections of reactive power for given operational points of the network. The results are then used to develop an adaptive voltage droop control method, where various droop settings are allocated to each ReGen plant according to the sensitivity indices of corresponding node voltages and the location of respective ReGen plants in the distribution system. Case studies are performed in time-domain to analyze the impact of voltage fluctuations due to active power variations of ReGen plants in order to verify the performance of the obtained voltage droop settings. The main outcome of this study is the provision of a generic guidance on how to coordinate the voltage stability support capabilities of ReGen plants in a distribution system with large ReGen penetration in order to ensure a resilient voltage controlled distribution system.**

***Index Terms*—Voltage droop control, Sensitivity analysis, Distribution system, Renewable energy sources, Wind power plants, PV plants, Coordinated control, Ancillary services.**

I. Introduction

TODAY, a large part of the wind power production in Denmark, i.e. 3799 MW, is coming from onshore wind turbines (WTs) [1], which are connected to the medium voltage grid and are distributed individually or in small scale clusters. Moreover, a 61 MW solar PV was commissioned in December 2015 near Kalundborg [2] which is the biggest solar PV plant in Scandinavia at this moment. However, the PV production nowadays mainly consists of dispersed residential small units up to 6 kW [3]. Larger PV systems of hundreds of kW are typically installed on large barns or farms and are connected directly on secondary side of MV/LV transformers [4].

The anticipated trend is that the increased share of installed renewable generation (ReGen) plants in Denmark in the coming years will mainly be accomplished in MV distribution systems by large scale concentrated PV plants (PVPs) and new generation wind power plants (WPPs). For example 500 MW of additional onshore capacity will be achieved by scraping 1300 MW of outdated onshore WTs and building of 1800 MW of modern WTs with increased controllability [3]. The PV generation capacity in Denmark of 783 MW today [5] will be increased at 1000 MW in 2020, mainly by industrial rooftop PVPs and ground mounted systems in the MW range [3].

Regarding the voltage profile within the distribution grid the aim is to keep the voltage profile close to the desired profile (±10%) and within the tolerance band margins with time frame of hours. The voltage levels may drop due to certain load types or increase due to generators in the grid or by reactive power shortages. The increasing penetration of ReGen plants into the distribution systems may reverse the power flow dependent on the present amount of generation and consumption leading to rising voltage levels. Voltages above nominal values are particularly present during high wind conditions and high solar irradiation, combined with low-load situations.

Reactive power control using capacitor banks and inductors may be a cheap solution [6]. However, this approach again has some drawbacks such as power quality issues during the switching time, the limited number of switchings allowed per day or the fact that it may solve locally the voltage challenges while not addressing the entire voltage profile on the feeder. Based on the above it is obvious that a capacitor/inductor bank for voltage support may not be a feasible option especially when large and fast voltage fluctuations are present in distribution grids with large penetration of wind and solar PV.

Another way to control the MV voltage is to use on-load tap changer (OLTC) transformers at substations. However, the volatile power profile of ReGen plants (see section II.B.) would cause a significant number of tap changes during one day in order to regulate the voltage profile, while the response time for changing the tap position is typically between 3 and 10 sec according to [7]. This may not be desired, as tap changers are the cause of 56 % of the total failures in transformers [8].

More advanced smart grid solutions for voltage control based on power electronic devices are offered by several companies [9]. Most of these devices are dedicated to low voltage application which means installation in LV grids. The cost related to this equipment is one of the main barriers for large scale deployment. Typically, the cost of such devices is 3 to 4 times bigger than the cost of a transformer in a secondary substation. MV solutions exist too, but again CAPEX and OPEX are not attractive for DSOs unless no other solutions exist. Thus, a simple solution to the above problems is provision of reactive power support from the existing ReGen plants in the distribution grid. Using this it will be possible to down-regulate the entire voltage profile in the distribution system and to keep the voltage within the limits at given nodes. Grid connection requirements for wind power and solar PV are requiring this capability and today's ReGen plants are offering it. However, this capability is not utilized by DSOs due to mainly the lack of technical infrastructure to communicate and control these units. The Danish DSOs have already started to install and deploy SCADA systems [10]. However, controlling the ReGen plants may not be feasible in short term due to lack of regulatory framework. It is foreseen that aggregators of these ReGen units may take the responsibility, in close cooperation with local DSOs, for hosting voltage control capabilities besides the energy trading. An ancillary market for provision of voltage/reactive provision is also expected in the near future [11]. Thus, the needs for coordination in providing reactive support and hence controlling voltage locally on a distribution grid is required in respect of the increasing number of dispersed units. This service may be provided by the same aggregators which nowadays are trading renewable energy or may be in the responsibility of the DSOs.

The focus of this paper is to develop voltage control and coordination functionalities for ReGen plants in distribution grids. An existing distribution grid in Denmark, which includes a number of flexible ReGen plants providing voltage control functionality, is used as a base case and described in Section II. Moreover, the voltage stability challenges in distribution systems with large penetration of ReGen are outlined by an exemplary test scenario. Section III presents a static analysis of the benchmark distribution grid. A voltage sensitivity analysis is performed to quantify node voltage variations due to injections of reactive power for given operational points of the network. The results of the static analysis are taken into account in Sections IV to determine two concepts for coordinating local voltage droop controllers. The architectures of the voltage control concepts are represented and their implementation evaluated. In Section V time domain analyses are performed in order to test the concepts for voltage control coordination. A model for the benchmark distribution grid and performance models for ReGen plants are used to analyze voltage control for a volatile power profile of the ReGen plants, used as a realistic test scenario that covers the crucial operating points with high solar irradiation and high wind speed. The outcome of this study serves as a generic guidance on how to coordinate the voltage stability support capabilities of ReGen plants in a distribution system with large ReGen penetration in order to ensure a resilient voltage controlled distribution system. The conclusion of this study is given in Section VI.

II. System Description and Voltage Stability Challenges

A. System Characterization of Benchmark Distribution Grid

In order to realistically estimate the impact of ReGen plants on the voltage profile and to assess the voltage control functionalities presented in this paper, a benchmark distribution grid (BDG) is developed. The BDG is based on a real MV grid operated by a local Distribution System Operator (DSO) in North Jutland/ Denmark. The MV grid comprises 15 secondary substations distributed along the feeder which have different types of loads e.g. households with or without electric heating, commercial, small and medium industry, farms/agriculture. Aggregated historical profiles are used for generating data for the loads. One of the feeders is shown in Fig. 1 and serves as a benchmark grid for the case studies presented in this paper. In

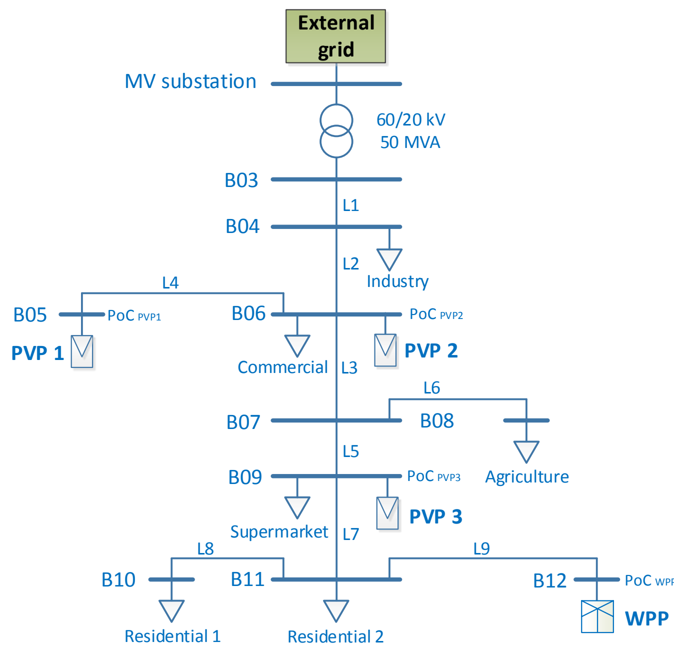

Figure 1. Structure of MV benchmark distribution grid with ReGen plants

order to account for realistic scenarios regarding the current and future penetration of renewables in Danish distribution grids, the BDG has been supplemented by the following ReGen plants providing voltage control functionality, i.e. one WPP with type-4 (full-scale converter connected) WTs and three PVPs:

- WPP (18 MW) representing 6 WTs of 3 MW each
- PVP 1 (10 MW) representing a remotely located ground-mounted system
- PVP 2 & 3 (2.5 MW each) representing typical rooftop systems mounted on top of large industrial plants and shopping centers

The MV cables in the BDG are dimensioned according to maximum expected power generation along the feeder. The grid connection of the particular BDG exhibits a short-circuit ratio of 10 and an X/R ratio of 10.

B. Identified Voltage Stability Challenges

Based on the actual trend of increased penetration of both solar and wind, the challenges to be expected in future are illustrated by means of the exemplary BDG. It is important to notice that the wind power and solar PV power production in Denmark is having large variations during the day due to the volatile wind speed and fast moving cloud conditions. Thus, large voltage fluctuations are expected in point of connection (PoC) of the ReGen plants. Typical daily active power profiles of the ReGen plants on a summer day, with one hour time resolution, are shown in Fig. 2. In Fig. 3 the resulting voltage profiles at the

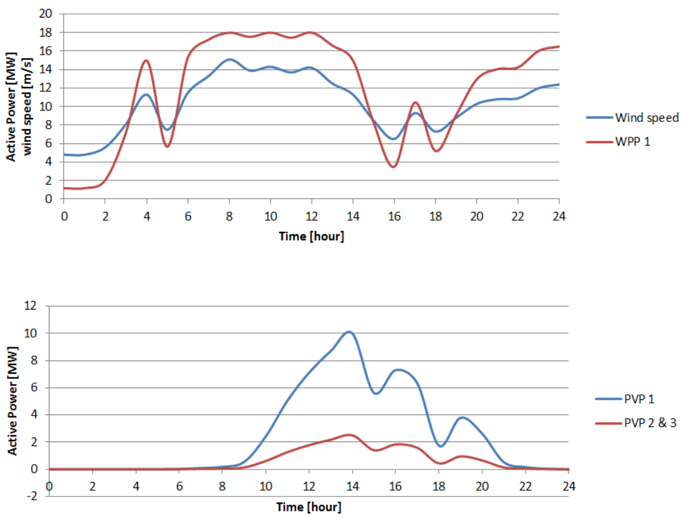

Figure 2. Exemplary daily profile of wind speed and power output of WPP with rated power of 18 MW (top graph) and typical daily power profile of PVPs with rated power of 10 MW and 2.5 MW respectively (bottom graph)

secondary side of the primary substation (20 kV) as well as at the respective PoC of the ReGen plants are depicted, presuming that they do not contribute to voltage control. It can be seen

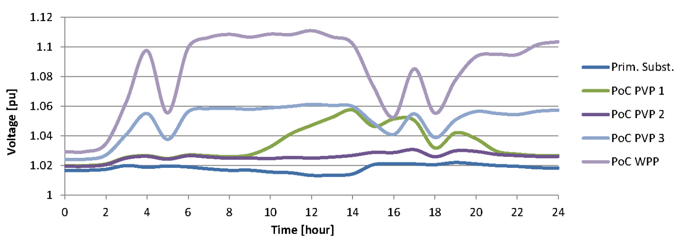

Figure 3. Voltage profile at primary substation and PoCs of ReGen plants

that the voltage levels fluctuate significantly depending on the power infeed of the ReGen plants. In particular the PoC of the WPP, being located remotely at the very end of the feeder, exhibits a volatile voltage profile of $\Delta V = 8\,\%$ throughout a whole day, even exceeding the limit of $1.1\,\mathrm{pu}$ during time periods with high wind speed and solar irradiation. It is obviously that an increased penetration of wind and PV into the distribution grids will lead to large voltage fluctuations and a high risk for exceeding the voltage limits. As a consequence disconnection of ReGen units is expected, but also damage of other equipment such as transformers, customer loads etc.

III. Static Analysis of the System

This chapter presents a static analysis of the BDG described in section II. Traditionally, DSOs are managing their system at the planning stage based on deterministic load flow studies in order to meet the reactive power demand and to verify line capacity and voltage regulation issues. With ReGen plants, as there can be plenty of them within a wide-spread area in the distribution system, it becomes crucial to also analyze how reactive power variations affect voltage changes in different points of the grid. A voltage sensitivity analysis is therefore a helpful tool to evaluate the system characteristics, as it provides information about the influence of changing generation and load parameters (ΔP and ΔQ) on the system voltages. Originating from the power flow theory, the Jacobian matrix can be determined for a certain operational point and will then provide the sensitivity between power flow and bus voltage changes as per Eq. 1 [12].

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{VP} & S_{VQ} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{1}$$

where $\Delta\theta$ is vector of voltage angle variations, ΔV is vector of nodal voltage variations and J^{-1} is the inverse of the Jacobian matrix. Since the objective is to maintain the magnitude of the system voltages within the limits by reactive power provision, the sensitivity matrices S_{VQ} is relevant for this study. As visualized in section II, the BDG includes 12 buses and the corresponding sensitivity matrices are given by Eq. 2, assuming a constant operational point for active power generation. The sensitivity coefficients extracted from the Jacobian matrix are not constant and they change with respect to the network operating point.

$$\begin{bmatrix} \Delta V_1 \\ \dots \\ \Delta V_{12} \end{bmatrix} = \begin{bmatrix} \frac{\delta V_1}{\delta Q_1} & \dots & \frac{\delta V_1}{\delta Q_{12}} \\ \vdots & \ddots & \vdots \\ \frac{\delta V_{12}}{\delta Q_1} & \dots & \frac{\delta V_{12}}{\delta Q_{12}} \end{bmatrix} \begin{bmatrix} \Delta Q_1 \\ \dots \\ \Delta Q_{12} \end{bmatrix} \tag{2}$$

The diagonal elements represent the voltage variation at a certain bus due to a variation of reactive power at the same point. The non-diagonal elements describe the voltage variation at a certain bus due to the variation in reactive power at a different point in the grid. High sensitivity means that even small changes of reactive power cause relatively large changes in voltage magnitude.

A. Test Scenarios

The test scenarios are defined as in Table I, taking into account various extreme operational points of ReGen plants in the BDG (assuming no reactive power support, Q = 0) and their impact on voltage sensitivity indices and the voltage profile on the feeder. The first scenario considers full active power production along the feeder. Scenario II and III investigate low solar irradiation / high wind speed and high solar irradiation / low wind speed respectively. The last scenario considers no active power production from ReGen plants.

Table I
Test Scenarios: Operational points of ReGen plants

Active Power [pu]	**PVP 1**	**PVP 2**	**PVP 3**	**WPP**
ActPow I	1	1	1	1
ActPow II	0	0	0	1
ActPow II	1	1	1	0
ActPow IV	0	0	0	0

The static analysis is performed, assuming that there is no reactive power support by ReGen plants, as this constitutes a starting point to analyze how reactive power contribution would affect the voltage levels. The power consumption along the feeder is kept constant for the considered scenarios, as the number of consumers and their load profile is not expected to vary significantly in relation to the generation profile.

Then, different voltage levels in the transmission system, which is modeled as external grid voltage in Fig. 1, can be present within the permitted range of ± 5 % [13] and thereby affecting the voltage characteristic within the distribution system. Following test scenarios are considered for the external grid voltage with three different voltage setpoints:

- $V_{EG} = 0.95\,\mathrm{pu}$
- $V_{EG} = 1.00\,\mathrm{pu}$
- $V_{EG} = 1.05\,\mathrm{pu}$

B. Results and Analysis

In traditional voltage sensitivity analyses the sensitivity indices have been used in order to identify instable operating modes [14] or points in the network being most prone to violate the voltage limits and requiring reactive power compensation according to the corresponding $\delta V/\delta Q$ index [15]. However, in this study it is proposed to evaluate the results of voltage sensitivity in order to quantify, from a system perspective, the impact of ReGen reactive power changes on the voltage levels in each busbar. Thus, in the following the numbers are presented as percentage voltage change dV [%] per percentage reactive power change dQ [%], which is based on the rated apparent power of the primary substation transformer $S_t = 50\,\mathrm{MVA}$.

In order to quantify the amount of voltage variation for a given change in reactive power, the diagonal elements of $\delta V/\delta Q$ matrix are evaluated in Fig. 4.

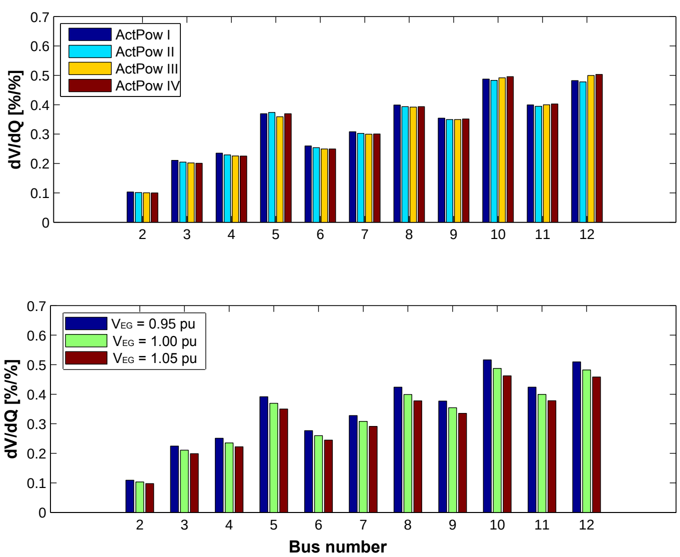

Figure 4. Diagonal elements of $\delta V/\delta Q$ sensitivity matrix for various operational points of ReGen plants (top graph) and external grid (bottom graph)

As for example at bus 12, absorbing $\Delta Q = -10\,\%$ would improve its own bus voltage by approximately $\Delta V \approx -5\,\%$. At bus 6 the corresponding bus voltage would be reduced by only $\Delta V \approx -2.5\,\%$ with the same amount of reactive power absorption at this bus. Now by comparing various test scenarios in Fig. 4, it can be concluded that $\delta V/\delta Q$ indices do not vary significantly; neither for different operational points of the ReGen plants (top graph) nor for various operational points of the external grid (bottom graph). The maximum deviation amounts to $\Delta\frac{\delta V_{B10}}{\delta Q_{B10}} = 1.4\,\%$ at bus B10. Hence, V-Q sensitivity in the system can be treated independent of the sizing of ReGen plants within the grid, i.e. their active power infeed, and the conditions of the external grid. Based on the obtained information, measures can be adopted for tuning the voltage control of each ReGen plant, as described later in section IV.

Fig. 5 illustrates all elements of the $\delta V/\delta Q$ matrix (see Eq. 2). The numbers within the color map describe how much change in voltage ΔV at bus Y will occur, when the reactive power will vary with $\Delta Q = 1\,\%$ at a certain bus number X.

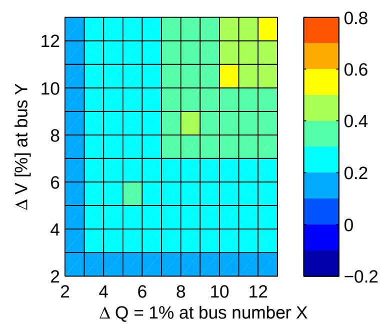

Figure 5. $\delta V/\delta Q$ sensitivity for various operational points of ReGen plants

It can be seen that V-Q sensitivity increases with increasing distance from the primary substation (bus B03 in Fig. 1). Hence, reactive power variations at the end of the feeder (bus B12) will cause larger voltage changes on adjacent busses than close to the primary substation.

Moreover, it can be concluded that the off-diagonal elements $(Y \neq X)$ at directly adjacent busses do not differ more than 0.2 % from the diagonal elements $(Y = X)$ at a certain bus. This means that reactive power provision by a ReGen plant will affect the voltage level at its own bus significantly and still has good voltage regulating effect on adjacent busses, in particular at the end of the feeder. From Fig. 3 it is can be seen that voltage regulation at the end of the feeder is essential, if ReGen plants are located in remote areas far away from the primary substation. In case of high power production of the WPP the feeder exhibits a rising voltage profile with voltages exceeding the steady-state limits.

IV. Development of Concepts for Voltage Control Coordination

Today's grid codes (GCs) require that ReGen plants shall be capable of providing reactive power automatically by either power factor (PF) control mode, reactive power (Q) control mode or voltage control mode [13]. PF control is referred to a passive reactive power control due to its dependency on active power changes and is thereby disqualified for control coordination. A ReGen plant operating in Q control mode receives a reference for reactive power and provides feedback signals to upper hierarchical layers. Thus, for coordinating voltage regulation it would require a central entity that utilizes the reactive power capabilites of the individual ReGen plants. Voltage control mode requires an inner control loop for controlling the reactive power injected into PoC and an outer voltage control loop aiming to regulate the voltage in PoC. A typical droop control function is specified in the GCs and generally implemented in ReGen plants. A ReGen plant receives reference signals for voltage and droop values and provides feedback signals to upper hierarchical layers, e.g. power production, voltage measurements and available reactive power (Fig. 6).

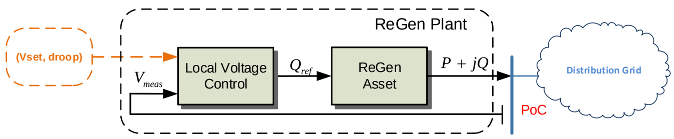

Figure 6. Scheme of Control Concept 1 - Manual Setting

Subsequently, two operational control concepts for local voltage regulation function of ReGen plants are outlined. The first concept implies that voltage control of each ReGen plant is purely related to the instructions by current GCs (uncoordinated), while the second concept proposes a decentralized coordination scheme which is based on an initial voltage sensitivity analysis of the power system.

A. Control Concept 1 - Manual Settings

According to ENTSO-E GC [13] the ReGen plants should be capable of adjusting the voltage between 0.95 to 1.05 pu. The voltage droop should take on values between 2 and 7 %. In this context droop is referred to "the ratio of the change in voltage, based on nominal voltage, to a change in reactive power infeed from zero to maximum reactive power, based on maximum reactive power". This means, those values regard the capabilities of the respective ReGen plants, but do not directly take into account the characteristics of the grid. As no further guidelines are provided of how to adjust the droop controllers, it may be assumed that the ReGen plants are asked to operate with some manual settings for voltage control (Fig. 7). An

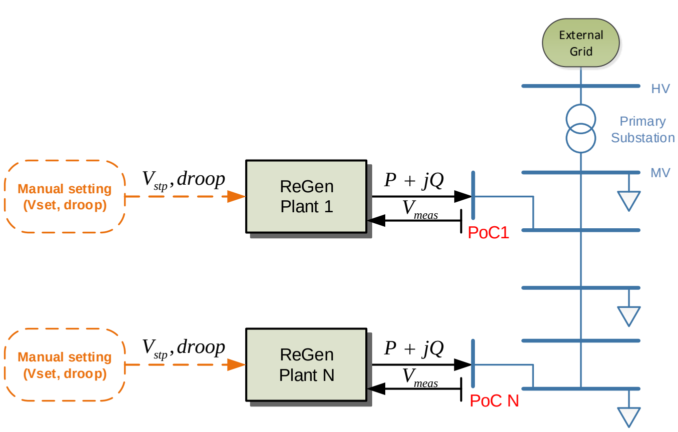

Figure 7. Scheme of Control Concept 1 - Manual Setting

aggregator or the DSO may specify these values within the GC recommendations for a given plant, however without taking into account other units connected to the same feeder. This control concept does not require any coordination and voltage control will be entirely dedicated to the individual ReGen plants.

B. Control Concept 2 - Decentralized Off-Line Coordination

This control concept is referred to as Decentralized Off-Line Coordination and illustrated in Fig. 8.

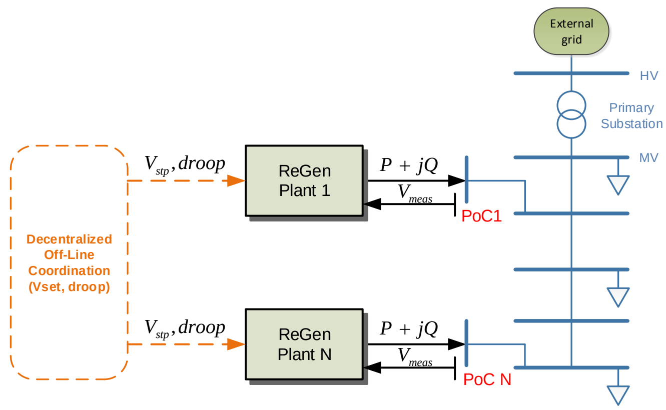

Figure 8. Scheme of Control Concept 2 - Decentralized Off-Line Coordination

For a given feeder, where several ReGen plants are installed, a voltage sensitivity analysis is performed as per section III. By using the derived droop values, each settings in ReGen plant are manually introduced by an aggregator or the responsible DSO. These settings may be updated when necessary, e.g. changes in the topology of the feeder, changes of cables, transformers etc.

Determination of droop values: As outlined in section III, the V-Q sensitivities at the system busses provide insight regarding the grid characteristics being relevant to control the voltages. This information reveals how much reactive power is actually required to regulate a change in voltage at a certain bus. Fig. 9 shows the inverse elements of Fig. 4, i.e. $\delta Q/\delta V$ indices instead of $\delta V/\delta Q$ indices. In this way it can be concluded how much Q [% of S_t] is required to change the voltage by 1 %. The numbers colored in red are related to the bus connections of all ReGen plants in the BDG.

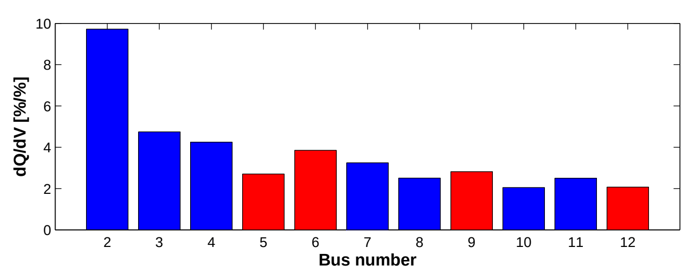

Figure 9. $\delta Q/\delta V$ sensitivity at all system busses

Now, provided a certain bus X exhibits a voltage deviation (e.g. by power fluctuations), the numbers in Fig. 9 determine how much Q the ReGen plant needs to feed in to counteract the voltage deviation at bus X. Moreover, the respective reactive power provision will have good voltage regulating effect on the adjacent busses, as it has been ascertained in section III by analyzing the off-diagonal elements of the V-Q sensitivity matrix. Consequential, the following droop values are derived for each ReGen plant in the system by using Eq. 3, where the actual value of percentage droop is defined according to the grid code [13]. Q_{max} is the maximum reactive power capability of a ReGen plant respectively.

$$droop = \frac{\delta V}{\delta Q} \cdot Q_{max} \tag{3}$$

The results are summarized in Table II.

Table II
DROOP SETTINGS FOR REGEN PLANTS

	PVP 1	PVP 2	PVP 3	WPP
$\delta V/\delta Q$ sensitivity [%/ % of S_t]	0.369	0.260	0.355	0.482
$\delta Q/\delta V$ sensitivity [% of S_t/ %]	2.707	3.852	2.821	2.073
Q_{max} [% of S_t] of ReGen plant	20	5	5	12
V(Q) droop [%] acc. to GC	7.39	1.30	1.77	5.79

As ascertained in section III, V-Q sensitivity can be evaluated independent of various operational conditions, i.e. various active power production levels and external grid voltages, and so can the obtained droop settings. For the voltage setpoint an arbitrary value of 1 pu can be selected, taking into account that the system voltages should be regulated around nominal value. Hence, this control concept does not require superior real-time coordination during grid operation. However, an initial static analysis of the grid as performed in section III is necessary to calculate the respective V(Q)-droop parameters for the ReGen plants. Any changes in grid topology, power generation units and loads may lead to an update of the settings.

V. TIME DOMAIN ANALYSIS OF DEVELOPED CONTROL CONCEPTS

In this section time domain analyses are performed in order to test the concepts for voltage control coordination, developed in previous section. Therefore, some performance models for PVPs and WPPs (Fig. 10) have been developed specifically for voltage stability studies with a frequency bandwidth of the model of maximum 5 Hz [16]. The block diagrams of those ReGen assets can be linked to Fig. 6.

A. Test Scenarios

A benchmark test scenario is applied to account for the extreme operational points of ReGen plants in the BDG, i.e. PVPs and WPPs at rated power, and simultaneously represents a realistic generation profile over time. In this context, real measurement data for wind speed and solar irradiation are used as inputs for the ReGen plant models. A time frame of one hour is considered sufficient to represent the extreme operational points at high wind speed and solar irradiation, as shown in Fig. 11. Two solar irradiation profiles denoted by G are applied, taking into account the cloud movement across the area between PVP 1 & 3 and PVP 2.

In order to represent the crucial operational points of the external transmission system, eventually leading to critical voltage rises, following test scenarios are considered:

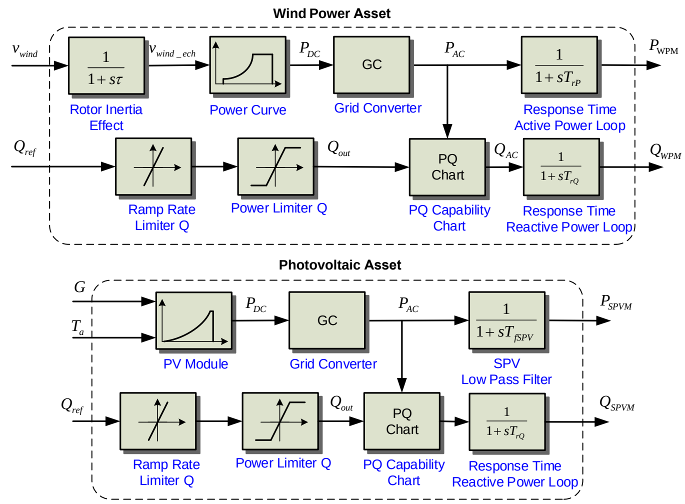

Figure 10. Block diagram of wind power and photovoltaic asset [16]

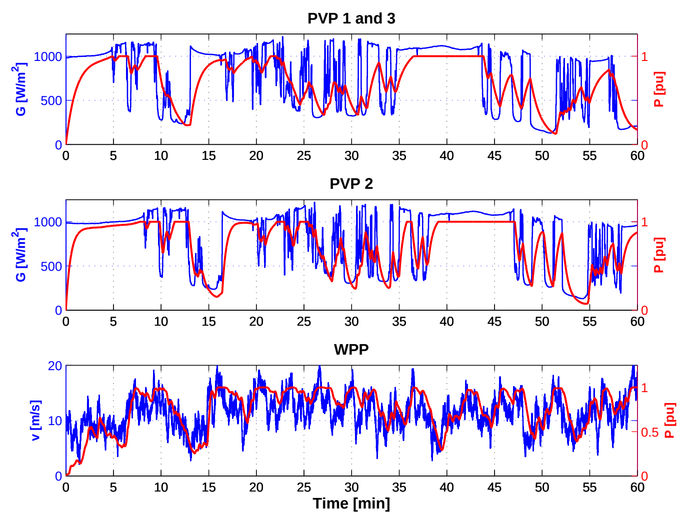

Figure 11. Solar irradiation and wind speed profiles and corresponding power outputs of ReGen plants

- $V_{EG} = 1.00\,\text{pu}$
- $V_{EG} = 1.05\,\text{pu}$

B. Evaluation Criteria

As shown in section II, the power generation profile of ReGen plants can lead to rising voltages exceeding the steady-state limits of $\pm 10\,\%$. The aim of voltage control is to keep the voltage profile within the tolerance band margins, hence being a major evaluation criterion for the developed control concepts. Moreover, control stability aspects need to be taken into account. Decentralized voltage control means that several ReGen plants try to regulate the voltage simultaneously without being coordinated by a superior control entity. Depending on the characteristics of the droop control, this can lead to hunting effects, if adjacent ReGen plants are controlling the voltage in the same way. It is to be evaluated whether the control actions by each ReGen plant have a stable settling point or potentially lead to temporary instability.

C. Test Cases

The aim is to analyze various droop settings for local voltage control of each ReGen plant. As mentioned in section IV, for Control Concept 1 it is assumed that the ReGen plants operate with some fixed droop settings being specified by the grid code requirements. As the voltage droop should take on values between 2 and 7 %, the following three test cases are considered to cover the entire spectrum:

- V(Q) droop = 2 % (*DroopMin*)
- V(Q) droop = 4.5 % (*DroopMed*)
- V(Q) droop = 7 % (*DroopMax*)

As no further guidelines are provided of how to adjust the droop controllers, it is assumed that each ReGen plant operates with equal fixed droop value.
On the other hand, decentralized off-line coordination (Control Concept 2) takes into account the V-Q sensitivities at the system busses to obtain suitable droop settings. They are presented in Table II for each ReGen plant respectively. Hence, another test case is introduced:

- V(Q) according to voltage sensitivity analysis (*DroopVSA*)

D. Results and Analysis

In Fig. 12 it is shown, assuming an ideal external grid voltage of $V_{EG} = 1\,\mathrm{pu}$, for each ReGen plant in the BDG the voltage profile throughout the considered time frame of 1 hour for various droop settings according to the specified test cases. Moreover, it is added the base case, showing the resulting profile if voltage droop control was inactive.

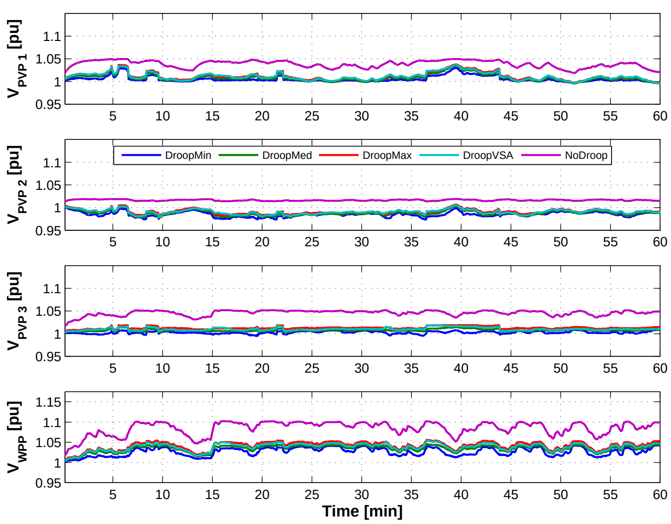

Figure 12. Voltage profile over one hour at PoC of ReGen plants for grid voltage of $V_{EG} = 1\,\mathrm{pu}$

It can be seen that both Control Concept 1 (Manual settings) and Control Concept 2 (De-centralized offline coordination) yield in sufficient depression of the voltage profile in order to meet the steady-state requirements. In particular the PoC of WPP at the end of the feeder experiences rising voltages up to above 1.10 pu, yet being reduced to values below 1.06 pu with voltage control.

Concerning the stability of voltage control actions, it can be remarked that reactive power set points are met according to the V(Q) droop within a settling time of less than 1 second.
Fig. 13 shows the voltage profile for an extrem scenario with a transmission system in alert state operation (grid voltage of $V_{EG} = 1.05\,\mathrm{pu}$). Both control concepts 1 and 2 are still able to decrease the voltage profile in the distribution grid to values below 1.10 pu.

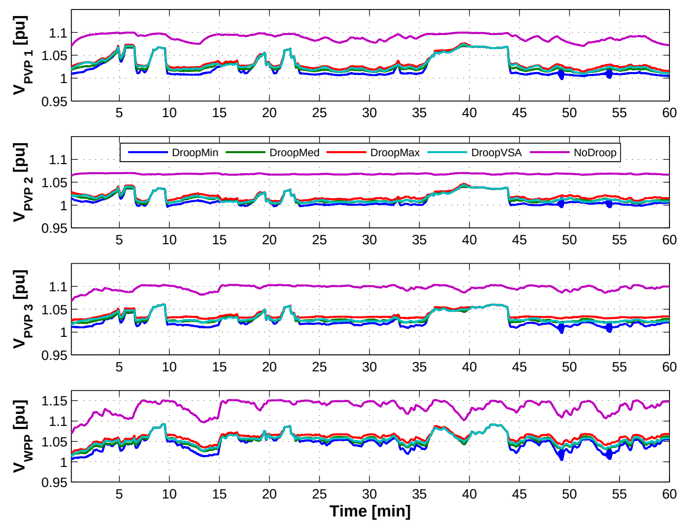

Figure 13. Voltage profile over one hour at PoC of ReGen plants for grid voltage of $V_{EG} = 1.05\,\mathrm{pu}$

However, by looking at the results obtained for the test case *DroopMin* , it can be seen that there appear two instable operating points at time $t \approx 49\,min$ and $t \approx 54\,min$, characterized by oscillatory behavior of the voltage over time. A zoom of the first event is provided in Fig. 14. Before the time $t_1 \approx 2926.1\,s$, the WPP operates at its capability limit of $Q_{WPP} = -6\,\mathrm{Mvar}$. The decreasing voltage at WPP results in less reactive power absorption (increasing Q_{WPP}). Positive ΔQ leads to positive ΔV at its own bus and adjacent busses, i.e. at PVP 2 and PVP 3, and even at remote busses (PVP 1) as indicated by the small voltage rise at t_1 for all ReGen plants. The anti-proportional droop characteristic in turn leads to negative ΔQ for positive ΔV. Now, simultaneously the active power generation of PVP 1 and 3 (Fig. 14 bottom graph), after peaking, decreases rapidly (negative ΔP) which lowers the voltage profile (negative ΔV). This in turn leads to positive ΔQ according to droop control. In this case, the local voltage droop controllers of some of the ReGen plants experience opposing control objectives that lead to hunting effects. These events of temporary instability occur only for flat droop characteristics as in the test case *DroopMin* with 2 %. For this droop setting, the ReGen plants react with relatively high amount of reactive power to voltage variations. It has been observed by further simulations that slightly steeper droop characteristics (e.g. 2.5 %) do not lead to control instability, while flatter droop characteristics (e.g. 1.5 %) result in even more instable operating points.
The time domain analysis of the developed concepts for voltage control coordination show, that an arbitrarily chosen droop

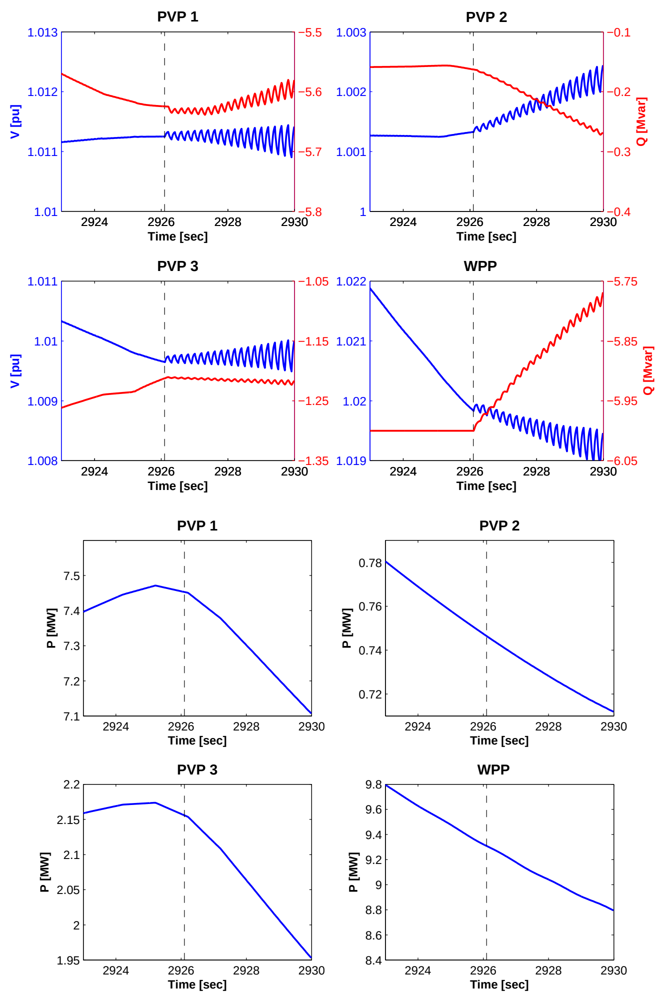

Figure 14. Voltage, reactive power (top graph) and active power (bottom graph) of all plants at beginning of instability at $t_1 = 48.75\,\mathrm{min} = 2926.1\,\mathrm{sec}$ for test case *DroopMin* = 2 %

setting according to Control Concept 1 can lead to instable operating points, if some ReGen plants feature a rather flat droop characteristic. The results reveal that the voltage profile is lowered sufficiently, if droop values are determined according to voltage sensitivity analysis (Control Concept 2).

VI. Conclusion

This paper has presented a decentralized control concept that is able to coordinate voltage control between multiple ReGen plants in distribution systems. Some considerations regarding current and future penetration of wind power and Solar PV in distributions grids are made. It is shown that voltage stability challenges with large penetration of wind and solar power are related to volatile voltage excursions due to fluctuating wind speed and solar irradiation. A voltage sensitivity analysis of the distribution system is performed as a useful tool to evaluate the influence of changing reactive power on the system voltages. It serves as the basis for developing a decentralized off-line coordination scheme which obtains the settings for the local voltage droop controllers of the individual ReGen plants according to the grid characteristics and independent of various operational points. Time domain analyses of the control concepts reveal that arbitrarily chosen droop setting can lead to instable operating points, while carefully selected droop settings, based on initial system analysis and potentially stipulated by an aggregator of ReGen plants, yields to satisfactory voltage regulation. A set of guidelines for the coordination of voltage droop settings for individual ReGen plants have been provided. Future work is addressed to develop and evaluate more advanced control concepts that utilize communication systems with on-line signal exchange between a central control entity and the individual ReGen plants. Control objectives for centralized coordination may include an optimized reactive power utilization of ReGen plants to mimimize line losses in the system or to provide sufficient capability required for fast reactive current injection during grid faults.

Acknowlegment

This work was carried out by the Department of Energy Technology at AAU in cooperation with DTU Wind Energy Department and Department of Electronic Systems at AAU. Energinet.dk is acknowledged for funding this work in contract number: PSO project 2015 no. 12347: "Ancillary Services from Renewable Power Plants (RePlan)", www.replanproject.dk.

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