Voltage control support and coordination between ReGen plants in distribution systems

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Content

Preface

This report is a deliverable in WP2 in the project "Ancillary services from Renewable power Plants" (RePlan). RePlan is funded as POS project 2015 no. 12347 by the Danish PSO-programme ForskEL, which is administered by Energinet.DK. RePlan is carried out in collaboration between DTU Wind Energy, DTU Elektro, Aalborg University Energy Technology, Aalborg University Wireless Communication Networks and Vestas Wind System A/S. DTU Wind Energy is manager of the project.

1 Scope of document

This deliverable report is summarizing the results of work package 2 (Voltage stability support from ReGen plants), including the related models, methodologies, development of controls and study cases. The objective of this work package is to identify voltage stability challenges related to the large penetration of ReGen plants into MV distribution systems, to develop controllers with the specific aim of regulating the voltage /reactive power and analyze the suitability for a coordinated voltage stability support from WPPs and PVPs in distribution levels.

2 Identification of Voltage Stability Challenges

This chapter presents the voltage stability challenges in power systems with large penetration of ReGen, being related to volatile voltage excursions in distribution systems due to ReGen plants. Related considerations regarding the increasing penetration of wind power and Solar PV in distributions grids are made. Technical specifications regarding voltage limits are provided. Present challenges are addressed by real measurements given by a local DSO in Denmark. 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 exemplary benchmark distribution grid.

2.1 Background

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 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]. It is important to notice that the solar PV power production in Denmark is having large variations during the day due to the fast moving cloud conditions. Thus, large voltage fluctuations are expected in the connection point. In order to illustrate the impact of changing solar irradiation during day time on the voltage levels measurements of voltage and active power for a secondary substation with many connected PV systems are shown in Figure 1. It can be seen that the daily power profile, shown for one PV system of 6 kW, causes rising voltages up to almost 1.05 pu during midday time of the first day, when solar irradiation is high. It can be assumed that the load consumption at the first day is relatively low in contrast to the following two days, where the voltage rise is during midday is less significant.

However, the example shows that a large number of PV systems at household level can have a significant impact on the voltage levels as seen in the secondary substations (MV/LV) and hence it will impact the medium voltage grid. It is also worth to say that currently, small PV systems in kW range do not contribute to voltage control.

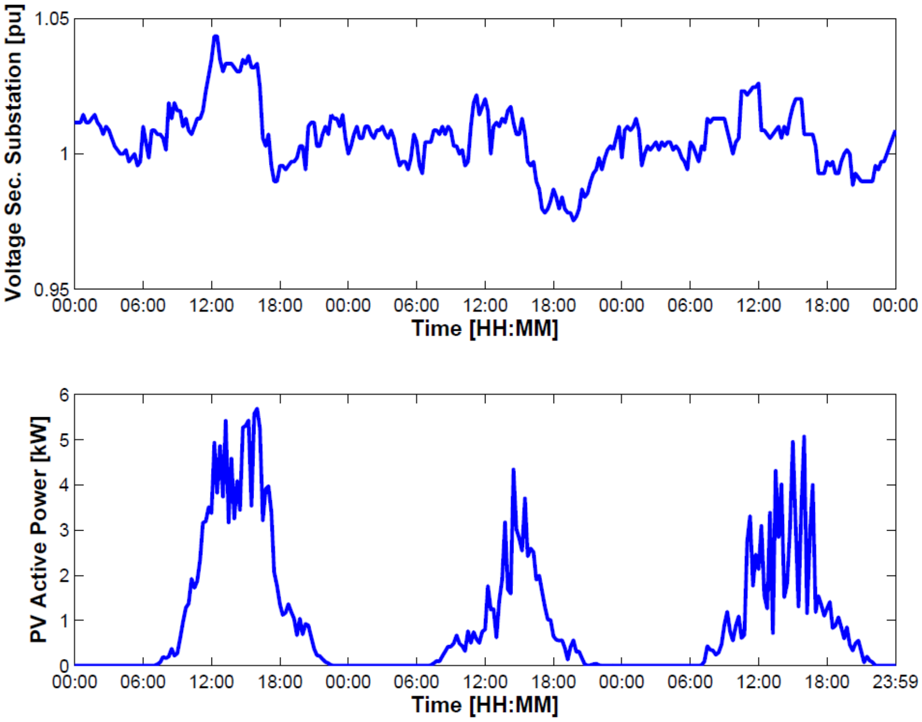


Figure 1: Voltage profile at secondary substation and power profile of one PV system (15 min values)

Looking at wind power in distribution grids, a good example of large voltage excursions in MV feeders is given in the following based on data from SydEnergy, a Danish DSO in Southern Jutland. The simplified Single Line Diagram of a 150 kV substation is given in Figure 2. The associated 62 kV feeders are hosting a large amount of wind power. In particular the substations in Hemmet (HEM) and Nymindegab (NYM) are having 42 MW and 18 MW respectively installed capacity of wind turbines [5].

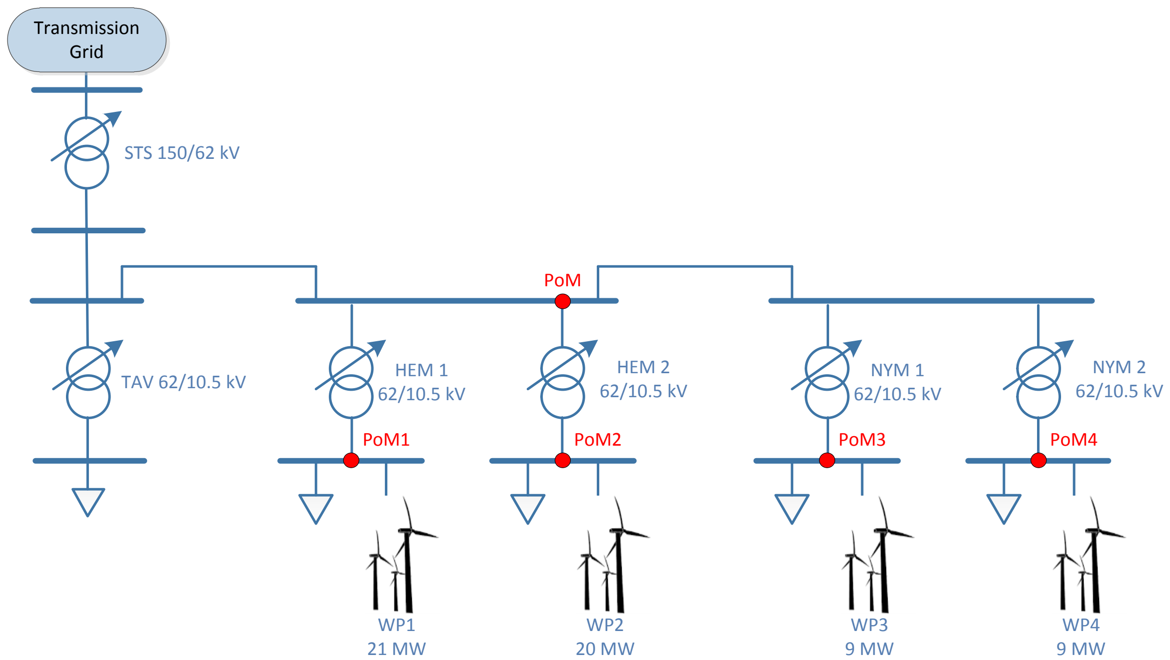


Figure 2: Simplified Single Line Diagram of a 150 kV substation

According to [6] some wind characteristics for the October 2014 in South- and SønderJylland are given in Figure 3.

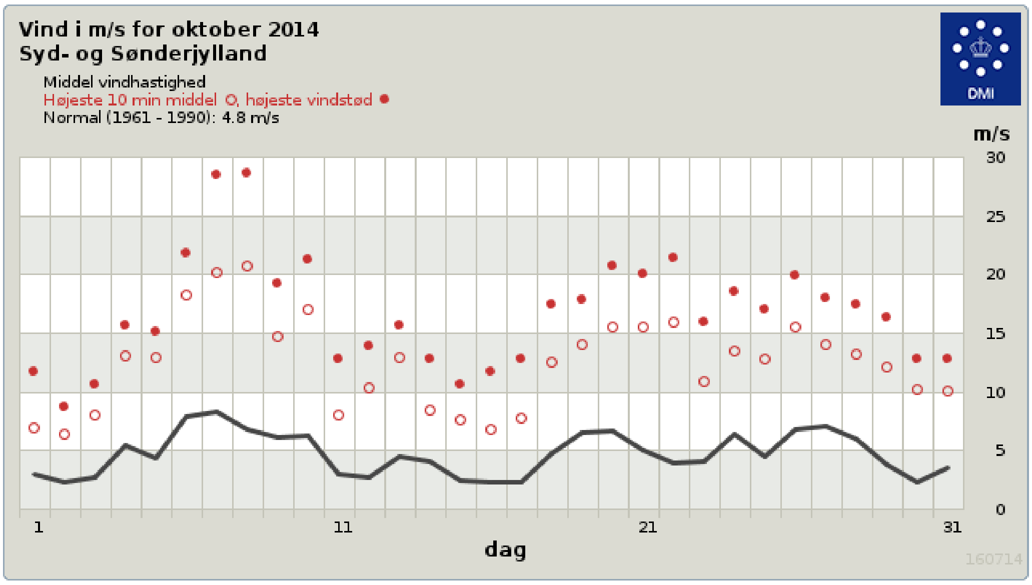


Figure 3: Wind speed characteristics for October month 2014 [6]

Notice that the average wind speed for October 8th was about 20 m/s with wind gusts of more than 25 m/sec.

Average voltage measurements with a resolution of 15 min on 62 kV and 10.5 kV busbars were recorded in some Point of Measurements (PoM) as shown in Figure 2. These voltages for the entire day are given in Figure 4 while Figure 5 is showing a zoom on measurements for the time interval 12:45 to 16:00 when a high voltage rise is observed.

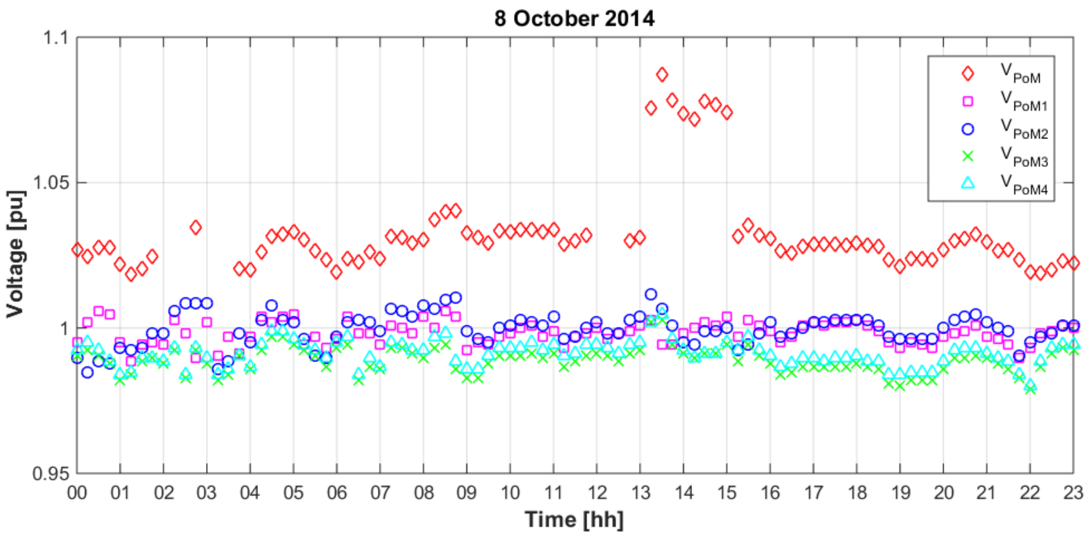


Figure 4: Voltage profile at transformers (15 min values) for 8th October 2014

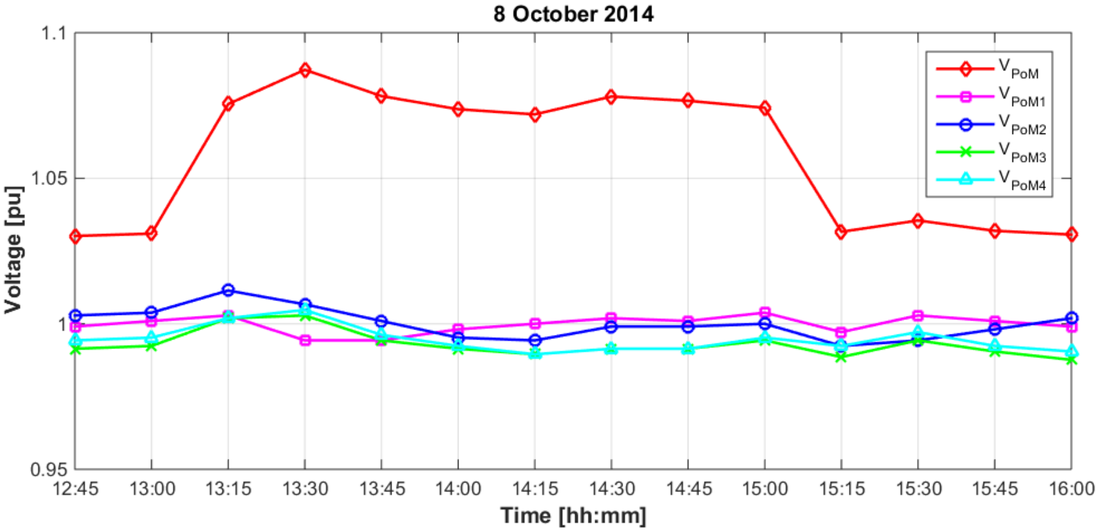


Figure 5. : Voltage profile at transformers (15 min values) for 8th October 2014 (zoom 12:45 – 16:00)

During this time interval the 62kV level voltage is above 1.05 pu and close to 1.09 pu. Prior to this voltage rise there are missing data for one hour due to bad data recordings. There is no data recording of the instantaneous voltage levels in this period of time. However, it is expected that the upper limit (+ 10 %) was exceeded.

According to SydEnergy this voltage rise was a result of full wind power production from the wind turbines installed in MV feeders. The effect of on-load tap changer (OLTC) actions in each transformer can be observed in Figure 5 while there is no actions outside this time interval as both 62 kV and 10.5 kV voltages are exhibiting the same profile. Notice that the OLTC is acting on the high voltage side of each transformer to regulate the voltage on 10 kV side close to 1 pu. Overall the voltages on 10.5 kV feeders are within the ±2% limits due to OLTC control while the 62 kV voltage is approaching the upper limit. High resolution data may reveal higher voltages than the permissible limits for very short time periods.

It is also worth to notice that this large voltage due to high wind power production was occurring in the mid-day hours when a high production from PV systems, that might be present in the system, is also expected.

Based on the measurement results, provided in this section for PV and wind power respectively, it can be anticipated that a combined effect of large power variations from PV and wind power in a MV feeder may lead to very large voltage fluctuations approaching or even exceeding the voltage limits especially in low load situations. Overall, Danish Energy Association is currently concerned about these voltage excursions due to the increasing number of renewable generation in the distribution grids as many DSOs especially in Jutland have started to experience this phenomenon. Unfortunately, few detailed high resolution measurements are available at this moment.

2.2 Future Challenges

The anticipated trend is that the increased share of installed 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 [7] will be increased at 1000 MW in 2020, mainly by commercial/ industrial rooftop PVPs and ground mounted systems in the MW range [3].

In order to realistically estimate the impact of ReGen plants on the voltage profile in the distribution system an exemplary MV feeder as shown in Figure 6 is considered in the following. This exemplary MV network is based on a grid near Aalborg operated by Himmerland Elforsyning, where 3 MW wind turbines were already present at the end of the feeder, and it was modified to accommodate realistic scenarios regarding penetration of renewables [8].

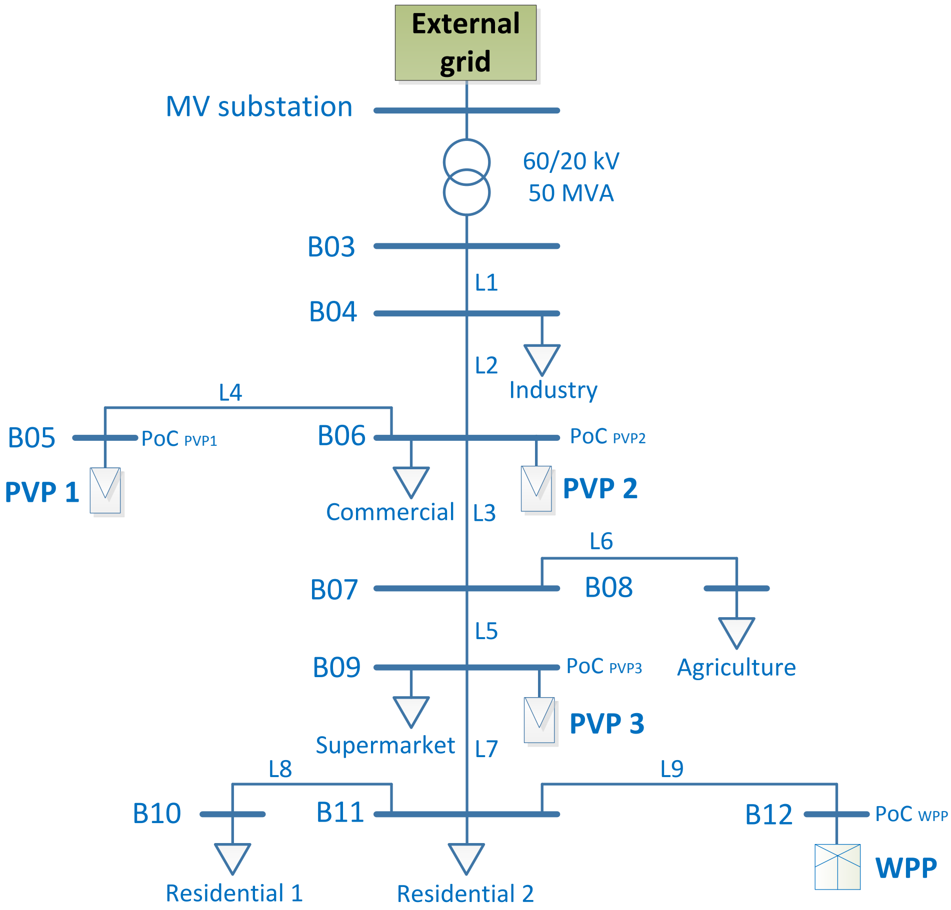


Figure 6: MV Benchmark distribution grid with ReGen plants

Three new WTs were added in the same connection point, so that 6 WTs are represented by one WPP in Figure 6. One ground mounted solar PV Plant of 10 MW (PVP1) and two other PV Plants (PVP 2 and PVP3) of each 2.5 MW related to large commercial consumers and a supermarket are considered. Typical daily active power profiles[1] of the ReGen plants on a summer day, with one hour time resolution, are shown in Figure 7 and Figure 8.

[1] Measurement data are taken from weather station at AAU: http://www.et.aau.dk/research-programmes/photovoltaic-systems/

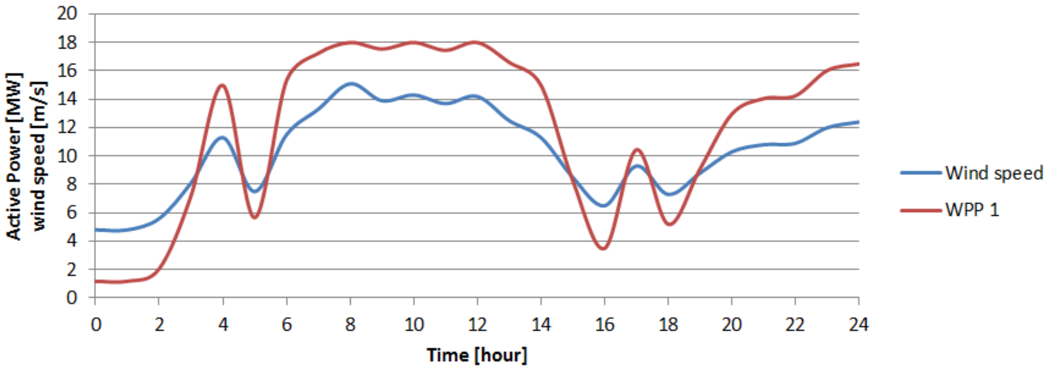


Figure 7: Exemplary daily profile of wind speed and power output of WPP with rated power of 18 MW [9]

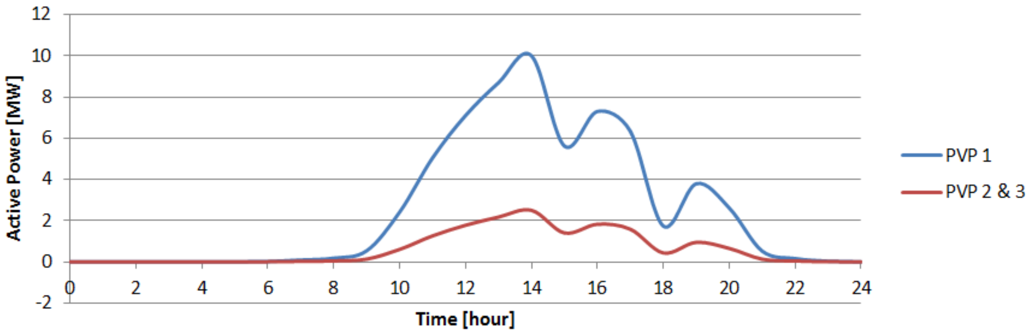


Figure 8: Typical daily power profile of PVPs with rated power of 10 MW and 2.5 MW respectively [9]

In Figure 9 the resulting voltage profiles at the secondary side of the primary substation (20 kV) as well as at the respective points of connection (PoC) of the ReGen plants are depicted, presuming that they do not contribute to voltage control. It can be seen 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 pu during time periods with high wind speed and solar irradiation.

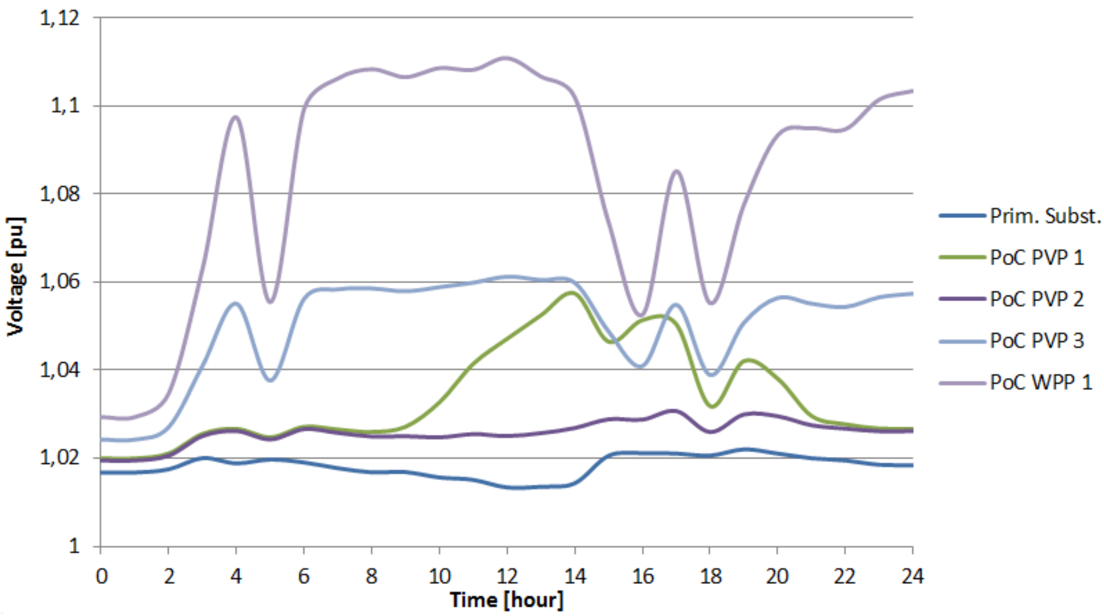


Figure 9: Voltage profile at primary substation (secondary side) and PoCs of ReGen plants

It is obviously that an increased penetration of wind and PV into the distribution grids can 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.

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 [10]. However, this approach again has some drawbacks such as:

- it shall be placed on a given node into the distribution grid determined by pre-design studies that accounts for all possible operation scenarios. Moreover, sizing of these devices shall be made with focus on minimizing costs while achieving the desired effect.
- it may solve locally the voltage challenges while not addressing the entire voltage profile on the feeder.
- it induces power quality issues during the switching time [11].
- it has a limited number of switchings allowed per day.
- it requires additional investments for DSOs.

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 OLTC transformers at substations. However, as the above examples are illustrating, the volatile power profile of ReGen plants 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 [12]. This may not be desired, as tap changers are the cause of 56 % of the total failures in transformers [13].

More advanced smart grid solutions for voltage control based on power electronic devices are offered by companies like ABB and Siemens [14]. Most of these devices are dedicated to a 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 units 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 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 [15]. 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 [16]. Thus, the needs for coordination in providing reactive support and hence voltage control locally on a distribution grid is required in respect of the increasing number of dispersed units.

2.3 Objectives in WP2

WP2 aims to develop voltage control and coordination functionalities for ReGen Plants in distributions grids. These control functionalities are expected to be in the responsibility of aggregators of grid support services. Practical considerations regarding hosting controller platform and the necessary in- and output signals are provided.

The following assumptions are considered in WP2:

- OLTC control is not taken into account as this is a main responsibility of DSOs. Moreover, a highly fluctuating voltage may lead to an undesired number of tap changes in a short time interval.
- Capacitor/inductor banks are not considered as the part of RePlan solutions due to additional voltage transients induced into the grid during the switchings and the limited number of switchings per day
- Developed control solutions shall use the existing ReGen technologies and shall be ready for implementation
- High data exchange solutions which requires optimization algorithms are outside the scope

3 Voltage Control Capabilities of ReGen Plants in Distribution Networks

This chapter presents the technical capabilities of ReGen plants for the voltage control to create the needed functionalities stipulated by the technical grid code requirements and the functional specifications described in chapter 2 and 4 of D-1.1 [17]. Those functionalities enable the provision of the voltage and reactive power support from ReGen plants. The definition of the most important parameters is presented by means of state-of-the-art analysis, predominantly originating from the results of REserviceS Project [18] [19].

3.1 Technical Capabilities of Wind Power Plants

In today's distribution systems both fixed-speed (type 1), limited variable speed (type 2) and variable speed WTs (type 3 & 4) are present to a large extent. While the former WTs (type 1 & 2) are practically obsolete, they are used at a number of older WPPs and are not expected to be replaced by more modern WTs until they reach the end of their economic life, typically 20 to 25 years from installation [20]. Type 1 and 2 WTs consume reactive power, whose supply is normally ensured by shunt capacitor banks installed at the turbine terminals. However, they are not capable to actively control voltage according to the functional specifications considered for coordinated voltage control. Hence, only the technical capabilities of WPPs with variable speed WTs (type 3 & 4) are presented and considered in RePlan.

Subsequently, various plant functionalities are evaluated based on estimations from manufacturers and developers coming from questionnaires, interviews, and these functionalities are also complemented by the literature [18].

3.1.1 Reactive Power Setpoint Processing Functionality

This capability is needed to be able to receive setpoints for the selected control mode including the change of the mode. Table 1 summarizes the WPP capabilities related to the stipulated grid code requirements [17].

Table 1: Wind Power Plant Capabilities for Q Setpoint Processing Functionality [18]

Feature	Grid Code Requirement	WPP Capability
Setpoint setting	0.95 to 1.05 pu in steps no greater than 0.01 pu	Yes
Commencement of response	Within 2 s	100 – 200 ms
Rise time	1 – 5 s	< 1 s
Settling time	10 s	≥ 1 s
Steady-state reactive tolerance	±5 % of Q_{max}	Yes

3.1.2 Reactive Power Provision Functionality

Reactive power can be supplied up to certain values which are defined by PQ diagrams. Table 2 summarizes the WPP capabilities for both type 3 and type 4 WTs related to the stipulated grid code requirements [17].

Table 2: Wind Power Plant Capabilities for Q Provision Functionality [18]

Feature	Grid Code Requirement	WPP Capability	
		Type 3	Type 4
Max. range of Q/Pmax during normal operation	0.33	Yes	Yes
Max. range of Q/Pmax during standstill	0.33	0.2	Yes

3.1.3 Reactive Power Control Scheme Functionality

In order to keep the voltage at the PCC within a tolerance band, the adjustment of reactive power exchanged with the grid has to be controlled by a specified mode. Table 3 summarizes the WPP capabilities related to the stipulated grid code requirements [17].

Table 3: Wind Power Plant Capabilities for Q Control Scheme Functionality [18]

Feature	Grid Code Requirement	WPP Capability
Power factor control	Fixed cos(phi) setpoint	Yes
Reactive power control	Fixed Q setpoint	Yes
Voltage control	Q(U) with droop of 2 – 7 %	Yes

3.2 Technical Capabilities of Photovoltaic Power Plants

Nowadays, various PV systems exist in the European power systems, ranging from residential systems connected to the LV level, commercial/industrial systems connected to LV or MV levels and ground mounted systems connected to MV or HV level. The largest share is found for commercial PV systems and the second largest share is represented by ground-mounted PV systems, while small residential systems clearly make up the smallest share [19]. Thus, for distribution system level it is reasonable to analyze the technical capabilities of PV plants based on the requirements for MV connections.

Subsequently, various plant functionalities are evaluated based on estimations from manufacturers and developers coming from questionnaires and interviews and complemented by literature [19].

3.2.1 Reactive Power Setpoint Processing Functionality

This capability is needed to be able to receive setpoints for the selected control mode including the change of the mode. Table 4 summarizes the PVP capabilities related to the stipulated grid code requirements [17].

Table 4: Photovoltaic Power Plant Capabilities for Q Setpoint Processing Functionality

Feature	Grid Code Requirement	PVP Capability
Setpoint setting	0.95 to 1.05 pu in steps no greater than 0.01 pu	Yes
Commencement of response	Within 2 s	Yes

Rise time	1 – 5 s	Yes
Settling time	10 s	0.5 – 6 s
Steady-state reactive tolerance	±5 % of Q_{max}	Yes

3.2.2 Reactive Power Provision Functionality

Reactive power can be supplied up to certain values which are defined by PQ diagrams. Table 5 summarizes the PVP capabilities related to the stipulated grid code requirements [17].

Table 5: Photovoltaic Power Plant Capabilities for Q Provision Functionality

Feature	Grid Code Requirement	PVP Capability
Max. range of Q/P_{max} during normal operation	< 1, dependent on actual active power	Yes
Max. range of Q/P_{max} during standstill	1	Yes

3.2.3 Reactive Power Control Scheme Functionality

In order to keep the voltage at the PCC within a tolerance band, the adjustment of reactive power exchanged with the grid has to be controlled by a specified mode. Table 6 summarizes the PVP capabilities related to the stipulated grid code requirements [17].

Table 6: Photovoltaic Power Plant Capabilities for Q Control Scheme Functionality

Feature	Grid Code Requirement	WPP Capability
Power factor control	Fixed cos(phi) setpoint	Yes
	Cos(phi) as function of P	Yes
Reactive power control	Q setpoints	Yes
Voltage control	Q(U) with droop of 2 – 7 %	Yes

3.3 Strengths and Limitations of ReGen Plants for Voltage Control

To summarize the results of the previous sections and to highlight the strengths and limitations of ReGen plants for voltage control, a SWOT[2]-Analysis for both WPPs and PVPs is presented in Table 7.

[2] **S**trengths, **W**eaknesses, **O**pportunities, **T**hreats

Table 7: SWOT-Analysis for Voltage Control Capabilities of ReGen Plants [18] [19]

Category	Wind Power Plants	Photovoltaic Power Plants
Strengths	• Rise and settling times of reactive power commitment are not a critical issue, since the control on WT level can be adjusted accordingly (one second to several minutes)	• Reactive current of PV inverter can be controlled with response times in the order of milliseconds
Weaknesses	• Commencement of Q response and setpoint tracking are limited by the complete signal chain between WPP controller and WTs dependent on the communication technology • Limited PQ capability of WPPs with type 3 WTs	• No overload flexibility, hence reactive power capability is dependent on actual solar irradiation
Opportunities	• Extension of converter capabilities of type 3 WTs to enhance the PQ capability	• Enhancement of converter control to ensure reactive power provision at night
Threats	• Possible integration of damping controllers for Power System Stabilizing feature may limit the voltage control capabilities	
	• If the system is performing Q(U) control, the dynamic as well as the voltage droop is affected by the given grid impedance of the connected grid	

3.4 Technical Capabilities of ReGen Plants applied in RePlan

Based on the state-of-the-art analysis the following technical capabilities of ReGen plants for voltage control are considered in this study:

- Reactive power setpoint processing functionality: Both WPP and PVP are able to achieve a new reactive power setpoint within 1 second.
- Reactive power provision functionality: according to the PQ capability charts shown in Figure 10.

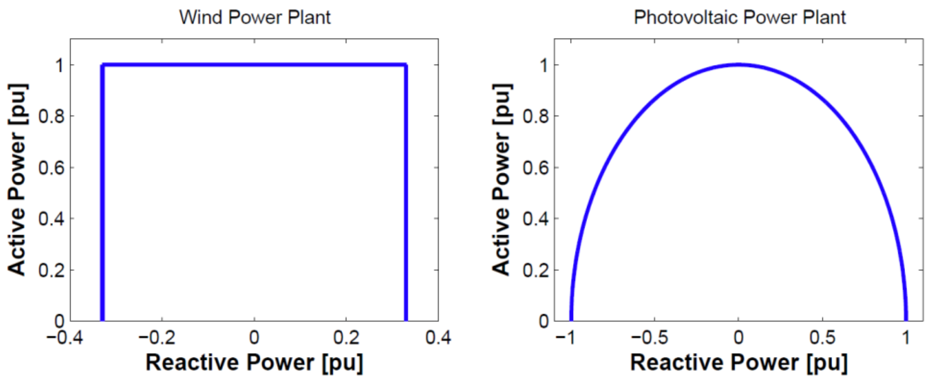


Figure 10: Reactive Power Capability charts for wind power and photovoltaic power plants [17] [18] [19]

4 System Models for Voltage Control

In this chapter the system models used in work package 2 are described. First, the model for the benchmark distribution grid is described. It will be used to perform system analyses related to voltage control of ReGen plants, i.e. for a static analysis of an exemplary distribution grid feeder (chapter 5) and the case studies for the voltage control concepts (chapter 7). Secondly, performance models for the ReGen plants are explained in this chapter. They will be used in order to verify the concepts of voltage control coordination between ReGen plants (chapter 7).

4.1 Benchmark Distribution Grid

In order to identify voltage stability challenges in distribution systems with large penetration of ReGen and to assess the voltage control functionalities developed in work package 2, a benchmark distribution grid (BDG) is developed. The BDG is based on a real MV grid operated by Himmerland Elforsyning (HEF) near Aalborg in North Jutland and it is considered as starting point for the definition of the BDG, which is described subsequently.

4.1.1 Assumptions and limitations

The following assumptions are used for definition of the BDG:

- All data used for generating the grid structure and layout are based on an existing MV grid;
- Realistic assumptions based on technical knowledge and experience are used when real data were not available;
- Aggregated historical profiles are used for generating data for loads;

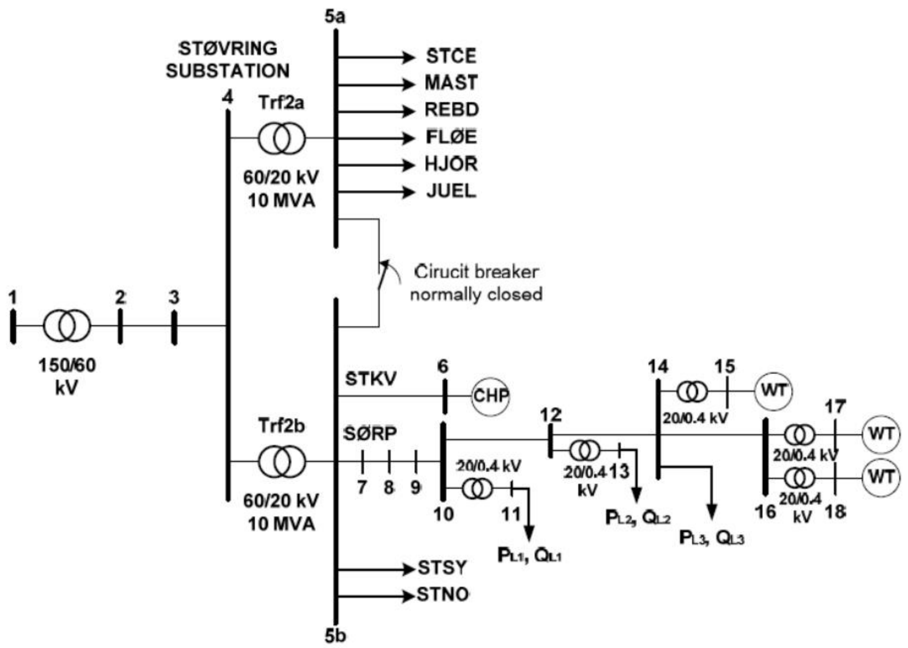
The following limitations are considered for the BDG:

- Time and geographical correlations between generation and consumption are not considered due to a relatively small area considered for the BDG. It is believed that the deviations generated by this assumption will not have an impact on the simulation results.
- Symmetrical and balanced three phase circuits are only used.
- Transients, power quality and protection issues are neglected.
- Reliability and dynamic stability in the grid operation and models are neglected.

4.1.2 Grid configuration from the benchmark area

A snapshot of the MV feeder used is shown in Figure 11.

The MV feeder comprises of 15 secondary substations distributed along the feeder and some kW wind turbines connected at the end of it. These substations have different types of loads e.g. households with or without electric heating, commercial, small and medium industry, farms/agriculture.



Network configuration of Støvring distribution system.

Figure 11: Primary Substation and MV feeder configuration from HEF grid [21]

4.1.3 Benchmark MV grid structure

The structure of the relevant BDG proposed for the RePlan project is given in Figure 12. The transformer normally supplies the simplified MV feeder connecting various loads and ReGen plants. This feeder serves as benchmark case for the radial feeder topology. The radial feeder is applied for the studies in this deliverable as being the most common topology in Danish distribution grids.

The consumers in the MV grid are represented as aggregated loads and are of following type:

- 1 supermarket
- 1-2 industrial consumers
- 3-4 commercial buildings
- 5 agricultural loads
- 133 households in the residential grid with additional demand for charging of electric vehicles

In 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 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

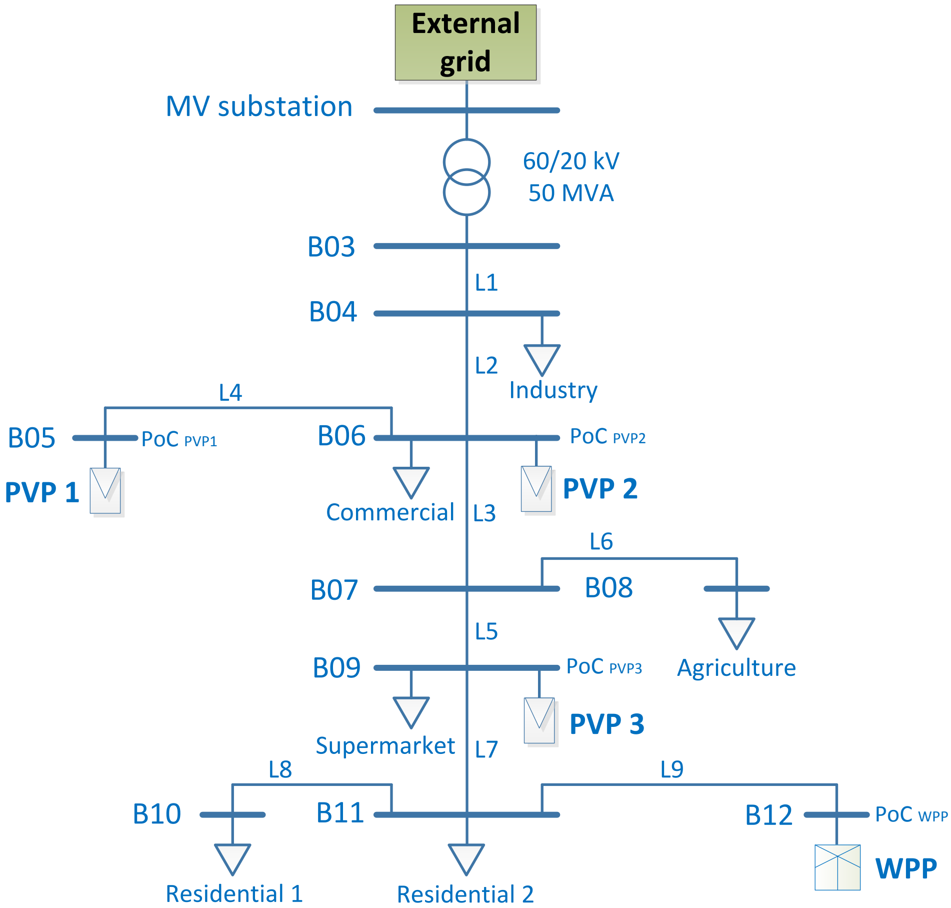


Figure 12: Structure of MV Benchmark Grid

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. Varying those parameters should be considered to reflect the ReGen integration into grids with different characteristics. E.g. a typical range of X/R ratio of DG connections is between 5 and 10.

Moreover, the internal grid characteristic can be altered to identify relevant key aspects being crucial for voltage control support by ReGen plants in DGs: Different line lengths to remotely located ReGen plants should be considered, as they affect the amount of reactive power to be provided. The placement of ReGen plants may be different depending on the geographical circumstances.

4.2 ReGen Plant Models

WP 2 aims to develop voltage control concepts for distribution systems incorporating various ReGen plants. In order to verify the concepts, performance models for ReGen plants are applied for the time domain studies in chapter 7.

4.2.1 General assumptions and limitations

The following common assumptions and limitations for the ReGen Plant models are considered:

- Aggregation of plant, i.e. internal grid and individual assets is neglected.

- Frequency bandwidth of the models is maximum 5 Hz.
- Internal control for Maximum-Power-Point-Tracking is embedded in steady state characteristics
- ReGen plant availability is not considered i.e. plant will inject active power into the grid according to available meteorological resource (wind or solar irradiation).
- Power curtailment and frequency control are not considered.
- Reactive power is considered to be controlled in Point-of-Connection (PoC) of the plant.
- Additional reactive power compensation units, e.g. capacitor banks or STATCOM devices, are considered embedded in the plant by providing the required reactive power capability in PoC for the entire plant according to grid connection requirements.
- Fault-ride through capability of the plant is not taken into account.
- Protection functionalities e.g. voltage limits, frequency limits, current limits, etc. are not taken into account.

4.2.2 Wind Power Module

A performance model for a wind power module (WPM) is depicted in Figure 13 and described in the following sections. This model is based on similar work described in [22] and [23] is developed specifically for voltage stability studies with a frequency bandwidth of the model of maximum 5 Hz. This implies that the wind time series will have a resolution of minimum 200 msec.

Block diagram

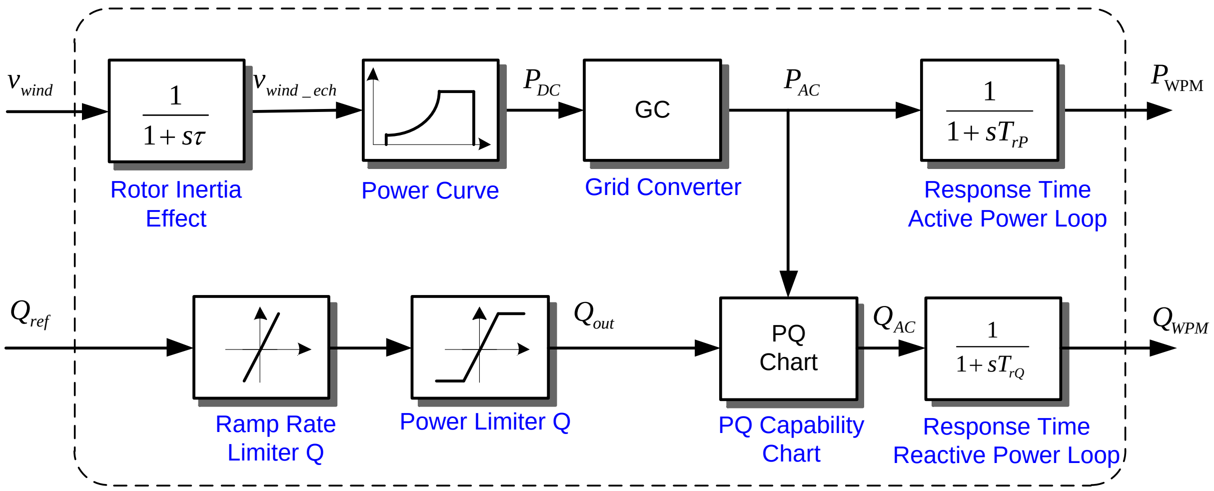


Figure 13: Block diagram of wind power module

Model Description

Rotor Inertia Effect:

Time and position variability of wind speed on the WT's rotor plane is smoothened by the rotor inertia as well as dynamic performance of the controllers. In order to capture this smoothening effect a first order filter is considered in the model. The parameters for this filter are calculated based on [23] and cross-checked with data provided in [24]. According to [23] the smoothening effect due to rotor inertia is a function of turbine mass and the blade length. This can further be correlated to the power rating of the turbine. A natural time constant τ_0 which is a measure of the response time for a wind turbine to reach rated speed from standstill is defined in [24]. Based on the data provided in [23] for MW class wind turbines this natural time constant of a MW class turbine can be expressed as a function of rated power output by:

$$\tau_0 = aP_{rated}^{b} \tag{1}$$

Where: a and b are coefficient calculated based on curve fitting using the data provided in [23].

The natural time constant for MW range is shown in Figure 14.

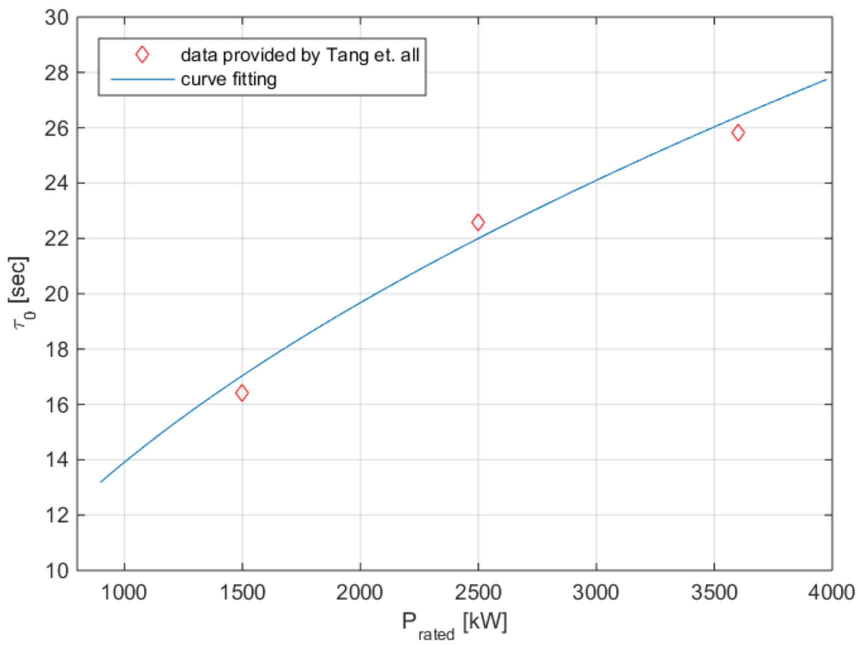


Figure 14: Natural time constant for given rated output of WT [23]

The time constant using for filtering is then defined as [23]:

$$\tau = \tau_0 \frac{v_{rated}}{v} \text{ [s]} \tag{2}$$

Where v_{rated} is rated wind speed of the wind turbine as given in specifications and v is the actual wind speed.

Power curve: The power curve is a look-up table relating the wind speed to the power production of the WPP. At low wind speeds the kinetic energy of the wind is too small to allow the turbines to produce any power so the power production is zero until the wind speed exceeds a lower threshold. For high wind speed the kinetic energy in the wind is higher than the mechanical and electrical parts of the wind plant can handle, so the power production is limited. The limited is also denoted "nominal power". Between the two limits, the power production grows with the wind speed in the third power (due to aero dynamical relations). At very high wind speeds the wind turbines will have to stop production entirely to avoid damage. The power curve will come as a one-dimensional look-up table relating wind speed and produced power and it contains all the optimized static operational points. This means that all WT controllers for speed/torque and pitch which are giving the MPPT are actually incorporated in this curve. The data provided for this look-up table are based on [25] for a 3 MW full scale power converter WT. The data in Figure 15 are normalized.

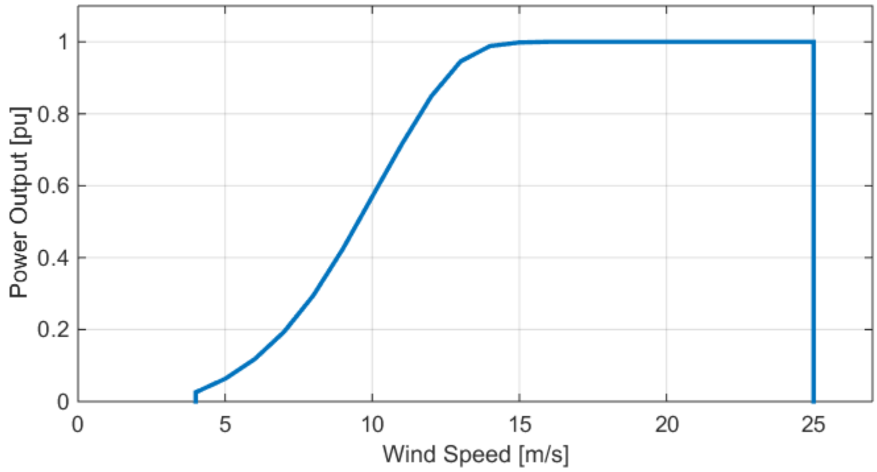


Figure 15: Power curve for 3 MW full scale converter WT [25]

Grid Converter

The grid converter is modeled as a gain and accounts for the overall efficiency of the electrical interface i.e. power converters and transformer. A value of 0.985 is considered [26].

Response Time P. The response time for the active power injected is considered in the PoC and accounts for controllers present in the active power control loop. A typical time response value of 1 second is considered according to [25].

Power Limiter Q: The reactive power reference is limited to the maximum capabilities of the plant i.e. ±0.5 pu according to [25].

Ramp Rate Limiter Q. The reactive power reference is limited in terms of ramp rates to maximum ± 20 pu/s according to [25].

PQ Chart: PQ chart characteristic for a MW wind turbine is considered as defined in Figure 10 in section 3.4. The main assumption here is that the WT/WPP is operating in active power control priority over reactive power.

Response Time Q. The response time for the reactive power injected in the grid is considered in the PoC and accounts for controllers present in the reactive power control loop. A typical value of 200 ms is considered according to [25].

Model Output. Active and Reactive power output of the Wind Power Module is in pu related to the rated power of 3 MW of the module.

4.2.3 Solar Photovoltaic Module

A performance model for a Solar PV module (SPVM) is depicted in Figure 16 and described in the following sections. This model is based on similar work described in [27] and [28] and it is developed specifically for voltage stability studies with a frequency bandwidth of the model of maximum 5 Hz. This implies that the solar irradiation time series applied to the model will have a resolution of minimum 200 msec.

Block diagram

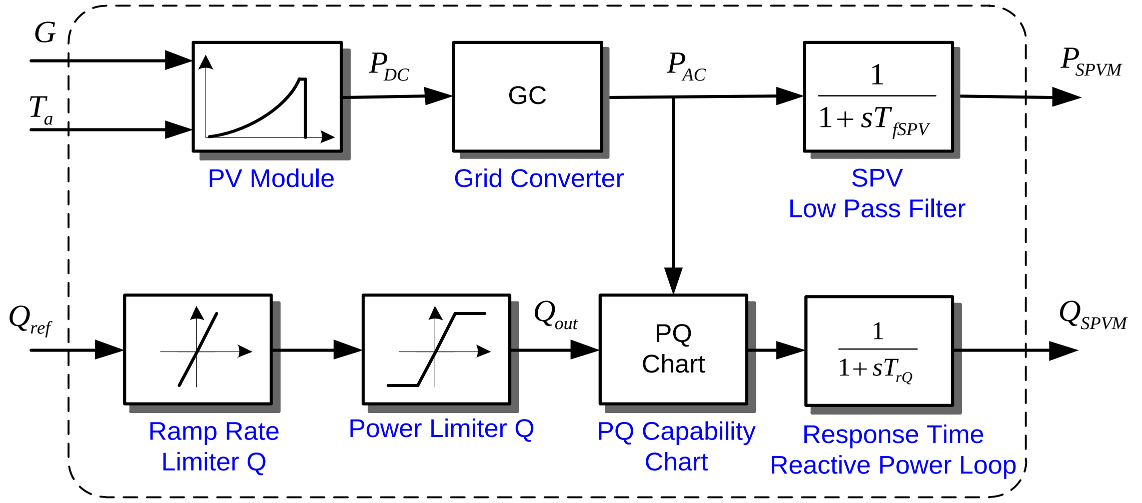


Figure 16: Block diagram of solar PV module

Model Description

PV Module: Typically the output power of a single PV module is a function of environmental temperature and solar irradiance. It is also depending on the performance of the Maximum-Power-Point-Tracking algorithm which is maximizing the power conversion between solar irradiation and electrical output of in the DC link circuit of power converter. The mathematical model of the PV Module is based on the main parameters of a real PV panel (given in datasheets), provides acceptable accuracy and it is described by [29]:

$$I = I_{sc}\left[1 - C_1\left(e^{\frac{V}{C_2 V_{oc}}} - 1\right)\right] \tag{3}$$

$$C_1 = \left(1 - \frac{I_m}{I_{sc}}\right)e^{\frac{V}{C_2 V_{oc}}} \tag{4}$$

$$C_2 = \left(\frac{V_m}{V_{oc}} - 1\right)\left[\ln\left(1 - \frac{I_m}{I_{sc}}\right)\right]^{-1} \tag{5}$$

Where

V [V] and I [A] are voltage and current of the PV Module and determine its operation point.

Voc [V] - the open circuit voltage, at different environmental conditions

Isc [A] - short circuit current, at different environmental conditions

Vm [V] . MPP voltage, at different environmental conditions

Im [A] - MPP current respectively, at different environmental conditions.

Relations between these quantities and PV parameters at Standard Test Conditions (STC) are given in Eq. (6) to (9), according to [29]:

$$V_{oc} = V'_{oc}\left[1 + c\left(T - T_{ref}\right) + \ln\left(1 + b\frac{G - G_{ref}}{G_{ref}}\right)\right] \tag{6}$$

$$V_{m} = V'_{m}\left[1 + c\left(T - T_{ref}\right) + \ln\left(1 + b\frac{G - G_{ref}}{G_{ref}}\right)\right] \tag{7}$$

$$I_{sc} = I'_{sc}\frac{G}{G_{ref}}\left[1 + a\left(T - T_{ref}\right)\right] \tag{8}$$

$$I_{m} = I'_{m}\frac{G}{G_{ref}}\left[1 + a\left(T - T_{ref}\right)\right] \tag{9}$$

V’oc [V], V’m [V], I’sc [A], I’m [A] are parameters of the PV generator in STC and are given in datasheets. The rest of the parameters of the model are given by [29]:

$a = 0.00055$, $b = 0.5$, $c = 0.00288$, $G_{ref} = 1000\ \frac{W}{m^2}$ and $T_{ref} = 298\ K$.

T [K] denotes temperature of the PV generator, which is related to the solar irradiance, Nominal Operating Cell Temperature (NOCT) and ambient temperature according to [29]:

$$T = T_a + \frac{G}{800}NOCT - 293 \tag{10}$$

Table 8: Datasheet of PV generator in STC

Rated power [Wp]	V'_m [V]	V'_{oc} [V]	I'_m [A]	I'_{sc} [A]	NOCT [K]
225	44.2	54.9	5.10	5.45	318

MPPT operation is considered using a Constant Voltage (CV) algorithm which is extracting the maximum power. The CV method is based on the fact that the voltage changes logarithmically with the solar irradiance and the voltage at maximum power is a fixed percentage from the open circuit voltage for a wide range of irradiations. As result, the MPP voltage is almost a constant percentage of the open circuit voltage, which is given by the manufacturers of the PV generator. However, this relation is not valid in partial shading conditions and operation of the CV algorithm is affected, but this aspect is irrelevant for this study.

Grid Converter

PV Module is connected to the grid converter, which emulates the power losses of a real PV inverter, multiplying the DC power with the efficiency η. It is assumed that the inverter efficiency is η=0.985 [26].

SPV Low Pass Filter

In order to correlate single point solar irradiance measurement with power out of a large PV system a low pass filter is used. The cut-off frequency of this filter is selected according to [28]. Based on different measurements campaign i.e. 2 months of 10 s data and 2 years of 10 min data from PV plant of different sizes [28] a formula for realistic estimation of the cut-off frequency $f_{cut-off}$ based on the areal of the PV plant is proposed in [27] as:

$$f_{cut-off} = aS^b \tag{11}$$

Where

a and b are coefficients determined based on curve fitting techniques using the measured data

S – is the area of the PV plant in hectares.

Using the results and procedure presented in [27] the cut-off frequency as a function of Installed capacity of the PV plant is shown in Figure Figure 17.

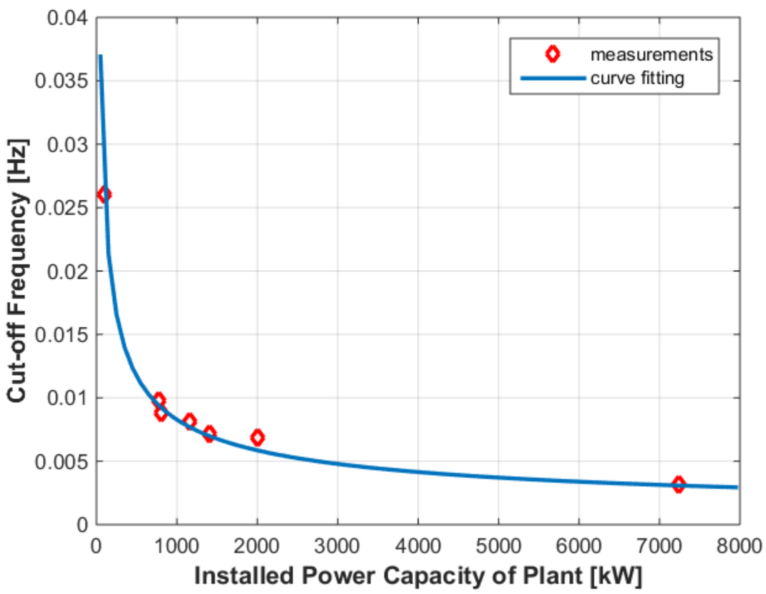


Figure 17: Cut-off frequency as function of installed PV capacity [27]

The cut-off frequency of the Low Pass Filter is calculated based on the following formula derived from [27]:

$$f_{cut-off} = aP_{installed}^b \text{ [Hz]} \tag{12}$$

Where

$a = 0.26\ and\ b = -0.499$

$P_{installed}$- is the installed power capacity of the PV plant in the Point-of-Connection in kW.

Thus the time filtering constant T_{fPVP} of the PV plant is expressed by:

$$T_{fSPV} = \frac{1}{2\pi f_{cut-off}} \text{ [s]} \tag{13}$$

The Time filtering constant accounts for:

- response time of MPPT algorithm
- response time due to electrical components such as filters, transformer, etc.
- smoothening effect due to spread of PV panels in the plant area.

Power Limiter Q: The reactive power reference is limited to the maximum capabilities of the plant i.e. ±1 pu.

Ramp Rate Limiter Q. The reactive power reference is limited in terms of ramp rates according to typical values of large power converters.

PQ Chart: Typical PQ chart characteristic for a converter based PV system as considered in Figure 10 in section 3.4 is implemented in the model. Available reactive power is calculated as a difference between the ideal available power and the actual reactive power production/consumption.

Response Time Q. The response time for the reactive power injected by PV plant in the grid is considered in the PoC and accounts for controllers present in the reactive power control loop.

Model Output. Active and Reactive power output of the Solar PV Module is in pu related to the rated power of 1 MW of the module.

4.2.4 Aggregation of ReGen Modules

In order to obtain the necessary power rating of a ReGen plant a simple aggregation technique is used.

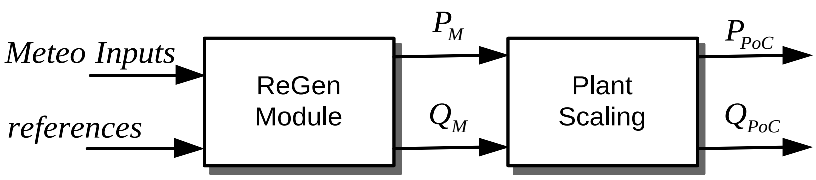


Figure 18: Aggregation of ReGen Modules

The following expressions are used to scale the module output [pu] to physical output [W] or [VAR]:

$$P_{PoC} = N_{Modules} P_{rated} P_M \quad (14)$$

$$Q_{PoC} = N_{Modules} P_{rated} Q_M \quad (15)$$

Where

$N_{Modules}$ – number of ReGen Modules connected to a given bus-bar

P_{rated} – rated power of module [W]

P_M- active power output of module [pu]

Q_M- reactive power output of module [pu]

5 Static Analysis of the System

This chapter presents a static analysis of the Benchmark Distribution Grid (BDG) described in section 4.1. Traditionally, DSOs are managing their system at the planning stage based on deterministic load flow studies in order to meet the loads demand and to verify line capacity and voltage regulation issues. With ReGen plants, as their power output fluctuates constantly, it becomes crucial to also analyze how power variations affect voltage changes in the grid. The theoretical background of such voltage sensitivity analysis is explained in this chapter. Subsequently the considered test cases and scenarios are outlined, before the results of the static analysis are presented and discussed. Finally, the outcomes are summarized and associated with controls to be developed in chapter 6.

5.1 Voltage Sensitivity Analysis

In chapter 2 it has been shown that the generation profile of ReGen plants may affect the voltage profile in the distribution system to various extents, depending on the operational point of the ReGen plants and the location within the grid. Changing system parameters has an effect on the grid voltages, where some may have significant impacts whereas others have less important impact. 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. (16) [30].

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{VP} & S_{VQ} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{16}$$

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 and we do not mind about the voltage angle values, the sensitivity matrices S_{VP} and S_{VQ} are relevant for this study as per Eq. (17).

$$\Delta V = S_{VP}\Delta P + S_{VQ}\Delta Q \tag{17}$$

The sensitivity coefficients extracted from the Jacobian matrix are <u>not</u> constant and they change with respect to the network operating point. In this regard the relevant test cases and scenarios are defined in subsequent section.

As visualized in chapter 4, the BDG includes 12 buses and the corresponding sensitivity matrices are given by Eq. (18).

$$\begin{bmatrix} \Delta V_1 \\ \vdots \\ \Delta V_{12} \end{bmatrix} = \begin{bmatrix} \frac{\delta V_1}{\delta P_1} & \cdots & \frac{\delta V_1}{\delta P_{12}} \\ \vdots & \ddots & \vdots \\ \frac{\delta V_{12}}{\delta P_1} & \cdots & \frac{\delta V_{12}}{\delta P_{12}} \end{bmatrix} \begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_{12} \end{bmatrix} + \begin{bmatrix} \frac{\delta V_1}{\delta Q_1} & \cdots & \frac{\delta V_1}{\delta Q_{12}} \\ \vdots & \ddots & \vdots \\ \frac{\delta V_{12}}{\delta Q_1} & \cdots & \frac{\delta V_{12}}{\delta Q_{12}} \end{bmatrix} \begin{bmatrix} \Delta Q_1 \\ \vdots \\ \Delta Q_{12} \end{bmatrix} \tag{18}$$

The diagonal elements represent the voltage variation at a certain bus due to a variation of active or reactive power at the same point. The non-diagonal elements describe the voltage variation at a certain bus due to the variation in active or reactive power at a different point in the grid.

Positive δV/δQ sensitivity indicates stable operation, while δV/δP can be either positive or negative and still constitute a stable grid. High sensitivity means that even small changes of active power or reactive power respectively cause relatively large changes in the voltage magnitude.

5.2 Test Cases and Scenarios

In this section the definition of test cases and scenarios for the static analysis of the BDG is outlined.

Test Cases

Following test cases are considered to account for various relevant grid configurations and their impact on voltage sensitivity indices and the voltage profile on the feeder:

The default short-circuit ratio (SCR = 10) at the DG point of connection indicates a relatively stiff external grid, while weaker grid connections can take on values down to SCR = 5. The X/R ratio of the external grid impedance depends on the components present in the transmission system and can take on values between 5 and 10. The X/R ratio of cables is generally lower than of an overhead line.

Regarding the lines within the DG, it is to be expected that long cables connected to remotely located ReGen plants, e.g. WTs in rural areas, have significant impact on the voltage profile along the feeder due to their large impedances. Line 4 (to spin-off bus 5) and line 9 (to bus 12 at the end of the feeder) have a length of 10 km each (see Figure 12), but may even longer (e.g. 20 km) than presently depending on the geographical circumstances.

The test cases are summarized as follows:

- Short-circuit ratio at connection point:
  - SCR = 10 **(SCR Base)**
  - SCR = 5 **(SCR Var)**
- X/R ratio of external grid impedance:
  - X/R = 10 **(XR Base)**
  - X/R = 5 **(XR Var)**
- Lengths of line 4 and 9:
  - L4 = L9 = 10 km **(LN Base)**
  - L4 = L9 = 20 km **(LN Var)**

Test Scenarios

Four ReGen plants (WPPs and PVPs) are placed in the BDG (see Figure 19), taking into account present cable capabilities and typical locations (WPPs and large ground-mounted PVPs are to be expected in remote rural areas, while medium sized PV systems on industrial / commercial buildings are located along the main feeder). However, in order to account for various types of ReGen plants located in the (BDG), they are referred to in generic terms such as:

- ReGen Plant 1 at bus B05
- ReGen Plant 2 at bus B06
- ReGen Plant 3 at bus B09
- ReGen Plant 4 at bus B12

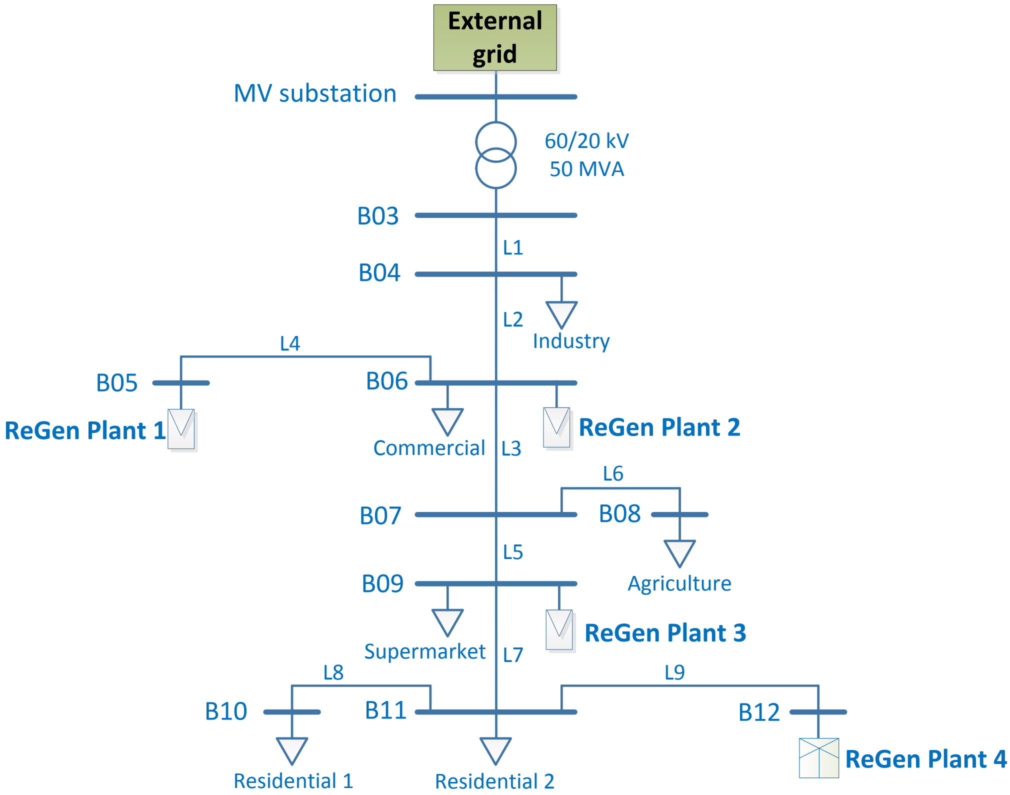


Figure 19: Structure of MV Benchmark Grid

The test scenarios according to Table 9 are considered to account for 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, assuming that there exist three PVPs (ReGen Plants 1,2,3) and one WPP at the end of the feeder. The last scenario considers no active power production.

Table 9: Test Scenarios according to operational points of ReGen Plants

Scenario	**P [pu]** ReGen Plant 1	**P [pu]** ReGen Plant 2	**P [pu]** ReGen Plant 3	**P [pu]** ReGen Plant 4
ActPow I	1	1	1	1
ActPow II	0	0	0	1
ActPow III	1	1	1	0
ActPow IV	0	0	0	0

The static analysis is performed, assuming that there is not 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 loads is not expected to vary significantly for a given BDG.

Then different voltage levels in the transmission system, which is modeled as external grid voltage in Figure 19, can be present within the permitted range of ± 5 % and thereby affecting the voltage characteristic within the distribution system. Following test scenarios are considered for the external grid voltage (Figure 12) with three different voltage setpoints:

- $V_{grid} = 0.95\ pu$ **(V 95)**
- $V_{grid} = 1.00\ pu$ **(V 100)**
- $V_{grid} = 1.05\ pu$ **(V 105)**

5.3 Results and Analysis

In this section the voltage sensitivity indices and voltage profiles obtained for the given BDG are presented and discussed. In traditional voltage sensitivity analyses those indices have been used in order to identify instable operating modes [31] or points in the network being most prone to violate the voltage limits and requiring reactive power compensation according to the corresponding δV/δQ index [32]. 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 active and reactive power changes on the voltage levels in each busbar. Thus, in the following the numbers are presented as

- percentage voltage change δV [%]
- per percentage active or reactive power change [%], based on the rated apparent power of the primary substation transformer $S_t = 50\ MVA$.

In this way, the numbers are easily relatable to the rated P-Q capabilities of the considered ReGen plants in the BDG according to Table 10.

Table 10: ReGen Capabilities based on rated power of primary substation transformer

	PVP 1	PVP 2	PVP 3	WPP
Max. P [MW]	10	2.5	2.5	18
Max. P [% of S_t]	20	5	5	36
Max. Q [Mvar]	10	2.5	2.5	6
Max. Q [% of S_t]	20	5	5	12

5.3.1 V-P Sensitivity

Figure 20 illustrates the δV/δP matrices of the BDG (see Eq. (18)) for different operational points of the ReGen plants. The external grid voltage is kept constant at $V_{grid} = 1.00\ pu$ (Scenario V100). The numbers within the color map describe how much change in voltage ΔV at bus Y will occur, when the active power will vary with $\Delta P = 1\ \%$ at a certain bus number X.

Figure 21 shows a single-line diagram of the BDG, scaled according to the line lengths and impedances of external grid and transformer. In Figure 20 it can be seen that V-P sensitivity increases with increasing distance from the primary substation (bus 3). Hence, active power variations at the end of the feeder (bus 12) will cause larger voltage fluctuations on adjacent busses than close to the primary substation (bus 2).

Moreover, it can be concluded that δV/δP of a certain bus X is highest for Y = X, meaning active power variations will cause largest voltage change on its own bus. In particular for spin-off busses (e.g. bus 5 and 8) a certain change of active power will affect the respective bus much more than the busses on the main stream of the feeder (seeFigure 21).

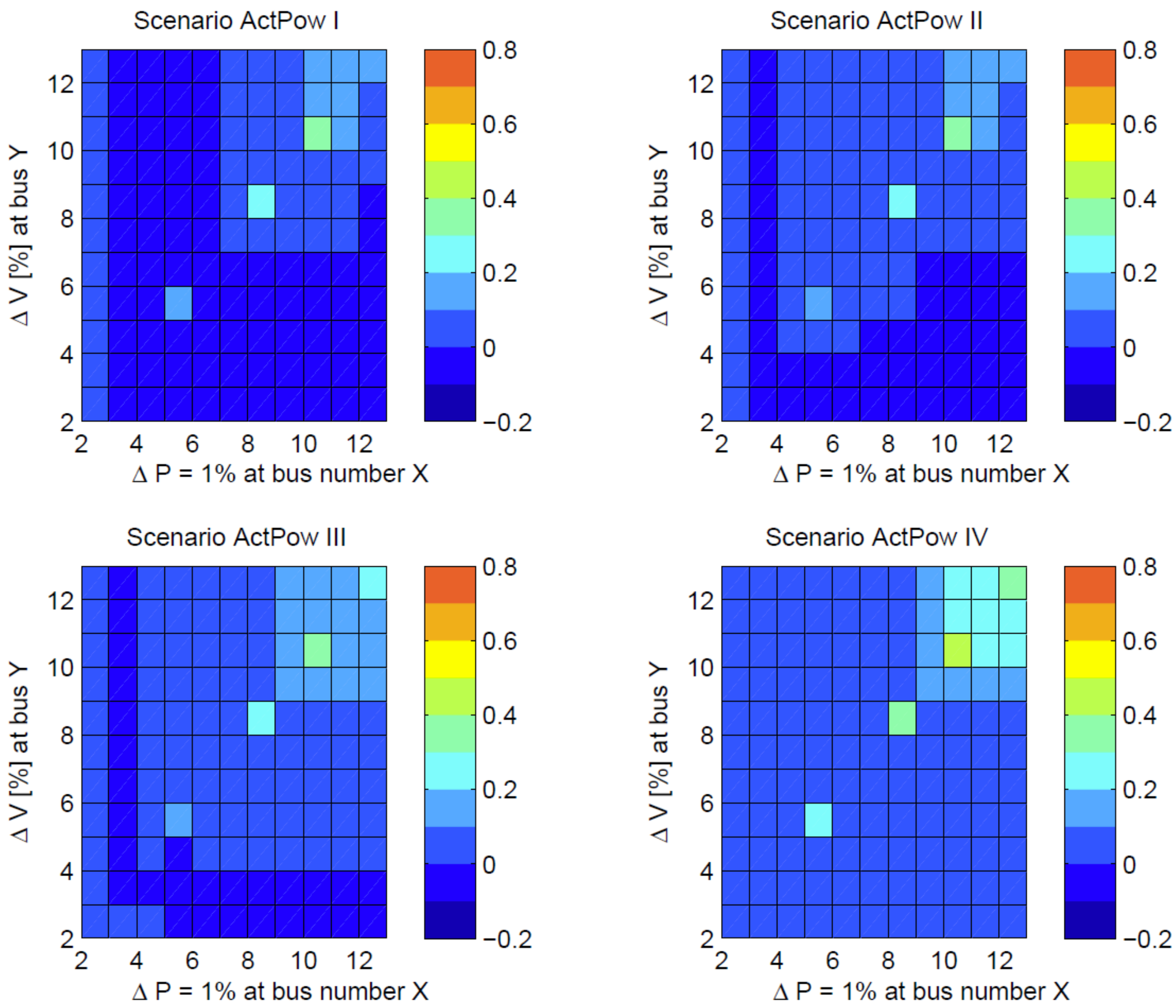


Figure 20: δV/δP sensitivity for various operational points of ReGen plants and external grid voltage $V_{EG} = 1\ pu$

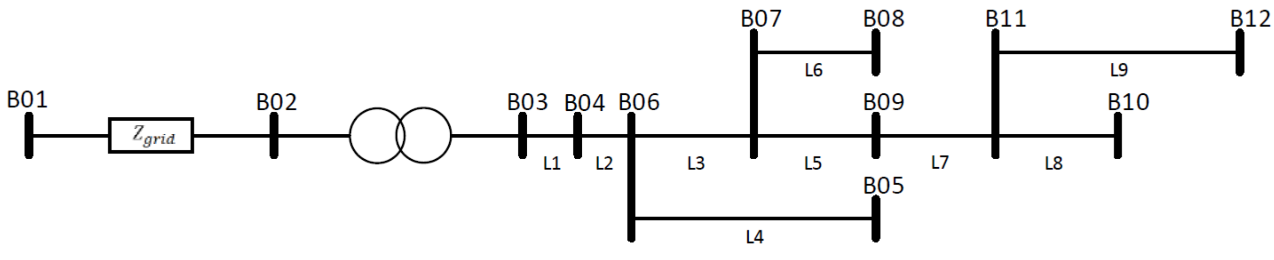


Figure 21: Scaled single-line diagram of MV Benchmark Grid

These diagonal elements of the δV/δP matrix (for X=Y) are depicted in Figure 22, where different operational points of ReGen plants (*ActPow I – IV*) are compared. By comparing the dark-blue-colored bar (full active power production) and the red-colored bar (no active power production) at each bus, it can be seen that the lower the actual active power generation along the feeder, the higher is the V-P sensitivity. For example considering scenario *ActPow IV*, where the power production from ReGen plants is zero: Now an active power increase of $\Delta P = 10\ \%$ by ReGen plant 4 would cause a voltage deviation of $\Delta V = 3\ \%$ at bus 12. On the contrary, when all ReGen plants are operating at rated power (scenario *ActPow I*), an active power change of $\Delta P = 20\ \%$ is required by ReGen plant 4 to achieve the same voltage change at bus 12. Hence, active power variations at far below nominal power of ReGen plants has much higher concern with regard to voltage fluctuations compared to operating points at high wind speed and high solar irradiation.

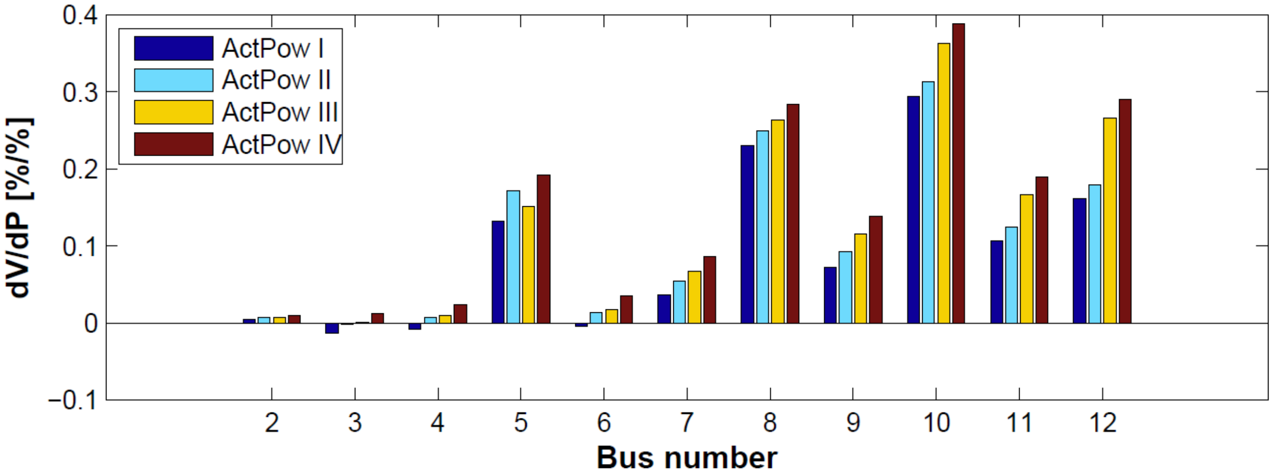


Figure 22: Diagonal elements of δV/δP sensitivity matrix for various operational points of ReGen plants

The general conclusions drawn for V-P sensitivity of the system are valid for all considered test cases.

5.3.2 V-Q Sensitivity

Figure 23 illustrates the δV/δQ matrices of the BDG (see Eq. (18)) for different operational points of the ReGen plants. By analyzing the heat map, similar conclusions can be drawn as for δV/δP in Figure 20:

- V-Q sensitivity increases with increasing distance from the primary substation.
- Moreover, δV/δQ of a certain bus X is highest for Y = X, meaning reactive power variations will cause largest voltage change on its own bus.

However, as seen in Figure 23 the off-diagonal elements at directly adjacent busses do not differ more than $0.2\ \%$ from the diagonal elements at a certain bus. This means that a certain amount of reactive power 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 Figure 24 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 ReGen plant 4 (scenarios *ActPow I & II*) the feeder exhibits a rising voltage profile with voltages exceeding the steady-state limits.

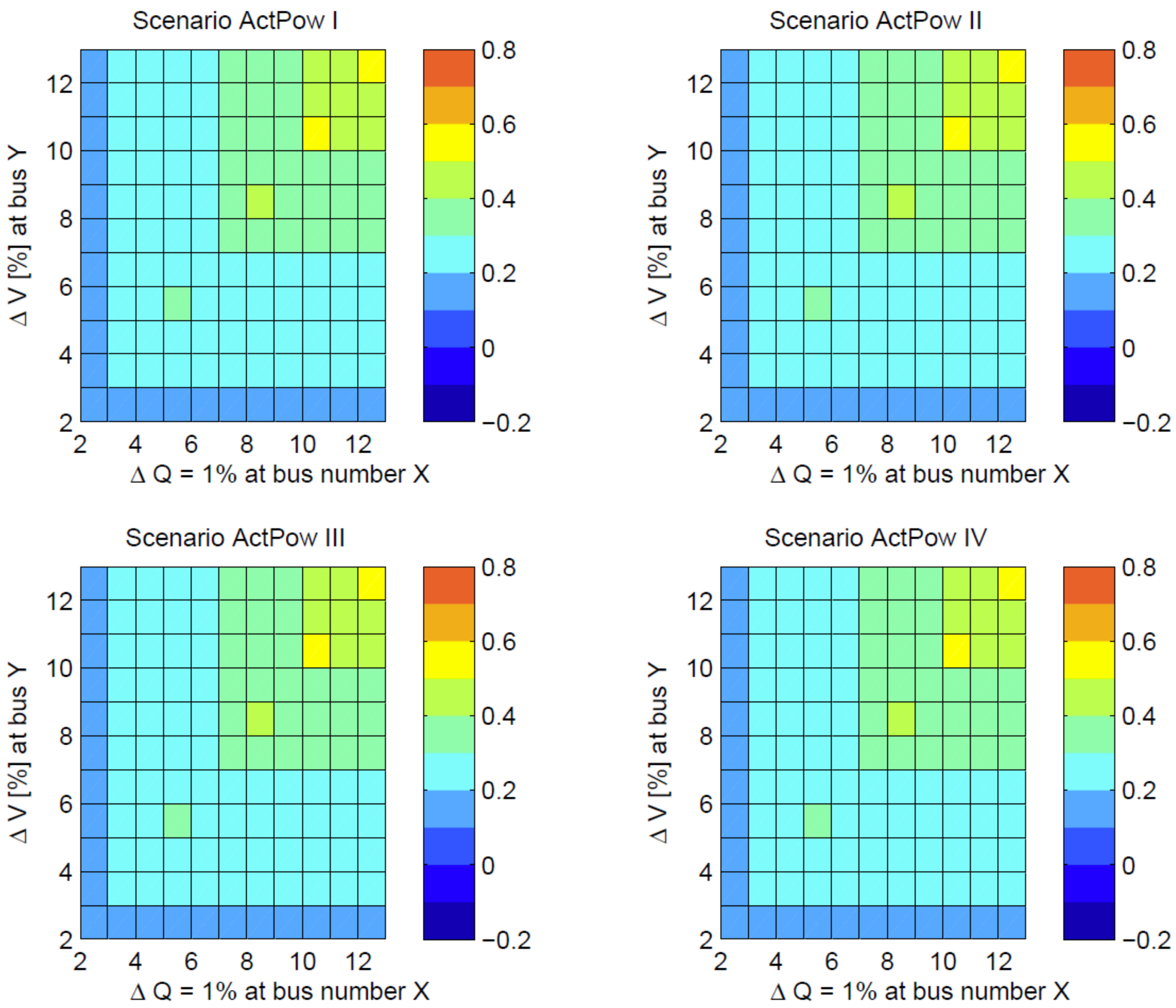


Figure 23: δV/δQ sensitivity for various operational points of ReGen plants

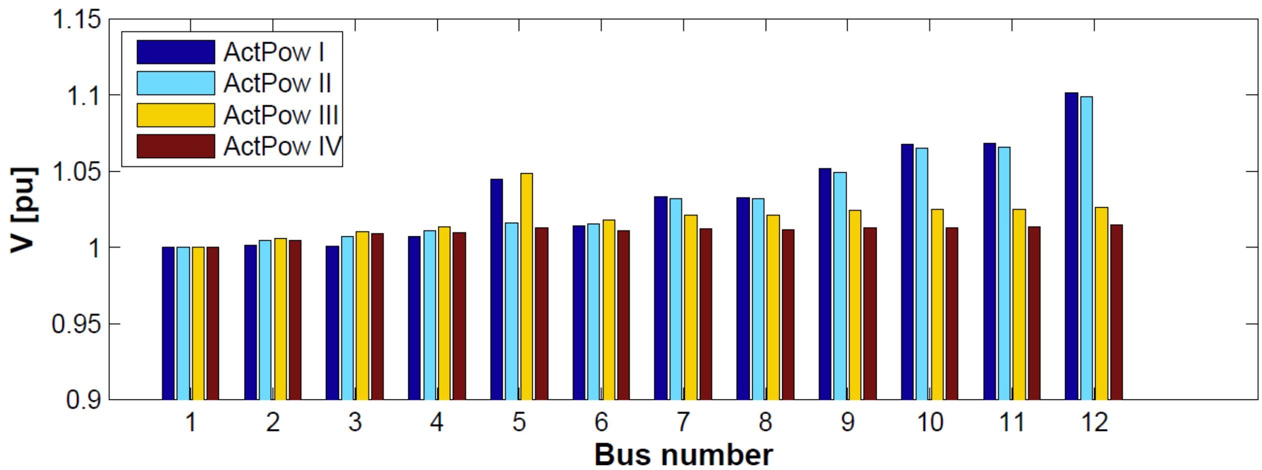


Figure 24: Voltage profile for various operational points of ReGen plants

In order to quantify the amount of voltage variation for a given change in reactive power, the diagonal elements of δV/δQ matrix are evaluated in Figure 25. As for example at bus 12, absorbing $\Delta Q = -10\ \%$ would improve its own bus voltage by approximately $\Delta V = -5\ \%$. At bus 6 the corresponding bus voltage would be reduced by only $\Delta V = -2.5\ \%$ with the same amount of reactive power absorption at this bus.

Now by comparing various test scenarios in Figure 25 and Figure 26, it can be concluded that δV/δQ indices do not vary significantly; neither for different operational points of the ReGen plants (Figure 25) nor for various operational points of the external grid (Figure 26). The bottom graphs respectively show that the maximum deviation amounts to $\Delta \frac{dV_{10}}{dQ_{10}} = 1.4\ \%$ 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 chapter 6.

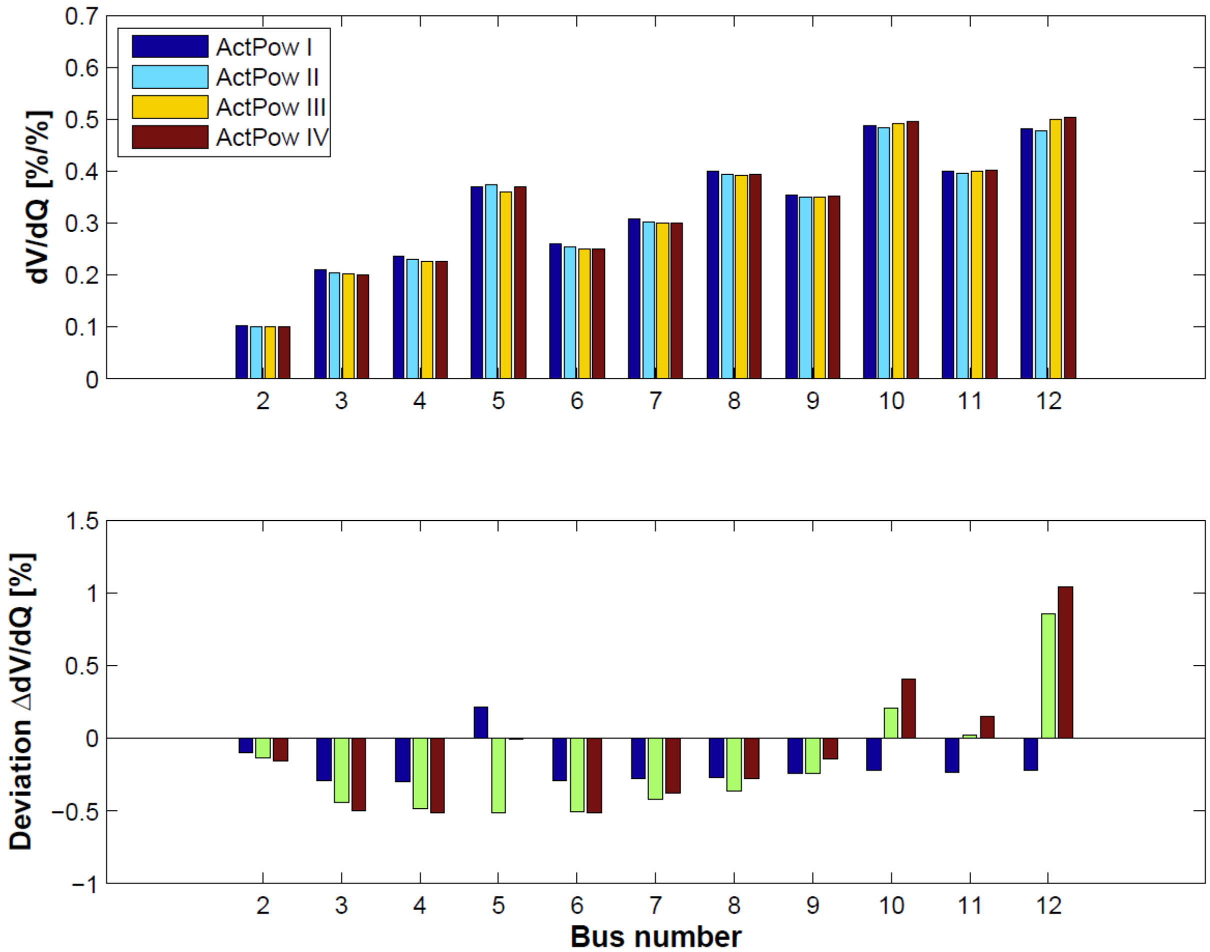


Figure 25: Diagonal elements of δV/δQ sensitivity matrix for various operational points of ReGen plants

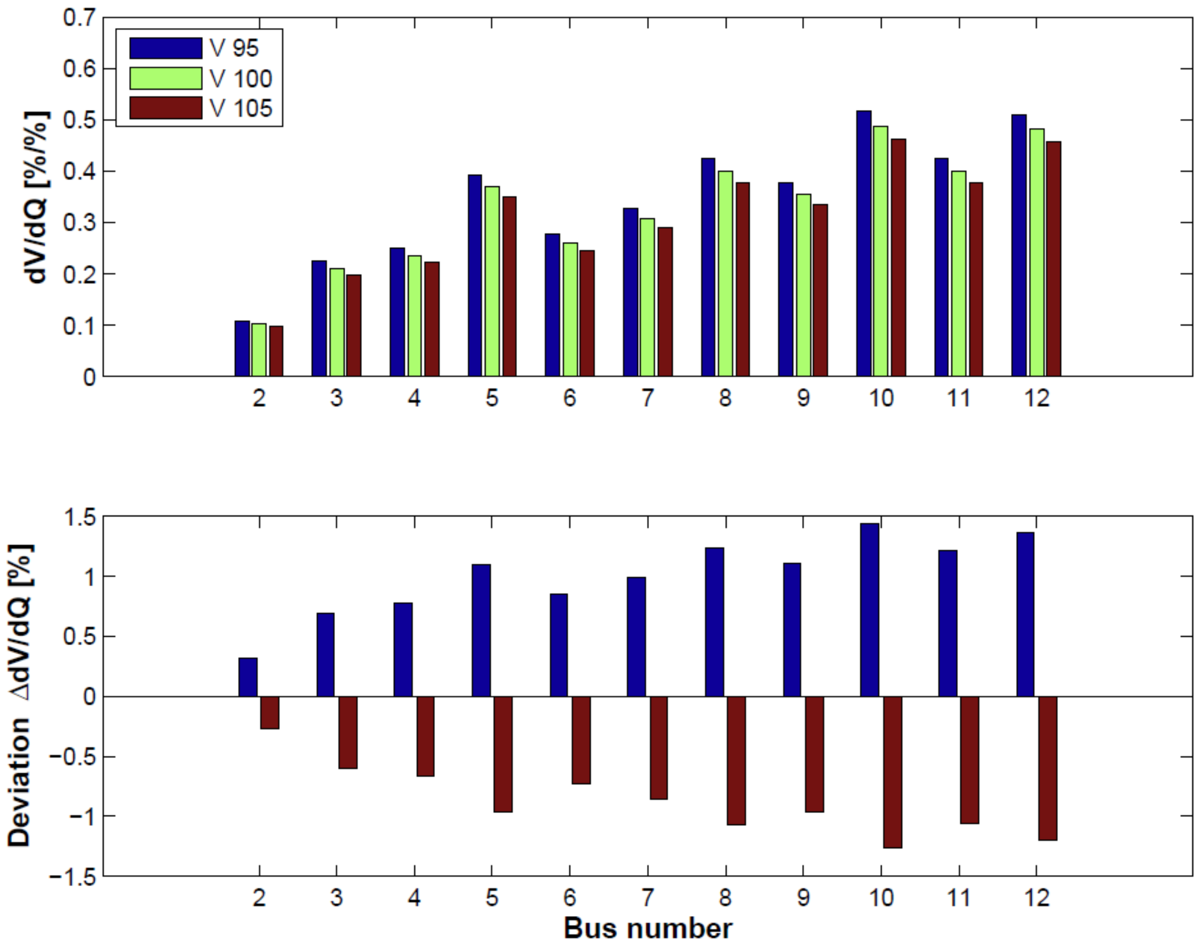


Figure 26: Diagonal elements of δV/δQ sensitivity matrix for various operational points of external grid

However, as we are concerned about reactive power provision for voltage control, it is essential for V-Q sensitivity to evaluate the impact of various grid configurations, i.e. the different test cases in scope.

Figure 27 compares two cases (*LN Base* & *LN Var*) for different line lengths of L4 and L9. It can be observed that δV/δQ indices increase significantly at bus 5 and 12, when their directly adjacent lines are extended. The deviations between base case and modified case ($\Delta\frac{dV_5}{dQ_5} = 5.2\ \%$ and $\Delta\frac{dV_{12}}{dQ_{12}} = 4.5\ \%$) are larger than in previous figures. It implies that the line length and hence parameters play a major role with regard to δV/δQ indices of the system. ***Voltage regulation at remote busses with long cable connections (rural areas) is more sensitive than at busses in close proximity to the primary substation (urban areas).***

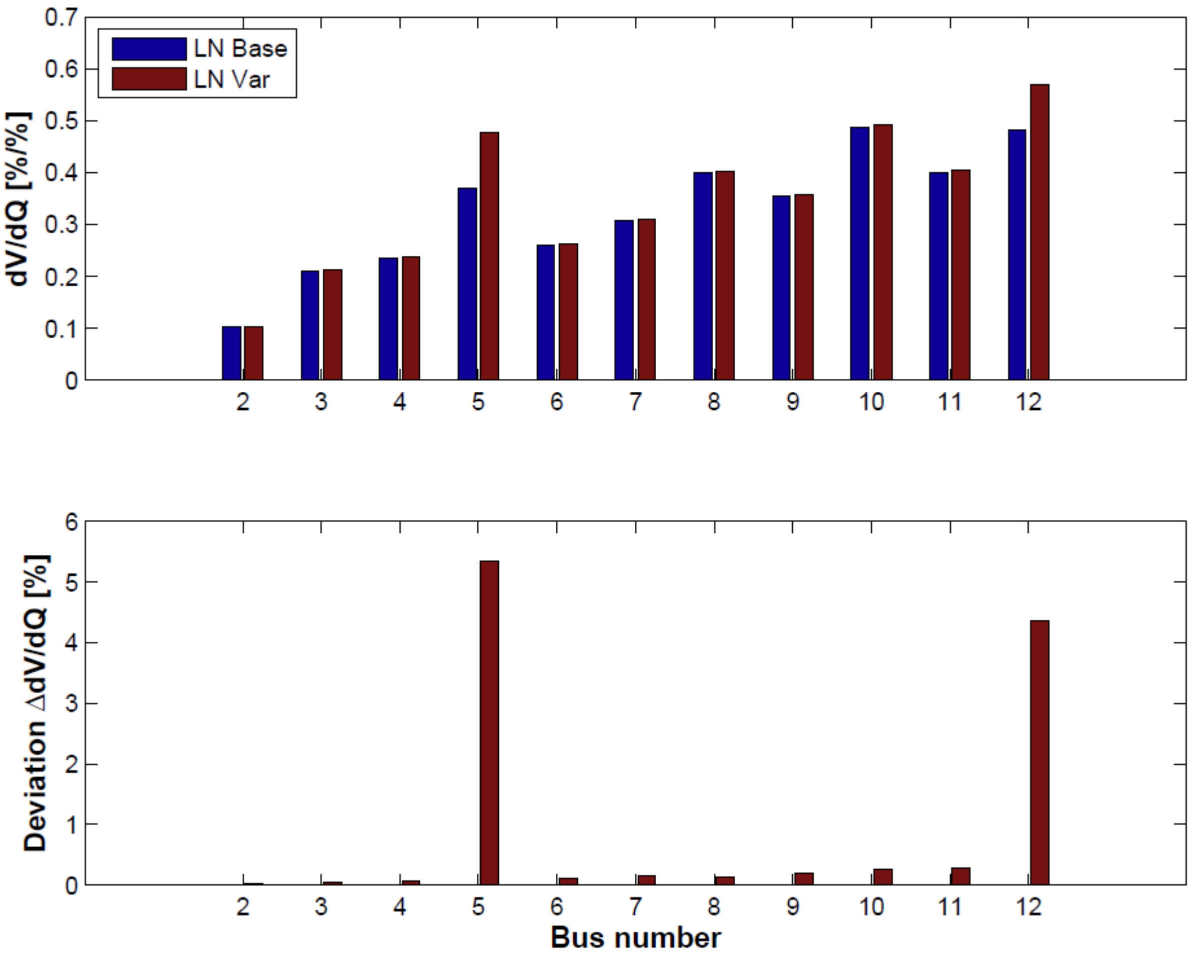


Figure 27: Diagonal elements of δV/δQ sensitivity matrix for different line lengths

By looking at the voltage profile for both test cases *LN Base* and *LN Var* in Figure 28 it can be seen that the voltages at bus 5 and 12 rise significantly, which is due to the increased resistance of the adjacent lines in combination with the power infeed from ReGen plant 1 and 4. As described by Eq. (19), the voltage difference between bus i and j is determined by the product of power flow and coupling resistance as well as the product of reactive power flow and coupling reactance [33].

$$\Delta V_{ij} = V_i - V_j \approx \frac{R_{ij}P_{ij} + X_{ij}Q_{ij}}{V_i} \tag{19}$$

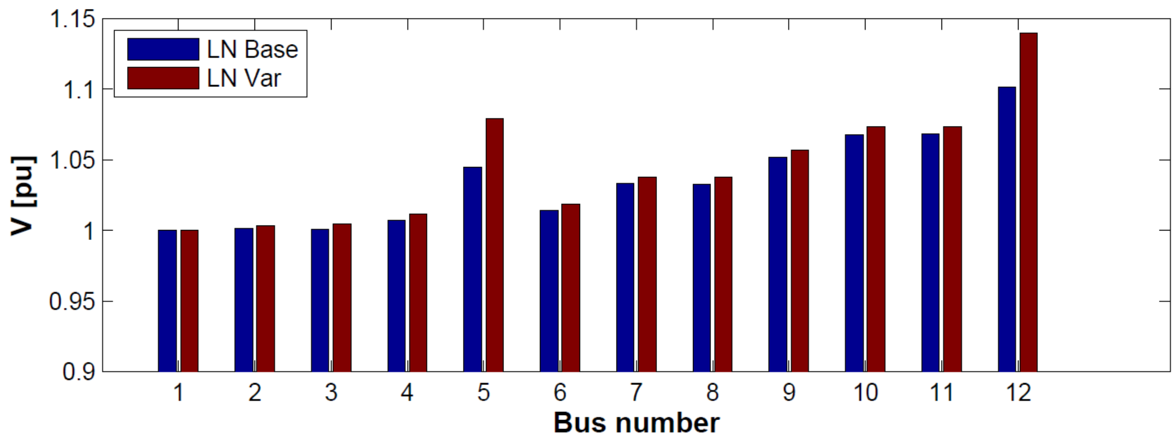


Figure 28: Voltage profile for different line lengths

Figure 29 and Figure 30 compare V-Q sensitivity for different X/R ratios (*XR Base* & *XR Var*) and different SCR of the external grid (*SCR Base* & *SCR Var*). It can be concluded that variations in X/R ratio do not affect the δV/δQ indices of the system, the maximum deviation amounts to $\Delta \frac{dV_{10}}{dQ_{10}} = -0.22\ \%$. On the other hand, lowering the SCR from 10 to 5 will lead to significant increase of δV/δQ indices at all busses by $\Delta \frac{dV}{dQ} = 6\ \%$.

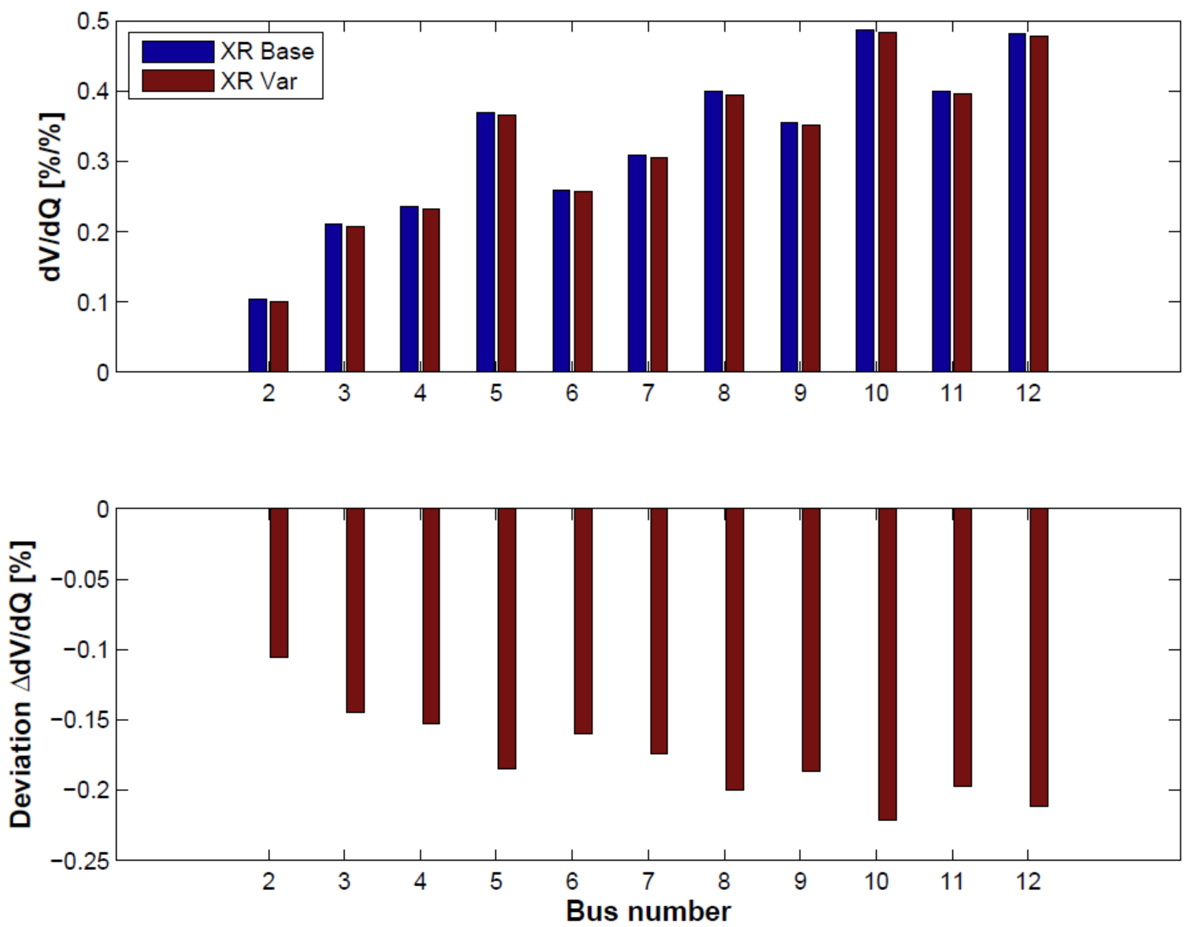


Figure 29: Diagonal elements of δV/δQ sensitivity matrix for different X/R ratios

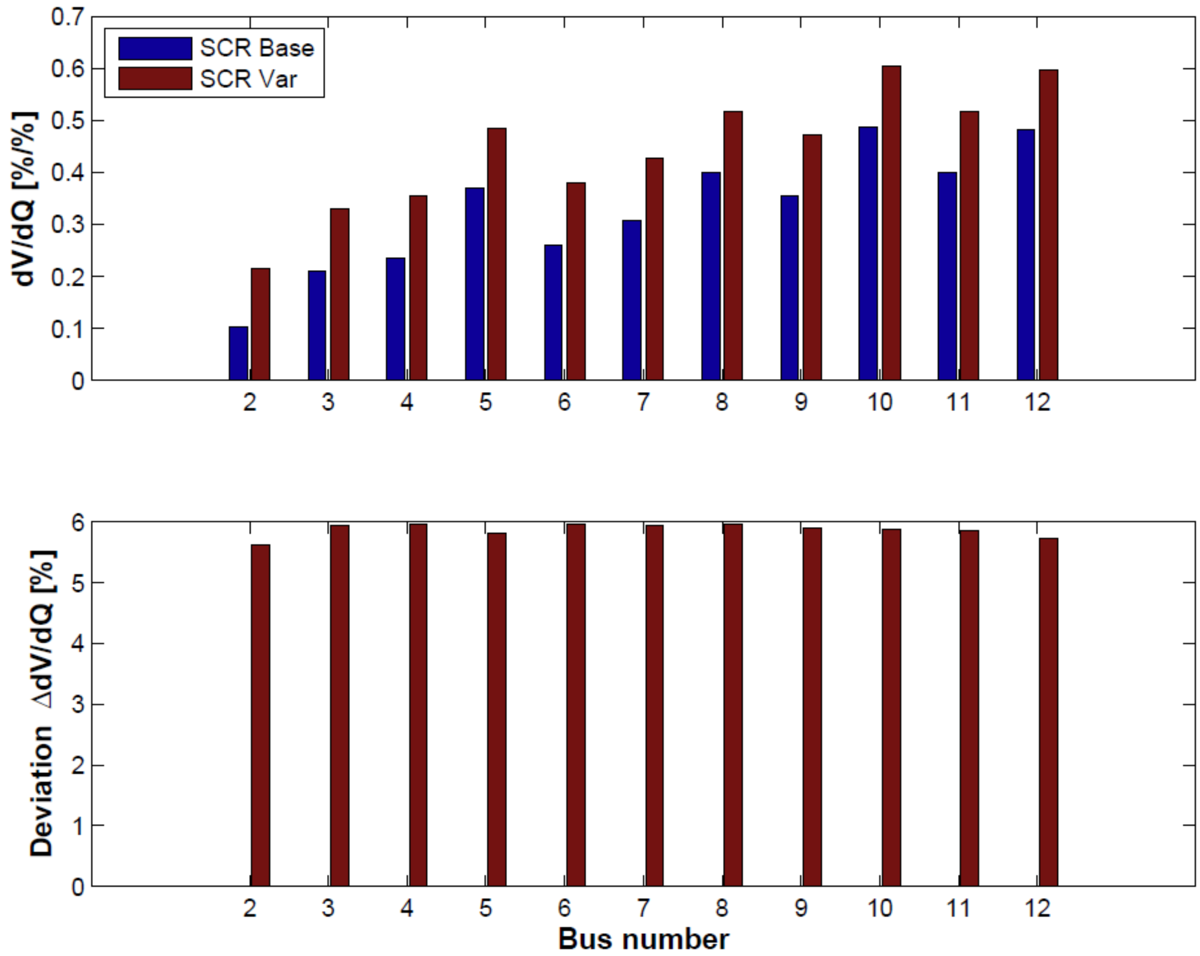


Figure 30: Diagonal elements of δV/δQ sensitivity matrix for different SCR

However, by looking at Figure 31 the voltage profile remains almost unchanged for modifying the grid stiffness.

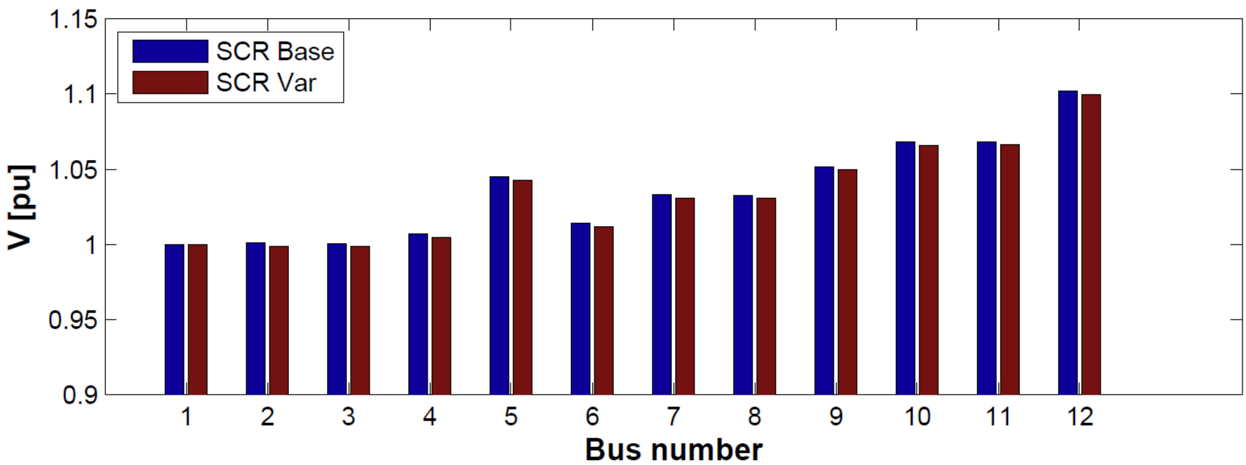


Figure 31: Voltage profile for different SCR

This means that ***weaker grid connections (low SCR) do not necessarily cause more considerable voltage stability challenges in distribution systems than stiffer grid connections (high SCR), but on the contrary give rise to more efficient voltage regulation by increased V-Q sensitivity***.

5.4 Summary

This chapter has presented a static evaluation of the BDG by means of load flow and voltage sensitivity analysis.

V-P sensitivity analysis has revealed some generic findings to quantify the expected voltage fluctuations due to active power infeed by ReGen plants, being dependent on both the location in the grid and the operational conditions of ReGen plants.

Analysing V-Q sensitivity has shown that ***operational conditions do not affect the δV/δQ indices considerably***. However, the various test cases evaluating different grid configurations have demonstrated that ***grid characteristics such as cable lengths and short-circuit ratio play a major role for the V-Q sensitivity at a certain bus***. The δV/δQ parameters express to which extent voltage changes due to a deviation of reactive power provision. This coherence is essentially applicable to a typical voltage droop control function with Q(V). Hence, the results of this chapter are considered for the development of voltage control concepts, described in following chapter.

Those control concepts will require thorough verification by applying relevant study cases for the BDG. Figure 32 summarizes the load flow results for all considered test cases and scenarios of the static analysis by illustrating the extreme voltage level of the feeder respectively. It can be seen that significant voltage challenges arise for high wind and solar irradiation (*ActPow I*) under grid voltages between 1 and 1.05 pu. ***The basic configuration (SCR Base, XR Base, LN Base) according to the BDG described in section 4.1 is sufficient to evaluate voltage control concepts being developed to counteract those challenges***.

			ActPow I			ActPow II			ActPow III			ActPow IV		
			V95	V100	V105	V95	V100	V105	V95	V100	V105	V95	V100	V105
SCR Base	XR Base	LN Base	1.05	1.10	1.15	1.05	1.10	1.15	1.00	1.05	1.10	0.96	1.01	1.07
		LN Var	1.09	1.14	1.19	1.09	1.14	1.19	1.03	1.08	1.13	0.97	1.03	1.08
	XR Var	LN Base	1.06	1.11	1.16	1.05	1.10	1.15	1.00	1.05	1.10	0.96	1.01	1.07
		LN Var	1.10	1.15	1.19	1.09	1.14	1.19	1.04	1.09	1.14	0.97	1.03	1.08
SCR Var	XR Base	LN Base	1.05	1.10	1.15	1.05	1.10	1.15	1.00	1.05	1.10	0.97	1.02	1.07
		LN Var	1.09	1.14	1.19	1.09	1.14	1.19	1.04	1.09	1.14	0.98	1.03	1.09
	XR Var	LN Base	1.06	1.11	1.16	1.06	1.11	1.16	1.01	1.06	1.11	0.97	1.02	1.07
		LN Var	1.10	1.15	1.20	1.10	1.15	1.20	1.05	1.10	1.15	0.98	1.03	1.09

0.95 ≤ V < 1.05   1.05 ≤ V < 1.10   V ≥ 1.10

Figure 32: Highest voltage on the feeder for all test cases and scenarios

6 Development of Voltage Control Concepts

In this chapter voltage control concepts are developed, taking into account the results of the static analysis in chapter 5. The architectures of the voltage control concepts will be represented respectively.
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 [34]. 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 generation unit operating in Q control mode receives a reference for reactive power, while in voltage control mode a voltage setpoint is provided.

In this context the following definitions will be used for ReGen units:

ReGen Asset – is a renewable generation unit consisting of a Solar PV system, individual wind turbines or a wind power plant which has only an inner control loop for regulating the reactive power in PoC. A ReGen Asset is receiving a reference for reactive power and may provide as feedback signals to upper hierarchical layers e.g. power production, voltage measurements, available reactive power, etc. A schematic of this is shown in Figure 33.

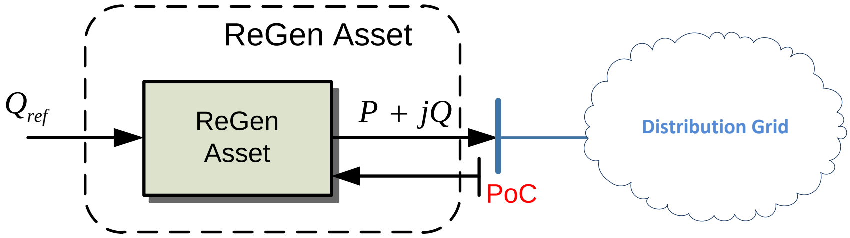


Figure 33: ReGen Asset

ReGen Plant – is a renewable generation plant consisting of Solar PV systems, individual wind turbines or a wind power plant that has:

- an inner control loop for controlling the reactive power injected into PoC
- an outer voltage control loop aiming to regulate the voltage in PoC. A typical droop controller is considered.

A ReGen Plant may receive reference for voltage and droop values and may provide as feedback signals to upper hierarchical layers e.g. power production, voltage measurements, available reactive power, etc. The schematic is depicted in Figure 34.

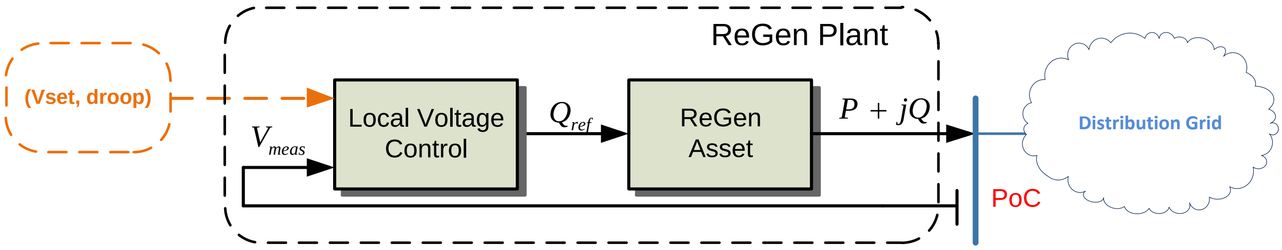


Figure 34: ReGen Plant

6.1 Control Concept 1 – Manual Droop Setting

According to ENTSO-E GC [34] 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 droop settings** for voltage control. 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 (Figure 35) does not require any control coordination and local voltage regulation will be entirely dedicated to the individual ReGen plants.

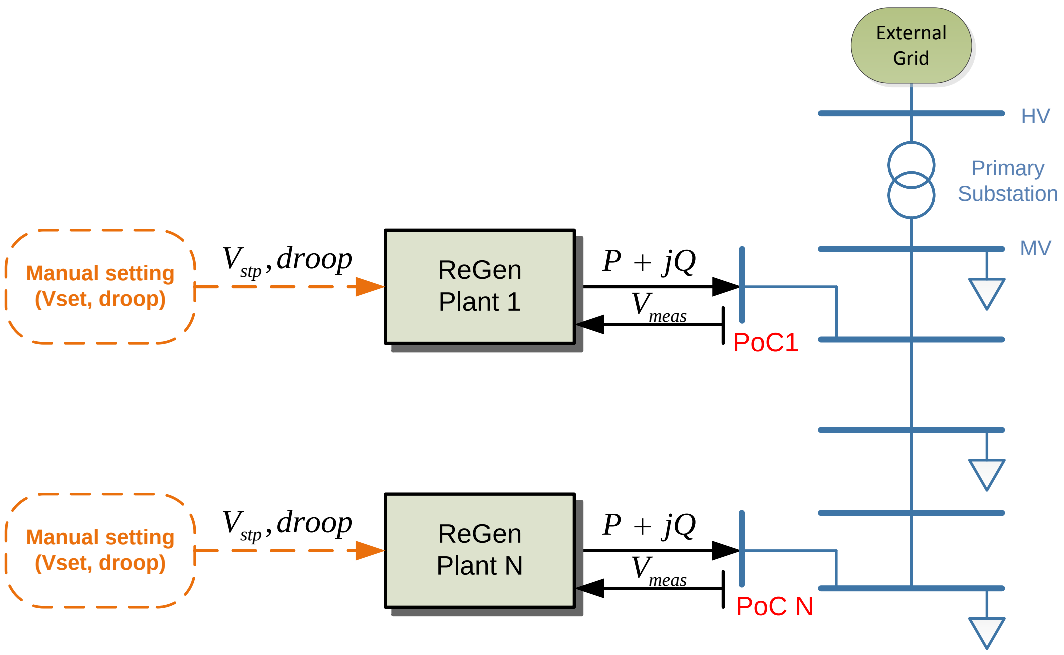


Figure 35: Scheme of control concept 1 – Manual Droop Setting

Responsibility	• DSO
Requirements	• Recommended value range from GC • Update rate: > month/year
Procedure	• Select arbitrary voltage setpoints: default 1 pu • Select a droop value according to GCs
Data exchange	none
Drawbacks	• Settings provided during commissioning phase or activation of voltage control capability may not reflect penetration of ReGen assets, changes in loads, etc. • Specific settings may lead to control instabilities

	• DSOs are not keeping track of settings and/or changes • May lead to increase of grid losses

6.2 Control Concept 2 – Distributed Off-Line Coordination

This control concept is referred to as **Distributed Off-Line Coordination** and illustrated in Figure 36.

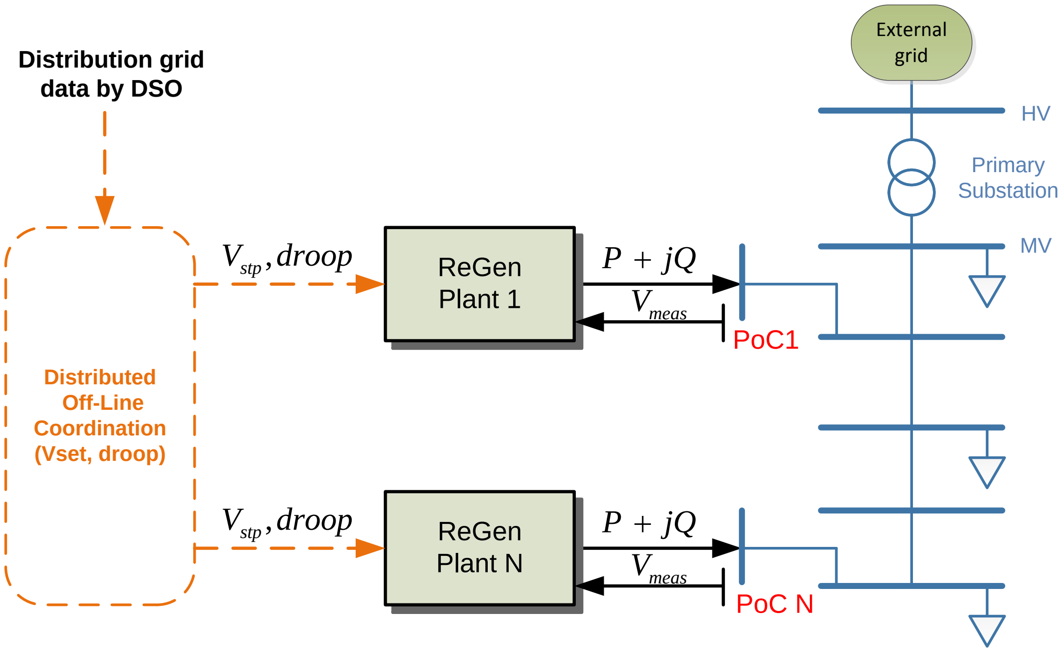


Figure 36: Scheme of control concept 2 - Distributed Off-Line Coordination

For a given feeder where several ReGen plants are installed a voltage sensitivity analysis is performed as per chapter 5. By using the derived droop values, each settings in ReGen plant are manually introduced by an aggregator of grid support services. 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 previous chapter, 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. Figure 37 shows the inverse elements of Figure 25, i.e. δQ/δV indices instead of δV/δQ 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.

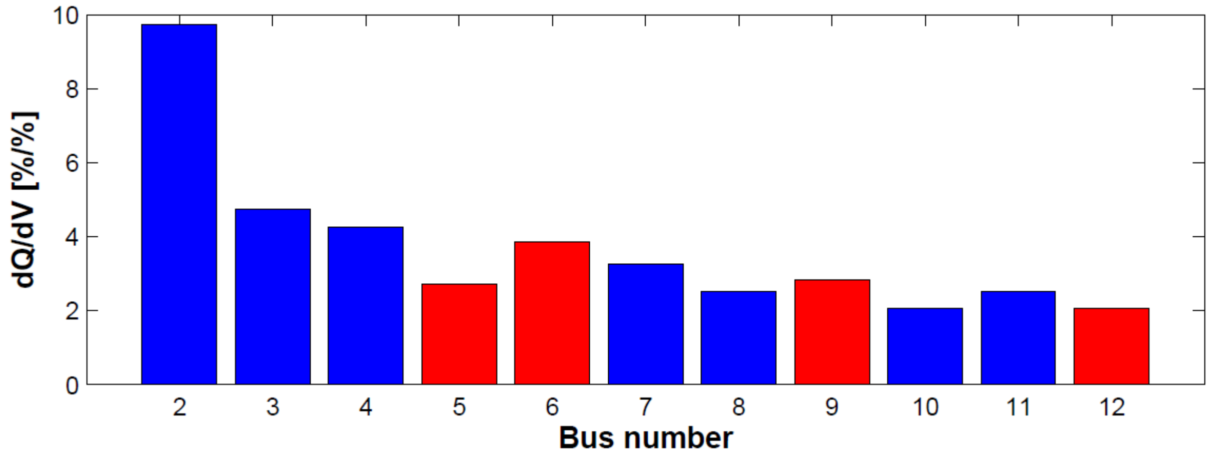


Figure 37: δQ/δV sensitivity at all system busses

Now, provided a certain bus X exhibits a voltage deviation (e.g. by power fluctuations), the numbers in Figure 37 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 5.3 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. (20), where the actual value of percentage droop is defined according to the grid code [34]. Q_{max} is the maximum reactive power capability of a ReGen plant respectively.

$$droop = \frac{dV}{dQ} \cdot Q_{max} \tag{20}$$

The results are summarized in Table 11.

Table 11: Droop settings for ReGen plants

	ReGen plant 1	**ReGen plant 2**	**ReGen plant 3**	**ReGen plant 4**
δV/δQ sensitivity [% / % of S_t]	0.3694	0.2596	0.3545	0.4823
δQ/δV sensitivity [% of S_t / %]	2.7070	3.8517	2.8206	2.0734
Max. Q [% of S_t]	20	5	5	12
V(Q) droop [%] acc. to GC	**7.39**	**1.30**	**1.77**	**5.79**

As ascertained in section 5.3, 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 chapter 5 is necessary to calculate the respective V(Q)-droop parameters for the ReGen plants.

Responsibility	• Aggregator
Requirements	• Detailed topology and parameters for MV feeders • Update rate: when necessary
Procedure	• Computation of Jacobian matrices • Voltage sensitivity analysis • Derivation of voltage droop values that will cover a wide range of scenarios • Select arbitrary voltage setpoints: default 1 pu
Data exchange	none
Drawbacks	• Any changes in grid topology, power generation units and loads may lead to an update of the settings • Initial scenarios may not cover all operational ranges • ReGen plants may not contribute considerably to voltage control, if their bus voltages are around nominal value • May lead to increase of grid losses

6.3 Control Concept 3 – Distributed On-Line Coordination

This proposed control concept is characterized by real-time coordination of the local voltage controllers by using available measurements in the grid. The scheme of **Distributed On-Line Coordination** control is shown in Figure 38.

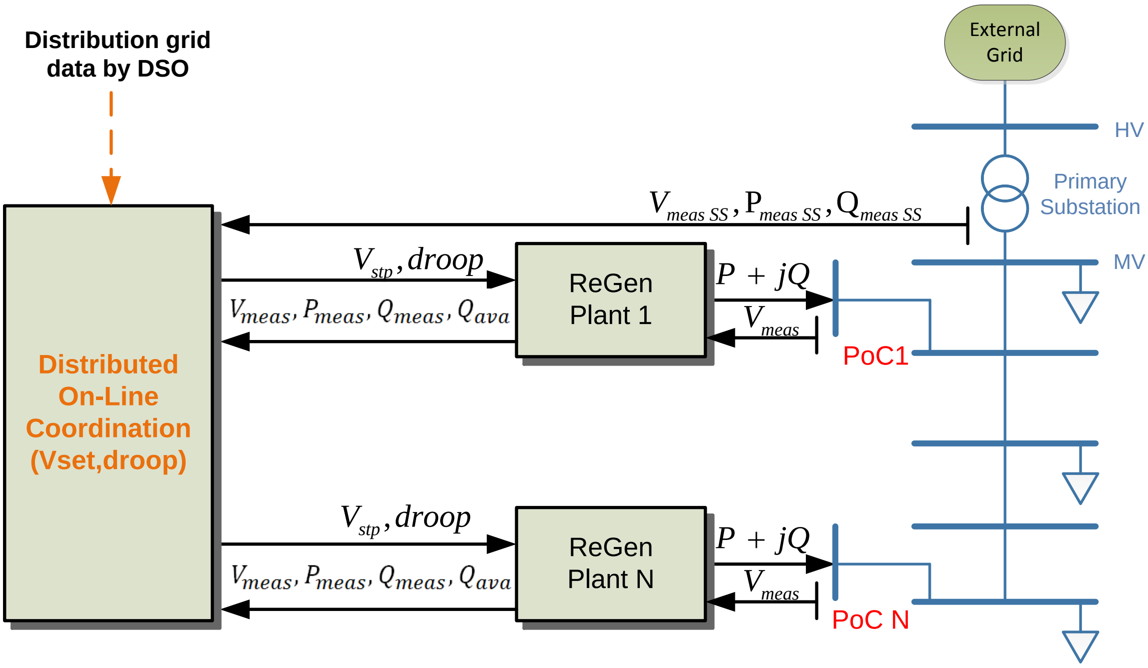


Figure 38: Scheme of control concept 3 - Distributed On-Line Coordination

Real-time information can only be provided for locations in the grid, where measuring devices are installed. As per GC requirement ReGen Plants need to provide signals such as active power production, reactive power availability and voltage at the connection point [35]. The DSO normally has available voltage and current measurements from the primary substation (MV or HV side). Those signals can be used for advanced coordination of the individual voltage droop settings of the ReGen Plants.

One reason for doing so is that off-line coordination of droop settings does not consider the actual operating points of the ReGen Plants. It has been ascertained that V-Q sensitivity does not depend on actual active power production (P) of the plants. However, it can be expected that the actual reactive power (Q) operating point will alter the δV/δQ indices and therefore the optimal droop settings to be derived. An on-line voltage sensitivity analysis can be performed to update the droop settings.

Another concern of using real-time information for coordinating voltage controls is related to the voltage dependent reactive power provision Q(V). Since droop control uses local voltage information, the amount of reactive power from the ReGen Plants will be proportional to the voltages measured at the local points. If now the local voltage does not deviate considerably from the setpoint of 1 pu, for none of the operating points of the ReGen Plant, not even at rated power output, this particular ReGen Plant will not give a significant contribution to reactive power support on the feeder at any time. This phenomenon can be shown by means of the analyzed BDG: From Figure 24 in section 5.3 it can be seen that the voltage at the connection point of ReGen Plant 2 (Bus 6) amounts to $V = 1.01\,pu$, for the worst case when all ReGen Plants feed in maximum active power. This voltage deviation of 1 % would enable ReGen Plant 2 to absorb only $Q = 0.25\,\%$, although it has the capability of providing $Q_{max} = 5\,\%$ (see Table 11). A method to achieve more reactive power support by the ReGen Plants may be realized by altering the voltage setpoint V_{stp} in the PoC.

On the other hand, reactive power provision may increase the losses within the grid by increasing the current loading of the lines. Hence, in situations where the voltage profiles are well within the tolerance band margins of ± 10 %, reactive power support by ReGen plants is not required. One approach to reduce the reactive power loading of the distribution grid is to adjust the voltage setpoint at each ReGen plant according to the prevailing voltage profile within the grid. This method is further specified in chapter 8.

Responsibility	• Aggregator
Requirements	• Detailed topology and parameters for MV feeders • On-line data exchange • Update rate: Periodical task in a controller (seconds / minutes) • Signal Processing of feedbacks from ReGen plants (filtering)
Procedures	For updating droop values: • Computation of Jacobian matrices for last operating point (averaging measurements over seconds / minutes) • Voltage sensitivity analysis • Derivation of voltage droop values For updating voltage setpoint: • Determine voltage setpoint with respect to the control objective, i.e. achieving more or less reactive power support by ReGen plants
Data exchange	• Voltage and power measurements from Primary Substation (MV or HV side) → DSO link

	• ReGen Plant: power production, reactive power availability, voltage measurements in PoC
Drawbacks	• Missing data may affect the control algorithm

6.4 Summary

The developed control concepts are summarized and evaluated according to following table:

Control Concept	Required system studies	Required measurements	ICT demand	Overall difficulty level for imple-mentation by Aggregator
1 – Manual Droop Setting	-	+	-	-
2 – Distributed Off-Line Coordination	++	+	-	+
3 – Distributed On-Line Coordination	++	++	+	++

7 Time Domain Analysis for Off-Line Coordination

In this chapter time domain analyses are performed in order to test two concepts for off-line coordination of voltage control (Control Concept 1 and 2), as developed in chapter 6. The system models described in chapter 4 are used to analyze voltage control in time domain for a volatile power profile of the ReGen plants, used as a benchmark test scenario that covers the crucial operating points with high solar irradiation and high wind speed. The ReGen plants models are implemented in *MATLAB/Simulink* and the phasor model of the BDG is implemented in OpalRT's real-time simulation platform *ePHASORsim*, yet it is used for off-line simulations in this chapter.

7.1 Evaluation Criteria

7.1.1 Crucial Criteria

Voltage profile management

As shown in chapter 5.4, the power generation profile of ReGen plants can lead to rising voltages exceeding the steady-state limits of ±10 %. The aim of voltage control is to keep the voltage profile within the tolerance band margins with time frame of hours, hence being a major evaluation criterion for the developed control concepts.

Stability of voltage control

Moreover, control stability aspects need to be taken into account. Distributed 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.

Voltage fluctuations

As mentioned in chapter 2, due to the voltage fluctuations caused by the intermittent nature of distributed generation the on-load tap changers together and other voltage-regulating devices within in the distribution grid can be switched excessively and both voltage quality and normal operation of the devices are endangered. In order to assess the voltage quality, variations of the RMS voltages within the MV grid are going to be evaluated. One useful index for quantifying voltage variations of distributed generation is the Voltage Fluctuation Index (VFI) [29]. The VFI is calculated as the mean difference between the RMS voltage in a given instant and the same value in the preceding instant:

$$VFI = \frac{\sum_{i=2}^{N} \left| V_{RMS,T_s}(t_i) - V_{RMS,T_s}(t_{i-1}) \right|}{N-1} \tag{21}$$

T_s is the sampling time of RMS voltages and N is the number of samples. As stated in chapter 4.2, the response time of the active power controller in ReGen plants is normally 1 second. Hence, it is considered appropriate to expect and evaluate voltage variations on a second base ($T_s = 1\ sec$). Then for a test period of e.g. 1 hour, the VFI would take into account 3600 samples. The VFI provides an idea of the magnitude and number of fluctuations. That is to say the higher the VFI is, the bigger is the voltage variation between each sample which also means more fluctuations existing in the overall interval evaluated. As an absolute value, the VFI index does not provide much information about present voltage fluctuations, but it is a good baseline when comparing fluctuations in different points of the grid and in different test cases.

In this time domain analysis the aim is to investigate whether the developed voltage controls do have positive or negative impact on the existing voltage fluctuations caused by the intermittent power profile of ReGen plants, i.e. whether voltage control mitigates or amplifies voltage variations. As a consequence, the VFI indices at all MV busses respectively are expressed as function of the VFI at the feeder connection point (bus B03 at secondary side of primary substation) calculated for a base case, where voltage control is disabled:

$$VFI_{Bxx,pu} = \frac{VFI_{Bxx}}{VFI_{B03,noVctrl}} \tag{22}$$

7.1.2 Target dependent criteria

Further evaluation criteria can be applied dependent on additional control objectives, providing that the crucial criteria, i.e. steady-state voltage stability of the system, are ensured.

Reactive power utilization of ReGen plants

One aspect is related to the reactive power utilization of each ReGen plant. Voltage droop control is limited with respect to the reactive power capability limits of the ReGen plants. A DSO may desire the plants to operate below those limits, in other words with a utilization rate below 100 %. In this way the DSO is able to ask for further reactive power support in emergency cases, e.g. under fault conditions when fast reactive current injection for voltage support is required in order to keep the ReGen plant connected to the system (fault-ride-through support).

Power losses

Another evaluation criterion for the proposed controls can be imposed by the DSO that aims for maximum power provision to the end-consumers with as few power losses as possible. Reactive power provision by ReGen plants may increase the current loading of the lines and thereby the resistive losses. Traditionally, percentage power losses in distribution systems are calculated based on the power input to the feeder at the primary substation. In this way, the mismatch between energy input and billed energy to the consumers is expressed. However, in the case of large-scale power generation within the distribution system, where the major part is fed into the transmission system, it gives meaning to refer the power losses to the total active power generation by the ReGen plants in the distribution grid:

$$P_{loss,tot,\%} = P_{loss,tot} \cdot 100\ \% = \frac{\sum P_{loss}}{\sum P_{gen}} \cdot 100\ \% \tag{23}$$

7.2 Test Cases and Scenarios

Test Cases

The control concepts for off-line coordination presented in chapter 6, i.e. control concept 1 and 2, are to be evaluated. In this context, the aim is to analyze various droop settings for local voltage control of each ReGen plant.

As mentioned in chapter 6.1, 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, distributed off-line coordination (Control Concept 2) takes into account the V-Q sensitivities at the system busses to obtain suitable droop settings. They have been calculated in chapter 6.2 for each ReGen plant respectively. Hence, another test case is introduced:

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

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 (Figure 39). In this context, real measurement data[3] for wind speed and solar irradiation are used as inputs for the ReGen plant models developed in chapter 4.2.

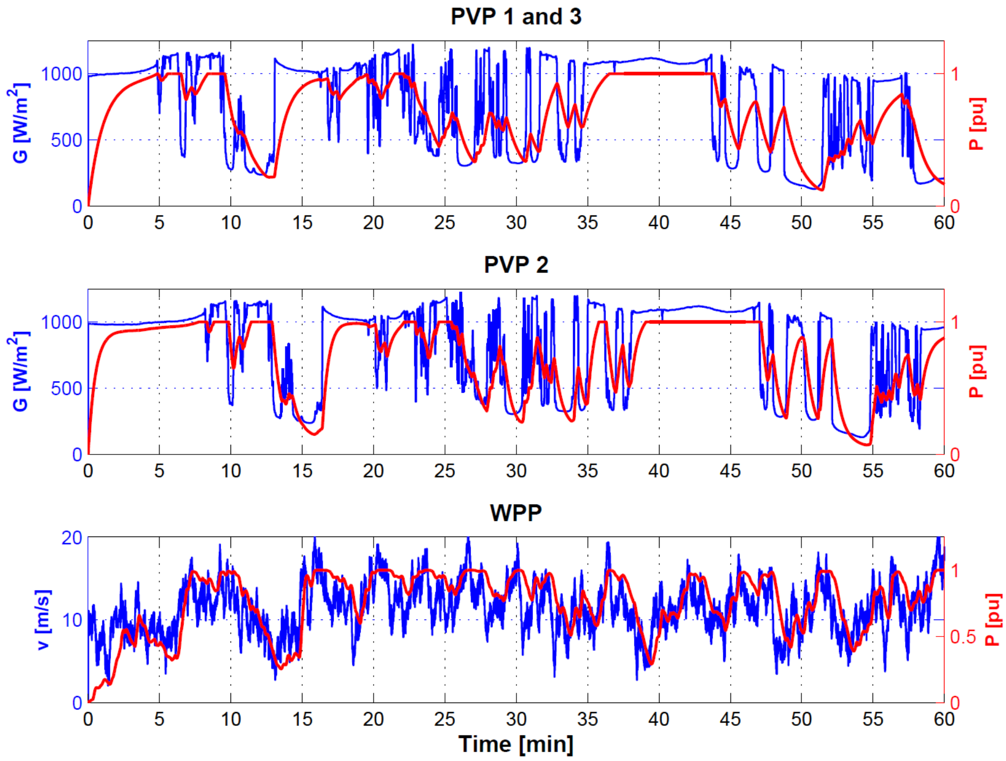


Figure 39: Solar irradiation and wind speed profiles

3 Measurement data are taken from weather station at AAU: http://www.et.aau.dk/research-programmes/photovoltaic-systems/

A time frame of one hour is considered sufficient to represent a volatile power profile covering the extreme operational points at high wind speed and solar irradiation. The wind speed (denoted by v) and solar irradiation (denoted by G) profiles and the corresponding power outputs in per-unit are shown in Figure 39.

An exemplary setup for the PV plants is considered according to the specified distances between ReGen plants in the BDG (Figure 40). An average wind speed of 35 m/s at cloud height is considered for the clouds moving from south-west direction. Hence, PVP 2 will experience the solar irradiation with a time delay of 100 sec. compared to PVP 1 and PVP 3.

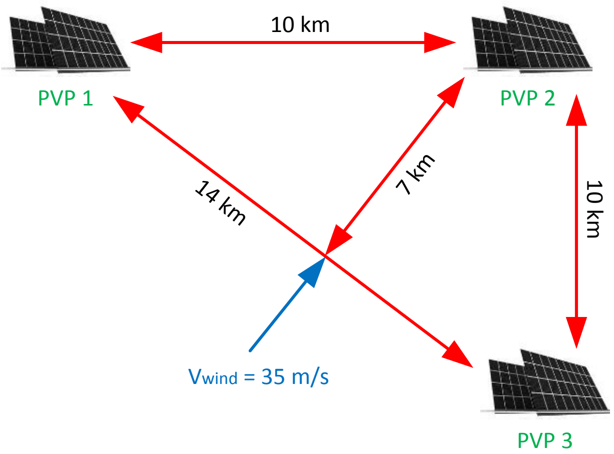


Figure 40: Exemplary setup for PV plants in the benchmark distribution grid

In order to represent the crucial operational points of the external transmission system, eventually leading to voltage stability problems (see chapter 5.4), following test scenarios are considered:

- $V_{grid} = 1.00\ pu$ **(V 100)** representing normal operational point of transmission system
- $V_{grid} = 1.05\ pu$ **(V 105)** representing alert state operational point of transmission system

7.3 Results and Analysis

7.3.1 Test scenario $V_{grid} = 1.00\ pu$ (V100)

In Figure 41 to Figure 44 it is shown for each ReGen plant in the BDG the active power, reactive power and voltage profile throughout the considered time frame of 1 hour for various droop settings according to the test cases specified in previous section. For the voltages it is added the base case, showing the resulting profile if voltage droop control was inactive (no reactive power provision by ReGen plants). It can be seen that both Control Concept 1 (Manual droop settings) and Control Concept 2 (Distributed offline coordination) yield in sufficient depression of the voltage profile in order to meet the steady-state requirements of ± 10 % (see also Appendix 12.1). In particular the connection point 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. The voltage control performance for each test case is summarized by listing the maximum voltage levels obtained throughout the time-domain simulation:

Table 12: Maximum voltage levels for $V_{grid} = 1.00\ pu$

Max. voltage	PVP 1	PVP 2	PVP 3	WPP
No Droop	***1.0497***	***1.0190***	***1.0519***	***1.1019***
DroopMin	1.0301	1.0122	1.0143	1.0479
DroopMed	1.0348	1.0114	1.0144	1.0451
DroopMax	1.0377	1.0114	1.0191	1.0558
DroopVSA	1.0364	1.0114	1.0189	1.0539

Concerning the stability of voltage control actions, it can be remarked in the figures that reactive power setpoints are met according to the V(Q) characteristics within a settling time of less than 1 second.

If the focus is on reactive power utilization of the ReGen plant, Figure 45 indicates the percentage time based on 1-hour period, when a ReGen plant reaches its reactive power capability limit. Already in Figure 41 to Figure 44 it can be concluded by observing the reactive power profiles (center plot) that all PVPs reach their Q capability limit quite often throughout the time period, which is due to the dependency on the actual active power generation $Q_{ava}(P)$ according to the PQ chart of PVPs. This fact is expressed by numbers in Figure 45. However, the WPP reaches its Q capability limit only under test case ***DroopMin***, and in fact during 64 % of the whole time period. In those events, the generating plants at the feeder will most likely have reached their total limit of reactive power provision. Hence, during fault events the DSO will require additional fast reacting Q compensation devices in order to support the system voltages.

During normal operation, an arbitrarily chosen droop setting according to Control Concept 1 (Manual Droop Setting) can lead to full reactive power utilization of all ReGen plants, prohibiting any reactive power margin that may be required during emergency operation!

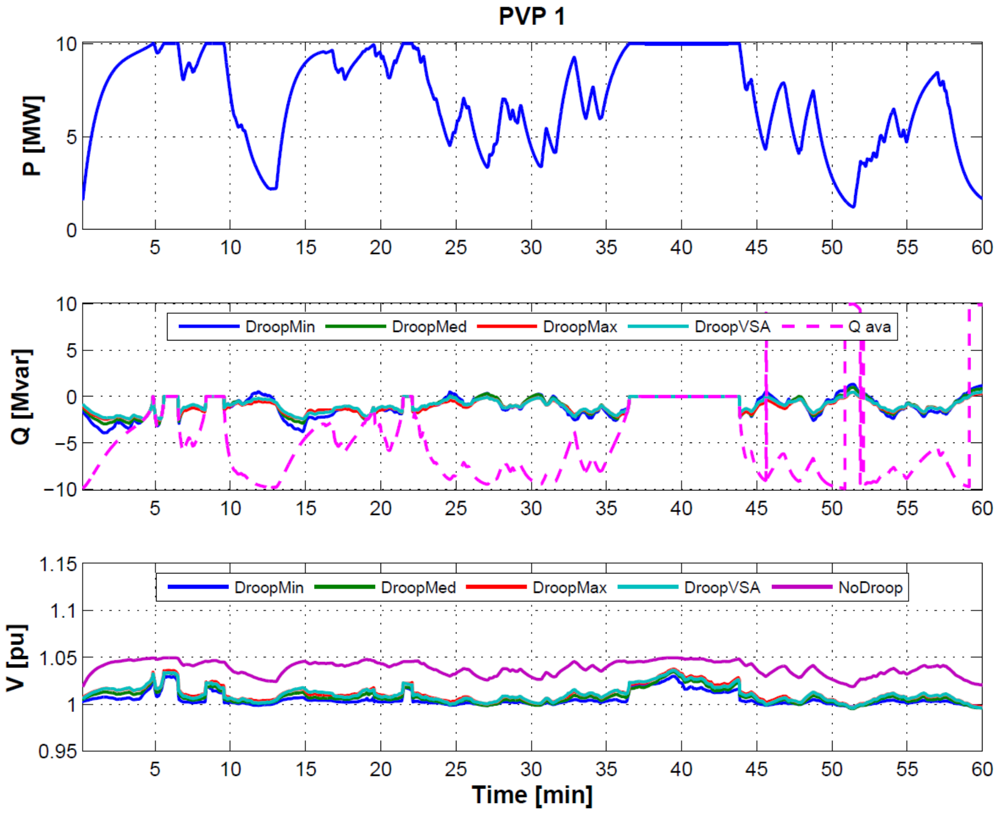


Figure 41: P, Q, V of PVP 1 over one hour for different droop settings and grid voltage of $V_{grid} = 1.00\ pu$

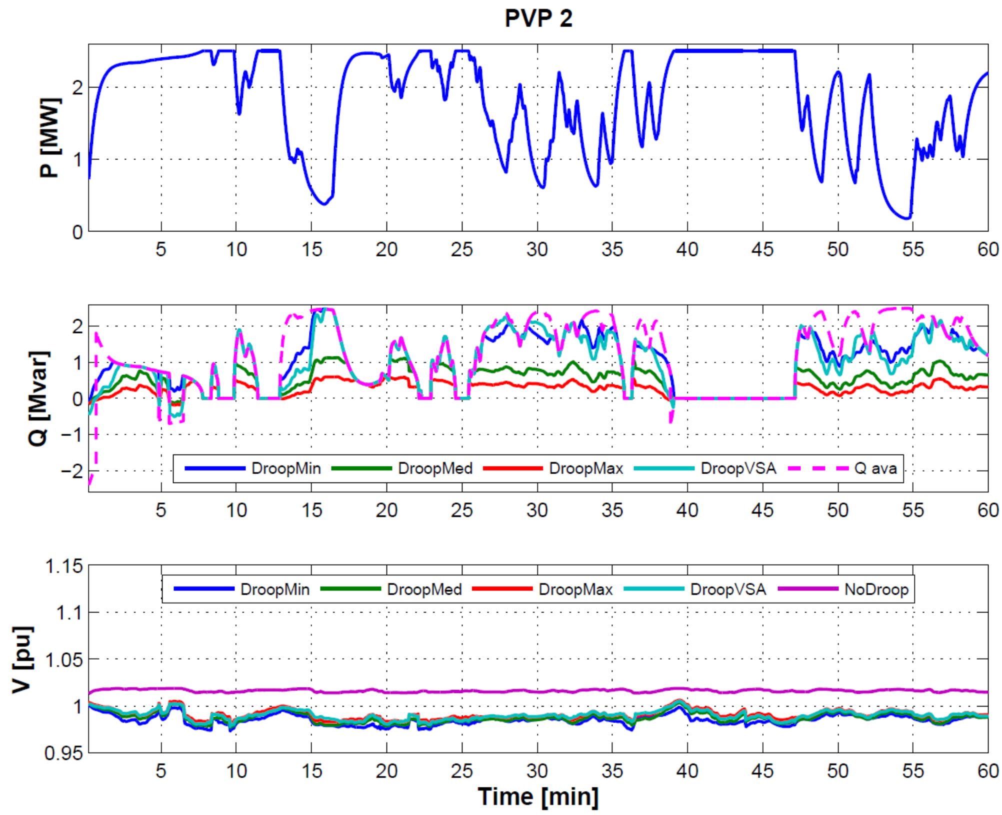


Figure 42: P, Q, V of PVP 2 over one hour for different droop settings and grid voltage of $V_{grid} = 1.00\ pu$

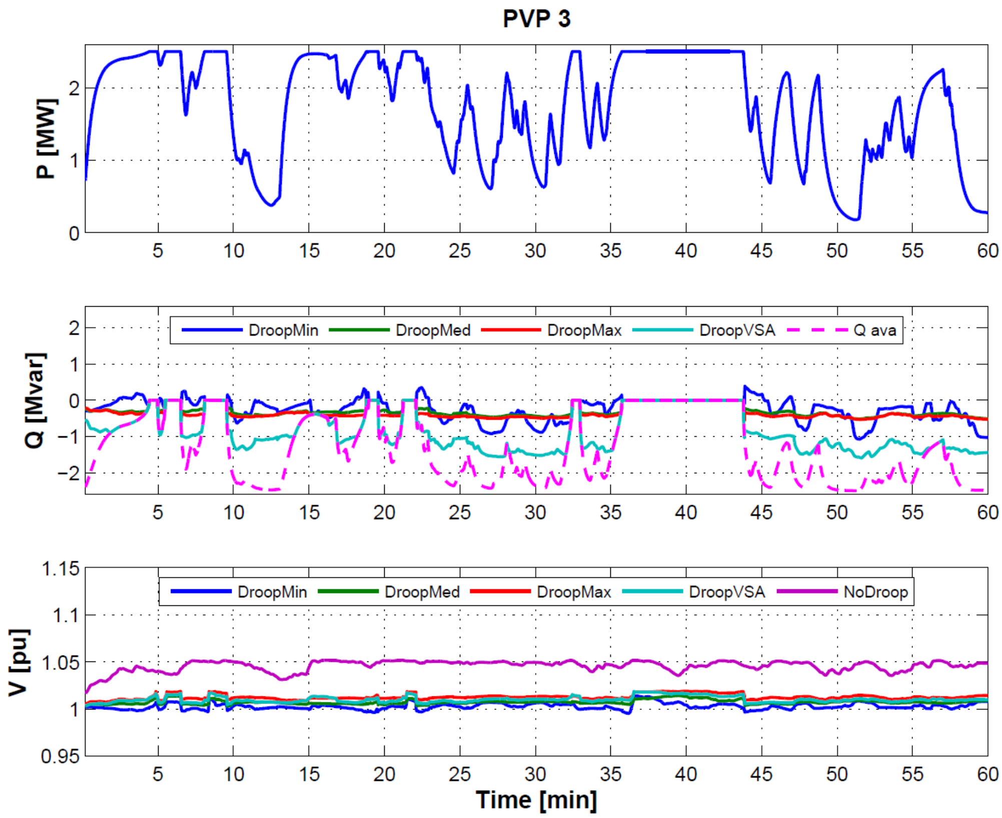


Figure 43: P, Q, V of PVP 3 over one hour for different droop settings and grid voltage of $V_{grid} = 1.00\ pu$

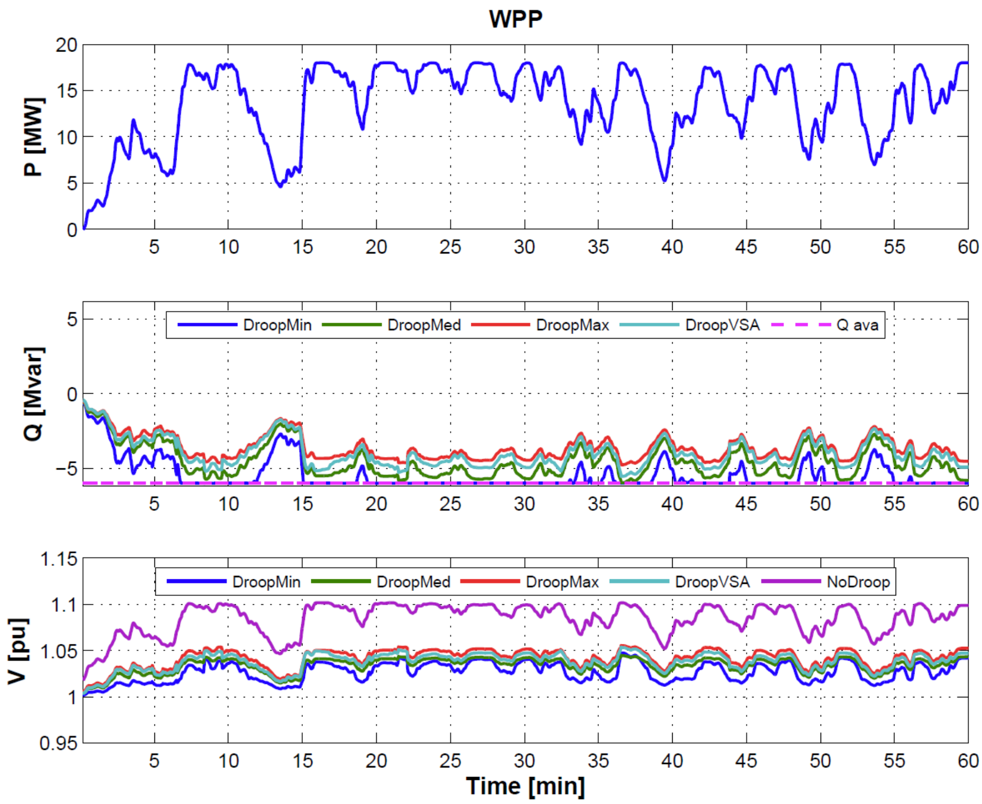


Figure 44: P, Q, V of WPP over one hour for different droop settings and grid voltage of $V_{grid} = 1.00\ pu$

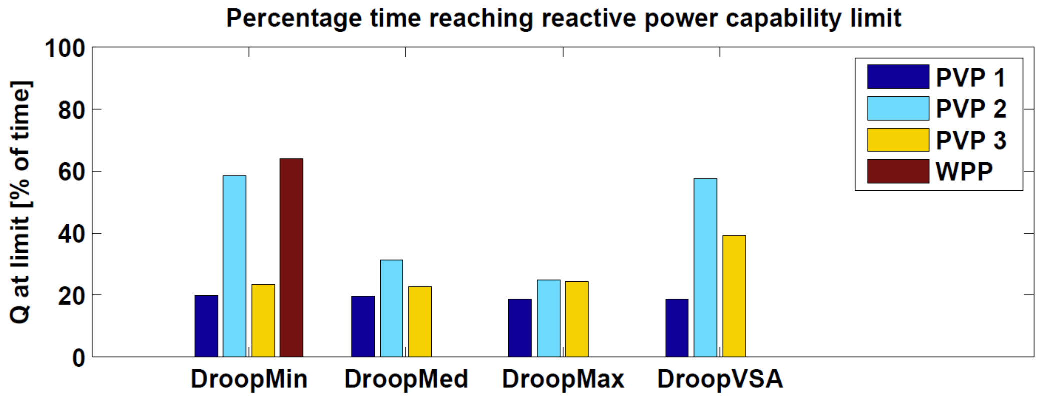


Figure 45: Reactive power utilization of ReGen plants for $V_{grid} = 1.00\ pu$

Another important aspect to be evaluated is the voltage fluctuations present during normal operation. Figure 46 compares the VFI of all test cases based on the VFI obtained for ***No Droop*** at bus B03. First of all, it can be seen for test case ***No Droop*** (red bars) that large voltage fluctuations are present at bus B05, where PVP1 is connected, and towards the end of the feeder, where WPP is connected to bus B12. This is to be expected due to the volatile power profile of ReGen plants and the large δP/δV sensitivity at remote busses (see chapter 5.3.1).

By evaluating the test cases with enabled voltage droop it can be concluded that at some busses (B03 to B08) voltage control amplifies voltage fluctuations, while at the remaining busses (B09 to B12) voltage fluctuations are mitigated by means of reactive power provision. All in all, there are no significant differences in the performance between Control Concept 1 and 2.

However, the fact that voltage control can have negative impact on voltage fluctuations may be a result of limited voltage control due to Q capability limits of the ReGen plants. As already outlined previously, the available reactive power of PVPs is a function of the actual active power generation, which introduces further variations of the voltage. As seen in Figure 45, voltage control by WPP is generally not limited throughout the simulation period and hence is able to smooth the voltage profile, leading to smaller VFI values at the end of the feeder compared to the base case (Figure 46).

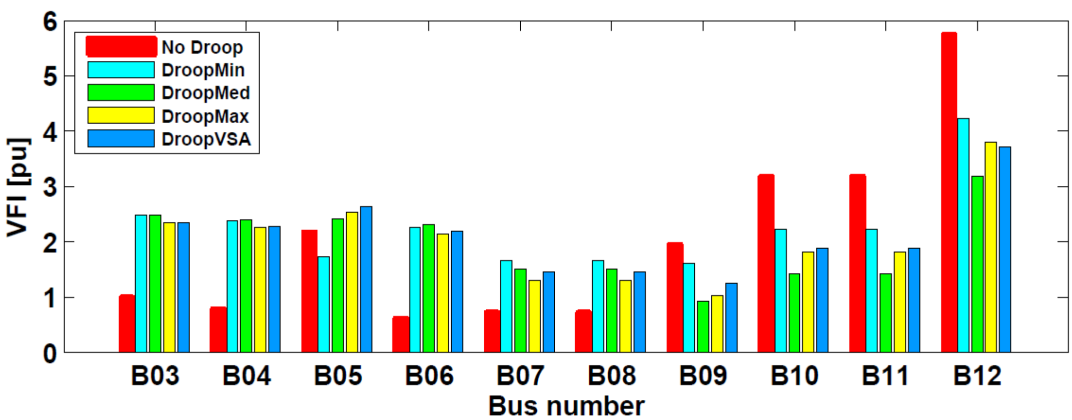


Figure 46: VFI for all MV busses and various droop settings and grid voltage of $V_{grid} = 1.00\ pu$

7.3.2 Test scenario $V_{grid} = 1.05\ pu$ (V105)

In Figure 47 to Figure 50 again it is shown for each ReGen plant the active power, reactive power and voltage profile throughout the considered time frame of 1 hour for various droop settings according to the specified test cases. Under this extreme scenario with a transmission system in alert state operation (grid voltage of 1.05 pu) both control concepts 1 and 2 are still able to decrease the voltage profile in the distribution grid to values below 1.1 pu (see also Appendix 12.1). No significant differences are observed for various test cases as illustrated by following table, listing the maximum voltage levels obtained throughout the time-domain simulation:

Table 13: Maximum voltage levels for $V_{grid} = 1.05\ pu$

Max. voltage	PVP 1	PVP 2	PVP 3	WPP
No Droop	***1.0996***	***1.0701***	***1.1033***	***1.1514***
DroopMin	1.0700	1.0623	1.0645	1.0922
DroopMed	1.0705	1.0623	1.0645	1.0922
DroopMax	1.0763	1.0623	1.0645	1.0922
DroopVSA	1.0738	1.0623	1.0645	1.0922

However, by looking at the results for voltage and reactive power obtained for ***DroopMin*** **(**Figure 47 to Figure 50, center & bottom plot, blue graph), it can be seen that there appear two instable operation points at time $t \approx 49\ min$ and $t \approx 54\ min.$, characterized by oscillatory behavior of V and Q over time. A zoom of the first event is provided in Figure 51:
Before the time $t_1 \approx 2926.1\ sec$, the WPP operates at its capability limit of $Q_{WPP} = -6\ Mvar$. 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 (Figure 52), after peaking, decreases rapidly (negative δP) which lowers the voltage profile (**negative δV**). 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. In Table 14 the droop settings of all test cases are expressed by Mvar per percentage voltage change. In can be seen that in test case ***DroopMin*** both PVP 1 and WPP show significantly large values for δQ/δV, eventually causing problems when being subject to opposing control objectives.

Table 14: Voltage droop setting δQ/δV for various test cases

δQ/δV [Mvar/%]	DroopMin = 2 %	DroopMed = 4.5 %	DroopMax = 7 %	DroopVSA
PVP 1	5.00	2.22	1.43	1.35
PVP 2	1.25	0.56	0.36	1.92
PVP 3	1.25	0.56	0.36	1.41
WPP	3.00	1.33	0.86	1.04

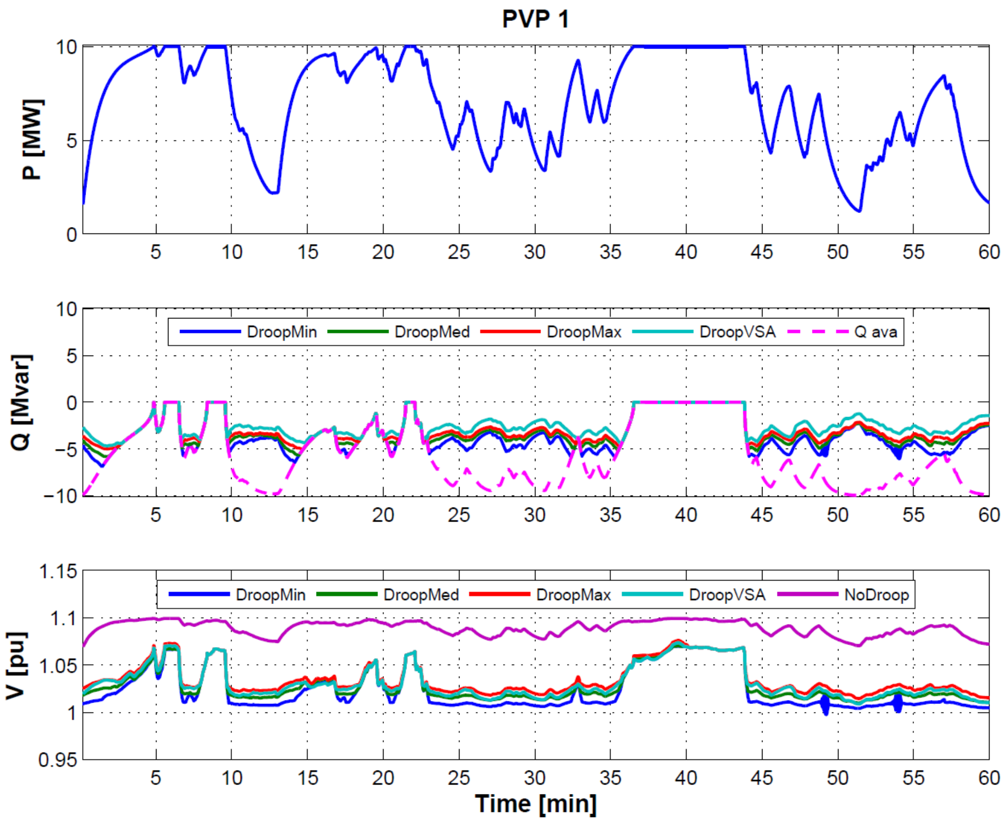


Figure 47: P, Q, V of PVP 1 over one hour for different droop settings and grid voltage of $V_{grid} = 1.05\ pu$

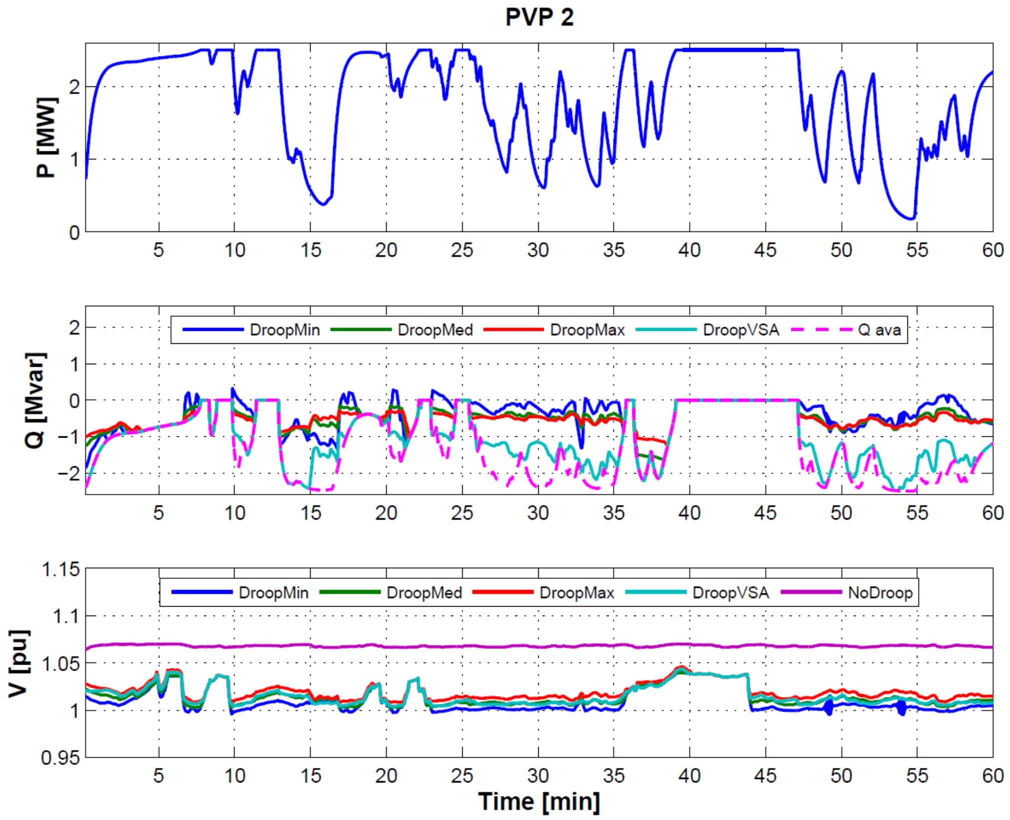


Figure 48: P, Q, V of PVP 2 over one hour for different droop settings and grid voltage of $V_{grid} = 1.05\ pu$

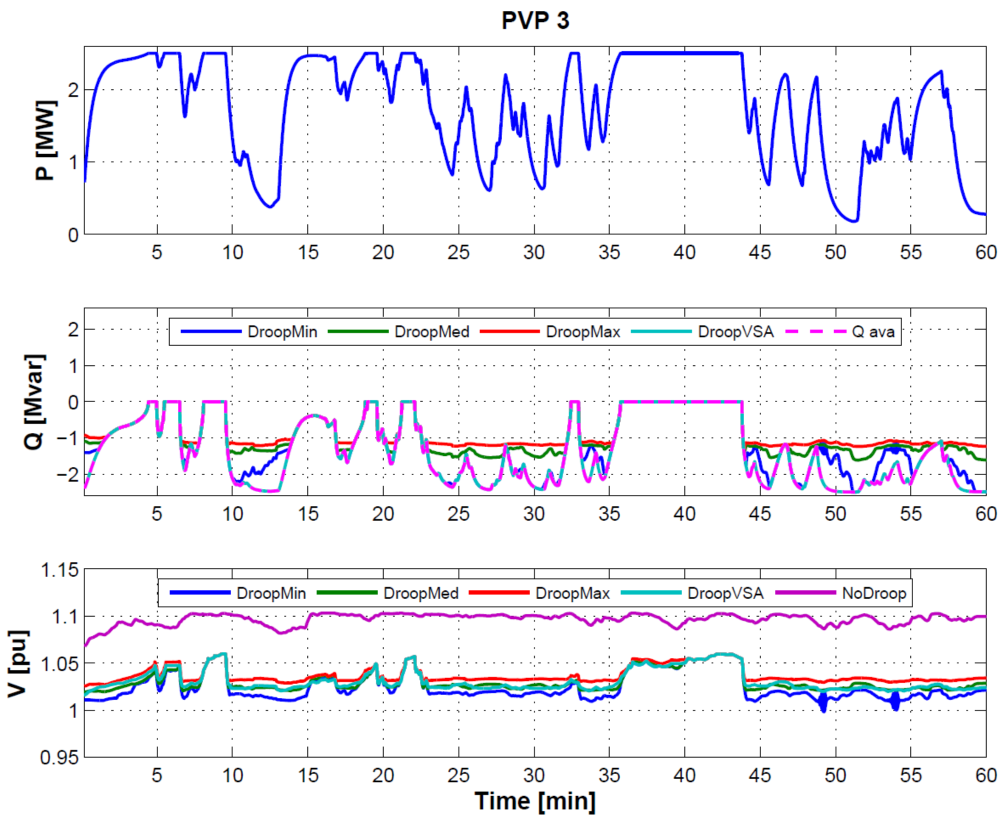


Figure 49: P, Q, V of PVP 3 over one hour for different droop settings and grid voltage of $V_{grid} = 1.05\ pu$

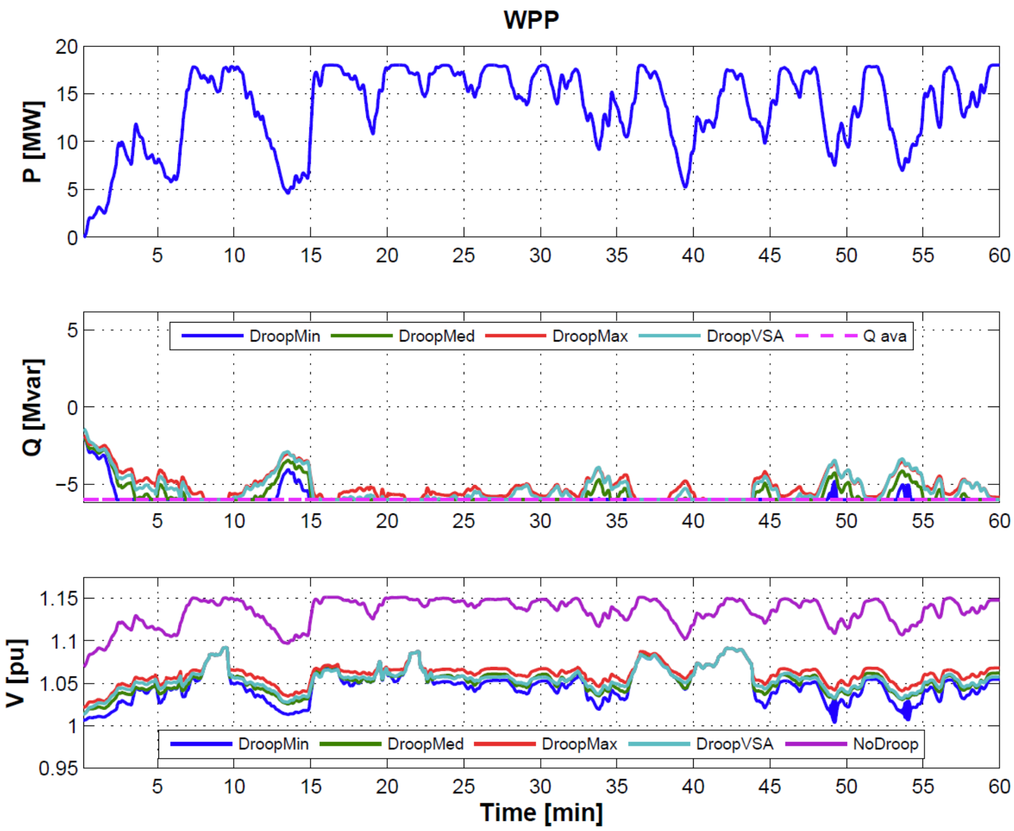


Figure 50: P, Q, V of WPP over one hour for different droop settings and grid voltage of $V_{grid} = 1.05\ pu$

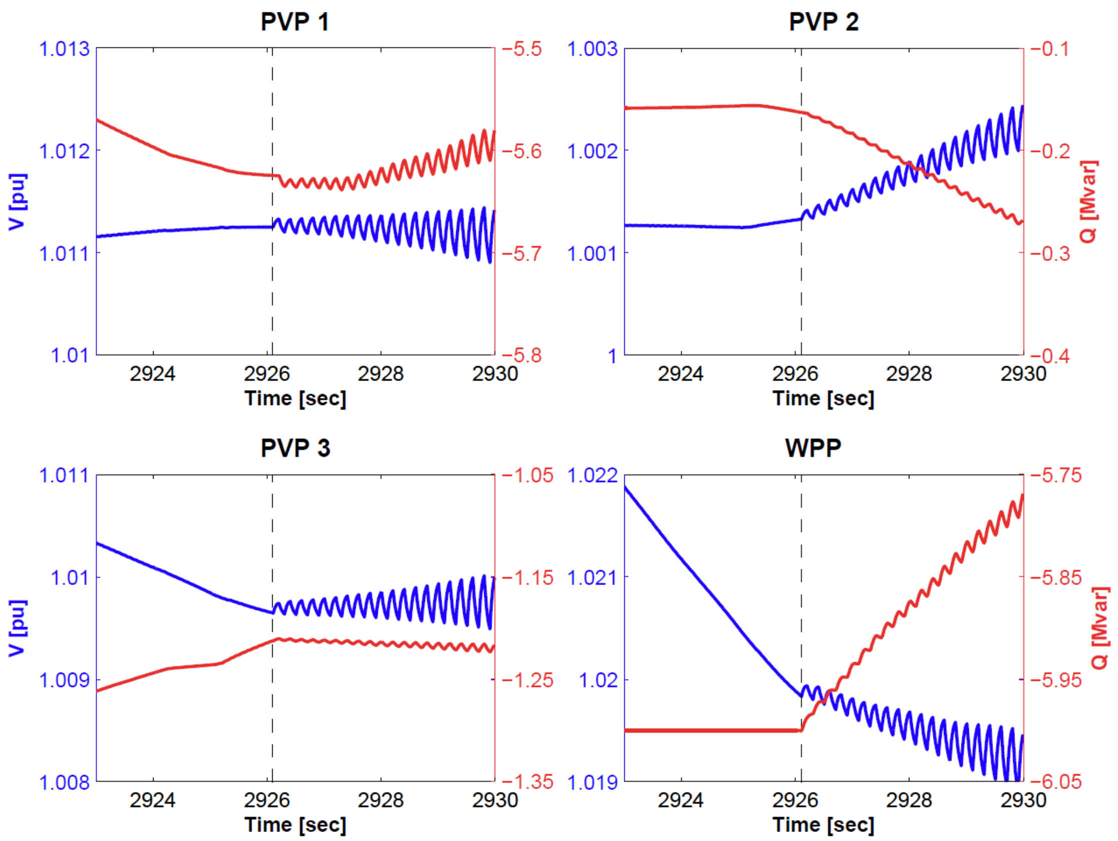


Figure 51: V & Q of all plants at beginning of instability at t1= 48.75 min = 2926.1 sec for DroopMin = 2 %

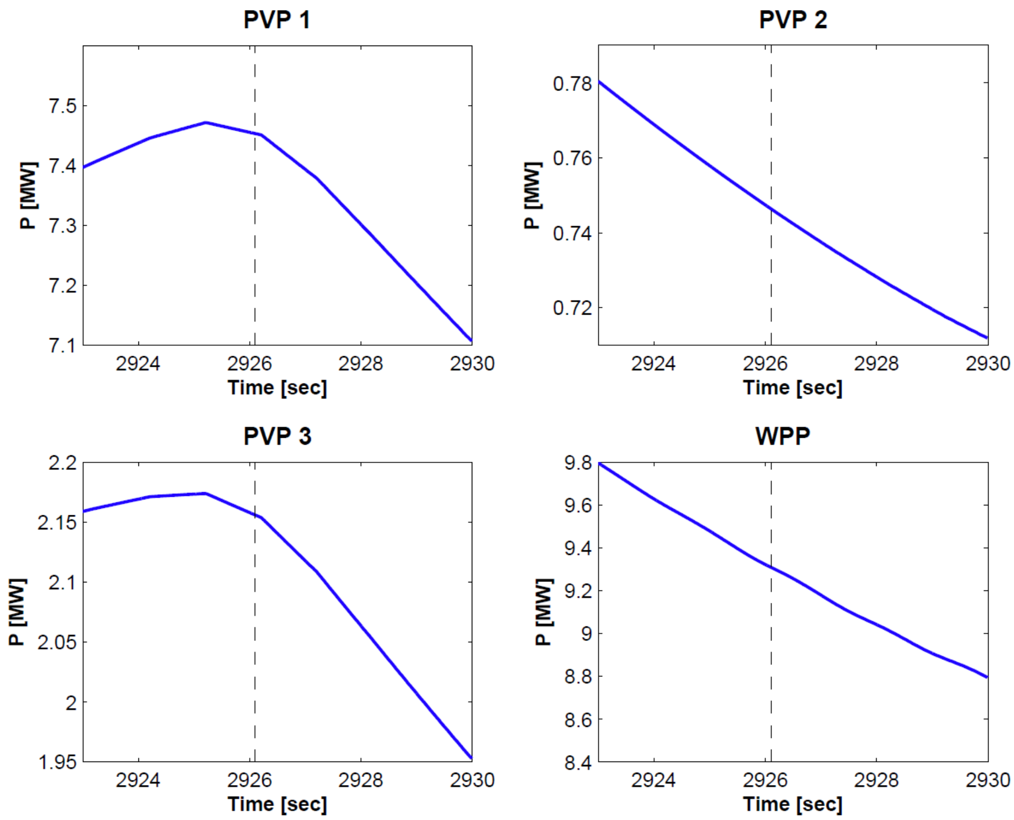


Figure 52: P of all plants at beginning of instability at t1= 48.75 min = 2926.1 sec for DroopMin = 2 %

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 corresponding results can be found in the Appendix 12.2.

An arbitrarily chosen droop setting according to Control Concept 1 (Manual Droop Setting) can lead to instable operating points, if some ReGen plants feature a rather flat droop characteristic!

By looking at the reactive power utilization of the ReGen plants, Figure 53 indicates the percentage time based on 1-hour period, when a ReGen plant reaches its reactive power capability limit. One of the observations is that even for test case **DroopVSA**, where droop settings are optimized according to the grid characteristic, both PVP 2 and PVP 3 reach their capability limit in the majority of the time.

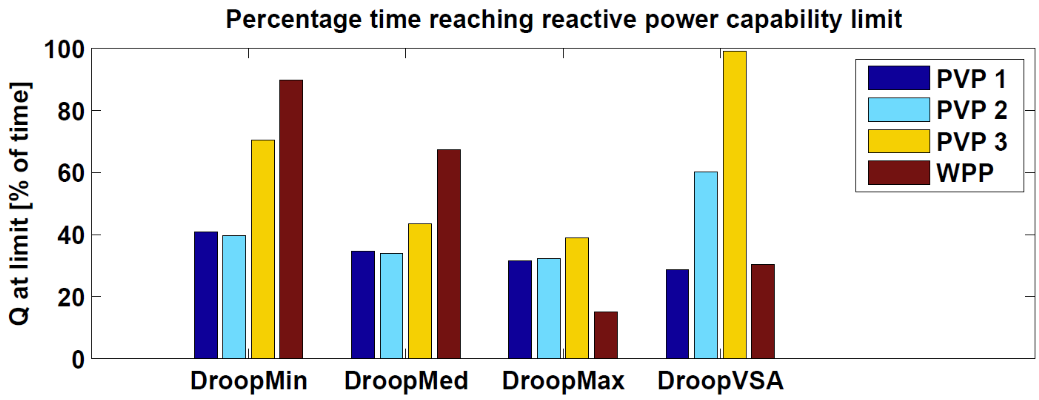


Figure 53: Reactive power utilization rate of ReGen plants for $V_{grid} = 1.05\ pu$

As mentioned earlier, this is due to the dependency on the actual active power generation $Q_{ava}(P)$ according to the PQ chart of PVPs. In particular during time periods of high power generation of PVPs leading to rising voltage profile, the available reactive power drops to $Q_{ava}(P = 1\ pu) = 0\ pu$. However, in this exemplary benchmark grid, the WPP at the end of the feeder is able to provide reactive power to sufficiently regulate the voltage profile. But it can be expected that voltage stability problems would occur, if this WPP did not exist or was even replaced by another PVP.
Such scenarios have been simulated and the results are illustrated in Figure 54. Disconnection of WPP at the end of the feeder will lead to rising voltage profile, leading to values close to the steady-state limit of 1.1 pu at PVP 1 (green graph). If ReGen plant 4 was another PVP with unaltered power ratings ($P_{rated} = 18\ MW$), the MV feeder lacks reactive power provision so that the voltage at some of the busses (at PVP 3 and PVP 4) exceed the tolerance band margins (red graph).

Analysis of present voltage fluctuations induced for this test scenario with $V_{grid} = 1.05\ pu$ is performed by means of Figure 55. It cannot be identified significant differences between different test cases with various voltage droop settings.
However, it can be observed that for ***DroopMin*** the VFI increases considerably towards the end of the feeder. Moreover, it can be seen that at all busses for almost all test cases the voltage fluctuations are amplified compared to the base case ***No Droop***. This negative impact of voltage control on voltage fluctuations is again explainable by Q capability limits of the ReGen plants (Figure 53).

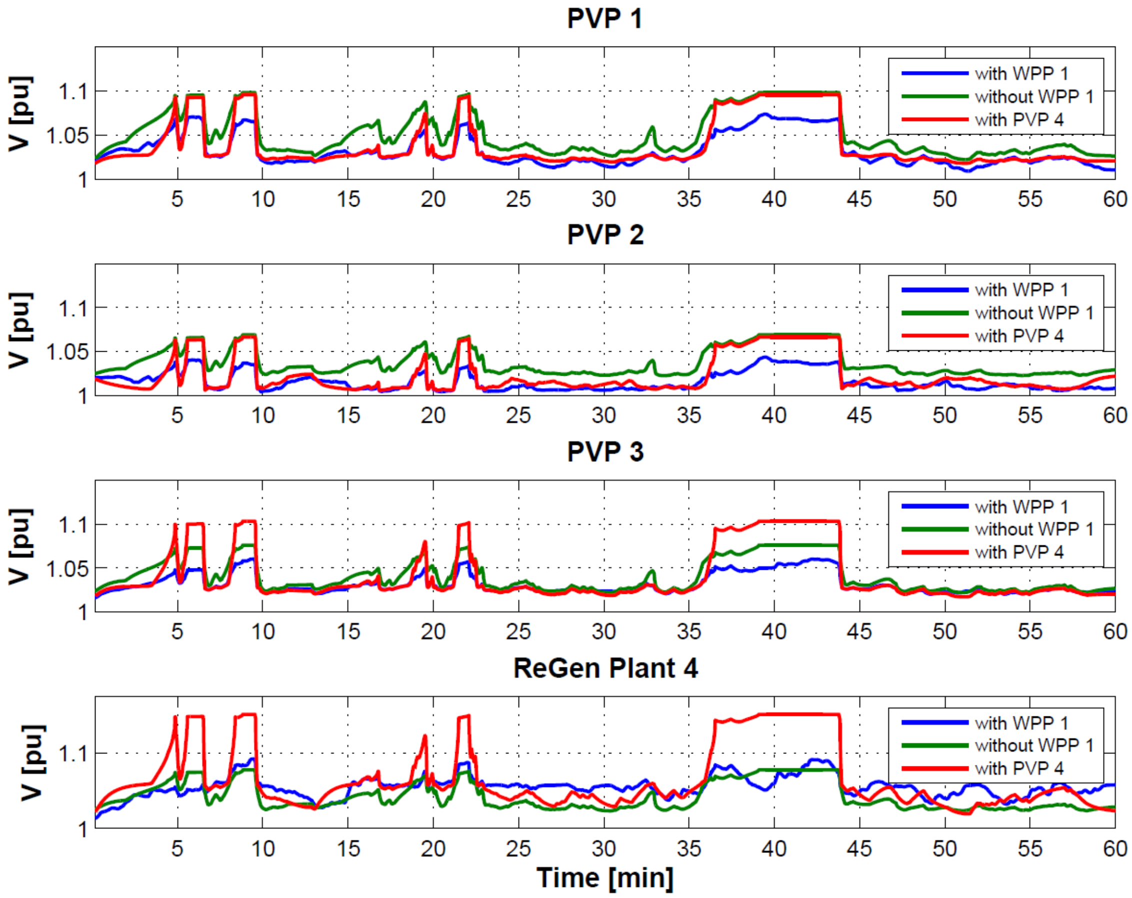


Figure 54: V for all plants for DroopVSA and different scenarios for ReGen Plant 4

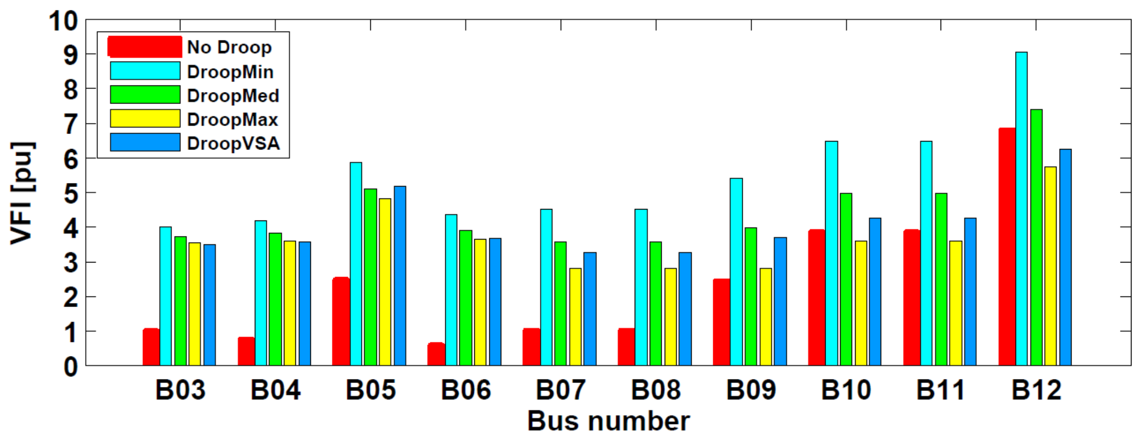


Figure 55: VFI for all MV busses and various droop settings and grid voltage of $V_{grid} = 1.05\ pu$

Every voltage droop control, whether configured arbitrarily (Control Concept 1) or according to grid characteristic (Control Concept 2), is limited by the physical reactive power capability of the ReGen plants. The actual grid code requirements for reactive power capability of PVPs can lead to

- *the occurrence of voltage stability problems in distribution systems, if no further reactive power compensation units are installed that can support the system during fault conditions.*
- *amplified voltage fluctuations, in particular in closed proximity to PVPs, as their available reactive power is function of the actual active power generation.*

7.3.3 Power Losses

Finally, the power losses across the feeder lines are evaluated for various droop settings and various grid voltages. Figure 56 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of one hour, for various droop settings and various external grid voltages.

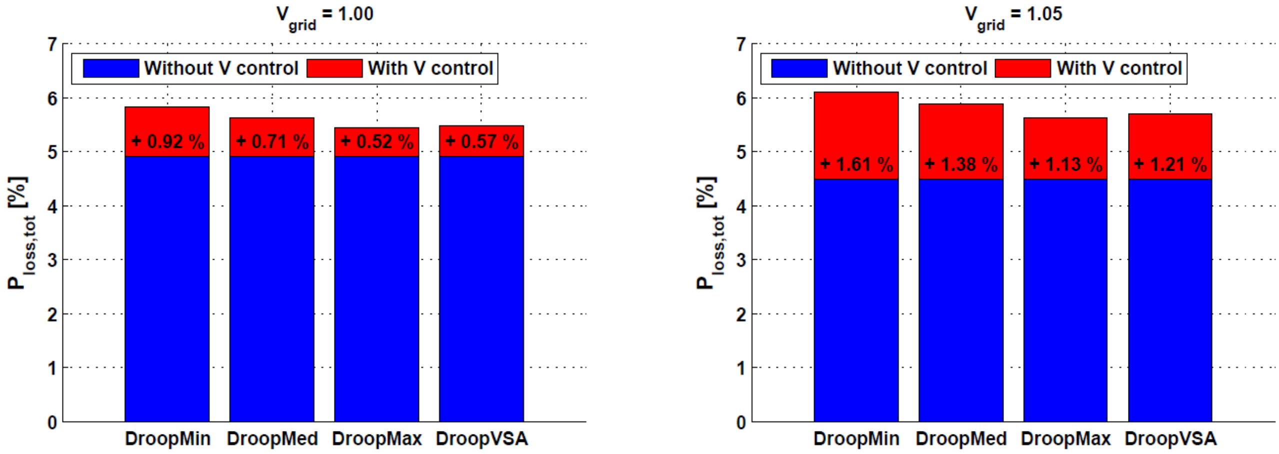


Figure 56: Power losses within the distribution grid for various droop settings (left: $V_{grid} = 1.00\ pu$, right: $V_{grid} = 1.05\ pu$)

Comparing the left- and right-hand figure shows that without voltage control (blue) the power losses decrease for an enhanced external grid voltage V_{grid}. This is due to a raised voltage profile along the feeder, resulting in lower current loading of the lines and thereby reduced power losses. In the case of voltage control (red on top of blue) the losses are higher for $V_{grid} = 1.05\ pu$ compared to $V_{grid} = 1\ pu$, since the feeder requires more reactive power to compensate the voltage rises, which leads to increased current loading of the lines.

By comparing the various droop settings it can be concluded that the flatter the droop characteristic, the higher the power losses. However, it has to be remarked that for all test cases the power losses are increased significantly compared to the benchmark case, where ReGen plants do not provide reactive power. For Control Concept 1 the highest loss increase amounts to 1.61 % and for Control Concept 2 the losses increase by 1.21 % (Figure 56).

Figure 57 shall demonstrate which feeder lines represent the major contribution to the total line losses obtained, for test cases without voltage control and with voltage control (for test case *DroopVSA*). It can be seen that around 27 % of the losses occur across line L9, being the longest line within the feeder with significant power transfer by the WPP infeed. Moreover, the figure shows that only for L9 the loss share increases in case of enabled voltage control compared to disabled voltage control. This is due to the fact that the WPP contributes with reactive power to the largest extent, while the PVPs are predominantly limited by their reactive power capability limit.

Voltage droop control increases the power losses within a distribution grid with high penetration of ReGen plants; the more the reactive power absorption of the ReGen plants, the higher the line losses!

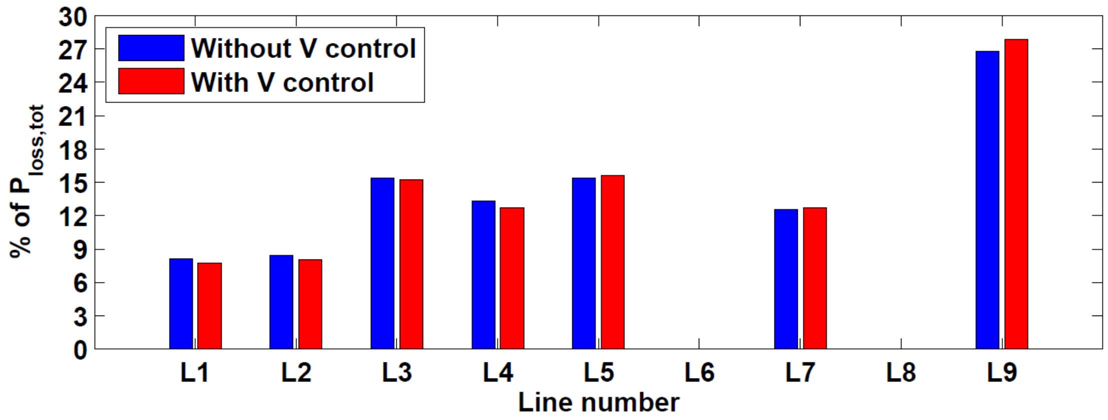


Figure 57: Share of power losses between the lines

7.4 Extended Reactive Power Capability of Photovoltaic Plants

The results of the section 7.3 have shown that voltage control by PVPs is limited due to their limited reactive power capability at high solar irradiation, leading to larger voltage fluctuations and an increased Q utilization rate. The PQ chart used in this study is stipulated by the grid code requirements and implies a $Q_{ava}(P)$ characteristic where the available reactive power is $Q_{ava}(P_{rat}) = 0$ at rated power.

7.4.1 Extended PQ Chart for Photovoltaic Plants

However, in [36] the actual physical limits of reactive power capacity in PV generators are investigated according to the system characteristics. Figure 58 shows the operational limits of a PV inverter.

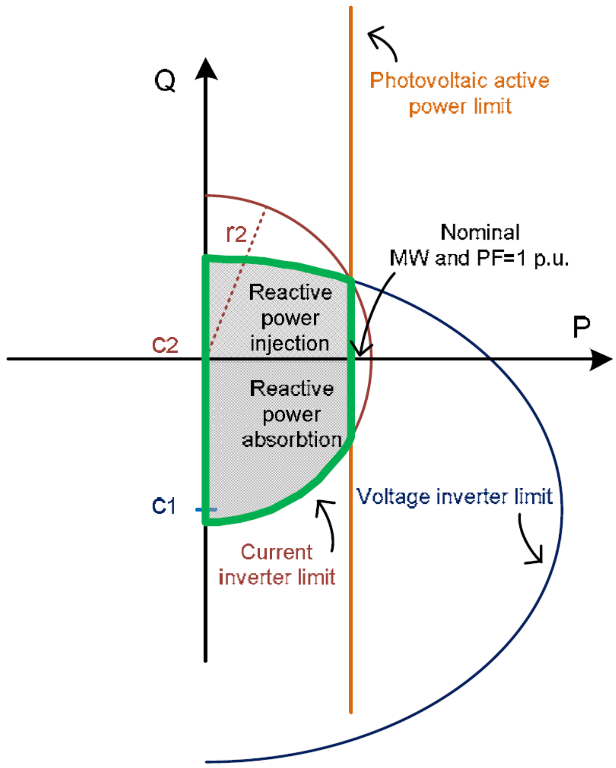


Figure 58: Active and reactive power capacity of PV generator [36]

The green envelope is a result of current inverter limit, voltage inverter limit and PV active power limit. The PV inverter injects a maximum current which imposes the limit of P and Q, in this way the nominal apparent power S of the PV inverter indicated by the radius r2. The nominal power is typically larger than the rated active power of the PV generator. If the PV inverter was designed to have available $Q_{av}(P_{rat}) = 0.33\ pu$, the nominal apparent power amounts to:

$$S = \sqrt{P^2 + Q^2} = \sqrt{1^2 + 0.33^2}pu = 1.054\ pu \tag{24}$$

This means the physical design of the components need to account for only 5.4 % higher current loading in order to feature similar reactive power capacity at rated power like a typical WPP.

Subsequently it is investigated how an extended PQ chart for the PVPs will affect the voltage control performance of Control Concept 2 in the benchmark distribution grid according to some selected evaluation criteria:

- Voltage fluctuations
- Reactive power utilization of ReGen plants
- Power losses

7.4.2 Results of Case Studies

Figure 59 and Figure 60 show the VFI at all system busses for the default and extended PQ chart of the PVPs based on the VFI obtained for the test case ***No Droop*** at bus B03. It can be seen that for the extended PQ chart the VFI is improved significantly compared to the default PQ chart. In many busses the voltage fluctuations are even reduced in comparison to the base case without voltage control.

Voltage control can have a positive impact on present voltage fluctuations, if sufficient reactive power capability of the ReGen plant is ensured!

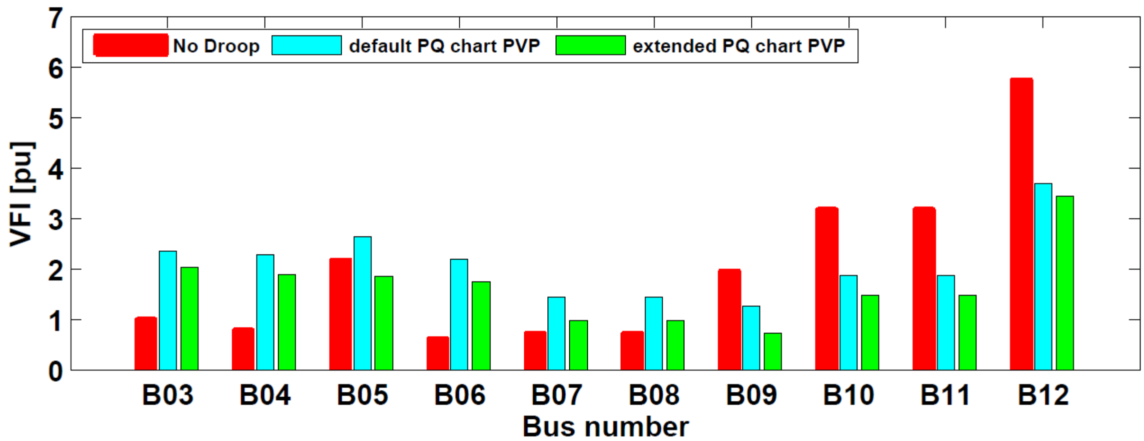


Figure 59: VFI for all MV busses and various PQ charts of PVP and grid voltage of $V_{grid} = 1.00\ pu$

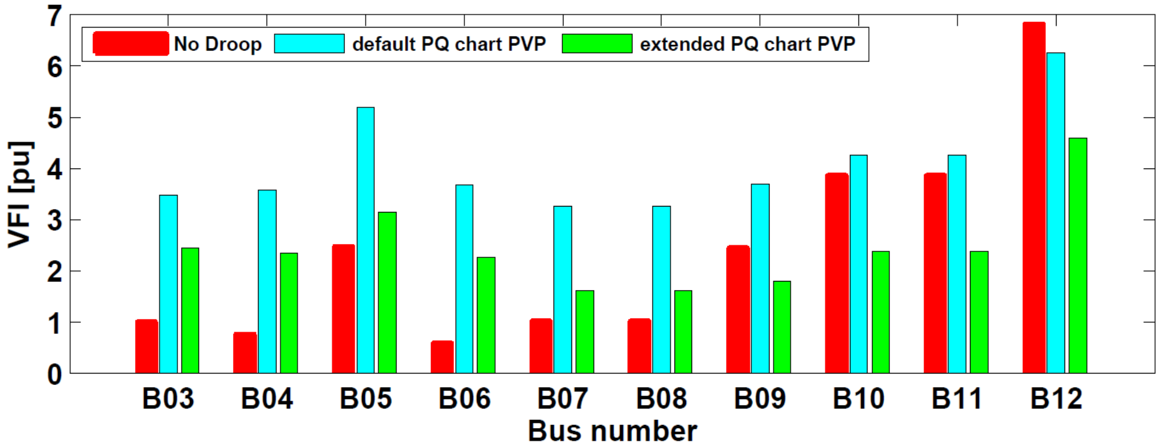


Figure 60: VFI for all MV busses and various PQ charts of PVP and grid voltage of $V_{grid} = 1.05\ pu$

In the previous chapter it has been shown that reactive power utilization rate of the ReGen plants can be significantly high, in particular for large voltage rises within the distribution grid. Figure 61 compares the reactive power utilization rate for the default and extended PQ chart of the PVPs. As expected, the numbers decrease for all PVPs due to enhanced Q capability. Additionally, also reactive power from the WPP is utilized to a lower extent, as feeder voltage control is significantly accomplished by all PVPs and therefore less dependent on reactive power support by the WPP.

Enhanced reactive power capability of Photovoltaic power plants reduces the reactive power utilization rate of all ReGen plants in the grid!

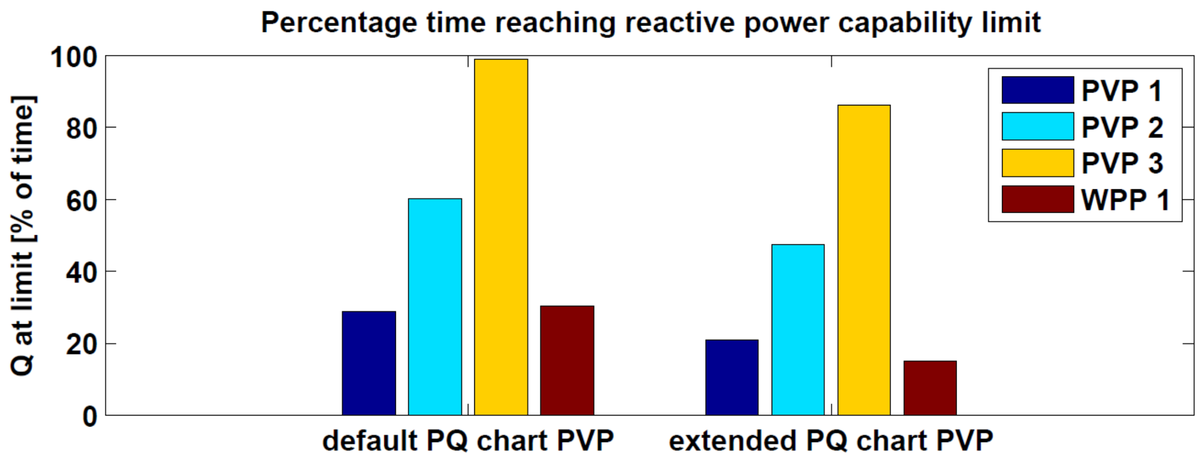


Figure 61: Reactive power utilization rate of ReGen plants for various PQ charts of PVP ($V_{grid} = 1.05\ pu$)

With regard to occurring power losses, the extended PQ chart of PVPs plays a minor role, as the loss increase due to additional reactive power support is almost balanced by less reactive power provision by the WPP. The loss increase amounts to only maximum 0.2 % compared to a test scenario with the default PQ chart for PVPs.

7.5 Summary

The performance of the developed controls can be summarized and evaluated according to Table 15:

Table 15: Evaluation of control concepts for off-line coordination

Control Concept	Voltage profile management	Stability of voltage control	Voltage fluctuations	Reactive power utilization of ReGen plants	Power losses
1 – Manual Droop Setting	☺	☹	😐	☹	☹
2 – Distributed Off-Line Coordination					
a) with default PQ chart of PVPs	☺	☺	😐	😐	😐
b) with extended PQ chart of PVPs	☺	☺	☺	☺	😐

The overall performance for voltage profile management is sufficient for both control concepts, as the voltage profile along the feeder is kept within the tolerance band margins of ± 10 %.

Control concept 1 can lead to temporary instability problems, if the droop characteristic of ReGen plants is too flat. On the other hand, deriving droop settings according to the system needs by V-Q-sensitivity analysis (Control Concept 2) will lead to stable operating points.

Voltage fluctuations are similarly present for both control concepts 1 and 2.a. PVPs may feature too little capacity, when dimensioned according to the present grid code requirements, and can thereby amplify voltage fluctuations. Mitigating voltage fluctuations can only be accomplished, if sufficient reactive power capability is ensured by all ReGen plants (Control concept 2.b).

Reactive power utilization is satisfactory for Control Concept 2.a, though hitting the limits during large voltage excursions, which is again due to the limited Q capability of PVPs. However, if the specified droop characteristic is too flat, Control Concept 1 can lead to unnecessarily high reactive power utilization of all ReGen plants, so that the distribution system lacks reactive power that would be required during emergency situations. Enhanced reactive power capability of PVPs (Control concept 2.b) reduces the reactive power utilization rate of all ReGen plants in the grid.

Power losses within the distribution grid are increased by voltage droop control for both control concepts. The more the ReGen plants contribute with reactive power provision, the higher the line losses. Consequently, Control Concept 1 can cause slightly higher power losses than Control Concept 2, if the droop characteristic is relatively flat.

8 Time Domain Analysis for On-Line Coordination

In this chapter time domain analyses are performed in order to test one concept for on-line coordination of voltage control (Control Concept 3), as developed in chapter 6. The system models described in chapter 4 are used to analyze voltage control in time domain for a volatile power profile of the ReGen plants, used as a benchmark test scenario that covers the crucial operating points with high solar irradiation and high wind speed (see chapter 7). The ReGen plants models are implemented in *MATLAB/Simulink* and the phasor model of the BDG is implemented in OpalRT's real-time simulation platform *ePHASORsim*. However, it is used for off-line simulations in this chapter, as on-line validation including the ICT layer will be part of work package 5.

It has been ascertained in chapter 7 (see summary in Table 15) that Control Concept 2 (Distributed Off-Line Coordination) provides satisfactory results with respect to voltage profile management and control stability. Moreover, if all ReGen plants have available sufficient reactive power capacity, i.e. with extended PQ chart for PVPs, this method for control coordination leads to improvement of the voltage fluctuations index and the reactive power utilization rate.

However, voltage droop control increases the power losses, since the reactive power absorption of ReGen plants causes higher current loading of the lines. For simulating the system with extended PQ chart of PVPs, the mean value of measured power loss accounts for 5.82 % of the total power generation in the distribution feeder, thereby increased by 1.32 % in comparison to disabled voltage control. This percent value seems relatively small, but expressed in absolute numbers this amounts to an average loss increase of around 330 kW. Reducing the power losses can benefit the DSO that aims for maximum power provision to the end-consumers.

Hence, in this chapter it will be evaluated, whether on-line coordination of voltage droop settings can decrease the power losses, while maintaining good performance with regard to the remaining evaluation criteria, i.e. voltage profile management, control stability, voltage fluctuations and reactive power utilization rate.

Two options for on-line coordination are taken into consideration: a) updating the voltage droop values and b) updating the voltage setpoint of the ReGen plants respectively. A reduction in power loss of around 0.5 % is considered significant for rating on-line control coordination as a meaningful control concept.

8.1 Option 1: Updating Droop Values

The key essence of Control Concept 2 is to derive the voltage droop values according to the actual grid characteristics and operational grid conditions. For the test scenarios of voltage sensitivity analysis in chapter 5 it has been presumed that there reactive power support by ReGen plants is disabled, as this constitutes a starting point to analyze how reactive power contribution would affect the voltage levels. The droop values for Control Concept 2 have been obtained accordingly. However, it needs to be investigated whether the actual reactive power operating point will alter the $\delta V/\delta Q$ indices and therefore the optimal droop settings to be derived during operation.

8.1.1 V-Q Sensitivity Indices

Following conclusions are made for voltage sensitivity analyses with various reactive power operating points of ReGen plants:

- The higher the reactive power injection (positive Q) by ReGen plants, the lower the resulting indices of the V-Q sensitivity matrix
- The higher the reactive power absorption (negative Q) by ReGen plants, the higher the resulting indices of the V-Q sensitivity matrix

Now, in order to quantify the change in sensitivity indices, the results of the time-domain analysis are used as a reference point. For the time period of one hour, it is to be determined when the largest amount Q is absorbed by the ReGen plants (Q_{min}). For this particular operating point we would expect the largest deviation in V-Q sensitivity compared to the operating point without reactive power support by ReGen plants.

This point is found under the conditions given in Table 16 and resulting in the V-Q sensitivity indices as per Figure 62.

Table 16: Minimum Q of ReGen plants

	PVP 1	PVP 2	PVP 3	WPP
P [MW]	7.93	2.35	1.54	17.83
P [pu]	0.79	0.94	0.62	0.99
Q_{min} [Mvar]	- 3.01	- 0.84	- 1.97	- 5.93

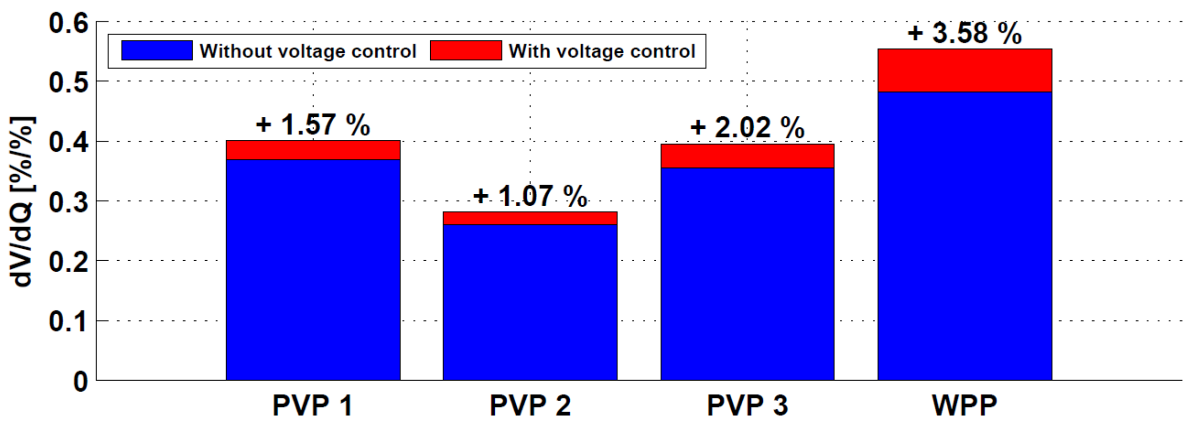


Figure 62: Diagonal elements of δV/δQ sensitivity matrix for PoC of ReGen plants - without and with voltage control

The blue-colored bars in Figure 62 show the δV/δQ sensitivity indices obtained for the droop settings in Control Concept 2. The red-colored bars show the maximum δV/δQ sensitivity indices obtained, if the droop settings were updated by an on-line sensitivity analysis, taking into account the actual active and reactive power operating point of the ReGen plants. As illustrated, δV/δQ is augmented by minimum 1.07 % and maximum 3.58 %.

Increased V-Q-sensitivity at the PoC of a certain ReGen plant means that the respective droop setting to be derived should take a larger value, thus leading to a steeper droop characteristic. This means that the ReGen plants will provide less dQ for a given voltage change dV. Hence, if we update the droop settings during operation, we may expect less reactive power flow within the grid, in this way fewer power losses across the lines. It is to be evaluated whether altering the droop values will have a significant impact on the power losses.

8.1.2 On-Line Voltage Sensitivity Analysis

Therefore voltage sensitivity analysis for the distribution feeder needs to be performed by the aggregator in regular time intervals. The in- and outputs are specified in Figure 63. The DSO needs to provide the grid data such as transformer and line parameters. Measurement signals for P and Q are delivered by the ReGen plants. P and Q by the consumers are provided by means of historical load profile data, as we would not expect measurement units at the load centers. However, it has been stated previously that load variations have a minor impact on the sensitivity analysis in contrast to the highly volatile behavior of renewable generation. Voltage sensitivity analysis is performed at certain time intervals T_s. Therefore the data from measurements and load profiles will be averaged over the respective time interval.

The output of the voltage sensitivity analysis generates the updated δV/δQ indices , which are used to update the droop settings of each ReGen plant.

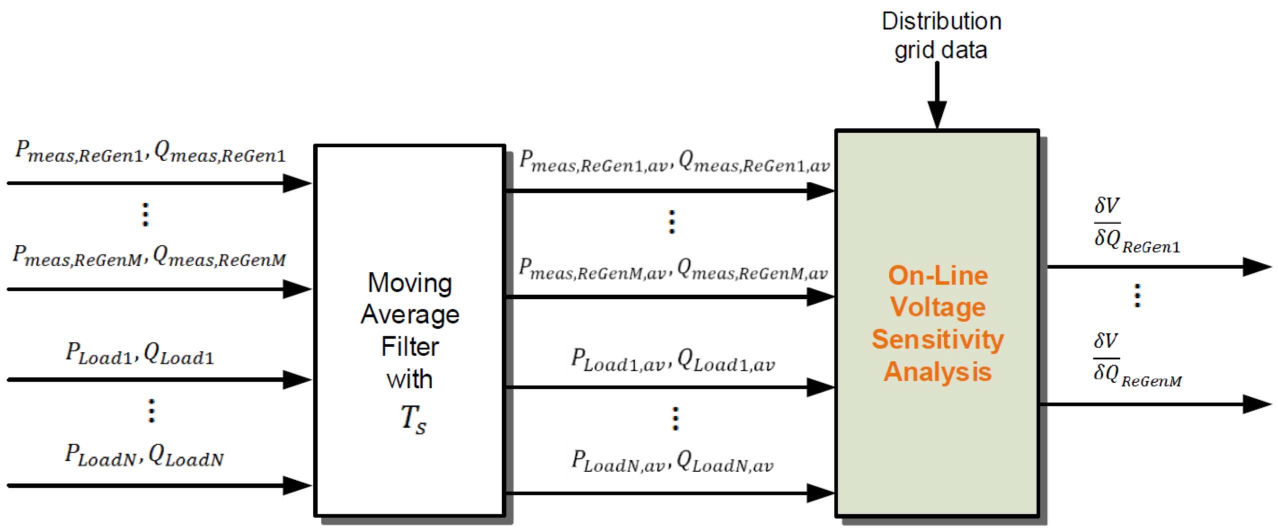


Figure 63: Scheme for on-line voltage sensitivity analysis

8.1.3 Test Cases

For adjusting the droop settings a definite update rate needs to be specified. According to [37] low sampling rates are recommended for reactive power compensation at MV level to account for large power fluctuations. It is suggested to use sampling rates **between 10 seconds and 15 minutes**, also considering the memory capacity of the recording data logger.

Various update rates T_s are considered to evaluate how droop settings of the ReGen plants will change during operation for the benchmark test scenario of one hour and what impact it has on the power losses within the grid:

1. $T_s = 15$ min.
2. $T_s = 5$ min.
3. $T_s = 1$ min.

4. $T_s = 10$ sec.

8.1.4 Test Results

Figure 64 shows the course of the voltage droop value over time under various update rates, exemplary for the WPP voltage controller. It can be seen that the varying droop value exceeds the default value (Control Concept 2) throughout the whole time period. This is due to the fact that for the majority of time the total amount of reactive power provided by the ReGen plants is $Q_{min} < 0$, leading to increased δV/δQ sensitivity indices and thereby increased droop values.

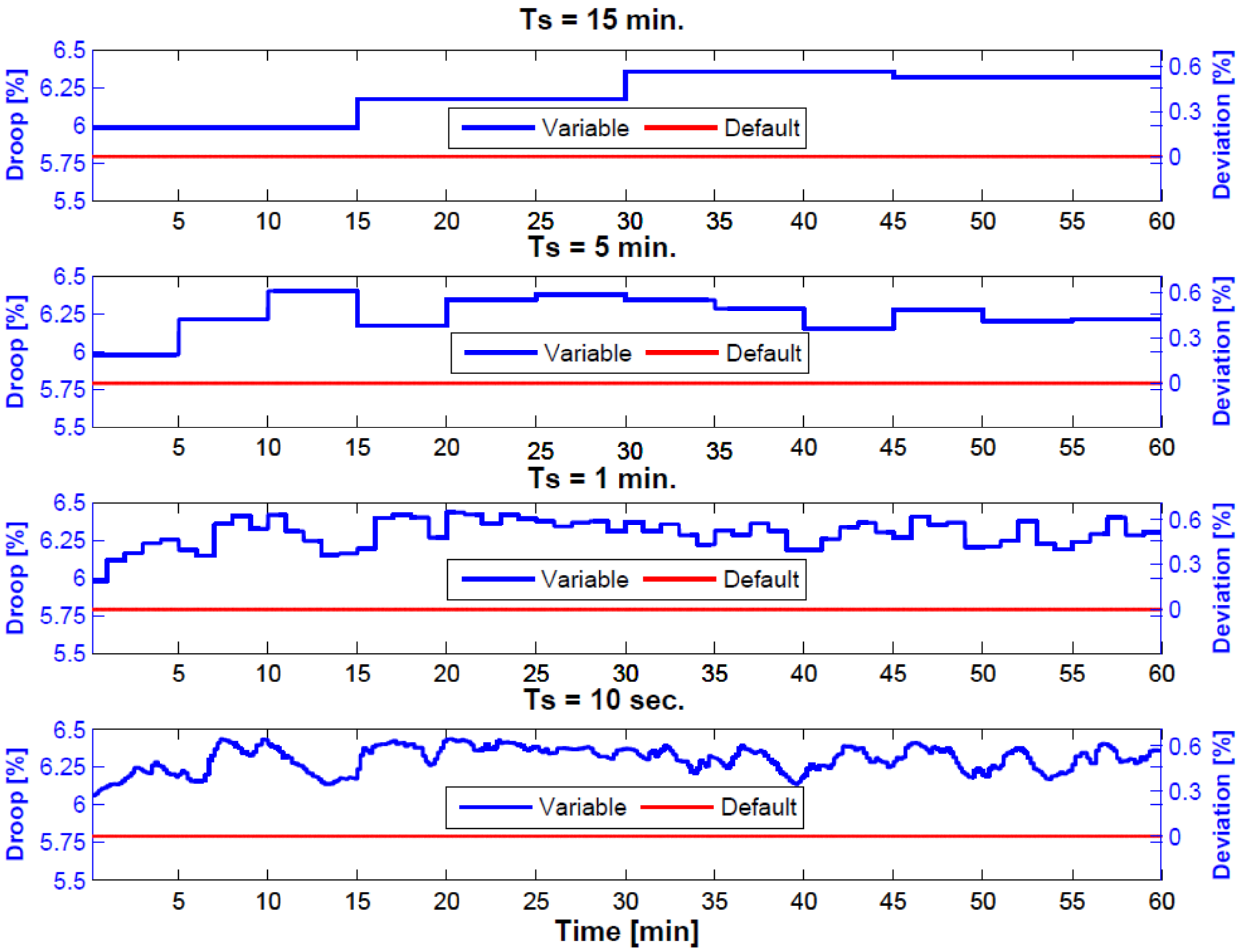


Figure 64: Default and variable voltage droop value for the WPP dependent on the update rate Ts

Similar results as in Figure 64 are obtained for the droop values of the PVPs.

The maximum deviation between variable and default droop values amounts to 0.65 %, obtained for the WPP voltage controller. When evaluating the power losses within the grid, it is ascertained that this change does have negligible impact, independent of the selected update rate for the droop settings. The maximum decrease in line losses amounts to 10 kW, which is 0.045 % of the total power generation by the ReGen plants.

Moreover, the change in droop values has negligible impact on the remaining evaluation criteria, i.e. voltage profile management, control stability, voltage fluctuations and reactive power utilization rate.

Performing on-line voltage sensitivity analysis in order to update the droop settings according to the actual operating point of ReGen plants does not significantly reduce the power losses within the distribution grid!

8.2 Option 2: Updating Voltage Setpoints

Another controller variable in the ReGen plant voltage controller, besides the droop value, is the voltage setpoint V_{stp}. Typically it is set to $V_{stp} = 1\,pu$ in order to target nominal voltage by providing reactive power. However, regarding the power losses within the grid, we may tolerate voltages which solely fulfill the tolerance band margins of ± 10 %, as long as a significant reduction of power losses is achieved.

Having this consideration in mind, it may not be necessary to provide reactive power support, as long as the voltage value is sufficiently below the upper limit of 1.1 pu. In other words, voltage control needs to be active, if the voltage takes on a certain critical value, denoted by V_{cr}. As per Figure 65, the voltage setpoint can be adjusted according to the actual measured voltage $V_{meas,av}$, as long as the measured voltage does not exceed the critical value. The measured voltage is averaged over the time period T_s, depending on the selected update rate for the setpoint.

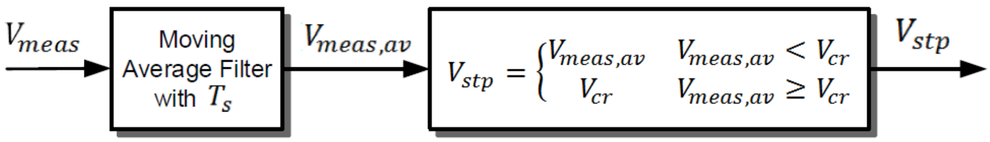


Figure 65: Algorithm for updating the voltage setpoint

For selecting the proper value of V_{cr} it needs to be ensured that the voltage profiles come below the threshold of 1.1 pu. Initial simulations have revealed that a margin of 5 % is sufficient for the voltage droop controller to regulate the voltage according to the requirements, even under extreme conditions with an external grid voltage of $V_{grid} = 1.05\,pu$, so that the following value is assigned:

$$V_{cr} = 1.05\,pu$$

8.2.1 Test Cases

For adjusting the voltage setpoint of each ReGen plant a definite update rate needs to be specified. Equally to Option 1 (Updating Droop Values), the following update rates T_s are considered to evaluate their impact on the power losses within the grid:

1. $T_s = 15$ min.
2. $T_s = 5$ min.
3. $T_s = 1$ min.
4. $T_s = 10$ sec.

8.2.2 Test Results

Figure 66 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of one hour, for both Control Concept 2 (CC 2 - constant voltage setpoint) and Control Concept 3 (CC 3 - various update rates for voltage setpoint).

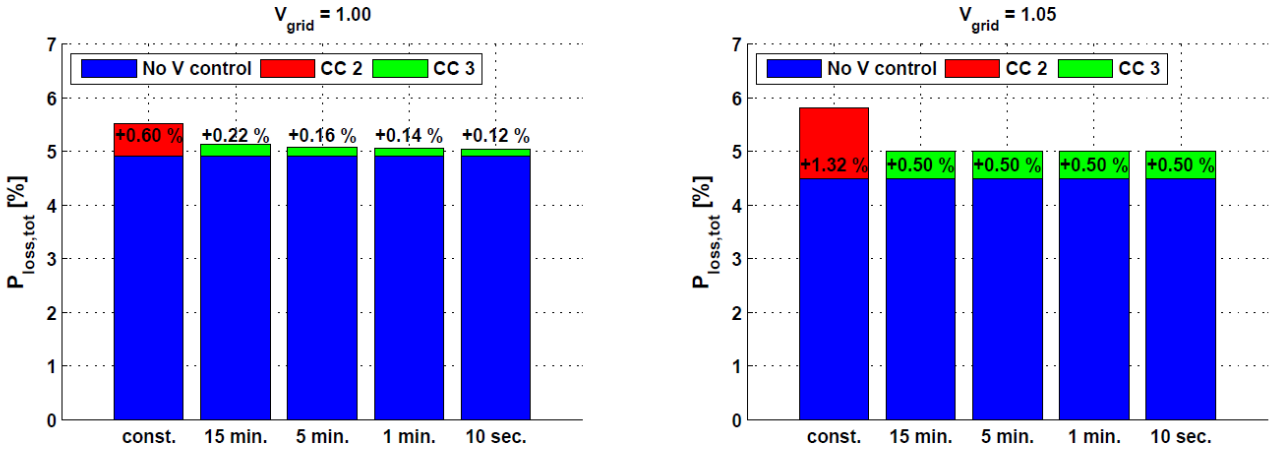


Figure 66: Power losses for various update rates Ts of voltage setpoint (left: $V_{grid} = 1.00\ pu$, right: $V_{grid} = 1.05\ pu$)

Comparing both control concepts shows that the power losses can be reduced by maximum 0.48 % (for $V_{grid} = 1.00\ pu$) and 0.82 % (for $V_{grid} = 1.05\ pu$), which in absolute numbers amounts to an average loss decrease of around 120 kW and 200 kW respectively.

By comparing various update rates for the voltage setpoint, no differences in the power losses are observed for $V_{grid} = 1.05\ pu$. This is due to the fact that the measured voltages along the feeder exceed the critical value ($V_{meas,av} \geq V_{cr}$) for the majority of time, hence the voltage setpoints are hold ($V_{stp} = V_{cr}$) independent of the update rate.

In the case of $V_{grid} = 1.00\ pu$, the power losses increase slightly for longer time intervals between updating the voltage setpoints. Here, as shown in Figure 67 to Figure 70, the measured voltages deceed the critical value for the majority of time ($V_{meas,av} < V_{cr}$). Hence, the voltage setpoints follow the averaged measured values $V_{stp} = V_{meas,av}$. However, since the mismatch between measured (V_{meas}) and averaged voltages ($V_{meas,av}$) increases for larger update rates T_s, the voltage droop controller of the ReGen plants will dispatch reactive power depending on the present voltage variations in the PoC. In Figure 67 to Figure 70 it can be observed how the update rate affects the reactive power provision of each ReGen plants. Based on the results for PVP 2 (Figure 68) it can be seen that reactive power is close to zero for $T_s = 10\ sec.$, while for longer time update intervals significant reactive power excursions occur.

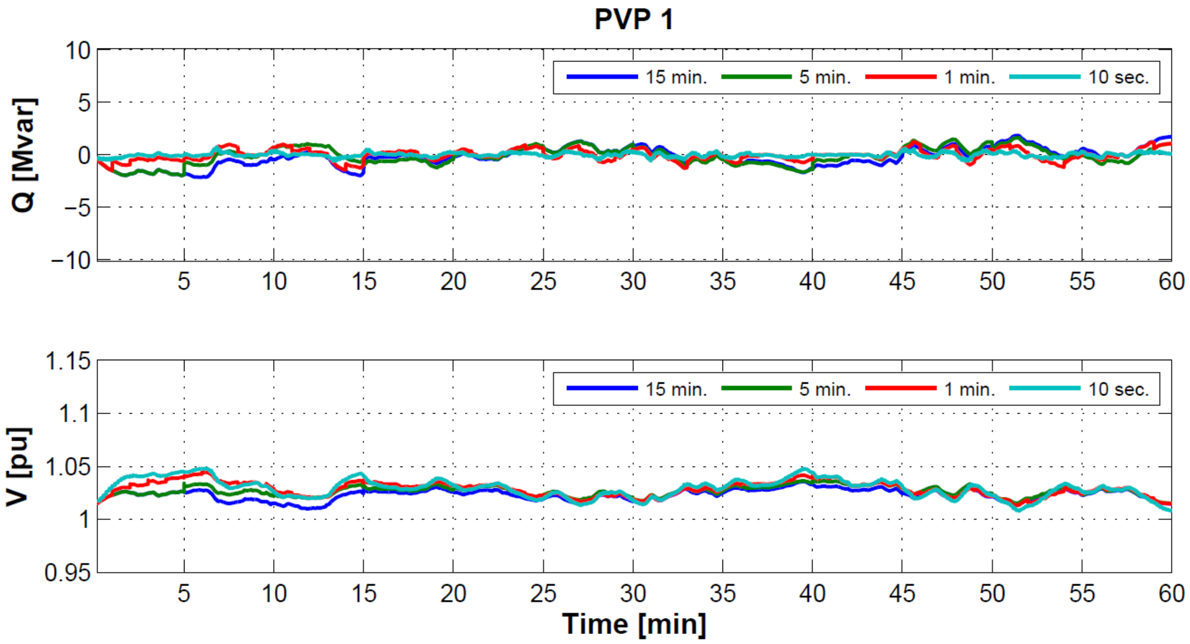


Figure 67: Q and V of PVP 1 over one hour for various update rates Ts for voltage setpoint and grid voltage of $V_{grid} = 1.00\ pu$

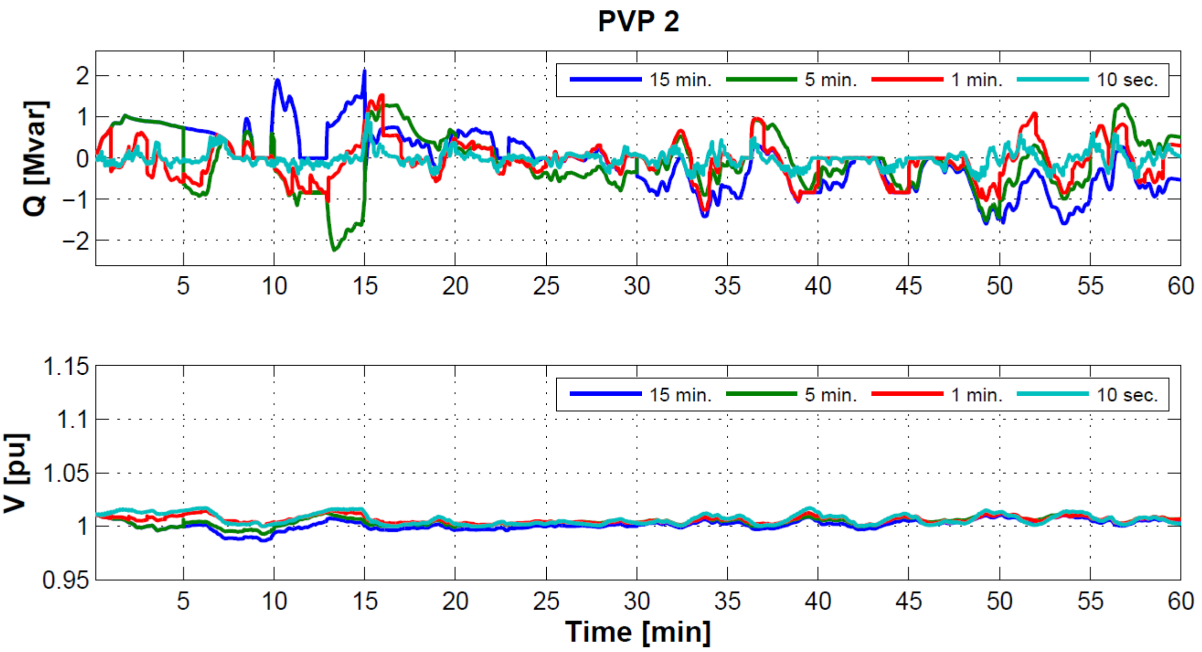


Figure 68: Q and V of PVP 2 over one hour for various update rates Ts for voltage setpoint and grid voltage of $V_{grid} = 1.00\ pu$

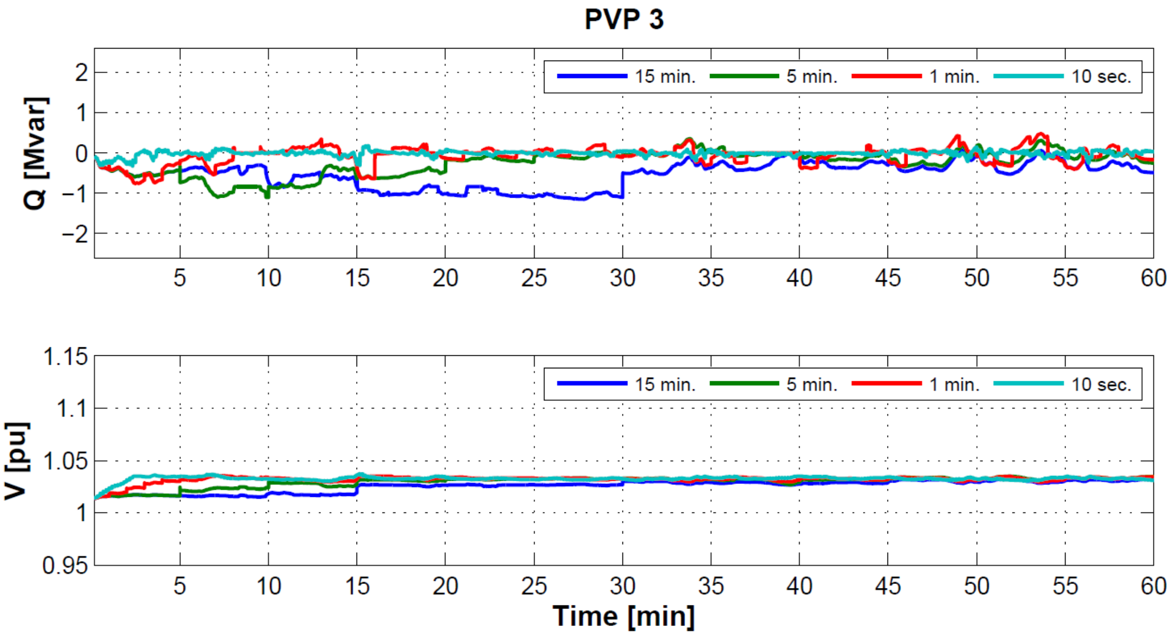


Figure 69: Q and V of PVP 3 over one hour for various update rates Ts for voltage setpoint and grid voltage of $V_{grid} = 1.00\ pu$

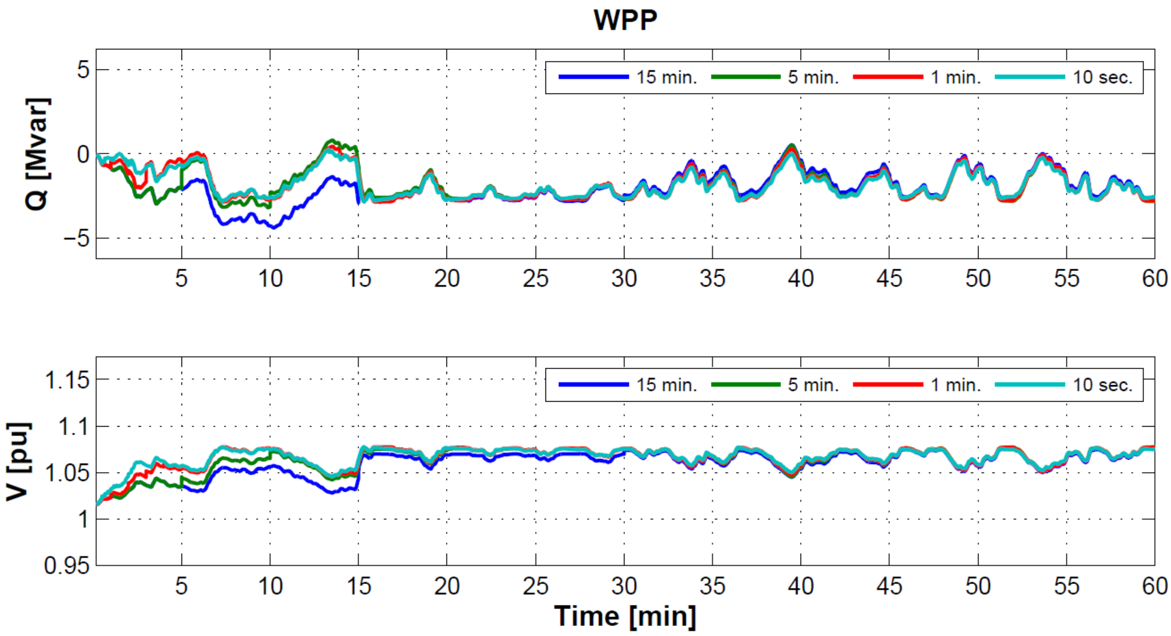


Figure 70: Q and V of WPP over one hour for various update rates Ts for voltage setpoint and grid voltage of $V_{grid} = 1.00\ pu$

With respect to reactive power utilization of the ReGen plants it is expected that updating the voltage setpoints reduces the amount of time, when ReGen plants operate at their Q capability limit. Figure 71 shows that reactive power utilization rate of all ReGen plants is lowest for the fastest update rate of $T_s = 10\ sec$.

Updating the voltage setpoints according to the actual operating point of ReGen plants reduces the power losses within the distribution grid to a measurable extent and simultaneously further decreases the reactive power utilization rate of the ReGen plants, in comparison to Control Concept 2 (Distributed Off-Line Coordination)!

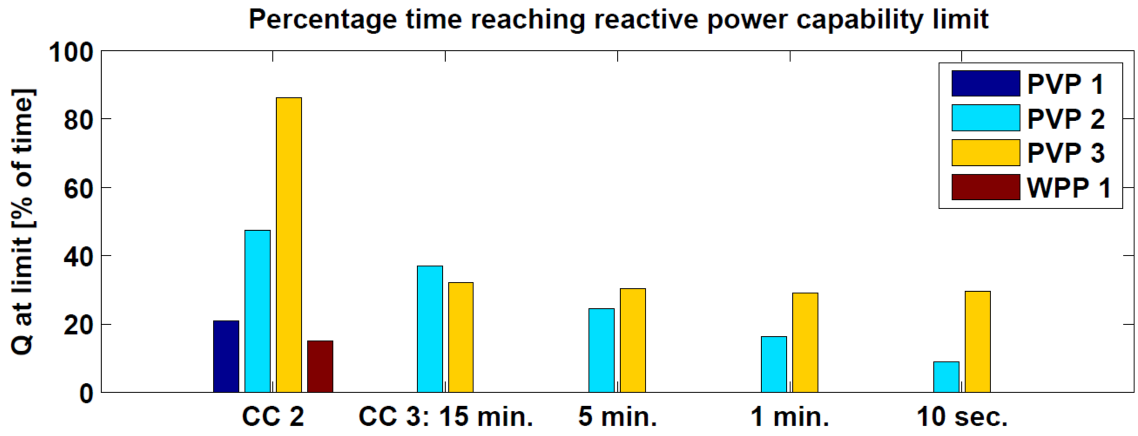


Figure 71: Reactive power utilization rate of ReGen plants for various update rates for the voltage setpoint ($V_{grid} = 1.05\ pu$)

Concerning the present fluctuations of the feeder voltages, Figure 72 and Figure 73 present the VFI at all system busses for Control Concept 2 and Control Concept 3 with various update rates of the voltage setpoint. Small differences are observed depending on the operational conditions of V_{grid} and the selected update rate.

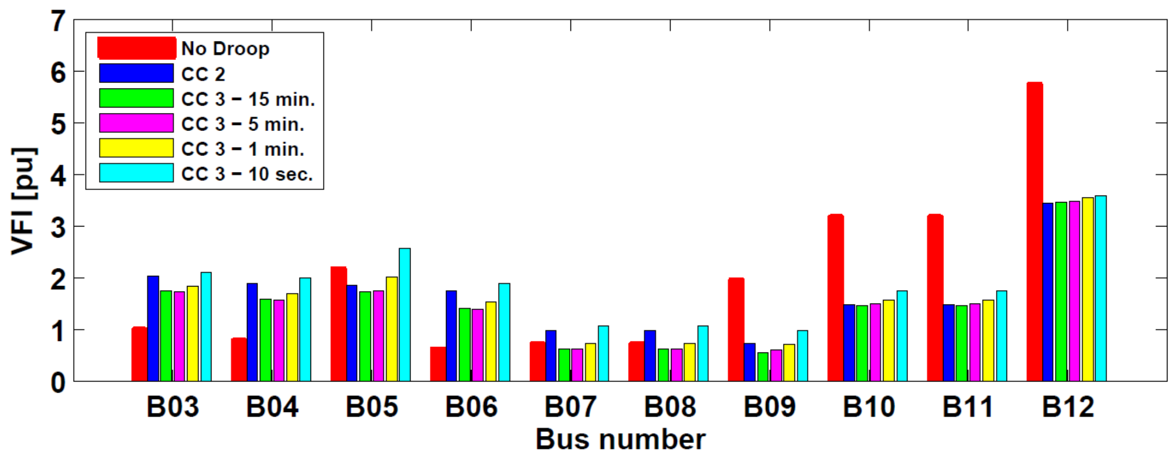


Figure 72: VFI for all MV busses and various various update rates for the voltage setpoint and grid voltage of $V_{grid} = 1.00\ pu$

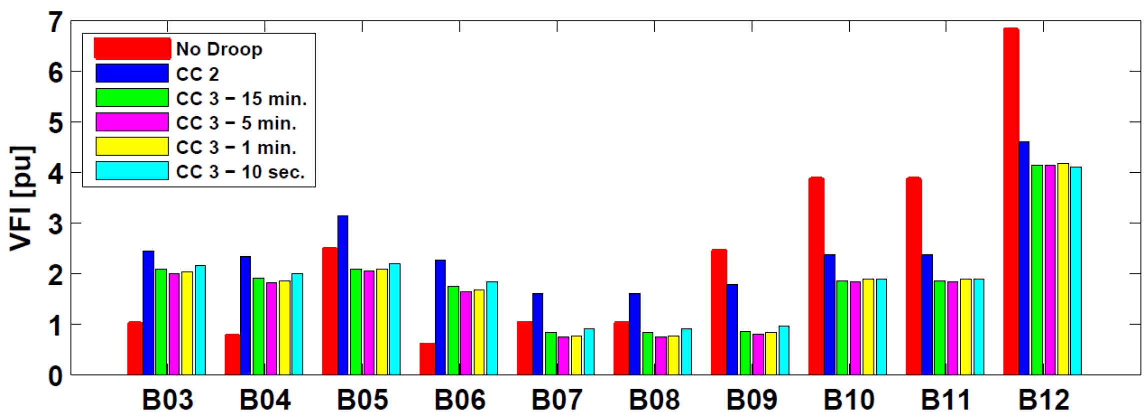


Figure 73: VFI for all MV busses and various various update rates for the voltage setpoint and grid voltage of $V_{grid} = 1.05\ pu$

All in all, Control Concept 3 does not deteriorate the present voltage fluctuations in comparison to Control Concept 2!

8.3 Summary

The performance of the Control Concept 3, for both considered options, can be summarized and evaluated according to Table 17:

Table 17: Evaluation of control concepts for on-line coordination

Control Concept	Voltage profile management	Stability of voltage control	Voltage fluctuations	Reactive power utilization of ReGen plants	Power losses
3 – Distributed On-Line Coordination					
Option 1: Updating Droop Values	☺	☺	☺	☺	😐
Option 2: Updating Voltage Setpoints	☺	☺	☺	☺☺	☺

The overall performance of On-Line Coordination for voltage profile management, control stability and the present voltage fluctuations is satisfactory and in this context not noticeably altered in comparison to Off-Line Coordination.

With regard to reactive power utilization of ReGen plants, Option 2 (Updating Voltage Setpoints) can benefit by limiting the time periods of providing reactive power to situations where the voltage profile is prone to violate the tolerance band margins of ± 10 %.

The power losses within the distribution grid are reduced to a measurable extent. It requires further analyses concerning the intervals at which the voltage setpoints are to be updated. The considered test scenario of one hour shows a tendency that the aggregator should dispatch setpoint signals to ReGen plants in time intervals of 10 seconds rather than of several minutes. However, power losses need to be evaluated for longer time periods (months or years) in order to provide meaningful recommendations for the controller specifications, taking into account the economic benefits for a DSO.

On the other hand, it is ascertained that Option 1 (Updating Droop Values) should not be considered for enhancing the performance of control coordination. The results of the study cases show that one-time determination of the droop values according to an initial system analysis (Control Concept 2) is sufficient, as the voltage sensitivity indices are insignificantly dependent of the operating grid conditions.

9 Communication Properties for On-Line Coordination

RePlan considers three ancillary services (AS) which are needed to ensure the system stability comprising both transmission and distribution level, detailed in Deliverable D1.1 [17]. These ancillary services vary in their scope and importance for the electrical grid stability. Thus, the requirements imposed on the ICT infrastructure should reflect the range of applications. However, a common requirement shared by all three services is a reliable and secure communication infrastructure. The individual ancillary service therefore has to be able to deal with impairments up to a complete breakdown of parts of the ICT infrastructure. For instance, if an interface exhibits increased latency, while the data rate decreases, possibly due to network congestion, this has to be detected and acted upon.

9.1 Communication Network Infrastructure

In order to have voltage stability support from ReGen plants to ensure the system stability, these plants should have a resilient online coordination with the aggregator control unit which, however, depends on the requirements imposed on the ICT infrastructure. Latency, data rate, redundancy, serviceability, reliability, costs of deployment and ownership are factors which define the requirements and finally lead to a choice of technologies presented in Deliverable D1.1 [17]. These requirements have been considered by taking into account a benchmark grid area around Støvring in Region Nordjylland in the geographic region of the Jutland peninsula known as Himmerland in Northern Denmark. Topologies and basic information about the same geographical area is used as a basis for all assessments.

The aggregator control unit (could be a hardware control unit) can be placed at the primary substation or far away somewhere else in Denmark at any control center. The distance between ReGen plants and the Aggregator can be one of the external influences on latency as well as other communication properties presented in [17]. This distance may have an impact on the time a signal takes to go from a ReGen plant to the aggregator, especially when ReGen plants and the aggregator operate on different carrier networks. To see how the measurements are influenced by being on different networks, the topology of Internet need to be investigated.

The Internet is a network of networks having a hierarchical structure consisting of regional, national and international Internet Service Provider (ISP) networks. End systems access the Internet through Internet Service Providers (ISPs), including residential ISPs such as local cable or telephone companies etc., as shown in Figure 74. Each ISP is in itself a network of packet switches and communication links. ISPs provide a variety of types of network access to the end systems, including residential broadband access such as cable modem or DSL, high-speed local area network access, wireless access, and 56 kbps dial-up modem access. ISPs also provide Internet access to content providers, connecting Web sites directly to the Internet (shown with a yellow path in Figure 74). The Internet is all about connecting end systems to each other, so the ISPs that provide access to end systems must also be interconnected. These lower-tier ISPs are interconnected through national and international upper-tier ISPs such as Level 3 Communications, AT&T, Sprint, and NTT. An upper-tier ISP consists of high-speed routers interconnected with high-speed fiber-optic links. Each ISP network, whether upper-tier or lower-tier, is managed independently and conforms to certain naming and address conventions.

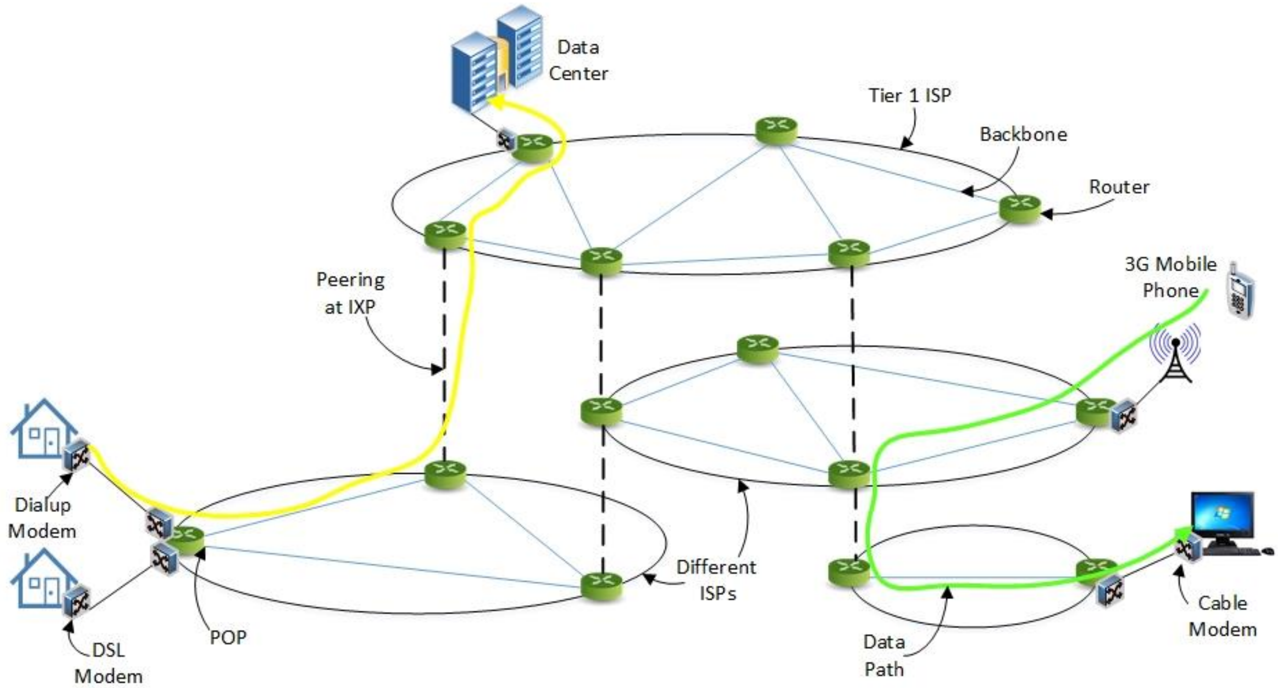


Figure 74: Overview of Internet Architecture [38]

Thus, to connect to the Internet, a controller/ReGen plant should connect to an ISP, from which the Internet access has been purchased. This lets them exchange information with all of the other accessible controllers/ReGen plants on the Internet. Here, as a base case we consider general purpose mobile networks as ISPs. There are, therefore, a number of ISPs available which are usually distinguished by how much bandwidth they provide and how much they cost, however, the most important attribute is connectivity.

The ISP network architecture is made up of long-distance transmission lines that interconnect routers at Point-of-Presence (POP) in the different cities that the ISPs serve. This equipment is called the backbone of the ISP. If an information packet is destined for a plant controller served directly by the ISP, it is routed over the backbone and delivered to that controller (shown in Figure 75 with green line). Otherwise, it must be handed over to another ISP (shown in Figure 75 with yellow line). The ISPs are connected to rest of the Internet through Internet eXchange Points (IXP). The IXP is where different ISPs connect and exchange information [39]. Therefore, for devices on different networks to communicate, the communication traffic needs to go through the IXP, even though the devices may physically be right next to each other. The connected ISPs are said to peer with each other.

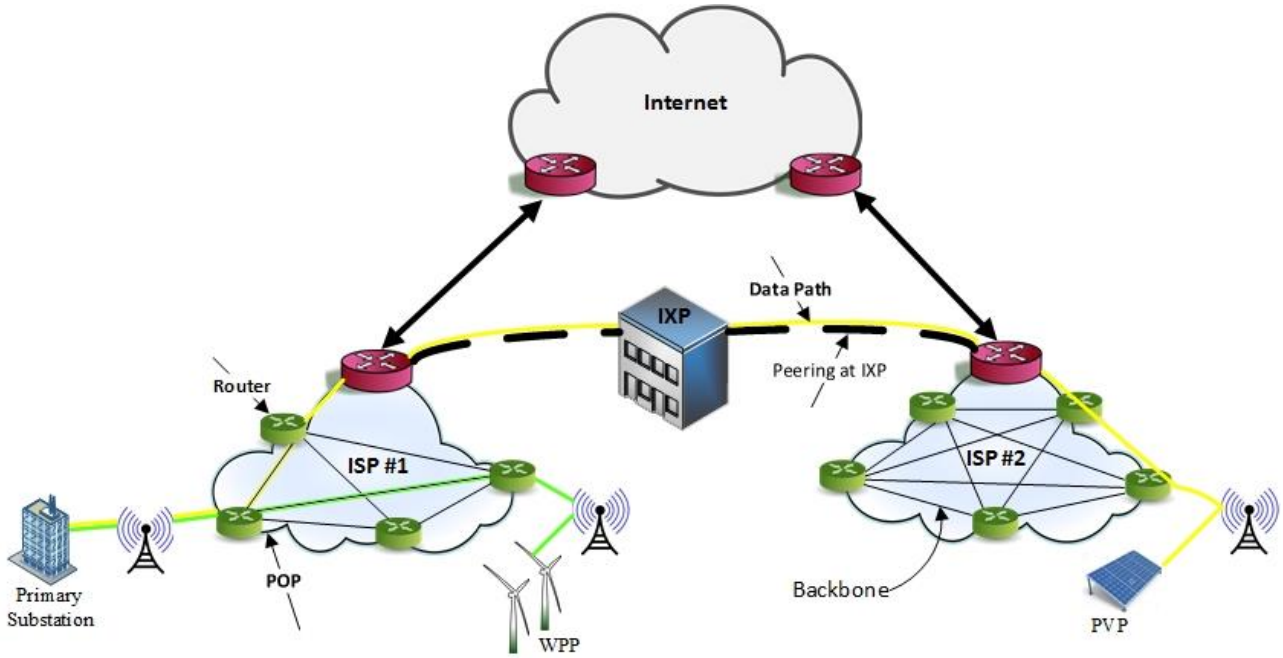


Figure 75: End-systems connected with same/different ISPs

In Denmark there are four IXPs i.e. in Lyngby, Ballerup, Skanderborg and Tåstrup [39], where a number of networks are connected to, which are connected to the rest of the Internet through other networks such as G´EANT and NORDUnet [40]. If the list of connected networks to the Danish Internet eXchange (DIX) is compared to the different available carriers/ISPs, it will be observed that the some of those are not directly connected at any DIX points. This is because these carriers are founded in other countries, and therefore have chosen to be connected to IXPs located in that particular country.

Consequently, for ReGen plants on other networks to connect to the server in aggregator control, the traffic will most likely go through any of the connected DIX. This means that the distance from ReGen plants to the server in aggregator control only varies from the DIX to the plants, due to different carrier networks. For instance, for the ReGen plants in Denmark using the Hi3G as an ISP, the traffic needs to go via Hi3G's network to the IXP Netnod in Stockholm [40] before reaching DIX and the aggregator. Whereas, if TDC is used as an ISP, the traffic only needs to go via TDC's network to the DIX in Lyngby before reaching the aggregator. This is, however, not taking the internal setup of the ISP networks into account, as this information is not freely available, which may vary a lot from ISP to ISP.

Figure 76 shows a GIS map for the particular benchmark grid (around Støvring) containing primary substation, ReGen plants (PVP 1, PVP 2, PVP 3, WPP) and placement of communication masts.

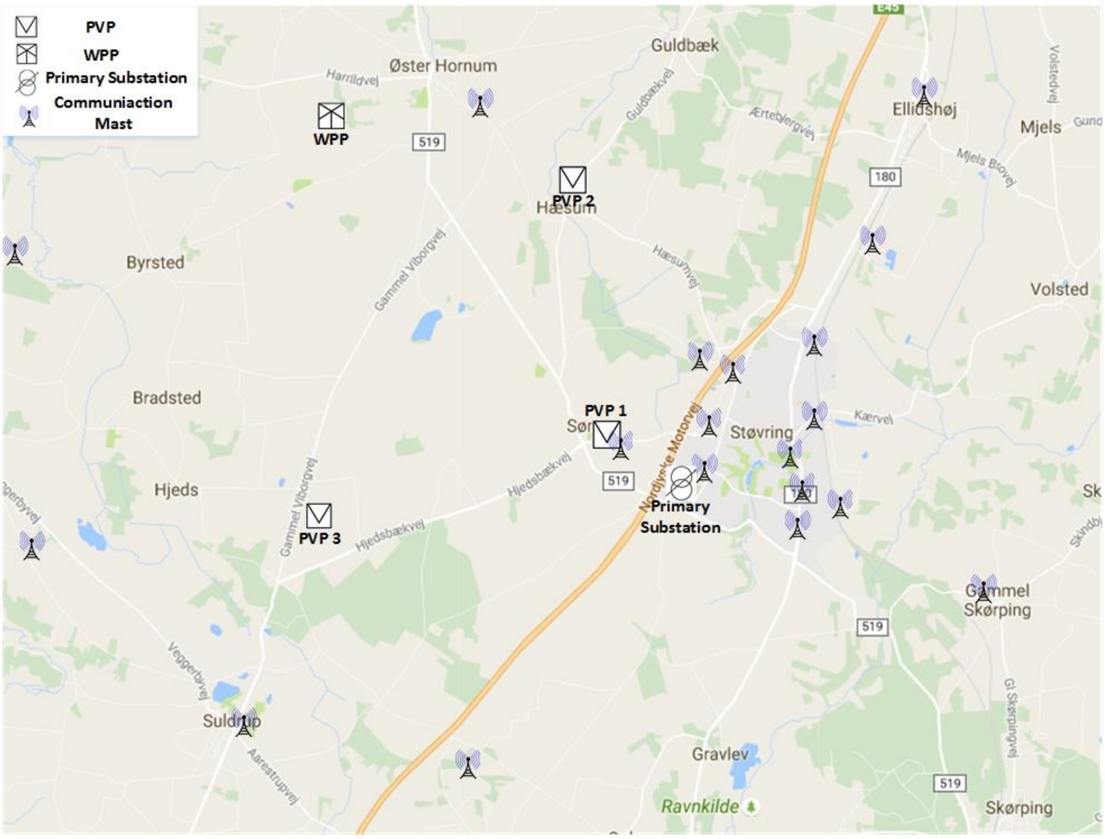


Figure 76: Layout of primary substation, ReGen plants and masts for wireless communication in the benchmark grid area

As can be seen from Figure 76, there are several communication masts around the grid assets. A plant controller/ReGen plant, however, usually connects to the nearest communication mast having the strongest signals. While associated with a mast, a controller periodically measures the strength of a beacon signal from its nearest mast (base-station) as well as beacon signals from nearby communication masts that it can "hear". These measurements are reported once or twice a second to the controller's current mast. A handoff (sometimes referred as handover) occurs when a controller changes its association from one communication mast to another while communicating with other end systems (e.g. ReGen plant controller). There may be several reasons for handoff to occur, including:

1. Current communication mast fails to operate.
2. The signal between current communication mast and the plant controller deteriorate to such an extent that the connection between a ReGen plant controller and the aggregator controller is in danger of being dropped.
3. Cell becomes overloaded, handling a large number of users. This congestion may be alleviated by handing off the connected stations to less congested nearby cells.

Communication between two end systems is initially (before handoff) routed through one communication mast, and after handoff is routed through another mast. It is important to note that a handoff between masts results not only in the controller transmitting/receiving to/from a new mast, but also in the rerouting of the ongoing communication from a switching point within the network to the new mast. All this would ultimately add to the delays in sending update information from a ReGen plant controller to the aggregator control unit. The amount of delay depends on network/system configuration and algorithms used for handoff services.

9.2 Transport Layer Protocol

The wireless networks differ significantly from their wired counterparts at both the link layer (as a result of wireless channel characteristics such as fading, multipath, and hidden terminals) and at the network layer (as a result of handoffs to change points of attachment to the network). There are, nevertheless, important differences at the transport layer as well. Transport protocols in general, and TCP in particular, can sometimes have very different performance in wired and wireless networks, and it is here, in terms of performance, that differences are manifested.

Since IEC-61850 and other related protocols and standards communicate over the TCP/IP protocol, only TCP is considered here despite of the possibility of using other transport protocols. As described in Deliverable D1.1 [17], TCP retransmits a segment that is either lost or corrupted on the path between sender and receiver. Therefore, packet loss in TCP is mapped into higher delays in communication. In case of wireless networks, loss can result from either network congestion (router buffer overflow) or from handoff (e.g., from delays in rerouting segments to a mobile's new point of attachment to the network). In all cases, TCP's receiver-to-sender ACK indicates only that a segment was not received intact; the sender is unaware of whether the segment was lost due to congestion, during handoff, or due to detected bit errors. In all cases, the sender's response is the same — to retransmit the segment.

Secondly, as a matter of fact, there is a three-way handshake to open a TCP/IP connection, and a four-way handshake to close it. However, once the connection has been established, if neither side sends any data, then no packets are sent over the connection. TCP is an idle protocol, happy to assume that the connection is active until proven otherwise.

Thus, there can be two possibilities of using TCP as a transport layer protocol in this context:

1. The connection between sender and receiver remains established forever after the first three-way handshake.
2. The connection between sender and receiver is always established/terminated after sending update information.

In the first case, since the communication link is once established between the two communicating entities, it needs to remain alive. For this, a keep-alive packet is sent after a specific interval of time to check for the dead peers as well as preventing disconnections due to network inactivity. This generates an extra traffic which can have an impact on routers, firewalls and even result in higher cost to be paid to the ISP.

However, in the second case, an extra delay is added (although very small, i.e. of the order of few micro-seconds) to establish/terminate a connection every time an information update is sent.

9.3 Test Scenarios

As mentioned in section 9.1, the aggregator can be placed locally in the primary substation that caters all the ReGen plants in the pre-defined area or far apart anywhere else in Denmark having multiple control areas. This gives rise to the following two test scenarios:

9.3.1 Test Scenario 1 – Aggregator placed in primary substation

In this test scenario, the aggregator has been placed in the local primary substation present in the benchmark grid area shown in Figure 76. This is shown in Figure 77.

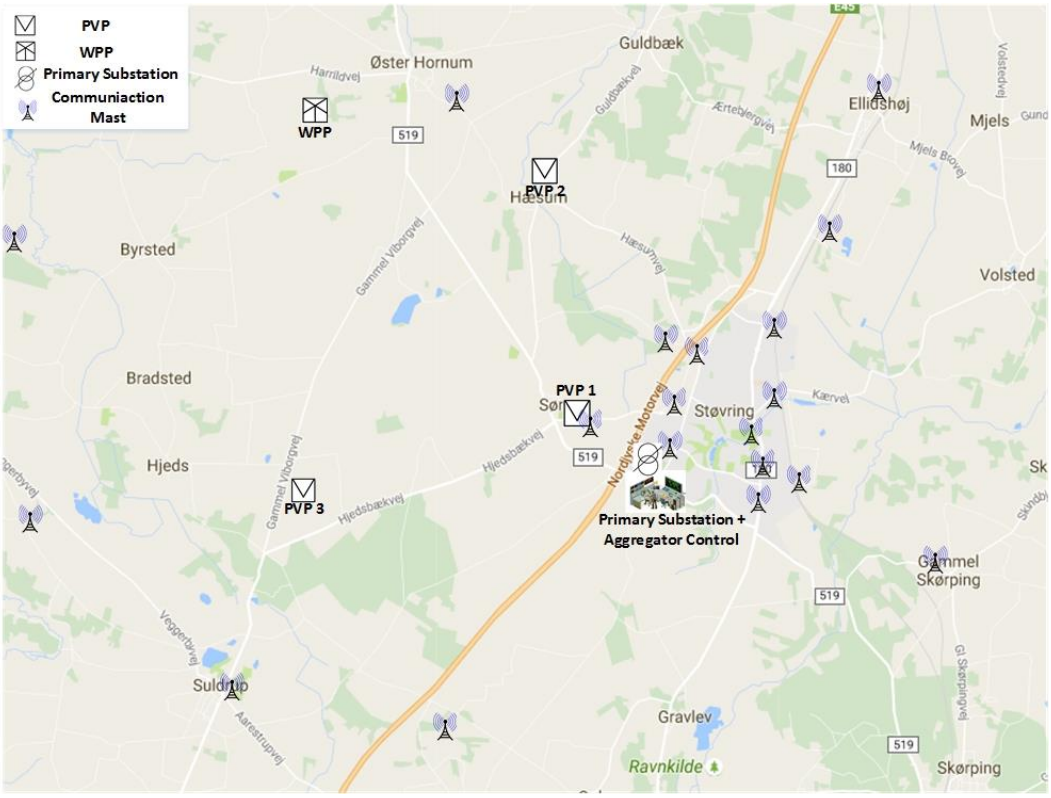


Figure 77: Concept of communication approach when aggregator is placed in local primary substation

9.3.2 Test Scenario 2 – Aggregator placed anywhere in Denmark

In the second test scenario, as shown in Figure 78, the aggregator control unit has been placed somewhere around 200 km away from the benchmark grid area. Multiple control stations are in charge of controlling several substations.

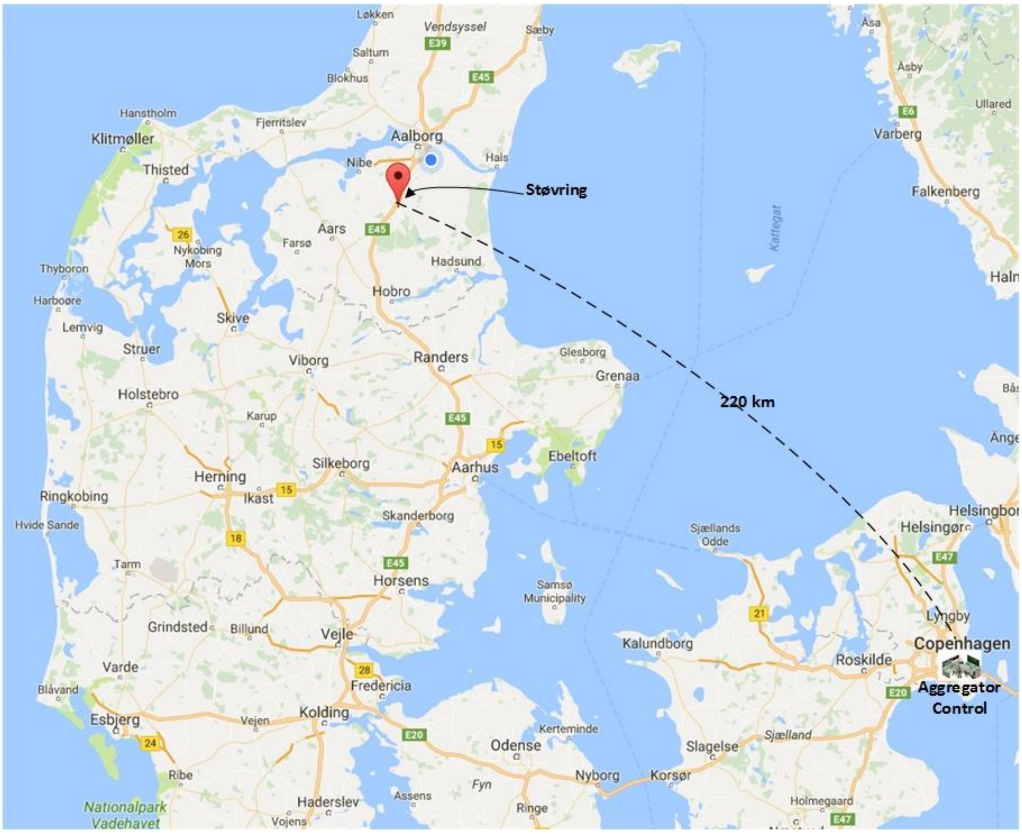


Figure 78: Concept of communication approach when aggregator is placed far away from the local primary substation

9.4 Test Cases

In order to get a realistic and accurate model of the network within the benchmark grid area, a system called NetMap [41] has been used. NetMap is a mobile network performance measurement system based on crowd sourcing, which continuously gathers information about the performance of the network connection from the device to the backbone of the connected network [41]. Based on the information gathered via NetMap a geographical Network Performance Map (NPM) of mobile networks can also be generated while mapping the performance of the devices [41].

NetMap has a clear advantage, as it offers a NPM based on actual measurements on existing networks, and by using actual end user devices in real end user scenarios. The NPM shows what network speeds to expect, based on real empirical and continuously updated data, and at the same time it provides a more realistic image of what the end system can expect as the measurements are performed with similar devices [41].

NetMap gives the measure of latency in the form of round trip times (RTT) measured using a large number of end devices located at different distances from the primary substation. Figure 79 shows the GIS map pointing out the location of the end devices from where the RTT values have been measured. The map shows relatively a good geographically spread of the devices, resulting in a decent coverage of the major area around the benchmark region.

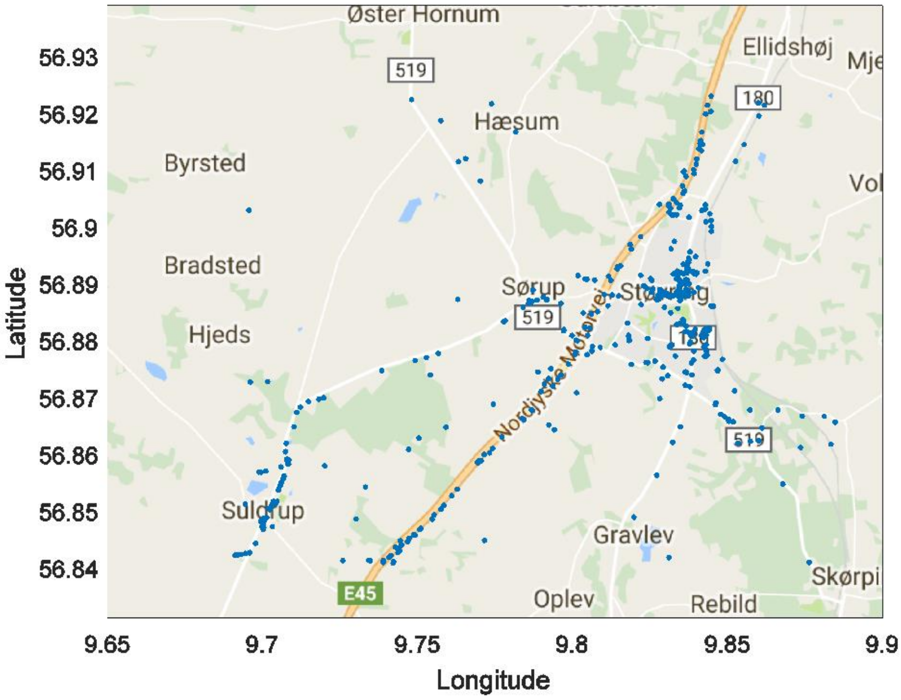


Figure 79: A geographical plot of the location of measurements in the benchmark region

9.4.1 Test Case 1 – End systems communicating via same/different ISP networks

As mentioned in section 9.1, ReGen plants and aggregator may operate on different carrier/ISP networks, which may influence the time an information packet takes to go from a ReGen plant to the aggregator control unit. But, since peering is used for exchanging traffic on the DIX and it is a bilateral agreement between two ISPs [39] for a certain service level, this change of ISPs does not make a huge difference. The delay may increase up to a few tens of milli-seconds (ranging between 10 – 50 ms). Similarly, there's a special peering called private peering which is used for connections between two ISP's going directly from one ISP to the other ISP, not passing the DIX switch [39]. Thus, in the present implementation, this change of ISP networks will have no significant effect on the end-to-end delay of information between the two end systems.

Figure 80 shows the distribution of RTT obtained from real time measurements for different locations of the end devices using different ISPs. However, there are different types of delay distributions that we may consider, e.g. deterministic and/or Erlang distribution, exponential distribution and heavy tailed as a part of the message. It can be observed in Figure 80 that for the maximum cases, RTT lies within the range of 30 ms, approximately, which means that a minimum of 15 ms (half of RTT) delay in the transfer of information update can be expected for the maximum times. However, this network being heterogeneous (shared by a large number of users), the delay may increase depending on the network conditions. In the worst case, this delay may jump to 500 ms, the frequency of occurrence of which is very rare, as seen in Figure 80.

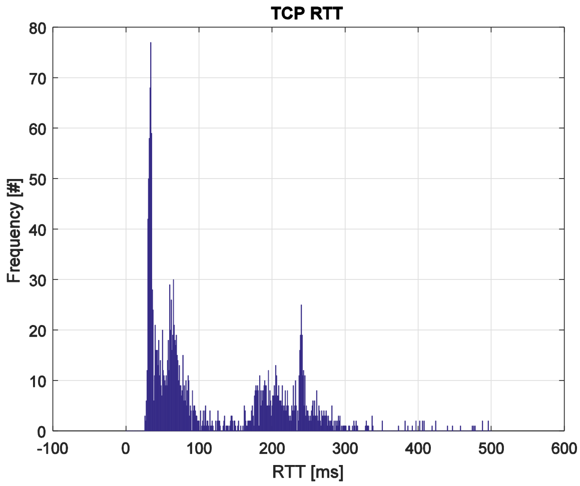


Figure 80: Distribution of TCP RTT measured around the benchmark region

Table 18: Identified latencies for test case 1 (end system communicating via same/different ISP networks)

Cases	Latency (RTT) [ms]	Description
Normal Performance	30	• ISP is the same within the network
Deviating Performance	30 – 50	• Different ISPs • Traffic goes via another IX point
	500	• Same/Different ISPs • Traffic may go via another IX point • Worst case

9.4.2 Test Case 2 – Communication Mast/Connection/Radio-Link Failure

In test case 2, we consider a case where, for instance, a plant controller has a radio connection with a certain base station (cell), and it suddenly fails. This failure can be due to equipment failure, radio link failure or any other problem within the base station. Although the probability of such failures is too low, but still can be expected and need to be considered while planning to rely for communication on public networks in critical systems like power grids. Anyhow, when such failures occur, there exist following two possibilities:

1. The area is covered by other cells
2. The area is not covered by other cells

1. The area is covered by other cells:

The end system detects that there is a problem at the physical layer, when it is out of synchronization for a certain number of consecutive times defined in a parameter by ISP [42]. A common value of this parameter is 20 times, but it can be much longer [42]. After detecting a physical layer problem, the end user starts a timer (let's call it T_1), configured by an ISP. If radio conditions are not experienced to be fair enough and T_1 expires, a Radio Link Failure (RLF) is declared. Afterwards, the end user attempts to re-establish the connection with the same cell, restarting the timer T_1. If, while the timer is running, the end user recovers the synchronization with the serving cell, it resets the timer and everything continues as it was (the recovery was possible).

If it does not succeed in a period of another time period T_2, the end user goes to an idle mode. Finally, it has to initiate the whole process, look for a suitable cell, connection setup and so on. This timer commonly is longer i.e. around 2 seconds but observed up to 5 seconds, for instance, in Telefónica's network. This timer is also configured by the ISP. A Handoff failure is declared if a RLF occurs during the handoff process. According to [42], the timer T_1 is parametrized with a value of 2 seconds. This large value assures that the end user has enough time to get back in synchronization after experiencing bad radio conditions and hence, avoiding RLF declaration. Similarly, a typical value for timer T_2 is 3s. Thus, the whole process may take few seconds to minutes and from few minutes to hours to recover, depending on the severity of the problem.

Now, once an end user in Automatic Mode has selected and registered on a VPLMN (Visitor Public Land Mobile Network) of its home country during the handoff process, it will make periodic attempts to return to its HPLMN (Home Public Land Mobile Network) [43]. The interval between attempts is stored in the SIM which is set by the ISP. The timer has a value between 6 minutes and 8 hours, with a step size of 6 minutes [43]. One value is designated to indicate that no periodic attempts will be made. In the absence of a permitted value in the SIM, or the SIM is phase 1 and therefore does not contain the data-field, a default value of 30 minutes is used by the end system [43].

2. The area is not covered by other cells

There are areas in the benchmark grid near ReGen plants where there is just one communication mast covering a larger area, as seen in Figure 76. If in such a case, the communication mast fails to operate and there's no nearest mast to connect to, the service remains disrupted until the same mast is fixed. The delay in service outages may vary from few minutes to hours depending upon the type of problem incurred.

While considering the worst cases, it is worth mentioning a problem seen a couple of years back in Norway at part state-owned telecoms firm Telenor that left as many as 3 million users without coverage for up to **18 hours** over the Pentecost holiday weekend caused by a signal storm [44]. Such outages must also be considered while targeting to design resilient communication systems.

Table 19: Identified latencies for test case 2 (communication mast/connection/radio-link failure)

Cases	Latency (RTT)	Description
Normal Performance	-	• Faultless connection to nearest comm. mast
Deviating Performance	2 s – 10 s	• Connection to nearest comm. mast fails and tries to connect to the same mast
	10 s – few minutes	• Connection to nearest comm. mast fails • Connection to second nearest mast
	Minutes to several hours	• Connection to nearest comm. mast fails • No nearest comm. mast available • Worst case

9.4.3 Test Case 3 – Cyber-attacks

We now consider a case where some hacker cyber-attacks the communication infrastructure. There can be many reasons for this attack e.g. to shut down or disrupt communication network, to impede critical information being sent and received etc. However, to see what impact such attacks have on the voltage control coordination, following two sub-cases can be defined:

A.) Simple cyber-attack:

- The hacker knows only the IP but not the system structure and sends TCP/UDP based flood attack over the known IP – stressing the link by traffic, so that signals are delayed.
- Half open TCP session result in low performance of the system

B.) Advanced cyber-attack:

- The hacker knows both IP and details about the system structure and sends false control signals from Aggregator to ReGen plant or false measurement signals from ReGen plant to Aggregator
- Generate D-DOS attack as both IP and system structure is compromised and can gain admin access during the DDOS attack.

Table 20: Identified performance metrics for test case 3 (cyber-attacks)

Cases	Latency (RTT)	False message	Description
Normal Performance	-	No	• No cyber attacks
Deviating Performance	Minutes to several hours	No	• Simple Cyber attack
	-	Yes	• Advanced Cyber attack

9.5 Test Results

From the two test scenarios defined, it can be concluded that the devices being close or far apart from each other does not make much difference. This is because the ISPs are deploying faster network technologies [41], e.g. HSPA+ and LTE/4G, enabling higher data transfer rates and QoS for the network users, making them accustomed to have high speed networks and capable devices. However, from the test-cases, it can be remarked that the network architecture/setup (Test-Case 1) can introduce signal delays in the range of milli-second to seconds, while failures in communication (Test Case 2) may impose latencies in the range of minutes up to hours, depending on how severe the failure is. Table 21 summarizes the communication properties, resulting from all considered test cases and both test scenarios.

Table 21: Resulting performance metrics for all test cases and scenarios

			Test Scenario 1	Test Scenario 2
Test Case 3	Test Case 2 (Normal)	Test Case 1 (Normal)	RTT: 30 – 50 ms	RTT: 30 – 50 ms

(Normal)		**Test Case 1 (Worst)**	RTT: 500 ms	RTT: 500 ms
	Test Case 2 (Worst)	**Test Case 1 (Normal)**	RTT: Minutes to several hours	RTT: Minutes to several hours
		Test Case 1 (Worst)	RTT: Minutes to several hours	RTT: Minutes to several hours
Test Case 3 (Simple Cyber-attack)	-	-	RTT: Minutes to several hours	RTT: Minutes to several hours
Test Case 3 (Advanced Cyber-attack)	-	-	False Message Signal	False Message Signal

9.6 Impact of Communication Properties on On-Line Voltage Control Coordination

In this section it is evaluated to which extent the obtained communication properties, being summarized in Table 21, will affect on-line coordination of voltage control functionalities in distribution grids. The latencies introduced by the communication network lead to delays of measurement signals being sent from the ReGen plants to the Aggregator as well as delays of reference signals being set from the Aggregator to the ReGen plants.

9.6.1 Test Cases

It has been ascertained in chapter 8 that continuously updating the voltage setpoints for the ReGen plants is the only effective option to improve the proposed distributed control concept with regard to the power losses within the grid. The results obtained in section 8.2 have shown that, for adjusting the voltage setpoint, various update rates in the second to minute range (10 sec., 1 min., 5 min., 15 min.) have a minor impact on the resulting power losses within the grid. Hence, with regard to the obtained latencies for various test cases in the communication network (Table 21), it can be remarked that RTTs in the time range of seconds to minutes would not affect the control performance significantly. As for instance, if communication has to happen via different ISP networks, the maximum signal delay of 500 ms is negligible, assuming that the update rate of the voltage setpoint is minimum 10 seconds. And even though a communication failure in the network will sustain for several minutes, the local voltage controller of the ReGen plant will apply the last sent setpoint, which results in negligible deviations in the power losses in the distribution feeder.

However, as revealed in the previous sections, under certain circumstances connection failures up to several hours can occur which may affect the power losses more significantly. These communication problems can be due to a failing communication mast without having any available back-up cell or due to simple cyber-attacks causing increased traffic on the communication link, which can lead to very long signal delays. Following test cases are considered in terms of hours of delay caused due to **communication failure**:

a. 1h

b. 6h

c. 12h

d. 24h

Moreover, a more sophisticated cyber-attack may happen where the hacker has also knowledge about details of the system structure. In this case, he is able to send false control signals from the Aggregator to the ReGen plants. According to the grid code requirements [34], a ReGen plant shall be able to receive external reference signals for the droop value and the voltage setpoint, which are ranged within reasonable intervals, though depending on the country specific requirements and grid conditions. Following test cases are considered for **false message signals**:

a. Manipulating droop values (within range of 0.1 … 10 %)

b. Manipulating voltage setpoints (within the nominal voltage range of 0.9 … 1.1 pu)

9.6.2 Test Scenarios

For testing long-lasting communication failures, a benchmark test scenario with a time frame of 24 h is applied according to Figure 81.

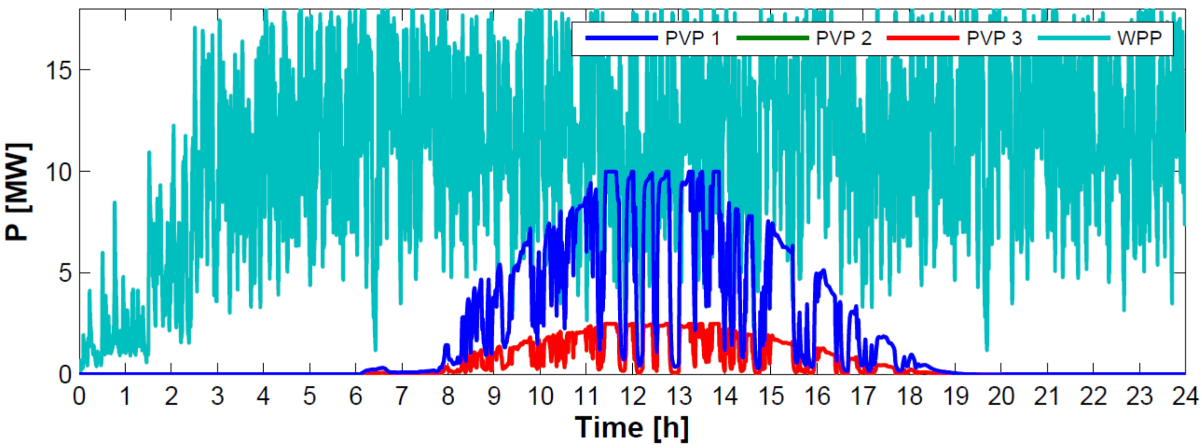


Figure 81: Benchmark test scenario (active power profile over 24 h) for evaluating communication failures

The test cases related to advanced cyber-attacks (false message signals) are evaluated by means of the 1 h test scenario according to Figure 39 in chapter 7.

9.6.3 Test Results

1. Communication failure

Figure 82 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of 24 hours, for both Control Concept 2 (CC 2 - constant voltage setpoint) and Control Concept 3 (CC 3), without and with various communication failures.

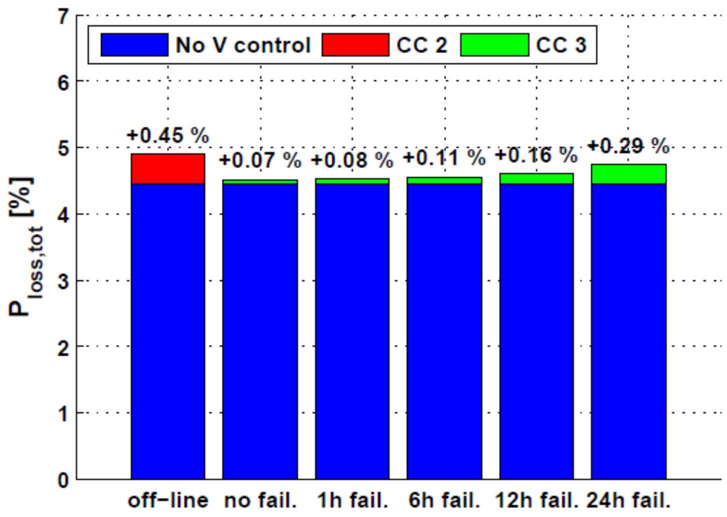


Figure 82: Power losses for various durations of communication failure for updating the voltage setpoints

It can be observed in Figure 82 that the power losses increase for longer communication failures. In Figure 83 the related voltage and reactive power profile is depicted, exemplary for a communication failure persisting for 12 hours.

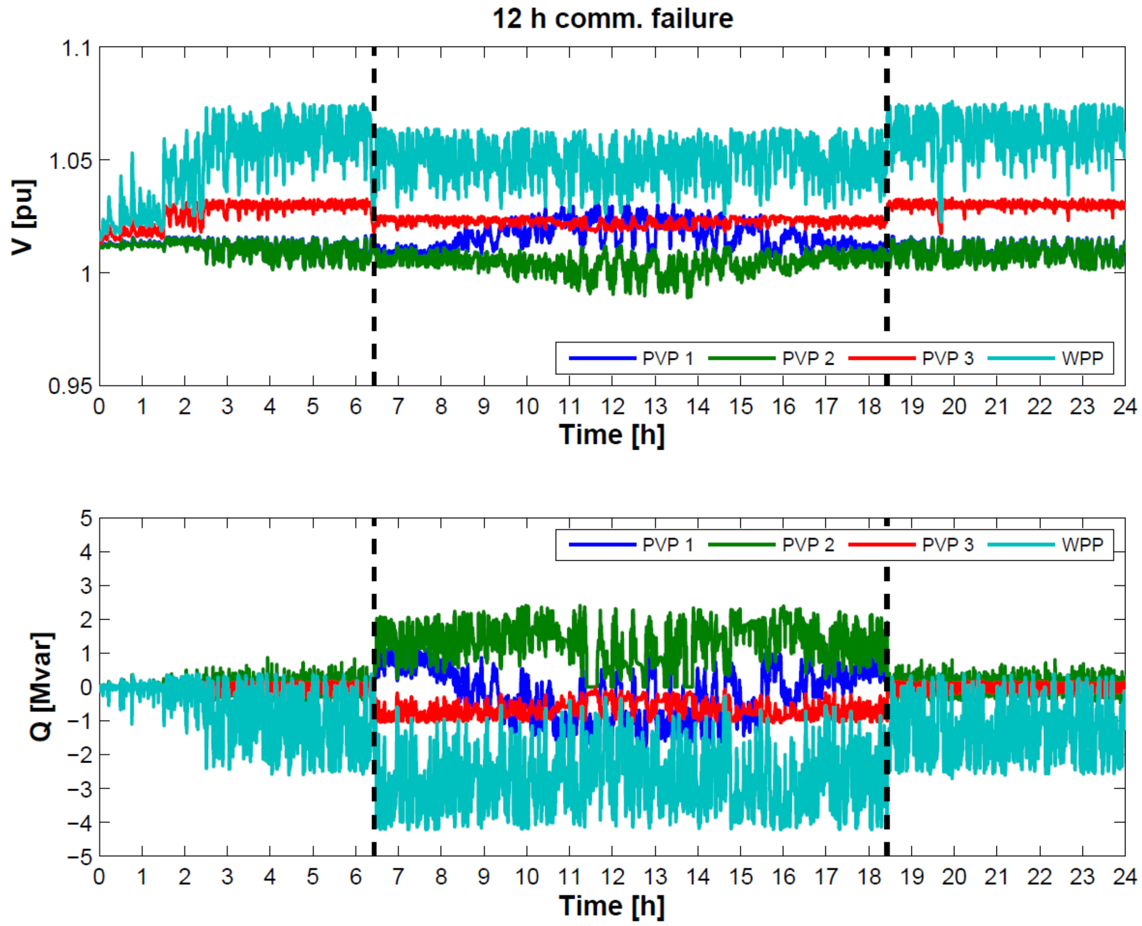


Figure 83: V and Q of all ReGen plants over one day for a communication failure occuring between 6 am and 6 pm

After occurrence of the failure at 6.20 AM the last sent voltage setpoint will be applied during the faulty period. This results in significant reactive power provision, since the voltage setpoint is not anymore updated according to the voltage measurements, hence increasing the power losses in the system.

2. **Cyber-attacks**

In chapter 7 it has been ascertained that relatively flat droop characteristics of the local voltage controller in the ReGen plants lead to instable voltage regulation within the distribution grid due to hunting effects between the individual controllers. In case a hacker is able to manipulate the droop values accordingly, by attacking the Aggregator control unit and sending updated reference signals to all ReGen plants, severe grid situations can occur. This is illustrated by Figure 84, showing the voltage and reactive power profile for a case when all droop values are set to 0.5 %, leading to a very flat droop characteristic.

At t = 500 s, the cyber-attack is initiated, leading to subsequent voltage oscillations. At t = 524 s, the WPP experiences a voltage exceeding the limit of 1.1 pu and needs to shut down. Voltage oscillations between all PVPs sustain, until PVP 1 shuts down at t = 795 s due to overvoltage.

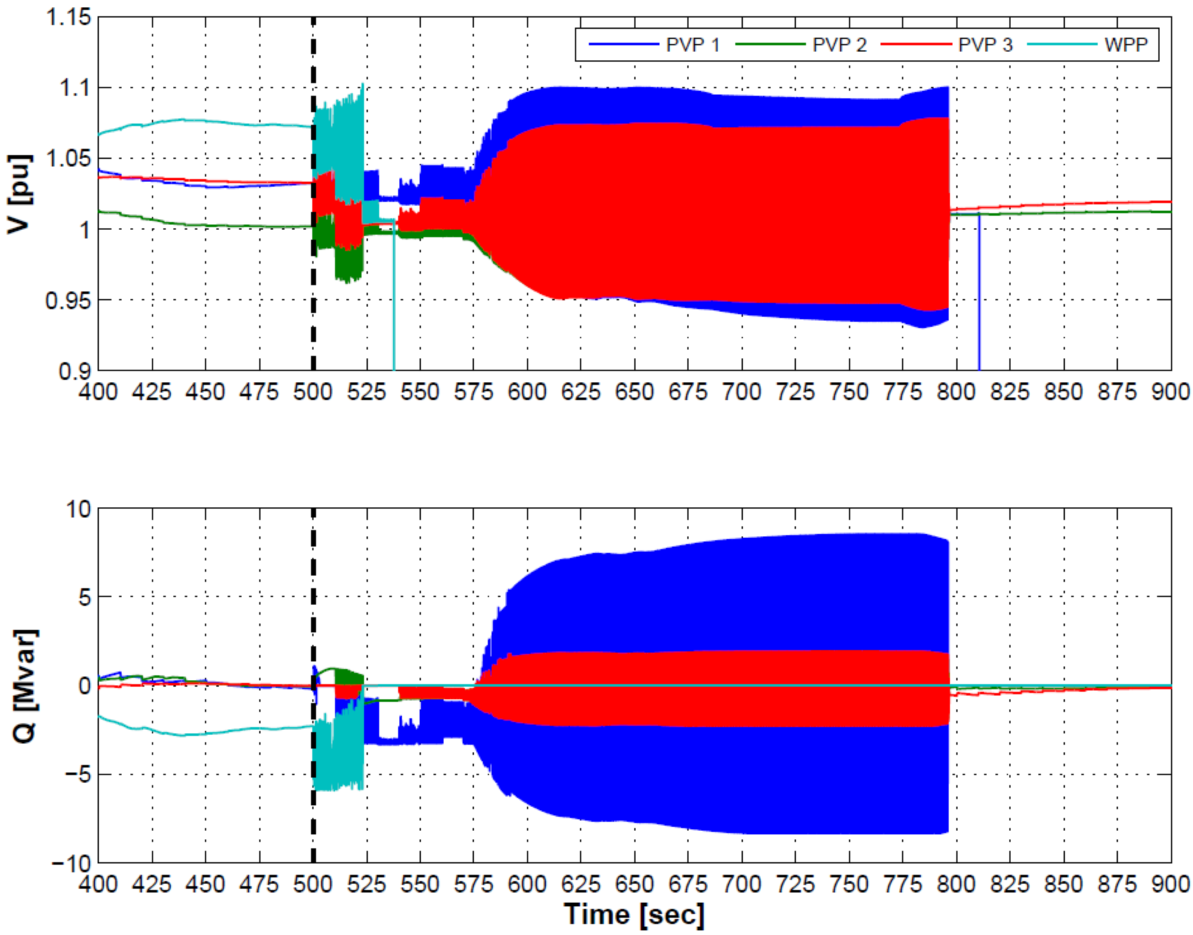


Figure 84: V and Q of all ReGen plants when subject to a cyber-attack (manipulating droop value at t = 500 s)

Figure 85 shows a case where the hacker was capable of manipulating the voltage setpoints being sent from Aggregator to the ReGen plants. At t = 500 s, a reference signal of $V_{set} = 1.08\,pu$ is sent to all ReGen plants, which instantaneously leads to a rising voltage profile in the distribution feeder. At t = 567 s, the

WPP shuts down due to overvoltage. The remaining PVPs will eventually provide reactive power (+Q) to boost the voltage according to the droop characteristic with the relatively high voltage setpoint.

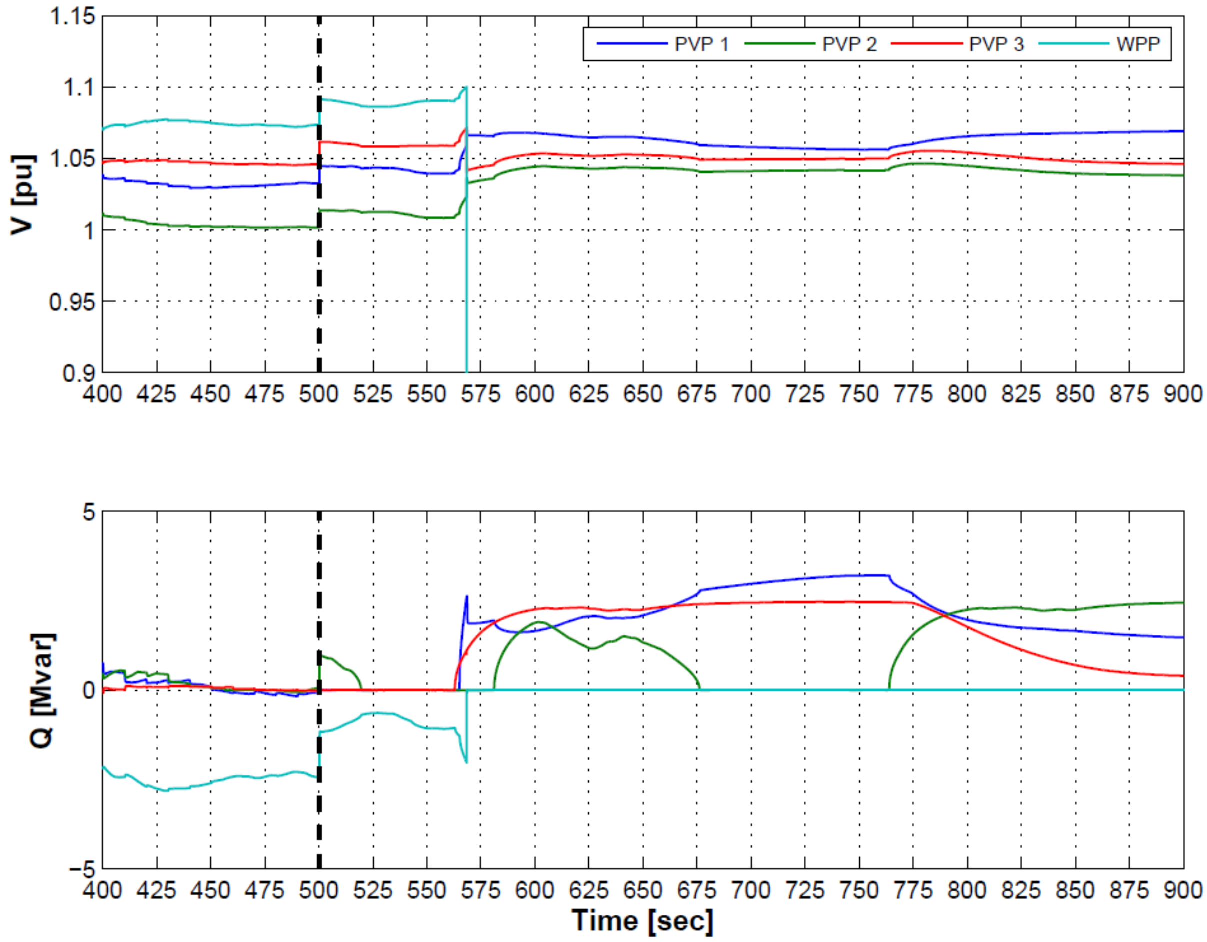


Figure 85: V and Q of all ReGen plants when subject to a cyber-attack (manipulating voltage setpoint at t = 500 s)

9.7 Summary

This chapter has provided an overview of all communication aspects related to on-line coordination of voltage control in distribution grids. The communication network infrastructure and the communication protocol (TCP/IP), being used as a standard for asset communication in energy systems, have introduced several test scenarios and cases that can be evaluated with respect to the related latency and validity of the signals being exchanged between Aggregator and ReGen plants.

The impact of communication properties on on-line voltage control coordination can be summarized by means of Table 22.

Table 22: Impact of communication properties on on-line voltage control coordination

Communication property	Latencies (seconds to minutes)	Latencies (several hours)	False message signals
Impact	☺	😐	☹

10 Conclusions and Recommendations

This document is presenting the results of the work on voltage control support and coordinated between ReGen plants in MV distribution systems.

In chapter 2 the voltage stability challenges in power systems with large penetration of ReGen are outlined. They are related to volatile voltage excursions in distribution systems due to ReGen plants. Some considerations regarding current penetration of wind power and Solar PV in distributions grids are made. Present challenges are addressed by real measurements given by a local DSO in Denmark. 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 exemplary benchmark distribution grid.

Chapter 3 presents the technical capabilities of ReGen plants for voltage control related to the required functionalities stipulated by the technical grid code requirements and the functional specifications that are described in deliverable D1.1 of RePlan project [17]. Those functionalities enable the provision of voltage stability support from ReGen plants. The definition of the most important parameters is presented by means of state-of-the-art analysis.

In chapter 4 the system models used in work package 2 are described. In order to identify voltage stability challenges in distribution systems with large penetration of ReGen and to assess the voltage control functionalities developed in this report, a benchmark distribution grid is developed which is based on a real MV grid operated by Himmerland Elforsyning (HEF) near Aalborg in North Jutland. In order to verify the developed control concepts, performance models for ReGen plants are applied for the study cases.

Chapter 5 presents a static analysis of the benchmark distribution grid. A voltage sensitivity analysis is performed to quantify node voltage variations due to injections of active and reactive power for given operational points of the network.

The results of the static analysis are taken into account in chapter 6 to develop voltage control concepts. The architectures of the voltage control concepts are represented and their characteristics (i.e. requirements, implementation procedures, data exchange) evaluated.

In chapter 7 and 8, time domain analyses are performed in order to test the voltage control concepts for off-line coordination and on-line coordination respectively. The system models described in chapter 4 are used to analyze voltage control in time domain for a volatile power profile of the ReGen plants, used as a benchmark test scenario that covers the crucial operating points with high solar irradiation and wind speed. The control concepts are evaluated based on some crucial and target dependent performance criteria.

Chapter 9 elaborates on the impact of communication properties on on-line voltage control coordination. Communication aspects related to the network infrastructure, protocols and possible cyber-attacks are evaluated with respect to the related latency and validity of the signals being exchanged between Aggregator and ReGen plants, resulting in deviating voltage control performance in the distribution grid. Latencies in the network do not affect the delivery and coordination of voltage service with respect to stable voltage profile management. However, present latencies in the range of several hours e.g. due to communication failures can increase the power losses within the grid due to less optimized control coordination. Special attention needs to paid to cyber-attacks, since false message signals being set to the ReGen plants can cause instable operation of voltage control.

Recommendations

The recommendations herein are primarily addressing the national Danish Grid Codes, the DSOs as well as Aggregators of grid support services.

A. National Danish Grid Code

- Requirements for the delivery of reactive power by PV power plants connected to MV level should be aligned with the actual system demands for voltage control in distribution systems. As per the present technical regulations [45], PV power plants are not required to provide any reactive power at rated active power output, while precisely high power infeeds by ReGen plants lead to rising voltage profile that needs to be regulated. It is proposed for the PV power plants to offer similar reactive power capability at rated active power as wind power plants (see section 7.4) in order to provide more flexibility with regard to voltage profile management and the reduction of voltage fluctuations.

B. Distribution System Operators

- Currently, no guidelines are available for the evaluation of voltage fluctuations in MV distribution systems. The so-called *Voltage Fluctuation Index* (*VFI*) is proposed to quantify voltage variations of distributed generation (see section 7.1). Applying the VFI as a relative number (in p.u. or %) serves as a good baseline when comparing voltage fluctuations in different points of the grid and for different test cases (e.g. bus voltage before / after grid connection of ReGen plant).
- Traditionally, power losses in distribution systems are calculated based on the power input to the feeder at the primary substation. In this way, the mismatch between energy input and billed energy to the consumers is expressed. However, in the case of large-scale power generation within the distribution system, where the major part is fed into the transmission system, it is proposed to refer the power losses to the total active power generation by the ReGen plants in the distribution grid (see section 7.1).

C. Aggregators of Grid Support Services

Aggregators of grid support services may take the responsibility, in close cooperation with local DSOs, for hosting voltage control capabilities. In this context, following recommendations are addressed:

- Voltage droop control functions of the individual ReGen plants should be parametrized based on an initial static analysis of the distribution grid, i.e. by voltage sensitivity analysis, in order to ensure satisfactory and stable voltage profile management of the feeder (see chapter 5 and section 6.2). In this way, ReGen plants can take over voltage regulation and simultaneously relieve the OLTC transformer at the primary substation from that task.
- In order to reduce the grid power losses being raised by reactive power compensation, the voltage setpoints of the individual ReGen plants should be updated in regular intervals (see sections 6.3 and 8.2). The update rate of reference signals can be in the second to minute range, but should not be faster than 10 seconds.
- Selecting the location of the Aggregator control unit (placed locally within the feeder area or at great distance in a control centre) does not have significant influence on the resulting

communication properties for the signal exchange between Aggregator and ReGen plants and thereby does not affect voltage control coordination functionalities.

11 Bibliography

[1] Danish Wind Industry Association, *The Danish Market*.: www.windpower.org, 2016.

[2] *Solcelleanlæg ved Lerchenborg - Miljørapport og VVM-redegørelse*.: Omnisol, Agrovi Videncenter, Juli 2014.

[3] *Energy needs in Denmark. Executive summary: "Overview of the Danish Power system and RES integration*.: www.store-project.eu.

[4] Volodymyr Myagkov, *Monitoring of harmonic distortions in distribution grids and their effect on temperature of substation transformers*.: Master Thesis - Aalborg University, 2016.

[5] Claudiu Ionita, Rifat Celiloglu , *Coordinated Control and Grid Support of Renewable Generation Plants*.: Project Report - Aalborg University, 2016.

[6] *Danish Meteorological Institute (DMI)*.: www.dmi.dk.

[7] Energinet.dk, *Environmental Reporting - Solar Power*.: www.energinet.dk, 2016.

[8] R. Pedersen, N. Silva, S. Bessler, A. Carrapatoso C. Sloth, *D4.1 - Control Framework and Models*.: SmartC2Net Project, 2014.

[9] *Environmental data measurements*.: Photovoltaic Systems Laboratory, Aalborg University; http://www.et.aau.dk/research-programmes/photovoltaic-systems, 2011.

[10] Nicolaos Cutululis, Andrej Gubina, Andrew Keane, Frans Van Hulle Hannele Holttinen, *D2.2 - Ancillary services: technical specifications, system needs and costs*.: REserviceS Project, 2012.

[11] F. Iov, F. Blaabjerg, J. Skaarup P. Sørensen, *Test and simulation of a dynamic phase compensation from MITA Teknik A/S*.: Risø-R-1438(EN), ISBN 87-550-3282-6.

[12] D. Dohnal, *On-load tap-changers for power transformers*.: Maschinenfabrik Reinhausen GmbH, 2013.

[13] Peter Morshuis, Johan Smit, Anton Janssen, Edward Gulski Rogier Jongen, *A statistical approach to processing power transformer failure data*.: 19th International Conference on Electricity Distribution, 2007.

[14] Branchefælleskab for Intelligent Energi, *Smartgrid-komponenter til distributionsnettet*.: Produktkatalog, 2014.

[15] *Nyt SCADA System - IT sikkerhed og Smartgrid*. Fredericia, Denmark: Net-Sam SCADA A/S, November 2013.

[16] Ivan Pineda, Paul Wilczek Frans Van Hulle, *Economic grid support services by wind and solar PV*.:

REserviceS Project, September 2014.

[17] Müfit Altin, Kamal Shahid, Rasmus L. Olsen, Florin Iov, Anca D. Hansen, Xue Han Lennart Petersen, *D1.1 - Specifications for ReGen plant model and control architecture*.: RePlan Project, 2016.

[18] Tobias Hennig, Nicolaos A. Cutululis, Frans Van Hulle Mariano Faiella, *D 3.1 - Capabilities and costs for ancillary services provision by wind power plants*.: REserviceS Project, 2013.

[19] Karel De Brabandere, Omar Gammoh, Jan De Decker, Manoël Rekinger, Scarlett Varga, Diana Craciun Paul Kreutzkamp, *D 4.1 - Ancillary Services by Solar PV - Capabilities and Costs of Provision*.: REserviceS Project, 2013.

[20] *Wind Turbine Plant Capabilities Report*.: Australian Energy Market Operator AEMO, 2013 - Wind Integration Studies.

[21] Rasmus L. Olsen et.al., *D6.2 - Integrated test beds - Description*.: SmartC2net Project, 2015.

[22] Mufit Altin, *Dynamic Frequency Response of Wind Power Plants*.: Aalborg University, Denmark, PhD Thesis, November 2012.

[23] M. Pathmanathan, W.L. Soong and N. Ertugrul C. Tang, *Effects of Inertia on Dynamic Performance of Wind Turbines*.: Proceed of Australasian Universities Power Engineering Conference, AUPEC 2008, paper P-087, E-ISBN: 978-1-4244-4162-4, 14-17 December 2008.

[24] A. Gonzalez Rodriguez and M. Burgos Payan A.G. Gonzalez Rodriguez, *Estimating Wind Turbines Mechanical Constants*. Sevilla, Spain: Proceed. of "INTERNATIONAL CONFERENCE ON RENEWABLE ENERGIES AND POWER QUALITY (ICREPQ'07)", paper 314 ISBN: 978-84-611-4707-6, 28- 30 Mach 2007.

[25] Vestas Wind Systems Technology R&D, *General Specification, V112–3.0 MW 50/60 Hz, Class 1*.: Document no.: 0011-9181 V05, August 2011.

[26] ABB, *ABB inverter station - PVS800-IS - 1.75 to 2 MW*.: Product description.

[27] L. Morroyo, E. Lorenzo, D. Alvira and E. Izco J. Marcos, *From irradiance to power fluctuations: the pv plant as a low pass filter*.: Progress in Photovoltaics: Research and Applications, 19:505-510, Wiley Online Library, January 2011.

[28] L. Morroyo, E. Lorenzo, D. Alvira and E. Izco J. Marcos, *Power output fluctuations in large scale PV plants: one year observations with one second resolution and a derived analytical model*.: Progress in Photovoltaics: Research and Applications, 19:218-227, Wiley Online Library, July 2010.

[29] Catalin-Iosif Ciontea, Dezso Sera, and Florin Iov, *Influence of Resolution of the Input Data on Distributed Generation Integration Studies*. Brasov, Romania: 14th International Conference on Optimization of Electrical and Electronic Equipment, 2014.

[30] Hadi Saadat, *Power System Analysis*.: McGraw-Hill, 1999.

[31] Prabha Kundur, *Power System Stability and Control*.: McGraw-Hill, Inc., 1993.

[32] H. Hasanvand, J. Lobry, F. Vallée B. Bakhshideh Zad, *Optimal reactive power control of DGs for voltage regulation of MV distribution systems using sensitivity analysis method and PSO algorithm*.: Electrical Power and Energy Systems 68, March 2014.

[33] Ali Keyhani and Mohammad Albaijat, *Smart Power Grids 2011*.: Springer, 2012.

[34] *ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators*.: entso-e, March 2013.

[35] Energinet.dk, *Technical regulation 3.2.5 for wind power plants with a power output above 11 kW*. Fredericia, 2015.

[36] Ricardo Albarracin, Monica Alonso , *Photovoltaic reactive power limits*.: 12th International Conference on Environment and Electrical Engineering (EEEIC), 2013.

[37] Francesc Fornieles-Castells, Josep Garcia-Fabrega , *Consumption Analysis Method for Optimizing Reactive Compensation at MV*. Israel: 16th International Annual Convention of the Society of Electrical and Electronics Engineers, 2015.

[38] Andrew S. Tanenbaum and D. Wetherall, *Computer networks*., 2011.

[39] DIX - Danish Internet eXchange point. [Online]. http://www.dix.dk/faq/#4

[40] Steffen Riber Christensen , Martin Sloth Dam , Lars Møller Mikkelsen , and Michael Sølvkær Pedersen , "Mismatch Probability Modelling of Central Decision Process with Multiple Information Providers and Empirical Network Models," 2012.

[41] Lars M. Mikkelsen , Steffen R. Thomsen , Michael S. Pedersen , and Tatiana K. Madsen , "NetMap - Creating a Map of Application Layer QoS Metrics of Mobile Networks Using Crowd Sourcing".

[42] ETSI 3rd Generation Partnership Project (3GPP), "Technical Specification - ETSI TS 136 331 V13.2.0 (2016-08),".

[43] Special Mobile Group (SMG), "Digital cellular telecommunications system (Phase 2+); Service Accessibility (GSM 02.11 version 7.0.1 Release 1998),".

[44] 'Signal storm' caused Telenor outages. [Online]. http://www.newsinenglish.no/2011/06/16/signal-storm-caused-telenor-outages/

[45] Energinet.dk, *Technical regulation 3.2.2 for PV power plants with a power output above 11 kW*. Fredericia, 2015.

[46] Erhan Demirok, *Control of Grid Interactive PV Inverters for High Penetration in Low Voltage Distribution Networks*.: PhD Thesis, Aalborg University, 2012.

[47] "IEC 61850-5, Communication networks and systems for power utility automation, Part 5: Communication requirements for functions and device," 2012.

[48] Ilya Grigorik, *High Performance Browser Networking*.: O'Reilly Media, Inc., 1005 Gravenstein Highway North, Sebastopol, CA 95472., 2013.

[49] Bradley Mitchell. (2016) Introduction to Latency on Computer Networks. [Online]. http://compnetworking.about.com/od/speedtests/a/network_latency.

[50] D Noguli´c, and M Družijani´c T Blaji´c, "Latency improvements in 3G long term Evolutiion," *Proceedings of the International Convention on Information and Communication Technology, Electronics and Microelectronics*, 2006.

[51] Byong-Kwan Yoo et al, "Communication architecture of the IEC 61850-based," *Journal of Electrical Engineering and Technology 6.5*, 2011.

[52] Neal Cardwell, Stefan Savage, and Thomas Anderson, "Modeling TCP Latency".

12 Appendix

12.1 Voltage profile at all system busses

Following figures show the voltage profile at all system busses for various droop settings and a grid voltage of 1 pu and 1.05 pu:

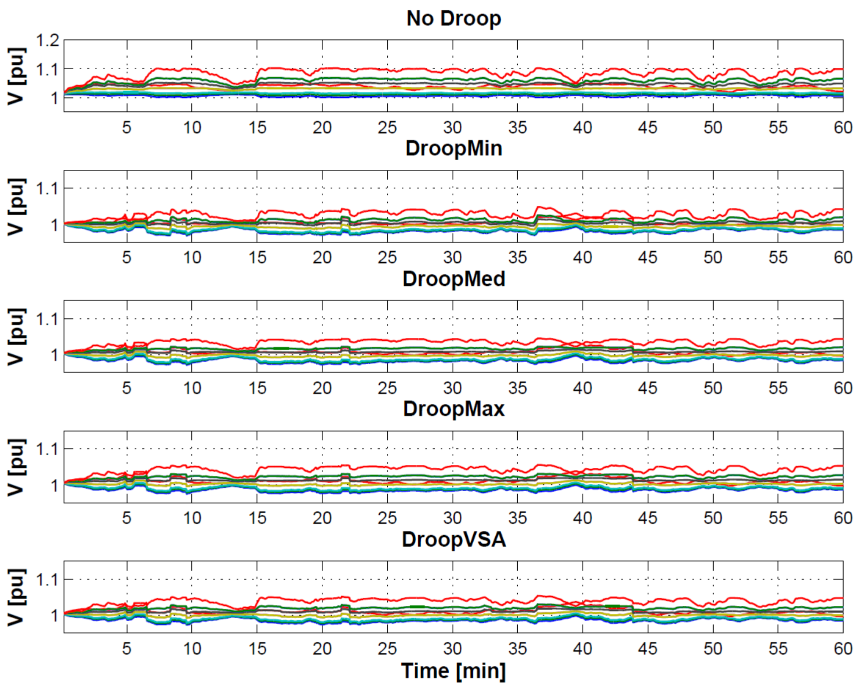


Figure 86: Voltage profile at all system busses for various droop settings and $V_{grid} = 1.00\ pu$

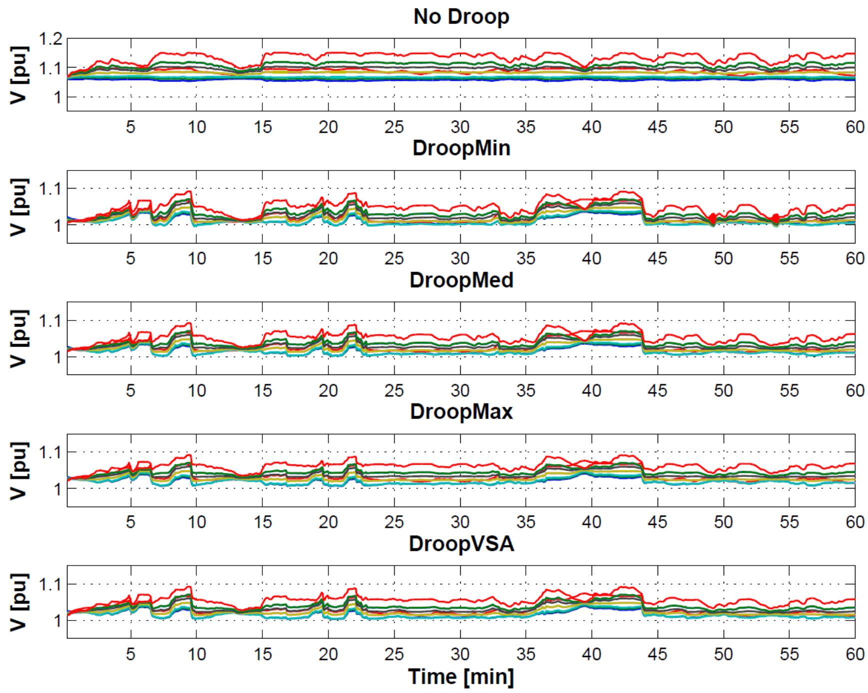


Figure 87: Voltage profile at all system busses for various droop settings and $V_{grid} = 1.05\ pu$

12.2 Instable operating points for test scenario $V_{grid} = 1.05\ pu$ (V105)

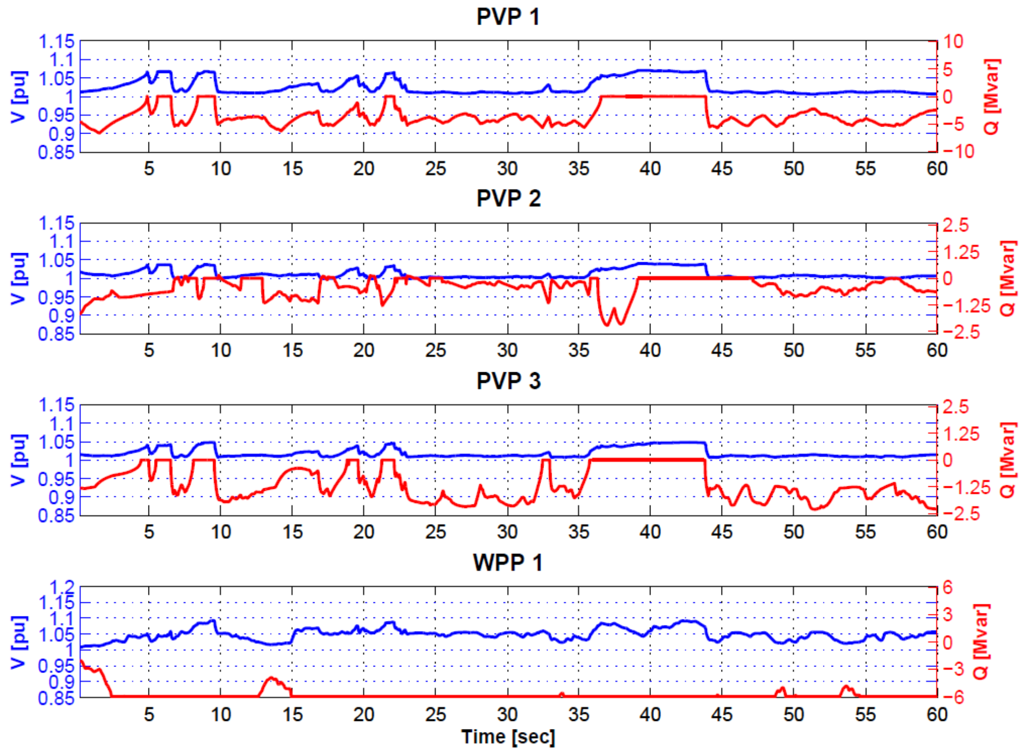


Figure 88: V & Q of all plants for Droop = 2.5 % and grid voltage of $V_{grid} = 1.05\ pu$

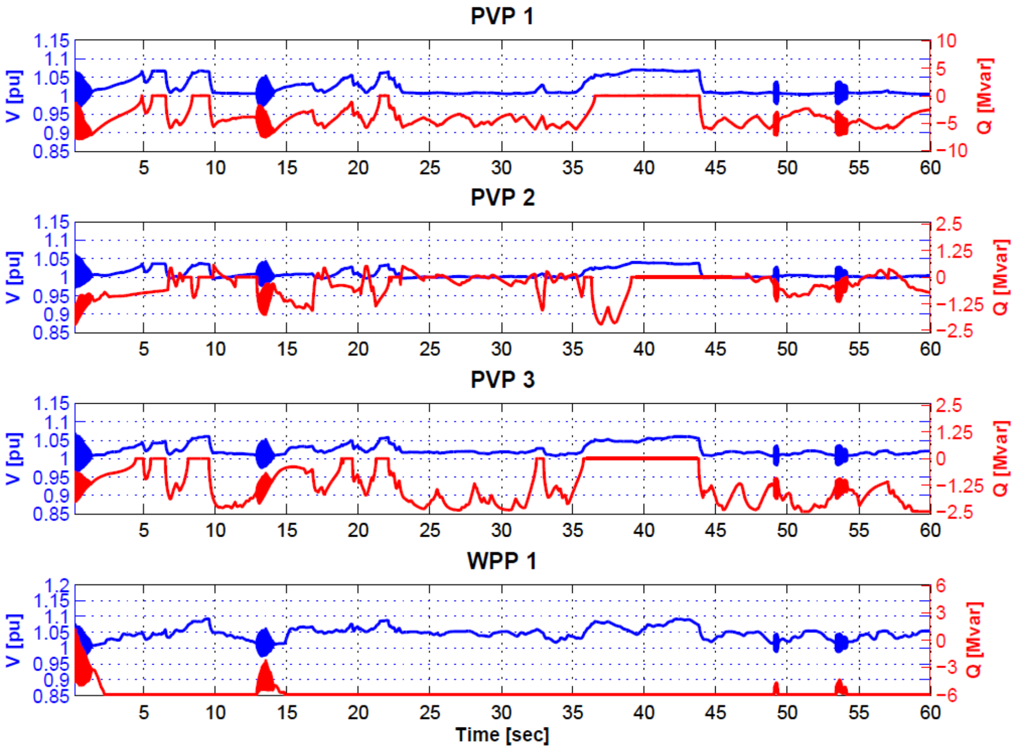


Figure 89: V & Q of all plants for Droop = 1.5 % and grid voltage of $V_{grid} = 1.05\ pu$