Distributed voltage control coordination between renewable generation plants in MV distribution grids

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Published in:
CIRED - Open Access Proceedings Journal

DOI (link to publication from Publisher):
10.1049/oap-cired.2017.0554

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Petersen, L., & Iov, F. (2017). Distributed voltage control coordination between renewable generation plants in MV distribution grids. *CIRED - Open Access Proceedings Journal* , *2017*(1), 1038-1042. https://doi.org/10.1049/oap-cired.2017.0554

24th International Conference & Exhibition on Electricity Distribution (CIRED)

12-15 June 2017

Session 3: Network operation, control and protection

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Journals
The Institution of Engineering and Technology

ISSN 2515-0855
doi: 10.1049/oap-cired.2017.0554
www.ietdl.org

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Abstract: This study focuses on distributed voltage control coordination between renewable generation plants in medium-voltage distribution grids (DGs). A distributed offline coordination concept has been defined in a previous publication, leading to satisfactory voltage regulation in the DG. However, here, it is shown that reactive power provision increases the power losses in the grid to a significant extent. A real-time coordination concept is developed which utilises communication systems with online signal exchange between the assets. Performed case studies reveal that this coordination scheme reduces the power losses within the DG to a measurable extent.

1 Introduction

Nowadays, an enormous part of the wind power generation in Denmark, i.e. 3799 MW, is achieved by onshore wind turbines (WTs) [1], being connected to the medium-voltage (MV) grid individually or in small-scale clusters. Moreover, a 61 MW solar photovoltaic (PV) was commissioned in 2015 near Kalundborg (DK) [2] which is the biggest solar PV plant (PVP) 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 kilowatt are typically installed on large barns or farms and are connected directly on the secondary side of MV/low-voltage (LV) transformers.

The anticipated trend is that the increased share of installed renewable generation (ReGen) plants in Denmark in the coming years will mainly be accomplished in MV distribution grids (DGs) by large-scale concentrated 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 [4] will be increased at 1000 MW in 2020, mainly by industrial rooftop PVPs and ground-mounted systems in the megawatt range [3].

One of the challenges with increased penetration of ReGen plants in DGs is to keep the voltage profile within the desired tolerance band margins (±10%). Studies performed on a benchmark DG (BDG) with high penetration of ReGen [5] have shown that the reversed power flow in the DG upstream towards the primary substation leads to rising voltage levels, at some remote busses eventually exceeding the limit of 1.1 pu during time periods with high wind speed and solar irradiation. Moreover, the volatile generation profile of wind power and solar PV causes significant voltage fluctuations (up to $\Delta VV = 8\%$) [5], which clearly reveals the need of continuous voltage control in DGs.

Up to now, on-load tap changer transformers equipped with automatic voltage control relays are the most widely used control device in MV DGs. However, a significant number of tap changes would be required throughout the day to regulate the voltage profile, as the power generation of ReGen plants has a volatile behaviour. This should be avoided, as tap changers are the cause of 56% of total failures in transformers [6]. Moreover, the typical response time of changing the tap position (3–10 s [7]) may be too slow for regulating the highly fluctuating voltage amplitude.

An alternative solution is to utilise the reactive power support functionalities from the existing ReGen plants in the DG. This capability is required by today's grid codes and already implemented in today's ReGen plants. However, due to the lack of technical infrastructure to communicate and control these units, this capability is not yet utilised by the distribution system operators (DSOs). It requires SCADA systems that are about to be installed and employed by the Danish DSOs in near future [8]. Then, due to lack of regulatory framework, it may not be feasible in short term to control the ReGen plants for reactive power support. However, an ancillary service market for voltage support services can be foreseen in the near future [9]. In this context, aggregation entities may take the responsibility, in close collaboration with local DSOs, to host voltage control capabilities besides energy trading. Hence, the need for coordination in providing reactive power support and hence controlling voltage locally on a DG is required, considering the increasing number of dispersed units.

The focus of this paper is to present two concepts for distributed voltage control coordination in DGs. Initially, the current voltage control capabilities of ReGen plants, i.e. WPPs and PVPs, are revealed. Then, an offline and online coordination scheme is presented for parametrising the local voltage controllers of each ReGen plant in a DG. It is ascertained in [5] that the former concept leads to satisfactory voltage regulation in the DG. However, reactive power provision by ReGen plants will increase the power losses in the grid. On this account, time domain analyses are performed in order to evaluate the concepts for voltage control coordination with regard to the grid losses. In the end of the paper, the summary of these studies is provided.

2 Voltage control capabilities of ReGen plants

In today's DGs, fixed-speed (type 1), limited speed (type 2), and variable speed WTs (types 3 and 4) are present to a large extent. While the former WTs (types 1 and 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 20–25 years from installation [10]. Types 1 and 2 WTs consume reactive power, whose supply is normally ensured by shunt capacitor banks installed at the turbine terminals. However, they do not have the functionality of actively controlling the voltage, in contrast to WPPs with types 3 and 4 WTs [11]

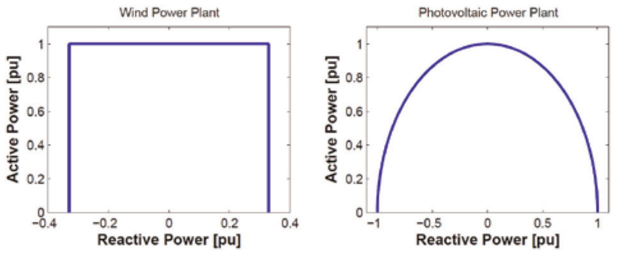

Fig. 1 *Reactive power capability charts for wind power and PV power plants [12, 14]*

which are capable of providing a range of at least $Q/P_{\max} = 0.33$ pu during normal operation (Fig. 1), being required by the Danish Grid Code [12].

PV systems connected to MV level have the capability for voltage control [13]. However, their reactive power provision functionality during normal operation is generally limited by the nominal apparent power of the inverter, so that $Q/P_{\max}$ depends on the actual active power production as per Fig. 1, which is in accordance with the Danish Grid Code [14].

In order to keep the voltage at the point of common coupling (PCC) within a tolerance band, the adjustment of reactive power with the grid has to be controlled by *power factor*, *reactive power*, or *voltage control* mode [12, 14].

Both WPPs and PVPs are able to fulfil the requirements for setpoint processing functionality within their dynamic range and voltage limits, i.e. a change of setpoint must be commenced within 2 s and completed no later than 10 s after receipt of an order to change the setpoint. The current ReGen plant controllers can be adjusted to achieve a new reactive power setpoint even within 1 s [11, 13].

3 Concepts for distributed voltage control coordination

In power factor control mode, the ReGen plant adjusts its reactive power output depending on the actual active power production. Hence, it is useless for the purpose of control coordination. Reactive power control requires a centralised control entity that dispatches reactive power setpoints to the individual ReGen plants based on some optimised control algorithm. A more simple approach can be realised by a distributed voltage control scheme, where each ReGen plants has an inner control loop for regulating the reactive power provision at point of connection (PoC) and an outer voltage control loop for controlling the voltage in the PoC (Fig. 2).

A typical droop function (Fig. 3) with a voltage reference point is to be configured for the ReGen plant controller, where $Q_{\min}$ (inductive) and $Q_{\max}$ (capacitive) refer to the capability limits of ReGen plants (Fig. 1).

3.1 Offline coordination

One concept of coordinating proper reference signals for voltage reference point and droop is proposed in [5] and is referred to as *distributed* (or *decentralised*) *offline coordination* (Fig. 4).

The idea of this approach is to determine the droop values of each ReGen plant controller by means of an initial static analysis of the DG, i.e. voltage sensitivity analysis, taking into account the impact of reactive power variations on voltage changes ($\delta V/\delta Q$) in

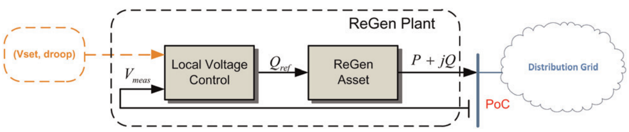

Fig. 2 *Voltage control scheme of ReGen plant [5]*

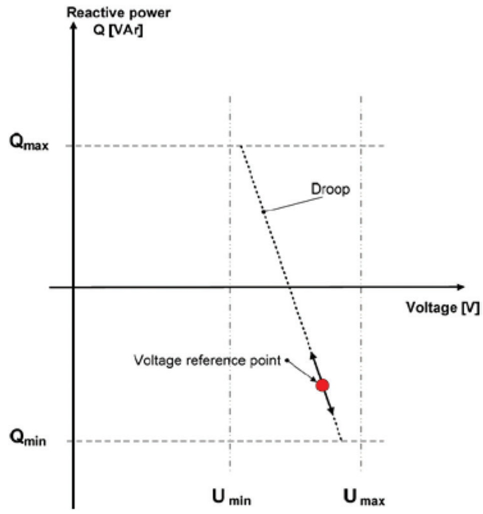

Fig. 3 *Voltage droop control for ReGen plant [12, 14]*

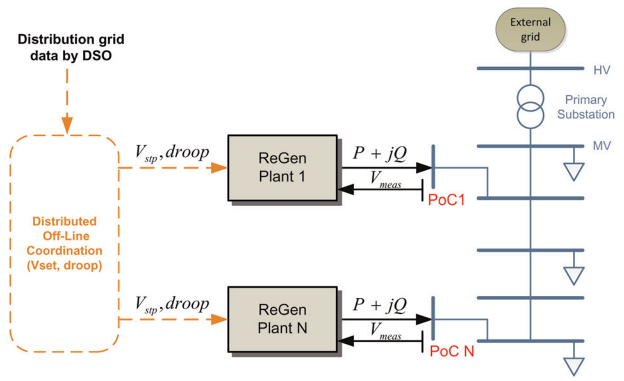

Fig. 4 *Scheme for distributed offline coordination [5]*

different points of the grid. These settings are manually introduced only once by an aggregator of grid support services or the responsible DSO and may be updated when necessary, e.g. changes in the feeder topology, cables, transformers etc. [5]. For the voltage reference point, an arbitrary value of $V_{\text{stp}} = 1$ pu can be selected, as the system voltages should be regulated around nominal value.

3.2 Online coordination

This proposed control concept is characterised by real-time coordination of the local voltage controllers using the available measurements in the grid. The scheme of *distributed online coordination* control is shown in Fig. 5, where an aggregator of grid support services or the responsible DSO may take over the task to update the controller settings of the ReGen plants continuously.

Real-time information can only be provided for locations in the grid, where measuring devices are installed. As per grid code requirement, ReGen plants need to provide signals such as active power production, reactive power availability, and voltage at the connection point [12, 14]. The DSO normally has available voltage and current measurements from the primary substation (MV or high-voltage side).

Those signals can be used for advanced coordination of the individual controller settings of the ReGen plants. Reactive power provision may increase the losses within the grid by increasing the current loading of the lines. Hence, in situations where the voltage

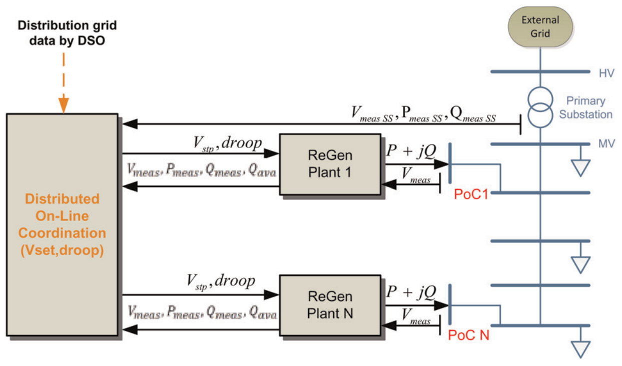

Fig. 5 *Scheme for distributed online coordination*

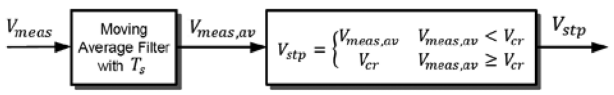

Fig. 6 *Algorithm for updating the voltage reference point*

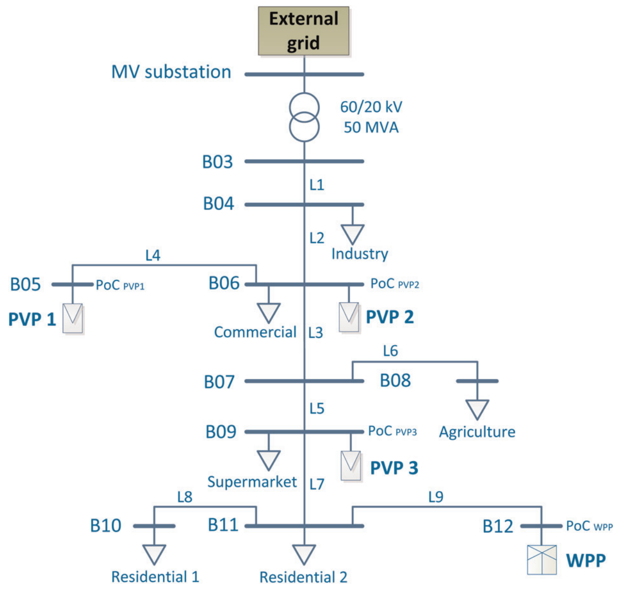

Fig. 7 *MV BDG with ReGen plants [5]*

Table 1 Evaluation of voltage control concepts

Control concept	Required system studies	Required measurements	ICT demand	Overall difficulty of implementation by aggreg./DSO
offline	++	+	−	+
online	++	++	+	++

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 DG is to adjust the voltage reference point at each ReGen plant according to the prevailing voltage profile within the grid. Then, voltage control needs to be efficient, only if the voltage takes on a certain critical value, denoted by V_{cr}. The critical voltage value can be set to $V_{\mathrm{cr}} = 1.05$ pu, allowing a margin of 5% for the voltage droop controller to regulate the voltage according to the requirements. As per Fig. 6, the voltage reference point is adjusted according to the actual measured voltage $V_{\mathrm{meas,av}}$, 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 reference point, being exchanged between the aggregator/DSO and the individual ReGen plants. An update rate of $T_{\mathrm{s}} = 10$ s can be recommended without imposing a high burden on the information and communication technology (ICT) [15].

Both control coordination concepts are summarised and evaluated according to Table 1.

4 Case studies for a BDG

4.1 Benchmark distribution grid

In order to assess the concepts for voltage control coordination presented in this paper, a BDG has been developed [5]. The BDG is based on a real MV grid, operated by a local DSO in Denmark, and shown in Fig. 7.

The following ReGen plants are represented in the BDG:

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

4.2 Test scenario and evaluation criteria

Time domain simulations are performed for a benchmark test scenario with a time frame of 1 h, representing a realistic power generation profile for the WPPs and PVPs by using real measurement data for wind speed and solar irradiation as illustrated in [5]. The ReGen plants are characterised by some performance models that have been developed specifically for voltage stability studies being applicable for a frequency bandwidth of the model of maximum 5 Hz [15].

In [5], it has been ascertained that offline coordination of the ReGen plant controllers leads to satisfactory voltage regulation within the BDG. For a test case without voltage control, the feeder experiences rising voltages up to >1.10 pu, yet being reduced to values sufficiently below the threshold by means of offline coordination of voltage control.

However, it needs to be evaluated to which extent reactive power compensation will increase the power losses in the grid. This evaluation criterion can be imposed by the DSO that aims for maximum power provision to the end-consumers with as few losses as possible. Traditionally, percentage power losses in DGs 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 DG, 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 DG:

$$P_{\mathrm{loss,tot,\%}} = P_{\mathrm{loss,tot}} \times 100\% = \frac{\sum P_{\mathrm{loss}}}{\sum P_{\mathrm{gen}}} \times 100\% \tag{1}$$

4.3 Test cases

The power losses are evaluated for the following test cases:

(i) no voltage control,
(ii) offline coordination,
(iii) online coordination.

In order to represent relevant operational points of the external transmission system ('External grid' in Fig. 7), the following voltage conditions are considered:

- $V_{grid} = 1.00$ pu, representing a normal operational point of the transmission system,
- $V_{grid} = 1.05$ pu, representing an alert state operational point of the transmission system.

4.4 Test results

Fig. 8 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of 1 h.

Comparing the left- and right-hand part of the 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 offline coordination (red on top of blue), the losses are higher for $V_{grid} = 1.05$ pu ($P_{loss,tot,\%} = 5.82\%$) compared with $V_{grid} = 1.00$ pu ($P_{loss,tot,\%} = 5.52\%$), since the feeder requires more reactive power to compensate the voltage rises (with a reference point of $V_{stp} = 1$ pu), which leads to increased current loading of the lines. The maximum increase in comparison to disabled voltage control is $\Delta P_{loss,tot,\%} = 1.32\%$. This per cent value seems relatively small, but expressed in absolute numbers, it amounts to an average loss increase of 330 kW. Reducing the power losses can benefit the DSO for maximum power provision to the end-consumers.

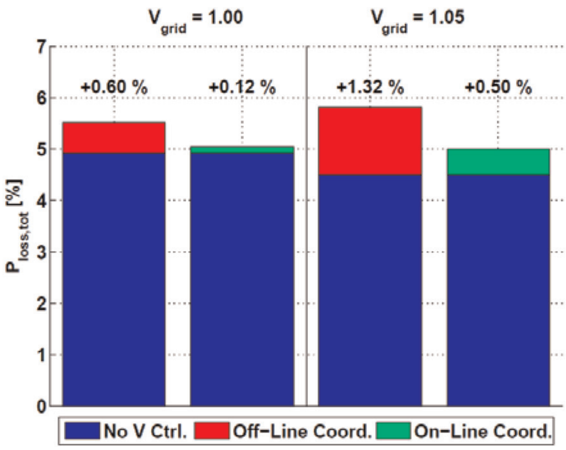

Fig. 8 *Power losses for various test cases and external grid voltages*

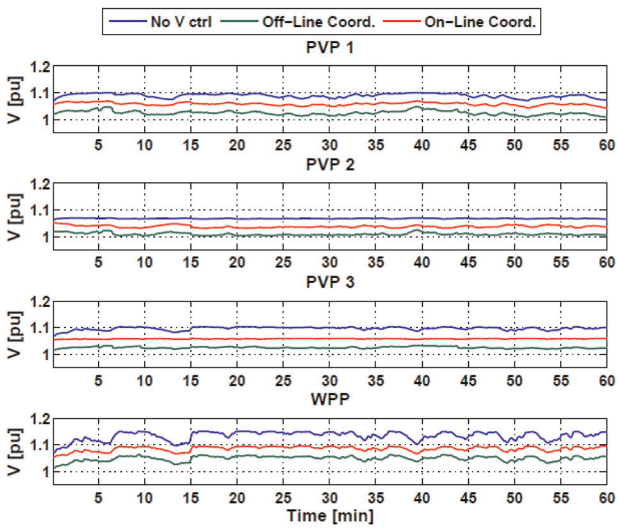

Fig. 9 *Voltage profile over 1 h at PoC of ReGen plants for various test cases and external grid voltage of* $V_{grid} = 1.05$ *pu*

This is achieved by means of online coordination of voltage control as illustrated in Fig. 8 (green on top of blue). In comparison to offline coordination, the power losses are decreased by $\Delta P_{loss,tot,\%} = 0.48\%$ (for $V_{grid} = 1.00$ pu) and $\Delta P_{loss,tot,\%} = 0.82\%$ (for $V_{grid} = 1.05$ pu), which in absolute numbers amounts to an average loss reduction of 120 and 200 kW, respectively.

The resulting voltage profiles at PoC of the ReGen plants for all test cases and exemplary for an external grid voltage of $V_{grid} = 1.05$ pu are shown in Fig. 9. It can be seen that online coordination leads to an enhanced voltage profile compared with offline coordination. However, satisfactory voltage profile management is achieved, as the voltages are kept below the threshold.

5 Summary

This paper has presented an offline and online coordination scheme for distributed voltage control of ReGen plants in DGs. Some considerations regarding current and future penetration of wind power and solar PV in DGs are made. It is shown that voltage stability challenges with large penetration of wind and solar power are related to rising voltage profiles and volatile voltage excursions due to fluctuating wind speed and solar irradiation. A distributed offline coordination concept has been defined in [5], using voltage sensitivity analysis to obtain the droop settings of the local voltage controller in each ReGen plant. It leads to satisfactory voltage regulation in the DG. However, in this paper, it has been shown that reactive power provision increases the power losses in the grid to a significant extent. A real-time coordination concept has been developed which utilises communication systems with online signal exchange between a central control entity (aggregator) and the ReGen plants. Using available measurements in the grid and updating the voltage reference points of each ReGen plant according to their actual operating point reduces the power losses within the DG to a measurable extent, as shown by the performed case studies.

6 Acknowledgments

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

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