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Control Aspects and the Design of a Small-Scale Test Virtual Power Plant

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Abstract—Nowadays the amount of distributed generation (DG) is growing rapidly. This is valid both for units connected to MV grids as well as LV networks. Although now the share of LV-connected units is quite limited, this situation might change with the increase of number of installed micro CHP units in residential areas, further stimulus of solar power production and introduction of electric and fuel cell based cars. Management and control of such small and medium-scale inverter-interfaced generation can be optimised using the virtual power plant (VPP) principle. Various control aspects of VPP as an attribute of the interconnected power system are analyzed, and the design of a small-scale experimental setup is proposed.

Index Terms—Distributed generation, virtual power plant, voltage and frequency control, inverter-interfaced distributed generator.

I. INTRODUCTION

LARGE-SCALE implementation of distributed generators leads to a gradual transition from the current 'vertically-operated power system', which is supported mainly by several big centralized generators, into a future 'horizontally-operated power system', having also a large number of small to medium-size distributed generators [1].

The significant increase of penetration level of DG has a strong impact on power system operation. MV and LV distribution networks, to which distributed generators are connected, cannot be considered as passive anymore. Active character of the distribution networks brings problems and uncertainties, but at the same time offers more possibilities for control [2].

Most of LV-connected DG units use power electronic converters as a means of connection to the grid. Due to the fact that such generation units operate at different frequencies compared to the traditional 50 or 60 Hz the presence of converters is necessary. Some units inject DC currents and voltages, like PV panel and fuel cells, some are operating at higher

frequencies, like microturbines. Moreover, certain units are fully controllable, while the others are of intermittent nature and in general cannot control its power output. The integration of large amount of such units in the existing power system will require introduction of new principles for grid operation. One of the concepts that can allow to achieve this integration is the virtual power plant (VPP) principle. A VPP is a cluster of DG units (such as microCHP, wind turbines, small hydro, back-up generator sets, etc.), which are collectively run by a central control entity. A VPP can also include energy storage of different types. The VPP principle is quite similar to the Active Network concept, which deals with the change of behavior of distribution networks from passive to active due to the introduction of DG units. In general, the definition of VPP is a bit broader than that of Active Network and is not necessarily limited to a network area (as for the Active Network concept). However, further only one particular case of VPP application is discussed, which can be used for an intelligent control of a residential house equipped with small-scale DG units or a group of several houses situated in a close neighborhood to each other.

In this paper control aspects and design objectives for a small-scale test 5 kW VPP, which will be implemented in hardware, are considered. First, classification of inverter-interfaced DG units is provided. Then, different schemes for VPP are considered and the possible functionality is discussed. The functions, which might be performed by VPP, include grid support during voltage and frequency variations, power quality conditioning both at the grid and the customer side (suppression of harmonics, flicker, voltage dips, etc.), and probable autonomous operation using energy storage in case of a grid blackout. The principles proposed in the paper might be applied to VPPs with larger rated power as well.

II. CLASSIFICATION OF INVERTER-INTERFACED DG UNITS

Inverter-interfaced DG units connected in parallel to the grid are distinguished by their contribution to the grid voltage and frequency control and are accordingly classified in three classes: grid-forming, grid-feeding and grid-supporting units [3]:

1. *Grid-forming units* define the grid voltage and frequency. These units are designed for stand-alone operation. Generally, such systems contain not more than one grid-forming ('master') unit as they act to some extent similar to an ideal voltage source with fixed frequency.

2. *Grid-feeding units* are designed to feed a certain amount of power, determined by their own needs and wishes, irrespective of grid conditions. These components do not contribute to grid voltage and frequency control.

3. *Grid-supporting units* participate in the control of the grid voltage and frequency by adjusting their active and reactive power output according to voltage and frequency droops, allowing power sharing and expandability. These units contribute to power balancing, making a trade-off between their power rating and the frequency and local voltage quality.

The differences between these three classes are summarized in Table 1.

Table 1. Classification of inverter-interfaced DG units [3]

	Grid-forming	*Grid-feeding*	*Grid-supporting*
Control mode	Voltage control	Maximum active power control	Active/reactive power control
Output frequency	Fixed frequency	Grid synchronized	Grid synchronized (frequency droop)
Grid contribution	Sole creator of grid	Passive	Active contribution
Application	Stand-alone	Grid-connected	Stand-alone / grid connected

The inverter-interfaced DG units connected to the present power system operate typically in a grid-feeding mode, not contributing to the grid frequency or voltage control. However, with the significant increase of penetration level of small to medium scale inverter-interfaced DG units this operating mode will not be acceptable anymore. So in the future such units will have to contribute to the grid control and, consequently, have to operate in a grid-supporting mode.

III. DESIGN OF A SMALL-SCALE TEST VPP

The design of a small-scale test 5 kW VPP described here is based on the three separate tasks as shown in Figure 1.

First of all, different possible hardware configurations have to be analyzed. The hardware configuration aspect is discussed in this section of the paper. Then, functions, which can be performed by the VPP, have to be defined. Functionality and control aspects related to the VPP are considered in the following sections of the paper. And finally control design has to be implemented according to the desired functionality and taking into account a selected hardware configuration.

In this paper the possible future structure of a typical residential household is considered in the framework of VPP principle.
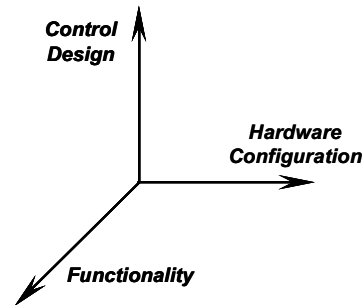

Figure 1. Illustration of design task of a small-scale VPP

Inverter-interfaced DG units can be classified by their topology in two groups: AC-based units connected to the grid with a rectifier and an inverter and DC-based units connected by means of a DC-DC converter (if it is necessary) and an inverter. The schemes of these two types of DG are shown in Figure 2.

Typical examples of AC-based inverter-interfaced DG units are microturbine (operating at higher frequencies) and wind turbine (operating at low frequencies). DC-based units include photovoltaic (PV) panels array and fuel cell. Electrical energy storage is also usually based on DC technology. One common feature for both types is the presence of a DC-link. Therefore, for the possible VPP hardware configuration depicted in Figure 3 a modular approach with a common DC bus joining all DG units, storage and loads is proposed. The connection to the grid is done by means of an inverter. Besides power electronic converters the VPP will include a wind turbine emulator (generator-motor setup), a PV panels array emulator (controllable DC source), electrical storage and, on later stages, household loads (both AC and DC). The grid can be emulated by a controllable AC power source. The electrical storage will consist of supercapacitors and lead-acid/lithium batteries.
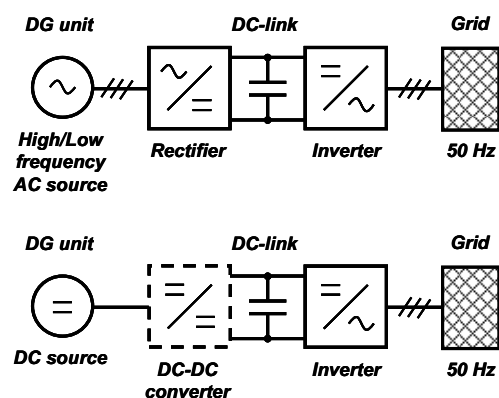

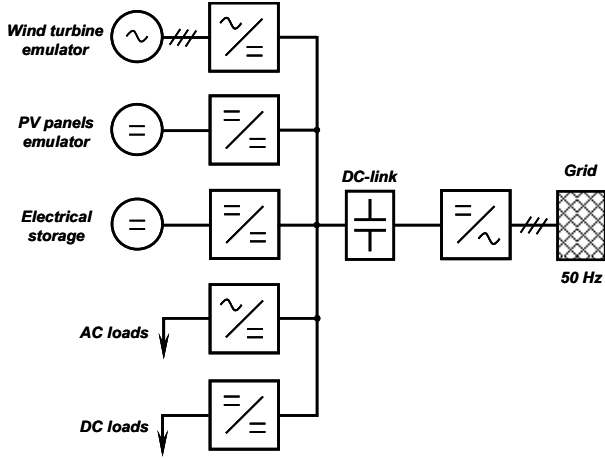Figure 2. Two types of inverter-interfaced DG units

Figure 3. VPP hardware configuration

Supercapacitors are characterized by long life duration (the number of charge-discharge cycles is nearly unlimited) and rapid charge-discharge. They might be used as fast-reacting energy storage. Lead-acid/lithium batteries have much shorter life duration (the number of charge-discharge cycles is in the order of several hundreds) and slow charge, however the discharge is also not so fast as for supercapacitors, which makes them suitable for a longer-term energy storage.

IV. FUNCTIONALITY OF PROPOSED VPP SCHEME

The control of proposed VPP scheme can include the following functions:

1. Load peak shaving using DG and storage (also referred as power matching) and demand side management (DSM).
2. Inertial response and primary frequency control.
3. Grid support during and after short-term voltage dips.
4. Power quality conditioning at the grid side (suppression of harmonics and flicker).
5. Power quality conditioning and uninterruptable power supply (UPS) function at the customer side.

Power matching is the capability of DG units and storage to smoothen the load profile. Example of a typical residential load profile during a working day [4] is provided in Figure 4.
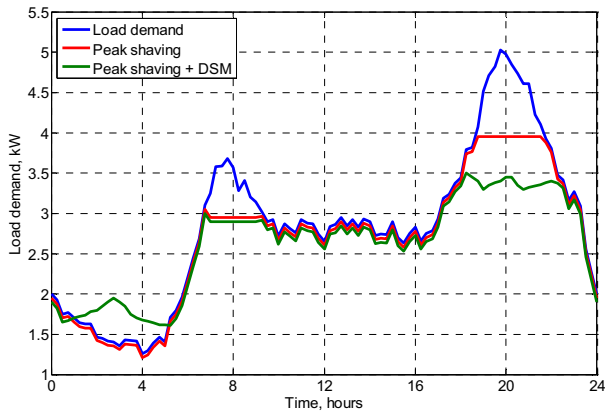

Figure 4. Typical residential load profile during a working day and possibilities for peak shaving and DSM

A large peak can be observed during the evening hours. This peak can be removed by proper control of DG units installed in the houses (PV panels array, microCHP unit, fuel cell, etc.) and storage (both thermal and electrical). The energy produced at night or during low load demand can be stored and used later to partially supply load demand during morning and evening hours. Storage might provide energy in case if either specified load demand threshold is exceeded or during scheduled time periods or taking into account both of these criteria. In the considered example the storage with energy capacity of 2 kWh can reduce the morning load peak from 3.6 to 3 kW and the evening peak from 5 to 4 kW. The higher is the storage capacity, the more possibilities are available for the further peak shaving and smoothing of the load profile. On the other hand, increase of the storage capacity leads to increase in the price of the energy storage unit.

Also capability for shifting of operation times for microCHP units can be employed. By allowing certain temperature variation (for example, ±1° C) the no-generation periods can be more evenly distributed in time without any change in the comfort level as shown in Figure 5. The upper part of the figure represents hysteresis temperature control, which implies that the microCHP unit starts/stops its operation only when the minimum/maximum temperature boundary is reached. There is no control over electrical power production. This is the control principle, which is typically used in microCHP units nowadays. The lower graph shows a smart temperature control, which takes into account not only the current heat demand, but also the current demand for electrical power production.

The load profile might be improved even further in case if *demand side management* is implemented. Non-critical loads can be controlled in such a way that they do not operate during the peak demand periods. It is proven experimentally that by applying these intelligent techniques the peak demand might be reduced by 30% up to 50% [6].
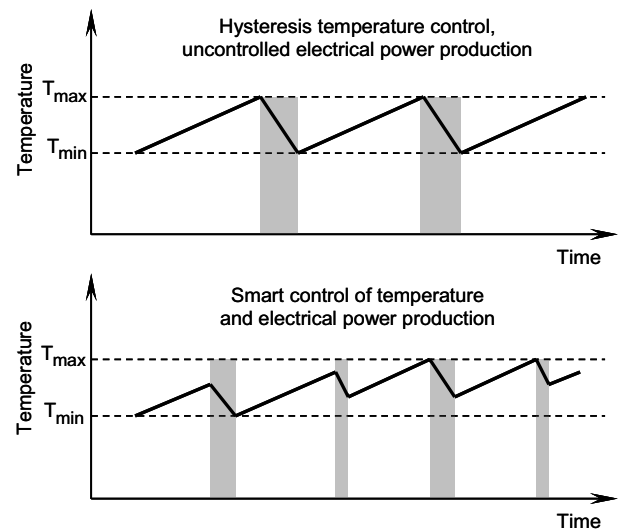

Figure 5. Operation shifting in a cooling process whilst obeying process state limits [5]

Nowadays in case of short-circuit in a network DG units are almost immediately switched off by their protection even for distant faults. In future, this will become not acceptable since the share of DG units will increase and their massive disconnection might lead to cascading events and consequent blackout. Therefore, DG units must have *fault ride-through capability* to support the grid after the fault. For inverter-interfaced DG units the control of power electronic converter has to detect the short-circuit and limit the current flowing through the converter very fast. This can be achieved by the techniques that are already used for high power wind turbines, for example, by crowbar protection, DC chopper, etc. The main principle of these techniques is in the blocking grid-side converter and bypassing the generator-side converter to prevent the damage of converters.

VPP can also contribute to the power quality improvement of the grid by injecting currents with specific frequencies in order to cancel out harmonics and flicker.

At the customer side perfect power quality can be achieved since the load and the grid are decoupled by power electronics. And in case of a severe network disturbance grid-side converter can be blocked, and energy storage can be used to supply local demand.

V. INERTIAL RESPONSE AND FREQUENCY CONTROL

Consider a traditional power system. A step increase in the load demand or an outage of a power plant will lead to the power imbalance and consequent decrease of system frequency (as shown by black line in Figure 6). The steepness of this decrease is determined by the value of total system inertia: the larger is the inertia, the smaller will be the deviation of frequency from the nominal value. In a very approximate way the system behavior can be described by the following equation:

$$\frac{d\omega}{dt} = \frac{1}{2H}\left(P_{gen} - P_{load}\right),\tag{1}$$

where ω – represents system frequency, H – total system inertia, P_{gen} and P_{load} – total active powers of generators and loads respectively. The frequency change is determined by the system inertial response because of physical nature of rotating synchronous machines, and mostly no frequency control action is taken in this period.

When the frequency drop reaches a certain limit (10 mHz for the UCTE grid [7]), frequency droop control (proportional control) is initiated. The value of the generated active power is increased according to the share predefined by the droop gain. However, such an increase does not happen instantly, the reaction depends on the speed, with which the power output of generating units can be changed. That is why the frequency continues to decrease further for a certain period of time even after droop control activation. When the generated power output is adjusted, the frequency restores to some steady-state value, typically a bit below or above nominal. According to the UCTE guidelines this steady-state value as a result of primary frequency control action has to be reached within 30

seconds. Too high gains for frequency droop control might result in significant frequency overshoot and, in extreme situations, in instability. Too low gains might lead to rapid frequency decrease in a case of a large disturbance.

Finally, the steady-state frequency deviation is eliminated by the secondary frequency control, which monitors the difference between actual and prescheduled power flows in the tie-lines between neighboring areas. According to the UCTE rules the time scale for the secondary frequency control action is limited by 15 minutes.
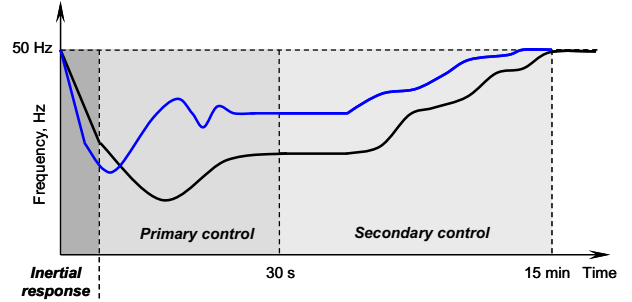

Figure 6. Frequency control in a power system: nowadays and future

In the present power system each generating unit with installed capacity higher than a specific value has to participate in the frequency control. For example, according to the Dutch grid code generators with installed power higher than 60 MW have to contribute to the grid frequency control.

However, due to the large penetration of small to medium-scale DG in the future even smaller units will have to participate in the frequency control. Besides that, since the share of inverter-interfaced units will continue to grow, the total system inertia will decrease significantly and the need for fast acting primary control will increase. Otherwise this might lead to large frequency deviations in case of a disturbance and without this might result in blackouts.

In order to avoid this, the inverter-interfaced DG units must follow the grid frequency up to certain predefined limits. In case of exceeding the limit, proportional droop control similar to the existing one might be activated, which will increase (or decrease) the power production proportionally to the frequency drop (or rise). Besides the proportional control block also the derivative block might be introduced, which will take into account the rate of frequency change. If the speed of the frequency decrease is fast then the active power generation can be boosted (energy storage might be used for this purpose) to prevent fast frequency decay, which is possible in systems with low rotational inertia. Since the reaction of power electronic converters and energy storage can be quite fast in comparison to the response of conventional generating units, the decreased system inertia and, consequently, faster frequency decrease in the initial several seconds following a disturbance can be compensated by this rapid reaction and dangerous situation can be avoided. The probable frequency behavior in this case is illustrated by blue line in Figure 6. After this reaction when the frequency will reach steady-state value, the secondary control might be activated while VPPs

will slowly decrease their power output back during a period between 30 seconds and 15 minutes after a disturbance. It is also necessary to mention that due to smaller inertia not only the initial frequency decay will be faster, but also the later frequency restoration after initiation of the primary control will go faster.

In order to make such behavior of the VPP possible it is proposed that the energy level maintained in the storage has to be equal to 50% of its nominal capacity during normal system operation.

It is proposed that inverter-interfaced units just follow the natural grid frequency (unless they are operating in the islanded mode, in which certain unit has to provide frequency reference) and not influence it in a direct way. Considering a hypothetical situation of a system with overly dominating inverter-interfaced DG units, in case all units follow fixed specified frequency value, there will be almost no frequency change even if a large power imbalance occurs. In a traditional power system the frequency might be considered as a natural communication signal, which indicates to all power plants that there is a power imbalance in the grid. This might not be the case in future power systems, and therefore existing frequency control principles have to be modified, which will take into account features of different generating units.

VI. POWER-VOLTAGE RELATION FOR VARIOUS GRIDS

In this section dependence of active and reactive power on voltage magnitude and voltage angle is analyzed for various networks.

Static behavior of a network (i.e., behavior determined by the load-flow equations) is to the large extent dependent on the parameters of cables or lines used for connection of the network elements. The active and reactive power flows through a cable/line are also functions of the voltage magnitudes and angles at the sending and receiving ends. Suppose the sending-end represents the generator. The receiving-end voltage is assumed to be fixed and can be interpreted as a point where the voltage is stiff. The sending and receiving ends are connected by means of a cable or a line, which can be represented by equivalent π-circuit shown in Figure 7.
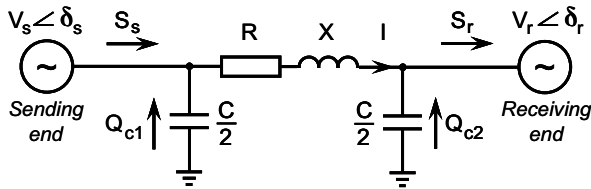

Figure 7. Equivalent circuit for a cable and a line

The general relationship between the voltage magnitudes/angles and the active/reactive powers can be easily derived:

$$\underline{S}_s = \underline{V}_s \underline{I}^* + jQ_{c1}$$
$$\underline{S}_r = \underline{V}_r \underline{I}^* + jQ_{c2} \tag{2}$$
$$\underline{I} = \frac{\underline{V}_s - \underline{V}_r}{R + jX} = \frac{\underline{V}_s - \underline{V}_r}{Ze^{j\varphi}}$$

Substituting the complex variable explicitly, the following relationships can be derived for the sending end:

$$P_s = \frac{V_s^2}{Z}cos\varphi - \frac{V_sV_r}{Z}cos\left(\delta_s - \delta_r + \varphi\right)$$
$$Q_s = \frac{V_s^2}{Z}sin\varphi - \frac{V_sV_r}{Z}sin\left(\delta_s - \delta_r + \varphi\right) + V_s^2\frac{\omega C}{2} \tag{3}$$

For the receiving end:

$$P_r = -\frac{V_r^2}{Z}cos\varphi + \frac{V_sV_r}{Z}cos\left(\delta_r - \delta_s + \varphi\right)$$
$$Q_r = -\frac{V_r^2}{Z}sin\varphi + \frac{V_sV_r}{Z}sin\left(\delta_r - \delta_s + \varphi\right) - V_r^2\frac{\omega C}{2} \tag{4}$$

For MV and LV lines/cables and for most of the HV lines the reactive power components Q_{c1} and Q_{c2} are very small and usually can be neglected without making a significant error.

For an ideal HV overhead line ($R << X$, $\varphi \approx 90°$, $Z \approx X$) equations (3) and (4) can be simplified to:

$$P_s = -\frac{V_sV_r}{X}sin\delta_v, \quad Q_s = \frac{V_s^2 - V_sV_r cos\delta_v}{X}$$
$$P_r = \frac{V_sV_r}{X}sin\delta_v, \quad Q_r = \frac{-V_r^2 + V_sV_r cos\delta_v}{X} \tag{5}$$

where $\delta_v = \delta_s - \delta_r$ is the angle difference between voltages of sending and receiving ends.

From (5) it can be further derived that for small values of δ_v (which is typically the case) the following relationship holds:

$$P_s \cong -\frac{V_sV_r}{X}\delta_v \cong K_P\delta_v,$$
$$Q_s \cong \frac{V_s^2}{X}\left(1 - \frac{V_r}{V_s}\right) \cong K_Q\Delta V,$$
$$P_r \cong \frac{V_sV_r}{X}\delta_v \cong -K_P\delta_v, \tag{6}$$
$$Q_r \cong \frac{V_r^2}{X}\left(\frac{V_s}{V_r} - 1\right) \cong -K_Q\Delta V$$

Therefore, for a HV line and small values of δ_v the active power flow is proportional to the voltage angle difference, while reactive power is proportional to the voltage magnitude difference. Such dependence allows to implement active power-frequency P-f and reactive power-voltage Q-V droop

control, since there is almost no coupling between the active power and the voltage magnitude difference, the reactive power and the voltage angle difference.

In a similar way the expressions for the other extreme situation, an ideal LV cable ($X << R$, $\varphi \approx 0°$, $Z \approx R$), can be obtained:

$$P_s = \frac{V_s^2 - V_s V_r cos\delta_v}{R}, \quad Q_s = -\frac{V_s V_r}{R} sin\delta_v$$
$$P_r = \frac{-V_r^2 + V_s V_r cos\delta_v}{R}, \quad Q_r = \frac{V_s V_r}{R} sin\delta_v \quad (7)$$

For the small values of δ_v:

$$P_s \cong \frac{V_s^2}{R}\left(1 - \frac{V_r}{V_s}\right) \cong K_P \Delta V,$$
$$Q_s \cong -\frac{V_s V_r}{R}\delta_v \cong K_Q \delta_v,$$
$$P_r \cong \frac{V_r^2}{R}\left(\frac{V_s}{V_r} - 1\right) \cong -K_P \Delta V, \quad (8)$$
$$Q_r \cong \frac{V_s V_r}{R}\delta_v \cong -K_Q \delta_v$$

For the LV cable and small values of δ_v, the situation is opposite to the HV line case: the active power flow is proportional to the voltage magnitude difference, while the reactive power is proportional to the voltage angle difference. Such dependence allows to implement active power-voltage P-V and reactive power-frequency Q-f droop control, since there is almost no coupling between active power and voltage angle difference, reactive power and voltage magnitude difference. This is actual for grid-supporting mode of operation of inverter-interfaced DG units in case of islanded or stand-alone applications. However, taking into account overall power system behavior the introduction of both droop concepts (P-f, Q-V and P-V, Q-f) at the same time appears to be contradictory and not feasible.

Now consider three different cases with realistic parameters: a HV network with overhead lines (high X/R ratio), a MV network also connected by means of overhead lines (moderate X/R ratio) and a MV/LV cable based network (low X/R ratio). Parameters of the lines and cables are provided in Table 2.

Receiving end active and reactive powers (P_r and Q_r) as a function of voltage angle and magnitude difference (δ_v and ΔV) for a HV line, a MV line and a MV/LV cable calculated with (3) and (4) are plotted in Figures 8-10 respectively.

Table 2. Parameters of lines and cables for various grids

	R [Ω /km]	X [Ω /km]	X/R
HV overhead line	0.050	0.430	8.6
MV overhead line	0.121	0.300	2.5
MV/LV cable	0.125	0.078	0.6

From technically acceptable and stability conditions:

$$P_r > 0, \quad \frac{dP_r}{d\delta_v} > 0 \quad (9)$$

the operating limits for the voltage angle difference can be determined: for the HV line $0°<\delta_v<90°$, for the MV line $0°<\delta_v< 68°$, for the MV/LV cable $0°<\delta_v<32°$ (these regions are hatched on the figures). It can be seen that for the small values of δ_v in case of HV and MV lines the active power is proportional to the voltage angle difference, while for a MV/LV cable their relationship is already not linear anymore.

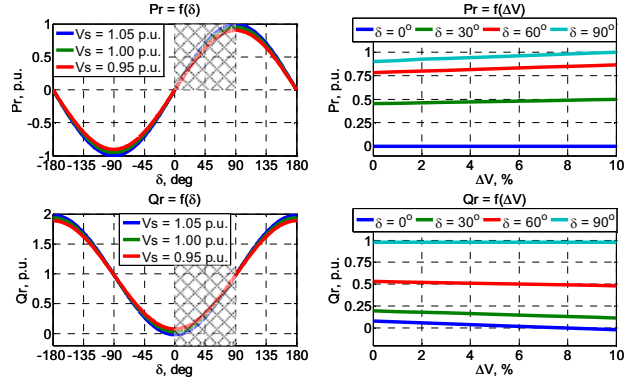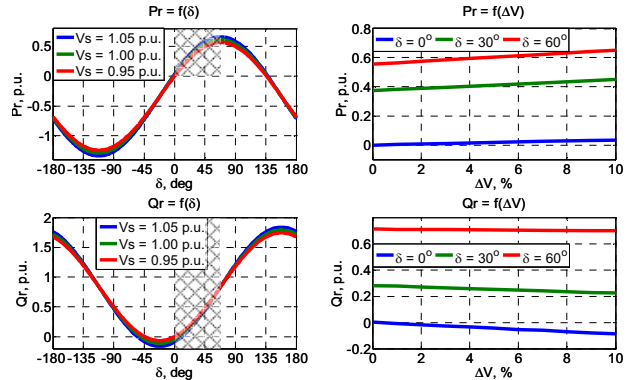Figure 8. P_r, Q_r as a function of δ_v, ΔV for a HV overhead line

Figure 9. P_r, Q_r as a function of δ_v, ΔV for a MV overhead line
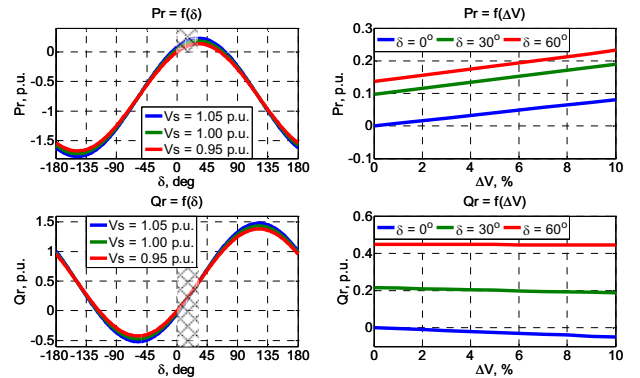

Figure 10. P_r, Q_r as a function of δ_v, ΔV for a MV/LV cable

Considering $Q_r = f(\delta_v)$ dependence for the small values of δ_v it can be concluded that for the HV line the reactive power and the voltage angle difference are nearly independent, for the MV line some nonlinear dependence appears, while for the MV/LV cable this dependence approaches to a linear shape.

Further, regarding $P_r = f(\Delta V)$ dependence for the ΔV values limited by standards and the small values of δ_v in the HV line case the active power is almost not influenced by the change in voltage magnitudes. The MV line exhibits a slightly different behavior, while for the MV/LV cable linear character can be clearly observed. The dependence between the variables can be illustrated in a quantitative way through the proportionality coefficients. For $P_r = f(\Delta V)$ relationship they are shown in Table 3. If the proportionality coefficient is 0, it means that variables are independent. If the value is 1, a change in ΔV (represented in p.u. instead of %) results in a same change in P_r (also expressed in p.u.). For the MV line and the MV/LV cable the critical angles are equal to $68°$ and $32°$ respectively. Therefore, for the larger angles no values are given in the table.

A similar analysis can be performed for the $Q_r = f(\Delta V)$ relationship (see Table 4). For the HV line operating at low values of δ_v, the reactive power flow strongly depends on the voltage magnitude. The same holds to a certain extent also for a MV line. For a cable even at 0° the influence is not very strong, although not negligible either.

Table 3. Proportionality coefficients for $P_r = f(\Delta V)$

δ_v	0°	15°	30°	60°	90°
HV line	0	0.246	0.476	0.826	0.952
MV line	0.356	0.573	0.750	0.942	–
MV\LV cable	0.808	0.911	0.952	–	–

Table 4. Proportionality coefficients for $Q_r = f(\Delta V)$

δ_v	0°	15°	30°	60°	90°
HV line	-0.952	-0.920	-0.826	-0.476	0
MV line	-0.883	-0.761	-0.587	-0.134	–
MV\LV cable	-0.504	-0.278	-0.033	–	–

The examples mentioned above show that network impedance significantly influences the character of power-voltage dependence and, consequently, may affect the principles used for the control. For some values of network parameters decoupling of variables is hardly possible (active and reactive powers depend both on the voltage magnitude and angle differences), so decoupled control might be difficult to achieve. For highly resistive LV networks and stand alone applications the active power-voltage and reactive power-frequency droop controls might be implemented. Although in case of the grid-connected operation this is not desirable. Problems with inverter-interfaced DG units operating in a grid-supporting mode might be avoided if certain inductance is introduced to emulate inductive character of HV network (for example, inductance in

the filter of power electronic converter might be increased or reactor might be placed in series with LV cable). However, this solution has a disadvantage of increased value of losses due to the increase of the total grid impedance.

VII. CONCLUSIONS

A high penetration level of the DG in a power system will influence the power system control. Small to medium-scale inverter-interfaced DG units will play an important role in the operation of future power systems. Grid-feeding behavior of DG units has to shift to a grid-supporting one. The VPP principle will allow to combine different generating units and loads, and can control them in an efficient manner. In this paper, possible functions for such control are discussed. Further research will be directed to design and to implement of these functions in a small-scale experimental setup. Development of such control systems will help the transition from a traditionally structured power system to an intelligent power system as is needed for the future.

VIII. REFERENCES

[1] M. Reza, P.H. Schavemaker, W.L. Kling, L. van der Sluis, "A research program on intelligent power systems: self controlling and self adapting power systems equipped to deal with the structural changes in the generation and the way of consumption," *CIRED 2003*, Barcelona, Spain, Paper: 4.70, May 2003.
[2] A. Ishchenko, J.M.A. Myrzik, W.L. Kling, "Control aspects of distribution networks with dispersed generation," *IEEE PowerTech 2005*, St. Petersburg, Russia, June 2005.
[3] K. de Brabandere, "Voltage and frequency droop control in low voltage grids by distributed generators with inverter front-end", *PhD Thesis*, ISBN 90-5682-745-6, Katholieke Universiteit Leuven, Leuven, Belgium, October 2006.
[4] A. Capasso, A. Invernizzi, R. Lamedica, A. Prudenzi, "Probabilistic processing of survey collected data in a residential load area for hourly demand profile estimation", *IEEE PowerTech 1993*, Athens, Greece, September 1993.
[5] K. Kok, C. Warmer, R. Kamphuis, P. Mellstrand, R. Gustavsson, "Distributed control in the electricity infrastructure", *Future Power Systems Conference (FPS) 2005*, Amsterdam, the Netherlands, November 2005.
[6] C.J. Warmer, M.P.F. Hommelberg, B. Roossien, J.K. Kok, J.W. Turkstra, "A field test using agents for coordination of residential microchp", *Intelligent Systems Applications to Power Systems (ISAP) 2007*, Kaohsiung, Taiwan, November 2007.
[7] UCTE, Operation Handbook, www.ucte.org.

IX. BIOGRAPHIES

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