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Harnessing PV inverter controls for increased hosting capacities of smart low voltage grids

Recent results from Austrian research and demonstration projects

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***Abstract*—Targeting an increased hosting capacity of low voltage grids for small distributed generation, PV inverter control concepts for maintaining tolerable voltage levels can be both effective and efficient measures. The effectiveness of such approaches for active (e.g. Volt/Watt) and reactive power controls (e.g. Volt/Var) particularly depends on the electrical characteristics of the respective grid (R/X ratio), whereas their efficiency is determined in comparison with alternative measures (e.g. conventional grid reinforcement). Furthermore, communication-based coordination of local inverter controls enables the optimization of the overall effect. Recent results from Austrian research and demonstration projects showcase the virtue of PV inverter control concepts in large-scale field trials following extensive simulation and lab testing. As a key finding, sound local-only controls can significantly enhance hosting capacities, whereas the additional benefit from a more complex, coordinated (tele-) control of small-scale units may likely be leveraged at unreasonable expenses only. Thus, low voltage grids integrating high PV penetrations have proven to be particularly smart when they do not rely on any operational communication infrastructure. Consequently, network planners are increasingly harnessing local inverter controls as an initial but essential smart grid instrument.**

Keywords—PV; hosting capacity; inverter control; smart grid; reactive power; low voltage; distributed generation; network planning; Volt/Var; Volt/Watt.

I. Problem and Motivation

In rural and semi-urban low voltage (LV) grids, maintaining tolerable voltage levels is usually the first restriction which limits a feeder's hosting capacity for distributed PV generators. A growing number of LV grids reach these limits, resulting in refused interconnection of additional generation units. To increase the usable hosting capacity, either the particular voltage band could be exhausted to a higher degree (by enhanced monitoring and/or probabilistic planning approaches), or the generators need to be employed to compensate for the immanent effect they have on the local voltage when feeding into the grid. The latter actively involves PV inverters, utilizing control mechanisms of active and reactive power. In terms of system architecture, these could be local-only controls (requiring no external communication links), or it could be an integration of distributed generators into a coordinated control. While local-only controls are likely to be the first and most cost-effective choice, optimization by coordinated (tele-) control of small-scale units may possibly be leveraged at high expenses only. In any case, a certain lack of experience has been discouraging grid operators from applying smart grid concepts instead of hardware reinforcements.

II. Methodology

The present paper discusses the usefulness of both local and coordinated control approaches for increasing LV hosting capacities by showcasing recent Austrian research and demonstration projects in the field of smart low voltage grids. The PV inverter's contribution to overcome hosting capacity restrictions with local-only controls is illustrated on the basis of the completed project *morePV2grid* in a first step. Technical findings and economic considerations of local controls are then complemented by introducing coordinated control concepts referring the ongoing project *DG DemoNet – Smart LV Grid*. Selected technical results as well as cost-benefit aspects (net present values) are provided on a preliminary basis.

III. PV Inverter Contribution to Solving the Problem

PV inverters are capable of controlling their active and reactive power exchange with the grid. Active power control (i.e. curtailment) can limit the PV-induced voltage rise, whereas reactive power exchange can either increase or decrease the local voltage. In the latter case, reactive power compensates the PV-induced voltage rise up to a certain degree. The effectiveness of reactive power control is mainly determined by local grid impedance conditions. The higher the local R/X ratio, the more reactive power is required to achieve the same relative voltage change. Figure 1 illustrates the effect of reactive power on voltage, depending on the power factor as well as the R/X ratio (top left).

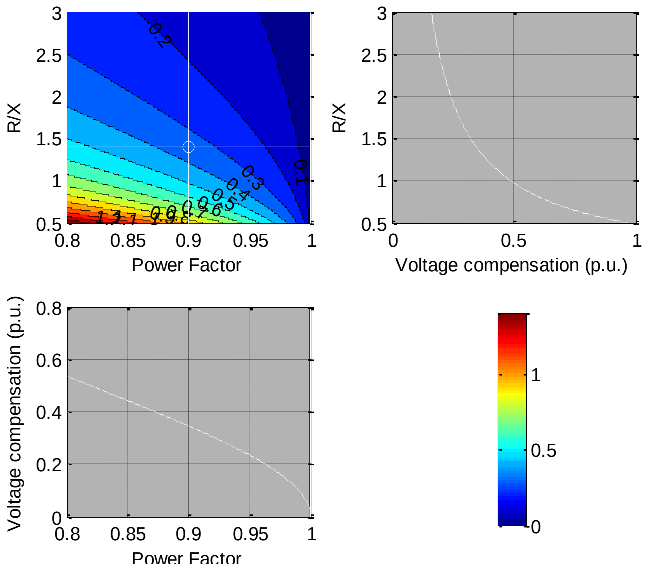

Figure 1. Effectiveness of reactive power for voltage compensation [1]

The (top left) marker indicates that operating the generation unit at a power factor of 0.9 in a node of an R/X ratio of 1.4 results in a compensation of the corresponding voltage rise (colour scaling) by approximately 35 %. The other charts show two sections with either a constant power factor of 0.9 (top right) or a constant R/X ratio of 1.4 (bottom left) [1].

IV. LOCAL-ONLY CONTROL: FRAMEWORK AND CONTROL CONCEPT OF MOREPV2GRID

Considering the illustrated technical limits, the generators' contribution to solve the problem of voltage rise can be defined. The project *morePV2grid* [2] agreed upon the following definition of the PV inverter's contribution to a local voltage control concept:

- Reactive power exchange is the primary, active power curtailment the secondary measure.
- Active and reactive power controls are operated in a coordinated and demand-oriented way. Reactive energy, additional grid losses, and cuts in PV system yields should be minimized.
- The overall stability must be ensured by avoiding undesirable interactions between interconnected generators that operate individual voltage controls.

Concerning control approaches, the project *morePV2grid* focused on a set power factor (PF) as well as on Watt/PF and Volt/Var modes in terms of reactive power, and analysed the Volt/Watt mode regarding active power control. The modes are illustrated below.

A. *Watt/PF*

Operating according to a Watt/PF characteristic provides reactive power depending on the level of active power of the particular generation unit. The settings usually define the minimum intended PF (i.e. maximum Var contribution) to be reached at maximum active power. As the voltage in the node of interconnection is not involved, this mode assumes that both the maximum voltage and thus the necessity of compensation coincide with maximum generation. Generally, Watt/PF modes can result in unnecessary reactive power flows (e.g. at times of high generation and high load) which increase grid losses; [2], cf. [3]).

B. *Volt/Var*

In Volt/Var operation, the reactive power provided by the generation unit directly responds to the local voltage level. The parameters (setpoints) of this characteristic can be adjusted for each unit to the individual circumstances of the particular local grid (at the time of commissioning). In order to avoid reactive power flows at voltages close to nominal, a deadband is usually applied (see Figure 2). In addition to primarily compensating for PV-induced voltage rise, the Volt/Var mode can inversely be utilized to increase the local voltage (e.g. at times of low generation and/or high load). In any case, the voltage feedback bears the immanent risk of undesirable interactions between interconnected generation units. However, this risk can be avoided by adequate control parameters (e.g. response time and change gradient; [2], cf. [4]).

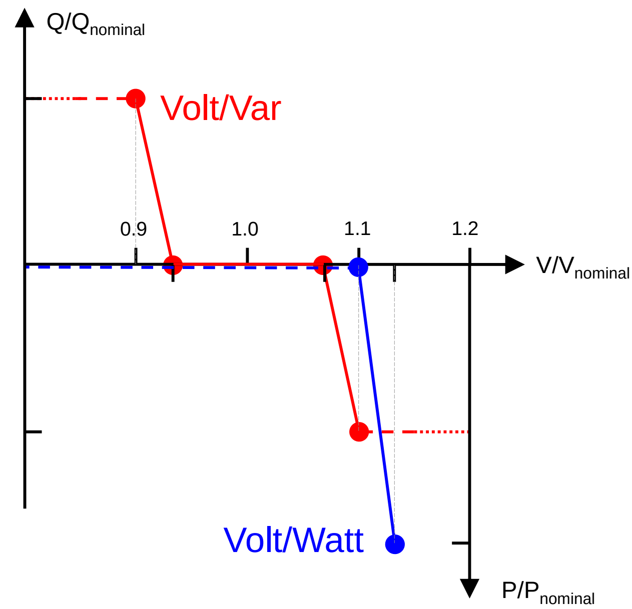

Figure 2. Volt/Var and Volt/Watt controls in selective combination

C. *Volt/Watt*

While reactive power can reduce the local voltage, a selective and gradual power curtailment ensures that PV-induced voltage rise does not exceed the limit allowed. It avoids a protective shutdown of the unit, or a series of reconnection attempts. With this measure, voltage rise is no longer restricting the hosting capacity. Particularly the combination of the voltage-depending modes Volt/Var and Volt/Watt can allow maximum PV penetration levels. As soon as the technically feasible contribution of reactive power is reached in Volt/Var mode (e.g. in terms of total current), further exceeding voltages are prevented by the gradually increasing curtailment of active power by a Volt/Watt characteristic (see Figure 2) to avoid tripping of the over-voltage protection.

V. Local-Only Control: Technical Results from morePV2grid

In *morePV2grid*, these local controls were analysed by means of static and dynamic simulations. Following the implementation into the inverter, a series of lab tests focused on the dynamic behaviour of the voltage-depending modes (Volt/Var, Volt/Watt). Both simulation and testing covered various patterns of parallel connection, such as inverters at different phases of one common node, and inverters at different nodes of the same phase, including a variation of the impedance between the nodes. In the process, controller parameters (e.g. measurement processing, response time and change gradient) were varied for assessing the stability of the control modes. It was concluded that a wide range of parameter settings as well as different settings of parallel units allow a stable operation. Particularly unfavourable settings which tend to lead to undesirable transient responses of the system could be clearly identified [2].

Concerning Volt/Var control, a large network reactance together with a high inverter power and a high droop factor (ΔVar[%]/ΔVolt[%]) causes a high open-loop gain of the control system. The higher the open-loop gain the larger the distance between the delay in the control and the Volt/Var controller time response must be. For the considered worst-case, the minimum ratio between delay and controller time response is about 0.5. For example, to reach a well-damped response (10 % damping ratio) with a time response of 3τ = 5 s, the delay shall stay below 0.80 s [4]. For a local Volt/Var control as applied in the field tests in *morePV2grid* and *DG DemoNet – Smart LV Grid*, unstable transient behaviour is eliminated because of negligibly short delay times.

In *morePV2grid*, a long-term field trial was employed to validate stability and effectiveness of the local controls. A number of inverters with integrated controls were interconnected along a semi-urban underground LV feeder. Monitoring revealed a maximum PV-induced voltage rise of 4.9 % above nominal (230 V). Reactive power controls generally managed to reduce the voltage by 1.3 base points, resulting in compensation by approximately 25 %. Thus, the particular LV grid featured relatively small voltage sensitivity against reactive power. However, this figure of sensitivity can be interpreted as rather typical with regards to the impedance characteristics of a semi-urban to rural LV grid with full underground cabling. Additionally, active power control (Volt/Watt) was tested in the field, and the selective curtailment proved to limit voltage rise to the preset value (as restrictively low as 103 % of nominal in order to showcase the positive effect) [2].

VI. Local-Only Control: Economic Considerations

Regarding financial aspects, the control-related costs for the PV installations are limited to additional investment costs for the adequate sizing of the inverter respecting the provision of reactive power (typically 5-10 % extra) on the one hand, and to operational shortfalls caused by selective curtailment on the other (below 1 % p.a. in the field trial of *morePV2grid* [2]). System integration costs on the sides of the DSO (network planning) and the inverter manufacturer (controller software) were not quantified within *morePV2grid* (see further considerations in X).

VII. Local-Only Control: Conclusions and Recommendations from morePV2grid

The achievable effect of local reactive power control on voltage is determined by the R/X ratio in the particular network node. The technically feasible compensation of PV-induced voltage rise ranges from 20 % to 80 %. In state-of-the-art LV grids with a high share of cabled lines, 30 % compensation is regarded as typical (i.e. 30 % more hosting capacity by reactive power employment at insignificantly changed losses). Selective modes (Volt/Var) are favourable as they tie reactive power flows to situations where voltage levels actually require a reducing effect. In addition, selective local curtailment (Volt/Watt) eliminates voltage rise as a restriction to local hosting capacity, yet at the expense of losses in PV energy yields. However, cuts will be limited in depth and short in time as the highest (restricting) voltages are likely to occur for short periods only. As a conclusion, sound local-only Volt/Var and Volt/Watt controls can significantly enhance hosting capacities at particularly low cost [2].

VIII. Local & Coordinated Controls: The Concept of DG DemoNet – Smart LV Grid

The project *DG DemoNet – Smart LV Grid* [5] employed local as well as coordinated voltage controls for increasing the hosting capacity of LV grids. The control concepts investigated basically relied on two different kinds of actors, namely PV inverters operating in Volt/Var and Volt/Watt mode, and transformers equipped with on-load-tap-change (OLTC) controllers at the secondary substations. The control concepts were structured in four stages which are described in the following sub-chapters [6]. The higher the stage, the more the complexity of the control process and the controller's requirements on grid information increases. Within the project, stage after stage was investigated, implemented, tested, and validated in the field. For field-testing coordinated controls involving three Austrian LV grids, the control stages were implemented on a controller that was operated at the particular secondary substation. The PV inverter control settings were dynamically reconfigurable by means of telecontrol. In addition, a forth demonstration grid exclusively utilized local controls of the PV inverters. In total, four LV field test grids hosting 136 PV installations (approximately 700 kW_{peak} of cumulated power) were involved in the project.

A. Stage 1 – local control

All actors in the grid act according to local measurements only, so no communication infrastructure is necessary. In this stage, the controller operates the transformer's OLTC in local busbar voltage control, and the PV inverters act according to their predefined, local Volt/Var and Volt/Watt characteristics (cf. IV).

B. Stage 2 – distributed control

In this stage, the PV inverters act in the same way as in stage 1 (i.e. according to local measurements), whereas the controller receives actual voltage measurements from predefined "critical nodes". Therefore, a communication infrastructure is necessary, which was chosen to be narrow band PLC in the demonstration grids. The controller's strategy for tap-change control is to avoid undervoltage prior to overvoltage because the controller assumes that a possible overvoltage problem will be resolved by the PV inverters' local controls (i.e. Volt/Var in a first, Volt/Watt in a second step, cf. IV).

C. *Stage 3 – coordinated control*

In this stage, the tap position is controlled in the same way as in stage 2. Additionally, the controller calculates one optimized Volt/Var characteristic for all PV inverters in the grid when the voltage rise in the grid gets high. The controller has no topology information, so one and the same characteristic is sent out to all PV inverters by means of telecontrol.

D. *Stage 4 – selective coordinated control*

This stage is an extension of stage 3, as the controller is able to calculate individual Volt/Var characteristics for each PV inverter in the grid. Therefore the controller does not necessarily need topology information, but at least an assignment between the received voltage measurements at the critical nodes and the PV inverters located nearby is necessary. With this assignment, the controller can address specific PV inverters that are located in a region where a specific control action should be performed.

IX. LOCAL & COORDINATED CONTROLS: SELECTED TECHNICAL RESULTS

A. *Impact of control modes on voltage bands*

The impact of *DG DemoNet – Smart LV Grid*'s control stages on two Austrian LV grids involved in the project are illustrated in Figure 3 and Figure 4. The voltage band that was used by a control strategy gives significant information about the hosting capacity of the grid. The smaller the voltage band, the more load or generation can be integrated into the grid while voltage limits according to EN 50160 are maintained. In the uncontrolled scenario (conventional grid operation), the OLTC position was set to default, and the PV inverters did not contribute reactive power (active power reduction was avoided by power system planning).

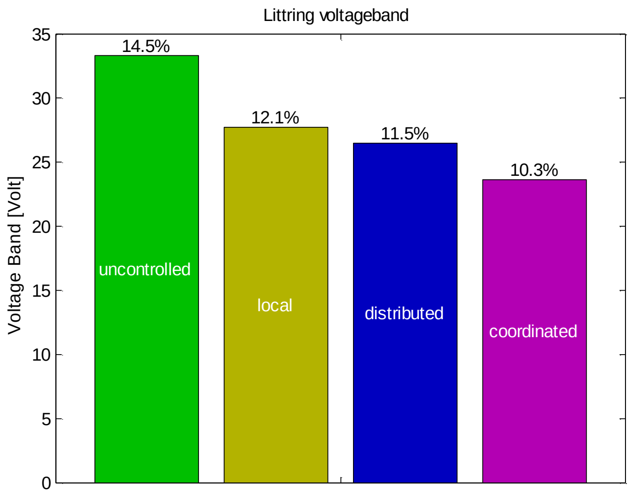

Figure 3. Voltage band allocation (10-minute average) in "Littring" for the control strategies "uncontrolled" (conventional grid operation), "local" (stage 1), "distributed" (stage 2) and "coordinated" (stage 3). Percent values on top of the bars show the voltage band referring to nominal (230 V).

"Littring" is a rural LV grid in Upper-Austria with four branches, a maximum branch length of more than 1100 m, 85 kW peak load and a distributed PV power of 135 kW_{peak}.

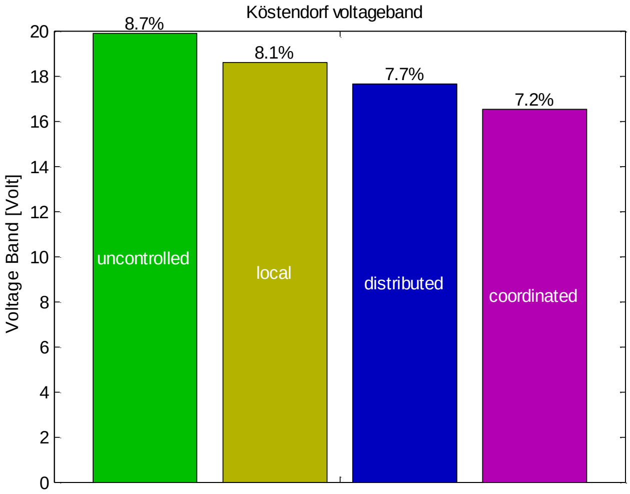

Figure 4. Voltage band allocation (10-minute average) in "Köstendorf" for the control strategies "uncontrolled" (conventional grid operation), "local" (stage 1), "distributed" (stage 2) and "coordinated" (stage 3). Percent values on top of the bars show the voltage band referring to nominal (230 V).

"Köstendorf" is a fully cabled LV grid in Salzburg with 6 branches, 165 kW peak load and a distributed PV generation of 195 kW_{peak}.

Both "Littring" and "Köstendorf" are connected to a rather stiff medium voltage, so that the voltage band shown above mainly results from the LV grid's voltage rise and voltage drop. With advancing control stages, the occupied voltage band slims down. In "Littring", the hosting capacity in the uncontrolled scenario is nearly at its limits, and significant improvements can be achieved with local Volt/Var control and local OLTC control. In "Köstendorf", the grid is rather strong due to the fact the grid is cabled (i.e. there are no overhead lines). Although there is more PV installed, the voltage band cannot be reduced significantly due to the fact that the potential to optimise is lower in this grid with a used voltage band of below 10 % in conventional grid operation.

Pointing out the results for "local" control (stage 1, see VIII) in the demonstration grids of "Littring" (Figure 3) and "Köstendorf" (Figure 4), it is worth mentioning that it was only the local inverter control (Volt/Var with a minimum power factor of 0.9) that contributed to the overall effect. In the underlying period of field trial, the respective (local) OLTC controllers persisted in center position.

B. *Consideration of grid losses*

Currents from reactive power flows add up to the total current which can result in additional grid losses. The results of the corresponding simulations for three different LV grids of the field tests and for each stage of control (see VIII) are given in 0Grid losses are related to the uncontrolled scenario (1.000) which was calculated with no reactive power control employed.

TABLE I. INFLUENCE OF REACTIVE POWER CONTROLS ON ELECTRICAL LOSSES

LV Grid	Losses per Control Stage		
	Local	*Distributed*	*Coordinated*
Eberstalzell	1.000	0.981	1.016
Littring	0.992	0.986	0.999
Köstendorf	1.000	0.997	1.039

Resulting from simulation, grid losses significantly depend on the Volt/Var settings as well as on the set voltage limits of the LV grid control. In case of the simulated grids, reactive power controls increased the grid losses by a maximum of approximately 4 %. Moreover, seasonal and weather-dependent influences add up to a 40 % variation. Generally, control-related reactive power flows do rather insignificantly increase grid losses and makes them a subordinate constraint of utilizing reactive power controls for improving hosting capacities of LV grids.

X. LOCAL & COORDINATED CONTROLS: COST-BENEFIT ASPECTS

Complementing the economic considerations of local-only controls the project *DG DemoNet – Smart LV Grid* estimates integration and maintenance costs on the sides of the DSO (network planning, customer service) and the inverter manufacturer (controller software). With regards to the requirements of coordinated controls, the following additional cost elements are identified:

- MV/LV transformer with on-load tap-changer and controller for coordinated control algorithms,
- Metering and power line communication infrastructure to get online voltage values from critical nodes and PV installations,
- ICT solutions to operate bidirectional communication signals (if necessary including suitable gateways) in order to influence the behaviour of PV installations and grid loads.

For the economic assessment, conventional grid reinforcements are compared to local and coordinated control solutions. The analyses are based on four demonstration cases, each related to one of the four field test grids involved in the project. The DSOs for the field test grids (i.e. demonstration cases) plan and calculate the necessary conventional grid reinforcements to host the PV generation capacity installed. However, in order to derive comparable results it is assumed that there is no possibility of enabling grid alteration switches to connect problematic grid branches to other grid segments. Otherwise, voltage problems could often be solved without grid reinforcements. Thus, an average value (for all demonstration cases) of approximately 180 €/kW_{peak} for grid reinforcements is calculated. The corresponding economic evaluation compared the net present values of capital (CAPEX) as well as operational (OPEX) expenditures of conventional grid reinforcement to local and coordinated control solutions.

With this in mind, the demonstration-related results show that sound local-only Volt/Var and Volt/Watt inverter controls can significantly enhance hosting capacities at particularly low cost in most cases. Thus, an average cost advantage (all four demonstration cases have cost advantages) of approximately 85 €/kW_{peak} can be identified if low conventional grid reinforcement cost apply and five hours of annual local control maintenance efforts are considered for each demonstration case (at an evaluation period of 50 years corresponding to the technical lifetime of conventional grid assets). This average value increases to about 150 €/kW_{peak} if no extra maintenance efforts due to local control can be expected.

Regarding coordinated control and its defined stages, the economic rating has not yet been completed. However, first evaluation results show that mainly additional CAPEX for OLTC infrastructure as well as for communication equipment significantly reduce cost advantages compared to conventional grid reinforcements. The most crucial parameter lies within the possible range of OPEX (mainly maintenance) in daily grid operation of each control stage. Therefore, the final phase of the *DG DemoNet – Smart LV Grid* will focus on the impact analysis of different OPEX settings.

XI. SUMMARY AND OUTLOOK

Technical considerations show that local PV inverter controls are capable to significantly reduce voltage rise (change) in LV grids. The positive effect of reactive power control at inverters is very much dependent on the networks' R/X ratio (20% to 80% of additional hosting capacity are feasible). One important result of the simulations and field tests is that concerns about the stability of dynamic voltage-dependent controls were cleared. Only with unnecessary small time constants together with large delays in the control, unstable behaviour is possible. Adding a voltage-dependent power curtailment solves any overvoltage problem with the disadvantage of wasting renewable energy. The combination of inverter-only control functions with on-load tap-changers at the secondary substation can reduce curtailment and/or can increase hosting capacities. By implementing communication for distributed and coordinated control, further improvements can be achieved. However, the field tests clearly showed that the effort for establishing a reliable communication-based control is high.

Regarding economic evaluations, local-only controls with PV inverters (Volt/Var, Volt/Watt) in many cases do significantly enhance hosting capacities at particularly low cost, as they do not rely on any external communication infrastructure. However, the demonstration cases of *DG DemoNet – Smart LV Grid* show that coordinated control strategies are likely to achieve economic feasibility only if moderate to high grid reinforcement costs can be expected. Even then, uncertainties towards the future development of OPEX in daily grid operation remain, most notably concerning ICT equipment as well as system maintenance. As a consequence from the DSO's perspective, coordinated control strategies in LV grids currently seem to be quite risky to be implemented on a large-scale. In any case, network planners are increasingly harnessing local-only inverter controls as an initial but essential smart LV grid instrument [3].

NOTICE OF PRELIMINARY RESULTS

Results and related interpretation derived from *DG DemoNet – Smart LV Grid* are provided on a preliminary basis. The final project report is expected to be published in 2015.

Acknowledgment

Both *morePV2grid* (project ref. no. 825441, 2010-2013) and *DG DemoNet – Smart LV Grid* (project ref. no. 829867, 2011-2014) were funded within the programme Neue Energien 2020 (New Energies 2020) by the Klima- und Energiefonds (Austrian Climate and Energy Fund).

Project partners of *morePV2grid*: Fronius International GmbH, AIT Austrian Institute of Technology GmbH, Netz Oberösterreich GmbH, MEA Solar GmbH.

Project partners of *DG DemoNet – Smart LV Grid*: AIT Austrian Institute of Technology GmbH, Siemens AG Österreich, Fronius International GmbH, Netz Oberösterreich GmbH, Salzburg Netz GmbH, Linz Strom Netz GmbH, Vienna University of Technology – Energy Economics Group, Vienna University of Technology – Institute of Computer Technology, Netz Burgenland Strom GmbH.

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