DG DEMONET - FINAL RESULTS OF FIELD TRIAL VALIDATION OF COORDINATED VOLT/VAR CONTROL

Roman SCHWALBE, Helfried BRUNNER, Benoit BLETTERÎE
AIT Austrian Institute of Technology – Austria
roman.schwalbe@ait.ac.at, helfried.brunner@ait.ac.at, benoit.bletterie@ait.ac.at

Wolfgang PRÜGGLER
TU Wien – Austria
prueggler@eeg.tuwien.ac.at

Andreas ABART
Netz Oberösterreich – Austria
andreas.abart@netzgmbh.at

Rudolf POINTER
Salzburg Netz – Austria
rudolf.pointner@salzburgnetz.at

Frank HERB
Vorarlberg Netz – Austria
frank.herb@vorarlbergnetz.at

ABSTRACT

This paper describes the final validation results and the key findings of the DG-DemoNet project, where coordinated and distributed voltage control concepts were developed, implemented and tested in field tests in two distribution systems with a high share of distributed generation. Based on the lessons learned in the field trial these control concepts are assessed from the technical and the economical point of view. The achievable extensions of available voltage band by applying distributed or coordinated voltage control in comparison to conventional grid control are analysed.

INTRODUCTION

Motivation

Due to given EU framework conditions there is a trend to distributed electricity generation. This development will strengthen in the near future.

Voltage rise has turned out to be the most critical system boundary for the integration of distributed generation (DG) in rural distribution grid structures. The distribution system operator (DSO) is responsible for maintaining voltage limits, but due to the organisational separation of electricity generation, trading, and distribution the DSO does not have direct access to the DGs.

Coordinated voltage control concepts as described in the next chapter can delay expensive and long-term grid reinforcement while enabling a higher share of DG. Furthermore existing grid infrastructure can be utilised more efficiently and the risk of false long-term investment decisions can be reduced, leading to higher flexibilities in DSO's power system planning.

Scope of the DG-DemoNet project was the development, planning and implementation of voltage control concepts allowing a cost-efficient integration of high shares of DG in MV networks. These concepts have to maintain a high level of quality of supply while achieving economic benefits in comparison to network reinforcement.

Voltage control concept

In 'distributed voltage control' real-time voltage measurements from predetermined 'critical nodes' (CN) are transmitted to the centrally operated voltage controller. This controller calculates an optimised voltage set value for the central HV/MV-transformer's automatic voltage controller (AVC). Primary goal of the distributed voltage controller is to keep all voltages within the specified voltage limits.

In addition to distributed voltage control, in 'coordinated voltage control' the voltage difference between the grid nodes is optimised by utilising the capability of controllable DG's to contribute reactive power. The reactive power set values for the DG's are calculated by the central controller based on the actual DG's operation point (active/reactive power measurements) and the topology information of the actual grid's switching state. Primary goal of the coordinated voltage control concept is to keep the voltage range between the highest and the lowest grid voltage (voltage spread) small in addition to the primary goal of the distributed voltage controller. Details are given in [1] and [3].

Previous Work

The voltage control concept that was operated during field trail phase is detailed in [1], where also important issues concerning comparability and benchmarking of voltage control concepts are discussed. The MV grids selected for field trial are described in [2] as well as the reactive power control of the controllable synchronous generators in the grids. Issues related to the deployment of the controller in the field and a listing of projects relating to coordinated voltage control can be found in [3]. Details about validating the controller by hardware-in-the-loop simulation are described in [4]. During the concept phase of the project the focus was on the rating how much DG can be connected to those grids with active grid integration concepts. In contrast to this, the main focus of the validation phase was to demonstrate the operability of the concepts and resulting advantages in grid operation due to the fact additional DG integration was not part of the field trial.

VALIDATION KEY FINDINGS

The main challenges that arose during the field trials carried out in 2012 - 2013 in two Austrian distribution grids "Lungau" and "Großes Walsertal" are described below as well as the field trial the key findings.

Communication infrastructure

The installation of measuring devices with real-time transmission in the grid connected to the controller via telecontrol (critical nodes at DGs or load sinks) was more effort than expected due the local conditions of the demonstration regions:

Especially in very mountainous regions where radio relay systems were not possible due to insufficient line-of-sight power line carrier (PLC) had to be used as last mile technology.

Due to the same reason a few CNs could not be installed because local conditions lead into economic inefficiency. In practise this was not a problem for the control concept as long as the possibility is given to select a representative node in the vicinity and introduce safety margins in the controller's configuration.

While the communication with outlying CNs sometimes suffered by short blackouts (that did not harm the control operation), the CNs connected via WiMAX[1] showed a very good reliability and excellent transmission characteristics.

All in all the communication infrastructure that was used turned out to be adequate and sufficient for coordinated voltage control in terms of reliability and transmission delays, which were below ten seconds. In the field test regions up to eighteen CNs and five DGs were operated leading to a demand of around thirty process variables that are updated within a sub-minute interval.

Total communication interruptions occurred rarely and did not last for more than two hours during the field test period. Partly, they were planned due to telecontrol system maintenance issues, but even unintended communication interruptions did not lead to critical grid situations due to the robust controller design: The local transformer's AVC controls the transformer's on-load-tap-changer (OLTC) according to the last given set value based on local measurements which is independent from any telecontrol communication.

Topology recognition system

Originally it was planned to implement the topology recognition system based on PLC and the principle that the way the power flows is equivalent to the way the data flows. Functional deficiencies in the PLC narrow band protocol made it necessary to implement a topology recognition system that depends on topology information given by the process control system that was available in both demonstration regions. This solution was a compromise and not intended in the original controller's architecture. In practise this topology recognition system sometimes lead to suboptimal grid operation due to faulty or incomplete information given to the controller. Although the controller continued operation in "Großes Walsertal" after the end of the project because of satisfying results and a good reliability, it turned out that the topology recognition system in its current implementation needs a redesign and the dependency on external tools has to be reconsidered.

DG's reactive power control

As described in [1] the ability to contribute reactive power was less than expected at existing and retrofitted DGs with the following reasons:

- Existing DGs were not designed for operation at cosφ=0.9 cap. when running at nominal power due to apparent power limitation.
- Technical difficulties at reactive power control retrofit limited the amount of reactive power.
- For older generators no PQ-diagram was available and therefore safety margins had to be maintained to avoid generator instability.

In the planning phase it was assumed that all generators participating coordinated voltage control can contribute reactive power with cosφ=0.9 cap., but the field test phase had to be operated partly with more than 50% reduction in controllable reactive power when DGs were at nominal power output.

Once reactive power control was established at the DG units, operation was reliable without incidents for the observed time period.

Relevance of the grid's switching state

The lack of controllable reactive power resulted in a reduction in the possibilities to alter voltages in the outlying parts of the grid. All the more, changes in the grid's voltage situation caused by a change in the grid's switching state get significant. As explained in [1], the spreading (distance between the highest and the lowest grid voltage) was reduced in "Lungau" by 1 to 2% by operating the grid in a "ring" switching state: The interconnection of a load-dominated branch with a generation-dominated branch to a "ring" switching state achieved a much more optimal voltage situation in the grid than it was possible by DG's reactive power control. In this switching state much less reactive power was necessary to keep grid voltages within the given voltage limits.

Integration of the controller into the operational management

The controller was integrated into the operational grid management in a passive way so that the control centre was only informed when the controller reported a problem. The control centre staff was instructed to turn off the controller in such cases and ask for support from experts. Even in cases of changing of the active transformer in the grid the controller had to operate completely transparent and automatically recognise that the transformer that needs to be controlled has changed.

Reliability of the voltage control concept

In both demonstration grids the coordinated voltage controller successfully managed grid operation over a pre-validation test phase of nearly one year and over the validation phase of several months.

During the field test phase the controller operation had to be interrupted by the DSOs due to incorrect operation only once in both grids. The reasons were in both cases topology issues and grid operation was continued without incidents.

---

[1] worldwide interoperability for microwave access

Overall the DSOs were satisfied with the flexibility, configurability and reliability of the controller implementation, and, as mentioned before, in “Großes Walsertal” the controller continued operation after the end of the project.

ECONOMIC VALIDATION

Cost Validation

The economic validation phase of the project showed that the implementation costs were underestimated by about 30% in the first cost benefit analyses (see [5]). Significant investment cost deviations were observed for the controller-OLTC-interoperability due to higher efforts for integration of the new controllers into existing systems. However, operational costs for the OLTC were lower as originally estimated. Regarding measuring cost at certain points in the grid evaluated cost are about 2.500 € above estimated values. Again integration cost but also operational costs were higher than expected. The same findings were observed for installing reactive power controllers at existing DG units. Hence, the DSOs prefer to enable reactive power control at DG units, which currently ask for grid connection or will in the future.

Cost reductions for e.g. controller-OLTC-interoperability or metering can be expected in the future, if analysed concepts transform to state of the art technologies. However, as such cost reduction would be highly uncertain assumptions the economic validation was performed with observed cost values of the validation project. It has to be mentioned, that these cost values were collected in the case studies "Großes Walsertal" as well as "Lungau". Those values were also used in the case study "Klaus Phyrn" as no real asset installations were performed there.

Table 1 summarizes results of performed cost calculations per case study in €/kW of additionally connected DG capacity. These results are related to the scenario assumption that during a timeframe of 20 years DG units with lower capacity demand grid integration in advance compared to units with higher capacities. These results in lower net present values of cost advantages or higher disadvantages compared to cable laying (see [5]).

	Klaus-Phyrn	Lungau	Großes Walsertal
Cable laying [€/kW]	92	222	252
Coordinated voltage control [€/kW]	134	127	58
Advantage of net present values of cost in [%]	-46%	43%	77%
DG capacity in [MW]	12.3	6.6	16.8

Table 1 Comparison of grid integration cost per case study

Especially case study "Klaus Phyrn" shows that also cost disadvantages can occur by implementing analysed Smart Grid solutions in a case where limited line reinforcement efficiently increases the hosting capacity. Hence, economic performance is linked strongly to the existing grid situation and therefore calculated results cannot be generalised.

Power system planning aspects

Economic evaluation showed that the solutions developed within this project are more likely to be economically feasible in recently renewed grids and possibly not competitive in older ones that have to be renewed in the near future. This is due to the fact, that the recovery value of older grid segments is low compared to new grid assets. From a power system planning perspective intelligent control concepts tend to make grid operation more complex (planning, operation, maintenance, dependency on ICT[2]). As a consequence, conventional grid reinforcement will be the preferred solution if grid infrastructure is close to the end of its lifetime. However, coordinated voltage control can offer flexibilities to power system planning to compensate unexpected requirements in recently renewed grids. Then, cost shifts of CAPEX[3] towards OPEX[4] are likely. Moreover, cost benefits of such alternatives are strongly linked to the length of the lines that would have to be replaced.

In cases where only one branch in a grid is affected, a decoupling solution with a series regulator can also be an even more economic solution.

TECHNICAL VALIDATION RESULTS

Validation phase setting

In the validation phase at the end of the field trials, the performance of the developed voltage control concepts (distributed and coordinated control scenario) was compared with the conventionally controlled grid (reference control scenario). Therefore the control strategy that operates the grid was switched in a daily cycle over a period of several months in winter/spring 2013 to record highly comparable data from each control strategy. In both grids the highest voltage drop occurs in winter (high loads), and the highest voltage rise occurs in spring (high generation due to snow melting), so in the inspected time period both extremes are contained.

In “Großes Walsertal” the change in control strategies on a daily basis is done between the three strategies ‘reference’, ‘distributed’ and ‘coordinated’, with the intention to demonstrate the benefit of the utilisation of DG’s reactive power (coord. control) in addition to the transformer’s AVC control based on actual grid voltage measurements (distr. control).

In “Lungau” the three control strategies ‘reference’, ‘coordinated’ and ZUQDE were rotated on a daily basis.

---

[2] information and communications technology

[3] capital expenditure

[4] operational expenditure

The third-party-solution ZUQDE had its demonstration phase in the same time period as the DG-DemoNet project and results of the project can be found in [6].

Terminology

Figure 1 illustrates the terminology that is used for discussion of the validation results:

- The 'available voltage band' is given by the grid code and defined as $U_{upperlimit} - U_{lowerlimit}$.
- The 'actual voltage range' (also voltage range) is defined as $U_{range}(t) = U_{max}(t) - U_{min}(t)$ where t identifies an arbitrary 10min averaging timespan during grid operation.
- The 'voltage band' that is 'used' by a control strategy is defined as $max_t(U_{max}(t)) - min_t(U_{min}(t))$ where t covers all timespans this control strategy was active in the grid.

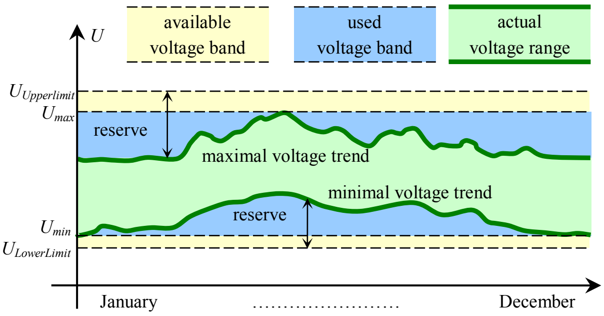

Figure 1 Terminology for discussion of validation results

Validation results

Figure 2 and Figure 3 compare the duration curves of the lowest and the highest voltage in the demonstration grids for the different control strategies. Table 2 and Table 3 provide the numbers to the most interesting values from the figures. In both grids the reference scenario was operated at a higher voltage level (1% in "Lungau" and 3% in "Großes Walsertal" due to a pending nominal voltage adjustment). In both grids the configured voltage limits were successfully maintained over the whole inspection period. In "Lungau" the controller was set to keep grid voltages as low as possible, while in "Großes Walsertal" the controller was set to keep grid voltages as high as possible within the given voltage band.

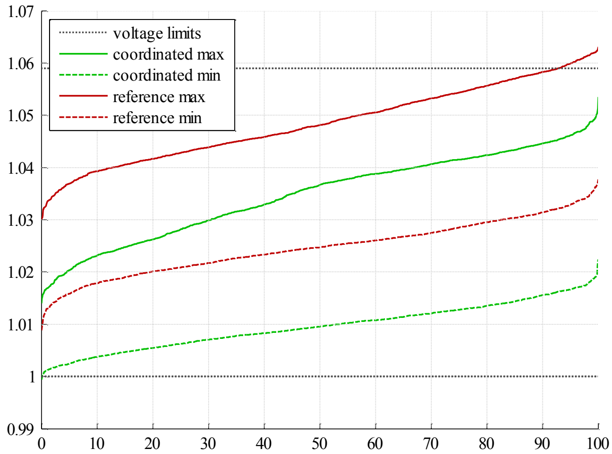

Figure 2 Duration curves of highest (max, solid) and lowest (min, dashed) grid voltage of different voltage control concepts 'reference' and 'coordinated' in "Lungau"

[% nominal voltage]	Reference	Coordinated
minimal grid voltage	100.9	100.0
maximal grid voltage	106.3	105.2
used voltage band	5.3	5.2
max. voltage range	3.9	4.0

Table 2 Voltage statistics "Lungau"

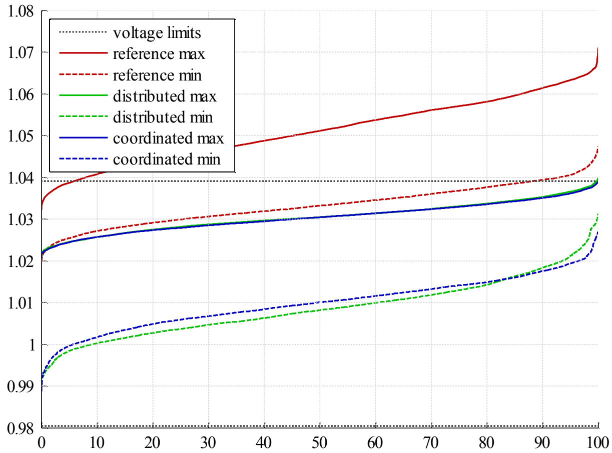

Figure 3 Duration curves of highest (max, solid) and lowest (min, dashed) grid voltage of different voltage control concepts 'reference', 'distributed' and 'coordinated' in "Großes Walsertal"

[% nominal voltage]	Reference	Distributed	Coordinated
minimal grid voltage	102.1	99.1	99.1
maximal grid voltage	106.9	104.0	103.9
used voltage band	4.8	4.8	4.8
max. voltage range	3.1	3.5	3.4

Table 3 Voltage statistics "Großes Walsertal"

Discussion of the results

It was expected that the 'coordinated' and the 'distributed' voltage control concept are able to use less voltage band than the conventional control. The main reason why this was not the case is that the conventional grid control operated the grid nearly optimal concerning the usage of voltage band – based on the following consideration:

The transformer's OLTC can alter grid voltages only in discrete steps according the nominal tap-change-height ΔU_{tap}. When a tap-change occurs in the grid at the time the voltage range is maximal $U_{range}^{max} = max_t(U_{range}(t))$, it is clear that the used voltage band of this period will be $U_{range}^{max} + \Delta U_{tap}$.

Considering a transformer's nominal tap-change-height of 1.6% of nominal voltage in “Lungau” shows that reference scenario performed excellent because the highest range that occurred in the grid was 3.9% while the used voltage band was only 5.3% (see Table 2).

Also in “Großes Walsertal” the reference scenario performed very well with a used voltage band of 4.8% while the maximum voltage range was 3.1% (see Table 2) and the transformer has a nominal tap-change-height of 1.1%. So in “Großes Walsertal” we could say that only 0.6% of voltage band were “wasted” during conventional control, but we have to consider the AVC’s deadband to avoid hunting leading to the fact that this result is excellent as well.

From this perspective it is clear that distributed or coordinated voltage control concepts could not bring a significant gain in the use of voltage band, although in both grids insignificant gains in the order of tenth of percent were demonstrated.

The reason for the optimal grid operation in “Lungau” is the optimal setting of the AVC’s line drop compensation within the reference scenario and the fact that some of the major DGs in “Lungau” operate with local Q(U) control in reference scenario. Simulations performed prior to the field tests concentrated on the normal switching state and lead to promising results. At this time it was not foreseeable that the grid will be operated in the ring switching state during the field test phase.

In “Großes Walsertal” the main reason was that local busbar voltage control did not waste voltage band because the line drop at the load branch with the lowest grid voltages was nearly constant over the whole year. Therefore down-tapping in times of high generation infeed and a high voltage rise at the branches with a high share of DGs does not bring savings in the used voltage band because this action would reduce voltages at the mentioned load branch as well.

Apart from that, another reason why coordinated voltage control performed only insignificantly better than distributed voltage control is the fact that significantly less controllable reactive power was available for coordinated voltage control due to the reasons already mentioned.

It must be noted that the reference scenario – which was operated at a 1 to 3% higher voltage level – might not be fully comparable to the other scenarios because it can be assumed that voltage range decreases when voltage level increases (voltage dependency of the loads).

OUTLOOK

Although the developed controller was prototype, the controller was able to fulfil the high demands of the DSOs concerning configurability and reliability. The experiences in the grids showed that it makes sense to dissolve the dependency of the topology recognition system on externally provided topology information. An intelligent solution would be desirable which autonomously recognises the topology information that is necessary for the control process.

CONCLUSION

The solutions that were realised during the DG-DemoNet project confirmed the feasibility and the success of the concept. It also showed that conventional alternatives to grid reinforcement like a ‘ring’ switching state and an optimally configured line drop compensation can also be cost efficient.

The three main challenges concerning the realisation of coordinated voltage control in the expected grids were

- Installation of the distributed measurement devices with telecontrol connection.
- Integration of existing DGs into the control process
- Topology recognition and the integration of the controller into the existing process control system

Even if the gain in voltage band usage was smaller than expected in the two inspected demonstration grids, principal functioning of the developed control concepts were validated. As during the validation of this project no significant DG capacities (e.g. of up to 17 MW in demo case “Großes Walsertal”) were installed in the demonstration grids, the total potential of the control concepts still relies on simulation results of former work. However, distributed and coordinated voltage control still can be expected to become a powerful and flexible tool for DSOs to economically integrate extra DGs in grids that recently were reinforced.

Even more, as the permanent observation of voltage situation at selected grid nodes gets more and more important to assure voltage quality at customer connection points, costs for necessary measurement devices can be shared among different use cases resulting in even higher cost advantages for DSOs and DG units.

REFERENCES

[1] R. Schwalbe et al, 2013, "DGDemoNet: Impact of Volt/Var Control on Increasing the Voltage Band Reserve - Results from Field Trial Validations", *CIRED 2013*, Stockholm.

[2] M. Stifter et al, 2012, "DG DemoNet: Experiences from Volt/VAr Control Field Trials and Control Algorithm Advancements", *IEEE ISGT Europe 2012*, Berlin.

[3] M. Stifter et al, 2011, "DG DemoNet Validation: Voltage Control from Simulation to Field Test", *IEEE ISGT Europe 2011*, Manchester.

[4] F. Andren et al, 2011, "Development and validation of a coordinated voltage controller using real-time simulation", *IEEE IECON 2011*, Melbourne.

[5] W. Prüggler et al, 2008, "Active Grid Integration of Distributed Generation utilizing existing infrastructure more efficiently - an Austrian case study", *IEEE EEM 2008*, Lisbon.

[6] T. Rieder, W. Schaffer, M. Diwold, A. Ilo, 2013, „Endbericht Projekt ZUQDE“, *www.smartgridssalzburg.at/forschungsfelder/stromnetze/zuqde*, (German).