U-Control – Recommendations for Distributed and Automated Voltage Control in Current and Future Distribution Grids

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***Abstract*— The continuing integration of distributed generators in distribution grids and reservations and uncertainties of distribution system operators regarding grid stability with new automated voltage controllers show a need for action. This is where the "U-Control" research project starts. Questions of effectiveness, stability, optimal parametrization and economics are investigated in a large consortium consisting of research institutes, distribution system operators and industry partners. Answers will be given in simulations, laboratory investigations and field tests. The project results lead to precise recommendations for action for distribution system operators, manufacturers and standardization committees. Intermediate results and recommendations are given in this paper.**

Keywords – renewable integration, voltage control, distribution grid, Q(U), VRDT, LVR

I. INTRODUCTION

Current and future changes in distribution grids in term of further integration of distributed generators (DG), the spread of electric cars and their charging infrastructure and other new loads like heat pumps keep the futures focus on voltage control. Innovative concepts for voltage control in distribution grids, such as voltage regulated distribution transformers (VRDT), line voltage regulators (LVR) or reactive power control with PV-inverters (Q(U) or cosφ(P)) represent cost efficient alternatives to conventional grid extension. Their ability to increase the hosting capacity in situations where the voltage rise represents the bottleneck of distribution grids were shown in different investigations [1] [2] [3] [4] [5]. Distribution system operators (DSO) are currently testing these units on a small scale. Due to the mentioned reasons, a further increasing integration of distributed and automated voltage controllers can be expected in future. Currently, precise standards and requirements regarding the controller parameters and required testing procedures do not consider all aspects of the new concepts. Also the interplay of different concepts in distribution grids and the possibility of controller interactions have not been investigated in detail yet. By comparing all currently available concepts regarding the effectiveness, the robustness and economical aspects, the research project "U-Control" aims to fill the existing gap.

II. PROJECT OVERVIEW

A. *Project target questions*

An objective comparison of all recent voltage controlling methods and components for distribution grids is one of the main aspects of the ‘U-Control’ project. Main targets of the project are the analysis of the effectiveness regarding the increase of the hosting capacity of low voltage grids with voltage controllers, the impact on grid losses and the economic efficiency of the concepts. The results of this investigation lead to recommendations for an efficient grid operation with distributed and automated voltage control.

To find and describe secure, stable and most efficient controller parameters is a second important objective. The focus is put on closed loop controllers like Q(U), VRDT and LVR, because only these types can lead to instabilities. Open questions are optimal and stable characteristics, controller performance, time constants, dead bands and limitations for reactive power rate limiters (dQ/dt). Furthermore, the possibility of controller interactions, for example between Q(U) and VRDT, was analyzed.

Requirements for low voltage controllers regarding the controller performance or the characteristics either do not exist in Germany so far or are restricted. This leads to the target question of developing and describing requirements regarding the controller performance. In discussion with DSO, standardization committees and manufacturers, requirements and recommendations for testing the controller performance in future are derived.

The last main aspect in the project is the implementation of the voltage controlling equipment in the grid planning process of DSO.

B. *Methodology*

The project consortium consists of four research institutes, two manufacturers and three DSO. The manufacturers and DSO support the project with know-how, voltage controlling components for laboratory and field tests and offer the possibility to validate the simulation and laboratory results in field tests. Figure 1 gives a short overview of the ‘U-Control’ project.

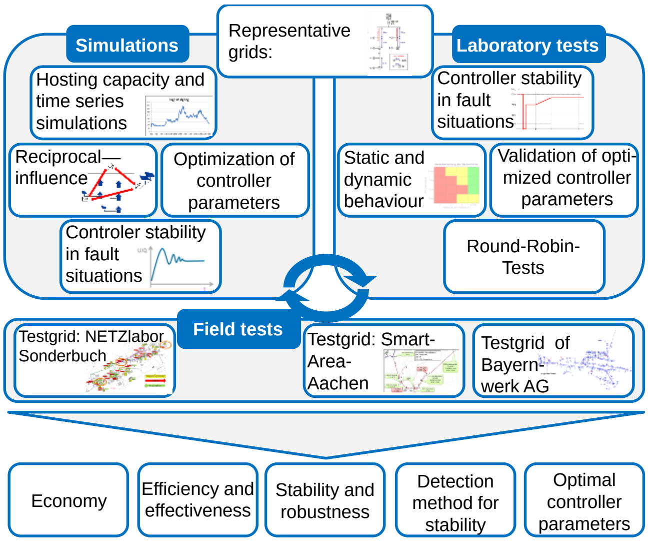

Figure 1. Overview of the project structure ‘U-Control’

The project results rely on three pillars: simulations (optimal power flow, dynamic simulation and load-flow algorithms), laboratory experiments in three independent laboratories and field tests in three independent test grids.

To obtain representative grids for the simulations, a large number of real low and medium voltage grids were analysed regarding several grid parameters. Afterwards, typical and worst-case reference grids, consisting of medium and low voltage levels were developed based on the analysis of real grid data as described in [6]. With these grids, different kinds of simulations were done. Steady state simulations evaluate the effectiveness of voltage control strategies by calculating the increase of the hosting capacity of DG when using VRDT, LVR and different concepts of reactive power control with PV inverters or STATCOM. Furthermore, an optimization of the Q(U) characteristic for various target functions, for example loss minimization, was done. Time series simulations provide information about reactive energy and grid losses, which are input parameters for the economical comparison. Time-coupled root-mean-square-(RMS) and electro-magnetic-transients- (EMT) simulations address the stability and robustness of voltage controllers and the dynamic behavior. Regular operation mode is considered as well as fault situations, such as voltage dips or islanding. Results allow conclusions about secure controller parameters [7][8]. In summary the simulations give answers to questions of effectiveness, efficiency, stability and optimal controller parameters.

In the second pillar of the project, the developed simulation models and results are validated in the three university laboratories. With real hardware, stability, efficiency and the optimized controller parameters are proven. Furthermore, in Round-Robin-Tests measurements of all the laboratories are compared, using the same device and measurement setting. These tests allow an additional validation of the laboratory conditions and a comparison of different implementations.

The last pillar, the three independent field tests in exemplary low voltage grids of the associated DSO, validates the results of the simulations and the laboratory tests and demonstrates the feasibility of a stable and secure low voltage grid operation with several decentralized and automated voltage controllers. Results can be found in [9] and [10].

The combined results from simulations, field and laboratory tests lead to final recommendations for DSO, manufacturers and the standardization committees (for example VDE FNN, DKE, etc.). The following chapter shows the developed recommendations until today. The project will be finished at the beginning of 2018.

III. RECOMMENDATIONS FOR ACTION

The analyses lead to numerous recommendations for actions, not only based on the results gained by the simulations and tests, but also as a consequence of the practical experiences made during the laboratory and field tests.

This chapter lists the cumulated recommendations for action derived at the current state of the project. For an efficient and clear dissemination each recommendation is directed at certain stakeholders.

The recommendations listed in this paper are focused on the results and only comprise a brief description of the methodology applied to derive them. In many cases, additional information can be found in the numerous publications associated to the project. A list of the publications is available on the project website: u-control.de.

A. Recommendations for Distribution System Operators

Effectivity: cosφ(P) vs. Q(U): The impact on the hosting capacity of DG of the mentioned different voltage control strategies cosφ(P), Q(U), RDT, LVR and STATCOM was observed. For this purpose, two different grid-models consisting of a medium voltage (MV) line section with subordinated low voltage (LV) grids were used [11]. A rural distribution grid with 34 connected low voltage grids and a suburban grid with 47 low voltage grids. For the determination of the hosting capacity a probabilistic approach was chosen, where DG ($P=P_{max}$) were placed randomly at possible connection points in the grid. Stop criteria for adding new DG were exceeding voltage limits according to EN50160 resp. 3 % criterion defined in VDE-AR-N4105 and current limits at any point in the grid. The hosting capacity is represented by the amount of installed power. This was done in 1000 iterations. Through this, the hosting capacity can be specified by 5 %, 50 % and 95% quantile, representing worst-case, median-case and best-case.

For the Q(U) controller, a standard characteristic curve starting at 1.03 p.u. and saturating at 1.07 p.u. was used (Figure 10. , based on the results given in the following sections of this paper.

Figure 2. shows the median of the reachable hosting capacities for Q(U) and cosφ(P) in the rural and suburban distribution grid (combination of MV and LV). For this purpose 1000 simulations were made with randomly distributed DG. It can be seen that the effectivity of cosφ(P) and Q(U) in the rural grid is quite equal, while in the suburban grid cosφ(P) can provide more hosting capacity than Q(U) because of the lines' higher rated current. Only in some few cases in the rural grid the hosting capacity at Q(U) application is a little smaller because of the voltage dependency and chosen standard characteristic. In the simulation, two different cosφ limits for cosφ(P) and Q(U) control were considered: cosφ = 0.95 and 0.9.

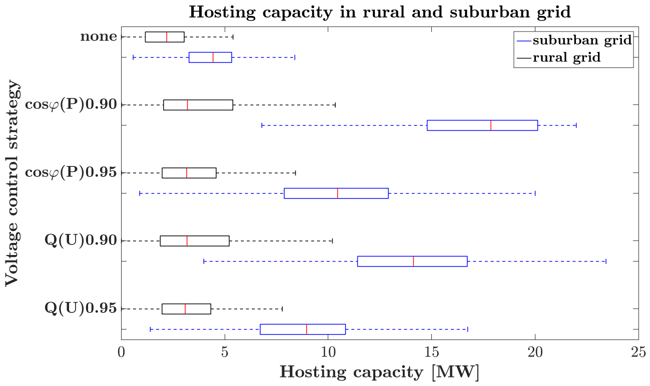

Figure 2. Hosting capacities cosφ(P) vs. Q(U), 50% quantils

Efficiency: cosφ(P) vs. Q(U): A time series simulation of a whole year with a resolution of 15 minutes is performed. Using default parameters, both Q(U) and cosφ(P) have good effects against voltage band violations. However, the yearly reactive energy consumption shown in Figure 3. is reduced by more than 90% using a Q(U) functionality compared to cosφ(P). It can therefore be concluded, that the Q(U) control is more efficient and should be favorably used.

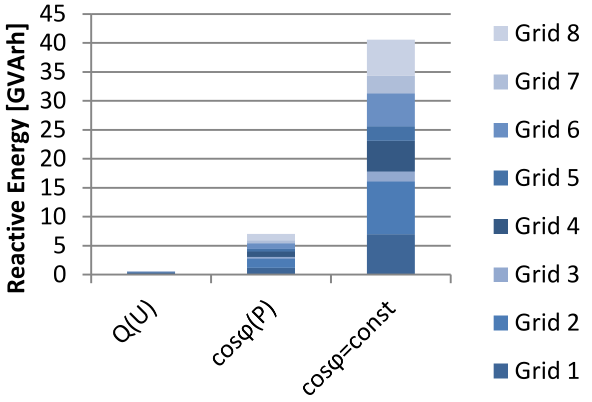

Figure 3. Reactive energy in different low voltage grids

Optimal Q(U) characteristic: The optimal parameters of the Q(U) characteristic are determined using an iterative optimization method. The approach allows optimization of the Q(U) parameters for a single grid or many different scenarios in order to find a good compromise regarding voltage reduction and reactive energy. Figure 4. shows the optimized reactive energy in one specific scenario. All generators have identical parameters for the Q(U) characteristic. It can be noted that a steeper curve (high slope gradient) with less difference between zero reactive power and maximum injection allows a more efficient operation from the grid operator`s point of view. Additionally to the decrease by steeper curves, it can be noted that the maximum reactive power also allows a reduced reactive energy. This can be reached by a wider dead band.

On the other hand, the provision of reactive power is less equally distributed over the plants installed in the grid. The wider the dead band, the higher is the maximal reactive power and the steeper is the slope. So, some DERs will provide much more reactive power than others.

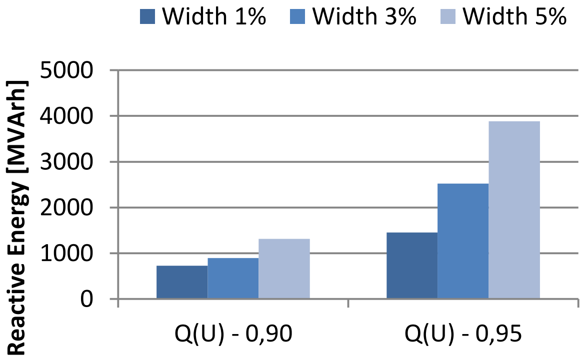

Figure 4. Results for optimized Q(U) characteristics for three voltage differences between Q = 0 and Q = Qmax

The conclusions are that the Q(U) characteristic should be as steep as possible for maximum efficiency with a big dead band. The big dead band significantly reduces the reactive energy. But due to the stability concerns regarding the Q(U) control the steepness of the curve should be limited.

Parameters of the Q(U) controller: Converters with Q(U) control represent closed control loops, which in theory can lead to oscillating voltages. To assure a stable operation of these units and meet the requirements for voltage quality – limitation of flicker and sudden voltage changes – the output characteristic of the Q(U) control should correspond to a first order transfer function (PT1-characteristic) as demanded in [12].

The dynamic behavior of converters with Q(U) control after a sudden change in voltage is described in [8, 13]. The analysis shows that even considering worst case conditions, converters with Q(U) control lead to a stable operation of the system, if the converters have a PT1 output characteristic.

Figure 5. shows the results of a parameter variation, considering a worst-case scenario (detailed description in [8]). The x-axis represents the variation of the time constant T_Q of the PT1-characteristic (set between 5 s and 60 s[1]), the y-axis represents the variation of the measurement delay (between 0.01 s and 1.2 s) and the z-axis represents the slope gradient of the Q(U) characteristic (between 1 % at the bottom and 5 % at the top, where 5 % means that Q_{max} is reached at a voltage of 1.05 p.u. starting from Q = 0 at 1 p.u. and represents the smallest slope gradient). The color scheme shows the resulting maximal voltage change at the critical unit in the system (largest impedance), caused by the voltage control. Since the voltage incident analyzed in these simulations is a voltage step of 6 %, the reaction of the Q(U) control should remain below this threshold.

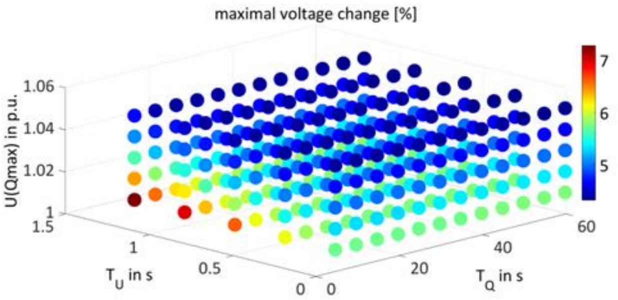

Figure 5. Maximal voltage change at the critical unit for different Q(U) controller parameters

To avoid an overreaction of the system ($\Delta U < 6$ %) due to reactive power injection, certain boundaries for parameters have to be taken into account:

- The *steepness of the slope gradient* of the Q(U) characteristic should be limited. The voltage difference between Q = 0 and $Q = Q_{max}$ should not be smaller than 2 % of the nominal voltage U_N.
- The *input delay* (normally caused by the voltage measurement) should be as small as possible and should not exceed 0.6 s.

Considering these limitations, the time constant of the PT1 characteristic can be set in a wide range between 3 s and 60 s, as demanded in [12]. In order to achieve a quick compensation of voltage deviations, which, in consequence, reduces the stress on the isolation and leads to a quick reactive power contribution, being helpful in cases of distant faults, a small time constant of T = 3 s recommended. The gain of the PT1 characteristic should always be set to K = 1.

Parameters of RDT and LVR controllers: RMS simulations considering inverters with Q(U) control in combination with an RDT and a LVR have shown that all three concepts for voltage control can be combined and lead to a stable dynamic behavior. LVRs based on power electronic technology are able to change the voltage on their secondary side continuously. The LVR in this simulation was modelled as an autotransformer, able to set the voltage on his secondary side in discrete voltage steps, which has a higher impact on the short term flicker.

To reduce short term flicker, the time delays set for the RDT and the LVR have to differ. In a worst case scenario with equal time delays RDT and LVR switch simultaneously and thereby cause a large voltage jump which can exceed flicker limits, depending on the tap sizes. The values should be larger than 3 s to limit possible interactions with the Q(U) controllers. A need for a larger time delay could not be found. The definition of a lower limit for an under voltage blocking by the DSO is recommended (see *B.*).

Positive interplay of Q(U) control with VRDT and LVR: Three independent field tests in cooperation with the DSO Bayernwerk AG, Netze BW and Infrawest have shown the positive interplay of the Q(U) control with VRDT and LVR [9] and [10]. Unwanted oscillating interactions of VRDT and Q(U) are not possible, assuming a correct parameterization of Q(U) control. Figure 6. schematically depicts a situation of a controller interaction. In the worst case, the Q(U) causes a VRDT controller step in the same direction of the first step. In a representative grid with a 630 kVA VRDT with 2.5 % step voltage and the recommended Q(U) characteristic from Figure 10. an installed PV power of 980 kVA is necessary for triggering a second VRDT step.

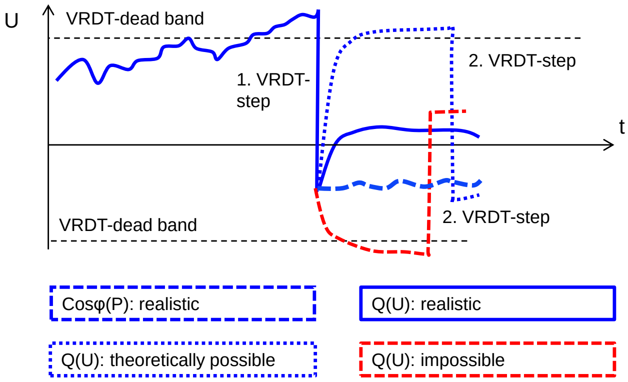

Figure 6. Possible voltage-time-courses in a VRDT-step-situation with Q(U) and cosφ(P)

The field tests demonstrate the positive interplay of VRDT and LVR with the PV inverter-based Q(U) control. 96 % of all VRDT controller steps lead to decreased or constant reactive power from Q(U). This confirms simulated savings potentials of the yearly reactive energy of 80 % up to 98 % towards the cosφ(P) function [5]. This potential increases with a large dead band and high slope gradient in the Q(U) characteristic. A common use of the Q(U) control and a VRDT or a LVR was tested in simulations, laboratory and field tests and can be recommended for practice.

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[1] Simulations with smaller time constants T_Q (down to 0.1 s) were performed separately.

B. *Recommendations for Manufacturers*

Implementing Q(U) control: The number of distributed and automated voltage controllers in the distribution grids is still increasing and the trend is set to continue. The more devices are installed, the more assemblers will parameter them and the more possibilities for failures result. The simulations, laboratory and field tests with all investigated voltage controllers reveal the possibilities for incorrect parametrizations, with different impacts on the grid stability. It can be recommended, that wrong parameterizations of all investigated voltage controllers should be excluded by manufacturers. This will prevent operating errors. For example, inverter manufacturers have taken different paths to implement a Q(U) control into their system. Even though the parameters themselves are named quite similar, their unit and/or their sign can be postulated differently. This leads to problems for DSO and assemblers. It has already been mentioned in [14] that the inverters tested show significant deviations between the expected behavior (due to the chosen parameters) and the laboratory measurements. Based on the analyses in the project “U-Control”, some brief recommendations to manufacturers can be given:

The Q(U) characteristic should be parameterized in a uniform manner across all manufacturers. A four-point implementation with each point specifying a voltage and a corresponding reactive power set point seems reasonable. The voltage should be given in the per unit system with three decimals.

There have been controversial discussions about the unit of the reactive power set point of the Q(U) characteristic. It can be stated, that the correct implementation would be an input in VAr, so that a maximum differential gain of the characteristic in VAr per volt will not be exceeded [15]. However, the effort for the DSO and the assemblers to specify each point of the characteristic in absolute values is unacceptable. Hence, the reactive power set point should be given in respect to the rated apparent power of the inverter and if a set point is chosen, which exceeds the maximum reactive power deliverable, a warning should be displayed.

The purpose of the Q(U) control is to make the inverter act as an inductance if the voltage is raised, and to act as a capacitance if the voltage is too low. A known vulnerability in the definition of the Q(U) characteristic is to mistake the sign of the reactive power and therefore inverting the functionality. Under- and overexcited, inductive- and capacitive operation mode, as well as reactive power consumption or feed-in are used expressions. The extensive wrong parameterization of under- and overexcited operation mode of the Q(U) is a critical example regarding a secure grid operation. Situations with raised voltage will be aggravated by overexcited operation mode of DG. Furthermore, situations with a oscillating interaction of e.g. VRDT and Q(U) become possible. Some manufacturers chose to work in the “load reference system” and some prefer the “generator reference system”. Since none of them can be preferred, it should be checked automatically, whether the defined four-point characteristic leads to a decrease of the voltage at the point of common coupling if the voltage is too high and vice versa. A predominantly inductive consumption line is to be assumed. If an alternative input method to the four-point characteristic is available, it should be ensured, that if it is switched between the input methods, the defined points are not carried over.

Simulations of fault situations with inverter models show the possibility of interactions of different grid functionalities of the inverter, like Q(U) and the anti-islanding- detection (AID), if the dynamic behavior of the Q(U) controller is not limited. In this case the reactive power set points of Q(U) and AID can compensate themselves to zero. A time delay up to two seconds of the islanding- detection becomes possible, if the maximum rate of change of the reactive power is too high. The simulation results are depicted in Figure 7. This leads to the recommendation of limiting the rate of change of the reactive power, caused by the Q(U), to 12.000 %(S_{max})/min (200 %(S_{max})/s).

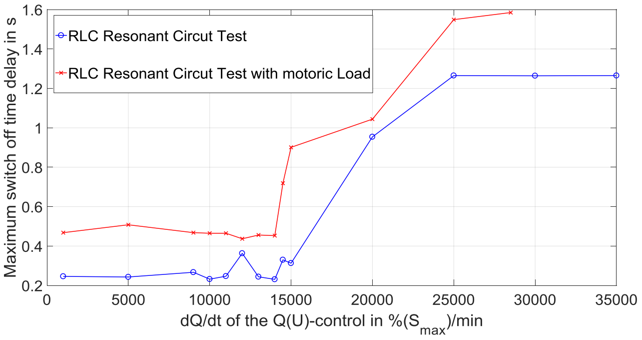

Figure 7. Maximum time switch off time delay of islanding-detection simulations with a Q(U) control with different Q ratelimiters

Manufacturers should limit the range of all relevant parameter of VRDT, LVR (e.g. bandwidth, time delay) in order to prevent unstable or unintended control reaction due to improper parameterization.

Voltage controller in fault situations: Testing of the fault ride through (FRT) capability of VRDT has shown the effectiveness of under voltage blocking [16]. Typically, voltage dips with a short duration (few 100 milliseconds) lead to pre fault conditions when they are cleared by the protection system [17]. Hence, a control reaction of a rather “slow” acting VRDT or LVR could not raise voltage during the dip, but leads to a higher voltage after the voltage recovery if a control reaction is tripped. A scheme is shown in Figure 8.

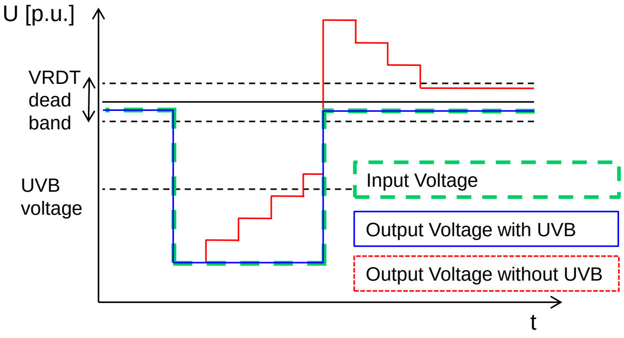

Figure 8. VRDT control scheme with and without under voltage blocking in exemplary voltage dip situation

The overvoltage may cause damage to connected low voltage devices or a shutdown to DG. This leads to the recommendation of implementing an under voltage blocking (UVB), which can be configured by the DSO. As new low voltage DG are proposed to ride through a fault with minimal active power and to react with fastest recovery of infeed after end of failure, an overshoot of voltage with tripping of the over voltage protection is possible when a voltage controller raises the voltage additionally. For new DG with FRT functionality a blocking of active and reactive power for the duration of failure is implemented. Nevertheless the Q(U) set point is calculated. Simulations and laboratory tests have shown a controller behavior as depicted in Figure 9. Because of the Q-rate limiter and the overexcited Q-set point after failure an overshoot of voltage becomes possible. Therefore it is recommended to reset the Q(U)-set point when leaving FRT-area.

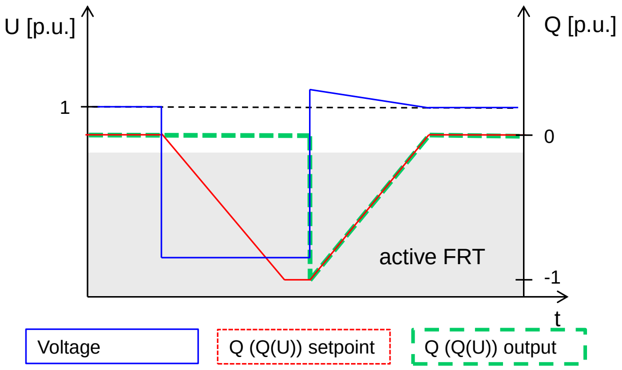

Figure 9. Q(U) control scheme in FRT situation without set point resetting

Voltage dips do not only lead to active control reaction of VRDT and LVT, but can also cause a temporary outage of the software (programmable logic control (PLC)) or hardware (power supply, relays and semiconductors). Experiences have shown that VRDT with on load tap changer are able to keep the pre-fault voltage ratio, even in case of a short-interruption, whereas tested LVR supports a bypass mode if the voltage is interrupted. Hence, a voltage step from maximum voltage ratio, e.g. 1.1 p.u. to 1.0 p.u. (bypass), is possible, if no under voltage blocking and no FRT capability is supported. After the voltage recovers, startup of PLC takes several seconds up to minutes and within this time, control reaction is not available whereas infeed of DG is approximately at pre fault condition. Hence, the voltage controller should either enable full FRT capability or blocking of control reaction with defined fallback mode (bypass).

C. *Recommendations for Grid Codes review*

The recommendations for grid code review contain aspects applicable in general. They have been elaborated during the projects internal discussions, in which the findings of the projects were harmonized with the amendment of the German standard VDE-AR-N 4105 [18]. This standard defines the technical requirements for generators connected to the low voltage distribution network, including the requirements for static voltage control.

As a result of this discussion, the members of U-Control project decided to write a formal objection, listing the aspects in the standard which should be altered based on the findings of the project:

Q(U) control should be defined as default setting for voltage control: As described in the recommendations for DSO, the stationary load-flow simulations show a significant reduction of reactive energy consumption using Q(U) control instead of cosφ(P) control, which was set as the default setting in the old version, as well as the draft of the amendment. Since the findings of the project show a similar integration potential for Q(U) and cosφ(P) control and possible stability issues can be avoided by limiting the scope of Q(U) control parameters, there is no reason left why Q(U) cannot be set as the default setting.

Default Q(U) characteristic: Optimizing the Q(U) characteristic for each generator can increase the efficiency of the voltage control concept, but is not practical on a large scale, since it requires a detailed analysis of the grid and the optimum can change with each newly connected generator. The most feasible option is to define a default characteristic, taking into account the conflict of objectives between efficiency and stability, as well as considering a safety margin to reduce the risk of violating voltage restrictions. The resulting Q(U) characteristic is depicted in Figure 10. This characteristic corresponds to the suggestion in the current draft. Its adequacy was proven in simulations, laboratory and field tests. Nevertheless, the standard should give DSO the possibility to set a different characteristic when justified.

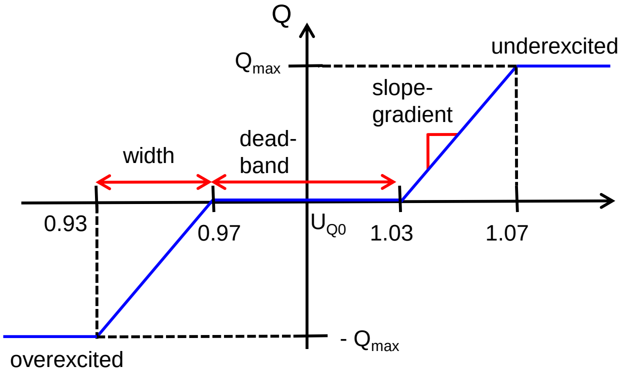

Figure 10. recommended default Q(U) characteristic

Use mean value of the voltage as input for the Q(U) control: In accordance with the European standard EN 50438 [12], the input for the Q(U) control should be the positive sequence voltage or the mean rms voltage of the three-phase system. The current draft instead mentions the maximum of the three voltages between phase and neutral-conductor, which can lead to unwanted behavior of the controller in distribution grids with a high degree of phase imbalance.

Inverter area of operation: The possible reactive power is mostly limited depending on the active power injection. The minimum requirements in VDE AR-N 4105 define a cone area, as depicted in Figure 11. Simulations of bigger operating areas with a ‘block’ show, that the Q(U) control becomes more efficient and therefore the block shape should be preferred over cone from the grid operator`s point of view, which allows full reactive power when the active power is above 20 % of its nominal value, with same rating of inverters. In Figure 12. , the result for one exemplary grid is shown. The parameters of the Q(U) control are optimized to meet the voltage constraint while minimizing the reactive energy. The yearly power infeed of the DG was 14 GWh.

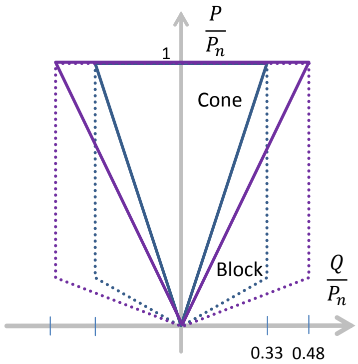

Figure 11. Different PQ-operating areas of an inverter

The possible savings for DSO are approximately 20 % in this scenario. From the plant operator´s point of view a ‘block’ operating area can strengthen the unequal distribution of the reactive power provision and can lead to higher inverter losses in few PV-plants.

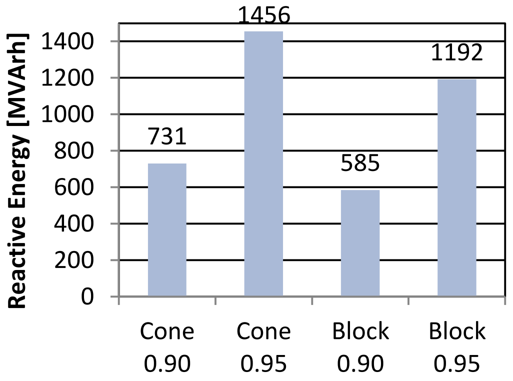

Figure 12. Comparison of different operating areas

Verification of dynamic behavior: The Q(U) controller connected to the grid represents a closed control loop. Hence it is of substantial importance to verify the correct dynamic behavior of the inverter and make sure it corresponds to the PT1 characteristic demanded in the standards, in order to ensure the stability of the system. Additional details for a recommended test procedure are presented in the following sub-chapter.

D. Recommendations for tests of new voltage controllers

To verify the recommendations and requirements given in *C.* and in the upcoming novation of the AR-N-4105, corresponding tests have to be established. As already known, the VDE 0124-100 standard instructs and guides through the test procedures for proving the conformity of generators according to the AR-N- 4105. Hence, a chapter regarding the Q(U) control has to be added to those standards. While the AR-N 4105 is currently in the phase of revising objections, the VDE 0124-100 just approached the renewal phase.

The required dynamic of the reactive power concepts is depicted in Figure 13. [18]. As one can see, a reactive power set point of Q_{set} is to be set and a transient dynamic close to the one of a first order lag element with a time constant of τ shall be reached. An appropriate reactive power set point should be chosen, so that non-linear effects (i.e. saturation) and other possible distortions are avoided.

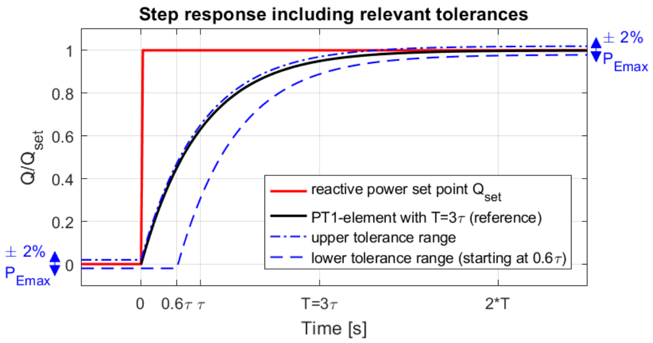

Figure 13. Recommended step response with proposed tolerances

Since a reactive power set point cannot directly be set for the Q(U) control, a suitable voltage step has to be induced to reach the reactive power set point. This voltage step depends on the impedance Z_l between the AC source and the device under test (DUT) as sketched in Figure 14.

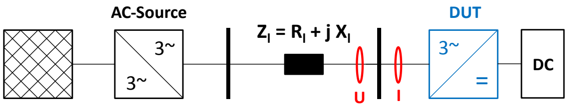

Figure 14. Schematic inverter test setup

To calculate the necessary voltage step V_{set} to reach Q_{set}, the Q(U) transfer functions from [13] are used to calculate the operating point according to Q(t ⟶ ∞). This can be done by applying Laplace’s final value theorem on the linearized control loop shown in [13, p. 5], which results in

$$U_{set} = 1.03\, U_N + \left(\frac{X_l}{3 \cdot U_N} + \frac{1}{k_{QU}}\right) \cdot Q_{set}. \tag{1}$$

While the offset 1.03 U_N is added to incorporate the dead band of the Q(U) characteristic introduced in section A, k_{QU} represents the differential gain of its linear section and equals to $Q_{max}/(0.04 \cdot U_N)$ in this example. The reactance X_l is defined to represent a worst-case scenario, so that the majority of real networks will be less critical and the required PT1 behavior will always be maintained. When raising the voltage at the AC source to U_{set}, the transient reaction of the Q(U) control can be measured and compared to the reference in Figure 13. If the tolerances are not violated, the test is passed.

In some cases, a voltage step cannot be induced, as for example if an AC source is not available or the generators apparent power is too high to be connected in a laboratory setup. If so, the voltage step has to be emulated in form of a software-based manipulation of the measured voltage feeding into the Q(U) control. This manipulation has to be implemented downstream of the voltage measurement, but as close as possible to it, to avoid any as distortion of the dynamic. Preferably, it is implemented directly downstream of the voltage RMS calculation. In opposite to generators, no test procedures for VRDT and LVR have been fixed within the standardization process until now. Hence, requirements and confirmation testing of the control reaction of new components has to be agreed between manufacturer and grid operator individually. Investigations with new components carried out in the laboratories of Aachen and Braunschweig show the need for a revision of new LVR. Figure 15. shows the voltage step response in case of improper parameterization of a LVR.

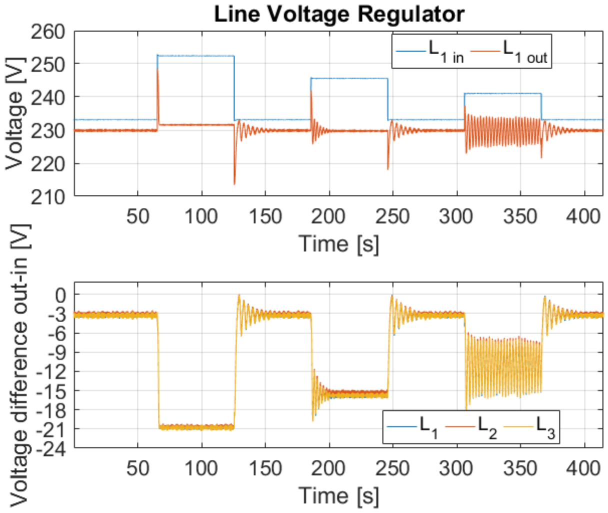

Figure 15. Result of step voltage response of a LVR.

The control parameter of the LVR is set up to maximal control rate and different voltage steps are applied to the grid connection side of the voltage controller. Measurements are taken on the input and output at the clamps of the LVR. The upper plot shows the respective voltages of the LVR. The lower plot represents the voltage droop at the LVR. It can be seen, that the voltage at the duty side oscillates after the lowest voltage step (from 1.01 p.u. to 1.04 p.u.). This is an undesired reaction but can be prevented by proper parameterization. The results show the need for testing of suitable parameterization and control reaction of new components before integrating them in to the grids as well as a need for limit the parameter range by manufacturer.

IV. CONCLUSION

The U-Control research project results lead to numerous precise recommendations for action for different stakeholders. Recommendations for review of the grid code VDE-AR-N 4105 were already given to the VDE. The complete catalogue of final recommendations will be published with the project report in 2018. The results of simulations, laboratory and field tests show especially for the closed loop controllers like Q(U), VRDT and LVR a need for action, regarding definition of stable and secure controller parameters, controller performance, characteristics, as well as definition of test procedures and test setups for new voltage controllers. Considering the given recommendations, a stable and secure grid operation with numerous decentralized and autonomous voltage controllers can be ensured. Current and future changes in distribution grids like the integration of energy-storage-systems, electric cars and their charging equipment keep the focus on voltage control. Other voltage quality aspects like harmonics flicker or unbalance factor should be observed.

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REFERENCES

[1] C. Elbs, R. Nenning, R. Pardatscher und R. Witzmann, Einsatz der Q(U)-Regelung bei der Vorarlberger Energienetze GmbH - Endbericht, Bregenz, 30.06.2014.

[2] M. Heidl, C. Winter, D. Hanek, B. Bletterie, S. Kadam, A. Abart, E. Traxler und K. Leeb, morePV2grid - more functionalities for increased integration of PV into gird - Projektbericht, Wien, 2013.

[3] P. Esslinger und R. Witzmann, Studie Q(U) - Schlussbericht der TU München in Kooperation mit der EnBW Regional AG, der E.ON Bayern AG, der SMA Solar Technology AG, der KACO new energy GmbH und der Siemens AG, München, 31.08.2012.

[4] S. Köppl, M. Gallet und U. Wagner, Smart Grid Controller - Technische und wirtschaftliche Analyse von regelbaren Ortsnetztransformatoren und Längsreglern in Netzgebieten mit einem hohen Anteil an Elektromobilität und Photovoltaik, München, August 2016.

[5] TU Braunschweig, RWTH Aachen, TU München und FGH e.V., „Vergleich von technischer Wirksamkeit sowie Wirtschaftlichkeit zeitnah verfügbarer Verfahren zur Sicherung der statischen Spannungshaltung in Niederspannungsnetzen mit starker dezentraler Einspeisung,“ Studie für den FNN, 2015.

[6] M. Lindner, C. Aigner, R. Witzmann, F. Wirtz, J. Brantl, I. Berber, M. Gödde und R. Frings, „Aktuelle Musternetze zur Untersuchung von Spannungsproblemen in der Niederspannung,“ 14. Symposium Energieinnovation, Graz, 2016.

[7] M. Lindner und R. Witzmann, Analytische Stabilitätsuntersuchungen von Spannungshaltungskonzepten am Beispiel der Q(U)-Regelung in der Niederspannung, Berlin: 4. Konferenz Zukünftige Stromnetze für Erneuerbare Energien, 2017.

[8] M. Schoeneberger, S. Patzack und H. Vennegeerts, Stability Assessment for Automated Voltage Controlling Equipment in Distribution Grids, Wien: Solar Integration Workshop, 14. - 15. November 2016.

[9] O. Marggraf, I. Berber und B. Engel, Kombinierte Spannungshaltung mittels regelbarem Ortsnetztransformator und Blindleistungsregelung im Feldversuch, Berlin: Konferenz Zukünftige Stromnetze für Erneuerbare Energien, 31. Januar - 01. Februar 2017.

[10] O. Marggraf, I. Berber und B. Engel, Sichere Netzintegration mittels Q(U)-Regelung und rONT im Praxistest, Kloster Banz Bad Staffelstein: 32. PV-Symposium, 08. - 10. März 2017.

[11] M. Lindner, C. Aigner, R. Witzmann, F. Wirtz, I. Berber, M. Gödde und R. Frings, *Aktuelle Musternetze zur Untersuchung von Spannunsproblemen in der Niederspannung*, Graz, 2016.

[12] VDE, Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks, German version of european standard DIN EN 50438:2013 (VDE 0435-901), Frankfurt, Germany: VDE, June 2014.

[13] M. Lindner, „A Dynamic Rms-Model of the Local Voltage Control System Q(V) Applied in Photovoltaic Inverters,“ in *CIRED*, Lyon, 2015.

[14] M. Lindner, R. Witzmann, O. Marggraf, S. Laudahn, B. Engel, S. Patzack, H. Vennegeerts, M. Gödde, F. Potratz und A. Schnettler, Ergebnisse der FNN-Studie zu neuen Verfahren der statischen Spannungshaltung, Berlin: Konferenz Zukünftige Stromnetze für Erneuerbare Energien , 27. - 28. Januar 2015.

[15] M. Lindner, „Analytische Stabilitätsuntersuchung von Spannungshaltungskonzepten am Beispiel der Q(U)-Regelung in der Niederspannung,“ in *4. Konferenz "Zukünftige Stromnetze für erneuerbare Energien"*, 2017.

[16] M. Poppen, C. Matrose, A. Schnettler, T. Smolka und P. Hahulla, Grid interaction conformity testing procedures for voltage regulated distribution transformers (vrdt), Cired Workshop Rome: Paper 0307, 11.-12. June 2014.

[17] Cigré working group C4.110, Voltage dip immunity of equipment and installations, April 2010.

[18] VDE/FNN, VDE-AR-N 4105: Erzeugungsanlagen am Niederspannungsnetz, Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz, 2017.