Derivation of a Q(U)-control tolerance band for inverters in order to meet voltage quality criteria

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Abstract— **Distributed generators (DGs) with Q(U)-control in low voltage distribution networks are able to increase the amount of DGs that can be connected to this voltage level while reducing the average network losses in comparison to other concepts for local voltage control, such as cosφ(P)-control. Stability issues of the Q(U)-control have been analyzed in numerous studies, leading to specifications which limit the parameter settings and define the dynamic behavior of the Q(U)-control in order to ensure a stable operation of the system and avoid voltage oscillations triggered by these DGs. Meeting these specifications is crucial to make sure the damping of the system is sufficient for all possible worst-case conditions. As a consequence test procedures have to be defined including a tolerance band limiting the deviation between the ideal dynamic behavior and the measurement. In this investigation, the amplitude and shape of the deviation are varied and the effects of this variation on the voltage quality are analyzed. By identifying the parameters causing a violation of voltage quality criteria, suggestions for the amplitude of the tolerance band to be considered in testing procedures can be derived.**

Keywords - voltage control, distribution network, dynamic behavior, testing, tolerance band

I. INTRODUCTION

The global targets of CO_2 emission reduction motivate the ongoing transition of the energy system. In Germany this transformation is called "Energiewende" and has caused a substantial increase of the installed power from DGs based on renewable energy sources, especially wind and solar-power, as well as generators fueled with biogas. Approximately 40 GW of photovoltaic generators are currently installed in the low voltage network [1]. This high infeed of DGs in distribution networks can cause violations of constraints for voltage and currents, making countermeasures necessary in order to increase the installed power from DGs even further.

In many cases, especially in rural areas with high network impedances due to the longer feeders the voltage constraints limit the further integration of DGs. A cost effective alternative to avoid or at least postpone costly investments in conventional network expansion is the use of concepts for voltage control. The European standard EN 50438 [2], which defines the requirements for the connection of micro-generators to the low-voltage network, as well as the draft of the amendment of the German standard VDE-AR-4105 [3], which applies to generators as well as energy storage systems with an apparent power output of S_{max} < 150 kVA or a connection to the low voltage network, allow three concepts for voltage control:

1. constant cosφ
2. cosφ(P)
3. Q(U)

Concepts 1 and 2 can be described as open control loops, since the output of the controller, which is the reactive power infeed, is only affected by the active power infeed. Therefore these concepts are inherently stable. The cosφ(P)-control is actually defined as the default concept for voltage control in the current German standard for DG connected to the low voltage network [4].

Numerous studies such as [5] and the results from the "U-Control" project [6], which this work is a part of, have shown the advantages of the Q(U)-control in comparison to the cosφ(P)-control. The most significant advantage is the high potential for loss reduction, since reactive power is only provided in situations where it is required.

A DG unit with Q(U)-control connected to the network through a non-negligible impedance represents a closed control-loop due to the physical link between the input (U) and output (Q) of the controller. This can be seen as a disadvantage of the Q(U)-control, since close control-loops are in theory prone to unstable behavior. Slow oscillations ($f \approx 0{,}05$ Hz) of the local voltage, induced by the Q(U)-control, could be shown during a field test at medium voltage level by deliberately setting erroneous parameters [7]. More unwanted oscillations could be observed in [5] and [8]. This demonstrates the importance of defining a set of stable Q(U)-parameters on the one hand and strict testing procedures on the other hand to ensure the correct operation of these units.

Stability analysis such as [9] [10] [11] show that, considering realistic network conditions, Q(U)-control is stable and has an adequate damping of oscillations if certain parameters are limited and the controller has the right output behavior. The parameters as well as the general working principle of the Q(U) controller are illustrated in chapter 2.

Some of these restrictions have already found consideration in the current standards. EN 50438 [2] explicitly defines the requirement of a configurable system response of the Q(U)-controller, which should correspond to a first order lag element / filter (PT1-characteristic). The same requirement has been introduced into the draft of VDE-AR-4105 [3]. While an agreement has been found for the desired dynamic behavior, the testing procedures to ensure the transfer from desires on paper to the practice in the field are yet to be defined.

The ideal PT1-characteristic can hardly be met in practice. But small deviations, which in general cannot be avoided, do not necessarily conclude a malfunction of the device under test or a threat for control stability. Therefore test procedures usually allow a certain tolerance between the desired and the measured behavior of the device, as illustrated in chapter 3. The definition of a tolerance band for the dynamic behavior of Q(U)-controllers is yet to be introduced into standards. Therefore this paper analyzes how the dimension of the tolerance band affects the voltage quality in the network, in order to deduce limits for the tolerance band. The considered criteria for voltage quality are described in chapter 4.

The methodology applied, based on RMS-simulations considering worst-case conditions, is explained in chapter 5. Chapter 6 shows the results of the simulations and chapter 7 summarizes the findings.

II. Q(U)-CONTROLLER

Figure 1 shows the simplified block representation of an ideal Q(U)-controller, consisting of a voltage measurement unit, the Q(U)-characteristic and a PT1-characteristic at the output. The control loop is closed by the network, representing the physical link between the reactive power infeed Q_{DG} and the local voltage at the point of common coupling U_{PCC}.

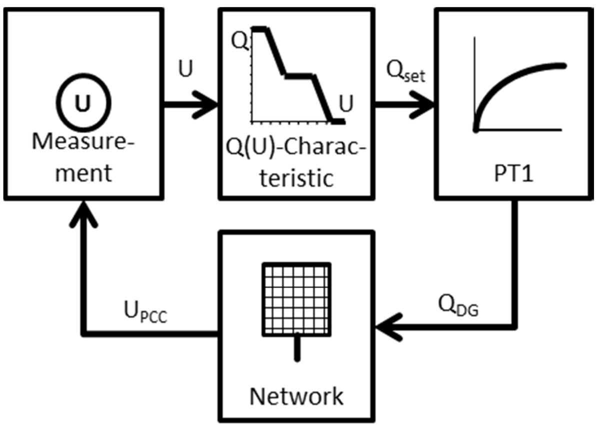

Figure 1 Block representation of ideal Q(U)-controller

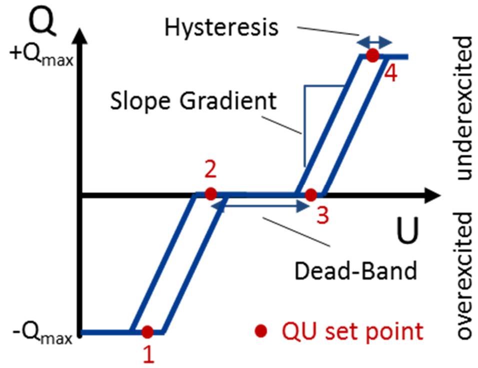

Figure 2 Parameters of Q(U)-characteristic

The Q(U)-characteristic can be described by three parameters: slope gradient, dead-band and hysteresis. The clearest way of setting slope gradient and dead-band is by defining four set points for Q and U, as depicted in Figure 2.

Based on the Q(U)-characteristic, the voltage measurement is translated into a reactive power set point Q_{set}. This set point is passed to the PT1-characteristic, which is a first order lag element with an adjustable time constant τ. The gain K should always remain at the value of 1, since large values reduce the damping coefficient of the system. Equation (1) shows the transfer function in the frequency domain.

$$H = \frac{K}{1+\tau\, s} \qquad (1)$$

III. TESTING PROCEDURES

The German standard DIN VDE 0124-100 [12] describes testing procedures for generators to be connected to the low voltage network. Concerning voltage control concepts it contains a test procedure, which specifies the accuracy of the reactive power infeed of inverters based on a fixed setting of the power factor by defining a tolerance of ±0.01 for the power factor measured at the inverter. Since the relation between the power factor and reactive power is non-linear, this leads to a slightly unsymmetrical tolerance band for the reactive power infeed of +4.6/-4.9 % of Q_{max} (for DG with S_{max} > 13.8 kVA, which should be able to reach power factors between 0.89 and 0.91). The measurement only considers the time after the dynamic response of the inverter has reached a steady state and uses the 30 s-average of the active and reactive power measurements.

The test procedure for the cosφ(P)-control consists of a series of active power steps. The cosφ set point, defined by the cosφ(P)-characteristic, has to be reached within a setting time of 10 s. In this case the test measures 200 ms-average values. The timer for the calculation of the setting time is stopped, as soon as the cosφ reaches the target value within a tolerance of ±0.02 cosφ.

These test procedures show that the dynamic behavior of the concepts for voltage control has been valued as negligible, since they only consider whether or not the correct value is reached within the defined setting time, but do not define any limits or specify a certain behavior for the period between start – active power step – and end –

tolerance band of power factor reached – of the dynamic process. The standards implicitly assume a proper dynamic behavior within the reactive power limits set by the DG, but see no need for verification within a test procedure. For a concept involving a closed control loop, the specifications and test procedures have to go one step further and analyze the dynamic behavior of the units in order to ensure a stable operation of system, also considering possible interactions between voltage controlling equipment. Therefore it is necessary to take a close look at the dynamic behavior of the DG with Q(U)-control.

Specifications for the dynamic behavior have been defined in the European standard DIN EN 50438 [2] and are also considered in the amendment of the equivalent German standard VDE-AR-N 4105 [3], both making the requirement of a PT1-characteristic as described in the introduction, based on stability considerations. What is yet to be defined is a test procedure for inverters with Q(U)-control taking into account a tolerance band.

The target of this paper is to derive the amplitude of the tolerance band. This tolerance band has to be applied on the dynamic response of a Q(U)-controller after a step of the input value, namely the local voltage measured by the inverter. Figure 3 shows the dynamic response of a Q(U)-controller with an ideal PT1-characteristic as defined in [2]. The parameters of the network and the Q(U)-characteristic have been arranged to reflect a step from 0 % to 80 % of the maximal reactive power of the inverter. The areas marked in blue represent moments of stationary operation, for which [3] defines a tolerance band of ±2 %, which is taken as general requirement in this paper. To focus on the dynamic behavior of the unit, it is necessary to assume the stationary behavior of the unit has been verified beforehand, meaning that the inverter reaches the correct operating point after the setting time 4*τ (assuming ±2 % tolerance band), where τ is the parameter of the PT1-characteristic (τ can be set between 3 and 60 s [2]). If the setting time is defined with a tolerance of ±5 %, the setting time would correspond to 3*τ. The area marked in green represents the time period of the dynamic response of the system, on which this paper is focused.

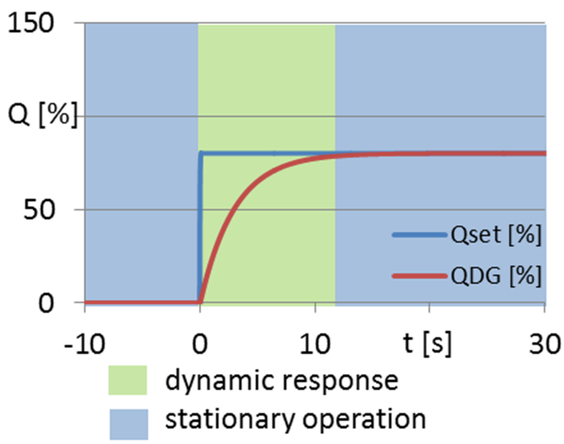

Figure 3 Ideal dynamic response of Q(U)-controller

Assuming the correct stationary value is always reached by the inverter, one way of evaluating whether or not the deviation between ideal and real behavior is too significant, is by using the criteria for voltage quality as a benchmark.

IV. Voltage Quality Criteria

A. *Sudden Voltage Changes- $\Delta U_{st} < 3\ \%$*

VDE-AR-N-4105 [4] defines a limit of 3 % of the nominal voltage for sudden voltage changes ΔU_{st} (st stands for "short term") caused by generators. This boundary was intended to limit the voltage change caused by the activation or deactivation of a DG, considering the voltage change due to a sudden change of the active power provided by the DG. In this investigation, the limit is applied considering the sudden voltage change caused by a change of the reactive power injection. ΔU_{st} is defined as the change between two consecutive values of the RMS-voltage.

B. *Short Term Flicker - $P_{st} < 1$*

The term "flicker" describes voltage changes of specific amplitude and frequency, able to cause lamps to change their brightness (flicker) in a way that is perceptible by the human eye. [4] explicitly defines a boundary for the long term flicker P_{lt} and also refers to DIN EN 61000-3-3 [13], which defines a limit of $P_{st} < 1$ and also describes how this variable has to be calculated and measured.

C. *Maximal Voltage Change - $\Delta U_{max} < \Delta U_{trigger}$*

This third voltage quality criterion is not part of current regulation in contrast to the criteria described before. It was introduced in the course of the U-Control project to limit the maximal voltage change caused by voltage controlling equipment (e.g. DGs with Q(U)-control). The limit of the maximal voltage change ΔU_{max} is not a constant value, instead the criterion states that the maximal change in voltage caused by voltage controlling equipment has to be smaller than the voltage change triggering a reaction of the voltage controlling equipment, $\Delta U_{trigger}$ (e.g. a voltage step in the upstream voltage level). It is designed to prevent an overreaction of multiple voltage controlling units.

V. Methodology for Tolerance Band Derivation

For the methodology applied in this paper it assumed that the Q(U)-controller reaches the correct set point within the defined setting time, meaning that the stationary operation of the controller has been verified beforehand. This can be achieved with the same test procedure which was applied for the cosφ(P)-control, replacing the active power steps with voltage steps and defining a minimal reactance between voltage source and the device under test. The minimal reactance is necessary in order to close the control loop. By assuming the general functionality of the controller under stationary conditions has been verified, the focus can consequently be set on the dynamic response.

To make sure the voltage quality criteria are always met, it is necessary to evaluate a network under worst case conditions, taking into account numerous units influencing the voltage.

A. *Derivation of worst-case scenario*

One important task at the beginning of the U-Control project was the identification of critical networks, based on the analysis of real network data. This analysis was carried out as part of the development of exemplary networks described in [14]. A low voltage network with worst case conditions for DG with Q(U)-control was identified by

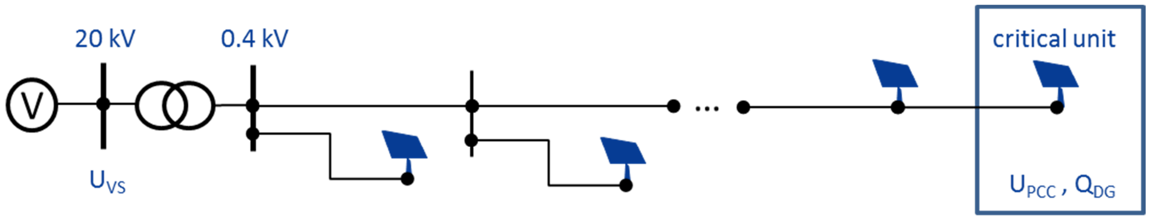

Figure 4 Simplified representation of network with highest QIP value, critical DG unit at the end of the line [10]

determining the so-called reactive power impact parameter (QIP) for about 200 German distribution networks.

The QIP is defined by the following equation:

$$QIP = \sum X_i * Q_{max,i} \tag{2}$$

$Q_{max,i}$ represents the maximal available reactive power from the DG and X_i the reactance between the PCC of the DG and the transformer. The network with the highest QIP is used as a test-case for worst-case condition, since it generates the strongest reaction (from numerous DGs) to a voltage change. It has a cumulated installed power from DGs of 1000 kW from 19 DG units. The critical unit identified in this network is a DG with a rated apparent power of 200 kVA and the highest network impedance between PCC and transformer, as shown in Figure 4. If voltage quality criteria are met at the critical unit, then they are met at all the other nodes in the network.

The worst case conditions for the Q(U)-characteristic are defined as in [10], but using a fixed slope gradient. Table 1 shows the parameters chosen for the Q(U)-controllers. Stability analyzes with ideal Q(U)-controllers show the necessity of limiting the steepness of the slope gradient in order to avoid an overreaction of the system. The voltage difference between Q = 0 and Q = Q_{max} (third and fourth set point in Figure 2) should not be smaller than 2 % of the nominal voltage U_N [6]. The time constant is set to the smallest possible value according to EN 50438.

TABLE 1 Q(U)-CONTROLLER PARAMETERS

Parameter	**Value**
Time constant τ	*3 s*
Gain K	*1*
ΔU_{Slope}	*0.02 p.u.*

To analyze the dynamic response of the system, a reaction of the Q(U)-controllers has to be triggered by changing the voltage. In this test case, the trigger is represented by a voltage step at the voltage source, which has been modelled at the medium voltage level. DIN EN 50160 [15] states, that under normal operation conditions voltage steps of up 6 % can occur several times a day. Note that this value is higher than allowed short term voltage changes caused by DGs (s. IV.A). This value is used to dimension the trigger. To avoid Q(U)-controllers running directly into saturation (Q = $\pm Q_{max}$) instead of operating in the linear Q(U) section due to very high or very low voltages the trigger is applied symmetrically around the nominal voltage, meaning that the voltage steps from 0.97 p.u. to 1.03 p.u..

B. Iterative testing procedure

Based on the worst case-scenario described before, the dimension of the tolerance band is derived using so called "pseudo-controllers". As described in chapter 2, a Q(U)-controller can be described as a concatenation of mathematical functions, determining an output value based on an input value, parameters and the output value of the controller from the last time step. The pseudo-controllers introduced in this chapter do not react to any input (therefore "pseudo"). Instead, their output is a predefined time series, which imitates the ideal output of the Q(U)-controller combined with a superposed signal, causing a deviation from the ideal dynamic response of the controller as depicted in Figure 5.

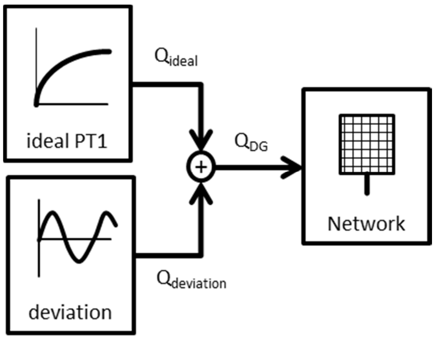

Figure 5 Block representation of "pseudo-controller"

The amplitude of the superposed signal is increased in an iterative process. If voltage quality criteria are met, this means that real DGs with Q(U)-control may deviate from the ideal dynamic behavior, by a value described by the amplitude of the deviation. If a voltage a quality criterion is violated, the amplitude was too big, which means a tolerance band should be smaller than the amplitude that caused the violation. In the following, amplitude of the deviation and tolerance band (TB) are used as synonyms.

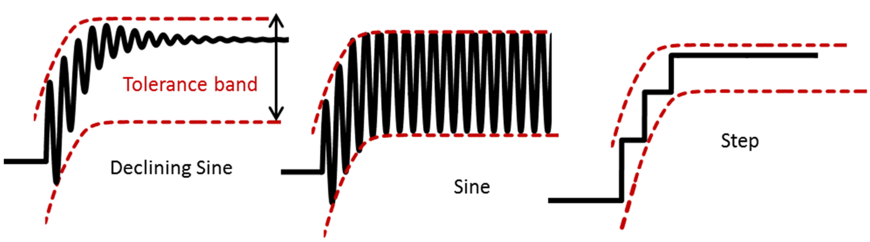

Figure 6 Exemplary shapes of pseudo controllers

Since voltage quality criteria are not only affected by the amplitude of the deviation, but also by the shape of the signal leading to a disturbance, it is necessary to test different shapes, as shown in Figure 6.

Three different shapes are applied to model the superposed signals for the pseudo-controllers. The sine shape with declining amplitude is used to recreate the behavior of second order transfer functions, which in practice may be implemented by mistake, for example by using a voltage measurement with a slow dynamic response. Since the frequency of a malfunctioning controller is unknown, the frequency is varied in order to examine the influence of the frequency on the voltage quality. The amplitude of the sine declines with a negative exponential function with the same time constant as the ideal PT1-characteristic. This makes sure the tolerance band for stationary operation is met in time.

To analyze a more critical disturbance the second shape is a sine with constant amplitude. Such a shape should not be observed in practice, because it causes an undamped oscillation of reactive power and therefore of the voltage with a relatively small frequency.

The third shape used is a step shape. The steps in reactive power are not constant. Constant steps synchronized for all units in the considered low voltage network would lead to high values of the short term voltage change ΔU_{st}, even for small values of the tolerance band. Instead, the step function is implemented in analogy to a bang-bang-controller: each time the upper tolerance band is reached the reactive power steps down to the lower tolerance band. This value is kept constant, till the next limit is reached. Since the 19 DG have different operating points along the network, the tolerance band is reached at different points in time for each unit, which makes synchronous reactive power steps of several units less probable.

C. *Additional criteria to assess voltage quality*

In addition to the voltage quality criteria described in chapter 4 two more indicators are used to assess the quality of the voltage at the critical unit, namely the root mean square value of the voltage deviation ($RMSE_U$) described in equation (3) and the maximum gradient of the reactive power (dQ/dt_{max}).

$$RMSE_U = \sqrt{\sum \frac{1}{N} (U_i - U_n)^{\,2}} \qquad (3)$$

As shown in equation (3), the RMS-formula is applied on the RMS-value of the voltage difference between the nominal voltage and the voltage at the critical unit affected by the pseudo-controller. By using this indicator, voltage quality is quantified by assessing the proximity to the nominal voltage. Higher average deviations from the nominal voltage can be interpreted as a lower voltage quality. The $RMSE_U$ and dQ/dt_{max} of the dynamic response with ideal Q(U)-controllers is used as a benchmark.

VI. Simulation Results

A. *Ideal PT1-characteristic – Benchmark*

The voltage quality criteria are first applied on the voltage time series of the critical unit in a scenario where all Q(U)-controllers behave as ideal PT1-elements. These values will be used as a benchmark to compare how the pseudo controllers alter the voltage quality. Table 2 shows the resulting values.

TABLE 2 VOLTAGE QUALITY CRITERIA WITH IDEAL PT1-CHARACTERISTIC

Criteria	Value
ΔU_{st}	***0.0004 p.u.***
ΔU_{max}	***0.06 p.u.***
P_{st}	***0.79***
$RMSE_U$	***6.86 V***
dQ/dt_{max}	***27.2 kvar/s***

The value of the maximal short term voltage change (disregarding the voltage step of the trigger) is only 0.04 %, which illustrates the smoothness of the reaction from ideal Q(U)-controllers. The maximal voltage change is exactly 6 % and is caused by the triggered voltage step. This means an overreaction of the Q(U)-controllers cannot be observed. The value of the short term flicker (0.79) is relatively close to 1, mainly due to the voltage step of 6 %. The $RMSE_U$ has a value of 6.89 V. To evaluate this quantity it is necessary to compare it with the results of other simulations. The maximal gradient of the reactive power can usually be seen exactly after the voltage jump.

B. *Declining sine shaped pseudo-controller*

81 combinations of frequency and amplitude/tolerance band (TB) were simulated, as shown in Table 3. The TB was varied between 1 % and 50 % (based on Q_{max} of each DG), with increasing step size (first column in Table 3). The frequency was varied between 0.1 Hz and 5 Hz.

TABLE 3 SHORT TERM FLICKER P_{ST} WITH DECLINING SINE SHAPED PSEUDO CONTROLLER

P_{st}	f = 0.1 Hz	0.2 Hz	0.3 Hz	0.4 Hz	0.5 Hz	1 Hz	2 Hz	3 Hz	5 Hz
TB = 1 %	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
2 %	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
5 %	0.79	0.79	0.79	0.79	0.79	0.79	0.80	0.79	0.79
10 %	0.79	0.79	0.79	0.79	0.79	0.78	0.80	0.79	0.81
15 %	0.79	0.79	0.80	0.79	0.79	0.78	0.81	0.80	0.92
20 %	0.79	0.79	0.80	0.79	0.79	0.78	0.83	0.88	1.06
30 %	0.79	0.80	0.80	0.79	0.79	0.78	0.96	1.01	1.36
40 %	0.79	0.80	0.80	0.79	0.79	0.82	1.06	1.16	1.68
50 %	0.80	0.80	0.80	0.80	0.79	0.86	1.17	1.37	1.99

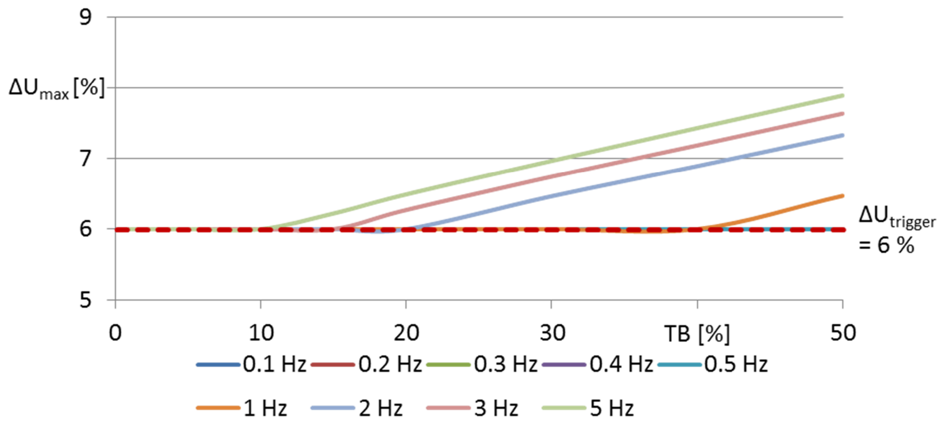

Figure 7 ΔU_{max} with declining sine pseudo-controller with different frequencies

The results show, as was to be expected, the strong influence of the frequency of the pseudo-controller on the short term flicker. For frequencies below 1 Hz the short term flicker varies between 0.78 and 0.8, which is almost equivalent to the benchmark of 0.79. For theses frequencies, the size of the TB has no detectable influence on the short term flicker. For higher frequencies the TB shows a considerable influence on the short term flicker, since human flicker perception reaches its maximum at 8,8 Hz. The limit of 1 (marked in yellow) is reached at a TB of 20 %, considering a frequency of 5 Hz.

A similar relation can be observed between the TB, frequency and the maximal voltage change as depicted in Figure 7. The maximal voltage change remains at the 6 % value, equivalent to the benchmark with ideal Q(U)-controllers, for frequencies below 1 Hz and for all values of TB. For higher frequencies the maximal voltage change is above 6 %, meaning that an unwanted overreaction of the controllers has been detected. For the frequency of 5 Hz overreaction already appears at a TB higher than 10% (e.g. ΔU_{max} = 6.22 % for TB=15%), which shows, this criteria is breached before the criteria short term flicker.

Table 4 shows the maximal values of the voltage quality criteria for all considered combinations of TB and frequency. It is noticeable, that the limit of 0.03 p.u. of the short term voltage change is not reached for any combination. The relation between $RMSE_U$ and dQ/dt_{max} and the magnitude of the TB is discussed in a separate subchapter.

TABLE 4 VOLTAGE QUALITY CRITERIA WITH DECLINING SINE – MAXIMAL VALUES

Criteria	Value
ΔU_{st}	***0.015 p.u.***
ΔU_{max}	***0.079 p.u.***
P_{st}	***1.99***
$RMSE_U$	***7.93 V***
dQ/dt_{max}	***1320 kvar/s***

C. Sine shaped pseudo-controller

The simulations described above are carried out once more, this time with the sine shaped pseudo-controller with constant amplitude during the dynamic response. As expected, the violations of voltage quality criteria are larger in comparison to the sine shape with declining amplitude as can be seen in Table 5. Only the dQ/dt_{max} stays constant, because the maximal gradient is found at the beginning of the dynamic response, where sine and declining sine are almost identical.

TABLE 5 VOLTAGE QUALITY CRITERIA WITH SINE – MAXIMAL VALUES

Criteria	Value
ΔU_{st}	***0.017 p.u.***
ΔU_{max}	***0.088 p.u.***
P_{st}	***3.61***
$RMSE_U$	***10.7 V***
dQ/dt_{max}	***1320 kvar/s***

The values of the power quality measures are not only higher, they are also reached at lower values of the TB In this case the short term flicker limit of 1 is reached at a frequency of 0.5 Hz and a TB of 50 % (P_{st} = 1.03). At a frequency of 5 Hz the limit is already reached at a TB of 10 % (P_{st} = 1.01).

D. Step shaped pseudo-controller

Even though the steps are not synchronized due to the methodology applied, the short term voltage change is the critical voltage quality criteria for the step shaped pseudo-controller, as shown in Table 6.

TABLE 6 VOLTAGE QUALITY CRITERIA WITH STEP SHAPE – MAXIMAL VALUES

Criteria	Value
ΔU_{st}	***0.036 p.u.***
ΔU_{max}	***0.062 p.u.***
P_{st}	***1.07***
$RMSE_U$	***12.3 V***
dQ/dt_{max}	***7076 kvar/s***

Figure 8 shows the maximal short term voltage change, caused by the step shaped pseudo-controller, for different magnitudes of the TB. The limit of 3 % is reached at a TB of 17 %. However, only an indication for a TB-limit can be derived from this result, since the overlap of different steps from DGs strongly depend on the network and DG-penetration.

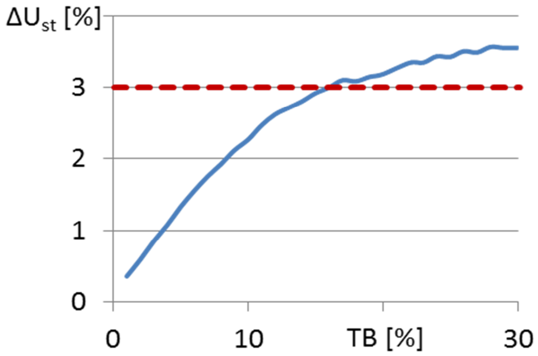

Figure 8 Short term voltage change of step shaped pseudo-controller, subject to TB

E. Analysis of $RMSE_U$ and dQ/dt_{max}

The relation between the amplitude of the TB and the resulting $RMSE_U$ is depicted in Figure 9. For the sine and declining sine shapes the maximal and minimal considered frequencies are shown. As to be expected the values of the pseudo-controllers are above the benchmark of the $RMSE_U$, calculated with the ideal PT1-characteristic. This means the deviations superposed by the pseudo-controllers lead to higher average deviations from the nominal voltage and a lower voltage quality. The worst values are caused by the step shaped pseudo-controllers and the sine shape with a frequency of 5 Hz.

The analysis of the reactive power gradient at the critical unit in Figure 10 shows a significant influence of the pseudo-controllers with a step and sine shape (5 Hz) on this indicator. The maximal gradient of the ideal PT1-characteristic, which is used as the benchmark, has a gradient of 27.2 kvar/s, while step shape reaches values above 7000 kvar/s, if the TB is set to values larger than 17 %. This gradient of the reactive power, in addition to the reactive power changes caused by the other units in the network, cause the high values of the short term voltage change, as shown in Figure 8.

The dQ/dt_{max} with the sine shaped pseudo-controller reaches 1320 kvar/s when allowing the maximal amplitude of the TB to reach 50 % of Q_{max}. Even though with the sine shaped pseudo-controllers, all DG in network have the highest dQ/dt_{max} at the same point in time, this value causes a sudden voltage change of 1.7 %, as shown in Table 5.

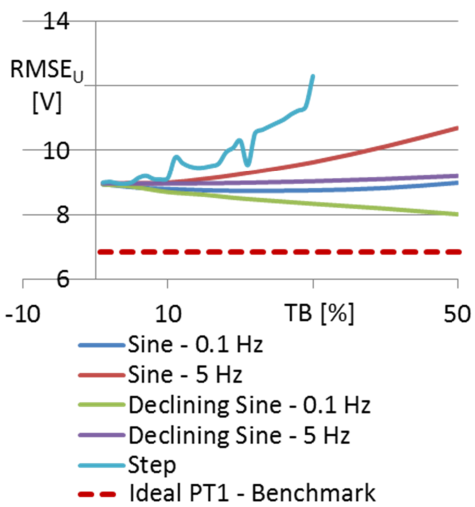

Figure 9 Comparison of $RMSE_U$ subject to TB, for different pseudo-controller

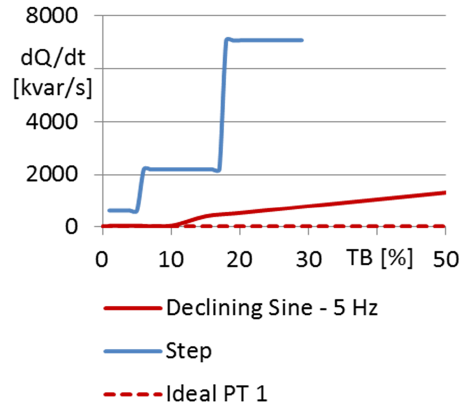

Figure 10 Comparison of dQ/dtmax subject to TB, for step and sine shaped pseudo-controllers

VII. CONCLUSION

This paper uses so called pseudo-controllers to determine how much a DG with Q(U)-control can be allowed to deviate from the ideal PT1-characteristic before voltage quality limits are reached. Three different shapes are used to model the pseudo-controllers.

The short term flicker limits using a declining sine-shaped pseudo-controller are reached, when the amplitude of the TB reaches 20 %, considering a signal with a frequency of 5 Hz is superposed on the ideal PT1-characteristic of the DGs. For a frequency of 1 Hz the amplitude of the signal can reach 50 %, without causing a violation of the short term flicker. To keep $\Delta U_{max} < \Delta U_{trigger}$ for all frequencies, the TB has to be below 15 %.

Considering a sine shaped signal with constant amplitude, the negative effect of the pseudo controllers on the voltage quality is significantly stronger, reaching the flicker limit at a TB of 15 % for a frequency of 5 Hz.

The step shaped signal has less influence on the short term flicker and ΔU_{max} then the shapes described before, but can lead to very high gradients of reactive power, which produce sudden changes of the voltage, reaching the limit of $U_{st} < 3$ % when the amplitude of the TB is set above 17 %.

These values indicate, that a TB to limit the deviation from the ideal dynamic behavior should have an amplitude around 10 to 20 % of the maximal reactive power which can be provided by the DG in order to meet the voltage quality criteria defined in the current standards. Furthermore, a TB, of 20 % can only be allowed, if the frequency of the oscillation is at 3 Hz or lower.

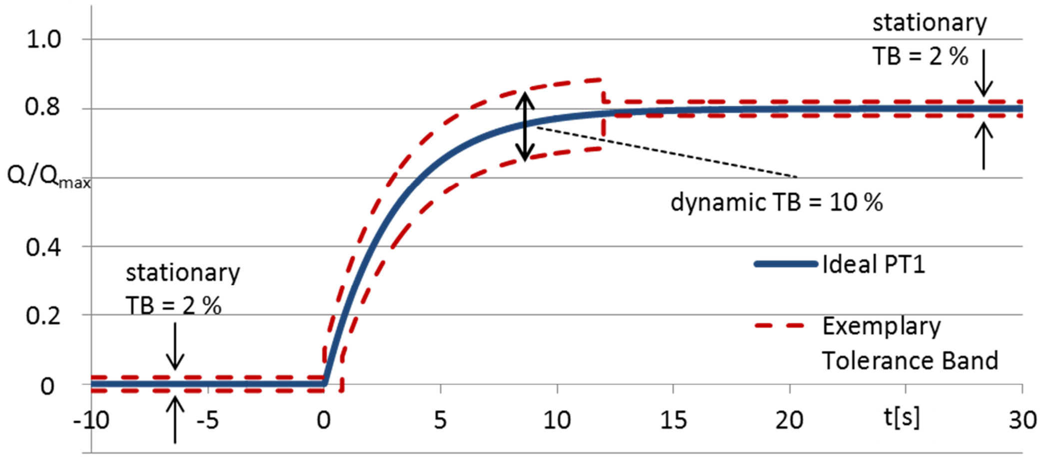

Figure 11 Exemplary tolerance band for a DG with Q(U)-control reacting to a voltage step, with τ = 3 s

An exemplary TB of 10 % of Q_{max} for the dynamic response of a DG with Q(U) is shown in Figure 11. The wider TB is only recommended for the dynamic process, allowing the reactive power from the DG to deviate from the ideal behavior. For the stationary operation the limits defined in [3] have to be applied. The figure shows a symmetric TB around the ideal PT1-characteristic (± 10 %) except for a short period directly after the dynamic response is triggered. The lower limit of the stationary TB is extended into the dynamic response for a short period of time (between 0 s and 1 s). This is done to prohibit a reactive power infeed from the DGs with Q(U)-control with the wrong sign since such a behavior can cause a breach of voltage limits.

Stepwise changing controllers, even if they remain within a small TB, have to be avoided, because they can cause sudden voltage steps, due the high reactive power gradient. This can be done, by limiting the allowed dQ/dt_{max}. Based on the results of the sine shaped pseudo-controllers, where the limit for the short term voltage jump was not breached, 1320 kvar/s could be used as a benchmark.

The focus in this paper is set on the possible deviation of the reactive power, but a complete test procedure also has to define a tolerance for the deviation in time. To deduce a tolerance for the setting time requires a different approach. In general, a delay is less critical for stability and voltage quality than reaching the setting time too early, which causes higher gradients of reactive power and therefore higher voltage gradients. Allowing a high tolerance for the setting time delay would lead to higher $RMSE_U$ values, but it would have no negative effects on other voltage quality criteria, as long as the setting time is significantly smaller than the tripping time of the installed protection.

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