Parameters Of Rapid Voltage Changes And Their Effects On Power Quality

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***Abstract*—With evolving grid structures and new components a continuous look at standards for power quality is necessary to ensure a high quality of energy distribution. In this paper the parameters of rapid voltage changes and their effects on flicker, especially in regards to new components e.g., photovoltaic, are discussed. Furthermore, standardized parameters for rapid voltage changes are investigated in their relation to flicker. The results of simulations show that especially the parameter d_{max} and the rate of change of rapid voltage changes influence the resulting flicker values the most. These simulations are backed by the results of measurements in a suburban low voltage grid. Lastly the impact of widespread use of Q(V) characteristics on flicker is investigated. Rapid voltage changes can slightly increase the resulting flicker values of a rapid voltage change. However, the benefits of Q(V) characteristics to power quality still outweigh this slight increase.**

Keywords — power quality, rapid voltage changes, flicker, standardization

I. Introduction

Due to the effort to change the energy production towards renewable sources the electrical grid is restructured to adapt to new methods of energy production. Power quality becomes an issue in new grid structures. Because of energy production by photovoltaic and new components, like electric vehicles and heat pumps, this development also affects low voltage grids [1]. In this paper two power quality traits are considered: Rapid voltage changes (RVC) and flicker. These two characteristics have a close relationship to each other, as RVC are a source of flicker, which can cause psychological stress. The relationships between RVC and flicker and the origin, as well as the influence of RVC in the low-voltage grid are the subject of the investigations here [2].

In this paper, measurements of a low voltage grid, as well as methods such as Q(V) characteristic, are considered. Most of the investigations are carried out in the form of simulations on sample grids. A smaller part of the investigations will take place in the form of laboratory measurements and the evaluation of measurement data from a field measurement campaign in a suburban grid.

II. Overview of Standards

The standard EN 50160 regulates which characteristics the voltage in public electricity supply grids must have [3]. Compliance with these characteristics is generally referred to as voltage quality [2]. These characteristics include limit values for the magnitude, frequency, harmonic content and flicker value of the voltage. Furthermore, events such as voltage fluctuations and supply dips, as well as voltage surges are also regulated [3].

Some of these characteristics have interdependencies. The flicker value is calculated with the course of the voltage. Accordingly, there is a strong dependence between voltage fluctuations and the flicker value [4]. Voltage fluctuations are named in EN 50160 as the source of flicker. Furthermore, switching operations, load changes and faults are named as causes of voltage fluctuations [3]. The term ‘voltage fluctuations’ covers several phenomena. One type of voltage fluctuations referred to in the standard are RVC. There are various definitions and limits for RVC [3].

RVC are changes in voltages that are within the permitted voltage band of 90 % - 110 % of the mains voltage U_n. If this voltage band is left, these are either voltage dips, for voltage values below 90 % U_n, or voltage overshoots, if the upper limit of 110 % U_n is exceeded. RVC in the low-voltage grid have a maximum level of 5 % U_n under normal conditions. Under special circumstances, however, heights of up to 10 % U_n can be reached several times a day [3].

EN 50160 does not set any limits for the occurrence of rapid voltage values for the German low-voltage grid (LV) or medium-voltage grid (MV). Only for the Norwegian low-voltage and MV grid are limit values for the level and number of RVC given in amendment A1. In addition, parameters and the determination procedure of RVC are defined. According to the Norwegian definition, only voltage changes that have a rate of change of 0.5 % U_n per second are RVC [5]. For German low-voltage grids, there is no more precise grid definition in EN 50160 than the one described in the first paragraph [3].

A more precise definition of RVC is given in IEC 61000-3-3 and IEC 61000-3-11. These standards regulate limit values of voltage changes, voltage fluctuations and flicker for electrical equipment in the low-voltage grid. However, the definition and limit values for RVC from these standards only apply to equipment, not to a grid -side consideration of voltage quality [6] [7].

III. Parameters of Rapid Voltage Changes

The standards IEC 61000-3-3 and IEC 61000-3-11 define the parameters of RVC. These parameters are used to detect and set limits for RVC. Table 1 below explains these parameters. These parameters are the only ones affected by the limits for RVC in these standards. Since this applies to both standards, no difference is made with regard to RVC for devices with a maximum rated current of 16A and devices with a rated current of up to 75A [6] [7].

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TABLE 1: PARAMETERS OF RAPID VOLTAGE CHANGES

Parameter	Definition
T_{max}	The time during which U_{hp} deviates from steady state by more than 3.3%
d_c	Difference between voltage values of two successive steady states
d_{max}	The largest difference between the last steady state and the following voltage values

If the parameters d_{max} and d_c are present in the case of a voltage reduction, they are assigned a positive value and in the case of a voltage increase a negative value [6].

The basis for determining RVC is the effective value of the voltage, which is determined over half a period between two zero crossings and is referred to as U_{hp}. An RVC is now present when the voltage leaves its steady state. This happens when a value of U_{hp} deviates by more than 0.2 % from the previous value. The voltage is back in the steady state when 100 consecutive U_{hp} values deviate by no more than 0.2 % from the first of the 100 values, the start value. At 50 Hz, this corresponds to a duration of one second [6].

Flicker describes and quantifies a disturbance caused by fluctuating light intensity. In the context of power quality, fluctuations in light intensity caused by fluctuations in the mains voltage are described by flicker [3].

Flicker is also considered in amendment 1 of EN 50160. The Norwegian regulation stipulates here that the P_{st} values in low-voltage grids are 95 % below 1.2 and the P_{lt} values in the grid are 100 % below 1. The limit values selected here for P_{lt} values are thus stricter than in German grids and the P_{st} values are also limited here, in contrast to German grids. Furthermore, deviating limit values are also set for MV grids, which is not the case in German MV grids [5].

EN 50160 refers to the fact that interharmonics can also cause flicker in some lamps. However, these are not regulated in the standard. It is pointed out that further research and subsequent regulation is needed in this area. Current research is discussed in the following chapter [3].

IV. LATEST RESEARCH ON RAPID VOLTAGE CHANGES

Both the methods for detecting RVC and the flicker meter are criticised in recent studies. The method for detecting RVC described in IEC 61000-4-3 can, among other things, overlook RVC if their progression is not particularly rapid [8].

The research evaluating the flicker meter is much more extensive than that evaluating the RVC detection method. The reason for the critical view of the flicker meter in recent studies is its design for incandescent lamps. This design means that the disturbance factor of fluctuating luminosity in other lamp types cannot be accurately assessed by the flicker meter [9]. This is because new lamp types often have non-linear behaviour, such as LEDs or compact fluorescent lamps. In lamps with non-linear behaviour, factors that are not measured by the flicker meter often lead to disturbing light flicker. Interharmonics in particular trigger this [10].

In order to measure the flicker behaviour of modern lamp types, a flickermeter was developed in a study that directly measures light and quantifies the flicker value based on the measurement. Measurements with this flicker meter confirmed the effects of interharmonics on lamps with non-linear behaviour. Furthermore, the flicker value is measured during voltage jumps. Here, the LED and the compact fluorescent lamp react similarly to the incandescent lamp when the voltage drops and react more strongly when the voltage rises. The investigations are limited to three voltage curves. A more detailed investigation of the influence of RVC on the flicker value is not carried out in the study [9] [11].

There are several studies dealing with the relationship of RVC and flicker. Especially the relationship of the parameters of an RVC with the short-time flicker value P_{st} is investigated. Several studies conclude that an evaluation of RVC via the short-term flicker value is not meaningful, as no correlation of P_{st} values to the parameters of RVC can be proven. However, this evaluation is possible via the instantaneous perceptual value P_{inst} [12] [13].

Regarding the general flicker load in low-voltage grids, a study shows that 53 % of low-voltage grids suffer from excessive flicker values [14]. Another study on the influence of photovoltaic systems and wind turbines shows that they can cause RVC [15]. Likewise, increased long-term flicker values were measured at photovoltaic plants [16]. In contrast, another study concludes that photovoltaics have no significant influence on the flicker value [17]. The research situation in this area is therefore not clear.

Another consequence of RVC are various disturbance phenomena, which are named in many studies but not investigated in detail [12] [8] [18]. All of these studies refer to the same primary source, which is a book on voltage quality from 1999 [19]. The disturbances mentioned occur in control processes for voltage angle-guided controls, motors directly connected to the supply grid and electronic devices in which the fluctuation of the voltage continues through the power supply unit to the electronics [19].

V. METHODS

The investigations carried out in this work are based on two methods, which are simulations and measured values. The results of the investigations are used to analyse the relationship between RVC and flicker in relation to their parameters. Another focus of the investigations is the effect of Photovoltaic-Systems operating with Q(V) characteristics. The PV systems operate at full capacity and their nominal power has been chosen so that it leads to a rise in voltage by 3% of the nominal voltage [20]. The simulations are carried out in PowerFactory 2020 using a model of a PV inverter as well as sample grids, which represent average, rural, small town and suburban grids as well as a rural grid with extremely high impedances [1]. The model of the PV inverter is described in [21] and the details of the measurement campaign are described in [1].

VI. RESULTS OF SIMULATIONS

This section discusses simulations that are carried out in the sample grids. In the following, the influences of the parameters of RVC and of PV inverters with active Q(V) characteristics are examined. For this purpose, the simulations without Q(V) characteristics are referred to as “base cases”.

Fig. 1 shows the results of the simulations for the base cases of d_{max} values. The maximum selected d_{max} value for all scenarios is 10 %. For an initial voltage of 1.00 p.u., higher values would lead to a violation of the voltage band, which means that it would no longer be an RVC according to EN 50160. For the consideration of the influence of the Q(V) characteristic, positive and negative d_{max} values are

considered separately. This is for the sake of clarity. At first, *Fig. 1* shows the results for positive d_{max} values.

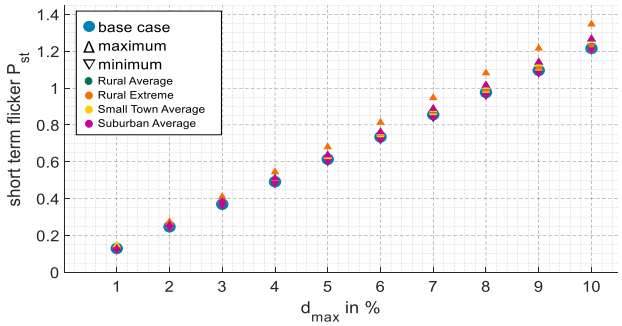

Fig. 1: Variations of positive d_{max} values

The short-term flicker values are increased by the operation of PV systems with a Q(V) characteristic. Here, increases in the short-term flicker value of up to 10.8 % occur, whereby this value only occurs in the "Rural Extreme" grid. In the other sample grids the values are closer together and the maximum increase is found in the grid "Suburban Average" with an increase of the short-term flicker value by 4.1 %. The minimum flicker values hardly differ from the base case with a maximum undershoot of 0.8 % in the grid "Rural Average". The location where the maximum short-term flicker values occur is the same in all scenarios with active Q(V) characteristic: The local grid transformer.

This is in line with expectations, as the influence of Q(V) characteristic is highest here due to the bundled reactive power of all strings and the high inductance of the transformer. The location where the minimum short-time flicker values occur is also very similar in all grids. This is always the end of the string with the most household connection points. Since the connected PV power is identical at each household connection point, this corresponds to the string with the highest PV power. One possible cause for this could be the distance to the transformer where the highest increases take place. Another cause is discussed in connection with the results for negative d_{max} values. These are shown in *Fig. 2*.

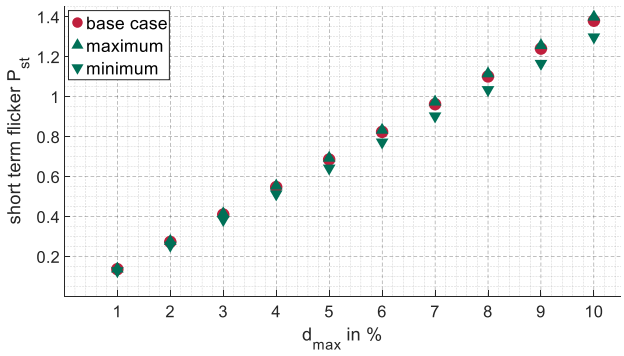

Fig. 2: Variations of negative d_{max} values

Due to the prioritisation on positive d_{max} values, only simulations in the "Rural Average" grid with active Q(V) characteristic are carried out for negative d_{max} values. Here, the maximum increase of the short-time flicker value is 1.4 % and is thus only slightly above the base case. The minimum values, on the other hand, show a different effect. The short-time flicker values are significantly reduced here with active Q(V) characteristic compared to the base case. The maximum reduction is 5.9 % and, like all other minimum values, is also at the end of the line with the most household connections. These values suggest that in the case of an RVC with a negative d_{max} value, the short-term flicker value is reduced by the operation of several PV systems with active Q(V) characteristic. The reason for this could be the staggered influence of the Q(V) characteristic along the string, which attenuates the RVC.

Regarding the effects of the parameter d_{max} on the short-term flicker values in the case of RVC, it can be stated that this parameter represents a solid evaluation basis due to its linear behaviour to the resulting flicker value. Furthermore, RVC whose d_{max} ends in a permanent change of the steady state are only problematic from higher d_{max} values. The effect can lead to both an increase in the resulting flicker values for positive d_{max} and a reduction for negative ones. A final finding is that the influence of the Q(V) characteristic in the pattern grids "rural average", "Small Town Average" and "suburban average" hardly differs. The maximum deviation of the short-term flicker values here is just 0.2 %. The situation is different for the "Rural Extreme" grid, with a maximum deviation of 6.1 %, which can be attributed to the significantly higher PV connection power per household connection point.

RATE OF CHANGE

In this section, short-time flicker values of RVC with varying rate of change are considered. The change is determined as a percentage of the nominal voltage. This criterion is used in EN 50160/A1 to define RVC. Accordingly, a voltage change is only an RVC from a change of 0.5 % per second [5]. This amendment to EN 50160 is valid for Norway and includes some tightening with regard to voltage quality characteristics. The simulations investigate the influence of this limit value of 0.5 %/s and the influence of Q(V) characteristic on voltage changes with a continuous rate. It applies as in the simulations for d_{max} that the d_c value corresponds to the respective d_{max} value. The respective T_{max} values result from the rate of change, as this specifies the time for reaching d_{max}.

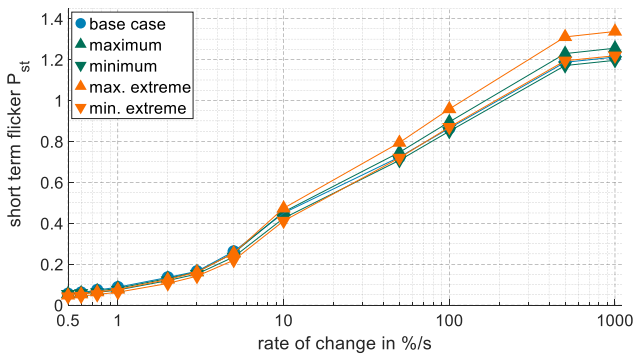

Fig. 3: Variations of rate of change

Fig. 3 shows the influence of PV feed-in with active Q(V) characteristic on positive d_{max} values. The ratio of minimum and maximum values in the grid at high rates of change reflects the behaviour already observed while investigating d_{max}. At the local grid transformer, the short-time flicker values are higher when operating with Q(V) characteristic and the effect is much more pronounced in the " Rural Extreme" grid. Furthermore, the minimum short-term flicker values deviate only slightly from the base case. However, this already known effect only sets in at rates of change above 10 %/s. At rates of change below this value, the maximum short-term

flicker values are below those of the base case. This effect is only slightly pronounced, but leads to the fact that operation with Q(V) characteristic results in an improvement in the grid without exception. The minimum short-term flicker values in this range are even up to 19.5 % lower than those of the base case.

However, this stronger deviation only occurs in the " Rural Extreme" grid. In " Rural Average" this deviation is only 11.4 %, which is nevertheless a relatively high effect of the Q(V) characteristic. Due to the low rate of change of these cases, these short-term flicker values are all in a range of P_{st}<0.3 and are thus rather uncritical with regard to the voltage quality. The effect of Q(V) characteristic on RVC at low rates of change therefore only becomes interesting if several such RVC are to be expected in an observation period.

Amendment 1 of EN 50160, which is valid in Norway, uses the rate of change as a criterion to classify whether a voltage change is considered an RVC. This has the advantage that grid engineers have an easy to consider parameter against which they can evaluate RVC. However, the selected threshold value of 0.5 %/s, from which a voltage change is evaluated as rapid, is very low for limiting flicker. Only from 2 %/s are the resulting short-term flicker values visibly increased. Whereby even with high d_{max} values, the resulting short-term flicker values are still unproblematic at a rate of change of 100 %/s. The effect of PV feed-in with active Q(V) characteristic is consistently positive at lower rates of change. The short-term flicker values are already low in this range and are further reduced by the Q(V) characteristic. Only at higher rates of change and positive d_{max} values does the Q(V) characteristic have a negative influence on the flicker values. However, this is still manageable and not higher than in the observations regarding d_{max}.

PARAMETER T_{max}

The parameter T_{max} indicates the time period in which the limit value of d_c is exceeded. This limit value is set to 3.3 % in IEC 61000-3-3. In this case d_c values of 10% are used. The results of the simulations are shown in *Fig. 4*.

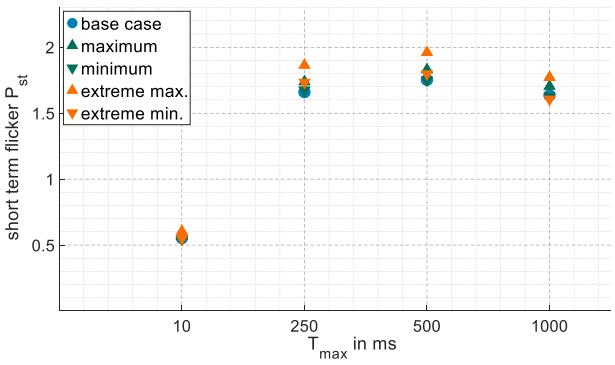

Fig. 4: Variations of T_{max}

The results with the influence of the Q(V) characteristic show hardly any unforeseen effects with variations of the parameter T_{max}. Only for very small T_{max} values there is a conspicuous effect. At T_{max}=10 ms, the Q(V) characteristic shows almost no influence on the resulting short-time flicker values. Here the reason is probably that the Q(V) characteristic reacts too slowly to have an influence in this period. For the other T_{max} values, the same effect is seen as already observed. The Q(V) characteristic increases the short-time flicker values at the local grid transformer, whereby the effect is less pronounced than with the variations of the parameter d_{max}. Only the minimum short-time flicker values at T_{max}=250 ms and T_{max}=500 ms are a little noticeable, as they are somewhat higher than those of the base case. However, this also only applies to the " Rural Extreme" grid and is rather negligible in the existing expression.

The two effects that could be observed across all simulations are the low short-term flicker values at T_{max} =10 ms and the maximum of the short-term flicker values at T_{max} =500 ms. With both effects, however, it is questionable to what extent they describe the actual behaviour of lamps. The low values at T_{max}=10 ms could merely result from the calculation method, which does not correctly capture the actual d_{max} by averaging half period cycles. Less questionable is the flicker maximum at T_{max} =500 ms. In IEC 61000-3-3, T_{max} =500 ms is set as the limit value for RVC. With regard to the flicker problem, it makes little sense to set the limit value at the time with maximum effect. According to the results of the simulations, a limit value of 1000 ms would not lead to higher flicker values of RVC. A sensible limit value for T_{max}, which should reduce the flicker values resulting from RVC, must be below 500 ms.

PARAMETER d_c

The last parameter that is considered separately is the maximum change of the steady state d_c. To determine the maximum effect of this parameter, T_{max} is set to the value at which the resulting flicker values reach their maximum. This value was determined in the former section and is T_{max}=500 ms.

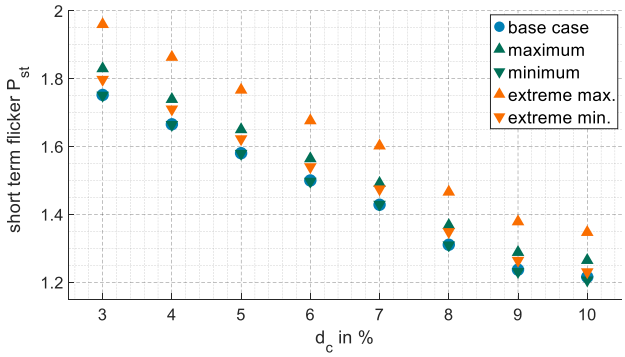

Fig. 5: Variations of d_c

The results show that even with varying d_c values, the operation of PV systems with active Q(V) characteristic can lead to an increase in flicker values if d_{max} is positive. In terms of amount, this increase does not differ noticeably between the different d_c values. The initial edge with a d_{max}=10 % seems to be decisive for the effect of the Q(V) characteristic on the short-term flicker value. The second edge with a negative d_{max} value should have no influence on the maximum short-term flicker value in the grid according to previous findings.

Furthermore, the minimum short-term flicker values do not show a large deviation from the base case. This suggests that only the initial edge is responsible for the effect of the Q(V) characteristic. The second edge has a negative d_{max} and should therefore lead to a reduction in the minimum short-term flicker values. Since this is not the case, mainly the d_{max} value has an influence on the effect of the Q(V) characteristic

with only a small difference at different d_c values. The Q(V) characteristic raises the short-term flicker value by a maximum of 11.8 % at d_c=3 % and a minimum of 10.8 % at d_c=10 %. These values apply to the grid "Rural Extreme". In "Rural Average" this effect is between a minimum increase of 4.0 % and a maximum of 4.4 %.

The investigations on d_c show that an RVC with a lower d_c value leads to higher short-term flicker values. This could be determined for all considered variations of d_c and d_{max} without exception. Furthermore, the d_c value has no significant effect on the effect of the Q(V) characteristic on the short-term flicker values. For these reasons, limiting the d_c value with regard to flicker does not make sense. Only a limitation in the difference between d_c and d_{max} would make sense in this regard. The disadvantage of such a limitation, however, would be that the already non-uniform definitions of parameters for RVC would have to be extended by another parameter.

VII. Results of Measurements

In the field measurement campaign described in this section, RVC, among power quality traits, were measured at three measurement points from 21.08.2020 to 23.09.2020 in a suburban grid [22]. The parameters d_{max}, d_c and also the short-term flicker values P_{st} were documented and are evaluated below. First, *Fig. 6* shows each measured RVC over the entire period. This means that for all three measuring points and phases all RVC are shown together. This initially only serves to provide an overview of the temporal distribution of RVC.

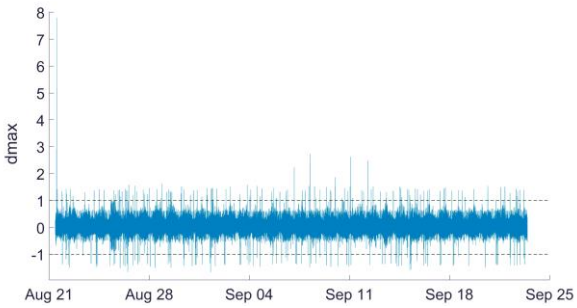

Fig. 6: All measured RVC over time

The observation of the distribution of voltage events over time shows a high basic load of RVC with maximum deflections in the range of 1 %<d_{max}<1 %. RVC with a d_{max} outside this range also occur regularly, but with more extreme values for positive d_{max} than for negative ones. The largest d_{max} value in terms of magnitude was measured at the beginning of the measurement with a value of over 7 %.

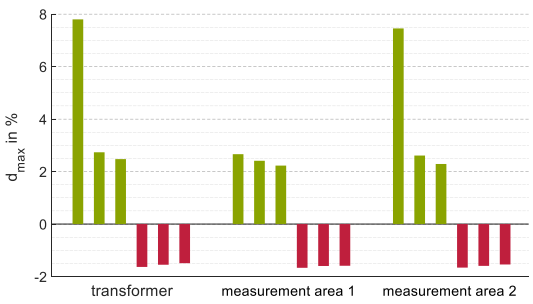

Fig. 7: Highest measured d_{max} values

Fig. 7 shows the three largest d_{max} values measured by amount for each measurement area. On the one hand, it can be seen in the figure that the positive d_{max} values are larger in amount. Secondly, it is noticeable that the maximum d_{max} value at the local grid transformer and in measurement area 2 is over 7 %, while the maximum value in measurement area 1 is only over 2. This is due to the fact that at the time when the RVC with d_{max}>7 % was measured, the measurement in measurement area 1 had not yet started. The measuring devices were first connected in the local grid transformer, then in measurement area 2 and finally in measurement area 1. The RVC occurred at 12:38 on 21.08, which is approx. 73 minutes after the start of measurement in measurement area 2, more than two hours after the start of measurement at the local grid transformer and 37 minutes before the start of measurement in measurement area 1. Thus, no statement can be made about the occurrence of this RVC in measurement area 1. A measurement error at the beginning of the measurement is unlikely due to the advanced measurement time at the local grid transformer.

Finally, the maximum and minimum values of the parameter d_c and the maximum values of the short-time flicker value P_{st} are shown in Table 2. While the maximum d_{max} value in measurement area 1 deviates strongly from the other measurement locations, this does not apply to the d_c values. These are quite similar in the negative as well as in the positive range for all measuring points. The reason for the similarity of these values could be that they were all caused by switching of a tap changer in a transformer station. The range in which these values lie would support this thesis, but it cannot be proven from the available data.

Table 2: Highest and lowest measured values

location of measurement	maximum		minimum		max.
	d_{max} (%)	d_c (%)	d_{max} (%)	d_c (%)	P_{st}
transformer	7,7972	1,4617	-1,6331	-1,5578	1,3498
measurement area 1	2,6618	1,506	-1,6662	-1,6004	0,6598
measurement area 2	7,4525	1,4803	-1,6588	-1,5578	1,3215

Furthermore, it is noticeable that the maximum short-term flicker values P_{st} at the local grid transformer and in measurement area 2 are very similar, while the value measured in measurement area 1 is significantly lower. A comparison of the times at which these short-term flicker values occurred shows that the maximum P_{st} values at the local grid transformer and in measurement area 2 were measured in the 10-minute interval in which the RVC with d_{max}>7 % occurred. In the almost identical measurement period, the highest P_{st} value was therefore still below 0.66.

The results of the field measurement campaign show that RVC can also occur with high d_{max} values in low-voltage grids. Furthermore, a high number of RVC with a 1 %< d_{max} <1 % occur. However, these cause manageable

flicker values, so that the only short-term flicker value above 1 occurred with the RVC with d_{max}> 7%. For the grid-side consideration of RVC, a threshold for RVC of d_{max}<1 % does not lead to any added value with regard to the flicker consideration. Moreover, RVC were never accompanied by steady state changes of d_c>1.7 % over the entire measurement period. Another important observation is the higher d_{max} values of RVC with positive values, i.e. changes that result in a reduction of the voltage. This is particularly interesting with regard to the findings of the behaviour of Q(V) characteristics to RVC with positive and negative d_{max}.

VIII. Summary

The flicker issue in particular is the focus of research due to new light sources. The flicker value calculated by the flicker meter is often not meaningful for these lamps because the luminance of these lamps can also fluctuate due to other factors, such as interharmonics. However, studies also show that the flicker value calculated by the flicker meter is also meaningful for new lamps in the case of rapid changes in voltage. RVC thus remain an important criterion for evaluating flicker.

The simulations in this paper show that in order to limit the flicker values, it can be useful to limit the maximum rate of change of an RVC and its maximum deviation from the steady state d_{max}. Limiting the parameters T_{max} and d_c does not make sense with regard to the flicker problem. The investigation of the influence of the Q(V) characteristic on RVC shows that this can lead to an increase in the short-time flicker values, but also to a reduction of them. The decisive factor here is the operator of the d_{max} values. If the operator of d_{max} is positive, the Q(V) characteristic leads to an increase of the flicker values at the transformer and if d_{max} is negative, it leads to a reduction of them towards the end of the string. However, this effect is unevenly distributed in the grid, which is why it cannot be observed at different points in the grid (string end or transformer). Therefore, it is mainly the increase that is interesting here, as this can lead to violations of limit values. The decreasing effect, which can occur with negative d_{max} values, cannot prevent limit violations in return, since this reduction becomes greater towards the end of a line and can no longer be observed at the local grid transformer.

The data from a field measurement campaign shows that RVC with higher d_{max} values also occur in low-voltage grids and cause high flicker values. Furthermore, it can be seen that positive d_{max} values are clearly more frequent in the grid.

The effect of Q(V) characteristic on flicker is only relevant at a high maximum reactive power, i.e., at high penetration of PV systems in the grid. Even at the highest possible PV power values, however, the advantages of Q(V) characteristic for the voltage quality clearly outweigh the disadvantages!

Acknowledgment

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IX. Literature

[1] C. Biedermann und et. al., Untersuchung und Verbesserung der Spannungsqualität vor dem Hintergrund des Anstiegs an Photovoltaik, Elektrofahrzeugen, PV-Batteriespeichersystemen und Power-to-Heat, 2020.

[2] O. Lang, Spannungsqualität, ein Durchblick, 2009.

[3] CENELEC , *EN 50160,* 2011.

[4] IEC, *IEC 61000-4-15,* 2011.

[5] CENELEC , *EN 50160/A1,* 2016.

[6] IEC, *IEC 61000-3-3,* 2013.

[7] IEC, *IEC 61000-3-11,* 2000.

[8] D. Macii und D. Petri, „Rapid Voltage Change Detection: Limits of the IEC Standard Approach and Possible Solutions,“ *IEEE Transactions on Instrumentation and Measurement,* pp. 382 - 392, February 2020.

[9] L. P. Frater und N. R. Watson, „Light Flicker Sensitivity of High Efficiency Compact Fluorescent Lamps,“ in *2007 Australasian Universities Power Engineering Conference,* Perth, WA, Australia , 2007.

[10] T. Kim, M. Rylander, E. J. Powers, W. M. Grady und A. Arapostathis, „LED Lamp Flicker Caused by Interharmonics,“ in *2008 IEEE Instrumentation and Measurement Technology Conference,* Victoria, BC, Canada , 2009.

[11] L. Frater, Light Flicker and Harmonic Modelling of Electrical Lighting, Christchurch, New Zealand, 2015.

[12] J. Barros und et. al., „Rapid Voltage Changes in Power System Networks and Their Effect on Flicker,“ *IEEE Transactions on Power Delivery,* pp. 262 - 270, February 2016.

[13] S. Lodetti und et al., „Flicker of Modern Lighting Technologies Due to Rapid Voltage Changes,“ *Power Quality: Monitoring, Mitigation, and New Types of Disturbances,* 5 March 2019.

[14] M. Kaspirek, L. Mikulas und D. Mezera, „Analysis of voltage quality parameters in LV distribution grids with connected distributed energy sources,“ *CIRED - Open Access Proceedings Journal,* pp. 513-516, October 2017.

[15] S. Lodetti, J. Bruna und J. J. Melero, „Methods for the Evaluation of New Power Quality Parameters: a Review of Rapid Voltage Changes and Supraharmonics,“ in *CIRED 2019,* Madrid, Spain, 2019.

[16] D. Mezera, „Voltage Quality in the Low Voltage Distribution Grids with the High Penetration of Distributed Energy Sources,“ in *16th International Scientific Conference on Electric Power Engineering (EPE),* Kouty nad Desnou, Czech Republic, 2015.

[17] A. Spring, G. Wirth, G. Becker, R. Pardatscher und R. Witzmann, „Effects of Flicker in a Distribution Grid with High PV Penetration. In Journal of Energy and Power Engineering,“ in *28th European Photovoltaic Solar Energy Conference and Exhibition,* Villepinte, France, 2014.

[18] D. Macii und D. Petri, „Fast detection of Rapid Voltage Change Events through Dynamic RMS Voltage Tracking,“ in *2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC),* Houston, TX, USA, 2018.

[19] D. Blume, J. Schlabbach und T. Stephanblome, Spannungsqualität in elektrischen Netzen, 1999.

[20] VDE, VDE-AR-N 4105, 2018.

[21] O. Marggraf, Auslegung und Bewertung autonomer Spannungsregelkonzepte für Verteilungsnetze, 2019.

[22] G.-L. Di Modica, C. Biedermann, T. Garn und B. Engel, Influence of Electric Vehicles, PV Systems, Home Storage Systems and Heat Pumps on the Voltage Quality in the Low-Voltage Grid, 2021.