Flicker source identification in meshed high voltage grids

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***Abstract*-- This paper describes a method to calculate the individual flicker emission of specific disturbers by means of simultaneous flicker level measurements in different bus bars of a meshed grid. The method is based on former investigations regarding the flicker propagation in meshed networks. With adequate flicker level measurements, the cubic flicker summation law and the specific flicker transfer factors which result out of the grid's impedance matrix, a detailed analysis of the flicker emission situation in a grid can be done. A case study with electric arc furnaces in a 110 kV grid is presented as application example, including a sensitivity analysis.**

***Index Terms*-- power quality, flicker emission, flicker transfer factor, meshed grid.**

I. INTRODUCTION

Among the different existing power quality parameters, the criterion "fast voltage variation" respectively "flicker" has a special position. It is the only criterion that can be "measured" without any instrument but only with the human eye. Flicker is the visible perception of variation in luminance produced by electric lights. These variations are caused by changes of the r.m.s. of the supply voltage.

The flicker disturbance level in a specific node of a network results from the (nonlinear) superposition of the flicker emissions of different disturbers connected in different points of the network. To forecast the flicker level in the point of common coupling of a new disturbing load in the planning phase, the contribution of all other existing disturbers must be considered. This so-called background flicker level in the planned PCC can be calculated (if the flicker emissions of all sources in the different points of the grid are known) or has to be measured before installation of the new plant. The flicker emission of the new plant superposes the existing background level – not only in the PCC, - in all points of the grid. The resulting new flicker levels have to remain within the tolerable limit. Furthermore it’s still necessary to reserve room for connecting further loads.

Measuring the flicker level in a specific point in the network, which represents the summation of the flicker emissions of all disturbers in this network, gives of course important information about the power quality. However, in some cases it is of great importance to get information about the flicker emission of single disturbers and the flicker propagation in the network.

This is necessary, for instance, if one wants to determine the free capacity for additional fluctuating loads, if compensating measures are necessary or have to be optimized, or if the interaction of different disturbers should be analyzed. Especially in case when in connection with the new plant also grid expansion measures, grid circuitry changes or new power plants are planned it is not possible to calculate the future flicker level just from the existing background level and the known calculable flicker emission of the new plant. In such case it is necessary to know the flicker emissions of the existing loads and to know how these emissions penetrate the grid.

However, the identification of these sources and especially the allocation of their share to the measured flicker level are difficult. CIGRE report 468 [1] provides a bundle of techniques for flicker emission assessment.

In literature several methods for identification of the flicker sources are described. In [2] a method based on current measurement is shown. [3] uses the transfer factor, derived from short circuit capacities in different nodes, and the usual exponential flicker summation law to determine the flicker emission of a specific disturber. Nevertheless, both methods work only in radial networks. In [4], based on evaluation of voltage fluctuations and current fluctuations, a new quantity, called flicker power, is defined. According to the sign of the flicker power, one can trace to the main disturbing flicker source also in a meshed grid.

In [5] flicker analysis in frequency domain is used, based on the evaluation of interharmonics to determine the transfer factors in a grid. In [6] a method determining those transfer factors by synchronized flicker measurement in different nodes of the grid combined with correlation analysis is described. The same method was used in [7] to validate the calculation of transfer factors by means of short circuit calculation.

Direct flicker emission measurements at the point of common coupling of fluctuating loads are possible and can be made, however, flicker emission measurement is not standardized up to now, and there are only few flickermeters able to perform this measurement task [8]. As this direct flicker emission measurement equipment is not available in most cases, a new approach based on simultaneous flicker level measurements in several nodes of the (meshed) grid combined with calculations based on transfer coefficients derived from grid analyses was developed by the authors.

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II. FLICKER SUPERPOSITION AND PROPAGATION

A. *Flicker superposition*

When speaking of flicker and voltage variations one has to make a clear distinction between these two terms.

Voltage variations (ΔV) are variations of the r.m.s. value of the supply voltage and can be measured directly by an appropriate voltmeter. They can be characterized by amplitude and frequency. In most cases a conversion into a relative quantity, related to the long term mean rms value $\overline{V}$, turns out to be practically. Voltage variations caused by different disturbers are superposed in a linear way in a network.

Flicker (P_{st}, P_{lt}) is the visible perception of variations in luminance produced by electric lights. It's more a physiological quantity than a physical one but it's the direct consequence of voltage variations. The flicker perception depends on the wave shape of the voltage variation. For identical wave shapes of ΔV the flicker level is proportional to the amplitude of ΔV.

The superposition of **voltage fluctuations**, caused by different fluctuating loads, occurs **linearly**, whereas the total **flicker level** as a result of the several independent flicker disturbing sources is typically determined with a **non-linear** superposition law:

$$P_{st} = \sqrt[m]{\sum_i P_{st,i}^m} \qquad (1)$$

The exponent m can vary depending on the characteristics of the disturber in a wider range:

m = 1	linear summation: only for exact simultaneous load changes
m = 2	used for the same kind of stochastic load changes, e.g., two electric arc furnaces during melting phase
m = 3	usually used value for the superposition of disturbers, is also applicable for superposition of the emission of a single disturber with background flicker
m = 4...8	to apply with disturbing devices who meet precautions to avoid the coincidence of unfavorable operation states (e.g. electric arc furnaces with coordinated timetables).

B. *Flicker emission and propagation*

The flicker emission is the flicker level caused by a single disturber if no other disturber exists in the grid. The level in the connection point of the flicker source – called flicker emission in the PCC – depends on the time course of its power changes and on the short circuit capacity of the grid. The fact that this source causes proportional flicker levels also in the other nodes of the grid, is called flicker propagation or flicker transfer.

The total flicker level in a specific node of a network results from the (nonlinear) superposition of the flicker emissions of different disturbers connected in the different nodes of the network.

The transfer of the flicker caused by a single device can be described by the flicker transfer coefficients as defined in [7]. Assuming a grid with N nodes, the flicker level (P_{st} or P_{lt}) P_i in each node i caused by a single disturber with its flicker emission Pe_f in node f can be calculated as follows:

$$\begin{pmatrix} P_1 \\ \vdots \\ P_f \\ \vdots \\ P_N \end{pmatrix} = \begin{pmatrix} kf_{1f} \\ \\ kf_{ff} \\ \\ kf_{Nf} \end{pmatrix} \cdot Pe_f \quad \text{with } kf_{if} = \begin{cases} 1 & \text{for } i = f \\ <1 & \text{for } i \neq f \end{cases} \qquad (2)$$

With different disturbers, the summation law (1) has to be used. This leads to the following generalized formula for the flicker level P as a result of different, independent disturbers with their flicker emission Pe:

$$\begin{pmatrix} P_1^m \\ \vdots \\ P_f^m \\ \vdots \\ P_N^m \end{pmatrix} = \begin{pmatrix} kf_{11}^m & \cdots & & \cdots & kf_{1N}^m \\ & \ddots & & & \\ \vdots & & kf_{ff}^m & & \vdots \\ & & & \ddots & \\ kf_{N1}^m & \cdots & & \cdots & kf_{NN}^m \end{pmatrix} \cdot \begin{pmatrix} Pe_1^m \\ \vdots \\ Pe_f^m \\ \vdots \\ Pe_N^m \end{pmatrix} \qquad (3)$$

with kf= 1 in the main diagonal and kf<1 off diagonal

III. DETERMINATION OF THE FLICKER EMISSION OF SINGLE DISTURBERS

As stated before, the total flicker level in a certain bus bar of the grid can be determined quite easy by simple measurement. If the flicker level measurement is done simultaneously, synchronized in several busbars, then one can calculate with a certain degree of accuracy the flicker emissions of the disturbers located in the busbars with

$$Pe^m = \left(kf^m\right)^{-1} \cdot P^m \qquad (4)$$

In (4) P^m represents the vector of the measured flicker levels in different busbars with each element raised to the power of m, kf^m is the matrix of the transfer coefficient with each element to the power of m according to (3). The result Pe^m is the vector of flicker emission for the single busbars.

If flicker measurement is not done in all busbars of a grid, those busses are not present in equation 3 and 4. Nevertheless, their flicker emission will show up as equivalent additional emission in the neighbored busses, which are covered by the measurement.

Of course, the accuracy is limited according to following reasons:

- The calculation of the flicker transfer coefficients from the grid data depends on the accuracy of the available data including the current switching topology and the operation of nearby power plants.
- The result also strongly depends on the choice of the summation exponent m. Typically this is not constant but may vary with time
- Finally, an additional error may be introduced by using flicker level measurement, which is not exactly synchronized. In that sense, the use of P_{lt} values is of advantage, since they are not that sensitive to small time shifts.

These errors in the raw data result for instance in the calculation of negative flicker emission in some nodes, which is physically not possible. However, sensitivity studies have shown that the result for busbars with larger disturbers are more or less stable concerning small changes of the transfer factors and the choice of the exponent m.

IV. CASE STUDY IN A 110 KV GRID

A. Analysis of the present state

In a meshed 110 kV grid, two major disturbers (steel plants) are connected. Synchronized flicker measurements had been carried out in seven substations of the grid, including the substations with the disturbing installations. Using the above described method, the flicker emission especially of the mentioned steel plants should be determined. Furthermore the analysis demonstrated that no further dominating flicker sources are present in this grid. To minimize problems out of unwanted time shifts between the measurements, P_{lt} values were chosen for evaluation since they are less sensitive to slightly unsynchronized measurement.

Figure 1 shows a simplified single line diagram of the investigated grid. Flicker level measurements were done in bus 1 to 7. The steel plants are connected in bus 2 and 3.

Figure 2 gives the measured P_{lt} values in the grid. Since the results in bus 4, 5, 6 and 7 are almost the same, only the time courses of bus 1, 2, 3 and 4 are explicitly drawn in this figure. As can be seen, all measurement results show more or less the same pattern of P_{lt} course, only different in magnitude. A conclusion regarding the flicker emission cannot be drawn directly from these measurements.

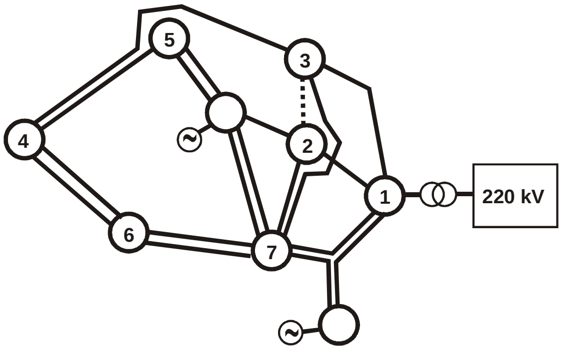

Figure 1: Simplified single line diagram of the analyzed grid; future connection between bus 2 and 3 as dashed line

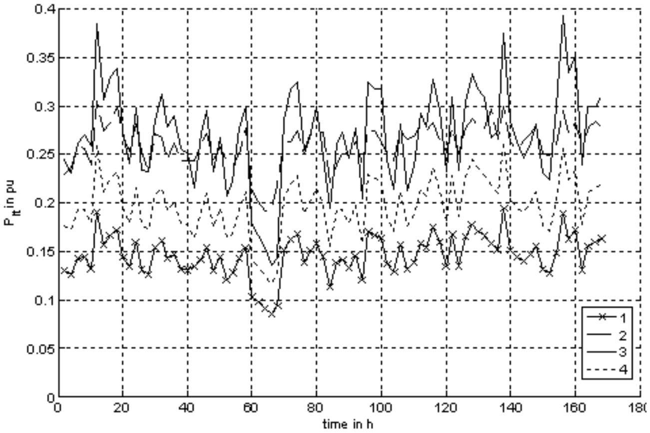

Figure 2: Measured P_{lt} levels in the grid

The full matrix of transfer coefficients kf had been calculated with the short circuit calculation method [7].

For the application of equation system (4) to the analyzed grid, a summation exponent of m=3 was chosen. The time courses of the resulting vector Pem are shown in figure 3. Again the results in the diagram are restricted to the results of bus 1 to 4 for not overloading the figure. It can be seen, that the installations in bus 2 and 3 are the dominating flicker disturbers as it was expected. The results for bus 1 and 4 to 7 are very small compared to the emissions of bus 2 and 3. However, they also include small negative values, which is physically not feasible and results from possible errors in the determination of the transfer coefficients and the assumption of a constant exponent m=3.

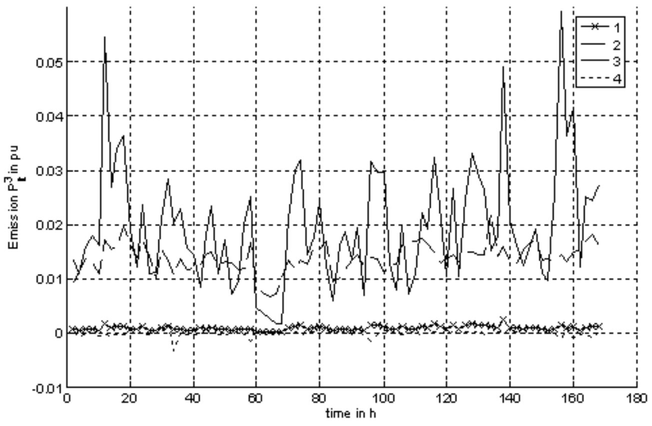

Figure 3: Time course of the calculated flicker emission Pe^m with m=3

In the next step the flicker emission Pe_i was calculated by

$$Pe_i = \sqrt[m]{Pe_i^m} \tag{5}$$

with all negative values of Pe^m set to zero. The result is shown in figure 4. It can be seen, that the main flicker source is located in bus 3 with varying level, showing a significant decrease on the weekend. The emission in bus 2 is a little bit smaller but more or less constant during the analyzed week. The flicker emission in bus 1, which is the connection to the 220 kV grid, can be interpreted as the background flicker level. The emission of bus 4 is rather small but obviously strongly influenced by the inherent errors of the used method.

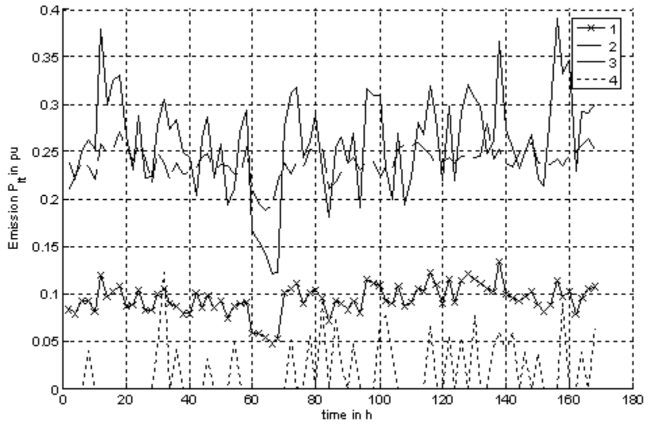

Figure 4: Time courses of the calculated flicker emissions Pe

To figure out the influence of a possible spread of the transfer coefficients, a different set – derived from measurement (table 1) – was analyzed as well. Also the exponent m was altered. To compare the resultant flicker emission, the cumulative probability functions of the Plt-emissions in bus 2 and 4 are shown in figure 5.

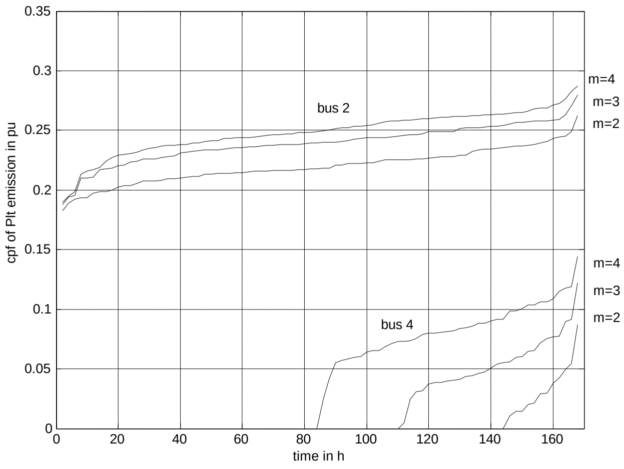

Figure 5: Cumulated probability function of Pe (flicker emission long term, P_{lt})with variation of m; solid line: bus 2, dashed line: bus 4

B. Analysis of the effect of future changes in the grid

The results from analyzing the grid and evaluating the measurement can be used to study the effect of future changes in the grid during the planning phase. In the following, the influence of the connection of the bus bars 2 and 3 will be analyzed. This change of the switching topology has mainly the following two effects:

- The increase of short circuit capacity in bus 2 and 3 leads to a decrease of the emission of the thereto connected disturbers. The new flicker emission can be easily calculated by multiplying the former determined emission by the ratio of the former short circuit capacity to the new short circuit capacity.
- Changing the grid topology changes also the transfer coefficients. Again, the new transfer coefficients can be calculated by means of short circuit calculation

With the new flicker emission and the adapted flicker transfer coefficients, the expected flicker level in the grid can be easily calculated by applying equation 3. The result for the new grid topology with coupled busbar 2 and 3 is shown in figure 6 and can be compared with the previous, measured results in figure 2.

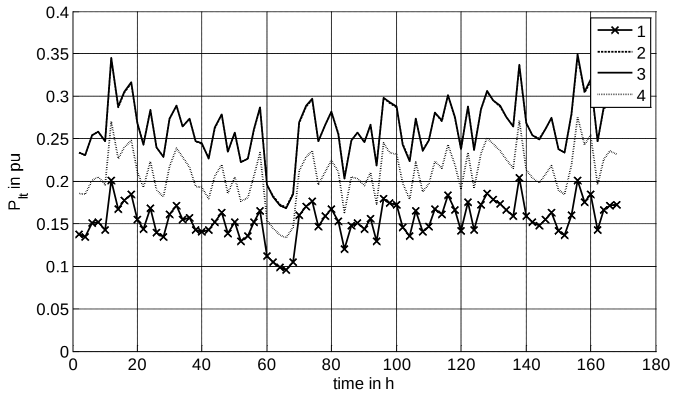

Figure 6: Time courses of the calculated flicker levels P_{lt} after changing the grid topology (coupling of bus 2 and 3)

C. Evaluation of flicker transfer coefficients

With the knowledge about the dominant flicker sources in bus 2 and 3, a rough determination of the transfer coefficients $kf_{2,i}$ from bus 2 and $kf_{3,i}$ from bus 3 to all the other busses was possible using the flicker measurement. A comparison of kf from calculation and derived from measurement shows a reasonable good congruence and is given in Table 1.

TABLE 1
COMPARISON OF TRANSFER COEFFICIENTS KF, CALCULATED AND DERIVED FROM MEASUREMENT

	calculation		measurement	
to	from 2	from 3	from 2	from 3
1	0.398	0.426	0.41	0.46
2	1.000	0.588	1.00	0.69
3	0.509	1.000	0.55	1.00
4	0.596	0.640	0.57	0.66
5	0.549	0.635	0.53	0.65
6	0.588	0.644	0.56	0.65
7	0.614	0.665	0.58	0.69

V. CONCLUSION

Flicker source identification, i.e. the detection of flicker sources and their emissions in power grids, becomes a task of growing importance for grid development and power quality planning. New flicker sources as well as changes in the grid (new lines or power plants) lead to changes in the flicker conditions and the resulting flicker levels in the grid. The changes in the grid lead to changes of the transfer coefficients and the short circuit capacities. If flicker emissions are known the resulting flicker levels in the grid can easily be calculated by using the adapted transfer coefficients and the summation law. However, the difficulty for the grid operator in existing grids is, that the disturbance behavior of the loads is mostly unknown, - as the consumed power of the loads is not the measure of their disturbance emissions. As a consequence, immense power quality measurement campaigns were undertaken in the past – delivering huge amounts of grid power quality data but not the sources and emissions of single consumers.

As a solution the authors propose a new method of flicker source identification based on simultaneous flicker level measurements in various nodes in combination with network computation analysis using inverse flicker transfer coefficient matrix for calculating flicker emissions from measured levels.

The algorithm of this approach is described and occurring error sources are discussed.

As practical application the results of a flicker prediction analysis for a new electric arc furnace in a meshed 110-kV-grid under consideration of grid expansion and grid circuitry changes is presented.

REFERENCES

[8] CIGRE report 468, "Review of Disturbance Emission Assessment Techniques", CIGRE/CIRED working group C4.109, 2011, ISBN: 978-2-85873-158-9
[2] A. M. Dan, “Identification of Flicker Sources”, 8th International Conference on Harmonics and Quality of Power ICHQP 98, Athens, October 14.-16. 1998, p1179-1181
[3] M. C. Simoes, S.M. Deckman, “Flicker Propagation and Attenuation”, 10th International Conference on Harmonics and Quality of Power ICHQP 2002, p. 644-648
[4] P. Axelberg, M. Bollen, “An Algorithm for Determining the Direction to a Flicker Source”, IEEE Transactions on Power Delivery, Vol. 21, No.2, April 2006, p.755-760
[5] A. Hernandez, J. G. Mayordomo, R. Asensi, L. Beites, “A Method on Interharmonics for Flicker Propagation Applied to Arc Furnaces”, IEEE Transactions on Power Delivery, Vol. 20, No.3, July 2005, p.2334-2342
[6] S. Perera, e.a., “Synchronized Flicker Measurement for Flicker Transfer Evaluation in Power Systems”, IEEE Transactions on Power Delivery, Vol. 21, No.3, July 2006, p.1477-1482
[7] H. Renner, M. Sakulin, „Flicker propagation in meshed high voltage networks“, 9th International Conference on Harmonics and Quality of Power ICHQP, Orlando, October 1.-4. 2000, p1023-1028
[8] M. Sakulin, H. Renner, "Field Experience with the Austrian UIE / IEC Flicker Analysis System", Proceedings of the XIIth UIE Congress, Electrotech 92, Montréal Canada, 1992, pp. 842 - 851.

BIOGRAPHIES

Herwig Renner was born in Graz, Austria, in 1965. He completed his doctoral degree in 1995 and his habilitation in 2003 at Graz University of Technology, where he works as associate professor at the Department for Electrical Power Systems. His main research work is in the area of electrical power quality and power system dynamics. He holds a position as guest docent at Aalto University (Finland), member of CIRED TC session 2 and member of several CIGRE working groups.