Survey on International Practice of Calculating Harmonic Current Emission Limits

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***Abstract*—The limitation of harmonic currents emitted by individual equipment and customer installations is essential in order to maintain harmonic voltages below compatibility or planning levels and consequently to ensure Electromagnetic Compatibility (EMC). At present a large variety of methods exists worldwide for calculating harmonic emission limits, majorly expressed as harmonic currents. As starting point for the revision of the methods currently used in Germany, a systematic search on available methods has been performed for more than 70 countries from all over the world. Finally 18 individual methods have been selected for a detailed qualitative comparison based on a set of characteristics, like voltage level, frequency range, allocation principle or network topology. The paper summarizes the results of the survey and provides an initial quantitative comparison of the selected methods based on two particular examples.**

***Index Terms*—harmonics, harmonic emission limits, network harmonic impedance, standards, survey**

I. INTRODUCTION

Harmonic voltages and currents in electricity networks are a concern of network operators since the introduction of devices with non-linear voltage-current characteristics. Harmonic currents injected into the network cause harmonic voltages at the network harmonic impedance. These result in a distortion of the supply voltage, which can adversely affect other devices or installations connected to the network. Network operators are responsible to maintain voltage harmonics within defined limits and consequently they have to take care that the harmonic currents injected by customer equipment or installations are adequately limited. For equipment with rated currents up to 16 A/75 A established international standards (IEC 61000-3-2/IEC 61000-3-12) are available. For larger installations, particular with significant harmonic sources (e.g. arc furnaces, HVDC converter stations, variable speed drives, etc.), the network operators usually set specific harmonic current emission limits according to individual rules or guidelines.

This paper is focused on methods applied for larger installations, which can significantly differ between different countries, e.g. in their complexity or covered frequency range. Therefore a comprehensive survey of the current international practice on emission limit calculation was initiated within a German research project in order to provide reliable input for the revision of the national rules and standards.

This paper is intended to provide a general overview of existing methods and their diversity. It shall serve not only as input for the above mentioned research project but also for the ongoing work in several CIGRE working groups like C4.40 or C4.42. Section II provides a brief description of the framework for the survey. An overview of the analyzed methods is given in section III. Section IV presents a qualitative comparison of the methods. Finally an initial quantitative comparison of the methods based on two examples for a LV and a MV network is provided in Section V.

Because of the space limit, a detailed description of each individual method is not in the scope of this paper. Furthermore it should be noted that the survey by nature cannot be entirely complete, as available information is often limited, particular from overseas.

II. FRAMEWORK OF SURVEY

A. Step 1: Method search

At the beginning all countries of the world have been grouped by continents. Next a priority between 0 (lowest priority) and 3 (highest priority) has been defined for each country depending on its assumed importance and development stage in terms of Power Quality assessment. While priority 3 means to carry out an intensive search for existing methods, countries with priority 0 have been excluded from the survey. This ensures a reasonable limitation of the required work. For illustration, priorities for some American countries are e.g. set to 3 for U.S.A., 2 for Mexico, 1 for Ecuador and 0 for El Salvador. In a first stage all identified documents have been classified according to the applicable type of installation (consumption/generation) and voltage level (LV/MV/HV/EHV). Table I provides a summary of the priority distribution for the different continents.

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TABLE I Overview of priority distribution of countries per continent

	Priority				*Total*
	3	*2*	*1*	*0*	
Africa	1	1	5	46	53
Americas	4	5	5	26	40
Asia	2	6	7	42	57
Europe	12	9	15	19	55
Oceania	2	0	3	0	5
Total	21	21	35	133	210

In the last stage of the method search the final set of documents for the further analysis has been decided by the project partners and respective short codes have been introduced.

B. Step 2: Method classification

For each of the finally selected documents a more detailed, but still qualitative comparison based on a set of characteristics with predefined answers was performed. Three categories, namely general characteristics, method-related characteristics and network-related characteristics have been introduced.

1) General characteristics

Table II provides a summary of the characteristics including the possible value sets. Harmonic limits can be provided in currents or voltages. While current harmonic limits usually apply to the individual customer installation, voltage harmonic limits can either be given as total values for the network (e.g. the compatibility levels) or as individual contribution by the individual customer installation. In case of total harmonic voltage limits an allocation of individual emission limits to different customer installations in a network is not possible.

TABLE II Set of general characteristics

Characteristic	*Set of possible answers*
G1: Voltage level	a. Low voltage (LV, $U_n \leq 1$ kV); b. Medium voltage (MV, 1 kV < $U_c \leq 35$ kV); c. High voltage (HV, 35 kV < $U_c \leq 150$ kV); d. Extra high voltage (EHV, U_c >150 kV)
G2: Type of installation	a. Consumer; b. Generation; c. Storage; d. Equal treatment of all types (yes/no)
G3: Type of limits	a. Harmonic currents; b. Harmonic voltages (at installation level); c. Harmonic voltages (at network level)
G4: Reference to popular standard	a. IEEE 519; b. IEC 61000-3-6/-3-14; c. Individual method

2) Method-related characteristics

Table III provides a summary of the characteristics including the possible value sets. The allocation principle is usually based on the ratio of an available capacity (provided as apparent power) and the size of a customer installation. This shall ensure that customers with a higher agreed power, which usually pay more for the connection, get higher emission allocated. Some methods use the capacity of the whole network (e.g. for an LV network the rated power of the MV/LV supply transformer), while other methods use only the prospective power of customer installations that can be connected to a particular connection point, often determined by the thermal operation limit of the feeding line.

TABLE III Set of method-related characteristics

Characteristic	*Set of possible answers*
M1: Frequency range	a. Harmonics; b. Interharmonics; c. Supraharmonics; d. THD; e. <upper limit>
M2: Summation of multiple installations	a. Summation exponent (IEC recommendations); b. Summation exponent (individual values); c. Consideration of phase angles; d. No information
M3: Allocation principle	a. Allocation based on network capacity; b. Allocation based on connection point capacity; c. No capacity based allocation; d. No information
M4: Number of input parameters	a. <respective value>

3) Network-related characteristics

Table IV provides a summary of the characteristics including the possible value sets. Regarding network topology in distribution networks some standards consider only radial networks with single infeed, as this can simplify the calculation of harmonic emission limits considerably.

TABLE IV Set of network-related characteristics

Characteristic	*Set of possible answers*
N1: Network impedance	a. Simplified impedance line $h*Z_{sc}$ b. Frequency-dependent network impedance c. Independent from network impedance d. Individual method e. No information
N2: Network topology	a. All types of networks b. Radial networks with single infeed only c. No information

C. Final selection of documents

The qualitative characterization of the selected documents has shown that 18 of them contain methods to calculate individual emission limits for large customer installations with an agreed power higher than 50 kVA (cf. Table V). In case a method is country-specific, the first two letters of the short code correspond to the two-letter-country code defined in ISO 3166-1 alpha-2. The last column of Table V lists all countries found by the authors, which apply the respective document. While for Table V the title of each document has been translated into English, the Reference section at the end of the paper provides the title in the original language.

D. Challenges and limitations

The activities have quickly shown that it is a great challenge to obtain the relevant information from everywhere in the world. Often the respective documents are not publicly available or only available in the native language of the country. Some of the documents apply only to a specific group of installations (e.g. wind power plants) and even within one country different network operators might apply different methods.

The evaluation of the methods in the following sections has been carried out as carefully as possible. However, it is still the result of the interpretation of the authors and might in

TABLE V Overview of identified documents including the calculation of limits for individual installations with an agreed power higher than 50 kVA

Ref.	*Short code*	*Title*	*Release of recent version*	*Applied in*
[1]	**IEEE_519**	Recommended Practice and Requirements for Harmonic Control in Electric Power Systems	2014	CA, CO, IN, MX, US, VE
[2]	**IEEE_1547**	Standard for Interconnecting Distributed Resources with Electric Power Systems	2008	CA, US
[3]	**IEC_3_6**	Assessment of harmonic emission limits for the connection of distorting installations to MV, HV and EHV power systems	2007	EE, ES, IE, IT, NA,ZA
[4]	**IEC_3_14**	Assessment of emission limits for the connection of disturbing installations to LV power systems	2007	ZA
[5]	**MC_AN_ENA**	ENA PQ Guideline for Harmonics	2013	AU, NZ
[6]	**MC_DACH**	Technical rules for the assessment of network disturbances	2007	AT, CH, CZ, DE, MK
[7]	**MC_DACH_HS**	Technical rules for the assessment of network disturbances – Amendment for the connection of customer installations to high voltage distribution networks	2012	AT, CH, CZ, DE
[8]	**BE_C1017**	Power Quality rules for network users connected to public medium and high voltage networks	2009	BE
[9]	**CA_C2501**	Technical requirements for the connection of distorting loads to the distribution network of Hydro-Quebec	2014	CA
[10]	**CN_14549**	Quality of electric energy supply - Harmonics in public supply network	1993	CN
[11]	**DE_4105**	Generating installations in low voltage networks	2011	DE
[12]	**DE_4120**	Technical rules for connection and operation of customer installations in high voltage networks (TAB Hochspannung)	2015	DE
[13]	**DE_BDEW**	Generating installations in medium voltage networks including amendments	2008	DE
[14]	**DK_TR**	Technical regulation 3.2.5 for wind power plants with a power output above 11kW	2014	DK (only wind)
[15]	**FI_HS**	Power Quality in Fingrid's 110 kV grid	2007	FI
[16]	**FR_CURTE**	Technical reference documentation (cp. 8.3)	2014	FR
[17]	**GB_G541**	Planning Levels for harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the UK	2005	GB
[18]	**SE_TR6**	Technical Rules for Power Quality: Part 1 & 2 (TR6-01 & TR6-02)	2006	SE

particular details differ from the "original" meaning.

III. QUALITATIVE COMPARISON

All documents listed in Table V have been studied in order to classify them according to the characteristics introduced in section II.B. Table VI exemplarily presents the detailed values for some of the characteristics. The next subsections summarize the results for all characteristics with regard to the three main categories. It should be noted that for selected characteristics multiple answers can apply for some documents and consequently the total number for all values of one characteristic might exceed 18.

TABLE VI Selected characteristics of methods (Upper frequency limit refers to a power frequency of 50 Hz except for [9])

Ref.	*Short code*	*M1: Frequency range*					*G2: Type of installation*				*G1: Voltage level*			
		Upper Limit (in kHz)	*Harmonics*	*Interharmonics*	*Supraharmonics (>2.5 kHz)*	*THD*	*Consuming installations*	*Generating installations*	*Storage installations*	*Equal treatment*	*Low voltage*	*Medium voltage*	*High voltage*	*Extra high voltage*
[1]	IEEE_519	2.5	x	x	-	x	x	x	-	-	x	x	x	x
[2]	IEEE_1547	2.0	x	-	-	x	-	x	-	NA	x	x	-	-
[3]	IEC_3_6	2.5	x	x	-	-	x	(x)	-	x	-	x	x	x
[4]	IEC_3_14	2.5	x	-	-	-	x	(x)	-	x	x	-	-	-
[5]	MC_AN_ENA	2.0	x	-	-	x	x	x	-	-	-	x	x	-
[6]	MC_DACH	2.5	x	(x)	-	x	x	x	-	-	x	x	-	-
[7]	MC_DACH_HS	2.5	x	x	-	x	x	x	-	-	-	-	x	-
[8]	BE_C1017	9.0	x	x	-	x	x	x	-	x	-	x	x	-
[9]	CA_C2501	3.0	x	x	-	x	x	-	-	NA	(x)	x	-	-
[10]	CN_14549	1.0	x	-	-	x	x	x	-	x	x	x	x	-
[11]	DE_4105	9.0	x	x	(x)	-	-	x	-	NA	x	-	-	-
[12]	DE_4120	9.0	x	x	(x)	-	-	x	-	NA	-	-	x	-
[13]	DE_BDEW	9.0	x	x	(x)	-	-	x	-	NA	-	x	-	-
[14]	DK_TR	2.5	x	x	-	x	-	x	-	NA	x	x	x	x
[15]	FI_HS	5.0	x	-	(x)	x	-	x	-	NA	-	-	x	-
[16]	FR_CURTE	2.0	x	-	-	x	-	x	-	NA	x	x	x	x
[17]	GB_G541	2.5	x	x	-	-	x	x	-	x	x	x	x	x
[18]	SE_TR6	2.5	x	-	-	x	x	x	-	x	-	-	-	x

Legend: "x" – included, "(x)" – partly included, "-" – not included, "NA" – not applicable

A. General characteristics

1) Voltage levels

Most standards apply for more than only one voltage level and often cover the full range from LV to HV. The individual limits are usually voltage level specific. It should be noted that the classification of voltage levels according to Table II is not consistent for every document. In some cases the applicable voltage range extends across the level borders according to Table II, in other cases even a single voltage level in Table II is not fully covered (e.g. DE_4120 considers only voltages between 60 kV and 150 kV).

2) Application range

The majority of the selected methods is both applicable for generators and consumers and among those, most of them provide equal treatment (cf. Table VI). In case of unequal treatment, limits are usually more stringent for generators (e.g. MC_DACH). The grid integration of storage devices, which can be operated as generator or consumer, has not been specifically addressed in any of the documents yet. Particular in case of unequal treatment of generators and consumers the handling of storage devices is not clear.

3) Type of limits

All 18 analyzed documents provide harmonic current limits for individual customer installations, which are mostly based on individual proportionality/weighting factors for each harmonic order. The limits are generally calculated based on the agreed power of the customer installation and the short circuit power at the connection point. Some documents consider only the agreed power (e.g. FR_CURTE). Nine of the 18 documents additionally provide total voltage limits at network level, while seven documents mention also installation-specific voltage limits.

4) Reference to popular standards

The most popular documents are IEEE_519, IEC_3_6 and MC_DACH, which are all applied at least in 6 countries.

B. Method-related characteristics

1) Frequency range

13 out of 18 methods have an upper frequency limit of 2/2.5 kHz. Five methods provide also emission limits above 2/2.5 kHz, usually up to 9 kHz (e.g. DE_BDEW). Most of the documents covering frequencies up to 9 kHz apply only to generators, while documents applying to both consumers and generators are usually limited to 2/2.5 kHz. All documents define limits for harmonics whereas only 11 documents define also limits for interharmonics. No document contains limits for frequencies higher than 9 kHz yet, because emission at these frequencies (supraharmonics) is a relatively new disturbance phenomenon.

2) Summation of multiple installations

Usually the emission of different installations does not add arithmetically, mainly due to an existing diversity in harmonic phase angles. Different approaches are applied to include this into the emission limit calculation. The approaches based on a summation exponent do not require explicit information about harmonic phase angles. Six methods use the summation exponent as recommended by IEC, which varies in the range $1 \leq \alpha \leq 2$ depending on the harmonic order. Most of the methods use specific, individual recommendations for the summation exponent. Only CN_14549 follows a very detailed approach allowing also the direct inclusion of harmonic phase angles of different installations.

TABLE VII Distribution of methods regarding summation of multiple installations

a	Summation exponent (IEC recommendations)	6
b	Summation exponent (individual values)	7
c	Consideration of harmonic phase angles	1
d	No information	6

3) Allocation principle

Depending on the applied philosophy, the allowable harmonic emission of a new customer installation is allocated either based on the share of its agreed power on the available (power) connection capacity. Some of the methods do not consider the connection capacity at all. One third of the documents do not provide any information about if and how harmonic emission is shared between multiple installations. Table VIII summarizes the different practices.

TABLE VIII Distribution of methods regarding allocation principle

a	Allocation based on network capacity	7
b	Allocation based on connection point capacity	3
c	No capacity based allocation	2
d	No information	6

Many existing allocation strategies consider up to now only consuming installations, because "conventional" generators does in general not emit, but damp harmonics. With the introduction of inverter-based distributed generation this situation changes and consequently generation has to be taken into account, e.g. if connection capacity is calculated. This is already included e.g. in MC_DACH_HS.

4) Number of input parameters

The number of input parameters is directly linked to the complexity of the method. Fig. 1 presents the histogram of the distribution of the amount of input parameters.

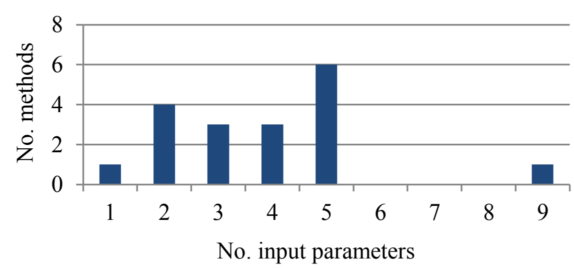

Figure 1. Distribution of amount of input parameters

The majority of the methods requires between 2 and 5 input parameters, which keeps simplicity and practicability of the methods at an acceptable level. However, CA_C2501 consists of two sub-methods and requires 9 input parameters, which results in a more difficult application. As all methods are usually applied in the planning stage, they strongly depend on the quality of the input data and the user should be aware of possible illusive accuracy.

C. Network-related characteristics

1) Impedance at connection point

The harmonic network impedance represents the link between the emitted harmonic currents and their contribution to the voltage distortion. As usually the current harmonic limits are based on assumptions about allowable contributions to the harmonic voltage levels, the accurate assessment of harmonic impedance is crucial. Table IX summarizes the different approaches and their frequency of application.

TABLE IX Distribution of methods regarding impedance at POC

a	Simplified impedance line $h{*}Z_{sc}$	4
b	Frequency-dependent network impedance	8
c	Independent from network impedance	3
d	Individual method	1
e	No information	3

The approach a. is based on the product of short circuit impedance and harmonic order. Particular in case of resonances and low X/R ratios this approach is insufficient and results in wrong impedance values. Using the "real" harmonic network impedance is most reliable, but depends particular in case of simulations strongly on the quality of the input parameters.

2) Network topology

As shown in Table X, most of the methods are applicable to all types of networks or do not provide information on any possible limitation. A few methods, particular for LV and MV networks are limited to single fed, radial networks, as this is the most commonly used topology in these networks and it simplifies the emission limit calculation considerably.

TABLE X Distribution of methods regarding impedance at POC

a	All types of networks	8
b	Radial networks with single infeed only	3
c	No information / not applicable	9

IV. Initial Quantitative Comparison

Two example installations are studied to get a first idea about the difference in the calculated emission limits between the methods. This is only an initial comparison, which shall illustrate the diversity between the methods. A more comprehensive comparison based on a probabilistic approach is in preparation.

Fig. 2 shows the example grid and the two customer installations at MV level (A) and at LV level (B). The total capacity of the networks is set to the rated power of its supply transformer. The global contribution for a particular harmonic order is calculated based on the planning levels applying a transfer coefficient of one. The harmonic impedance is

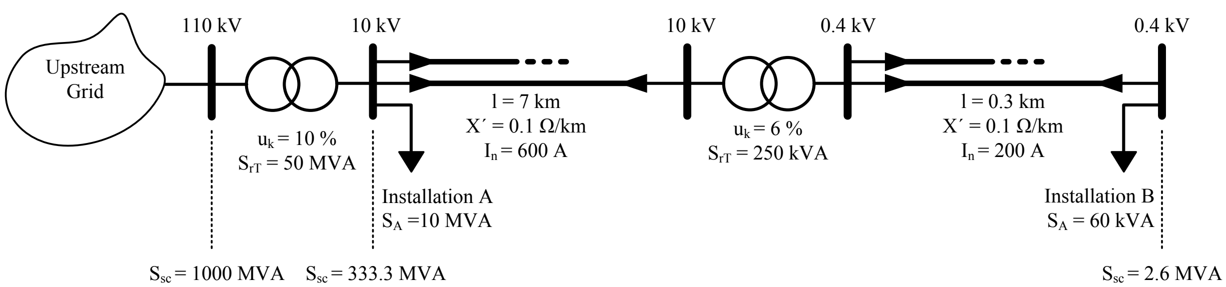

Figure 2. Example distribution network

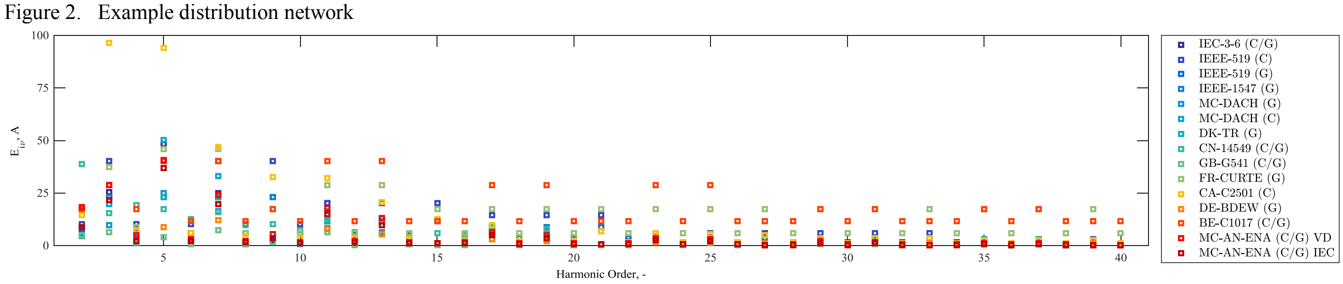

Figure 3. Absolute allocated harmonic current for customer installation A (C – consuming installation / G – generating installation)

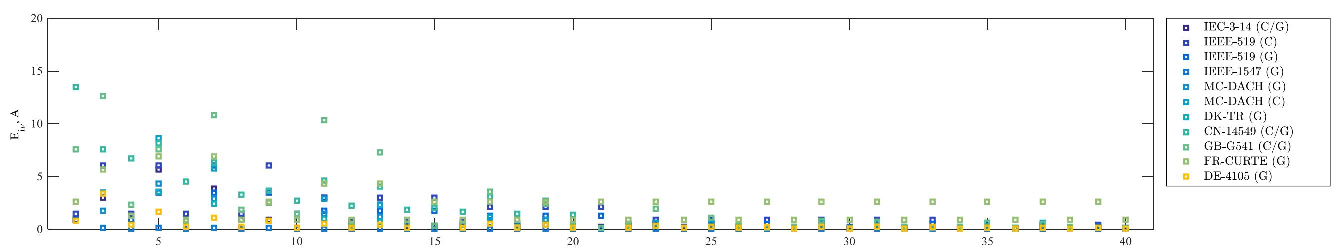

Figure 4. Absolute allocated harmonic current for customer installation B (C – consuming installation / G – generating installation)

assumed to be inductive and is calculated according to the method a. in Table IX ($h*Z_{sc}$).

The calculated harmonic current limits up to 40^{th} order are presented in Fig. 3 and 4. In case a document does not treat consuming and generating installations equal, they are considered individually. For example according to MC_DACH consuming installations (C) receive always twice the limit of generating installations (G) for similar agreed power and same point of connection. In case of equal treatment the symbol C/G is used in the legend. MC_AN_ENA is considered twice, as it provides two calculation methods: based on the IEC Standard (IEC) and based on the Voltage Droop concept (VD).

Even if the identification of each method is difficult due to the limited set of colors, the figures show that harmonic current limits largely vary between the methods and harmonic orders. The ratio between the most and less stringent value per harmonic can reach up to factor 333.

V. Conclusions

The paper presents an international survey of methodologies for the calculation of harmonic emission limits for customer installations. While some countries have very specific and detailed rules for allocating harmonic current emission limits, other countries do only provide voltage harmonic limits for the whole network or do not define any rules at all.

A qualitative comparison of methods providing individual harmonic current emission limits has shown that the differences between the methods can be significant, e.g. in the number of input parameters, the allocation principle or how the network harmonic impedance is treated. For any of the methods the quality of the input data is a crucial issue. The final accuracy of more complex methods compared to simpler ones might be only illusive as long as the necessary input data are not sufficiently reliable.

The continuous transformation in the networks results in several issues, which are not yet properly addressed in the present methodologies. In the future the determination of total connection capacity has to include in addition to consuming installations also generating and storage installations. This issue is also closely linked to the question of equal vs. non-equal treatment of the different types of installation. Due to the quickly increasing number of electronic equipment utilizing switching frequencies significantly higher than 2/2.5 kHz, the extension of the considered frequency range up to 150 kHz is required. The consideration of diversity between different installations should be extended to enable the consideration of harmonic phase angles, in case such information is available. Last but not least reliable methods to (continuously) assess the harmonic emission of a customer installation are essential in order to identify the final impact of emitted harmonic currents to the voltage distortion in the network. All aspects mentioned above should be taken into account in the ongoing activities in revising existing or developing new standards and guidelines and assessment methodologies.

The next steps within this project are a comprehensive comparison of the identified methods by probabilistic simulations and the improvement of the existing allocation methods in the German rules for network disturbance assessment. Methods for the assessment of the contribution of an individual customer installation are also considered.

Even if all the information provided in the paper has been compiled very carefully, some information might be missing or misinterpreted. Therefore any feedback in terms of missing methods or required adjustments is highly appreciated.

VI. Acknowledgment

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