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Probabilistic Assessment of the Impact of Distributed Generation and Non-linear Load on Harmonic Propagation in Power Networks

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Abstract – The paper investigates the uncertainties involved in the assessment of annual harmonic performance of a distribution network with distributed generation and non-liner loads. Considering a random variable locations and injections of harmonic sources, both generation and load, a probabilistic assessment of harmonic propagation through the network is performed. The influence of variable and diverse distributed generation in particular is clearly documented.

Keywords: Harmonics, THD, Probabilistic, Monte Carlo

I. INTRODUCTION

The voltage harmonics present in power networks are considered as one of the main power quality performance measures of those networks. In distribution networks the main continuous sources of harmonics are the traditional non-linear loads such as transformers, rotating machines and arc furnaces. More recent types of non-linear loads are the electronic devices supplied by switched-mode power supplies and the fluorescent lighting. However, the strongest impact on the distribution network harmonic performance can be expected from the increasing number of electric vehicles and power electronic interface connected distributed generators (DG) [1].

Harmonics can have negative impacts on both power system equipment and customer's equipment. Three main consequences of voltage distortion [1] are thermal stress, insulation stress and load disruption. The thermal stress is due to the increased losses and the presence of the triple harmonics in neutral current, even for a balanced source. The insulation stress is caused by the increase of the peak voltage due to harmonics which leads to reduced life time of the insulators. The load disruption usually occurs with sensitive loads which are designed to operate under nearly pure sinusoidal voltage, or with the loads that depend on the zero crossing of the wave; examples of these loads are the communication equipment and the electronic clocks. Also, the harmonics presence in the networks can cause telephone interference (high harmonic orders in particular), mal-operation of protection devices and switchgears, problems in the metering and instrumentation, and damage of capacitors and cables under resonance conditions [2].

The general aims of harmonic studies are to analyze the network under different frequencies and to identify the extent of the presence of higher harmonics in supply voltage and also to identify the resonance frequencies, if any, for a network. Different models were developed to perform harmonic analysis of networks in the past [3]. The most common model used involves modelling the non-linearity of the load by a current source for each frequency. This method gives about 10% accuracy in the voltage distortion [2]. In general the models used in a harmonic study depend on the purpose of the study, the amount and the period of the data collected and the accuracy level needed [3]. Probabilistic models that can take into account operating mode and multiple switching operation uncertainties were developed in [4]. Other stochastic harmonic load models were developed in [5] where the uncertainties considered were loading conditions, load compositions and aggregate harmonic load parameters. The impact of the DG on the harmonic performance was investigated in [6], focusing mainly on the interaction between the grid and the DG inverters' harmonics.

The uncertainty of the output of the DG (and consequently their potentially different harmonic contribution) as well as the possibility of variable locations of harmonic sources (both DG and electric vehicles) must be included in assessment of harmonic performance of a network as it may vary significantly during the year. Therefore, longer periods of evaluation and probabilistic modelling of harmonic sources is necessary to assess the influence of the spatial and temporal variation of stochastic/intermittent generation and load on harmonic propagation. These however, have not been comprehensively addressed in the past.

This paper presents a probabilistic methodology to model and study harmonic propagation through the power network over specified time period. The uncertainties considered include the harmonic injections from diverse, but fixed location sources (renewable generation, i.e., wind, PV and other converter connected generation) and from variable location sources, e.g., non-linear loads, electric vehicles (EV), etc.. Furthermore, these two are combined with harmonic generation by non-linear loads considering their daily and annual variation in harmonic output. The total voltage harmonic distortion (THD_V) is used as the main performance measure. The variation in harmonic performance of the network during the year is clearly demonstrated on a 295 bus generic distribution network case study.

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II. MEASUREMENT OF HARMONICS AND PRESENTATION OF RESULTS

Statistical measurements of harmonics have been performed and practically applied since 1985 [7]. The authors of [7] emphasized the importance of the statistical analysis of harmonics, they indicated that harmonics are a stochastic phenomenon which requires measurements throughout a sufficient period, normally seven days covering weekend and weekday. Also for the power quality assessment for a certain location, it is only logical to perform a statistical comparison between the network performance and the predefined limits or compatibility levels [7].

The IEC 61000.3.6, harmonic limit standard for MV and LV system recommends that the evaluation of the emission should be performed statistically, to take into account the time variation of the phenomenon. It is a common practice to take harmonic measurements for at least one week, and to compare the 95th percentile of the measured THD with the planning values specified in relevant standard. Based on that comparison the utility could get penalized if the limit is exceeded [8]. However, a recent survey performed by ERGEG with different types of respondents (utilities, academia, research centers) stated that most of the respondents agreed that “95%-of-time” clause should be avoided and the limits should be applied for 100% of the time, to have a more efficient and transparent voltage quality limits. The report also indicates that 5% of a week is 8.4 hours, which is a long time to have voltage quality phenomena that exceed standards limits [9]. As per the IEEE 519 standard [2] if the harmonics are fluctuating with time, i.e., the harmonic sources are time dependent, the harmonic analysis must be done over a period of time. The period of study (or data collection) T_D must be divided into intervals m and a number of measurements k must be taken in each interval T, ($T_D=mT$) the mean value of the current is given by (1)

$$I_{mean}=\sum_{1}^{k}\frac{I_{kh}}{k} \tag{1}$$

In [5] the day was divided into two intervals, day and night time, taking 15 measurements from different types of loads in each interval and representing the results (THD_C and THD_V) statistically on histograms and PDFs. (The PDFs have the advantage of clearly showing the minimum and maximum values of a sample.) Another study was performed in [10] taking measurements from two sights for a 6 hours period with a 1 minute intervals and again the results (THD_C and THD_V) were presented statistically on histograms and CDFs. The advantage of CDFs is that they show the percentage of the time (from the study period) the THD will be below a certain value, however, the probability of the maximum THD values, which could be critical for some purposes, is missed. It is worth mentioning that the recommended methods for the presentation of the results of harmonic studies/measurements, as per the IEEE standards, are harmonic spectrum tables, harmonic spectrum bar charts, PDF and CDF [2]. All the methods discussed above are effective to perform harmonic analysis in the networks with non-linear loads that can be represented by a daily loading curve or for the study of a certain load with a repetitive cycle and known harmonic spectra.

III. TEST SYSTEM AND MODELLING OF HARMONIC SOURCES

A. *Test Network*

The test network used in these studies is the 295 bus Generic Distribution Network (GDN). The network parameters are based on realistic UK distribution network parameters [11, 12]. The network is consists of 295 buses, 276 branches (overhead lines and cables), and 37 transformers with various winding connections. The network comprises five 400 kV buses, and four 275 kV buses (transmission level connection points) a sub-transmission level of twenty-three 132 kV buses and twenty-five 33 kV buses, and a distribution level of 233 buses of 11 kV level and four 0.4 kV buses. Detailed description and parameters of the test network can be found on [13]. Although the harmonic evaluation in this study is performed for the 11 kV buses only, the non-linear loads are connected to buses at different voltage levels.

B. *Load*

The loads were divided into three types, industrial, commercial and domestic. 147 buses have a combination of 80% domestic and 20% commercial load, and 3 buses are dedicated as industrial loads only. Annual hourly loading curves were extracted from 2010 survey of different types of loads, and applied to each load in the network. Corresponding to each type of load annual load duration curve (LDC) was produced, three in total. The LDCs were divided into 11 segments; the 1% peak period of the year (88 hours), then 9% segment (788 hours), and the remaining 9 segments with 10% of the year each (876 hours). The median of each segment was taken as representative loading for the whole segment, and the corresponding hour was taken as a test point for simulation (33 testing points; 11 per LDC), see Fig. 1.

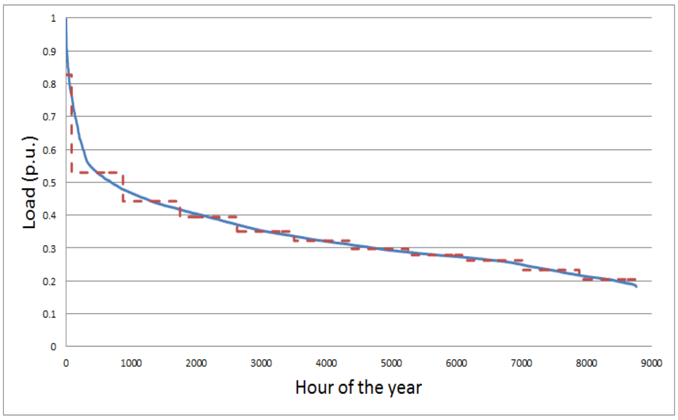


Fig. 1. The LDC for domestic load, continuous (blue, solid), piecewise (red, dotted)

For example the median of the first segment of the curve (Fig. 1) is the 44th hour, which corresponds to domestic loading of 0.827 p.u. (this loading actually occurs in the 5635th hour of the year, i.e., 18:00 on a Monday of 2010). At that hour the commercial and industrial loads are at 0.522 p.u. and

0.623 p.u. of their peak, respectively. Also for the Commercial LDC the peak segment is represented by the 44th hour which has a p.u. value of 0.894 of the peak (5510^{th} hour of the year, i.e., 13:00 on a Wednesday) which corresponds to domestic loads at 0.53 p.u. and industrial load of 0.877 p.u. of the peak loading, respectively. The same testing hours selection was applied to the industrial LDC. This testing hours selection from separate LDCs was adopted to account for the effect of different types of loads on the harmonic injections. In selecting the test points from the LDCs, it was ensured that they include weekdays and weekends, days and nights.

Based on [4] the non-linearity of the loads in the network can vary depending on the rating and the operating condition. Some loads have steady harmonic performance (fluorescent lamps), some loads can vary deterministically (battery chargers), and some can perform randomly (arc welders). Four categories of non-linear loads can be considered in the probabilistic study of harmonics [4];

- constant number of known injections loads;
- random number of known injections loads;
- constant number of random injections loads;
- random number of random injections loads.

The study presented in the paper focuses on the third category, however, although the number of loads is kept constant the locations are varied randomly.

The Monte Carlo simulations adopted in this paper are based on random values of the amplitude and angle of each non-linear load injection, as it will be detailed in Section IV. These random values are selected from uniformly distributed ranges. The selection of uniform distribution was based on several past reports [8, 14, 15]. Four harmonic spectra are used for the selected loads. The uniformly distributed ranges of these spectra were adopted, with slight modification, from [16], see Table I. These values were obtained from harmonic current measurements for medium THD_I loads dominated by the 3rd, 5th, 7th and 9th harmonic currents, e.g., personal computers, TV set, fluorescent lamps etc. [16]. This type of harmonic spectra was used for domestic and commercial non-linear loads. For the industrial loads, e.g., three-phase adjustable speed drives, the harmonic spectra is mainly dominated by 3rd, 5th, 7th and 11th harmonics, Table I [16].

TABLE I: Harmonic current spectra amplitude ranges of non-linear loads (adopted with modifications from [16])

Harmonic order	Type 1 (Domestic and Commercial)	Type 2 (Industrial)
1	100%	100%
3	0-69%	0-4.7%
5	0-48%	0-32%
7	0-28%	0-16%
9	0-27%	0%
11	0%	0-6.5%

C. Distributed Generators

The DGs were connected at twelve different buses. The buses were chosen to cover all different locations which might have effects on the performance of the network, i.e., at the start of a feeder (close to the MV/LV sub-station), at the middle of a feeder and at the end of a feeder. The maximum DG penetration in the year occurs at a point when the DG generation covers 24.45% of the real load (31.3 MW out of 128 MW total load), all DGs work at unity power factor. In this study reverse injection, voltage control, output curtailment or hosting capacity problems are not considered as the main scope of this study is to measure the harmonics phenomenon caused or influenced by the DG. Three types of DGs were considered, wind generators, photovoltaic and fuel cells. The wind generators were modelled as three phase asynchronous generators of DFIG type with max output of 0.6 p.u. based on their full capacity. The fuel cell and photovoltaic generators were modelled as single phase static generators connected via 6 pulse converters. The wind and photovoltaic generators have an annual hourly output curves, extracted from realistic outputs data based on the UK weather [17, 18] (the maximum output of these two types of DGs is at different times of the year) while the fuel cells were assumed to have a constant output. The wind generators (two in total) have maximum outputs of 2.5 and 5 MW, the five PV generators have maximum outputs that range from 1 to 5 MW (total maximum 15MW), and the five fuel cells have a constant output of 2.82 MW in total. There are, in total, 12 fixed locations with DG in the network (see Fig. 6).

The harmonic spectra of the wind generators were extracted from [19], Table II. The spectra of the PV and fuel cells can be calculated from the theoretical formula in (2),

$$I_{hp.u.} \approx \frac{1}{h} \tag{2}$$

but due to the smoothing effect of commutation the practical values could be less than the theoretical values [1]. The 6 pulse converter has the harmonic order of 6n ± 1 where n=1, 2, 3… the first four harmonic orders were considered with the ranges shown in Table II, these values are obtained from real PV and storage inverters with current harmonic injection limit that follows the EN 61000-3-2 standard [20], the ranges considered were up to 50% of the ratio I_h/I_{h_limit} recorded in [20] to account for natural harmonic cancellation due to multiple inverters connected at different locations but to a same phase.

TABLE II: Harmonic current spectra amplitude ranges of DG

Harmonic order	Wind Gen.	PV	Fuel Cells
1	100%	100%	100%
5	0-1.9%	0-0.1%	0-0.05%
7	0-0.4%	0-0.1%	0-0.1%
11	0-0.1%	0-0.2%	0-0.15%
13	0-0.1%	0-0.3%	0-0.2%

D. Harmonic Sources

The non-linear loads and static generators were modelled as current sources injecting harmonic currents as a ratio of the fundamental current. The probabilistic ranges of harmonic injections of each source were applied and MC simulations performed to account for the uncertainties resulting from the variable non-linear portions of the selected loads and variable switching frequency of converters.

IV. METHODOLOGY

All simulations were performed using DIgSILENT PowerFactory (v15.0.1). In all simulations the sources, DGs and 20 randomly selected loads, were modelled as harmonic current sources. Each harmonic current injection (magnitude and angle), for each phase, were varied randomly with uniform distribution within given range using Monte Carlo (MC) simulations. The ranges were determined based on the documented harmonic performance of different types of DG and different types of non-linear load (see Table I and Table II). The angles range was always (0-180) degrees for all harmonic sources. Thus, a single harmonic simulation is performed by injecting random values of harmonic currents from 12 fixed (DG) and 20 randomly selected harmonic sources in the network (loads). Harmonic load flow was run and THD per phase for each bus was calculated. Although the impedance frequency dependencies can be modelled in DIgSILENT PowerFactory, as polynomials of any degree, this function was disabled in simulations to reduce the computational burden. All 32 harmonic sources inject random harmonics in the network in every simulation, however, the location of 20 harmonic generating loads changes every hour. The loading curves were segmented to identify different loading points; fifty iterations per 10% segments, five per the 1% segments and 45 per the 9% segments were performed and for three different LDC per load type. This yields a sample size of 1500, *i.e., 3x5 (for the 1st peaks) plus 3x45 (for the 2nd peaks) plus 3x9x50 (for the remaining segments)* values of THD per phase per bus for the whole year.

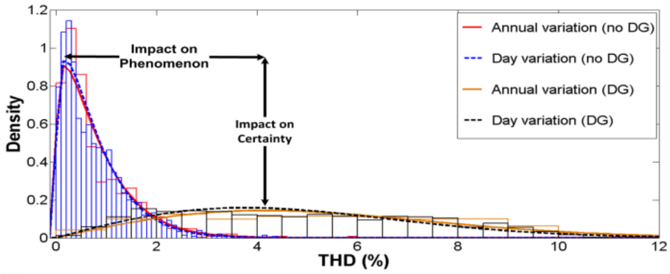
The other assessment method used was hour-by-hour harmonic injection for a single day with the same models of DGs and non-linear loads as in the annual simulations method. A summer day (high PV output) was selected and the simulations were run for the 24 hours of that day with the same number of iterations per hour. This assessment method was used in order to compare the annual performance and the daily performance of a bus and the effect of seasonality on the bus harmonic performance. Depending on the location and the load type at the bus, some buses showed the same harmonic performance for annual and daily load variation.

Based on these simulations the mean value of THD and corresponding standard deviation for each bus were calculated throughout the year. The simulations were run for the case with and without DGs connected to the network

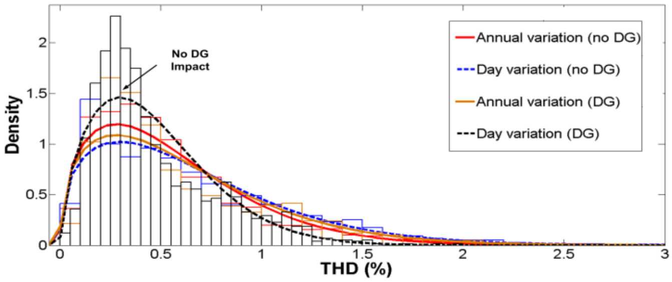
V. RESULTS OF SIMULATIONS

From the MC simulations, four samples of THD results were collected for each phase of each bus. These include annual harmonic performance with and without DGs, and daily harmonic performance with and without DGs. From the histograms of the samples of results obtained in simulations it was observed that the histograms without DGs are not normally distributed, same as in [7] where results of real measurements were presented. The histograms of the results with DG for majority of the buses are more symmetrical around the mean value, i.e. normally distributed. Weibull distributions were, therefore, used to fit the data as they have the flexibility of representing both, the skewed and symmetrical data samples.

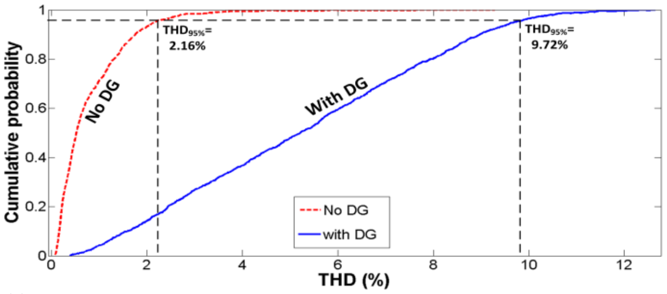
Fig. 2(a) shows the PDFs of the THD_V for phase A of bus 196 for four scenarios. The impacts of DGs on harmonic performance of the bus can be clearly seen. Fig. 2(b) shows PDFs of THD_V of phase A of bus 229 where the impact of the DG is negligible. Fig. 3 shows CDFs of THD_V of the same buses (only annual variation showed).



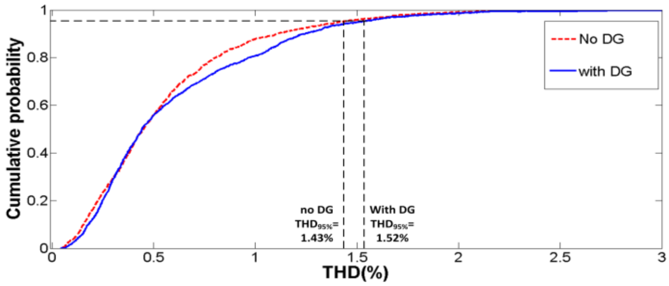
(a) Bus 196



(b) Bus 229
Fig. 2. Daily/Annual THD PDF of phase A for the buses (a) 196 (b) 229



(a) Bus 196



(b) Bus 229
Fig. 3. Daily/Annual THD CDF of phase A for the buses (a) 196 (b) 229

It can be seen from Fig. 3 that the 95th percentile of the samples for bus 196 exceeds the standard specified limits of 5% and 8% for the IEEE and IEC standards, respectively. It should be mentioned though that this measure is usually applied for shorter period of study with higher resolution of measurements (e.g. for 1 week with 3 minutes intervals of measurements [21]). Therefore, the comparison among the buses was performed taking the mean value of harmonic distortion as a measure instead.

Before the connection of the DGs, the worst affected buses in terms of average THD during the year were 137, 138, 136, 135, 134, 133, 132, 130, 129 and 131. The mean value of THD ranged between 0.95% and 0.82% and the standard deviation between 1.13% and 0.88% for the three phases of the worst affected buses. As the network was fully balanced before introducing the single phase DGs, a very small difference in harmonic performance of different phases was observed in spite of harmonic injection by randomly distributed non-linear three phase loads.

TABLE III. The most affected buses harmonic performance

(a) Phase A

bus	**μ**	**σ**	**max**	**range**
196	5.250	2.751	12.645	12.269
178	5.230	2.747	12.600	12.233
177	5.227	2.745	12.591	12.224
176	5.221	2.742	12.579	12.212
175	5.205	2.733	12.541	12.175
174	5.196	2.728	12.519	12.153
173	5.192	2.726	12.510	12.144
209	5.192	2.723	12.509	12.140
208	5.192	2.723	12.509	12.139
207	5.192	2.723	12.508	12.139

(b) Phase B

bus	**μ**	**σ**	**max**	**range**
136	5.680	1.685	10.577	10.440
137	5.585	1.674	10.527	10.393
138	5.585	1.674	10.527	10.393
135	5.571	1.651	10.360	10.226
134	5.484	1.620	10.161	10.030
133	5.228	1.532	9.621	9.498
132	5.075	1.481	9.336	9.219
130	4.914	1.427	9.039	8.926
129	4.914	1.427	9.039	8.926
131	4.914	1.427	9.038	8.926

(c) Phase C

bus	**μ**	**σ**	**max**	**range**
225	3.703	2.242	13.347	13.166
77	3.693	2.231	13.254	13.072
152	3.656	2.209	13.182	12.982
151	3.656	2.209	13.182	12.982
232	3.640	2.193	13.008	12.828
224	3.628	2.186	12.963	12.782
150	3.592	2.163	12.905	12.697
149	3.592	2.163	12.904	12.697
148	3.501	2.099	12.497	12.284
147	3.501	2.099	12.496	12.283

Table 3 (a), (b) and (c) show the mean, standard deviation, maximum value and the range of harmonics, for the three phases of the ten worst affected buses (in terms of THD), after the connection of the DGs. From these tables another negative impact of the DGs (specially the single phase DG) on the harmonic performance can be easily noticed, i.e., different harmonic distortion in different phases. The worst affected buses, in each phase, following connection of DGs are 196, 136 and 225, for phases A, B and C respectively. The mean values of THD for ten most affected buses range from 3.5% to 5.68%, and the standard deviation ranges from 1.43% to 2.75%. There is a noticeable increase in mean values of THD compared to the network without DGs. The first (bus 196) has domestic and commercial loads connected and the latter two have only industrial loads connected. Single phase DGs are connected to all three buses, but interestingly not to the worst performing phase. Bus 196 has the largest harmonic distortion in phase A, yet the DG is connected to phase C. This demonstrates that harmonic performance will not depend only on the proximity to the sources but also on harmonic propagation from distant sources depending on the impedances of the network at different frequencies. Fig. 4 shows the average and 95th percentiles of THD values for Phase B (the worst performing phase) for the 11 kV buses. Four curves were plotted to show the annual variation average before and after the connection of the DGs and the annual variation 95th percentiles before and after the connection of the DGs. The negative impact of the DGs connection can be clearly noted for the group of buses (129-232) where a jump in the 95th percentiles from around 3% up to more than 13% was recorded, also the average THD increased from about 0.8% to about 4.5% reaching more than 5% for some buses. On the other hand some buses showed better performance following the connection of the DGs. Bus groups (1-11), (29-36) and (55-73) had THD 95th percentiles values higher than 3% prior the connection of DGs which were reduced to around 1.7% following the connection of the DGs, also for the same group of buses a slight improvement on the average THD was recorded.

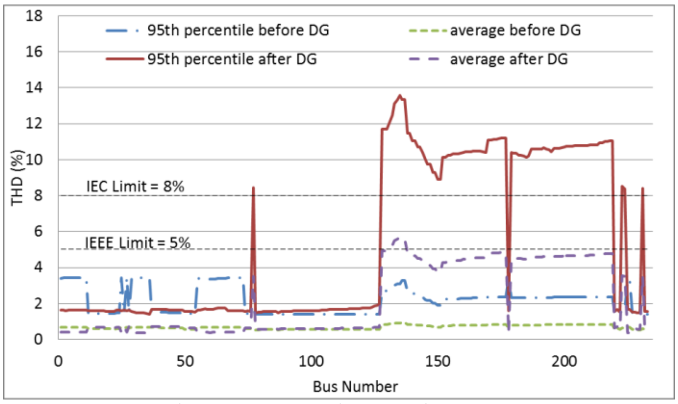


Fig. 4. THD results for all the buses before and after DGs connection

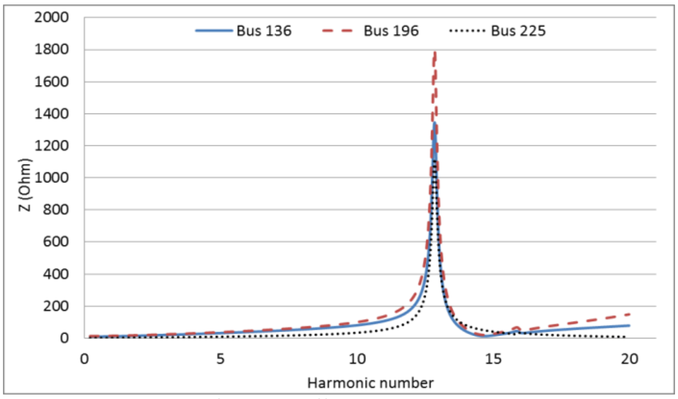
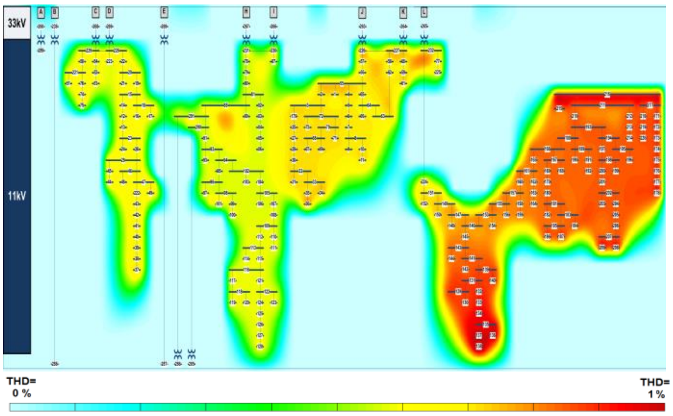
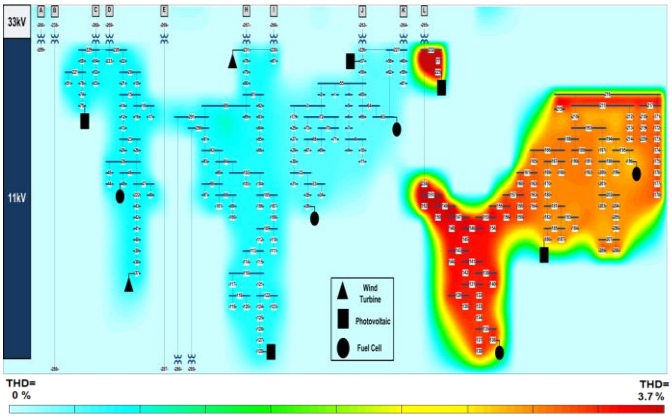


Fig. 5. Frequency scan of the most effected buses

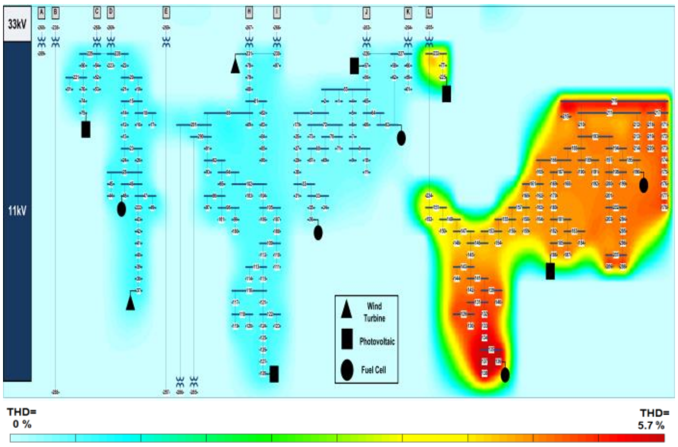
The observed high values of THD at some of the buses following connection of DGs caused further investigation into the cause of this. A frequency scan for the most affected buses is shown in Fig. 5. The figure shows harmonic resonance conditions near the thirteenth harmonic, which did not cause a problem in the system before the connection of the DGs as there were no harmonic sources injecting thirteenth harmonic. This explains the high values of THDs as well as the importance of performing thorough harmonic studies in the network prior to connection of DGs.



(a) Harmonic performance without DGs (max THD = 1%)



(b) Harmonic performance of the least affected phase following DG connection (max THD = 3.7%)



(c) Harmonic performance of the most affected phase following DG connections (max THD = 5.7%)

Fig. 6. Heat Maps identifying the most affected areas before and after DG connections

Fig. 6 (a), (b) and (c) show the most affected areas using heat maps. Fig. 6 (a) shows the affected areas of the network before the connection of the DGs based on average THD (all three phases). The colour code ranges between 0% average THD (blue) and 1% average THD (red). Fig. 6 (b) and 6 (c) show the affected areas following the connection of the DGs for the best performing phase (Phase C) and the worst performing phase (Phase B), respectively. Note that the scale for colour coding in these three figures is different due to different THD values.

It can be seen from Fig. 6 (a), before the connection of the DGs, that all the 11 kV buses have very similar performance, the average THD ranged between 0.5% and 1%, yet Substation L (the utmost right substation at the top of Fig. 6 to which all the busses in the right hand side of the figure are connected) has the most affected buses. This area contains the three industrial loads and a high number of commercial and domestic load buses. Following the connection of the DGs the area connected to Substation L was still the most affected area, the THD in this case however, ranged from 2.8% up to 3.7% for Phase C (Fig. 6 (b)), while in the rest of the network the maximum average THD was 0.7%. Similar performance can be seen for the most affected phase in this case, phase B (Fig. 6 (c)) though the THD in this case is higher and ranged from 3.5% to 5.7% while the maximum average THD for buses connected to other substations was 0.7%.

VI. CONCLUSION

The paper presented results of initial studies of harmonic propagation in distribution networks with multiple distributed generators and non-linear loads. A Monte Carlo simulation was used to account for uncertainty in harmonic generation by different DG types and different non-linear loads. The variability in DG harmonic generation due to different operating principles of different types of DG was taken into account as well as variation in both location and harmonic generation of non-linear loads. The assessment was performed for two time frames, a 24 hour period and a whole year.

The results of the study showed that distributed generation (single phase generation in particular) could contribute significantly to the increase of harmonics in the network (beyond standard specified limits) in spite of reasonably small harmonic generation by individual DGs.

The increase of harmonic levels (measured by THD in this study) is not confined to location of DGs. Quite contrary, the most affected areas are those where DG harmonic contribution combines with existing contribution of non-linear loads or where harmonic injections by DGs resulted in harmonic resonance. The overall effect of DGs seems to be the increase of harmonic levels across the network and in particular in the areas which are already exposed to higher harmonics due to the presence of non-linear loads. Furthermore, the presence of DGs increases the range of THD that can be observed in the network (higher standard deviation of PDF), i.e., increases the uncertainty of expected THD.

The study clearly demonstrates that the impact of DG on harmonic levels in the network need to be studied by considering different types of both, DGs and non-linear loads and different operating conditions during the year. Considering the estimated increase of THD in this study due to the operation of DGs it is essential to use as realistic parameters (harmonic injection levels) as possible for both DGs and non-linear loads. Due to high variability of the types and locations of DGs and non-linear loads (loads can change location during the day, e.g., electric vehicles and DGs effectively change location by for example not operating during part of the day/night even though they remain connected at the same bus) and operating conditions during the year the probabilistic studies are inevitable. These studies will enable robust estimation of harmonic levels in the network, identify the worst performing areas and facilitate development of appropriate mitigating solutions. The long term harmonic measurements are needed though to finely tune the parameters used in simulations and to ensure accurate numerical results. If these measurements are available the methodology can be further used to estimate the maximum DG penetration and the critical locations of DG from the point of view of harmonic limit violations.

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