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Influence of Transformer Rating on Power Quality Indices in Low Voltage Residential Networks

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***Abstract*—This paper proposes a methodology to assess the influence of transformer rated power on the power quality indices at low voltage residential networks. Taking into account the stochastic nature of residential loads and the possibility of photovoltaic generation, a Monte-Carlo simulation is performed in order to account for the probabilistic aspects of the problem.**

In this work, different transformer ratings are simulated and the effect on power quality parameters, such as voltage unbalance and voltage total harmonic distortion (THD), is calculated under probabilistic basis. These power quality indices are compared to the compliance limits proposed in standard EN50160.

The work proposed in this paper allows predicting power quality affection caused by changes in the ratio between transformer rated power and network aggregated demand, as well as establishing general conclusions regarding desirable transformer size in order to not to exceed power quality limits.

***Index Terms*—Distribution Transformer, EN50160, Power Quality, Probabilistic Assessment, Residential Network, THD, Unbalance.**

I. INTRODUCTION

The next generation grid is very different from the grid of today and the past. Nowadays, and even more in the future, power comes from distributed sources that are frequently integrated in the network by means of electronic converters, such as photovoltaic generation (PV). On the load side, there is an increasing use of power electronics-based loads with non-traditional consumption patterns [1]. In this scenario, there is a potential threat that power quality (PQ) can be degraded by the mass adoption of these new technologies [2]. For instance, harmonics are one of the most concerning disturbances in residential networks since power electronic based devices connected in domestic environments produce non sinusoidal currents [1]. On the other hand, residential loads also involve high level of uncertainties as well as PV generation which is characterized by a stochastic behaviour. Consequently, in order to assess the impact of these technologies, deterministic formulations are not representative of the true performance of the distribution system and the uncertainty associated with input data must be accounted for [3]. This paper aims to evaluate PQ voltage levels of future distribution networks with increasing participation of nonlinear loads and PV distributed generation by using a probabilistic approach in order to take into account the uncertainties related to the random performance and allocation of loads and PV generation. This work allows predicting the impact on power quality caused by changes in transformer rated power and network aggregated demand ratio, as well as establishing general conclusions regarding desirable transformer size in order to not to exceed power quality limits established in standard EN50160 [4].

Very frequently, power quality assessment in distribution networks has been analyzed in a deterministic way [5], [6]. In [7], [8], a probabilistic study of low voltage networks is proposed but PQ disturbances are not considered. Harmonic distortion is analyzed probabilisticaly in [9]–[12] but the effect of transformer rating on the obtained results is not analysed.

The method proposed here focuses on the probabilistic assessment of harmonic voltage distortion for a Low Voltage (LV) residential distribution network. The transformer rating is a key aspect on the levels of PQ indices and, therefore, it has a definitive impact on the compliance of PQ limits.

The methodology proposed in this work can be extended for assessing the impact of other technologies that may degrade power quality and even for different power quality disturbances.

II. METHODOLOGY

In order to take into account the uncertain behaviour of devices connected to distribution network, a probabilistic approach based on Monte Carlo method is used for the assessment of PQ impact. Output results are compared to the limits specified in international standards and, in particular, in standard EN50160 [4].

The applied methodology is described in the following subsections.

A. Residential Loads Profiles and PV generation

Stochastic Residential weekly demand and PV generation are simulated with the tool provided in [13], based on Markov chains [14]. This tool generates stochastic active power profiles

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from a certain number of dwellings by computing load demand of typical domestic devices and statistics on their use. Profiles depend on number of occupants per residence, meteorological data or building size, among others.

Standard EN50160 requires a resolution of 10 minutes, so the power demand and generation estimated with [13] is averaged to meet this condition [9].

The number of occupants per residence required by the model in order to generate domestic demand curves is extracted from Spanish statistics and forecasts [15] for 2030.

In order to randomize the process, a set of 100 weekly load profiles have been generated for three occupancy levels (few, many and average occupants) and for winter period where demand is higher and PQ disturbances can reach higher severity levels [9]. An example of a residential load curve is shown in Fig. 1 for a randomly selected week of the pool. According to the simulated occupancy level, in each simulation a weekly load profile from the appropriate pool is randomly selected for each residence.

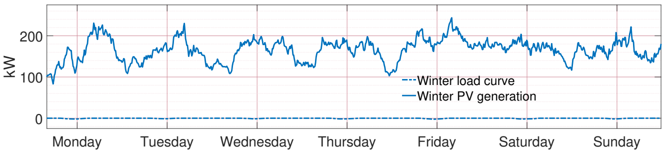

Fig. 1. Mean weekly aggregated load and PV generation profile for 55 residences.

B. Harmonic Analysis

By 2030, 60% of residential loads are supposed to be nonlinear [1]. In this work, the harmonic emission of non linear loads is estimated by means of [3], [16]. According to this approach, harmonic spectrum of aggregated residential profiles follows a distribution with two load types (loads type a and loads type b) whose participation in the total load is obtained from a normal distribution with mean and typical standard deviation that vary depending on the time of the day as shown in Table I. Table II shows the limit interval values for uniform probability distribution of the harmonic magnitude and phase of both types of loads.

TABLE I
WEIGHTED CONTRIBUTION OF EACH OF THE HARMONIC TYPE [3]

Period (hrs)	f_a		f_b	
	μ	σ	μ	σ
8:00 - 18:00	0.1	0.03	0.9	0.3
18:00 - 8:00	0.6	0.2	0.4	0.12

PV harmonic emission has been modelled according to harmonic spectrum provided in [17].

For the voltage harmonic assessment, residential loads and PV devices are modelled as constant P and Q for the fundamental frequency. Loads at harmonic frequencies are modelled as Norton equivalent, as proposed in [18] and [19].

TABLE II
HARMONIC SPECTRUM FOR RESIDENTIAL LOADS [3]

Harmonic current spectrum for residential loads			
Harmonic order		Type a	Type b
3^{rd}	Mag [%]	10 - 20	50 - 70
	Phase [°]	230 - 290	120 - 180
5^{th}	Mag [%]	5 - 10	40 - 60
	Phase [°]	90 - 150	200 - 260
7^{th}	Mag [%]	2 - 4	30 - 40
	Phase [°]	40 - (-10)	200 - 260

C. Methodology for PQ Assessment

The process to assess PQ follows the following steps:

1) Generation of weekly stochastic power demand profiles for residential loads.
2) Random allocation of load profiles to network buses.
3) Calculation of PV generated power profile.
4) Assessment of unbalance and voltage harmonic levels obtained by means of harmonic injection caused by nonlinear loads and PV generation.
5) Calculation of PQ indices according to EN50160.
6) Steps 2) - 5) are repeated numerous times in the Monte Carlo simulation in order to get probabilistic assessment of PQ harmonic indices. In this study, 160 simulations have been performed.

In addition, this process has been performed for several scenarios with different values of rated power of the main substation transformer in order to assess the influence of this parameter on PQ levels.

D. Simulation Characteristics

As it has been previously explained, 160 weeks have been simulated for each value of selected transformer rated power. Each simulation consists on a power flow and a harmonic propagation analysis, both performed with the power system simulator OpenDSS [20]. This tool is a distribution system simulators suitable for studies like performed here. Besides this, OpenDSS allows interaction with Matlab, where random input data, control of different simulations in Monte-Carlo methodology and result acquisition and analyse has been done.

III. SIMULATION FRAMEWORK

This study is applied to IEEE European low voltage (LV) test feeder [21]. IEEE European LV test feeder represents a distribution system and is based on European typical distribution grids. This means that it has fundamental frequency of 50 Hz and a radial configuration, as shown in the simplified one-line diagram in Fig. 2. The network is composed of 906 buses and 55 single-phase residential loads, allocated to a phase of the system. Each load represents an individual domestic consumer.

The feeder is connected to medium voltage by a Dy 800 kVA transformer substation that steps the voltage down from 11 kV to 416 V. This transformer is over-rated when compared to power demand of the specified loads, . The average aggregated power of the loads is 64 kVA according to the network

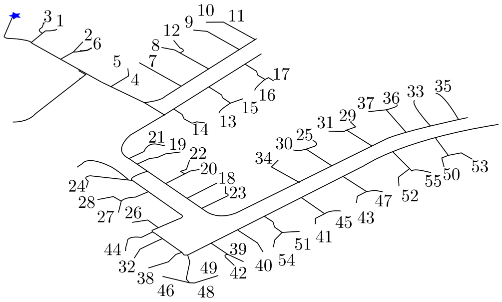

Fig. 2. One-line diagram of the LV European test feeder.

specifications. In this paper, demand power is obtained for each week as described in section II-A. Fig. 3 shows the frequency distribution of demanded aggregated power in all the simulated weeks. The mean value of aggregated apparent power is 182.5 kVA, and 90% of demanded power values are between 120.9 and 233.8 kVA.

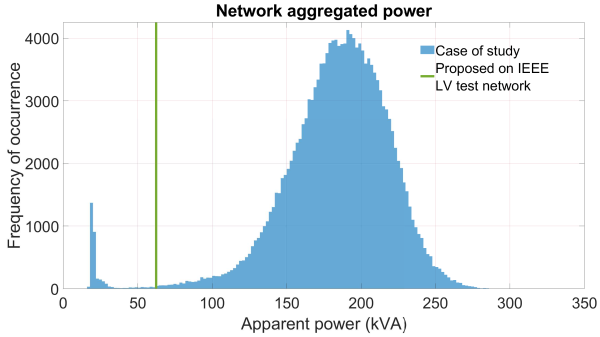

Fig. 3. Aggregated apparent power demand for residences in network.

IV. RESULTS

The simulations carried out allow obtaining the voltage at fundamental frequency and at harmonic frequencies for all network buses and for each 10 minutes interval of every simulated week, that is, 1008 values are obtained per week. With these values, the 95^{th} percentiles of each week can be calculated and compared with EN50160 stated limits. Since 160 weeks are simulated, compliance with standard thresholds can be established under probabilistic basis. This process has been repeated for different rated power values of the main transformer, ranging between 80 and 800 kVA (in steps of 10% rated power) in order to assess the influence of this parameter.

A. Unbalance

Unbalance problems appear when a residential consumer experiences voltage unbalance levels that exceed the established limit, in this case, when the unbalance ratio at its connection point is over 2% during more than 5% of the time of the week. Figure 4 shows the boxplot with the percentage of clients of the whole network that experience unbalance problems in the simulated weeks when different transformer ratings are assumed for the main transformer of the feeder. In the lower horizontal axis the kVA rating of the transformer is shown while the upper horizontal axis shows the ratio between the transformer rating and the mean demanded power. As it can be seen, when transformer rated power is slightly above average demand ($S_{transformer}/S_{demanded} = 1.36$) the percentage of clients with problems starts to be a matter of concern.

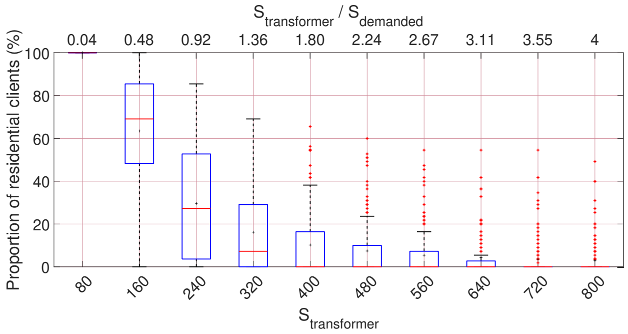

Fig. 4. Number of clients suffering from unbalance problems with different transformer ratings.

The assessment of the percentage of clients suffering from unbalance problems can hide the real variation of unbalance levels with transformer rating, because all values above the limit are considered as an exceedance problem without consideration of their severity. To overcome this limitation of the analysis, Fig. 5 shows the mean, maximum, minimum and median value of 95^{th} percentile of unbalance at the farthest bus from substation (bus 53), considering the 160 simulated weeks. In this figure, a strong elbow can be seen around $S_{transformer}/S_{demanded} = 0.92$. Decreasing transformer power rating below this value produces a severe increase in the unbalance levels. In any case, in all simulations percentile 95^{th} is above limits at some weeks.

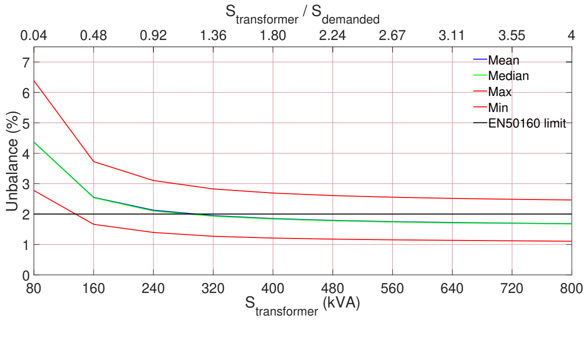

Fig. 5. 95^{th} percentile of unbalance at bus 53.

Considering 160 simulations for each transformer rating provides a close estimation of the range of variability of reality, as Monte-Carlo method assumes. Therefore, the probability of exceeding standard limits in a certain week can be addressed. This result is showed in Fig. 6 for unbalance. The same elbow as the one shown in previous figure is depicted here, indicating that a reduction of the transformer rating below the average demanded power almost triplicates the probability of unbalance problems.

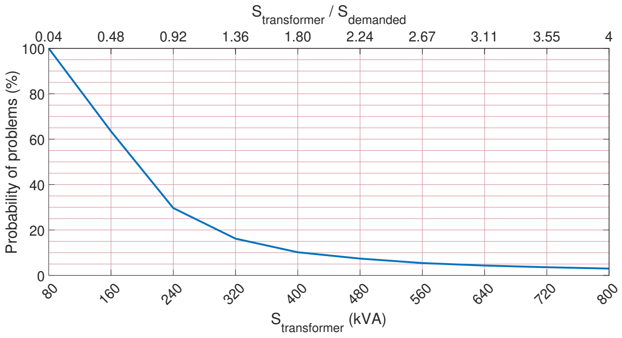

Fig. 6. Probability of unbalance problems for different transformer ratings.

B. Harmonics

A similar assessment can be done for voltage harmonics. In this case, the analysis is focused on THD, whose limit is established in 8% by EN50160. In Fig. 7 the number of clients experiencing THD problems is plotted for different transformer rated powers. That is, the figure shows the percentage of clients with THD over 8% during more than 5% of the time in the simulated weeks. Results on the two smallest transformers simulated (80 and 160 kVA) show that all clients experience THD values over the limit in all the weeks. Again, looking only at the number of clients with problems might be masking details on the extent of the severity.

In Fig. 8, the maximum, minimum, mean and median 95^{th} THD percentile values are shown for all the simulated weeks at the farthest node from the substation (bus 53). At this bus, with low short circuit power, all simulated weeks exceed the EN50160 THD limit.

The trend shown in Fig. 8 is not the same for all buses in the network. Fig. 9 shows the same analysis at the secondary of the main transformer. In this case limit outstripping is noticeable when transformer rated power is only around 1.25 average demanded load. If rated power decreases below this limit, THD is exceeded in all the simulated weeks. Buses in the network placed between the secondary of the main transformer and the farthest bus 53 have intermediate situations.

In the same way as it was summarized for unbalance, Fig. 10 shows the probability of exceeding THD limits in the whole network. Here, a quick increase in probability of problems starts when the transformer power is below 2.25 times average demanded power. With transformer rating around the power demanded by the loads at network, THD problem probability is 100%.

It is important to bear in mind that in real networks, very frequently, the function of the rated 800 kVA transformer is allocated to two parallel 400 kVA transformers, to fulfil with $n+1$ requirements [22]. In this case, a scenario with just a 400 kVA transformer can occur whenever one transformer is under maintenance. In this situation, the network is not strong enough to assure the same level of THD, and an increase on

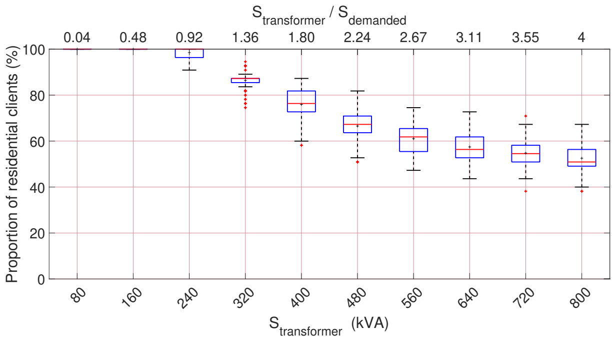

Fig. 7. Number of clients suffering from THD problems with different transformer ratings.

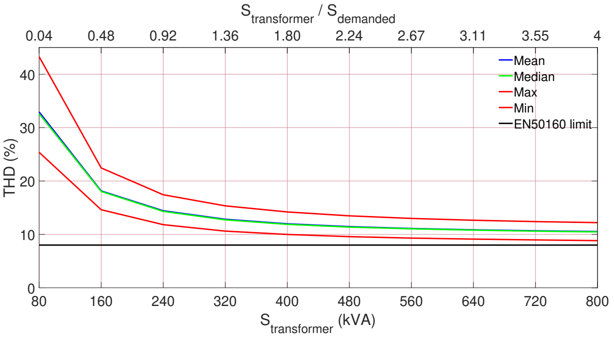

Fig. 8. 95^{th} percentile of THD at bus 53.

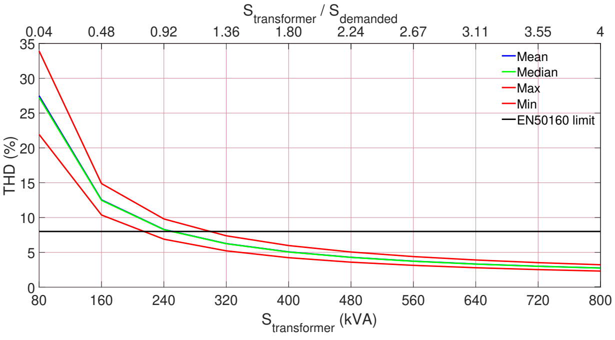

Fig. 9. 95^{th} percentile of THD at secondary of transformer.

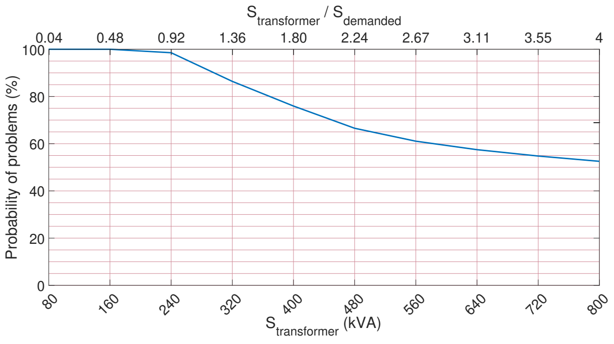

Fig. 10. Probability of THD problems for different transformer ratings.

demanded power or a de-rating of transformer can lead to severe PQ limit violations.

V. CONCLUSION

In this paper, a method for the assessment of power quality in a low voltage distribution network has been presented, focusing on the influence of the distribution transformer rated power on unbalance and THD. Results are compared to standard limits established in EN50160.

A Monte-Carlo methodology has been applied in order to take into account the uncertain nature of loads. Different simulations for different rated powers of transformers have been tested for the same loads. This methodology allows the prediction of power quality indices if transformer rated power is reduced, but is also suitable for foreseeing what would happen if the load increases.

Finally, a reduction of transformer rated power produces a predictable increase on THD and unbalance. Simulations in this work show that this increase is not linear with transformer rated power, but it shows an elbow at some point around $S_{transformer}/S_{demanded} = 1.5$. For THD, a saturation is found when transformer is only about 0.9 times the demanded power, resulting on a 100% probability of violating limits.

The methodology proposed can be easily extended to other distribution networks and, also, to different PQ disturbances.

REFERENCES

[1] H. Sharma, M. Rylander, and D. Dorr, "Grid impacts due to increased penetration of newer harmonic sources," *IEEE Transactions on Industry Applications*, vol. 52, no. 1, pp. 99–104, Jan 2016.

[2] M. Bollen, S. Rönnberg, F. Zavoda, R. Langella, S. Djokic, P. Cuifo, J. Meyer, and V. Cuk, "Consequences of smart grids for power quality: Overview of the results from cigre joint working group c4.24/cired," in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Sep. 2017, pp. 1–6.

[3] M. T. Au and J. V. Milanovic, "Development of stochastic aggregate harmonic load model based on field measurements," *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 323–330, Jan 2007.

[4] *Voltage Characteristics of Electricity Supplied by Public Distribution Networks: EN 50160:2010*, CENELEC Standard EN 50 160:2010, 2010.

[5] Y. . Wang, R. M. O'Connell, and G. Brownfield, "Modeling and prediction of distribution system voltage distortion caused by nonlinear residential loads," *IEEE Transactions on Power Delivery*, vol. 16, no. 4, pp. 744–751, Oct 2001.

[6] H. E. Mazin, E. E. Nino, W. Xu, and J. Yong, "A study on the harmonic contributions of residential loads," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1592–1599, Jul 2011. [Online]. Available: https://ieeexplore.ieee.org/document/5910684

[7] A. Navarro-Espinosa and L. F. Ochoa, "Probabilistic impact assessment of low carbon technologies in lv distribution systems," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2192–2203, May 2016.

[8] Z. Liu and J. V. Milanović, "Probabilistic estimation of propagation of unbalance in distribution network with asymmetrical loads," in *8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012)*, Oct 2012, pp. 1–6.

[9] P. Rodríguez-Pajarón, A. Hernández, and J. Milanovic, "Probabilistic assessment of harmonics in a residential network," in *2020 19th International Conference on Harmonics and Quality of Power (ICHQP)*, March 2020, pp. 1–6, accepted.

[10] D. Salles, C. Jiang, W. Xu, W. Freitas, and H. E. Mazin, "Assessing the collective harmonic impact of modern residential loads—part I: Methodology," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 1937–1946, Oct 2012.

[11] M. M. Silva, M. L. y. Gonzalez, W. Uturbey, E. G. Carrano, and S. R. Silva, "Evaluating harmonic voltage distortion in load-variating unbalanced networks using monte carlo simulations," *Transmission Distribution IET Generation*, vol. 9, no. 9, pp. 855–865, 2015.

[12] G. G. Ye, M. M. Nijhuis, V. V. Cuk, and J. S. Cobben, "Stochastic residential harmonic source modeling for grid impact studies," *Energies*, vol. 10, no. 3, p. 372, 2017. [Online]. Available: https://www.narcis.nl/publication/RecordID/oai:library.tue.nl:866653

[13] D. A. Brodén, K. Paridari, and L. Nordström, "Matlab applications to generate synthetic electricity load profiles of office buildings and detached houses," in *2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Dec 2017, pp. 1–6.

[14] C. Sandels, J. Widén, and L. Nordström, "Forecasting household consumer electricity load profiles with a combined physical and behavioral approach," *Applied Energy*, vol. 131, pp. 267 – 278, 2014.

[15] Instituto Nacional de Estadística, España. (2018, October) Proyección de hogares 2018. Available: http://www.ine.es/dyngs/INEbase/listaoperaciones.htm.

[16] M. T. Au and J. V. Milanovic, "Establishing harmonic distortion level of distribution network based on stochastic aggregate harmonic load models," *IEEE Transactions on Power Delivery*, vol. 22, no. 2, pp. 1086–1092, April 2007.

[17] I. T. Papaioannou, A. S. Bouhouras, A. G. Marinopoulos, M. C. Alexiadis, C. S. Demoulias, and D. P. Labridis, "Harmonic impact of small photovoltaic systems connected to the lv distribution network," in *2008 5th International Conference on the European Electricity Market*, May 2008, pp. 1–6.

[18] P. Rodríguez-Pajarón, H.Mendonça, and A. Hernández, "Probabilistic assessment of harmonics in a residential network," in *2020 19th International Conference on Harmonics and Quality of Power (ICHQP)*, Sep. 2020, pp. 1–6, accepted.

[19] M. F. McGranaghan, S. Santoso, R. C. Dugan, and H. W. Beaty, *Electrical Power Systems Quality*, 3rd ed. New York, US: McGraw-Hill Professional, 2012, ch. Applied harmonics, pp. 255 – 324.

[20] R. C. Dugan and T. E. McDermott, "An open source platform for collaborating on smart grid research," in *2011 IEEE Power and Energy Society General Meeting*, July 2011, pp. 1–5.

[21] Distribution System Analysis Subcommitteee: Distribution Test Feeder Working Group, "IEEE european low voltage test feeder," webpage, May 2015, available: http://sites.ieee.org/pes-testfeeders/resources/.

[22] C. Bayliss and B. Hardy, *Transmission and Distribution Electrical Engineering*. Oxford: Elsevier Science & Technology, 2011, iD: 827639. [Online]. Available: http://ebookcentral.proquest.com/lib/upmes/detail.action?docID=827639