ASSESSMENT OF HARMONIC DISTORTION LEVELS IN LV NETWORKS WITH INCREASING PENETRATION LEVELS OF INVERTER CONNECTED EMBEDDED GENERATION

Adam DYŠKO, Graeme M. BURT, James R. MCDONALD
University of Strathclyde – UK

Ian B. B. HUNTER
SP PowerSystems Ltd – UK

SUMMARY

The paper presents a new simulation based method for harmonic distortion level evaluation at the point of common coupling in power system distribution networks. The proposed method aims to calculate the anticipated levels of voltage and current distortion by performing comparative simulation studies based on the information on the existing power quality profiles and the planned future network configuration including inverter connected embedded generation. Time domain simulation is used in order to calculate current and voltage waveforms which then can be analysed with FFT algorithm. The paper gives a detailed explanation of the method followed by the case study performed on a fragment of an actual LV distribution network. In order to provide a holistic assessment of harmonic distortion weekly profiles are analysed in 10 minute intervals which is consistent with the approach proposed in the European standard EN 50160.

INTRODUCTION

With growing penetration levels of small-scale embedded generation utilities express an increasing concern about power quality in the MV and LV parts of the distribution networks. The notion of possible deterioration of power quality comes mainly from the fact that many small as well as some medium-scale generators are connected to the utility networks by means of the power electronic based interfaces. Sources of energy such as photovoltaics and fuel cells generate DC power and require 50Hz inverters in order to connect to the power grid which due to their non-linear characteristics introduce higher harmonics. Practical assessment of harmonic distortion levels is not a straightforward task because of the interconnectivity of the power system and the non-linear nature of the problem. The influence of the particular inverter connected generator may significantly differ depending on the location in the network. Moreover, distortion is never static and changes with load demand and generation output. All of these factors contribute to the complexity of the power quality harmonic analysis and therefore it is often not obvious which harmonic level should be treated as an index for the assessment of the distortion level. A number of approaches are presented in the engineering standards and recommendations. For example according to the European standard EN 50160 [1] 95% of the 10 minute mean rms values of each individual harmonic voltage should be less than or equal to the specified levels. Similarly, the British standard G5/4 [2] recommends measurements of one week of 3 second or 10 minute average values. On the other hand “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems” [3] list harmonic distortion levels for the “worst case” for normal operation (conditions lasting longer than one hour). For shorter periods, during startups or unusual conditions, the limits may be exceeded by 50%. There are also some suggestions as to how to estimate future distortion levels.

There are also a large number of technical publications referring to harmonic distortion assessment. Frequently appearing solution to this problem is a combination of the analytical methods with empirical data obtained from field measurements. In [4] the authors assess harmonic distortion levels caused by power factor correction capacitors using HARMFLO (Harmonic Power Flow Study Program) software. The results are compared with field tests. Similarly, in [5] and [6] the simulation results are compared with monitoring data. As to more general concepts of harmonic propagation in power networks including the models of different power system non-linear components, the work of the “Task Force on Harmonics Modeling and Simulation” is very relevant [7, 8].

The method proposed in this paper suggests a systematic simulation based approach which leads to the prediction of the harmonic distortion levels with future non-linear embedded generators and loads. It aims to be a network design supporting tool which will allow to estimate voltage distortion in a holistic manner utilising existing load and harmonic profiles in conjunction with the models and the profiles of the generators to be connected to the network. For the prototype case studies, the ATP simulation software was used for power system transient simulation and LabView software for harmonic analysis.

METHODOLOGY

Calibration of the network parameters

The basis for the calibration procedure is the monitoring data collected in the substation supplying the distribution network for a period of at least one week. In most cases one week is sufficient to capture load and power quality characteristic of the network. Depending on the climatic changes during the year it may be necessary to collect the data in two or three different seasons.

Calibration of loads. In most distribution systems the load levels fluctuate during the day within a wide range of values. This has a direct influence on current flows in the network as
well as distortion levels because they are evaluated as relative values with respect to fundamental frequency amplitude.

The monitoring equipment is usually installed at the substation level and therefore the load measurements can be collected for individual circuits supplying groups of loads only. The loads are calibrated at each interval according to the collected for individual circuits supplying groups of loads at the substation level and therefore the load measurements can be resolved on the basis of the installed capacity of the individual customers.

The monitored data consists of useful information concerning the loads (P<sub>M</sub>, Q<sub>M</sub>) divided proportionally to the estimated initial values of the loads (P<sub>i</sub>, Q<sub>i</sub>) using the formula (1) and new calibrated values of the loads (P<sub>C</sub>, Q<sub>C</sub>) are assigned to the individual loads.

The estimated proportions of the loads (P<sub>i</sub>, Q<sub>i</sub>) may be resolved on the basis of the installed capacity of the individual customers.

### Calibration of the harmonic levels

The second aspect of network calibration is the representation of the existing distortion levels. As it is often not possible to calibrate harmonics accurately across the whole network the calibration is performed for the specific location in the network. Usually, it is a point of common coupling e.g. 11/0.4 kV substation busbar. The sinusoidal voltage and current sources connected to the distribution network model as shown in Fig. 2 help to generate required harmonic distortion at the specific location. The element Z<sub>th</sub> represents the impedance of the supply system, Z<sub>th</sub> is the equivalent impedance of the loads, V<sub>th</sub> is the voltage at the point of common coupling, and V<sub>sh</sub>, I<sub>sh</sub> are the parameters of the voltage and current harmonic sources.

The idea of the harmonic calibration consists in adjusting the parameters of the sources V<sub>sh</sub>, I<sub>sh</sub> so that the voltage waveform V<sub>th</sub> contains the required harmonic levels (extracted from the monitoring data).

### Principle of the comparative method based on profiles

The principle of the comparative method based on profiles is to provide the framework for comparative power quality studies. The comparison is performed in two stages: (1) calibration of the network parameters for accurate simulation of the existing distortion profile (as described in previous sections), and (2) simulation of the anticipated distortion profile using the calibrated network in conjunction with the models of the generators and non-linear loads to be connected to the network. Therefore, the distribution network model is prepared in two versions: network (a) representing the system with all existing generators and loads and network (b) with additional embedded sources of energy and possible loads.

Network data prepared in this way acts as a template for systematic simulation of the distortion profile. The network is calibrated and the profile is evaluated in pre-defined time steps (e.g. every 10min) depending on the available load and monitoring data. Finally, the harmonic profiles (individual harmonics or THD) can be collected and presented in a report.
Problem of the phase shift of individual harmonics

One of the challenges in assessing the changes in distortion levels is the relative phase shift of the existing harmonics with respect to those generated by the inverters. For example, if the harmonics generated by the additional sources are in phase with the existing ones then the increase in distortion level is to be expected. Otherwise the distortion may become smaller than the original level. In order to represent properly the phases of individual harmonics it is essential that the monitoring equipment store the FFT analysis results as amplitude and phase. This way the simulated existing distortion level can be adequately calibrated in terms of the phase shift of individual harmonics and will be always set correctly with respect to the harmonics generated by the connected inverters.

Interpretation of the results

The results should be presented as daily (or weekly) harmonic distortion profiles of THD and perhaps of some most significant individual harmonics. Additionally, it is proposed to present the distortion profiles in the form of duration curves, which allow for convenient comparison with standard limits, with other studies and with other parts of the utility network. Furthermore this data can then be used for further statistical analyses in support of targeting associated network reinforcement. This format will be demonstrated during the case study.

CASE STUDY

Network model and data

In order to illustrate the methodology a case study was performed on a fragment of the actual distribution network as presented in Fig. 3. The network consists of four LV circuits supplying various types of customers. Circuit 1 supplies an industrial estate, circuits 2 and 3 provide electricity to the residential area and circuit 4 supplies a commercial street. The monitoring equipment was installed on the LV side of the 11/0.4 kV substation in order to capture the load demand and current distortion profiles in all the circuits and the voltage distortion level on the LV busbar.

The aim of the study was to investigate the impact of inverter connected PV generation installations in the residential area on the substation voltage distortion profile. Three different penetration levels were considered: 25kW, 50kW and 75kW of installed PV generation capacity. The maximum installed generation was represented by six lumped units connected across the residential circuits as indicated in Fig. 3 each one representing 12.5kW. For 25kW and 50kW two and four units were used respectively.

Fig. 4 presents a weekly profile of voltage odd harmonics up to the 9th. Even harmonics are not presented, as their level was negligible in this case. A midweek day (Wednesday) was selected from the weekly profile (ref. Fig. 4).

PV generator modelling

Two different dynamic models of the inverter connected PV panels were utilised in order to characterise the distortion introduced by the sources. The first model illustrated in Fig. 5 was built using ATP controlled switches forming a single phase four valve bridge driven by the standard PWM algorithm with sinusoidal reference signal. The magnitude of the DC voltage and the phase of the PWM reference signal were controlled by the PI controller measuring active and reactive power. This allowed adjusting the generated active power according to the profile of the sun radiation by changing DC source magnitude and maintaining the unity power factor by the phase of the PWM reference signal. More detailed description of the PV generator modelling can be found in the publication [10].
Second model is presented in Fig. 6. It contains a MODELS controlled current source connected to the algorithm which synthesises the current waveform from individual harmonics. This way it was possible to reproduce accurately the current waveform which in this case was obtained from the laboratory testing of the commercially available 800W inverter designed for PV systems.

Profile simulation results

Each calculated harmonic profile included 144 simulations performed in 10-min time intervals. At each interval the necessary network load and distortion calibrations were performed.

The final result for the PWM generator model is presented in Fig’s 7-8. Five curves are presented in each figure indicating gradual changes in harmonic distortion with increasing levels of EG penetration compared with the measured levels. It is important to note that the THD duration curves give an immediate indication as to the level of distortion consistent with power quality standards. Taking the intersect with the dotted vertical line at the 5% mark (refer Fig. 8) gives a direct reading of the maximum distortion level which is not exceeded during 95% of the time. On the other hand, the daily profiles indicate the time relation between the new PV generation distortion and the existing distortion giving insight into potential power quality problems caused by the lack of diversity between existing and introduced distortion profiles.

For example in Fig. 7 it can be observed for 25kW generation level that, although, the distortion is increased during the day it has practically no impact on the normative distortion level (refer to 5% mark on duration curve in Fig. 8). With 50kW PV penetration the distortion level rises approx. from THD=1.93% to THD=2.26% and further 25kW causes the increase to THD=2.71%. This indicates that the relationship between the penetration level and harmonic distortion is not linear.

The influence of the PV penetration on the normative THD level for two inverter models is presented in Fig. 9 which shows that for both inverters above certain penetration threshold distortion starts to increase more rapidly and almost proportionally to the EG generation. For PWM inverter model this threshold appears around 25kW and for the synthesised model it is closer to 50kW. These characteristics are dependent on the inverter model as well as the daily profile
and that is why the simulation studies including detailed profile analysis such as the one presented in this paper are necessary in order to assess realistically the future power quality parameters.

**Harmonic phase shift considerations**

In order to investigate how the phase shift between the existing harmonics and the ones introduced by new generators can influence the resulting distortion level, a series of profile simulations were performed changing the angle of all existing harmonics with respect to the ones of the synthesised generator. Fig. 10 presents the results of phase shift scan for the penetration level of 25kW (midday) using the synthesised inverter model. The existing distortion level is marked by the dotted line at about 1.8%. It can be observed that the resulting THD index can change from minimum to maximum with an angular difference of merely 45° (e.g. minimum at approx. 210° and then following maximum at approx. 255°). The result here confirms the measurements which indicated the predominance of the 5th harmonic in the harmonic spectrum of the existing distortion (ref. to Fig. 4); the phase scan in Fig. 10 has five distinct peaks when the angle of the fundamental frequency changes by 360°. This illustrates the potential for angular shift to be used for active compensation of dominant harmonics in the network when combined with on-line monitoring and programmable inverters.

![Graph showing influence of phase shift on voltage distortion level](image)

**Fig. 10. Influence of the phase shift on the resulting voltage distortion level (EG penetration 25kW)**

**CONCLUSIONS**

The paper presented a systematic simulation based methodology for the assessment of the harmonic distortion levels with the inclusion of the influence of the future inverter connected sources of renewable energy installed in LV networks. This methodology is aimed to assist the utilities in network development planning activities as it is anticipated that the levels of small generation penetration will continue to rise together with the participation of power electronics. An effort has been made to prepare an illustrative case study based on actual network and monitoring data. The results revealed also certain general characteristics of the harmonic distortion under varying EG penetration. It was demonstrated that distortion levels (as defined by the power quality standards) are not rising proportionally to the EG penetration levels. Although initially the harmonic distortion may not be noticeable (i.e. the distortion read from the THD duration curves at 5%), above a certain level a rapid deterioration of power quality can be expected in the network (ref. to Fig. 9). It is therefore essential that power utilities are equipped with appropriate simulation tools in order to anticipate the maximum permissible levels of small EG penetration which may vary in each case and is a function of existing network parameters and profiles as well as EG penetration level and the type of inverter. Moreover, as the sophistication of power electronic inverter increases and the microprocessor based controllers become increasingly more popular the method has a potential be used for the investigation of certain harmonic eliminating switching strategies and can therefore serve as a tool for investigating the methods of power quality improvement.

**ACKNOWLEDGEMENT**

The authors would like to express their gratitude to ScottishPower for providing network details and the monitoring data.

**REFERENCES**