Probabilistic Estimation of Harmonic Distortion in Non-Radial Distribution Network

PROBABILISTIC ESTIMATION OF HARMONIC DISTORTION IN NON-RADIAL DISTRIBUTION NETWORK

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ABSTRACT

Harmonic estimation in distribution networks is commonly carried out based on typically radial topology. Considering the increasing penetration level of power electronics interfaced net-zero technologies, the cumulated effect of harmonic pollutions in upstream meshed distribution networks is foreseen. Based on a recent study that demonstrated a methodology to estimate harmonic distortions in partially monitored radial distribution networks, this study extends the general application of the methodology to non-radial distribution networks. A sensitivity-based electrical distance was proposed to facilitate and to solve the problem of determining the optimal/minimum number and locations of power quality monitors when the voltage drop and harmonic distortions are not highly correlated. The approach is validated against a highly interconnected (mashed) section of a distribution system.

INTRODUCTION

In future net-zero distribution networks, there is expecting increasing proliferation of power electronic (PE) based technologies, e.g. offshore wind farms, PV plants, storage technologies, FACTS, HVDC lines, and electrical vehicles, etc. These PE components will bring up the uncertainty levels and amplify the disturbance of the power system and consequently challenging the regulation of power quality (PQ) issues, especially the harmonic issues that will result in additional power loss and unexpected financial losses. The estimation of harmonics is therefore essential for system operators to regulate and prevent potential harmonic issues [1,2].

A recent study [3] demonstrated a harmonic state estimation (HSE) methodology for estimating harmonic distortions in partially monitored, typically radial, residential distribution networks. Even though this method has been proven to be very effective and reliable, it remains challenging to implement it directly to the meshed networks due to the higher complexity of the power flows and harmonic injection variations in the network.

To address this problem, as a continuation of the previous study, this paper first proposes an alternative method, which is sensitivity-based electrical distance, to solve the problem of determining the optimal/minimum number and locations of PQ monitors when the voltage drop and harmonic distortions are not highly correlated in the meshed network. To obtain satisfactory estimation of harmonic current injections, the harmonic distortions from nonlinear loads are fitted and estimated separately according to different load types. The approach is illustrated on a 48-bus meshed section of the modified 295-bus Generic Distribution Network (GDN) [4] consisting of 23 132 kV buses, 25 33 kV buses, 4 low-voltage 11 kV networks and 9 buses with NL loads.

METHODOLOGY

Overview

The main idea of the proposed methodology is to estimate the harmonic distortions at unmonitored buses with the information of harmonic measurements at a limited number of buses. Fig. 1 summarises the required information for the proposed harmonic estimation methodology. In the previous week, it was necessary to determine first the optimal number and location of PQ monitors. This relies on the information of weekly voltage profile at all buses, and possibly the system configuration and relevant system parameters (which is not necessarily required). Based on the harmonic measurements from the installed PQ monitors, and the non-linear load demands at the corresponding buses, a Kernel non-parametric (KNP) distribution fitted model could be obtained [3]. In the present week, this model is utilized to estimate harmonic injections from all the non-linear load buses based on the information of real-time harmonic measurements and the non-linear load demands. The active power of NL loads can be obtained by the conventional meters or assumed to be predicted in advance as in [5]. Then together with the information of V, P, and Q profiles at all the buses, the harmonic distortion at all the unmonitored buses can be calculated as in [3].

The accuracy of the estimation process depends on the strategic placement of the PQ monitors within clusters of buses with a high correlation in terms of total harmonic distortion (THD). In [3], it was found that the Pearson correlation matrix of voltage-drop level (ΔV_k) between the time interval *t* and *t+1* was highly correlated to the corresponding harmonic distortion levels, as defined in (1).

$$\Delta V_k = (V_0^t - V_k^t) - (V_0^{t+1} - V_k^{t+1}) \quad (1)$$

where V_k and V_0 refer to the fundamental voltage values at

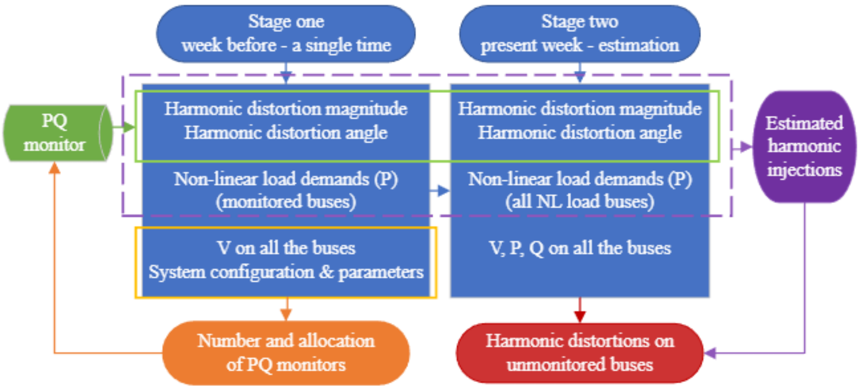

Fig. 1. Required information for proposed harmonic estimation methodology.

bus k and at the secondary of the substation transformers, respectively.

This correlation has been proven very effective in radial distribution network. However, it is not quite adaptive in a highly interconnected meshed network. In a radial distribution network, since the loads distributed along identical radial feeders are supplied by a common power source, these load buses are electrically close to each other in terms of power flow direction and the variation of voltage distortions. However, in a meshed network there are multiple interconnections among buses and hence there are multiple routes for power flow and harmonic propagation among them [6]. Meshed networks have advantages, among the others, to achieve an acceptable voltage regulation but finding electrically close buses becomes more challenging and thus decreasing the effect of voltage/harmonic correlation methodology.

In order to find proper locations of PQ monitors suitable for harmonic estimation in a meshed network, a sensitivity-based method, Morris Screening Method [7], was used to identify the electrical distance and sensitivity of voltage variations to voltage drops at the monitored buses, named here method M1. This method, can be also used to determine the sensitivity of harmonic variations at unmonitored buses with respect to the harmonic distortions injected at the monitored load buses, named here method M2. To do this, basic network parameters and topologies are assumed to be known, as generally is the case in practical MV meshed distribution systems where network models and parameters are commonly available.

Electrical Distance Sensitivity

In power system analysis, electrical distance is a measure that characterizes the relationship between different nodes in the system. It can be used to identify the internal and external connections between nodes and to provide useful information for power system analysis and control [8]. The sensitivity-based electrical distance is calculated using the sensitivity matrix of the system, which can be obtained from the system's state equations. The sensitivity-based method is computationally efficient and has been used in several applications such as state estimation, topological analysis, and optimal power flow analysis [8]. The degree of voltage coupling ($\alpha_{i,j}$) can be represented as the attenuation of voltage variations between objective nodes (ΔV_i, ΔV_j), as shown in (2).

$$\alpha_{i,j} = \frac{\Delta V_i}{\Delta V_j} \tag{2}$$

In order to simplify the computational complexity and to accommodate the variations of system operating conditions and uncertainties, this study simplifies the calculation of the sensitivity-based electrical distance as in equation (3-4).

$$\alpha_{i,j} = \frac{1}{h-1} \sum_{t=1}^{h-1} \left| \frac{V_i^t - V_i^{t+1}}{V_j^t - V_j^{t+1}} \right| \tag{3}$$

$$d_{i,j} = \left| log\ (\alpha_{i,j}) \right| \tag{4}$$

where α_{ij} refers to the degree of voltage variations at node i (selected from all buses) with respect to the disturbance at node j (selected from load buses). The variable t and $t+1$ represent the adjacent time interval between t and $t+1$. An average value of α_{ij} is taken, considering the entire sampling time span (h). A smaller α_{ij} represents a weaker electrical connection between node i and node j.

The electrical distance from a bus to itself, i.e., when $i=j$, $\alpha=1$, is the shortest among all the other buses. Therefore, the electrical distance between node i and node j ($d_{i,j}$) is standardised by using $log\ (\alpha_{i,j})$ as shown in (4). The more $d_{i,j}$ is approaching 0, the shorter the electrical distance between the two nodes.

Through this approach, a sensitivity-based electrical distance matrix (M_v) can be computed which illustrates the connection level between load buses and all other buses in the system. In order to determine the optimal/minimum number and locations of PQ meters, a voltage sensitivity threshold (λv) is applied to classify the sensitivity-based electrical distance into 0 and 1. All electrical distances *below* the threshold are set as 1, meaning that the voltage variations in between are highly correlated. Electrical distances *above* the threshold are set as 0, signifying that the voltage variations in between are not correlated. A similar sensitivity matrix can be defined to establish harmonic variations at unmonitored buses with respect to the harmonic distortions injected at the monitored load buses by setting a harmonic sensitivity threshold (λ_h).

Optimal Monitor Locations

In order to determine the appropriate PQ monitor locations and to cluster different unmonitored buses into the monitored group, the following steps are as taken.

i. Decrease the voltage sensitivity threshold (λv) from the max value to the min value of M_v in 20 steps so that different matrices (C) of classified electrical distance can be found.

ii. Following each step an optimization is performed (as in [3]) to identify the smallest number/best location of PQ monitors. This optimal solution ensures that all the buses (rows in matrix C) are covered by at least one true value with respect to the selected monitored load buses (columns in matrix C). The locations identified by the selected columns are considered as the best place for installing the PQ monitors.

iii. Buses that have a high correlation with the monitored column are grouped together, i.e., each group will have one monitored bus and the buses highly correlated with it. The number of groups equals to the total number of monitored buses.

iv. To prevent assigning the same bus multiple times, the unmonitored bus, which is highly correlated with multiple monitored buses should be assigned to the group where the bus with the shortest electrical distance is located. Meanwhile, if a monitored bus is also correlated to other monitored buses, it will be removed from the other groups.

Under some conditions, a higher threshold may result in no true values in some rows of matrix C. Therefore, matrix C is selected as the first matrix when an optimal solution was found while decreasing threshold λv. The process of placing PQ monitors is carried out only once prior to the harmonic estimation.

Harmonic Estimation

In radial distribution networks, different categories of non-linear loads (e.g., lighting, TV, e-heating, etc.) are generally considered as aggregated power demand at PCC bus. In [3], the harmonic distortions were fitted and estimated in terms of typical distributions of the aggregated demand. In this study, to obtain more accurate estimation of harmonic current injections (in both magnitude and phase angle) from different types of nonlinear loads, the harmonic measurements are fitted and estimated separately according to different load types, based on the Kernel non-parametric (KNP) distribution. The estimated values are then combined in proportion to their total demand at the bus. As in the methodology detailed in [3], the parameters of KNP distributions are established by the load demand and the harmonic currents measured by PQ monitors.

TEST NETWORK

The meshed section of a Generic Distribution Network (GDN) is considered as the test network in this study, as shown in Fig. 2. There are in total 48 buses, 9 non-linear loads, and 4 low-voltage distribution networks connected to the 132 kV and 33 kV feeders. The detailed modelling of network parameters and the probabilistic operation of the distribution generations (DG) can be found in [4]. The network was modelled and simulated using the software DigSILENT/PowerFactory [9]. In order to accommodate different system operating conditions and uncertainties, Monte Carlo (MC) based probabilistic approach was applied during the simulation. In accordance with the standard EN50160 [10], the simulation lasts for one week and it was performed with a 10-mins time-step.

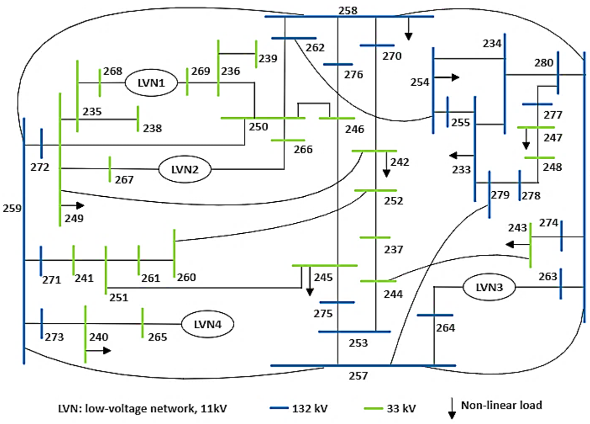

Fig. 2. Simplified 48-bus meshed section of the modified 295 GDN.

In the modelling of probabilistic harmonic propagations, several harmonic sources were considered, i.e., the wind and PV generation, storage, and non-linear loads which comprising of 80% domestic load (D type) and 20% commercial load (C type). Different types of nonlinear loads (typically producing 3rd, 5th, 7th, 9th, and 11th harmonic) and distributed generators (typically producing by 5th, 7th, 11th, and 13th harmonic) with different levels of harmonic injections were modelled probabilistically as uniformly distributed ranges from 0 to the values summarised in [8]. For all types of harmonic sources, the harmonic angle injections were randomly sampled using uniform distribution within a range of (0°, 180°). The harmonic load flow (HLF) was then performed to obtain the individual harmonic distortions and the total harmonic distortions (THD) at all buses in the 48-bus meshed section of GDN. The harmonic simulation though, was performed based on the entire GDN so that the influence of the operation of the distributed generators and non-linear loads on the harmonic propagation throughout the whole network is accounted for.

CASE STUDY

Estimation Accuracy

The proposed harmonic estimation methodology based on the electrical distance sensitivity (M1) is initially tested and applied in the 132 kV meshed section of GDN. In this case (Case 1.1), it was found that PQ monitors are required to be installed at Bus 233 and Bus 258. The absolute estimation errors of THD at different buses are fitted as cumulative distribution functions (CDFs) and are plotted as in Fig. 3. It can be seen that for the majority of the buses, the estimations errors are centered at approximately 0% and are distributed within a narrow span of ±0.2%. In other words, if the actual harmonic distortion is 3%, the corresponding estimated values will be within a range from 2.8% to 3.2%. The average 95th absolute estimation error of all these buses is approximately 0.1%, which sufficiently accurate.

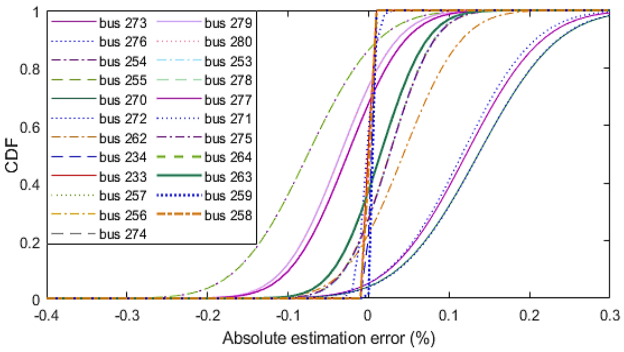

Fig. 3. Fitted CDFs of absolute estimation errors of THD for Case 1.1.

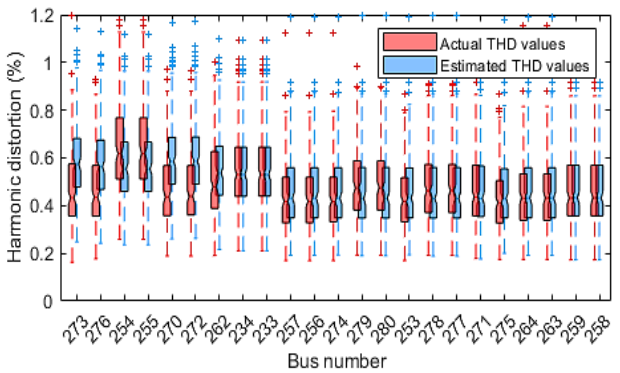

Fig. 4. Boxplots of estimated and actual THD values for Case 1.1.

For more intuitive comparisons, Fig. 4 shows the boxplots of the actual and estimated THD values at different buses. It can be observed that the medians, widths, and boundaries of the distributions are roughly overlapping. This indicates that the estimated and actual THD are coincident with each other and thus the proposed methodology is efficient in harmonic estimation.

The other proposed harmonic estimation methodology, based on the harmonic sensitivity analysis – M2 is also tested in this network (Case 2.2). Table I summarises the corresponding results of the average 95th percentile absolute estimations errors and the average mean values at all unmonitored buses. It can be seen that both estimation errors are relatively larger compared with the errors in Case 1.1. Therefore, compared to M1, the method M2 is not suitable to be applied independently for the harmonic estimation.

Effect of the Estimated Harmonic Injections

In order to investigate the effect of separately fitting and estimating harmonic distortions considering different types of loads, several cases are studied for comparison. In Case 1.2 (using M1) and Case 2.2 (using M2), the harmonic injections from unmonitored nonlinear loads are estimated regardless of load types. In Case 1.3 (using M1) and Case 2.3 (using M2), the harmonic injections from unmonitored nonlinear loads are substituted by their actual values so that the estimation error introduced by the estimated harmonic injections can be eliminated in the final estimation of THD. Table I summarizes the corresponding results of the average 95th percentile absolute estimations errors and the average mean values at all unmonitored buses.

Table I. Estimation errors fo all cases.

	Average 95th absolute estimation error	Average mean value
Case 1.1	0.1179%	0.0534%
Case 1.2	0.1507%	0.0752%
Case 1.3	0.1161%	0.0526%
Case 2.1	0.3100%	0.1639%
Case 2.2	0.4150 %	0. 2073%
Case 2.3	0.3083%	0.1647%
Case 3.1	0.3572%	0.1586%
Case 3.2	0.9000%	0.4131%

It can be seen that independently of the estimation methodology used, the estimation accuracy will reduce when estimating harmonic injections without considering the variety of load types. If different types of harmonic injections are estimated separately, however, the estimation errors will be similar to the cases where the actual harmonic injections are applied.

Therefore, it is recommended to fit and estimate the harmonic injections considering different load types. By doing so, the estimated harmonic injections will be sufficiently accurate and will not affect the final accuracy of the THD estimation.

Validation of the Model

In order to validate the general applicability of the proposed methodology, both M1 and M2 are applied to the entire meshed section of GDN, i.e., with 48 buses in total, refer to as Case 3.1 (using M1) and Case 3.2 (using M2), respectively. The corresponding results of the average 95th percentile absolute estimations errors and the average mean values are summarized in Table 1. For Case 3.1, the boxplots of absolute estimation errors and the boxplots of estimated and actual THD values are shown in Fig. 5 and Fig. 6, respectively.

In this case, the PQ monitors are required to be installed at three different locations (Bus 242, Bus 247, and Bus 258), which is approximately 6% (3/48) of the total buses in the network. For 46/48= 96% of the buses, the absolute errors are distributed within a range of ±0.5%. For the other two buses the mean values are around 0.5% and the average 95th absolute estimation error is approximately 1.5%. According to standard IEC TR 61000-3-6 [11], this error is acceptable compared with the 6.5% THD limit at distribution networks.

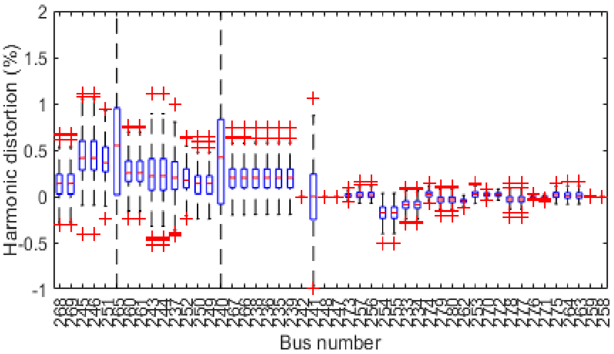

Fig. 5. Boxplots of absolute estimation errors for Case 3.1.

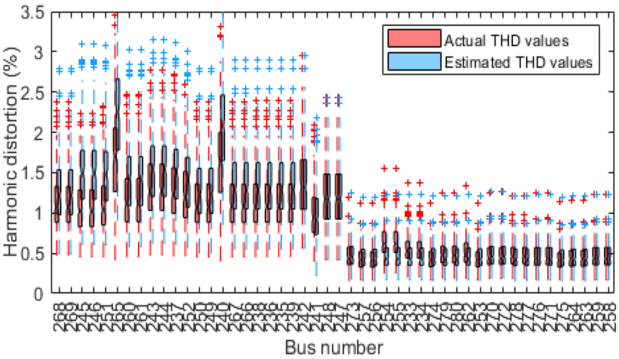

Fig. 6. Boxplots of estimated and actual THD values for Case 3.1.

Therefore, the proposed methodology can sufficiently accurately estimate the harmonic distortions at the unmonitored buses in meshed distribution network with PQ monitors installed at approximately 6% of the buses in the network.

It can be also seen that the estimation errors become larger when using M2 than M1. Therefore, method M1 (based on electrical distance sensitivity) is superior to the method M2 (based on harmonic sensitivity) and can be applied independently for harmonic estimation. The accuracy of harmonic estimation in a complex, highly interconnected power system when combining these two methodologies will be studied further in the future work.

CONCLUSION

This preliminary study, that builds on and extends the methodology proposed in [3] for harmonic estimation in radial low voltage distribution networks, demonstrates that the efficient application of sensitivity-based electrical distance method can provide sufficiently accurate assessment of harmonic distortions in higher voltage, non-radial distribution networks.

The approach reduces the extensive monitor installations in the networks, facilitates the assessment of harmonic propagations and mitigation solutions, and will further contribute to the forecast of potential harmonic issues in future net-zero power networks.

Acknowledgments

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