Optimization Framework for Harmonic Mitigation in Transmission Networks with Renewable Generation

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Abstract

This paper introduces the optimization framework for harmonic mitigation in transmission networks. The paper defines two possible harmonic mitigation problems, one with the global mitigation, and the other with the zonal harmonic mitigation which provides differentiated harmonic performance to customers in different zones of the networks. This paper analyzes the construction of appropriate objective functions for the two forms of problem descriptions as mentioned above, and introduces the approaches of selecting feasible/cost-effective mitigation schemes and appropriate locations for placing device-based mitigation solutions. The paper emphasizes the necessity to include the uncertainties of operating conditions in optimization process in order to construct realistic scenarios for harmonic performance assessment. It discusses the approaches that are widely used for sampling operating scenarios, and especially introduces the detailed procedure of using clustering techniques to select representative operating scenarios for covering the uncertainties of network behavior in simulation.

1 Introduction

Harmonic phenomena have attracted great attention in the last decade mainly due to the increased connection of power electronic interfaced equipment/machines across the network, ranging from electricity generation to consumption. With the trend of using greener energy nowadays, the presence of distributed generation units (usually for renewable energy generation) using advanced technology of power conversion is significantly increased in contemporary power systems. Though the advanced power conversion brings lots of benefits to grid development, it also introduces harmonics into the grids. The harmonic phenomena may propagate to other parts of the network, or develop into more severe resonance conditions. Non-linear loads are traditionally mainly related to the applications of heavy industries. However, nowadays they are more widely distributed in the grids and may be located at any corner of the network, and pretty much at any voltage level.

With the increased and widely distributed harmonic injection sources, network operation and management face great challenge in solving the issues caused by harmonic phenomena, such as thermal stress of insulation, interferences to communication infrastructure, increased power losses, mal-function of switchgears and devices [1], etc. The utilities and regulatory bodies have acknowledged the importance of harmonic performance improvement, and a number of standards have specified the required harmonic performance, e.g., IEEE 519 [2]. DNOs could face heavy penalties if their network sections violate the thresholds specified by the corresponding regulatory body. To prevent the avoidable financial losses, network operation should make sure that the harmonic performance in the network is always under the thresholds that are specified by the regulatory body.

Furthermore, some customers may have equipment that is more sensitive to harmonic phenomena (and/or the resonance conditions caused by the propagation of harmonic phenomena) than others. Usually the same types of customers gather together in certain area, e.g., residential, commercial and industrial areas. Therefore customers' requirement on harmonic performance usually varies depending on areas. Some of the customers would even like to pay more to utilities in order to receive higher harmonic performance than that given by regulatory body. Considering the overall mitigation efficiency, it is not necessary to provide exceeding harmonic performance to certain areas where customers do not have strict requirement on harmonic performance. The mitigation can be implemented in a way that all customers' requirements are met to certain extents, and the adverse impacts of harmonic phenomena on grids and end-users are minimized. In this way, the harmonic performance is adjusted/tailored to actual needs, and the use of extra resources/investment to improve non-required harmonic performance is avoided. Actually, this concept of having differentiated qualities of electricity supply was initialized in 1989 [3]. It has been addressed for certain customer attributes [4, 5] and in some specific areas like reliability options [6]. However it has not been addressed much in general area of power quality or in harmonic mitigation. With the more challenging harmonic issues faced by current and future transmission networks, proper mitigation approaches are urgently needed to take into account the differentiated requirements of harmonic performance from various customers.

This paper analyses the potential consequence of harmonic phenomena and introduces the optimization framework for providing differentiated harmonic performance while accounting for other aspects of realistic network operation. The approaches of selecting the potential mitigation solutions based on global and zonal analysis are analyzed in the paper. This paper also introduces the application of greedy based optimization approach to simplify the optimization process and efficiently search for the optimal mitigation strategy. It also discusses the importance of addressing uncertainties in simulation in order to yield the final mitigation strategy that is suitable for the realistic network operation. This paper also discusses the approaches of sampling operating scenarios for network assessment, and especially introduces clustering based sampling techniques which are particularly suitable for large scale optimization based applications.

2. Consequence of harmonic phenomena

Harmonic phenomena cause great financial losses to both utilities and customers as a result of penalty, loss, malfunction of equipment/machines, and damage to the equipment etc. CIGRE/CIRED C4.107 identifies the critical effects of harmonic phenomena from the financial point of view, and introduces approaches that are used to evaluate the financial losses caused by harmonic distortion [7]. Specifically, the consequence of the presence of harmonic phenomena (or the resonant operating conditions) can be analyzed from the following aspects:

2.1 Energy/power losses

The energy/power losses due to harmonic phenomena can be reflected by a number of forms, such as dielectric losses, copper losses and core losses in the connected equipment/machines. The power losses can be calculated separately for each type of machine, due to the fact that the impacts of harmonic phenomena on different types of machines vary and consequently their evaluations vary as well. For instance, the power losses for electrical motors can be evaluated by the following equation [7]:

$$P_M = 3\sum_{h=h_1}^{h_{\max}} \left(\frac{V^h}{Z_M^h}\right)^2 R_M^h + P_{co}^1 \sum_{h=h_1}^{h_{\max}} \left(\frac{V^h}{Z_M^h}\right)^{m_M} \frac{1}{h^{0.6}} \qquad (1)$$

where R and Z are the equivalent resistance and impedance respectively; V^h denotes the voltage harmonic at order h; and P_{CO} is the core loss.

2.2 Losses due to premature ageing

The power losses in core/copper of machines caused by harmonic phenomena usually result in increased temperature in the machines. This imposes extra thermal stresses to the insulation materials, and potentially causes malfunction of the machines and the reduced life time of service. Furthermore, the presence of harmonics may cause the increase of peak factor in voltage, and consequently results in additional electric stress to the machines. The thermal life time can be simplified and modeled as [8, 9]:

$$L = L_0'\left(K_p\right)^{-n_p} e^{-(Bc\theta)} \qquad (2)$$

where K_p is the peak factor of the voltage waveform, defined as the ratio between the distorted voltage and the peak value of the fundamental voltage. Coefficient n_p is related to and set based on the distorted shape of the waveforms.

2.3 Losses due to equipment malfunction

Equipment malfunctions may cause significant financial losses to the utilities and customers depending on how critical the failed equipment/machines are in the operating system or in the manufacturing process. The financial losses to the customers can be usually obtained by estimation/surveys from the customers. As for the malfunction of equipment in grids, it has wider effects and can impact all customers who are closely related to or fed by the equipment. Equipment malfunctions can also cause premature ageing issues as discussed earlier.

There are also other potential losses caused by harmonic phenomena, such as the derating of equipment. Sometimes the harmful effects of harmonic phenomena are unnoticed until the actual failure of the equipment. For instance, transformers can run for a long period under the presence of harmonic voltages and currents, but may fail quickly when there are certain triggers/changes in operating conditions. Therefore, it is very important to properly mitigate the harmonic phenomena even when there is no reported equipment failure that is obviously caused by harmonic phenomena. The utilities should properly examine the harmonic performance in the grids, and optimally mitigate the harmonic phenomena by taking into account both technical and financial aspects, in order to prevent the propagation of harmonics causing wider effect on the grids' and customers' equipment and their operation.

3. Optimization Framework for Harmonic Mitigation

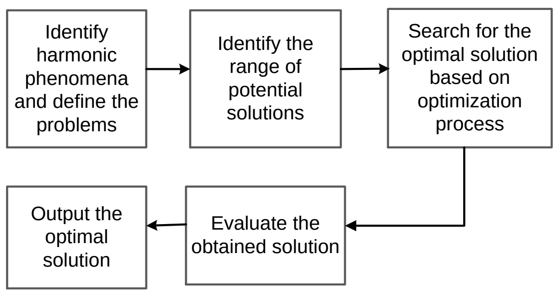

Fig. 1. Optimization framework for harmonic mitigation.

Harmonic mitigation as an optimization problem can be solved by following the optimization framework provided in Fig. 1. Once the critical issues are identified, the problem can be formalized by properly designing the objective function to address the concern and optimization purpose. Then the potential solution options for solving the issues can be investigated and included in the pool of potential mitigation schemes and subsequently used later in optimization. The optimal mitigation strategy selected by the optimization approaches will be evaluated properly to see whether it causes any other issues in network operation.

3.1 Problem Description and the Definition of Objective Functions

3.1.1 Global Harmonic Mitigation: The harmonic performance can be improved uniformly and globally across the whole network. The harmonic performance at all buses can be aggregated and used as the objective function to be optimized. To be specific, the optimization objective function can be designed in a way to reflect the effect of mitigation scheme on harmonic performance and assess how far the received harmonic performance is away from the thresholds set by regulation. In literature, Total Harmonic Distortion (THD) [10] is widely used to assess the harmonic performance. Assume its threshold is denoted as $\mathrm{THD}_{\mathrm{TH}}$. Given the performance index and specified thresholds, the objective function can be defined as the gap between two of them if the received harmonic performance is worse than the constraint/thresholds, as given by Global Harmonic Gap Index (GHGI), which is defined as (3).

$$GHGI = \sum_{j=1}^{B} \left| THD_j - \mathrm{THD}_{\mathrm{TH}} \right|_{THD_j > THD_{\mathrm{TH}}} \tag{3}$$

where B is the total number of buses in the network; and j is the bus index.

3.1.2 Differentiated Zonal Harmonic Mitigation: As discussed in Section I, the requirement on harmonic performance could vary from area to area depending on the majority of customers in that particular area. To provide the services zonally, the zonal harmonic performance requirements should be determined before defining the objective function. The zones can be obtained by the nature of customers connected to the grid, and in general the area can be labeled as residential area, commercial or industrial areas. If needed, the grid can be even divided into more detailed/smaller areas depending on trade-off between mitigation efficiency and the level of area division [8]. Once the zone division is obtained, the corresponding harmonic performance thresholds can be determined by the percentage of customers whose requirements on harmonic performance have been fulfilled. References [8, 15] provide the detailed approach of demarcating grid into zones. Fig. 2 gives the three steps that can be used to obtain the zonal division and zonal harmonic performance thresholds. With the obtained zones and defined zonal harmonic performance thresholds, the objective function can be defined by aggregating the gaps between the actual THD and zonal thresholds in different areas, and forming the total harmonic performance index, named as Zonal Harmonic Gap Index (ZHGI), as defined in (4).

$$ZHGI = \sum_{i=1}^{N} \left(\sum_{j=1}^{B_i} \left| THD_{i,j} - \mathrm{THD}_{\mathrm{TH},i} \right|_{THD_{i,j} > THD_{\mathrm{TH},i}} \right) \tag{4}$$

This rest of the paper mainly focuses on the differentiated zonal harmonic mitigation problem and the optimization procedure used to solve the problem. Actually, if the whole grid is considered as one area, the approach for zonal harmonic mitigation can be used to solve the global mitigation problem. The optimization procedures are the same for these two cases, with the only difference of setting the number of zones. Between these two problems, zonal mitigation is more complicated and it aims at providing more detailed customer-tailored services.

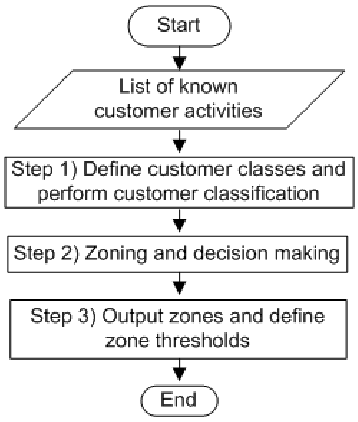

Fig. 2 Flowchart of zone division [11].

3.2 Determination of Potential Mitigation Schemes

In literature, various mitigation schemes have been explored to provide sufficient/required harmonic performance, from equipment level to network level. In terms of the equipment/device level, the harmonic injection devices (such as converters etc.) can be improved by re-programming or design such that the harmonic injection by the harmonic sources can be reduced. This can be considered as potential and feasible mitigation approaches due to the flexibility and controllability of the advanced power electronic devices nowadays. Apart from that, passive filters are usually considered as potential mitigation solutions at transmission level if the initial investment cost and power rating in transmission networks are considered. They are widely used for mitigation purpose by industries and utilities with the benefit of cost-effectiveness. By connecting filters in critical location in the grids, the overall harmonic performance at the network level can be improved. As for the potential locations for placing passive filters, they can be selected globally and zonally based on the analysis of the harmonic performance and sensitivity of the planned filter installation to the mitigation effect. After these locations are selected, they can be fed to the optimizer to search for the optimal filter placement.

3.2.1 Global filter placement: The harmonic performance (i.e., THD) is assessed for each bus. Then the buses are ranked based on the severity of harmonic phenomena (THD) in descending order (step 1 in Fig. 3). For instance, if bus B_i has the highest THD, its rank is 1, and denoted as $R_{\mathrm{THD}}(B_i)=1$. Then the location at bus B_i is initialized for filter placement (step 2 in Fig. 3). When the passive filter is preliminarily installed at the selected location, the rest of buses are ranked again based on new evaluated THDs and the bus which has the most severe THD after placing the previous selected filter is selected and included in the mitigation strategy (step 3 in Fig. 3). The aforementioned procedure of ranking and filter selection is repeated until reaching the pre-defined number of filters. Furthermore, the locations with the intersections of two or more branches are also preliminarily made available for passive filter placement (step 4 in Fig. 3), as it is believed the filter placed at the branch interaction can stop the propagation of harmonic phenomena from one area to others.

3.2.2 Zonal filter placement: To make sure the potential filter placement also facilitate the zonal harmonic performance provision, the filter placement should be also selected zonally. The steps used to select the zonal filter placements are the same as that for the global filter placement, except that in such case the bus ranking is based on zones rather than the whole grid (step 5 in Fig. 3). In selecting the location for filter placement, the feasibility in terms of geography and transportation should be also accounted for.

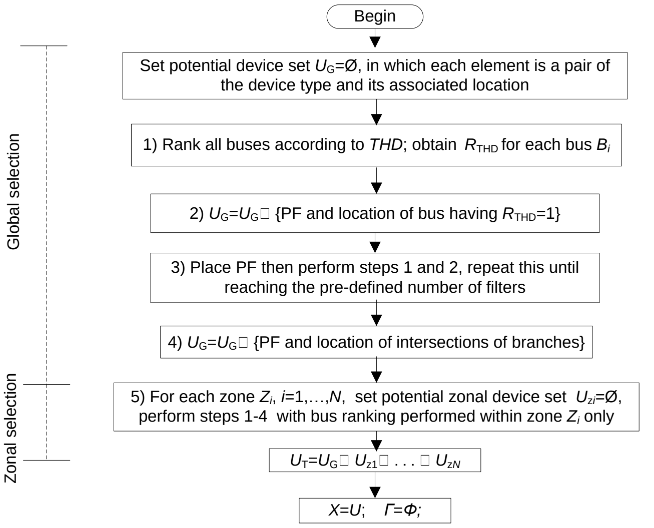

Fig. 3 Flowchart of selecting potential filter placement.

3.3 Greedy Based Optimisation.

Optimization approaches can be applied to search for the optimal strategy which consists of a number of solutions from the pool of potential mitigation schemes (i.e., the solutions selected from Section III-B). Various conventional and artificial intelligence based optimization approaches have been explored for planning problems, such as evolutionary algorithm [12], heuristic techniques [13, 14], and hybrid approaches etc. Greedy algorithms are applied in solving large-scale optimization problems due to its benefit of simple implementation and relatively low computational load [15, 16]. Greedy based approach has shown its superiority in finding device based mitigation strategy [11]. Fig. 4 provides the greedy algorithm based optimization procedure, in which the problem is divided into a number of consecutive stages, and at each stage the greedy algorithm is applied to select the best solution under the given operating condition.

At the first stage, a pool of potential solutions selected from Section III-B is denoted as set *U*. This set consists of the solutions that include the types of the solution and the implementing locations. If there are M_D potential solutions selected in Section III-B, and for each solution there are M_I possible ratings, in total there will be a pool of $M_D \times M_I$ potential solutions which consists of not only the locations and types, but also the ratings of the filters. These solutions are initially made available for searching the optimization space. The greedy algorithm is adopted to choose the best solution from set *U*, as shown in Fig. 4. The solution which has the minimum assessed objective function at each stage (denoted as *s*) will be included in the pool of final solution set *Γ*. After the selection, *X* will be updated while excluding the previously selected solutions. At the next stage, the previously selected solution will be placed in the network before the next selection. The placement of selected solution results in a different operating condition, and the greedy algorithm is used to search for the best solution at this stage while excluding the previously selected solutions. The procedure of greedy selection repeats until the maximum number of solutions is reached, or the requirement of harmonic performance is met. At last, the final set of *Γ* is produced as the final optimal mitigation strategy.

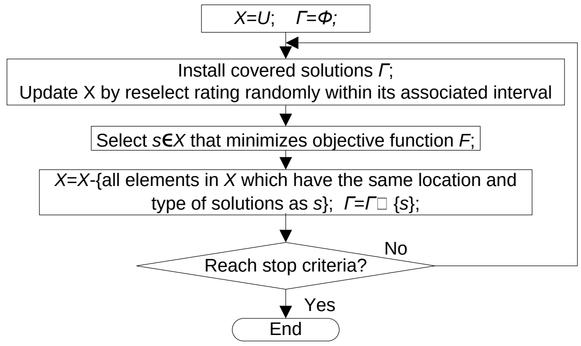

Fig. 4. Illustration of optimization process

3.4 Addressing Uncertainty in Optimization Process

In optimization, the harmonic performance varies depending on the operating conditions, including loading, outputs of distributed generation, network parameters and network topologies etc. However, the operating conditions vary throughout the day, week, month and year. This results in great difficulty in constructing realistic operating conditions in order to provide accurate harmonic performance assessment. Furthermore, the uncertainties of different parameters vary as well, depending on how the parameters are obtained and how reliable the information sources are. The study in literature shows that the integration of prior-knowledge of uncertainties of network behavior can greatly improve the performance in optimization and network analysis [17]. Therefore, it is important to address network uncertainties in simulation during the optimization process.

The uncertainties can be mainly addressed by the following aspects:

3.4.1 Uncertainty in Measurements: Measurements are important sources of information that can be used to model the operating conditions for network simulations. There are mainly two classes of measurements, real meter measurements and Pseudo-measurements. The former provides more accurate information while the latter is usually obtained by estimation and forecasting approaches which provide relatively less accurate information depending on the reliability of the data sources and the estimation approaches themselves. Distributed generation outputs (renewable generation in particular) can be measured and aggregated (or estimated) based on historical data or realistic output data considering the weather [18]. The loading of different types of customers (including commercial, industrial and residential loads) can be extracted from surveys [19]. A wide range of data for power system modelling and uncertainty analysis are given in [20], which provide actual loading, PV and wind profiles in European counties in the past decade. This can be used to model realistic network operation conditions for optimization.

3.4.2 Uncertainty in network topology and network parameters: Network topologies vary depending on the actual network states. Switchgear is used as tool for constraint management or capacity control, and their operation results in varying network topologies. The uncertainty of network topologies should be addressed during network analysis in order to accurately simulate the realistic network behavior. Furthermore, even with the given topologies, the network parameters are uncertain and they are usually not given directly, such as line impedances [21], short-circuit impedances [22] and OLTCT impedance [23] etc. Thus their values can only be estimated by indirect measurements or estimation.

The uncertainties mentioned above should be addressed in simulation settings in order to construct realistic operating conditions. The scenarios that will be included in simulation can be selected accordingly depending on the optimization purpose. For instance, for general harmonic performance assessment, all possible operating scenarios can be included in simulation for example using Monte Carlo approaches [21]. If the purpose of the optimization is to obtain strict constraint management, the study may focus on the worst operating scenarios in order to diminish constraint violation in actual network operation.

In solving optimization problems in large scale power networks, there is usually a constraint regarding computation load, as the optimization process usually requires many iterations before reaching the final optimal strategies. Thus Monte Carlo approach is not promising for this application due to the large number of possible operation scenarios existing in actual network operation. Therefore in this case, representative operating points can be selected and included in optimization process. The representative operating points can be sampled/selected based on probabilistic approaches which get the most likely operating conditions in actual operation.

In practice, the patterns of operating conditions repeat in season and year, and there is no need to repeat the similar operating conditions in network assessment. To reduce the repetition of running similar operating conditions in harmonic performance assessment, representative operating points can be selected and included in optimization process. The representative operating points can be selected using clustering techniques [11, 24], which cluster the inputs of data based on their similarity, i.e., the distance between the operating points. The inputs to the clustering approaches may include the loading profiles of different loads and profiles of different types of renewable energy generation. A number of clustering approaches have been explored to select the representative operating points, such as K-means, fuzzy c-means, agglomerative clustering algorithm and Gaussian mixture distribution algorithm. In [11] K-means with the clustering criterions of Calinski-Harabasz is used to select the representative operating points for power quality optimization. The sets of clusters obtained by various clustering techniques can be validated using Silhouette [25], and the best set can be used to generate the representative operationg points (i.e., the centres of the obtained clusters) for the simulation.

3.5 Simulation Results

The IEEE 68-bus test network, a realistic complex meshed transmission network, is used for the study here [26]. The network has five distinct areas interconnected with inter-area tie lines, which is suitable for testing the concept of the system area mapping proposed in the paper. The result is given in Fig. 5, which shows the THD obtained with mitigation is well below the thresholds.

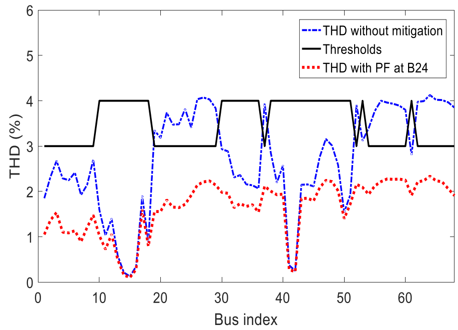

Figure 5 THD performance (with the obtained mitigation strategy) compared with the zonal thresholds

4. Conclusion

This paper lays foundation for the two possible forms of harmonic mitigation problems:

a) Global harmonic mitigation: the problem is to optimize the harmonic performance globally throughout the whole network, and make sure the harmonic performance across the network is within the same global harmonic performance threshold.

b) Zonal harmonic mitigation: based on the differentiated harmonic performance requirements, the network is divided into zones and each zone has its own harmonic performance threshold. The optimization is to make sure the harmonic performance at different zones is within the zonal harmonic thresholds rather than the global one.

Accordingly, the paper introduces two indices, Global Harmonic Gap Index and Zonal Harmonic Gap Index, which are used as the objective functions for solving the aforementioned two problems respectively. The paper also introduces the greedy based optimization approach, which divides the optimization process into a number of consecutive stages and at each stage the best solution is selected and included in the final optimal mitigation strategy. Finally the paper also identifies the uncertainties that should be considered in the optimization process, and introduces the clustering based approach for selecting the representative operating points that will be used in harmonic performance

assessment to cope with large number of potential operating points that should be considered during the optimisation. This approach can greatly reduce the computational load required in optimization applications especially in large-scale power systems.
With the quick network expansions and continuously increased renewable energy penetration, the planning of harmonic mitigation should also consider the future possible harmonic issues. In this way, it will provide a more cost-effective and long-term mitigation solution, and can maximize the mitigation capability to facilitate the future network issues. The future possible harmonic injection can be estimated based on the agreed contracts or grid infrastructure planning such as the planning of the installation of distributed generations. The harmonic injection by end-users can be estimated based on the potential customers that will have heavy non-linear loads.

5 Acknowledgements

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