Planning Approaches for the Strategic Placement of Passive Harmonic Filters in Radial Distribution Networks

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***Abstract*—This paper presents an approach to determine strategic buses for harmonic filter placement by correlating the sensitivity index based on the inherent structure theory network (ISTN) and harmonic current injection at buses of the distribution network/feeder. The strategic buses for the harmonic filter are characterized as either the bus with maximum total harmonic voltage distortion ($\mathrm{THD_V}$) in a distribution feeder, or the bus where the placement of the harmonic filter would result in maximum reduction in the overall average $\mathrm{THD_V}$ in the distribution feeder. The advantage of using this approach is that it provides insight into the interaction of the network structure with harmonic current sources in the distribution network in regards to the performance of harmonic filters. The assessment of the performance of a strategically placed passive harmonic filter based on the proposed approach is evaluated for peak and offpeak load scenarios on a radial distribution network. The results indicate that passive harmonic filters that are placed based on harmonic current emission levels perform better than harmonic filters placed based on ISTN alone. The strategically placed passive harmonic filters are highly effective in controlling harmonic propagation in distribution networks.**

***Index Terms*—Harmonics, passive filters, power quality, sensitivity index.**

I. Introduction

THE increase in harmonic levels in distribution networks in recent years is largely caused by a constant growth in nonlinear loads (electronics and power electronics devices) in the customer installations. Taken individually, they are mostly single-phase low-power devices that draw nonlinear currents from the network. Due to a very large number of individual devices in customer facilities (or in the part of the network) and despite the natural harmonic cancellation, they may cause significant harmonic distortion at the utility substation. The individual devices in commercial areas, which particularly abound in nonlinear loads, include fluorescent lighting, computers, and their peripherals, office machines, heat pumps, and central air-conditioning (HVAC) with variable speed drives.

Natural or forced harmonic cancellation at the commercial building service entrance resulting from the load diversity and/or load supply via transformers having different winding connections is not always sufficient to bring down the overall harmonic content in currents drawn from the network. When these nonlinear currents propagate through the network, they cause nonlinear voltage drops on network impedances and, as such, contribute to voltage distortion in the network. Even though resulting voltage harmonic distortion is much lower than the current harmonic distortion (due to reasonably low network impedances), additional filtering is often necessary to control voltage harmonic levels in distribution networks.

Single-tuned passive filters are an economical and efficient solution and are therefore commonly used in mitigating harmonic propagation [1]–[4]. A general filter planning methodology for feeders without large harmonic sources connected to them, based on measured bus voltage harmonics at substations, is described in [5]. References [2], [4], [6], and [7] optimize capacitors (tuned filters), based on cost and harmonic constraints for the strategic placement of harmonic filters. In [8], an approach to identify sensitive buses for the placement of a harmonic filter based on ISTN, followed by the optimization of related objective functions was used. The optimization approach, besides being very complex, requires accurate information on harmonic current sources at buses and provides little insight into the harmonic performance of the network, in particular, at the planning stage where load information is based on approximation and where there is a need to analyze harmonic propagation for various load scenarios for contingencies, fundamental frequency performance, etc. Hence, it is of prime importance that the approach used to improve the harmonic performance of the distribution network provides the planner with sufficient insight pertaining to harmonic propagation and strategic placement of harmonic filters.

In this paper, a sensitivity index (SI), based on ISTN [8], is used to determine candidate buses for the placement of harmonic filters. Harmonic current injection at each bus of the distribution feeder is then incorporated into the sensitivity index to form a new normalized sensitivity index (NSI) that includes the influence of harmonic current on the placement of harmonic filters. To assess the performance of the harmonic filters placed at the respective buses based on NSI, simulation is performed on a real 11-kV radial distribution feeder with aggregate harmonic loads at the buses for peak load and offpeak load scenarios.

II. Inherent Structure Theory of Network and Sensitivity Index

The admittance matrix of a power system at the fundamental frequency can be analyzed in terms of its eigenvalues and eigenvectors. This concept is useful to create a framework in which

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the system response to disturbances (e.g., system voltage sensitivity, voltage control, fault levels, etc.) can be well understood and analyzed. At harmonic frequencies, similar concepts are used to explore power system response to harmonic disturbances (i.e., harmonic voltage sensitivity at different buses arising from the injection of harmonic currents [8]).

The h harmonic order admittance matrix $\mathbf{Y}^h$ of the N-bus power system can be formulated in terms of its eigenvalues λ_i^h and eigenvectors $\mathbf{v}_i^h$ [8] as

$$\mathbf{Y}^h = (\mathbf{V}^h)\mathrm{diag}(\boldsymbol{\lambda}^h)(\mathbf{V}^h)^{-1} \tag{1}$$

where $\mathbf{V}^h = (\mathbf{v}_1^h, \ldots\ldots\ldots, \mathbf{v}_N^h)$, and $\mathrm{diag}(\boldsymbol{\lambda}^h)$ is the diagonal matrix whose elements are the eigenvalues of $\mathbf{Y}^h$.

The harmonic impedance matrix is given by

$$\mathbf{Z}^h = (\mathbf{V}^h)\mathrm{diag}(1/\boldsymbol{\lambda}^h)(\mathbf{V}^h)^{-1} \tag{2}$$

and harmonic voltages $\overline{\mathbf{U}}^h$ at each bus by

$$\overline{\mathbf{U}}^h = (\mathbf{V}^h)\mathrm{diag}(1/\boldsymbol{\lambda}^h)(\mathbf{V}^h)^{-1}\mathbf{I}^h \tag{3}$$

where $\mathbf{I}^h$ is the harmonic current injected at each bus.

Equation (3) can be rewritten as

$$\overline{\mathbf{U}}^h = \sum_{i=1}^{N} \frac{1}{\lambda_i^h}\mathbf{v}_i^h \left(\mathbf{w}_i^h\right)^T \overline{\mathbf{I}}^h \tag{4}$$

where $\mathbf{w}_i^h$ is the ith left eigenvector of the matrix $\mathbf{Y}^h$.

Based on (4), it has been shown in [8] that the eigenvalue of the minimum modulus is often associated with the scalar factor $\{(\mathbf{w}_i^h)^T\overline{\mathbf{I}}^h\}$ of the maximum modulus. It further shown that as an approximation to compute harmonic voltages $\overline{\mathbf{U}}^h$, in most cases, it is sufficient to consider only the term associated with the eigenvalue of minimum modulus λ_k given by

$$\overline{\mathbf{U}}^h \cong \frac{1}{\lambda_k^h}\mathbf{v}_k^h \left(\mathbf{w}_k^h\right)^T \overline{\mathbf{I}}^h. \tag{5}$$

The sensitivity matrix $\mathbf{S}_i^h$ of the ith eigenvalue is then

$$\mathbf{S}_i^h = \mathbf{w}_i^h \left(\mathbf{v}_i^h\right)^T = \begin{bmatrix} \frac{\partial\lambda_i^h}{\partial y_{11}^h} & \cdots & \frac{\partial\lambda_i^h}{\partial y_{1N}^h} \\ \vdots & \ddots & \vdots \\ \frac{\partial\lambda_i^h}{\partial y_{N1}^h} & \cdots & \frac{\partial\lambda_i^h}{\partial y_{NN}^h} \end{bmatrix}. \tag{6}$$

Each element of the matrix $\mathbf{S}_i^h$ represents the sensitivity coefficient relating to the change in the ith eigenvalue to the element of the $\mathbf{Y}^h$ matrix.

As the interest here is only in terms associated with the eigenvalue of minimum modulus λ_k^h, the corresponding sensitivity matrix becomes

$$\mathbf{S}_k^h = \mathbf{w}_k^h \left(\mathbf{v}_k^h\right)^T = \begin{bmatrix} \frac{\partial\lambda_k^h}{\partial y_{11}^h} & \cdots & \frac{\partial\lambda_k^h}{\partial y_{1N}^h} \\ \vdots & \ddots & \vdots \\ \frac{\partial\lambda_k^h}{\partial y_{N1}^h} & \cdots & \frac{\partial\lambda_k^h}{\partial y_{NN}^h} \end{bmatrix}. \tag{7}$$

Equations (5) and (7) can be combined and written as

$$\overline{\mathbf{U}}^h \cong \frac{1}{\lambda_k^h}\left(\mathbf{S}_k^h\right)^T \overline{\mathbf{I}}^h. \tag{8}$$

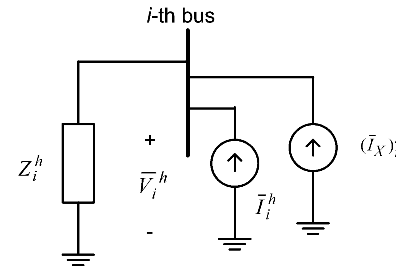

Fig. 1. Harmonic equivalent circuit.

It can be observed from the sensitivity matrix in (6) that placing a shunt filter at the i^{th} bus implied a change in value of the i^{th} diagonal element (∂y_{ii}^h) of the admittance matrix and correspondingly leads to a change in the eigenvalue of minimum modulus $(\partial\lambda_k^h)$. The sensitivity index of each bus to the placement of harmonic filters therefore refers to the values of the set of diagonal elements of the sensitivity matrix where the highest value implied its association with the most sensitive bus [8].

III. Influence of Harmonic Current Sources on Bus Sensitivity

The harmonic equivalent circuit of the ith bus of a distribution network can be represented as shown in Fig. 1.

The harmonic voltage developed at bus i can be then expressed as

$$\overline{V}_i^h = \left(\overline{I}_i^h + (\overline{I}_X)_i^h\right)\overline{Z}_i^h \tag{9}$$

where $\overline{Z}_i^h$ is the system harmonic impedance at bus i, $\overline{I}_i^h$ is the harmonic current injection at the ith bus, $(\overline{I}_X)_i^h$ is the sum of equivalent harmonic currents resulting from harmonic current injection at all buses except the ith bus, calculated based on superposition theorem, and $\overline{V}_i^h$ is the harmonic voltage developed at the ith bus.

The sensitivity index described in Section II is essentially an indicator that shows the relative magnitude of the system harmonic impedance of each bus, or the relative magnitude of the harmonic voltage developed across the bus of interest. This is verified through simulation with 1-A current injection at each bus of a distribution feeder. The corresponding system harmonic impedances are shown in Fig. 2 where it is indicated that the sensitivity index at each bus has a similar trend with its system harmonic impedance.

However, in the case when harmonic current injection at the buses is not equal in magnitude, the harmonic voltage (or impedance) at the respective buses has a completely different trend from the sensitivity index obtained based on ISTN as shown in Fig. 3. For example, the most sensitive bus indicated by SI is bus 19, whereas the bus with the highest $\mathrm{THD_V}$ is bus 10. This shows that the location and magnitude of harmonic current injection has an influence on bus sensitivity.

When an ideal harmonic filter (tuned to the h harmonic order) is connected in shunt at the ith bus, the filter acts as a short circuit and absorbs the h harmonic current injection at the ith

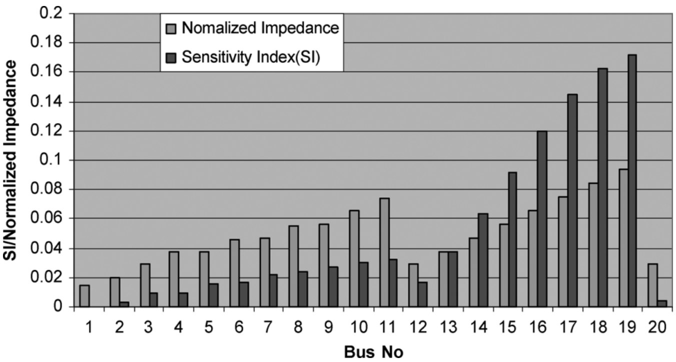

Fig. 2. Bus impedance and sensitivity index of buses based on a fixed 1-A, 5th harmonic current injection at all buses.

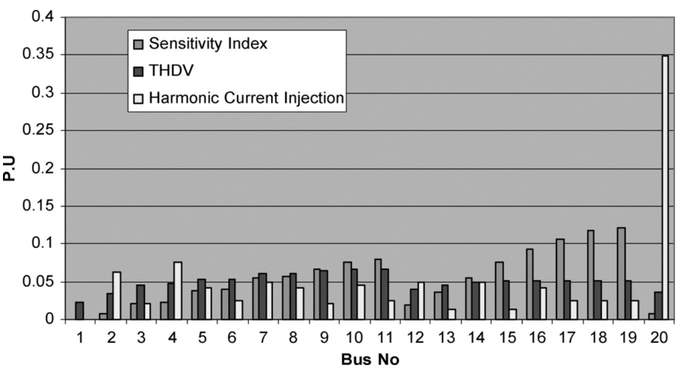

Fig. 3. Harmonic current injection, sensitivity index, and resulting $\mathrm{THD_V}$ of a 20-bus radial distribution feeder.

bus (effectively preventing the harmonic current from propagating to other parts of the network/feeder and causing harmonic voltage distortion) and, at the same time, diverts some of the harmonic currents originating from other buses away from the utility source, thereby causing $\overline{V}_i^h = 0$ and an overall reduction in harmonic voltage at the feeder. Therefore, it would clearly be an advantage to select the bus with the highest harmonic current injection for the placement of the harmonic filter. As shown in Fig. 3, the identification of strategic buses for the placement of harmonic filters should not be based on the sensitivity index alone, but also on the magnitude of harmonic current injection at each bus.

Keeping in mind that harmonic impedance at the bus of interest is reflected by its sensitivity index and assuming that the magnitude of harmonic current injection $(\bar{I}_i^h)$ at the bus is known, then in order to establish the ranking of the respective bus sensitivity, a general expression for $(\bar{I}_X)_i^h$ is needed. In the case of the radial distribution feeder, the magnitude of $(\bar{I}_X)_i^h$ is approximately inversely proportional to the distance of the bus of interest from the utility source. Since the SI is an indicator of the electrical distance from the utility source, it can be assumed that

$$(I_X)_i^h \cong \frac{1}{\mathrm{SI}_i^h}. \tag{10}$$

It has been discussed earlier in this section that SI_i^h can be taken to reflect $\overline{Z}_i^h$ and, consequently, $\overline{V}_i^h$ $(\mathrm{THD_V})$. Hence, based on (9) and using normalized values, a new normalized sensitivity index (NSI_i^h) that incorporates the magnitude of harmonic current injection at different buses can be written as follows:

$$\mathrm{NSI}_i^h = \frac{\mathrm{SI}_i^h \left[\frac{|I_i^h|}{\sum_{i=1}^{N} |I_i^h|} + \frac{1/\mathrm{SI}_i^h}{\sum_{i=1}^{N} 1/\mathrm{SI}_i^h} \right]}{\sum_{i=1}^{N} \mathrm{SI}_i^h \left[\frac{|I_i^h|}{\sum_{i=1}^{N} |I_i^h|} + \frac{1\mathrm{SI}_i^h}{\sum_{i=1}^{N} 1/SI_i^h} \right]}. \tag{11}$$

IV. Strategic Placement of Passive Harmonic Filters

The objective of filter placement procedure in a distribution network/feeder is to use the minimum number of filters to effectively improve harmonic performance of the network/feeder. At the planning stage where exact information on harmonic current injection at buses is usually unavailable and changing design could modify network parameters, it is helpful to gain insight into the harmonic performance of the distribution network/feeder in regards to changes in magnitude and location of the harmonic current injection or network/feeder configuration.

In general, placing a harmonic filter at a strategic bus of a distribution network/feeder is aimed at achieving either one or both of the following:

- a reduction in the maximum $\mathrm{THD_V}$ developed as a result of harmonic current injection in the network/feeder;
- a maximum reduction in overall average $\mathrm{THD_V}$ in the network/feeder.

In regards to bus sensitivity, it should be noted that the primary objective of placing a harmonic filter at the most sensitive bus is that a maximum reduction in $\mathrm{THD_V}$ (from the highest $\mathrm{THD_V}$ value to almost zero) occurs at that particular bus in the distribution network/feeder. Consequently, some reduction in $\mathrm{THD_V}$ at other buses is expected to occur. However, the maximum reduction in overall average $\mathrm{THD_V}$ in the feeder may not necessarily be achieved. Ideally, the main purpose of identifying the most sensitive bus in the network/feeder is that the connection of a relatively large harmonic current source (nonlinear loads) can be avoided at such buses. However, in practice, utility engineers may not always have the options to select buses for the connection of large nonlinear loads. Generally, new loads (aggregate of linear and nonlinear) are connected to the nearest available source. Hence, there is a need to identify locations (buses) where strategic placement of harmonic filter(s) will cause a reduction in $\mathrm{THD_V}$ at the most sensitive bus or to identify potentially sensitive bus(es) where $\mathrm{THD_V}$ might exceed predefined limits. Three approaches for the strategic placement of filters are proposed.

If the loading condition of the distribution network/feeder is such that the magnitudes of harmonic current injection at each bus are approximately equal, the sensitivity index based on ISTN could be used to identify the most sensitive bus.

For unevenly distributed harmonic current injections (a more realistic case in actual distribution networks) at the buses, however, a new normalized sensitivity index (NSI), given by (11), is proposed.

In the case where the strategic placement of the harmonic filter is to achieve a maximum reduction in the overall average $\mathrm{THD_V}$ in the network/feeder, a more straightforward approach based on the average harmonic current emission level is proposed. As mentioned in Section III, besides effecting a structural change in the network/feeder, the harmonic filter provides a low impedance path for the flow of harmonic current (sink) originating from the bus of connection and buses in close proximity with the harmonic filter and thereby preventing these harmonic currents from propagating to other parts of the network/feeder; hence, resulting in an overall reduction of harmonic voltage distortion at all buses. Since we are looking at the reduction of overall average $\mathrm{THD_V}$ of the whole distribution network/feeder instead of $\mathrm{THD_V}$ at specific buses, the effect of sinking a large magnitude of harmonic currents from the network is expected to have a greater impact on $\mathrm{THD_V}$ reduction than modification of the network structure. Therefore, it is proposed that the most effective buses to achieve the maximum reduction in overall average $\mathrm{THD_V}$ are those buses found in regions with a large magnitude of harmonic current injection. An index, called the harmonic current emission level index (CELI_i), is therefore defined by taking into account normalized values of the approximate sum of harmonic current emissions at each bus. For example, with reference to Fig. 4, the harmonic current emission level index of bus 2 (CELI_2) is computed as follows:

$$\mathrm{CELI}_2 = \frac{E_2}{\sum_{i=1}^{N} E_i} \quad (12)$$

where $E_2 = \sum_{h=3,5,7\ldots}(|I_1^h| + |I_2^h| + |I_3^h| + |I_{12}^h| + |I_{20}^h|)$.

V. Application Example

The topology of the medium-voltage (11 k) distribution network is typically radial where a number of substations is interconnected to form a feeder. Normally, several feeders (11 kV) are fed from the 275-kV or 132-kV grid systems through stepdown transformers. In this case example, two 132/11-kV stepdown transformers are used to feed 10 outgoing 11-kV feeders (all radial) that supply a city center. Network and load information were used to build the $\mathbf{Y}^h$ matrix of the distribution network. Sensitivity indices that were obtained were found to be inconsistent if more than one feeder was included in the $\mathbf{Y}^h$ matrix. This means that the sensitivity index must be derived on an individual feeder basis for the radial distribution network. Hence, for this example, a single 11-kV radial feeder from the distribution network is modeled. The harmonic voltage distortion from higher voltages and aggregate harmonic loads at the 11-kV source is modeled as background harmonics. The feeder under study is a 20-bus radial feeder with mixed load types consisting of commercial (shopping complexes, offices, hotels), residential, and industrial customers (Fig. 4).

Planning for harmonic filters in medium-voltage distribution feeders typically requires network and aggregate load data. In this example, the harmonic model is built based on typical harmonic current spectra of different classes of aggregate harmonic loads, their expected power demand, and linear/nonlinear load participation developed from sample harmonic field measurements (see Tables I and II). It should be noted that the aggregate harmonic load data are derived based on representative statistical models and not on actual harmonic measurements taken at each of the substations in the feeder as the approach proposed in this paper requires only approximate and indicative data for strategic filter placement.

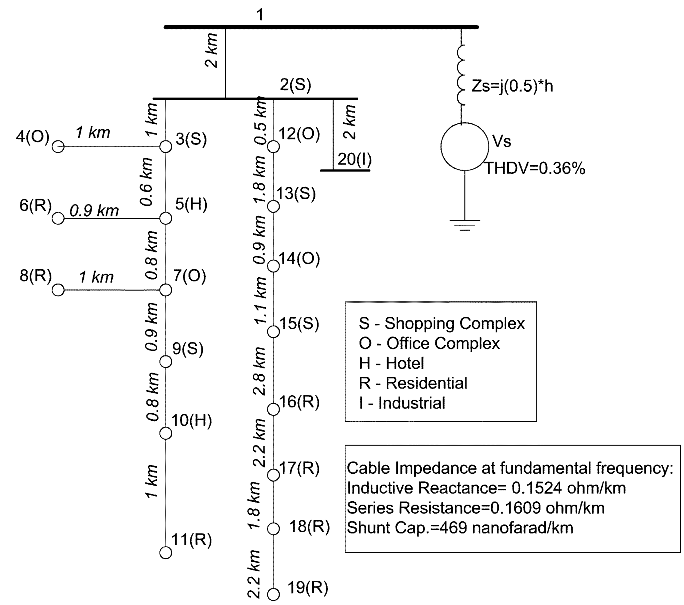

Fig. 4. Single-line diagram of the distribution feeder.

TABLE I
HARMONIC CURRENT SPECTRA OF DIFFERENT CLASSES OF AGGREGATE HARMONIC LOADS DURING THE PEAK LOAD PERIOD

AGGREGATE LOAD TYPE	% NONLINEAR LOAD	HARMONIC CURRENT SPECTRUM		
		5th	7th	11th
Shopping Complex	40.0	0.94%	1.0%	0.17%
Office Complex	40.0	5.39%	2.78%	0.04%
Hotel	40.0	3.23%	1.32%	1.28%
Residential	60.0	2.4%	2.2%	1.6%
Industrial	60.0	4.3%	3.3%	1.2%

TABLE II
HARMONIC CURRENT SPECTRA OF DIFFERENT CLASSES OF AGGREGATE HARMONIC LOADS DURING OFFPEAK LOAD PERIOD

AGGREGATE LOAD TYPE	% NONLINEAR LOAD	HARMONIC CURRENT SPECTRUM		
		5th	7th	11th
Shopping Complex	90.0	5.4%	3.5%	0.9%
Office Complex	90.0	10.0%	3.2%	0.46%
Hotel	30.0	2.0%	0.7%	3.8%
Residential	30.0	4.3%	3.2%	2.1%
Industrial	60.0	4.9%	1.2%	1.5%

Power factor correction capacitors are placed at every bus except at the residential load buses, as residential loads comprise many individual small loads. To study the harmonic performance of the distribution feeder, commercial software SuperHarm is used to model the distribution feeder and its aggregate harmonic load [9].

Before any harmonic filter is considered for the planned distribution feeder, simulation is performed to ascertain that network parameters and loads information used in the model are within acceptable ranges. Summary results of the funda-

TABLE III
SUMMARY RESULTS FROM SIMULATION

Load Scenarios	V_{rms} (p.u)	THD_V (%)
Off Peak	0.996 – 1.003	0.62 – 0.97
Peak	0.99 – 1.009	0.86 – 2.53

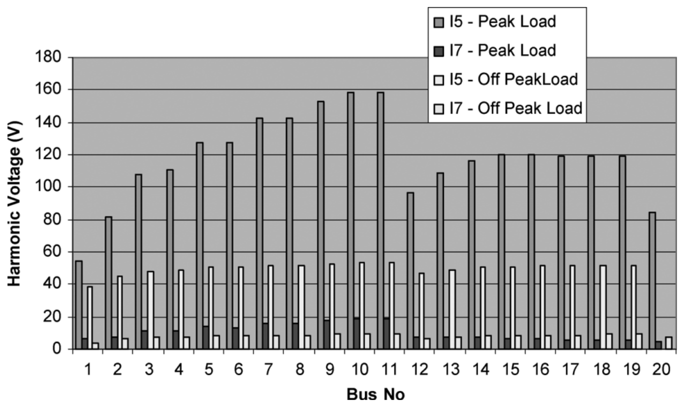

Fig. 5. Fifth and seventh harmonic voltage during peak and offpeak load periods.

mental voltage and total harmonic voltage distortion (THD_V) are shown in Table III and they are in close agreement with measured values for the typical radial distribution feeder.

In considering a harmonic filter for a distribution feeder, the first task is to identify the most effective bus for the placement of the filter (assuming that one filter is sufficient to achieve the desired total harmonic voltage distortion) based on new sensitivity index (11). The results are shown in Fig. 5. It can be observed that the most sensitive bus for the placement of the harmonic filter for the planned distribution feeder is at bus 10 for the peak load period and offpeak load period.

A. Frequency Response of the Distribution Feeder

Frequency response is critical in determining the effectiveness of the harmonic filter as it provides information on the existence of any resonance condition in the feeder. Parallel resonance results in a sharp rise in voltage at the resonance frequency, which depends on the ratio of the equivalent capacitor reactance to inductor reactance across a particular bus [10]. The equivalent resistance at the respective bus influences the peak voltage at resonance frequency.

A frequency scan for a $1\angle 0^\circ$ p.u. current injection at bus 2 is performed to determine the frequency response of the feeder. Fig. 6 shows the frequency response at bus 19 (the most sensitive bus without considering the influence of harmonic current). Frequency responses at other buses of the feeder have similar shape and resonance frequencies but different voltage magnitude depending on the respective bus sensitivity. The large voltage magnitude at resonance frequency (7th harmonic) during the offpeak load period is primarily due to low resistive loads presence in the feeder, whereas during the peak load period, harmonic voltage is very much suppressed (damped) at the resonance frequencies (Fig. 6) due to larger resistive loads.

Based on the frequency response curves shown in Fig. 6 and harmonic current spectra of the aggregate harmonic loads (harmonic current sources), a passive filter is tuned [1], [11] to effectively reduce the overall THD_V of the feeder and mitigate the THD_V level of the most sensitive bus. Clearly, in this case, the harmonic filter would have to be tuned to the 5th and 7th harmonic as both harmonic sources and parallel resonance are dominated by the 5th and 7th harmonic. However, it is assumed that due to economic reasons, only one single-tuned passive harmonic filter should be used. The 7th order harmonic filter is ruled out since the 7th harmonic voltage distortion is significantly less than the 5th, and as the 7th harmonic order resonance occurs during the offpeak load period (see Fig. 6) where harmonic current injection is significantly lower based on the aggregate harmonic load model shown in Tables I and II.

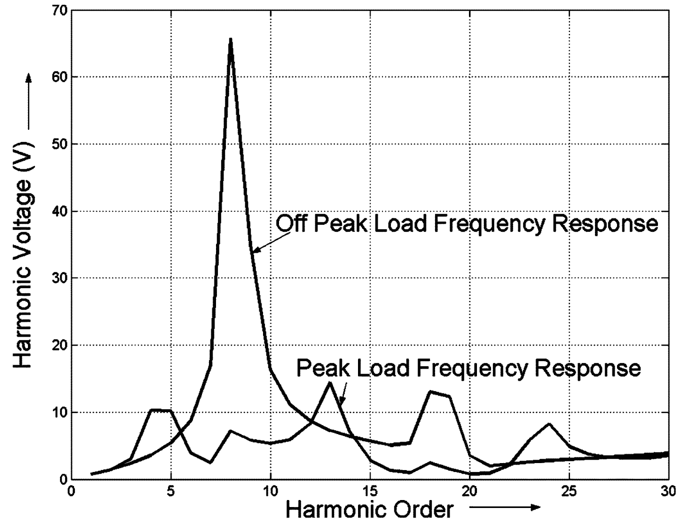

Fig. 6. Frequency response of the distribution feeder at bus 19.

B. Identification of Strategic Buses

Strategic buses for the placement of harmonic filters are identified based on (11) and (12). Fig. 7 shows the results obtained with the new sensitivity index derived using (11) against the base case (without any harmonic current injection) sensitivity index and THD_V at each bus for the peak load scenario. The new sensitivity index indicates buses 10 and 16 to be the most sensitive buses compared to the base-case sensitivity index, which indicates buses 18 and 19. Comparing THD_V at each bus in Fig. 7 with the new sensitivity index, it is clear that the new sensitivity index is in closer agreement with THD_V at buses with bus 10 having the highest THD_V. Hence, based on existing load scenarios placing a harmonic filter at bus 10 or 16 will eliminate the highest harmonic voltage point (bus) along the feeder and modify the THD_V profile as shown in Figs. 8 and 9. Therefore, bus 10 is considered to be the most strategic bus for filter placement. With a filter at bus 10, there is a much larger margin for any increase in harmonic current injection (nonlinear load) at buses 8, 9, 10, and 11, which used to be buses that are potentially at the risk of exceeding the harmonic distortion limit.

Another approach to the identification of strategic buses for harmonic filter is based on (12). In this approach, the effectiveness of the filter is measured by the quantum of reduction in overall average THD_V of the feeder. The harmonic current

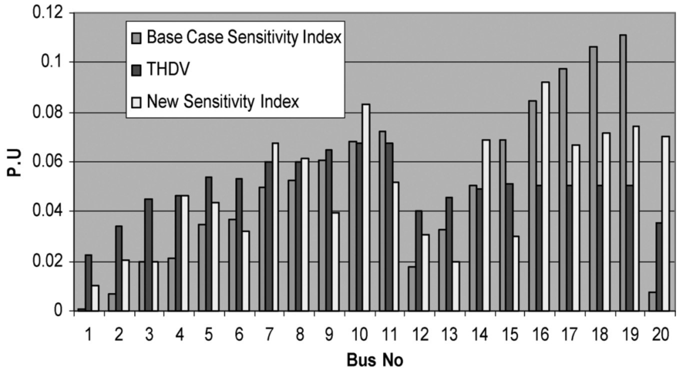

Fig. 7. Ranking of buses based on the new sensitivity index and $\mathrm{THD_V}$ during peak load.

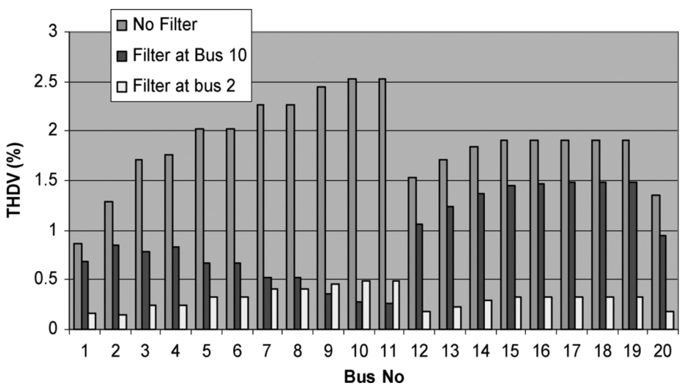

Fig. 8. $\mathrm{THD_V}$ profile with the harmonic filter placed at bus 10 and bus 2 during peak load.

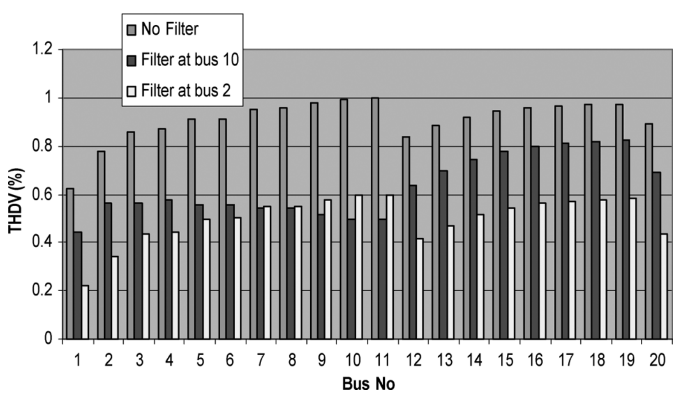

Fig. 9. $\mathrm{THD_V}$ profile with harmonic filter placed at bus 10 and bus 2 during the offpeak load.

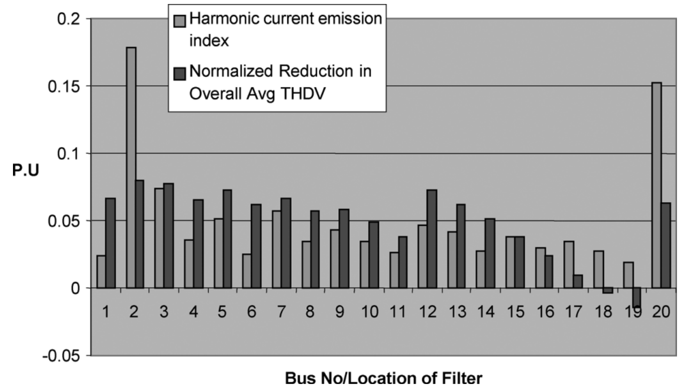

Fig. 10. Harmonic current emission index and reduction in overall average $\mathrm{THD_V}$ of feeder during the peak load.

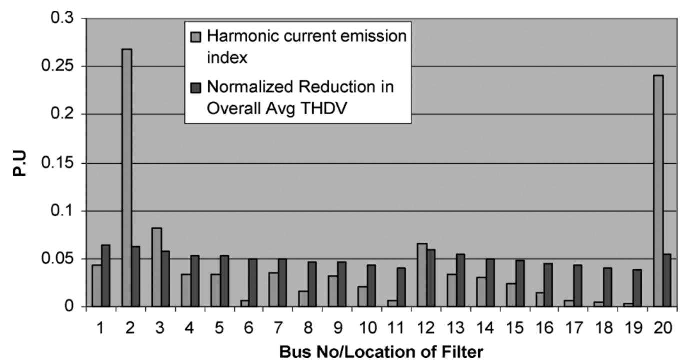

Fig. 11. Harmonic current emission index and reduction in overall average $\mathrm{THD_V}$ of feeder during the offpeak load.

emission index (CELI) is calculated based on (12). Bus 2 is found to have the largest CELI in this case. Comparative results are shown in Figs. 10 and 11. Clearly, with a harmonic filter placed at bus 2, there is the highest reduction in overall average $\mathrm{THD_V}$ in the feeder for both peak and offpeak load scenarios.

Depending on the performance requirement of the harmonic filter, two buses (bus 10 and 2) have been identified as strategic buses for the placement of the filter. Bus 10 is the most sensitive bus in terms of reducing the maximum $\mathrm{THD_V}$ in the feeder whereas bus 2 is the most effective in terms of reducing the overall average $\mathrm{THD_V}$ in the feeder. With the constraint of using only one harmonic filter in the feeder, bus 2 would be a more strategic choice as can be observed from Figs. 8 and 9. The filter at bus 2 results in a much better reduction in overall $\mathrm{THD_V}$ with a slight expanse at bus 9, 10, and 11 for both peak and offpeak load conditions (Figs. 8 and 9).

VI. Robustness of the Solution

Information related to harmonic current injection at the buses is exploited to determine the most effective bus for the placement of the harmonic filter. In the example, the harmonic filter placed at bus 2 is highly effective in improving harmonic performance of the feeder as shown in Table IV. (Total demand of distribution feeder during peak load and offpeak load is 390 A and 99 A, respectively.) Robustness of the solution is maintained for both the peak and offpeak load condition so long as the nonlinear load variation at the buses follows an approximately fixed ratio. Changes in the distribution of harmonic currents (nonlinear loads) along the feeder are expected to have a significant impact on the harmonic performance of the feeder. For example, if due to relocation of industries, the harmonic source at bus 20 (which is significantly larger than all other harmonic sources) is moved to bus 16, and deterioration in the distribution feeder's harmonic performance can be expected, although there is no change in the network structure (see Fig. 12). In the case when there is a major network structural change (e.g., due to a cable fault between buses 1 and 2), an alternative source is used to feed the feeder at bus 11. An enhancement in harmonic performance can be expected as the harmonic filter is now at the

TABLE IV
SUMMARY OF DISTRIBUTION FEEDER'S PERFORMANCE WITH THE FILTER AT BUS 2

LOAD CONDITION	REDUCTION IN OVERALL THD_V	REDUCTION IN PEAK THD_V	FUNDAMENTAL VOLTAGE REGULATION
Peak	84%	80%	1.009 – 0.99 p.u
Off Peak	45%	40%	1.006 - 1.00 p.u

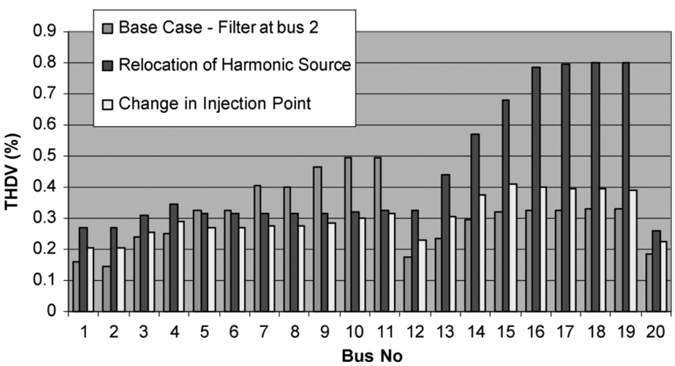

Fig. 12. Robustness of the feeder's harmonic performance to changes in harmonic source and network structure.

buses of higher sensitivity and high harmonic current emission level (see Fig. 12).

VII. CONCLUSION

This paper presented three approaches (two based on sensitivity indices and one based on average harmonic current emission level) to identify strategic buses for the placement of harmonic filters in the radial distribution feeder, the bus sensitivity method, and the harmonic current emission level method. Two of those (more suitable for application in realistic distribution networks) were discussed and illustrated in detail. While the approaches can only be considered as approximation techniques, the results are promising. In particular, the approaches provide insight into the interaction of harmonic current sources, network structure (sensitivity index), and location of the harmonic filter. They clearly demonstrate that highly sensitive network buses having relatively high harmonic current emission levels are strategically effective buses for the placement of harmonic filters. Harmonic filters placed at those buses are able to modify (i.e., reduce) the sensitivity of the respective buses and act as sinks for harmonic currents. Two new indices are proposed in the paper that can be used as a guide for the strategic placement of harmonic filters. This type of information is very useful for distribution planning engineers.

The methods proposed in the paper do not require precise harmonic measurements and load parameters as input data. Since they are based on normalized values, typically, network parameters, power demand, and types of aggregate loads (commercial, residential, or industrial) at each bus are sufficient for the identification of strategic buses for harmonic filter placement.

The robustness and limitations of methodologies proposed are also discussed and illustrated.

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