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Harmonic Source Identification in Power Distribution System and Meter Placement using Network Impedance Approach

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Abstract: The growing use of non-linear loads in the electrical systems has made harmonics a serious problem. Harmonic disturbance leads to degradation of power quality by deforming the current or voltage waveforms, thus, necessitating the effective techniques for harmonics detection. The purpose of this study is to propose a method for a single harmonic source identification in power distribution system by implementing a network impedance technique, and optimize the meters allocation by optimum meter placement algorithm (OMPA). The main advantage of this technique is that it results in enhanced accuracy with minimum vulnerability towards deviations in the measurements. Moreover, it minimizes the number of nodes for meter allocations, thereby resulting in economic advantages. To validate the results and effectiveness of the proposed methodology, a standard IEEE 13-Bus industrial network is designed using ETAP software and the algorithm is developed in MATLAB software. The validation of proposed algorithm OMPA is done by comparing its results with Monte Carlo Algorithm (MCA) technique. The results show that without any deviation in the network impedances, OMPA gives 89% accuracy as compared to 75% accuracy of MC. With the deviations in the harmonic impedances, the accuracy of both algorithms is decreased. For the deviation value $\eth = 1^{-13}$ in the harmonic impedances, the overall accuracy of OMPA stays at 75%, while that of MCA drops down to 56%. The developed algorithm OMPA is not only better in performance in harmonics identification with minimum number of meters, but also shows more resistance to the variations in the harmonic impedances as compared to MCA.

Keywords: Accuracy, Deviation, Harmonics, Impedance, Optimization

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1. INTRODUCTION

The growing use of power electronic and other non-linear devices by the domestic, industrial and commercial consumers has led to a serious problem in the power quality, i.e. harmonics [1]. Usually harmonic related problems are not taken seriously as they do not show any instantaneous deteriorating effect, but in the long-run, the existence of harmonics can lead to certain serious problems such as waveform distortion, degradation of power quality, overheating of the electrical equipment, power losses and, in some cases, malfunctioning of the control systems [2, 3]. Recognition of origin of harmonics is, therefore, important for the regulation of energy quality in order to minimize the risks.

In a distribution system, the abundance of power electronic tools cause harmonic distortion which, if not addressed promptly and effectively, results in the serious operational issues in electrical systems [4]. Harmonic distortions can cause several damages and disturbances including wire overheating, power loss and capacitor bank failure [5, 6]. Plus, high levels of harmonic distortion can cause certain effects such as increased temperature of transformer, capacitor, motor or generator, maloperation of electronic equipment (which relies on voltage zero crossing detection or is sensitive to wave shape), incorrect readings on meters etc. Moreover, when power electronic components, which are source of harmonics, are connected to the network, their harmonic currents impact the operation of circuit breakers as a consequence of circuit breakage [7]. This is primarily the source of the nuisance tripping. In this way, the harmonics cause maloperation of overcurrent safety mechanisms in the power system [8]. Therefore, the existence of harmonics has rendered a serious concern in power quality and reliability issues which necessitates efficient and reliable techniques for the identification and elimination of harmonics in a power system.

Extensive research works have been carried out to develop algorithms and strategies to identify and minimize harmonic sources in an electrical system. In this regard, a number of harmonics locating techniques are being utilized nowadays to identify and rectify harmonics related issues, but every method has certain requirements which make them either non-economical or complicated. The requirements of prior information about system parameters, history of load profiles, actual network impedance for each harmonic order, real and reactive power flows in the system for every harmonic frequency make these methods among the costly or complex solutions [9, 10]. The authors in literature [11] proposed a novel method for non-invasive estimation of utility harmonic impedance based on complex independent component analysis (ICA). The limitation of this method is that resonance in the utility impedance leads to inefficiency of the results. In [12], the authors present an analysis technique to evaluate the static harmonic statistically. Along with the analysis of static harmonics, the proposed method also investigates the impact of measurement noise on the measurements. The results show that any error or deviations in the measurement can significantly degrade the performance of the proposed method. The ref. [13] demonstrates the constrained neural network-based approach for the harmonics' identification. Although, neural network-based method is really effective in the identification of harmonics, but it cannot distinguish between closely linked electrical buses that are located far from meters location. Furthermore, this method demands considerable amount of time for computation as it requires the information of a lot of system parameters for computation. The authors in the literatures [14, 15] discuss the limitation of the previous studies that have presented active power flow method for the harmonic identification at the point of common coupling (PCC). Active power flow method is easy to implement but it has certain limitations. As the identification is done on PCC, therefore, the precise location of origin of harmonics cannot be found using this method. A network impedance method for the localization of source of disturbance in a power system is presented in [16]. This method is easy to implement and is applicable to DC source too. The downside of this method is that it needs bulk of prior information about system parameters to get the desired results. The error in the measurements can drastically degrade the results. In the literature [17], an intelligent algorithm 'Particle Swarm Optimization' is proposed for optimum meter placement and measurement of node voltages. The method is applicable to ring-configured electrical systems. The main advantage of this method is that the results are immune to extraneous noise. However, this is just an optimization technique. It needs to be linked with a harmonic source identification technique to locate harmonic source with optimized meters.

Most of the techniques used to locate the harmonic sources require a large set of parameters such as voltage, real power (P), and reactive power (Q) at each harmonic frequency. The acquisition of these parameters require complex computation rendering the solution to be non-economical at large scale [4]. Therefore, it is utmost important to develop method which ensures the harmonic source identification with enhanced accuracy along with the minimum cost.

In this paper, impedance-based optimum meter placement algorithm (OMPA) is presented to identify the harmonic source in a power network of any size. Moreover, the optimization strategy reduces the requirement of number of meters to be installed at nodes. The efficacy of the proposed algorithm is validated by comparing the results with those of Monte Carlo Algorithm (MCA). The structure of the paper is as follows. Section II presents the system design and flowchart of the research work. The formulation of OMPA and MCA are briefed in the section III. The results and detailed discussion are presented in section IV, followed by the conclusion in section V.

2. SYSTEM DESIGN

Figure 1 demonstrates step-by-step flowchart of this research work's methodology. First, software modelling of the IEEE 13-Bus network is done on ETAP. Then, after the balancing of the system, the impedances of the electrical network are transformed into harmonic impedances. Based on the calculated harmonic impedances, harmonic impedance matrix Z^h_{bus} is formulated. At the second stage, MATLAB is used to develop an algorithm OMPA to identify the harmonic source in the network based on the Z^h_{bus} and harmonic node voltages. After the algorithm is formulated and its application on the network is verified, its accuracy is compared with MC algorithm against a variety of harmonic impedances.

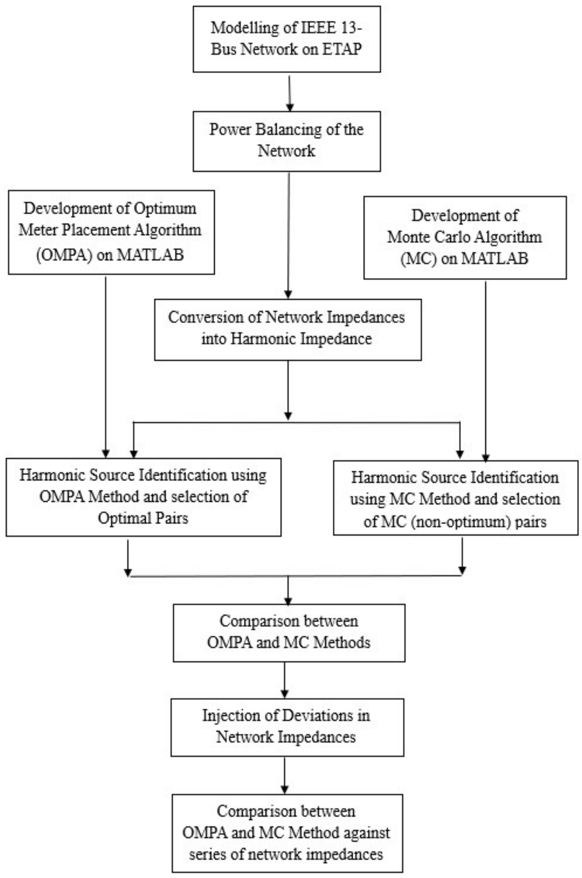

Figure 1. Flowchart of the proposed methodology

3. FORMULATION OF ALGORITHMS

To locate the harmonic sources in a standard IEEE 13-Bus industrial power network, OMPA method is developed for harmonic identification as well as node optimization. This section details the development method of OMPA along with the development of a competitor method MC.

3.1 Development of OMPA

In this section, the proposed algorithm OMPA is explained in detail. The harmonic index h is omitted for the sake of simplicity. This is to be noted that before proceeding with OMPA approach, the modelling, balancing and calculation of harmonic impedances have already been performed. The factor Δ is used to depict the impedance ratio for any node i such that:

$$\Delta_i^{x,y} = \frac{z_{x,i}}{z_{y,i}} \quad (1)$$

In Equation (1), x and y represent the rows of the Z^h_{bus}, and i represents the column of the Z^h_{bus}. For a network consisting of n nodes, i.e. n x n matrix of harmonic impedances, the range of x, y and i are as follows:

$x = 1,2,3\ldots, n$, $y = 2,3,4,\ldots, n$, and $i = 1,2,3,\ldots, n$

1. Finding the impedance ratios ($\Delta^{x,y}$) and measured voltage ratios ($V^{x,y}$) for all possible pairs (x, y) of buses in the IEEE 13-bus network.
2. Selection of the impedance ratios ($\Delta^{x,y}$) which are equal to their respective bus voltage ratios ($V^{x,y}$).
3. Noting down the location of impedance ratios ($\Delta^{x,y}$) in the Z^h_{bus} which are equal to the corresponding bus voltage ratios ($V^{x,y}$).
4. Finding the number of repetition of impedance ratios ($\Delta^{x,y}$) which are equal to bus voltages ($V^{x,y}$) under consideration.
5. Selecting the impedance ratio ($\Delta^{x,y}$) with the **most** number of repetition (M_{OPMA}). This impedance ratio is the optimum impedance ratio for the identification of harmonic source, denoted as $\Delta^{x,y}_{optimum}$.

Until this point, the optimum impedance ratio ($\Delta^{x,y}_{optimum}$) is obtained to identify the location of the harmonic source. The next step is the optimization of the meter placement, which is identified by the selection of optimum pair of nodes. The most optimum pair of bus voltages for meter placement is found by the following strategy:

6. The voltage ratios ($V^{x,y}$) which results in the least number of repetition of $\Delta^{x,y}_{optimum}$, preferable only one in the first location, is selected as the optimum bus voltage pair.
7. The column number of the impedance ratio ($\Delta^{x,y}$) of the optimized bus voltage pair ($V^{x,y}$) represents the harmonic source bus.
8. If there are more than one voltage pair ($V^{x,y}$) resulting in only one $\Delta^{x,y}_{optimum}$, the pair ($\Delta^{x,y}$) with the highest index of column number is selected as the $\Delta^{x,y}_{optimum}$, and corresponding bus voltage ratio ($V^{x,y}$) is selected as the optimum pair for meter placement.
9. If there is no voltage pair ($V^{x,y}$) fulfilling the conditions of $\Delta^{x,y}_{optimum}$, i.e. only one impedance ratio ($\Delta^{x,y}$) matches the bus voltage ration ($V^{x,y}$), then a voltage pair ($V^{x,y}$) is selected with least number of repetition. If there are more than one voltage pairs with the same number of repetitions, then the pair with higher index number is selected.

3.2 Development of MCA

The accuracy of the OMPA method is validated by comparing its results with another approach, i.e. MC method. The MC computation is based on the selection of measurement pairs which are not optimized unlike OMPA. The simulations of OMPA and MC methods are performed for a series of Z^h_{bus} values against each harmonic order. The MC algorithm is developed as follows:

1. Finding the impedance ratios ($\Delta^{x,y}$) and measured voltage ratios ($V^{x,y}$) for all possible pairs (x, y) of buses in the IEEE 13-bus network.
2. Selection of the impedance ratios ($\Delta^{x,y}$) which are equal to their respective bus voltage ratios ($V^{x,y}$).
3. Noting down the location of impedance ratios ($\Delta^{x,y}$), in the Z^h_{bus}, which are equal to corresponding bus voltage ratios ($V^{x,y}$).
4. Finding the number of repetition of impedance ratios ($\Delta^{x,y}$) which are equal to bus voltage ratio ($V^{x,y}$) under consideration.
5. Selecting any impedance ratio ($\Delta^{x,y}$) arbitrarily which matches with the corresponding bus voltage ratio ($V^{x,y}$). This impedance ratio is the non-optimum impedance ratio for the identification of harmonic source, denoted as $\Delta^{x,y}_{non,ptimum}$, and the corresponding pair of voltages is selected as non-optimum bus voltage pair.
6. The column number of the impedance ratio ($\Delta^{x,y}$) of the non-optimized bus voltage pair ($V^{x,y}$) represents the harmonic source bus.

3.3 Deviations in Harmonic Impedances

The method of measuring the harmonic impedances of the network may cause deviations in the elements of harmonic Z^h_{bus}. To account for a deviation, and subsequent impact on the efficacy of OMPA and MC algorithms, a random variable ẟ is added to each element of the Z^h_{bus}. The random variable ẟ is expressed as:

$$ẟ = N\ (\mu, \rho) \quad (2)$$

In Equation (2), the ẟ represents a pseudo-random variable from a normal distribution having mean μ and a standard deviation of ρ. The random variable ẟ is added in the elements of the bus admittance matrix in the initial steps of impedance bus creation. The random variable ẟ is added to the admittance of the capacitive elements as follows:

$$Y_C^{ẟ} = j(\omega C + ẟ) \quad (3)$$

In Equation (3), C represents the capacitance of the circuit element.

The admittance of the resistive-inductive components, after the inclusion of the random variable ẟ, is expressed as follows:

$$Y_{RL}^{ẟ} = \frac{1}{R + ẟ + j(\omega L + ẟ)} \quad (4)$$

In Equation (4), R represents the resistance and L denotes the inductance of the circuit element.

3.4 Comparison between OMPA and MC Algorithm

The comparison of the proposed OMPA method and MC algorithm is carried out as following steps.

1. Formulation of harmonic Z^h_{bus} for the original values of impedance in the network.
2. Execution of OMPA algorithm to obtain optimum pairs as explained in the 3.1. The optimum pairs as a result of OMPA algorithm are noted down.
3. Execution of MC algorithm to obtain non-optimum pairs as explained in the 3.2. The non-optimum pairs as a result of the simulations are noted down.
4. Incorporation of a deviation in the Z^h_{bus} by the addition of a random variable $\eth$ as described in 3.3.
5. Injection of current source of a specific harmonic order at every load bus, one-by-one, and obtaining the results of OMPA algorithm for each injection.
6. Injection of the same current source of a specific harmonic order at every load bus, one-by-one, and obtaining the results of MC algorithm.
7. The step 5 and the step 6 are repeated for a range of harmonic orders, i.e. 5^{th} to 37^{th} each, for a series of values of impedance deviation $\eth$.
8. The simulation results of OMPA and MC are plotted in the form of graphs with respect to each value of $\eth$, and accuracy is compared.

4. RESULTS AND DISCUSSIONS

In this section, the results of both OMPA and MCA in the identification of harmonic source in the IEEE 13-bus network are presented in details.

4.1 Accuracy of OMPA in Harmonics Identification

This OMPA method is tested on IEEE 13-Bus system to locate harmonic sources, and Figure 1 presents the accuracy of OMPA in identifying the harmonic source for each order of harmonic. The overall accuracy of OMPA is 89%.

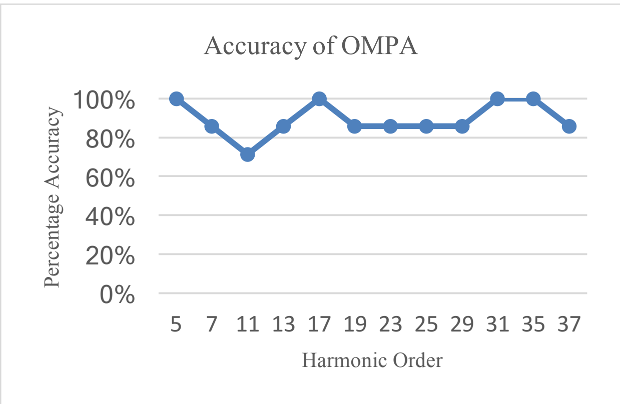

Figure 1. Accuracy of OMPA in harmonics identification

It can be seen that for some harmonic orders, the accuracy of source identification is 100%, i.e. the harmonic injection at any node of the system can be precisely located by using this algorithm. Furthermore, for certain harmonic orders, the accuracy is relatively lesser. The decreased accuracy in these cases is because of the limited number of decimal points in MATLAB. MATLAB can compute until fifteen (15) decimal points and for some cases the difference between harmonic impedances lie beyond that range, making it unidentifiable for the simulation tool. Moreover, the network impedance to harmonic impedance conversion formulae are obtained from ref [18] in which the numbers are limited to three (03) decimal points thereby limiting the precision of results.

4.1.1 Optimization of Nodes for Meters Placement

The results of the optimization strategy show that out of thirteen (13) nodes of IEEE 13-Bus system, only nine (09) nodes are sufficient for meters placement. Thus, the harmonics identification can be carried out efficiently along with the economical edge. Figure 2 shows the nodes which are optimized by the OMPA.

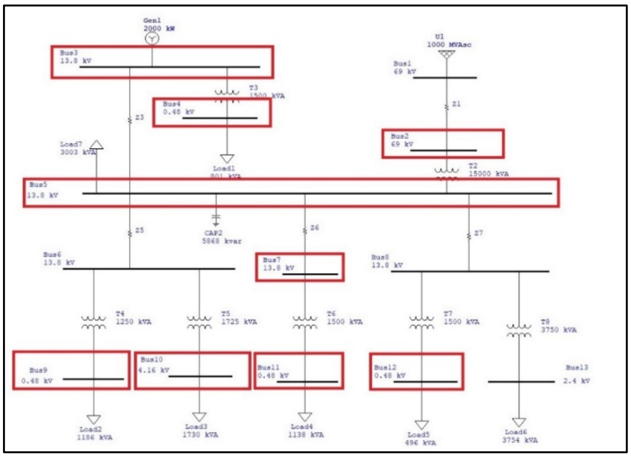

Figure 2. Optimized locations for meters' placement

4.2 Accuracy of MCA in Harmonics Identification

The Figure 3 details the accuracy of MCA in identifying the harmonic source for each order of harmonic. The MC algorithm is 100% efficient for only two (02) out of twelve (12) harmonic orders, and has its minimum accuracy for 11^{th} harmonic order, i.e. 14%.

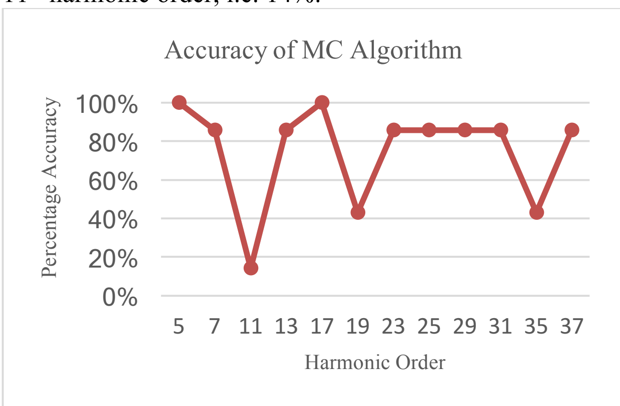

Figure 3. Accuracy of MCA in harmonics identification

4.3 Impact of Deviations in Harmonic Impedances

To assess the impact of the impedance deviation on the efficiency of OMPA and MC algorithms, different values of random variable $\eth$ are added, separately, to each element of the Y^h_{bus}. Hence, the resultant Z^h_{bus} is also changed for each value of $\eth$. The accuracy of OMPA and MC methods are compared for $\eth$ = 1^{-15}, 1^{-14}, and 1^{-13}

separately. The Figure 4 to Figure 6 compare the results of OMPA and MC methods against $\partial = 1^{-15}$, 1^{-14}, and 1^{-13}, respectively.

The results show that accuracy of both methods decrease with the increase in the deviation in the harmonic impedances, but OMPA is less affected by these deviations as compared to MC algorithm. For $\partial = 1^{-15}$, the overall accuracy of OMPA is 82%, while that of MC is 74%. For individual harmonics, the maximum accuracy of OMPA is 100%, while that of MC is 86%. The minimum accuracy of OMPA for individual harmonic order is 57% but that of MC is 29%. Similarly, for $\partial = 1^{-14}$, the overall accuracy of OMPA is 79%, while that of MC is 64%. The individual harmonic order maximum accuracy of both OMPA and MC is 100%, while the minimum accuracy of OMPA is 57% as compared to 29% of MC. Likewise, for $\partial = 1^{-13}$, the overall accuracy of OMPA is 75%, while that of MC is 56%. The maximum and minimum accuracy of OMPA is 100% and 57%, respectively, while these values for MC algorithm are 86% and 14% respectively. The results prove that the deviation in the harmonic impedance can have detrimental impact on the efficiency of both methods, but OMPA is robust and less vulnerable to these deviations as compared to MC algorithm.

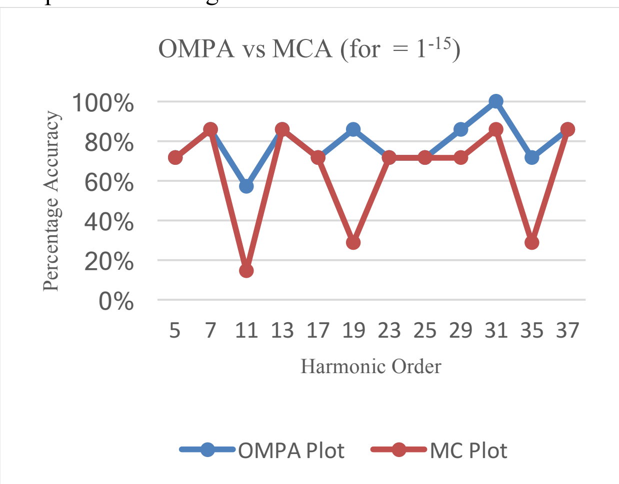

Figure 4. Comparison between OMPA and MCA ($\partial=1^{-15}$)

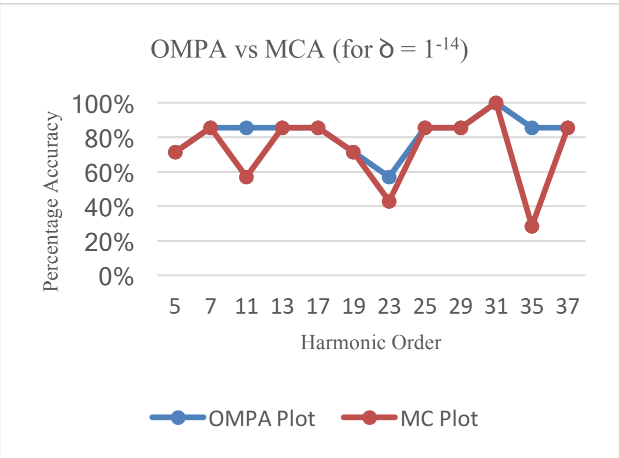

Figure 5. Comparison between OMPA and MCA ($\partial=1^{-14}$)

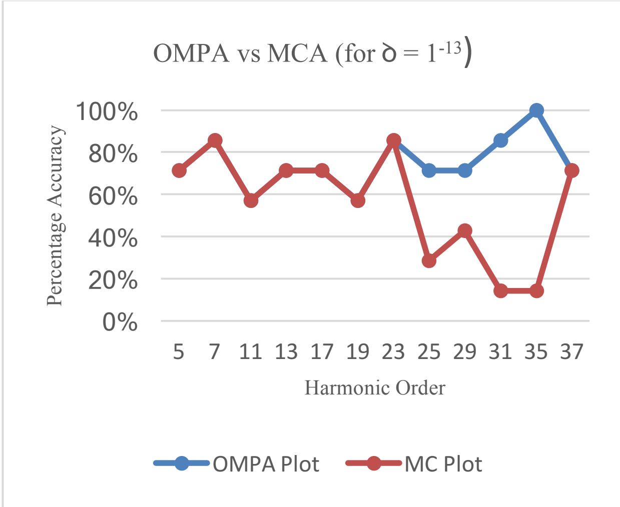

Figure 6. Comparison between OMPA and MCA ($\partial=1^{-13}$)

5. CONCLUSION

In this research work, a network impedance-based method is used to identify a single harmonic source location in any power system. In addition to precision of locating the harmonics in the system, the meter placement is also an important issue to be addressed. Moreover, the limitations and shortcomings of the methods adopted to calculate harmonic impedances also affect the accuracy of the results. The results show that the OMPA algorithm, developed in this research work, not only results in enhanced efficiency but also minimizes the locations for meters allocation with an optimization algorithm. Moreover, OMPA is relatively invulnerable to the deviations in harmonic impedances. To validate the performance, the results of OMPA are compared with MC method to identify harmonic sources in a standard IEEE 13-Bus network. The results reveal that with no deviations in the harmonic impedance the accuracy of OMPA is 89%, 14% more than that of MC. Furthermore, the OMPA requires only nine (09) out of thirteen (13) nodes for meter placement to locate harmonic injection at any load bus. On the other hand, MC needs meters to be placed at all thirteen (13) nodes for harmonics identification. When the harmonic impedances deviate from original value, the OMPA shows a better performance as compared to MC algorithm. For the deviation values of random variable $\partial = 1^{-15}$, 1^{-14} and 1^{-13} in the harmonic impedances, the overall accuracy of OMPA is 82%, 79% and 75% against the accuracy of MC 74%, 64% and 56%, respectively. It is concluded that the developed algorithm OMPA is not only deliver a superior performance in locating harmonic sources in a power network with minimum number of meters, but also shows more immunity to the deviations in the harmonic impedances as compared to MC algorithm.

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