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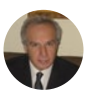

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A Large-Change Sensitivity Based Approach for Distributed Harmonic Resonance Assessment in Multi-Area Interconnected Power Systems

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***Abstract*—This paper presents a distributed simulation based method for harmonic resonance assessment (HRA) in multi-area large-scale power systems. Further consideration is devoted to the early harmonic frequency-scan formulation to shape them into a Bordered Blocked Diagonal Form (BBDF), which is suitable for parallel processing. The proposed algorithm (BBDF) allows operator of each area of an interconnected system to independently conduct the HRA. A large-change sensitivity based approach is then handled in a secure platform to apply the effects of whole network to each single area. The introduced decentralized HRA is capable to find the exact values as those of the interconnected system through TCP/IP communication media. The developed method is successfully implemented in an existing software package and applied to IEEE 14-bus harmonic test system, followed by a discussion on results.**

***Index Terms*—Distributed simulation, frequency-domain (FD), frequency-scan technique (FST), Harmonic Resonance Assessment (HRA), Large-Change Sensitivity (LCS).**

I. Introduction

The power system is highly nonlinear system that its performance is influenced by many parameters. Therefore, different aspects of a power system needs to be studied for a secure and reliable operation, including stability, reliability, and special studies such as harmonics [1].

Harmonic resonance has become a concern for power system operators by proliferation of harmonic-producing loads and increasing consciousness of harmonic effects. As reported in the specialized literature, Frequency Scan Technique (FST) is the most well-known tool for Harmonic Resonance Assessments (HRA)[2]. The aim of FST is to calculate the driving point impedance by observing the system from the current injection bus at different frequencies. The obtained harmonic impedance is an important parameter characterizing the frequency response of power system. It is mainly used for designing harmonic filters, fault detection, checking harmonic emission limits and predicting the system resonance[3],[4].

Considering the importance of this issue, several researches have been conducted in literature [5]-[18].

An improved modal analysis is reported in[9], which considers both parallel and series resonance employing the dummy branch method. In[10] an advanced modal analysis is introduced via s-domain network and applied to industrial systems. Reference [11] proposes an alternative formulation for harmonic resonance mode analysis utilizing real symmetrical nodal matrices.

Besides the above studies, ample investigations have been carried out to illustrate the importance of the HRA. Reference[13] introduces analytical expressions to locate the resonance frequencies of a typical medium voltage distribution system in the presence of capacitor and shunt filter banks. In addition, a summary of the most important issues with respect to harmonics and resonances within wind power plants has been reported in [15]. Besides these, HRA has been widely used for filter design in power systems [16]-[17]. In [18] a novel decentralized control technique is proposed to compensate for the impact of grids with high harmonics distortion on current controller of distributed PV inverters. In the output impedance of high inverter is controlled using local measurements without communication requirements.

Despite extensive models and algorithms proposed in the noted literature, the HRA of real-life networks is faced with some challenging issues[19]; mainly, lack of computing resources, which raises in large-scale networks. Moreover, the interconnected networks are composed of multiple areas; each of them are usually owned and operated by an independent entity. In such situations, it is not possible for an area to access the network layouts and detailed data of the neighboring areas. In addition, the operator of each area may not have enough data of its customers, such as factories and small manufacturers. The aforementioned comments are important because the exact models of nonlinear devices accompanied by configuration of the neighboring networks have significant effects on harmonic analysis of each single area.

In order to deal with such issues, a parallel distributed computing approach is reported in [20] for harmonic analysis of multi-bus systems. Although computational burden and accuracy issues are greatly resolved by developing parallel-computing-based time-domain methods, lack of observability of nearby networks and load identity are still a problem.

This paper presents a new approach for distributed HRA of multi-area interconnected power systems. As the most noteworthy contribution of this paper, Large-Change Sensitivity (LCS) concept is introduced and adopted to FST to find harmonic impedance characteristic in the Frequency Domain (FD). To do so, both linear and non-linear devices are modeled based on well-known techniques [21], and the system admittance matrix is obtained as a frequency dependent block diagonal form. A distributed HRA is then applied in a secure platform by sending the least volume of data from each individual area to the wide area coordinator (WAC) through TCP/IP communication facility. The proposed method is developed within an existing software package, and it is applied on several networks including the IEEE 14-bus test system[22] followed by presenting the results, and comparing them to those of previous researches.

II. HARMONIC RESONANCE ASSESSMENT (HRA) AND MODELING

A. Frequency Scan Technique (FST)

There are several widespread FD-based techniques for power system harmonic analysis reported in literature. As stated in the specialized literature, FST is probably the only practically applicable method that can reveal resonance frequencies and identify the existence of resonance[6]. The FST is a characterization of the system equivalent impedance at a bus in the system as a function of frequency. A significant advantage of the FST is that the impedance of large-scale systems can be obtained during different operational conditions via a quite simple manner. The general solution procedure of the current injection based FST to find the impedance spectrum seen at the bus of interest, i, can be described as follows:

1) Define initial $\underline{h}$, final $\overline{h}$, and variation Δh values of the swept harmonics.
2) Set harmonic order h equal to the initial harmonic value $h = \underline{h}$.
3) Calculate equivalent admittance for the AC components of the network at order h (Y_h).
4) Form the admittance matrix in factorized form at harmonic order h.
5) Set the harmonic current array with 1 p.u. current injected at bus i, and zero currents at all other buses (I_h).
6) Calculate bus voltages through (1) and set voltage of bus i equal to its Thevenin impedance at harmonic order h as shown in (2).

$$[V_h] = [Y_h]^{(-1)}[I_h] \tag{1}$$

$$Z_i(h) = V_h(i) \tag{2}$$

7) Set a new harmonic order by $h = h + \Delta h$.
8) Steps 3−7 are repeated until $h \leq \overline{h}$.

B. Identification of Resonance Frequencies by FST

Harmonic frequencies are determined based on a comparison applied to Imaginary Part Of the Harmonic Impedance (IPOHI). While a user defines $\underline{h}$, $\overline{h}$, and Δh, the FST is run in each frequency interval (Δh), and the harmonic impedance looking from the bus of interest is calculated. In any scanning stage, the calculated IPOHI is compared to that of the previous stage. The algorithm declares that a resonance frequency exists between h and $h = h + \Delta h$ if the label of IPOHI has been swapped. If the IPOHI has changed from a negative value to a positive one, a series resonance is identified. Similarly, there is a parallel resonance if the IPOHI has altered from a positive amount into a negative one.

III. LARGE-CHANGE SENSITIVITY (LCS) AND NETWORK DECOMPOSITION

A. LCS Concept

Assume an n sized linear network which can be written by the following equation using nodal analysis:

$$[W_0] = [T_0][X_0] \tag{3}$$

where $T_0(n*n)$ is the network matrix with its entries composed of nominal values, $X_0(n*1)$ is the network state vector, and $W_0(n*1)$ is the input excitation vector containing the independent sources. The solution of (3) is obtained by:

$$[X_0] = [T_0]^{-1}[W_0] \tag{4}$$

Now, assume m components of the network have been changed arbitrary in rage of zero to infinity so that $m \ll n$. Direct approach for solving the new system entails refactorization of T, which has been updated with the perturbed component parameters, and applying forward/backward substitutions to find the new state, X. However, the LCS makes it possible to find the exact values of the new state, X, without resolving the whole problem. In fact, it confines the required computations only on the changed elements employing an initial solution such as X_0 [23].

Let us assume the network modified by m component perturbations is described by (5) [24]:

$$[T][X] = ([T_0] + [P].[\alpha].[Q]^t)[X] = [W] \tag{5}$$

where, T and X are the new network matrix and network state, respectively. Moreover, both $P(n*m)$ and $Q(n*m)$ contain 0 and ±1 entries which indicate location of the perturbed components as reported in (6). The diagonal matrix $\alpha(m*m)$ holds the m component perturbation [24].

$$\begin{aligned}[P] &= [P_1 P_2 ... P_m] \\ [Q] &= [Q_1 Q_2 ... Q_m] \\ [\alpha] &= diag[\alpha_i], i = 1, ..., m\end{aligned} \tag{6}$$

It has been proven in the LCS theory that the following equation ensures the integrity of finding exact solution of the new network [25]:

$$[X] = [X_0] - [T_0]^{-1}[P][z] \tag{7}$$

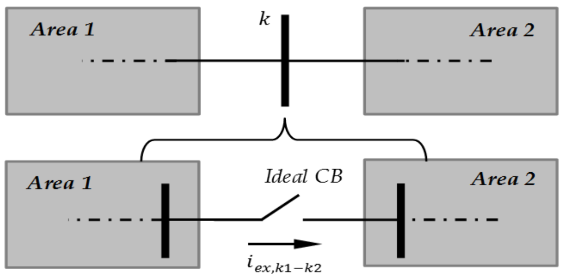


Fig. 1: An illustrative example represents an interconnected network composed of two areas linked by an ideal CB

where

$$[z] = [K]^{-1}[Q]^{t}[X_0] \tag{8}$$

$$[K] = \left([\alpha]^{-1} + [Q]^{t}[T_0]^{-1}[P]\right)^{-1} \tag{9}$$

As it is seen in (7), while network solution of nominal values X_0 are known, the solution of the new system X can be found considering the effects of the perturbed components z. Equations (7)-(9) are the key relations of the LCS theory, which will be developed to solve the distributed HRA in this paper.

B. Electrical Network Decomposition

Based on the Diakoptic techniques, an electrical system can be divided into several subsystems, which have been connected to each other through a series of ideal circuit breakers (CBs).

This paper employs the Diakoptic technique based on the node-tearing approach shown in Fig.1. Figure 1 shows that a common bus k ,which connects two areas, is duplicated into each area as $k1$ and $k2$, respectively. An ideal CB connects these buses to each other. Let us assume variable F as the CB status, in which $F = 0$ represents an open CB and $F = 1$ a closed CB. Then, the effect of the CB status can be modeled by:

$$[(V_{k1} - V_{k2})F + (F-1)i_{ex,k1-k2}] \tag{10}$$

where V_{k1} and V_{k2} represent voltages at nodes $k1$ and $k2$, respectively. Also, in (10), $i_{ex,k1-k2}$ represents an exchange current between the two areas shown in Fig. 1. If the CB is open, $F = 0$, $i_{ex,k1-k2} = 0$ and $V_{k1} \neq V_{k2}$ while if the CB is closed, $F = 1$ and $V_{k1} = V_{k2}$. Based on the Diakoptic theory, an incidence matrix $C_i = [c_{jk}]$ can be defined for the interconnected network in which the entries are calculated as follows [22]:

$$c_{jk} = \begin{cases} +1 & \textit{if bus } j \textit{ connected to the } k^{th} \textit{ ideal CB and currents outgoinig} \\ -1 & \textit{if bus } j \textit{ connected to the } k^{th} \textit{ ideal CB and currents ingoinig} \\ 0 & \textit{if bus } j \textit{ is not a boundary bus} \end{cases} \tag{11}$$

While it is assumed that the subnetworks are connected through n^M fictitious ideal CBs, (10) can be written in a matrix form containing the whole network by considering C_i:

$$\sum_{i=1}^{n^s} F.[C_i]^t.[V_i] + (F-1).[I].[I_{ex}] = 0, \forall h \in \Omega_H \tag{12}$$

where, V_i represents nodal voltage vector of subnetwork i, and I is an $n^M * n^M$ identity matrix. I_{ex} is an $n^M * 1$ vector shows the current exchange between subnetwroks. The above equation accompanied by the LCS theory is used to form the proposed distributed HRA as described next.

IV. The Proposed Solution Approach

Consider an interconnected power system which is divided into n^S subnetworks through n^M fictitious ideal CBs as interconnected tie lines. Assume subnetwork i with n_i^S buses which is called as the “main subnetwork” in the following descriptions. The distributed HRA of the main subnetwork can be generally defined as a problem which aims to find the Thevenin harmonic impedance spectrum looking from bus j located at this subnetwork.

As discussed in previous section, the CBs can be either open or closed. When all CBs are open ($F = 0$), the HRA is conducted by the main subnetwork through the FST as described in section $II.A$. Thus:

$$[Z_{i_{j,h}}] = [Y_{i_h}]^{-1}[I_{i_{j,h}}], \forall i \in \{1, 2, ..., n^S\}$$
$$j \in \{1, 2, ..., n_i^S\}, h \in \Omega_H \tag{13}$$

$$I_{i_{j,h}} = [I_{k,i,j}], \forall i \in \{1, 2, ..., n^S\}$$
$$j, k \in \{1, 2, ..., n_i^S\}, h \in \Omega_H \tag{14}$$

$$I_{k,i,j} = \begin{cases} 0 & k \neq j \\ 1 & k = j \end{cases} \quad \forall \;\; k \in \{\, 1, 2, ..., n_{n_i}^S\} \tag{15}$$

where $Z_{i_{j,h}}$ represents harmonic impedance vector of the main subnetwork looking from bus j, in which the j^{th} element shows the Thevenin harmonic impedance. Y_{i_h} is harmonic admittance matrix, and and $I_{i_{j,h}}$ illustrates harmonic current source vector of subnetwork i injected from bus j at harmonic order h. $I_{i_{j,h}} = [I_k]$ is an $n_i^S{*}1$ vector and shows the harmonic current injected into the grid. Considering the FST technique, the harmonic current array must set with 1 p.u. current injected at bus j and zero current at all other buses as represented in (15). Since the CBs are open, equation (13) is exclusively conducted on the main subnetwork.

Once the CBs are closed ($F = 1$), a large change has been applied to the CBs status. Therefore, CBs are the elements which should be considered in the LCS theory. Considering an illustrative example shown in Fig.1, it is expected that an unknown vector of current exchanges $I_{ex_{i,j,h}}$ to be applied to the main subnetwork i in order to properly model the effects of its neighboring subsystems. Thus, exact values of harmonic impedance vector of subnetwork i at harmonic h looking from bus j can be calculated as the following:

$$[Z_{i_{j,h}}] = [Y_{i_h}]^{-1}[I_{i_{j,h}}] + [Y_{i_h}]^{-1}[C_i][I_{ex_{i,j,h}}]$$
$$\forall i \in \{1, 2, ..., n^S\}, j \in \{1, 2, ..., n_i^S\}, h \in \Omega_H \tag{16}$$

A general expression of the proposed distributed HRA can be obtained by combining (13) and (16) into a common framework as shown in (17). It has BBDF format and can be easily used in parallel computing.

$$\begin{bmatrix} Y_{1_h} & \cdots & 0 & \cdots & 0 & C_1 \\ \vdots & \ddots & \vdots & \cdots & \vdots & \vdots \\ 0 & \cdots & Y_{i_h} & \cdots & 0 & C_i \\ \vdots & & \vdots & \ddots & \vdots & \\ 0 & \cdots & 0 & \cdots & Y & C \\ F.C_1^t & \cdots & F.C_i^t & \cdots & F.C_{n^S}^t & (F-1).I \end{bmatrix} \begin{bmatrix} V_{1_h} \\ \vdots \\ Z_{i_{jh}} \\ \vdots \\ V_{n_h^S} \\ I_{ex_{ijh}} \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ I_{i_{jh}} \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (17)$$

A piecewise approach is employed to efficiently solve (17) in a multi-area interconnected network as described below.

A. Solution of Subnetworks when CBs are Open

While CBs are open ($F = 0$). It should be noted that since there is no harmonic current source in the neighboring areas of subnetwork i, the obtained voltage values of those areas would be equal to zero. Hence, (18) should be solely solved for the main subnetwork which is indicated as i in this section.

$$[Z^0_{i_{j,h}}] = [Y_{i_h}]^{-1}.[I_{i_{j,h}}], \forall j \in \{1,2,...,n_i^S\}, h \in \Omega_H \quad (18)$$

B. Solution of The Integrated Network when CBs are Closed

In this case, CBs are closed ($F = 1$). As shown in (7), these states can be obtained by employing initial states X_0. Hence, the following counterparts serve the current problem:

$$\begin{aligned} [P]^t &= [0 \ \ ... \ \ 0 \ \ I]_{n^M * n'} \\ [Q]^t &= [C_1^t \ \ ... \ \ C_{n^S}^t \ \ I]_{n^M * n'} \\ [\alpha] &= I_{n^M * n^M} \end{aligned} \quad (19)$$

where $n' = n^B + 2n^M$. Substituting the above parameters into (7) results in (20) to (22):

$$[K]_{n^M * n^M} = \sum_{K=1}^{n^S} [C_K]^t.Y_{K_h}^{-1}.[C_K], \forall h \in \Omega_H \quad (20)$$

$$[I^c_{ex_{i,j,h}}] = [z]_{n^M * 1} = [K]^{-1}[Q]^t[X^0_{i,j,h}], \forall h \in \Omega_H \quad (21)$$

$$X^0_{i,j,h} = \begin{bmatrix} V^0_{1_h} & \cdots & V^0_{i_h} & \cdots & V^0_{n_h^S} & I^0_{ex_{i,j,h}} \end{bmatrix} \quad (22)$$

Thus, the piecewise nodal admittance equation of each individual subnetwork is as follows:

$$\begin{aligned} &[Z^c_{i_{j,h}}] = [Z^0_{i_{j,h}}] - [Y_{i_h}]^{-1}.[c_i].[I^c_{ex_{i,j,h}}] \\ &\forall i \in \{1,2,...,n^S\}, j \in \{1,2,...,n_i^S\}, h \in \Omega_H \end{aligned} \quad (23)$$

C. The Proposed Distributed HRA Algorithm

Evoke the interconnected network consisting of n^S subnetworks discussed in section $III.A$. Each subnetwork has a Persenal Computer (PC) which is connected to the Wide Area Coordinator (WAC) through a communication media. In order, to solve the distributed HRA by the proposed method, a subnetwork such as i, which is called as the main subnetwork, sends a request to the WAC. The proposed HRA algorithm follows a process that consists of three sections which are conducted in parallel. First, the main subnetwork sends some data including $\underline{h}$, $\overline{h}$, Δh, and ${n_i}^S$ to the WAC. Then, the WAC defines direction of currents which flow through each CB and send them to the associated subnetworks. It might be helpful to mention that the current direction of CBs will be used to set entries of C_i as described in section $III.B$. At any harmonic order, each subnetwork forms the factorized admittance matrix of its network and sends $[C_k]^t.Y_{k_h}^{-1}.[C_k]$ to the WAC. Moreover, the main subnetwork finds $Z^0_{i_{j,h}}$ as reported in (18) and sends $[C_i]^t.[Z^0_{i_{j,h}}]$ to the WAC. Hereafter, the WAC calculates (20)-(22) and sends $I^c_{ex_{i,j,h}}$ to the main subnetwork. Finally, the main subnetwork employs (23) to find the exact harmonic impedance values $Z^c_{i_{j,h}}$ and checks the possibility of resonance. The same process is repeated until all available harmonic orders are considered in all desired buses

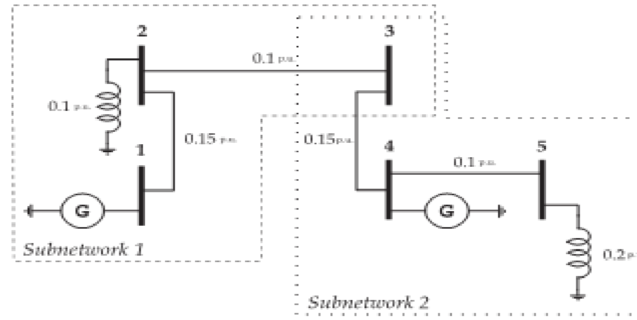


Fig. 2: An illustrative example

D. An Illustrative Example

In this section, an illustrative example is used to clarify the performance of the proposed distributed computing based approach. Figure 2 depicts a simple network with four buses in which the reported values are associated to harmonic 5. It is assumed that the generators will not produce harmonics and their sub-transient inductances are ignored in this study. The purpose is to find the Thevenin impedance seen from bus 2 at harmonic 5. In case of centralized analysis, the solution simply achieves by inverting the system admittance matrix as stated bellow:

$$Y = \begin{bmatrix} 0.15 & -0.15 & 0 & 0 & 0 \\ -0.15 & 0.35 & -0.1 & 0 & 0 \\ 0 & -0.1 & 0.25 & -0.15 & 0 \\ 0 & 0 & -0.15 & 0.25 & -0.1 \\ 0 & 0 & 0 & -0.1 & 0.3 \end{bmatrix} \quad (24)$$

$$Z_{22} = Y_{-1}(2,2) = 7.6 \quad (25)$$

Assume that the network is decomposed into two subnetworks via “bus 3 as the boundary bus. Since it is assumed that each subnetwork is operated by an individual entity, they have no access to network layout as well as detailed data of their neighboring areas. Considering the proposed distributed HRA, subnetwork 1 sends a request to WAC to start the simulation process. The WAC sends the current direction of CBs (1 or -1) to each area. Here, we assumed “1 for subnetwork 1 and “-1 for subnetwork 2. Then, each subnetwork forms the admittance matrix and sends $[C_k]^t.Y_{k,h}^{-1}.[C_k]$ to the WAC:

Subnetwork 1:

$$Y_{1_5}=\begin{bmatrix}0.15 & -0.15 & 0\\ -0.15 & 0.35 & -0.1\\ 0 & -0.1 & 0.1\end{bmatrix}, C_1=\begin{bmatrix}0\\0\\1\end{bmatrix}, C_1^t.Y_{1_5}^{-1}.C_1=20 \quad (26)$$

Subnetwork 2:

$$Y_{2_5}=\begin{bmatrix}0.15 & -0.15 & 0\\ -0.15 & 0.25 & -0.1\\ 0 & -0.1 & 0.3\end{bmatrix}, C_1=\begin{bmatrix}-1\\0\\0\end{bmatrix}, C_2^t.Y_{2_5}^{-1}.C_2=21.6667 \quad (27)$$

Moreover, subnetwork 1 forms the current vector based on (14)-(15) and sends $C_1^t.Z_{1_{2,5}}^0$ to WAC which is calculated by (20): Subnetwork 1:

$$I_{1_{2,5}}=\begin{bmatrix}0\\1\\0\end{bmatrix}, Z_{1_{2,5}}^0=Y_{1_5}^{-1}.I_{1_{2,5}}=\begin{bmatrix}10\\10\\10\end{bmatrix}, C_1^t.Z_{1_{2,5}}^0=10 \quad (28)$$

Considering the framework reported in Fig. 3, the WAC finds $I_{ex_{1,2,5}}^c$ by (23)-(25):

$$K=C_1^t.Y_{1_5}^{-1}.C_1+C_2^t.Y_{2_5}^{-1}.C_2=20+21.6667=41.6667 \quad (29)$$

$$I_{ex_{1,2,5}}^c=K^{-1}.Q^t.X_{1,2,5}^0=\frac{1}{41.6667}.C_1^t.Z_{1_{2,5}}^0=0.23999 \quad (30)$$

Finally, subnetwork 1 receives $I_{ex_{1,2,5}}^c$ and finds the exact solution by (27):

$$Z_{ex_{1,2,5}}^c=Z_{ex_{1,2,5}}^0-Y_{1_5}^{-1}.C_1.I_{ex_{1,2,5}}^c=$$

$$\begin{bmatrix}10\\10\\10\end{bmatrix}-\begin{bmatrix}16.6667 & 10 & 10\\ 10 & 10 & 10\\ 10 & 10 & 20\end{bmatrix}\begin{bmatrix}0\\0\\1\end{bmatrix}0.23999=\begin{bmatrix}7.6\\7.6\\5.2\end{bmatrix} \quad (31)$$

Subnetwork 1:

$$Z_{22}=Z_{1_{2,5}}^c(2,1)=7.6 \quad (32)$$

So, the proposed distributed approach has led to a same solution as that of the centralized algorithm found in (29).

V. TESTS AND RESULTS

A. Computer Implementation and Test Systems

Aimed at solving the distributed HRA by the proposed method, it has been practically implemented in an existing software package, i.e., PASHA [26],[27],[28]. The developed algorithm has been successfully tested on several networks. However, due to space limitation simulation, results are presented for IEEE 14-bus harmonic test system[22]. The FST is conducted for HRA of the test system. Both parallel and series resonances are considered in this study, and the obtained results are reported in Fig. 3. As seen in this figure, the resonance frequencies are illustrated for each bus. The major parallel resonances occur around harmonic orders 3, 11, 25, 33 and 39. In addition, buses 1, 4 and 5 are the most affected nodes of the system. The simulation results reveal that the upper buses observe minimum impacts by harmonic resonance.

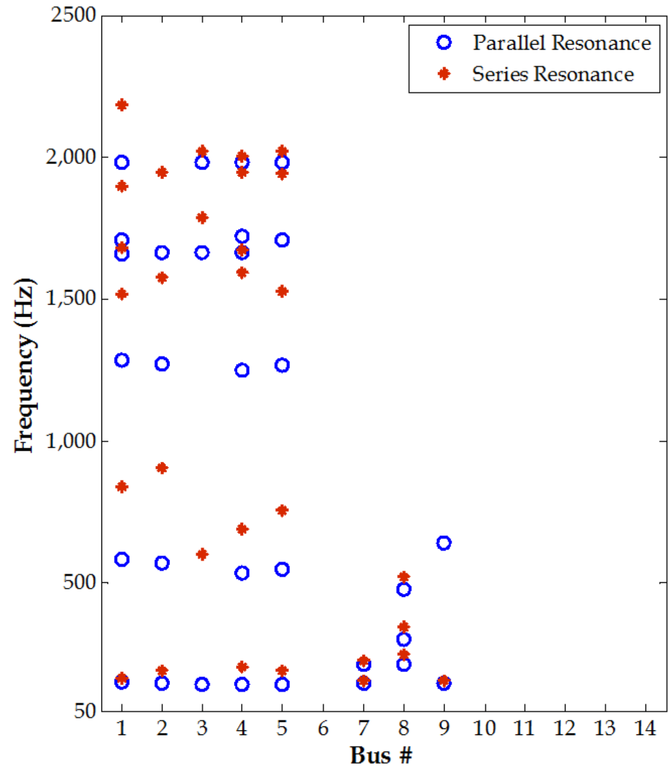
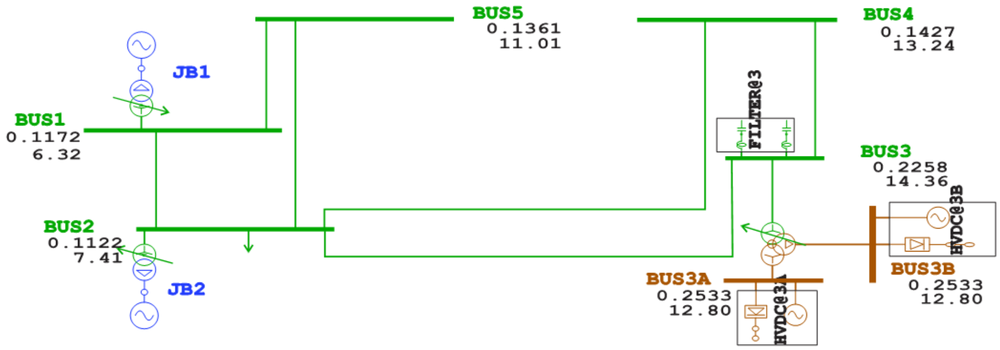


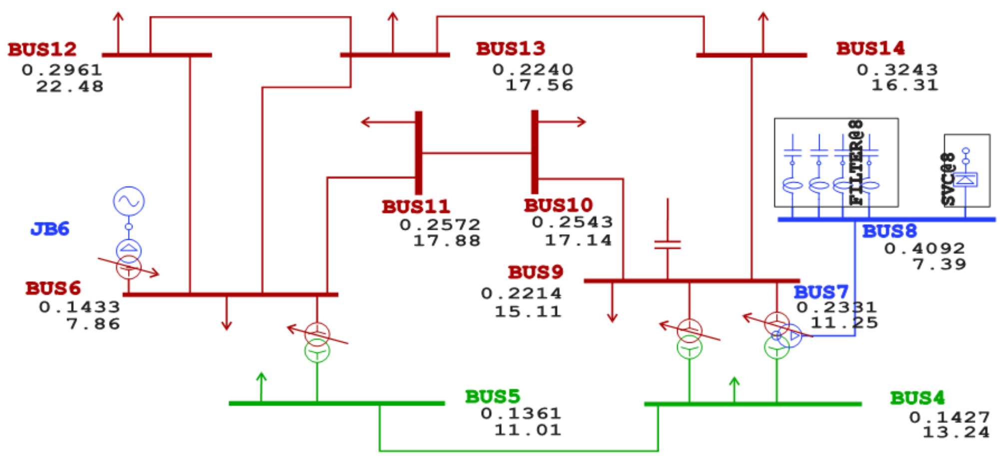
Fig. 3: HRA of the IEEE 14-bus harmonic test system

B. Distributed HRA of the Test System

In order to investigate the performance of the proposed distributed HRA, the test system is torn into two subnetworks. The lower part of the IEEE 14-bus test system which consists of buses 1 to 5 is selected as subnetwork I. Subnetwork II represents the upper part of the test system and includes buses 4 to 14. Hence, buses 4 and 5 are the boundary buses between the two areas. Subnetworks are simulated on two separate computers located on a 100 Mbps local area network (LAN), and a third computer is assigned to operate as WAC [29]. While subsystem I is selected as the main subnetwork, the distributed simulation request is sent from this subsystem to the WAC. The computations have been carried out based on the approach described in section IV and the obtained results are reported in Figs. 4-8. Figure 4 represents the subnetwork structure, in which magnitude and phase of the Thevenin impedance looking from each busbar at the fundamental frequency are displayed beneath the busbar names. As seen in this figure, the maximum impedance value is associated to bus 3 and the minimum value belongs to bus 2. Detailed harmonic impedance data at several frequencies are shown in Fig. 5,6. While CBs are open, the main subnetwork has no information about the neighboring areas, and the harmonic impedances are calculated based on (18). As seen in Fig. 5, in this case the driving point impedance looking into the system from all buses are too high; in some buses such as 4 and 5 the impedance magnitude may experience values more than 30 p.u. While CBs are closed, the interconnected network is



(a) Thevenin impedances of subnetwork I at the nominal frequency



(b) Thevenin impedances of subnetwork II at the nominal frequency

Fig. 4: Thevenin impedances of subnetworks

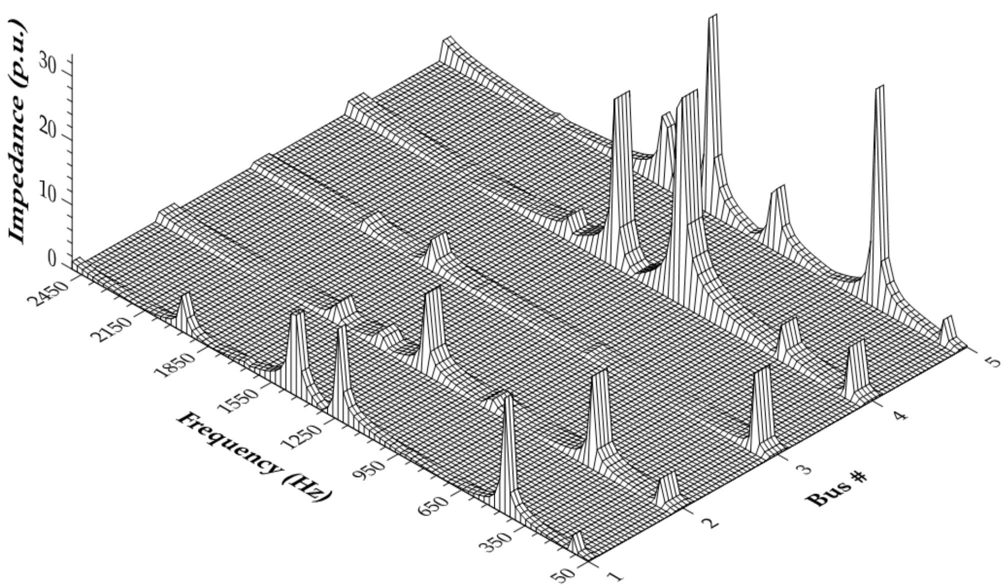


Fig. 5: Harmonic impedance of subnetwork, solution when CBs are open

solved by the LCS theory, and the previous results are revised based on the received exchanged currents. Figure 6 depicts the revised harmonic impedance spectrum. As can be seen in this figure, solutions are substantially changed in comparison

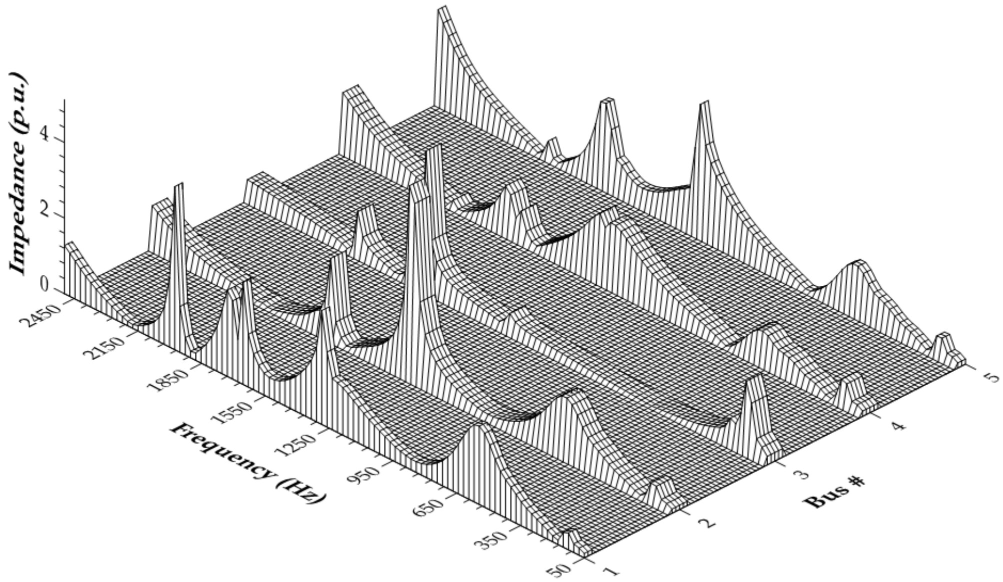


Fig. 6: Harmonic impedance of subnetwork, solution when CBs are closed

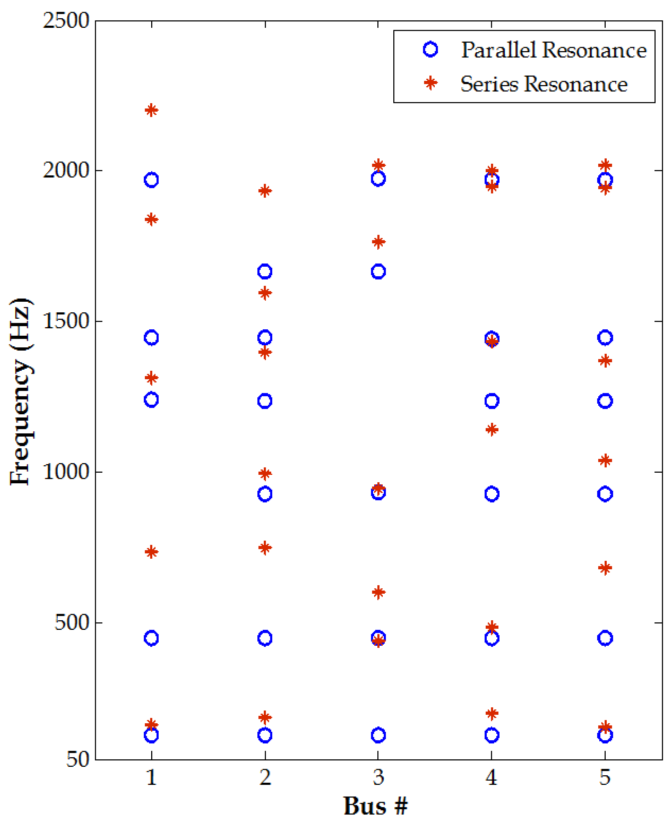


Fig. 7: HRA of subnetwork,solution when CBs are open

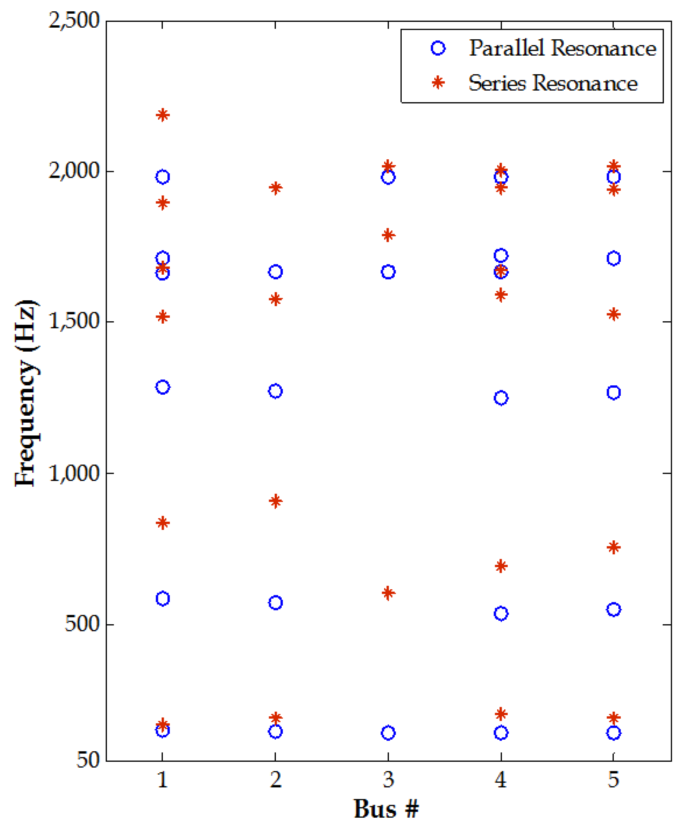


Fig. 8: HRA of subnetwork,solution when CBs are closed

to those presented in Fig. 5. The listed results clearly show the effects of detailed modeling of neighboring subnetworks on harmonic impedance calculations.

Besides the above simulation, the HRA is conducted based on the technique reported in section II, and the obtained results are shown in Figs. 7,8. As seen in this figure, the left plot represents the HRA in case of open CBs and the right plot is related to the closed CBs. Considering parallel and series resonance frequencies illustrated in Figures 7 and 8. Although the entire subnetwork buses are affected by the neighboring areas, the highest difference of HRA is shown in buses 3 and 5. In terms of quantity, the most difference has happened at intermediate frequency in the range of harmonics order 11 to 31. Comparing Figures 3 and 8 reveals that the proposed approach could reach to the same solutions as those of the centralized method.

From the simulation time viewpoint, it is observed that while the centralized HRA of IEEE 14-bus harmonic test system takes about 8.17 seconds, the distributed HRA performs in almost 5.60 seconds, which is lesser than the centralized solution. Although the parallel speed up efficiency is not the primary aim of the proposed distributed framework, it is empirically seen in simulations that the overall simulation time of the distributed HRA is substantially decreased while subnetworks are increased. For instance, while the test system is torn into 3 and 4 subnetworks, the distributed HRA has been carried out in 4.84 and 3.25 seconds, respectively.

VI. CONCLUSION

Aimed at reporting a distributed computing based approach for HA, a new method was put forward in this paper. The developed method is based on geographical decomposition strategy using Diakoptics and LCS as a mathematical basis for harmonic resonance calculations. A distributed cluster of PCs connected through TCP/IP is used to run the distributed HRA on a network of workstations. In ideal situation that the utilities subsystems are represented on their own PCs, it can act as a plug and play solution sink, which avoids using the approximate subnetwork equivalent representation. The obtained results and discussions reported in the paper show that the proposed approach can be used as an effective method for distributed HRA within real-life large-scale power systems.

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