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Optimal Measurement Placement for Static Harmonic State Estimation in the Power Systems based on Genetic Algorithm

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Abstract – In this paper, a method for optimal measurement placement in the problem of static harmonic state estimation in power systems is proposed. At first, for achieving to a suitable method by considering the precision factor of the estimation, a procedure based on Genetic Algorithm (GA) for optimal placement is suggested. Optimal placement by regarding the precision factor has an evident solution, and the proposed method is successful in achieving the mentioned solution. But, the previous applied method, which is called the Sequential Elimination (SE) algorithm, can not achieve to the evident solution of the mentioned problem. Finally, considering both precision and economic factors together in solving the optimal placement problem, a practical method based on GA is proposed. The simulation results are shown an improvement in the precision of the estimation by using the proposed method.

Keywords: Genetic algorithms, Measurement placement, Optimization, Static harmonic State estimation

1. Introduction

In recent years, harmonic current injecting to the power system networks has been developed because of the rapid increase of the use of non-linear loads in the power networks. The injected harmonic current to the power systems by a customer which is connected to a feeder propagates throughout the power networks and leads to distort the sinusoidal shape of the bus voltages and currents flowing through the transmission lines. Sometimes, resonant generated by non-linear loads causes to intensive perturbations far from harmonic sources. Thus, harmonic sources connected to a feeder degrade the quality of service to other customers on the same feeder or on the adjacent feeders. Moreover, mentioned harmonic perturbations lead to serious problems in the power systems, such as overheating and failures in instruments, interruption of the sensitive loads, incorrect operation of protective relays and communication interference. Therefore, restricting the harmonic pollution in the power system is a problem which is very vital by the electric utility companies that caused to harmonic standards constitution [1]. The general tenets of such standards usually require that the electric utility companies maintain the sinusoidal waveform of the bus voltage, whereas the entities served must maintain the certain harmonic limits in the load current. Thus, evaluation of harmonic pollutions in the power systems is one of the important indices of power system quality assessments. After these assessments, harmonic pollution of the power networks can be controlled or be restricted by using a suitable method such as active or passive filtering [2]. Furthermore, considering the cost of measurements and problems related to distance of measuring equipments, only partial measurement could be performed in a power system. So, in recent years, harmonic state estimation strategies are used for identification of the quantity of harmonic sources in the power system networks [3-11]. Harmonic state estimation in power systems is proposed by Heydt [3]. But, state estimation in power system networks at the fundamental frequency has been used since 1960's [12]. The precision of the estimator is one of the most important issues in the estimation process, which directly depends on the number of measuring equipments and measurement placements. Moreover, there is a restriction for increasing the number of measuring equipments in the harmonic state estimation methods, because of the high cost of these equipments. Therefore, it is necessary to reduce the number of required equipments and optimize the location of placements, to access the best precision. In other words, the goal is to reach the best precision with the less measuring cost. Up to now, several methods are suggested for optimal measurement placement. These methods generally depend on the calculation technique of the estimator. In [4], estimation of the power system voltage harmonics is accomplished based on Neural Networks (NN) by using the measured currents flowing through the power system lines. In [5], based on the minimum variance criterion and by using a probability function for existence of harmonic sources in various buses of the power system networks, a mathematical index is obtained. The optimal measurement placement could be demonstrated by minimizing the mentioned index.

In this paper, GA is used for finding the optimal placement of the measuring equipments in the harmonic state estimation. It should be noted that the least square method

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is applied as a statistical criterion in the estimation algorithm. The results of using the proposed method for IEEE standard 30-bus test power system are compared to the sequential elimination method [6]. The computer simulation results are specified that the proposed method has a suitable improvement for harmonic estimation in the power networks.

This paper, reviews the basics of harmonic state estimation using the least square estimator in section (2). In section (3), optimal measurement placement by considering the precision factor is studied. In this section, at first, the previously used method, called sequential elimination algorithm, is described. Then the suggested method for measurement placement based on GA is introduced. By considering both precision and economic factors, the practical method for optimal measurement placement in the harmonic state estimation based on GA is expanded in section (4). The simulation results of applying the GA-based method to IEEE 30-bus standard test system are compared to the results of applying the SE-based method in section (5). Finally, the concluding remarks are presented in section (6).

2. Determination and solving of normal equation in harmonic state estimator with the least square criterion

A general mathematical model for relating the measurement vector Z to the state variable vector X is as follow:

$$Z(h) = H(h)X(h) + E(h) \tag{1}$$

where Z(h) is the measurement vector, H(h) is the measurement matrix, X(h) is the system state variable vector, E(h) is the measurement noise and h is the harmonic order.

H(h) can be considered as a matrix whose elements are relating the measurement vector to the state variable vector. If the vector of nodal voltages select as the estimated state variable, then:

- For the nodal harmonic current measurements ($I_N(h)$), the relation to the nodal voltages is:

$$I_N(h) = Y_{NN}(h)V_N(h) \tag{2}$$

where $Y_{NN}(h)$ is the node to node admittance matrix at the h^{th} harmonic order.

- For the nodal harmonic voltage measurements ($V_N(h)$), the relation to the nodal voltages is:

$$V_N(h) = I \times V_N(h) \tag{3}$$

where I is the identity matrix.

- For the line harmonic current measurements ($I_L(h)$), the relation to the nodal voltages is:

$$I_L(h) = Y_{LN}(h)V_N(h) \tag{4}$$

where $Y_{LN}(h)$ is the line to node admittance matrix for the h^{th} harmonic order.

If all of the measuring equipments are similar, the measurement noise or measurement error will be the same for all of the measurements. Hence, the measurement noise, do not affect the solution of harmonic state estimation. Then the measurement error vector, E(h) in (1) can be eliminated. Indeed, the measurement error probability can be used for weighting the measurements and if all weights are the same, then weighting does not affect the solution of estimation. So, measurement noise could be eliminated. Otherwise, each measurement would usually be weighted by the inverse of the error variance of the related measurement equipment [7].

By partitioning the system node set (N), into two subsets of non-source busbars (No), and suspicious busbars (Ns), the node voltages vector, V_N and the node currents vector, I_N can be partitioned as follows:

$$V_N = \begin{bmatrix} V_{No} \\ V_{Ns} \end{bmatrix}, \quad I_N = \begin{bmatrix} I_{No} \\ I_{Ns} \end{bmatrix} \tag{5}$$

where in (5),

$$I_{No} = 0 \tag{6}$$

By considering the partitioned vectors in (5), the relation (2) can be rewritten as follows:

$$\begin{bmatrix} I_{No} \\ I_{Ns} \end{bmatrix} = \begin{bmatrix} \overline{Y}_{NoNo} & \overline{Y}_{NoNs} \\ \overline{Y}_{NsNo} & \overline{Y}_{NsNs} \end{bmatrix} \begin{bmatrix} V_{No} \\ V_{Ns} \end{bmatrix} \tag{7}$$

From (6) and (7), we will have:

$$V_{No} = -\overline{Y}_{NoNo}^{-1}\overline{Y}_{NoNs}V_{Ns} \tag{8}$$

Moreover, the relation (1), which is obtained from (2)-(4), and by considering the subvectors in (5), it can be rewritten as:

$$Z = \begin{bmatrix} H_{Ns} & H_{No} \end{bmatrix} \begin{bmatrix} V_{Ns} \\ V_{No} \end{bmatrix} \tag{9}$$

By substituting V_{No} from (8) to (9), the following relation will be obtained:

$$Z = \left[H_{Ns} + H_{No}\left(-\overline{Y}_{NoNo}^{-1}\overline{Y}_{NoNs}\right)\right]V_{Ns} \tag{10}$$

Considering $H = \left[H_{Ns} + H_{No}\left(-\overline{Y}_{NoNo}^{-1}\overline{Y}_{NoNs}\right)\right]$ the relation (10) can be rewritten as follows:

$$Z = HV_{Ns} \tag{11}$$

Furthermore, after obtaining the subvector V_{Ns} the subvector V_{No} can be calculated from (8). Hence, system state vector and all of the electrical quantities of the power system for h^{th} harmonic order can be determined, subsequently. In this paper, the subvector V_{Ns} is considered as the system state vector which is shown by X in (1). In other words, considering the general equation (1), an estimation of system state vector can be obtained from (12).

$$X = \left(H^T H\right)^{-1} H^T Z \tag{12}$$

3. Optimal measurement placement by considering the precision factor

It is notable that in harmonic state estimation, by the least square estimator, it is an essential condition that the number of measurements in the power system, which is the same as the number of the measurement matrix rows, should be equal to the number of under estimating variables [6]. In other words, for having an observable power network and furthermore, performing the estimation with the least number of measuring devices, considering the economic restrictions, the estimation should be done in completely determined condition. In underdetermine conditions, the matrix (H^TH) appeared in (12) is usually singular (with infinite condition number) or ill-conditioned (with a large condition number). In these situations, Singular Value Decomposition (SVD) should be applied [13]. By using SVD, only some of the elements of the estimated vector, which are related to the observable islands in the power network, are faithful. Moreover, when a gross error is involved in the measurements due to the sensor failures or telecommunication failures, pseudo-measurements should be added into the available measurements to make the estimation possible throughout the network. Pseudo-measurements can usually be obtained from the previous estimations or from the prime studies on the harmonic contents of the electrical loads which are connected to the power network. Generally, in solving the system normal equation, (11); the less condition number for the measurement matrix H, whose ideal value is unity and can be obtained for the unit matrix, leads to the less error in calculating the pseudo-inverse appeared in (12) and the most precise estimation will be obtained [3]. Thus, a reasonable measurement placement method in a power network is to allocate the places in the power network to have a measurement matrix with the least condition number. Regarding the above illustrations, the posed problem up to now has obvious answers, which are the system state variables. If we measure all of the system suspicious bus voltages, we will reach the most precise estimation. Because, it is clear that by performing this measurement there will be no need to calculate the system variables by estimating methods. From a different point of view, in this situation, the measurement matrix H will be the identity matrix with unity condition number. However, as it is described in section (4), this evident answer is not acceptable regarding the economic matter. Practically, optimal measurement placement in harmonic state estimation using the least square estimator should be accomplished by the proposed algorithm in the section (4) which considers both of economic and precision factors with each other. In the mentioned algorithm, one of the following procedures will be applied to compass the best possible precision.

3.1 Optimal measurement placement by considering the precision factor using the sequential elimination algorithm [6]

In the sequential elimination algorithm, at first, it is assumed that the measurement is performed in all of the available points of the power network. So, for constituting the measurement matrix H, we should place three matrices $Y_{NN}(h)$, I, and $Y_{LN}(h)$ which are appeared in relations (2) to (4), with each other. Finally, the measurement matrix H can be obtained as shown in (10), by partitioning system busbars into suspicious busbars and non-source busbars and by regarding the relations (7), (8) and (9). Thereafter, by using the sequential elimination algorithm, unsuitable measurements can be eliminated to determine the optimal measurements in the power system network. This process can be accomplished in an elaborate loop. The outer loop should be iterated $(q-n_s)$ times, where q is the total number of available measurements and n_s is the number of suspicious busbars in the power system network. At the end of an iteration of the outer loop, one of the measurement matrix rows should be eliminated. The inner loop will be iterated in an iteration of the outer loop for r times, where r is the number of remainder rows in the measurement matrix H. During of an iteration of the inner loop, one of the measurement matrix rows will be eliminated temporarily and the condition number of the corresponding measurement matrix will be calculated and saved. After egression from the inner loop, the saved condition numbers will be investigated and the row, that by eliminating causes to have the minimum condition number, will be eliminated.

3.2 Optimal measurement placement by considering the precision factor using GA

In this paper, for solving the optimal measurement placement for harmonic state estimation, GA with the binary coding is used. For this purpose, the length of each chromosome will set equal to q, where q is the number of all possible measurements in the power system network. As it has been explained before, to obtain a unique solution (i.e., completely observable system), the number of measuring equipments should be selected the same as the number of under estimating states. So, in each chromosome, n_s genes are 1, represented the measured points and other genes are 0, represented unmeasured points. In other words, each chromosome is a representation of a set of n_s selected points for placing meters from q possible points in the power network. In this case one-by-one correspondence will be established between the rows of the full measurement matrix of the power system network, which has been described in the previous section, and the location of each gene in the chromosome. Regarding the location of active genes (genes equal to 1) in each chromosome, the measurement matrix H corresponding to that chromosome will be constituted and the condition number of that measurement matrix can be calculated. The inverse of the measurement matrix condition number is selected as the objective function in the mentioned GA for optimal measurement placement in harmonic state estimation. By this selection, the objective function value is always in the interval $[0,1]$ and the goal is to maximize this objective function to reach the best measurement placement. In the GA, only the mutation operator is applied. The simulation results are shown degradation of the answer by using the cross-over operator, because in this problem, despite of many problems that have been solved by GA, using the cross-over operator exterminates the possibility of smooth search. Indeed, by using the cross-over operator, the location of placements changes abruptly, and it is undesirable.

However, as it is necessary that the number of active genes in a chromosome be equal to the number of used measuring equipments, in applying the mutation operator, for each chromosome, one of the active genes and one of the inactive genes will be selected randomly using a uniformly distributed probability function, and the content of selected genes will be reversed, i.e., will be changed from 1 to 0 and from 0 to 1. The used GA, is supervised, i.e., if the best fitness be constant during twenty iteration, the mutation probability function will be increased abruptly, and in the next iterations, the mutation probability will decrease by the rate of 95% to return to the prime value. During of the decreasing of the mutation probability, if the best fitness did not have a sensible variation, the GA will be terminated and the best chromosome will be the answer of the optimal measurement placement problem.

The simulation results for IEEE 14-bus standard test case, which can be accessible in [6], are shown that by considering the precision factor, the sequential elimination algorithm is unsuccessful in finding the evident answer of optimal measurement placement problem whereas the proposed GA in this paper is usually successful. Indeed, the evident answer will be achieved if all n_s combinations of q, where n_s and q are introduced in subsection (3.1), be investigated, and this is impossible in a practical power network because of the large dimensions of the network. For example, in a power network with 19 busbars and 150 possible locations for measurement, optimal measurement placement is involving the investigation of 5.54×10^{23} possible combinations (all of possible combinations). Thus, the proposed method in this paper based on GA for optimal measurement placement problem is a reasonable method.

4. Optimal measurement placement by considering both precision and economic factors

The harmonic measurement system for harmonic state estimation in the power networks can be divided into two parts. One part is to contain the local measurement substations, which are applied to gather partial synchronized measurements from various points of the power system network. The second part is the center of gathering measured data is called master station. In the master station, measurements will process by the calculator of the estimator to obtain an estimation of the system states. In each local substation, some CTs and PTs are needed for measuring the desired quantities. A processor for compensating and eliminating the measurement errors and for converting the measured quantities to the phasor type is needed too. Moreover, a Global Positioning System (GPS) receiver is needed for synchronizing the measurements and also a transmitter for transmission of the measurements to the master station. On the other hand, we want to perform the estimation in a completely determined situation, the total number of required CTs and PTs is always constant and is equal to the number of system states. Hence, the measurement cost will only decrease by decreasing the number of required GPS receivers and transmitters or in other words by reducing the number of local measurement sites. For this purpose, the following algorithm is suggested for optimal measurement placement problem in harmonic state estimation by regarding both precision and economic factors:

1. The power system network should be partitioned into different sub-sections such that in each sub-station one local measurement substation for performing the measurements is needed. It is clear that each section contains all the busbars and the connected lines to those busbars which are situated in a high voltage station and regarding the descriptions in section (2), three different types of measurements including busbars harmonic voltages, harmonic currents injected to busbars and harmonic currents flowing through the lines, could be performed in each section.
2. Considering the full measurement placement in each section, the measurement matrix corresponding to each section should be determined. Then the condition number of the mentioned matrices should be calculated. The measurement matrix with the least condition number will be selected as the first priority. If all of the measurement matrices corresponding to single local sites had infinite condition numbers, the combinations of the local measurement sites should be considered, i.e., in the next stages, at first, the double combinations of the local sites should be considered, and then the triple combinations should be considered, and so on. This procedure should be continued to obtaining at least one measurement matrix with the limited condition number.
3. By using one of the mentioned methods for optimal measurement placement by considering the precision factor in section (3), i.e., sequential elimination or GA, it should be decreased the number of available measuring points in the set or sets that have been obtained from the previous step to reach the number of measurements equal to the number of system states. If the number of measurement sets obtained from the second step is more than one, it is clear that we should select the set of measurements for placing the sensors that after applying the sequential elimination or GA, leads to the least condition number for obtained measurement matrix H in (11). The procedure of implementing the above algorithm is shown in the Fig. 1.

As it has been explained in section (3), the GA is more successful than the sequential elimination algorithm in solving the optimal measurement placement in harmonic state estimation just by regarding the precision factor. Hence, it is proposed to use the method based on GA in the second step of the proposed algorithm for optimal measurement placement. The simulation results in section (5) also show the improvement in measurement placement using the GA, compared to the sequential elimination algorithm. Moreover, in all of the proposed measurement placement methods, measurement placement is performed in one harmonic order and the obtained results are applied for estimating the system harmonic state in other concerned harmonic orders. This results in the degradation of the estimation in harmonic orders far from the harmonic order in which measurement placement is carried out. But, in this paper a method is proposed to combine the effect of all concerned harmonic orders. In this method, the goal functions in GA-based and SE-based measurement placement methods are reformed as (13) and (14), respectively. In these relations cond[H(h_i)] denotes the condition number of the measurement matrix H at harmonic order h_i and w_i is the weighting factor for harmonic order h_i.

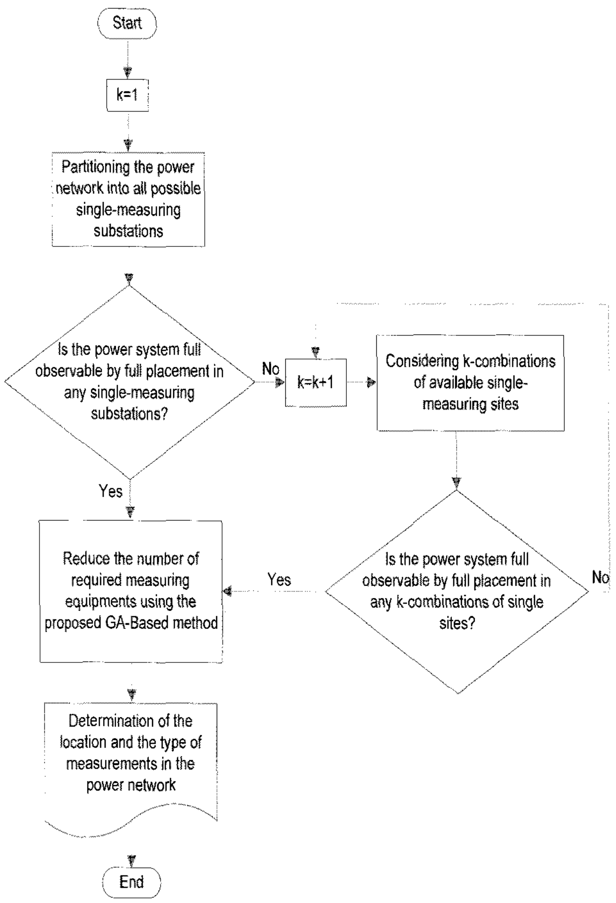

Fig. 1. The procedure of the proposed optimal measurement placement in the harmonic state estimation

$$GF_{GA}(h_1, h_2, \ldots, h_n) = \frac{w_1}{\mathrm{cond}[H(h_1)]} + \frac{w_2}{\mathrm{cond}[H(h_2)]} + \cdots + \frac{w_n}{\mathrm{cond}[H(h_n)]} \tag{13}$$

$$GF_{SE}(h_1, h_2, \ldots, h_n) = w_1 \times \mathrm{cond}[H(h_1)] + w_2 \times \mathrm{cond}[H(h_2)] + \cdots + w_n \times \mathrm{cond}[H(h_n)] \tag{14}$$

Indeed, by using the above mentioned goal functions we combined the effect of all concerned harmonic orders in measurement placement problem, although, we assigned different weights to different harmonic orders that make it possible to conduct the solution of measurement placement problem toward the important harmonic orders.

5. Simulation results

The one-line diagram of IEEE 30-bus standard test system is shown in Fig. 2. The full data of the mentioned system can be found in [14].

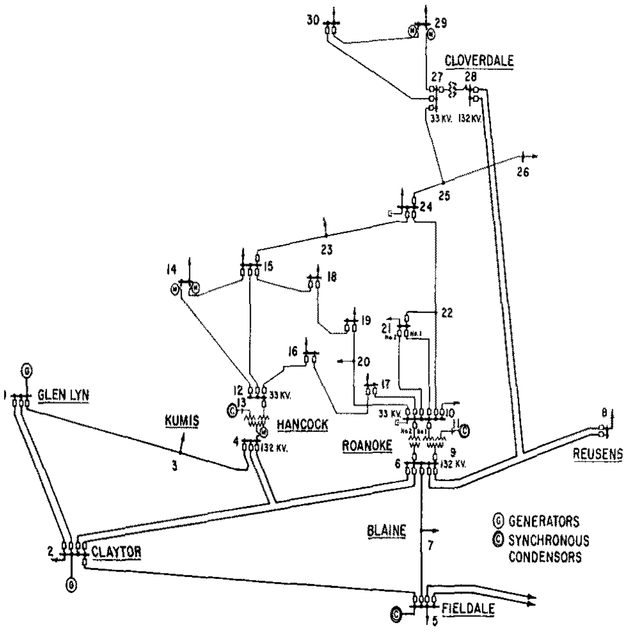

Fig. 2. One-line diagram of IEEE 30-bus standard test system

Table 1. Local measurement substations

The Number of Local Measuring Substations	The Bus Numbers at Each Local Measuring Substation
1	2
2	4, 12, 13
3	6, 9, 10, 11
4	18
5	24
6	27, 28

The loads are connected to 19 busbars of this power network. Hence, the number of system state variables, to be estimated which also is equal to the number of required measurements for estimation, is 19. But using the algorithm described in section (4), only 6 local measuring substations, which are listed in Table 1, are used for performing the estimation. In this Table, the bus numbers in each local substation are given. But it is clear that all of the lines connected to these busbars are included.

Four harmonic sources are connected to the system busbars with the following numbers: 10, 15, 24, and 30.

Harmonic sources connected to the busbars with the numbers: 10, 15, and 24 are three-phase rectifiers and the harmonic source which is connected to the busbar number 30 is a three-phase thyristor-controlled pure resistive load. The magnitude of the harmonic current injected by a three-phase rectifier at h^{th} harmonic order is 1/h of the corresponding fundamental load current and the phase angle is h times of the corresponding fundamental load current phase angle, with an additional 180° shift for the 5^{th}, 11^{th}, and 17^{th} harmonic orders [15]. The harmonic current injected by the thyristor-controlled pure resistive load at the h^{th} harmonic order is [15]:

$$\bar{I}_h = a_h + jb_h \tag{15}$$

where

$$a_h = \frac{\sqrt{2}V}{\pi R}\left[\frac{\sin(h+1)\alpha}{(h+1)} - \frac{\sin(h-1)\alpha}{(h-1)}\right] \tag{16}$$

and

$$b_h = \frac{\sqrt{2}V}{\pi R}\left[\frac{\cos(h+1)\alpha - \cos(h+1)\pi}{(h+1)} - \frac{\cos(h-1)\alpha - \cos(h-1)\pi}{(h-1)}\right] \tag{17}$$

In two recent relations V is the magnitude of the corresponding bus voltage, R is the load resistance and α is the firing angle which is selected 30° in simulations.

The simulation results related to GA-based and SE-based methods in the optimal measurement placement for static harmonic state estimation by considering the same weighting factors for different harmonic orders including 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th} and 19^{th} orders are given in Table 2. It should be noted that, under consideration power network is a three-phase balanced network. Moreover, harmonic sources are connected to the power network via Y-Δ transformer connections. Hence, the multipliers of the third harmonic order will not propagate into the power network.

Table 2. Measurement placement obtained by using GA-based and SE-based methods

Placement Method	Bus Voltages	Bus Injected Currents	Line currents
GA-Based Method	4, 12, 27	-	7, 8, 23, 31, 37, 38, 42,46, 58, 59, 71, 72, 74, 80, 81, 84
SE-Based Method	12, 27	-	5, 7, 8, 21, 23, 35, 37, 38, 43, 46, 58, 59, 71, 72, 74, 80, 81

In order to search for the exact location of each placement, the directional graph of under consideration power network is given in Fig. A in the Appendix.

In Table 3, a comparison is performed between the condition number of measurement matrices and the sum of the squared estimation errors in per-unit system for different harmonic orders.

It should be noted that to access the practical conditions, a Gaussian random noise vector in the range of 10% of the measured values is added to the measured vector.

Table 3. Comparison between condition numbers and sum of squared errors, using two placement methods

Concerned Harmonic Orders	GA-Based Measurement Placement		SE-Based Measurement Placement	
	Cond[H]	Sum of Squared Errors	Cond[H]	Sum of Squared Errors
5	16.2166	7.4019e-5	20.6709	1.6126e-4
7	16.6358	5.3040e-5	20.0810	7.9187e-5
11	15.4673	1.7366e-4	18.9569	4.3008e-4
13	15.4429	3.2415e-4	18.4841	9.9819e-4
17	15.4206	1.3273e-4	17.9888	2.8488e-4
19	16.2626	1.0603e-4	18.1245	2.9004e-4

As it can be seen in Table 3, in all of the concerned harmonic orders, the condition number of the measurement matrix and subsequently, the sum of the squared estimation errors obtained by placing the sensors using GA-based method is superior in comparison to the results obtained using the SE-based placement method.

Finally, to show the improvement of static harmonic state estimation using the proposed measurement placement method in this paper, the absolute values of the system busbars actual voltages, which are obtained using harmonic load-flow, are compared to the absolute values of the system busbars estimated voltages, for both of the GA-based and SE-based measurement methods. The absolute values of the system busbars actual voltages, the absolute values of the system busbars estimated voltages and the absolute values of the estimation errors (all of them in per-unit), using the placements obtained by GA-based and SE-based placement methods are shown in Fig. 3, and Fig. 4, respectively.

As it can be seen in these two figures the absolute value of estimation errors in different harmonic orders and in various system busbars, will significantly be decreased by using the GA-based placement, compared to the method in which SE-based placement is used. For more illustrations, in Table A in the Appendix, the absolute value of the estimation errors and the relative percentage errors at all of the system busbars and in all concerned harmonic orders are compared with each other, using two mentioned measurement placement methods.

In Fig. 5, summation of the condition numbers of the measurement matrices in all concerned harmonic orders for the best individual in successive generations of GA is plotted. It should be noted that for a better specification, we have limited the range of variations on y-axis of the graph. So, the values of the sum of the condition numbers for the best individual in the some of the primary generations are eliminated from the mentioned graph.

In the implementation of the proposed GA in this simulation, 50 chromosomes are used. The initial value of mutation probability is set as Pm = 0.01, and if the best fitness remains constant during 20 iterations, the mutation probability will be increased to Pm = 0.05, and then by the rate of 95 percents, the mutation probability will be decreased to its normal value. The mutation operator will be operated on 60 percents of all chromosomes in each generation, and other chromosomes accompanying with the best chromosome, will directly be passed into the next generation. The maximum number of iterations in implementation of the proposed GA in this paper is set to 500. Considering the mentioned reasons in section (3.2) the cross-over operator is not applied in implementation of the proposed GA.

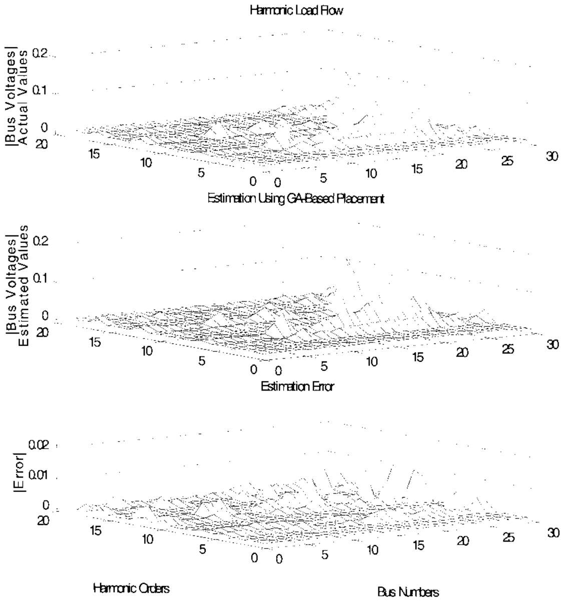

Fig. 3. Actual value of bus voltages, estimated value of bus voltages and absolute value of estimation errors using GA-based method in measurement placement

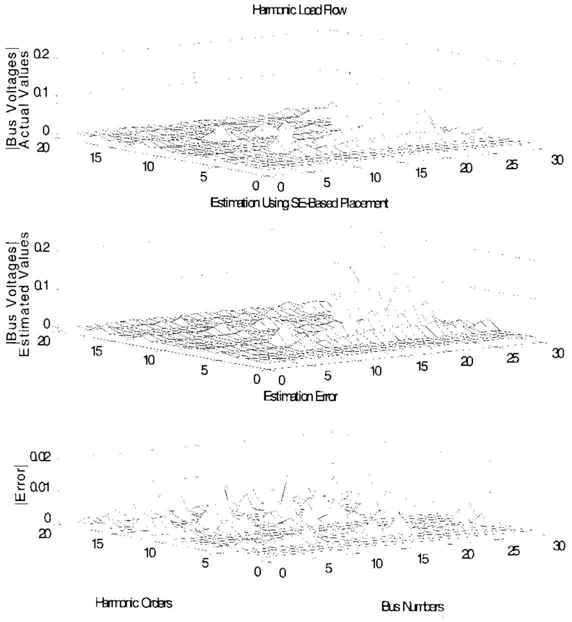

Fig. 4. Actual value of bus voltages, estimated value of bus voltages and absolute value of estimation errors using SE-based method measurement placement

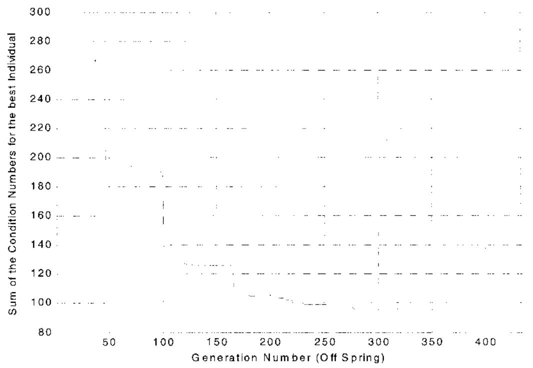

Fig. 5. Sum of the condition numbers of the measurement matrices in all concerned harmonic orders for the best individual in successive generations

6. Conclusion

In this paper, a method, which is based on GA for optimal measurement placement in harmonic state estimation by considering the precision factor, has been proposed. Then, a practical algorithm considering the economic factor for optimal placement has been used, by partitioning the power system network into several sections that in each section only one local measuring substation is needed. At the next stage, the optimal measurement placement problem for harmonic state estimation in power systems has been solved by incorporating both precision and economic factors. Finally, improvement in the precision of the estimation by using the proposed method in this paper has been verified by simulations on the IEEE 30-bus standard test system.

Appendix

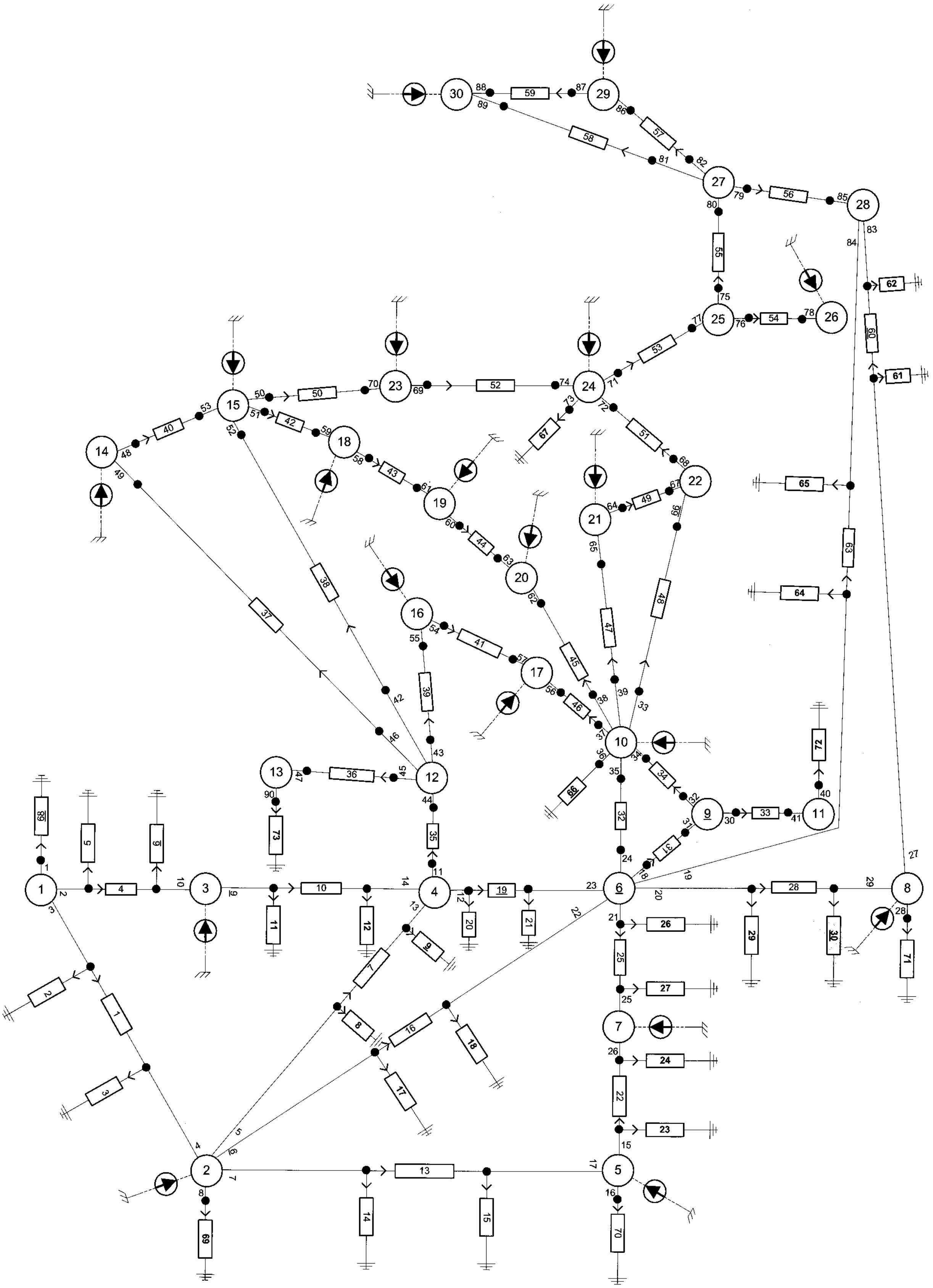

Fig. A. Directional graph of IEEE 30-bus standard test system

Table A. Comparison between absolute errors and relative error percentages, by using GA-based and SE-based measurement placement methods in static harmonic state estimation

Bus No.	Placement Method	Absolute Errors (Volt) and Relative Error Percentages at Each Harmonic Order					
		5th	7th	11th	13th	17th	19th
1	GA-Based	64.76(22.7%)	76.66(10.6%)	162.81(24.5%)	508.82(22.1%)	326.50(24.4%)	0.87(0.2%)
	SE-Based	179.50(62.9%)	14.97(2.1%)	410.70(61.8%)	725.40(31.5%)	253.65(19.0%)	17.19(3.6%)
2	GA-Based	57.19(20.2%)	29.45(4.1%)	153.12(24.2%)	617.15(28.9%)	264.78(24.5%)	34.88(9.7%)
	SE-Based	133.90(47.2%)	51.84(7.3%)	382.79(60.6%)	392.41(18.4%)	176.4(16.3%)	174.39(48.4%)
3	GA-Based	153.83(35.7%)	118.49(12.3%)	139.44(24.2%)	146.03(11.3%)	5.01(13.1%)	57.02(28.9%)
	SE-Based	164.75(38.2%)	24.85(2.6%)	348.12(60.3%)	569.67(43.9%)	17.48(45.7%)	85.24(43.2%)
4	GA-Based	97.43(21.4%)	104.30(10.7%)	47.09(9.5%)	37.71(4.3%)	24.98(7.4%)	17.47(6.1%)
	SE-Based	176.89(38.8%)	6.28(0.6%)	109.01(22.1%)	421.45(48.6%)	98.90(29.3%)	179.54(63.1%)
5	GA-Based	35.00(18.8%)	57.47(12.9%)	66.01(19.4%)	36.61(3.8%)	37.70(28.9%)	80.57(29.5%)
	SE-Based	50.01(26.9%)	123.88(27.8%)	105.99(31.2%)	90.27(9.3%)	53.86(41.3%)	402.85(147.3%)
6	GA-Based	35.27(11.3%)	91.15(13.4%)	91.34(31.2%)	26.18(9.9%)	74.34(15.6%)	74.45(15.6%)
	SE-Based	236.23(75.8%)	38.89(5.7%)	210.77(71.9%)	283.49(107.3%)	83.93(8.4%)	148.21(31.1%)
7	GA-Based	42.27(16.3%)	219.62(37.0%)	227.40(67.0%)	32.50(5.2%)	25.27(3.1%)	94.36(17.1%)
	SE-Based	279.47(107.8%)	66.28(11.2%)	159.52(47.0%)	282.67(44.9%)	40.61(4.9%)	205.77(37.3%)
8	GA-Based	36.34(12.3%)	137.48(21.3%)	49.80(21.8%)	41.43(61.2%)	464.16(36.0%)	114.32(19.5%)
	SE-Based	191.90(68.4%)	162.99(25.2%)	233.47(102.2%)	72.57(107.2%)	185.58(14.4%)	169.81(29.0%)
9	GA-Based	1.32(9.8%)	0.82(2.6%)	0.53(11.3%)	2.82(14.2%)	0.13(5.3%)	0.03(3.2%)
	SE-Based	2.03(15.1%)	0.09(0.3%)	2.35(49.7%)	5.94(29.8%)	0.62(25.4%)	0.52(48.3%)
10	GA-Based	63.94(7.8%)	31.69(1.6%)	37.01(12.5%)	152.70(12.8%)	6.10(32.5%)	3.77(57.4%)
	SE-Based	158.16(19.3%)	8.29(0.4%)	175.86(59.4%)	435.63(36.4%)	23.69(126.2%)	2.37(36.1%)
11	GA-Based	7.93(9.8%)	4.92(2.6%)	3.19(11.3%)	16.96(14.2%)	7.69(23.9%)	0.21(3.2%)
	SE-Based	12.22(15.1%)	0.54(0.3%)	14.11(49.7%)	35.68(29.8%)	11.63(36.1%)	8.84(137%)
12	GA-Based	35.86(7.4%)	9.62(1.3%)	0.07(0.0%)	6.43(2.0%)	1.52(2.3%)	10.35(9.4%)
	SE-Based	17.19(3.5%)	101.71(13.7%)	3.73(2.6%)	17.23(5.4%)	1.03(1.6%)	26.32(23.9%)
13	GA-Based	1.35(1.3%)	10.93(6.9%)	1.47(7.2%)	0.75(1.1%)	1.62(11.5%)	2.80(11.9%)
	SE-Based	13.93(13.5%)	5.81(3.7%)	2.36(11.6%)	3.68(5.4%)	0.22(1.6%)	5.62(23.9%)
14	GA-Based	13.85(2.3%)	13.67(1.7%)	53.53(30.1%)	45.01(7.0%)	6.71(5.9%)	15.27(9.4%)
	SE-Based	2.17(0.4%)	29.27(3.6%)	39.93(22.5%)	22.12(3.4%)	70.14(62.5%)	50.38(30.9%)
15	GA-Based	32.40(4.5%)	5.82(0.6%)	58.25(26.6%)	74.13(8.0%)	12.05(7.8%)	8.20(3.9%)
	SE-Based	69.86(9.7%)	41.19(4.6%)	70.40(32.2%)	97.29(10.5%)	33.00(21.4%)	50.24(23.7%)
16	GA-Based	9.40(1.5%)	45.23(3.7%)	28.07(17.2%)	67.85(21.3%)	8.32(20.5%)	22.71(37.4%)
	SE-Based	34.02(5.5%)	26.27(2.1%)	49.61(30.4%)	54.63(17.2%)	9.42(23.2%)	21.03(34.6%)
17	GA-Based	51.65(6.9%)	30.52(1.8%)	47.32(19.1%)	110.77(12.1%)	7.63(34.9%)	3.25(23.4%)
	SE-Based	180.12(24.0%)	14.41(0.8%)	225.09(90.7%)	468.21(51.0%)	20.07(91.8%)	29.88(215.1%)
18	GA-Based	51.50(7.1%)	7.33(0.6%)	27.53(16.9%)	54.94(25.6%)	27.46(27.7%)	45.32(34.6%)
	SE-Based	47.53(6.6%)	49.82(4.1%)	36.69(22.5%)	43.36(20.2%)	21.26(21.5%)	48.26(36.8%)
19	GA-Based	56.84(7.7%)	9.06(0.6%)	28.83(16.4%)	115.67(44.1%)	10.33(15.2%)	9.83(11.5%)
	SE-Based	60.47(8.2%)	49.12(3.5%)	71.33(40.6%)	51.71(19.7%)	0.96(1.4%)	55.48(65.3%)
20	GA-Based	107.19(14.2%)	32.66(2.1%)	10.22(5.2%)	94.94(19.6%)	14.06(26.3%)	12.28(19.7%)
	SE-Based	207.99(27.6%)	16.37(1.1%)	27.52(13.9%)	274.59(56.7%)	21.87(40.9%)	19.39(31.1%)
21	GA-Based	53.32(6.2%)	56.41(2.9%)	18.86(18.8%)	40.72(35.4%)	7.00(6.4%)	31.49(32.9%)
	SE-Based	40.93(4.8%)	11.05(0.6%)	39.10(39.0%)	182.99(159.2%)	18.85(17.2%)	9.49(9.9%)
22	GA-Based	36.86(4.2%)	44.14(2.3%)	13.20(12.2%)	0.63(0.2%)	34.86(24.0%)	7.54(6.1%)
	SE-Based	16.59(1.9%)	6.20(0.3%)	88.60(82.2%)	102.88(40.7%)	98.14(67.5%)	7.05(5.7%)
23	GA-Based	10.64(1.2%)	6.77(0.5%)	12.96(3.1%)	73.66(3.0%)	2.02(1.2%)	20.11(15.5%)
	SE-Based	59.08(6.9%)	47.12(3.4%)	67.65(16.3%)	105.04(4.3%)	16.78(10.0%)	68.23(52.4%)
24	GA-Based	8.84(0.8%)	9.30(0.4%)	4.76(0.5%)	2.31(0.1%)	86.46(14.5%)	14.35(3.0%)
	SE-Based	33.57(2.9%)	36.53(1.8%)	2.67(0.3%)	38.12(0.8%)	31.45(5.3%)	44.56(9.2%)
25	GA-Based	8.40(1.2%)	5.82(0.5%)	70.26(9.5%)	97.64(3.1%)	18.33(2.6%)	57.02(18.7%)
	SE-Based	44.97(6.7%)	46.63(4.1%)	67.77(9.2%)	72.29(2.3%)	79.18(11.2%)	53.26(17.5%)
26	GA-Based	41.81(6.4%)	48.98(4.4%)	236.92(33%)	302.76(9.8%)	183.17(26.6%)	113.27(38.2%)
	SE-Based	16.51(2.5%)	8.85(0.8%)	260.97(36.4%)	390.28(12.6%)	36.07(5.2%)	165.01(55.7%)
27	GA-Based	37.24(7.7%)	42.55(7.1%)	8.46(1.3%)	148.36(6.7%)	0.89(0.1%)	3.90(1.3%)
	SE-Based	8.36(1.7%)	57.53(9.6%)	55.75(8.8%)	3.52(0.1%)	25.20(3.1%)	1.88(0.6%)
28	GA-Based	87.01(18.6%)	67.91(7.5%)	10.52(47.4%)	221.90(22.6%)	215.70(11.1%)	176.62(32.2%)
	SE-Based	102.70(22%)	1.61(0.2%)	13.66(61.6%)	517.14(52.6%)	145.55(7.5%)	111.66(20.4%)
29	GA-Based	110.42(17.8%)	133.27(38.8%)	321.92(37.1%)	341.83(13.4%)	71.56(6.9%)	127.57(22.4%)
	SE-Based	101.46(16.4%)	129.45(29.9%)	219.43(25.3%)	217.17(8.5%)	141.57(13.6%)	217.93(38.2%)
30	GA-Based	103.95(11.8%)	171.19(31.6%)	247.35(21.0%)	304.24(10.7%)	48.12(3.6%)	133.80(15.0%)
	SE-Based	108.34(12.3%)	168.60(31.1%)	259.35(22.0%)	296.10(10.4%)	307.19(23%)	88.27(9.9%)

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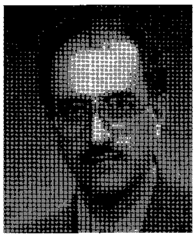

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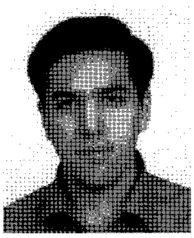

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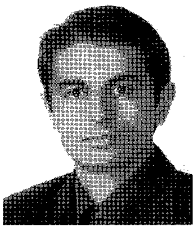

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