CHAPTER 4

Test Systems and Test Results

Two test systems are used to test the proposed measurement placement algorithm. These test systems also illustrate the complexity of designing a measurement system to perform HSE. The first test system is the Lower South Island of New Zealand system, which is a three-phase unbalance power system. The second is the IEEE 14-bus test system and this is a balanced system hence single-phase representation is adequate. All nodes or busbars with loads connected are treated as suspicious nodes. The remaining nodes are non-harmonic source nodes. It is assumed that the suitable measurement equipment capable taking synchronized measurement is available. The proposed algorithm for measurement placement and HSE is written using MATLAB®.

4.1. Test Systems

4.1.1 Test system I: The New Zealand Test System

The proposed algorithm is tested using the 220 kV interconnected transmission grid below Roxburgh in the South Island of New Zealand. Three-phase modeling is applied to take into account imbalances and the coupling between phases at harmonic frequencies. This is achieved by using a transmission line parameter to calculate the electrical parameters of the lines from their physical geometry [17, 29, 32].

Figure 4.1 shows the three-phase diagram of the test network. The system includes 8 transmission lines represented by the equivalent Π model. The three synchronous generators are modeled as shunt branches and generate no harmonic currents. The five transformers are connected in star-delta. In the test system, there are 27 nodes, 111 branches, and 87 lines. Three loads are connected at Tiwai 220 kV (nodes 1–3), Invercargill 33 kV (nodes 22–24) and Roxburgh 33 kV (nodes 4–6). The actual harmonic sources are twelve-pulse rectifiers at Tiwai. Because a three-phase system is used, each busbar includes three nodes. Therefore, there are 18 non-harmonic source nodes (N_0) and 9 suspicious nodes (state variables, N_s) in the test system. There are 141 possible measurement locations (M), given that there are 27 locations for injection current measurements, 27 locations for node voltage measurements and 87 locations for line current measurements. All parameters for this test system can be found in [17].

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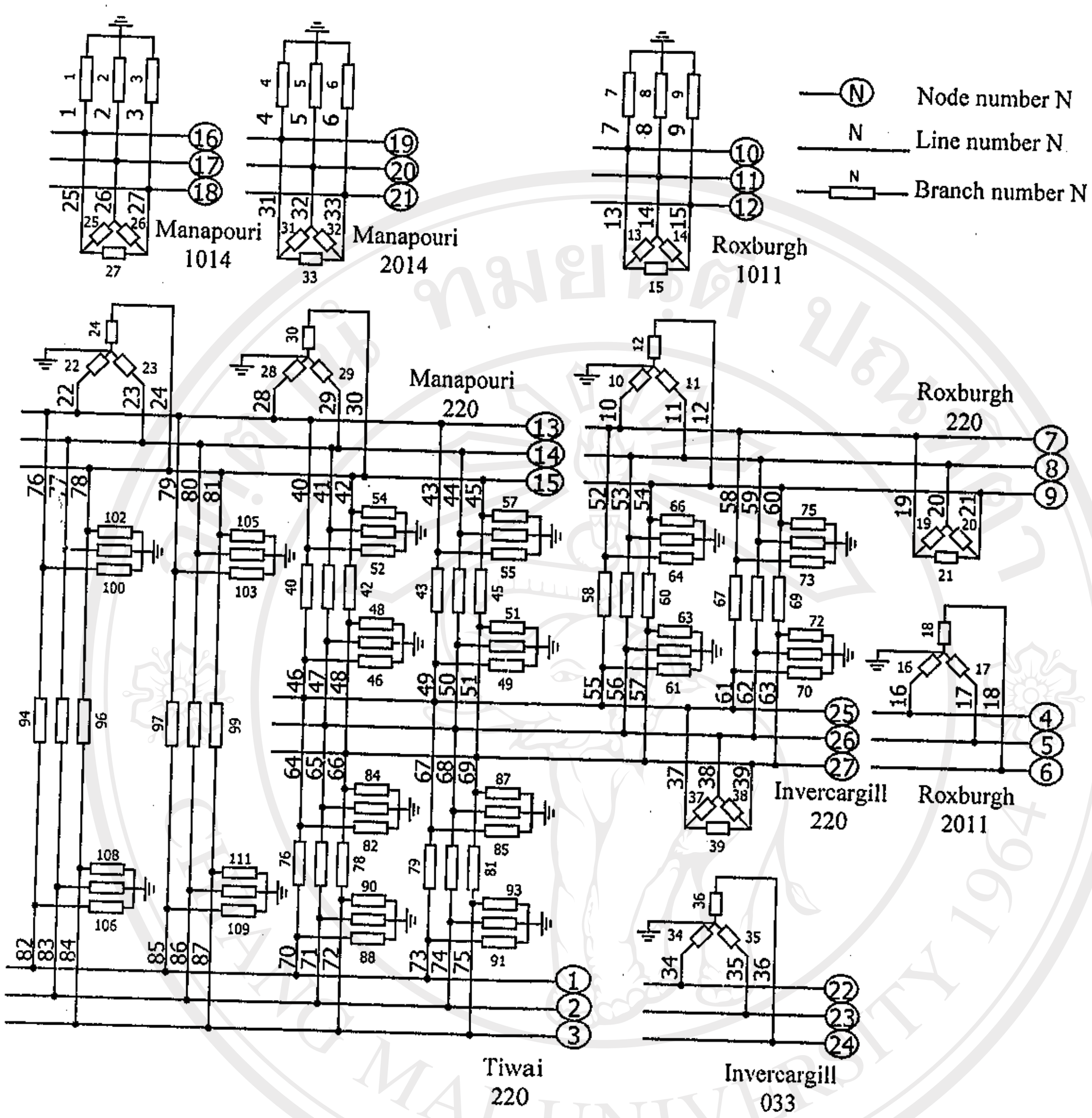

Figure 4.1 The New Zealand test system.

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4.1.2 Test system II: The IEEE 14-Bus Test System

A schematic of the IEEE 14-bus test system is shown in Figure 4.2. There are 14 busbars, 35 branches, and 41 lines. The equivalent Π model is used to represent each transmission line, with the electrical parameters being calculated from the physical geometry using a transmission line parameter program [32]. As the physical geometry is not available for the IEEE 14-bus test system a trial and error procedure is used to obtain a physical geometry that gives, as close as possible, the correct positive sequence impedance (R and X) and susceptance (B) at fundamental frequency. For all short lines, the susceptance is not modeled (as set to zero in the IEEE 14-bus system). For all long lines it is possible to model all R, X, and B values with an absolute error less than 9×10^{-4}. All parameters for this test system are shown in Appendix A. While, the TL program has been described in Appendix B.

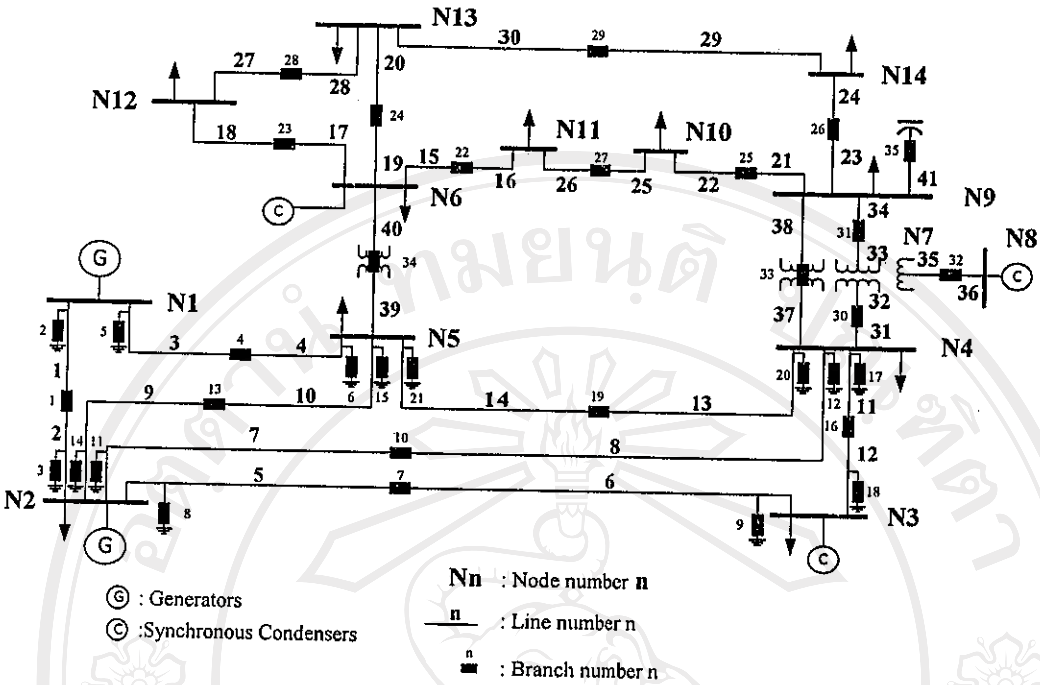

Figure 4.2 The IEEE 14-bus test system.

The TL program in Appendix B uses phase components, where for telephone interference, the zero sequence component is of primary importance. The sequence components (indicated by subscripts 012 for positive, negative, and zero sequences, respectively) are obtained from the phase quantities (abc) using the relationship [30]:

$$Y_{012} = T_S^{-1} Y_{abc} T_S \tag{4-1}$$

where T_S is a transformation matrix.

$$T_S = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad \text{and} \quad a = \frac{1}{2} - j\frac{\sqrt{3}}{2} \tag{4-2}$$

Transformation of equation (4-1) will then yield a diagonal matrix of positive, negative, and zero sequences, respectively. In this case the mutually coupled three-phase system has been replaced by three uncoupled symmetrical systems. In addition, if the generation and load were balanced, then current would flow in the positive-sequence network only and the other two sequence networks may be ignored. This is essentially a situation with the single-phase harmonic penetration analysis. [30]

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The system consists of 10 loads connected at busbars 3, 4, 5, 8–14. There are 4 non-harmonic source nodes (N_0) and 10 suspicious nodes (state variables, N_s) in the test system. The two harmonic current sources are a twelve-pulse HVDC terminal at busbar 3 and an SVC at busbar 8. The source spectra are provided in Table 1.4 of [31]. There are 69 possible measurement locations (M), given that there are 14 injections current measurements, 14 busbars voltage measurements and 41 lines current measurements.

Actually the state variable of the test system I and II are 27 and 14, respectively. Using HSE algorithm as described in section II, the number of state variable can be reduced to the number of suspicious nodes. There are 9 and 10 for the test system I and II, respectively.

4.2 Test Results

To obtain a unique solution for an N-bus system, the minimum required numbers of harmonic instruments (P), for all possible locations (M), has to be equal to the number of state variables. As a result, the optimal number of harmonic instruments is equal to the number of state variables. In the proposed algorithm, the measurement matrix of each harmonic order is considered one at a time with the objective of minimizing the number of measurements. Two cases are considered: Case I is starting from all possible locations (2N+L locations); while in Case II, harmonic current injections and busbar voltage at non-harmonic source busbars are not included (2N+L–$2N_0$ locations). The measurement placements obtained by using this algorithm, which make the two test systems full observable, are shown in Tables 4.1 and 4.2.

Table 4.1 Measurement placement of the New Zealand test system.

Harmonic order	Case	Injection current	Node voltage	Line current
5	I	22,24	No	16,18,21-24,35
	II	6,24	No	16,17,22-24,34,35
7	I	4,22,24	2	11,17,19,35,73
	II	4,23,24	No	11,17,21,34,73,75
11	I	4	22-24	56,61,63,76,81
	II	No	22-24	12,17,55,56,79,81
13	I	No	4-6,22-24	22,74,75
	II	No	2,4-6,22-24	54,58
17	I	No	5,6,8,22-24	12,16,24
	II	No	1,3-6,22-24	26
19	I	No	4-6,22-27	No
	II	No	1-6,22-24	No
23	I	No	4-6,22-24	54,65,67
	II	No	4-6,22-24	52,66,68
25	I	No	3-6,22-24	34,42
	II	22	3-6,22-24	42

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Table 4.2 Measurement placement of the IEEE 14-bus test system.

Harmonic order	Case	Injection current	Busbars voltage	Line current
5	I	No	3,8-14	7,40
	II	No	3-5,8-14	No
7	I	No	3,4,9,10,12-14	3,16,36
	II	No	3-5,8-14	No
11	I	No	3,5,8,10-12,14	7,20,34
	II	No	3-5,8-14	No
13	I	No	3,5,8,10-12,14	7,20,34
	II	No	3-5,8-14	No
17	I	No	4,8,10-12,14	3,5,20,34
	II	No	3-5,8-14	No
19	I	No	3-5,8-14	No
	II	No	3-5,8-14	No
23	I	No	3-5,8-14	No
	II	No	3-5,8-14	No
25	I	No	4,5,8,10-12,14	5,20,34
	II	No	3-5,8-14	No

It should be noted that the network configurations of the two test systems are completely different. In addition, the ratio of state variables to possible locations is quite different. There are 9 state variables for 141 possible locations in test system I, while test system II has 10 state variables for 69 possible locations. When the number of state variables is quite high compare with the number of possible locations (in Case I of the test system II) measurement placement solution resulted in all 10 suspicious busbar voltages.

Moreover the measurement placements are different among harmonic orders, but all of the measurement placements from all harmonic orders as shown in Table 4.1 and Table 4.2 are sufficient to uniquely calculate all state variables for all harmonic orders of the system correctly. Example, harmonic instruments location from harmonic order 5 in Case I can be used to calculate all state variables for all harmonic orders. In such a case, both normal equation and SVD can be used to solve the problem.

The example of measurement placement in Table 4.1 and Table 4.2 from 5th harmonic of case II have been shown in Figure 4.3 and Figure 4.4, respectively.

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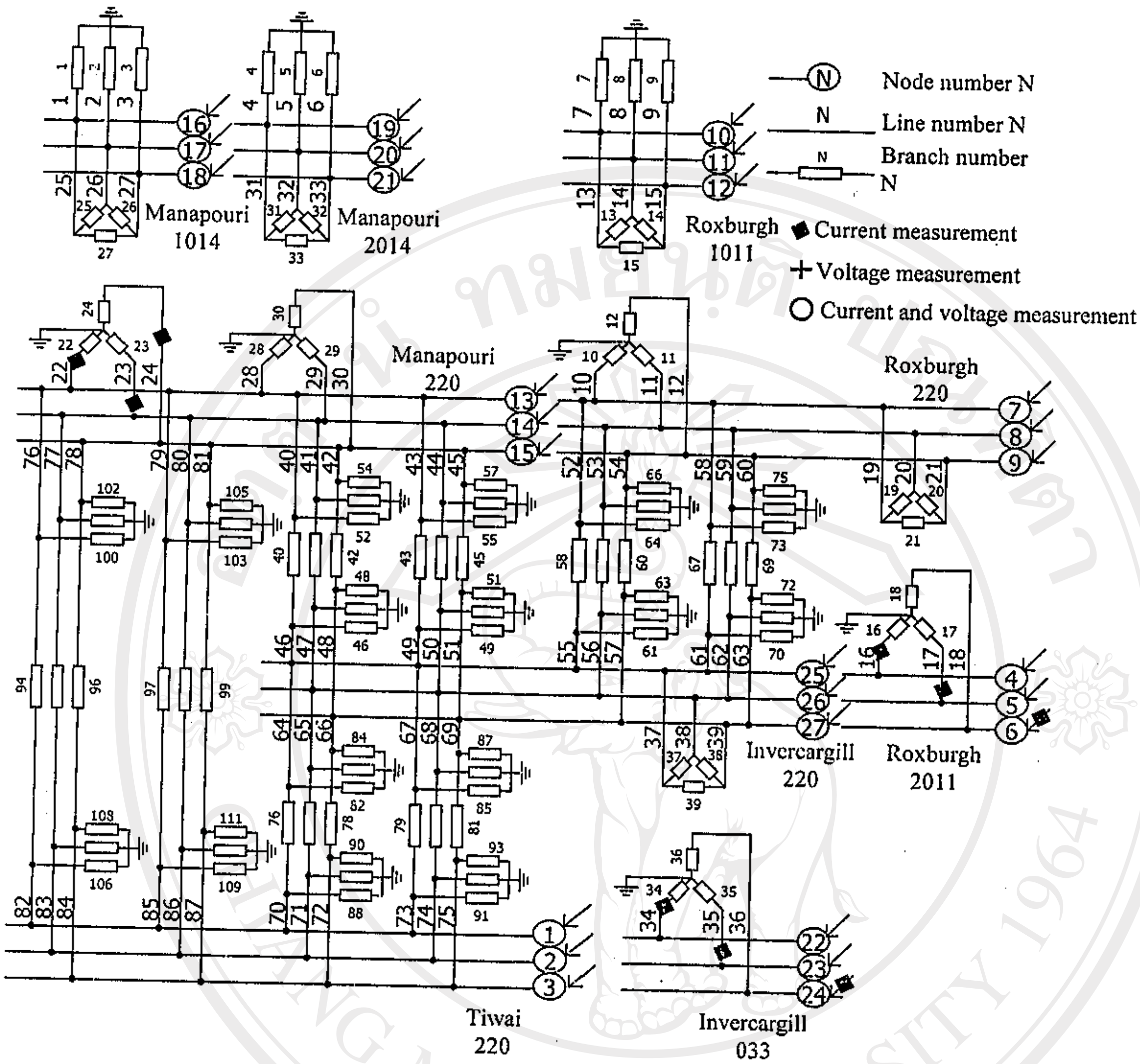

Figure 4.3 Example of measurement placement of the New Zealand test system.

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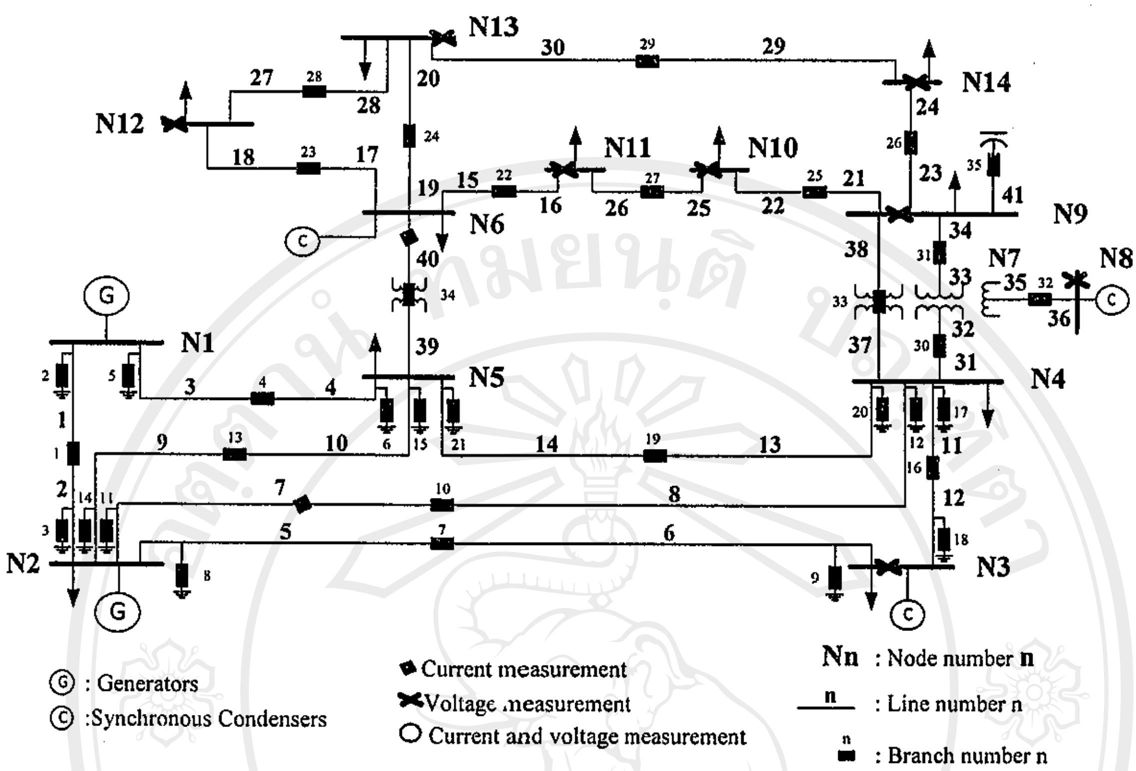

Figure 4.4 Example of measurement placement of the IEEE 14-bus test system.

However, minimizing the number of channels (harmonic instrument) does not necessarily result in lower cost because the predominant cost is in the base unit (site), while the incremental cost for additional channels is relative small. Again, an optimal measurement placement of this proposed method is to minimize the number of sites and also to minimize the number of total harmonic instruments (to be equal to the number of state variables) thus reducing the monitoring costs attached to HSE. At the same time, using minimum condition number of the measurement matrix with sequential elimination simultaneously increases the HSE solvability.

To minimize the number of site, a trial and error procedure base on condition number analysis will be used.

1. Fully measurement placement at all possible locations at each site should be considered (shown in Table 4.3). The site that has minimum condition number and measurement matrix is not singular should be selected in the first priority. Next, perform HSE with this fully measurement placement, if it is enough to solve all state variables (all singular value of a measurement matrix are non-zero), then use the proposed algorithm to reduce the number of harmonic instruments. On the other hand, if one site is not enough to solve the problem, more sites may be added using condition number analysis, one by one.

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2. If the numbers of possible locations in each site quite small compare with the number of state variables (such as test system II), the number of possible harmonic instruments in each site should be considered. The more possible locations, the more harmonic instruments could be placed. For example, busbars 4, 7–8, and 9 (each site has 7 or 8 possible location) of test system II, which has a dominant number of possible location compare with the other sites, should be selected first (shown in Table 4.4). It should be note that the IEEE 14-bus test system has 13 sites in total, busbars 7–8 are in the same site.

Table 4.3 Fully measurement placement of the New Zealand test system.

Site	Injection current and Node voltage	Line current	Possible locations	Condition number
Tiwai	1–3	70–75,82–87	18	3.16×10^{16}
Roxburgh	4–12	7–21,52–54,58–60	39	7.45×10^{16}
Manapouri	13–21	1–6,22–33,40–45,76–81	48	1.37×10^{17}
Invercargill	22–27	34–39,46–51, 55–57,61–69	36	5.46×10^{9}

Table 4.4 Fully measurement placement in dominant site of the IEEE14-bus test system.

Site	Number of sites	Injection current and Node voltage	Line current	Possible locations	Condition number
Busbar 4	1	Busbar 4	8,11,13,31,37	7	Infinity
Busbars 7–8	1	Busbars 7–8	32,33,35,36	8	Infinity
Busbar 9	1	Busbar 9	21,23,34,38,41	7	Infinity
Busbars 4, 7–8,9	3	Busbars 4, 7–8,9	8,11,13,21,23, 31–38,41	22	Infinity
Busbars 5,6	2	Busbars 5,6	4,10,14,15,17, 19,39,40	12	Infinity
Busbars 2,4, 7–8,9	4	Busbars 2, 4,7–8,9	2,5,7,8,9,11,13,21, 23,31–38,41	28	Infinity
Busbars 4,5 7–8,9	4	Busbars 4,5 7–8,9	4,8,10,11,13,14,21, 23,31–39,41	28	1.17×10^{18}
Busbars 4,6 7–8,9	4	Busbars 4,6 7–8,9	8,11,13,15,17,19,21, 23,31–38,40,41	28	20.21

It should be noted that, "Infinity" in Table 4.4 is generated by MATLAB®. It returns the IEEE arithmetic representation for positive infinity. Infinity is also produced by operations like dividing by zero, e.g. 1.0/0.0, or from overflow, e.g. 1×10^{1000}.

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From the simulation result using fully placement be shown in Table 4.3, only fully placement at Invercargill (as shown in Figure 4.5) that measurement matrix is not singular (double precision). It should be noted that, the condition number quite large (some singular value of a measurement matrix near zero). So, a measurement matrix may be not sufficient to solve all state variables correctly. HSE has to be performed to test solvability. Form HSE we know that fully placement at this site can be solved all state variable. Then the proposed algorithm with those possible locations is employed. The optimal measurement placements of this system, using the measurement matrix of the 5th harmonic, are node voltages at busbars 22, 25–27 and line currents at lines 56, 61, 63, 65 & 69 (as shown in Figure 4.6), the condition number is reduced to be 3.43×10^{9}. To solve HSE directly (without any extra computation effort) in such cases requires SVD. This yields correct answer at all busbars.

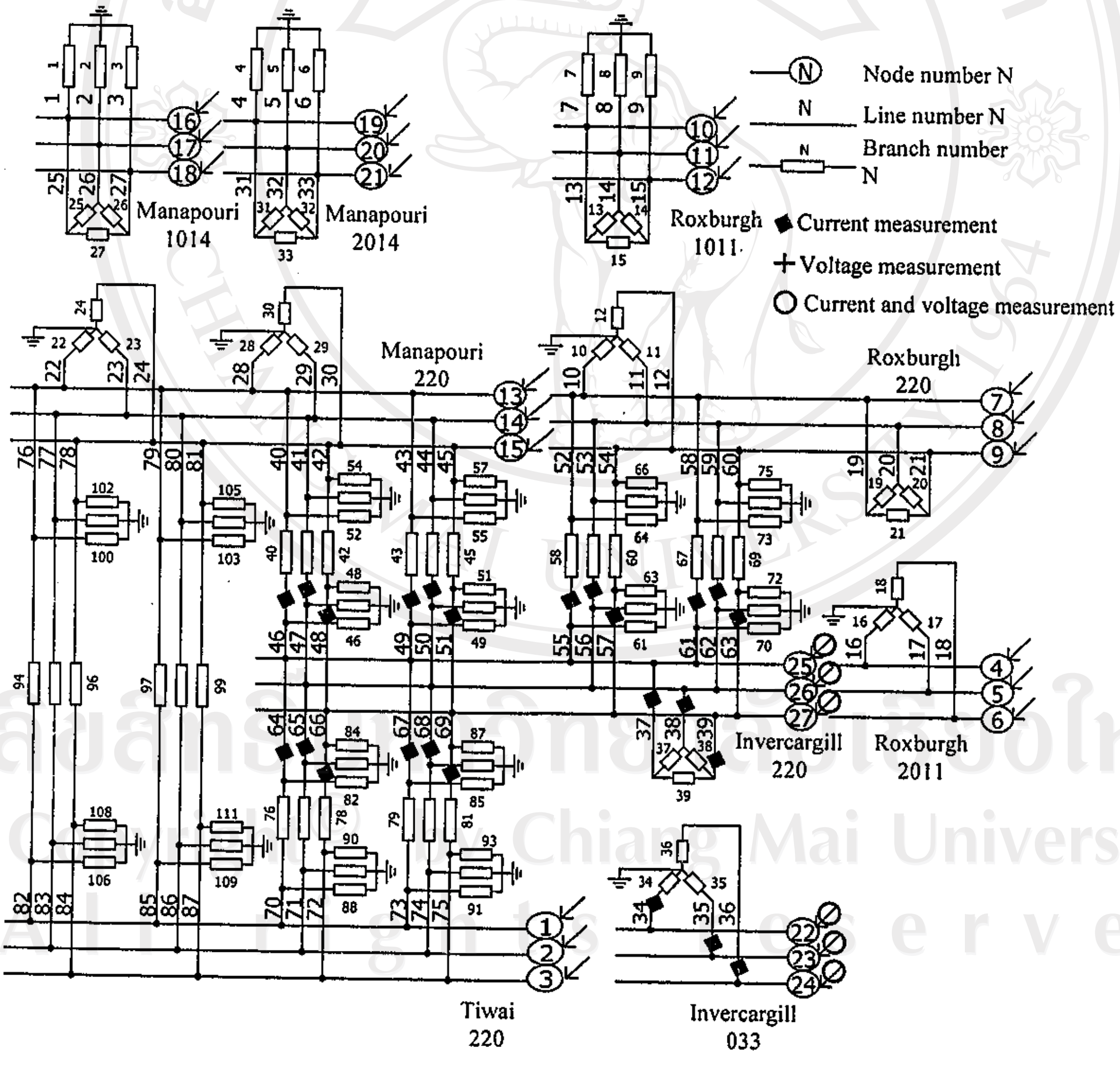

Figure 4.5 Fully measurement placement at Invercargill of the New Zealand test system.

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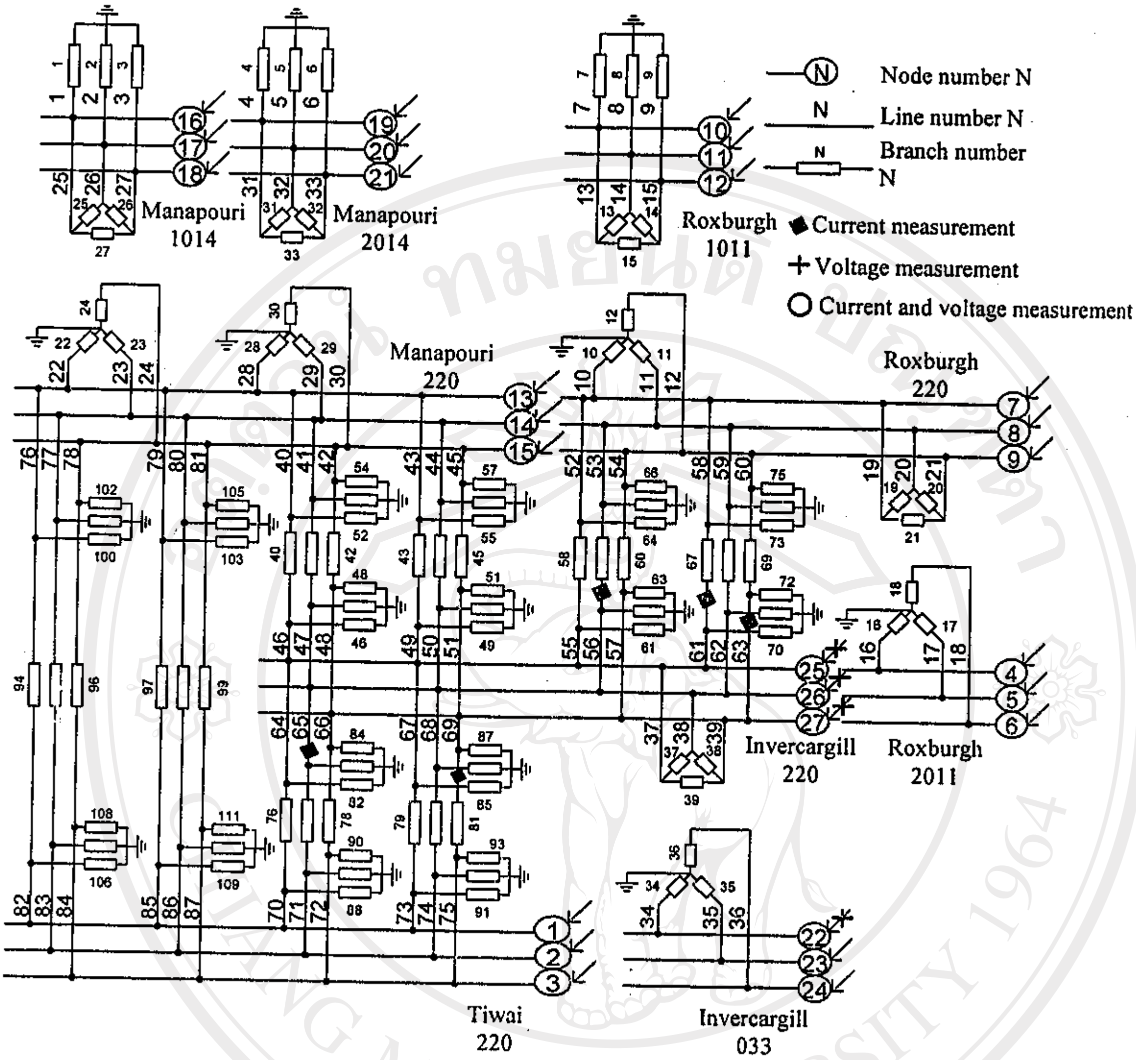

Figure 4.6 Reduced measurement point from Figure 4.5 using the proposed algorithm.

To minimize the number of sites for test system II, the earlier guideline is considered. From the network configuration, the process should start from busbars 4, 7–8, 9 (3 sites). The value of the condition number of busbars 4, 7–8, 9 (infinity; fourth line of Table IV) indicates that the measurement matrix is singular. Hence more sites have to be added, i.e. busbars 2 or 5 or 6 (site by site), which each gives many possible measurement locations (6 locations). From the condition number of each four sites, 20.21, it is known that fully placement at busbars 4, 6, 7–8, 9 (as shown in Figure 4.7) are sufficient to solve all state variables (all singular value of a measurement matrix are non-zero).

Again the proposed algorithm is employed. The optimal measurement placements of this system, using the measurement matrix of the 5th harmonic, are node voltages at busbars 6, 7 and line currents in lines 11, 15, 17, 21, 23, 32, 36 & 40 as shown in Figure 4.8. Using the proposed algorithm, the condition number is reduced to be 8.97.

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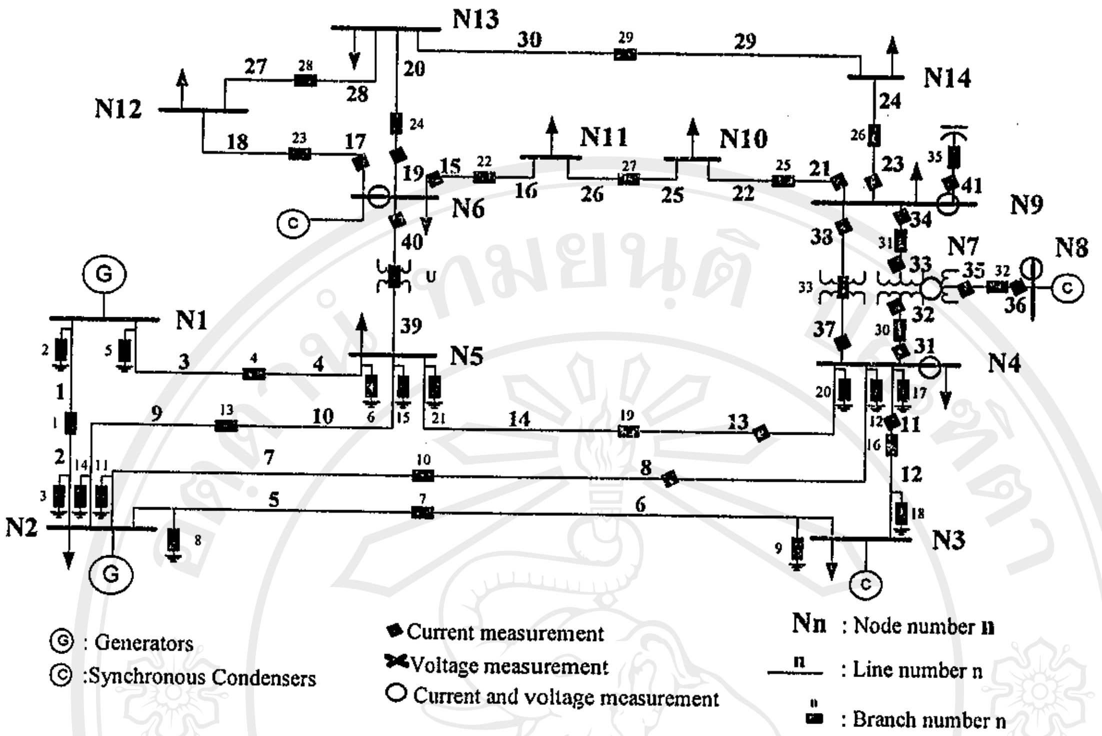

Figure 4.7 Fully measurement placement at 4 sites of the IEEE14-bus test system.

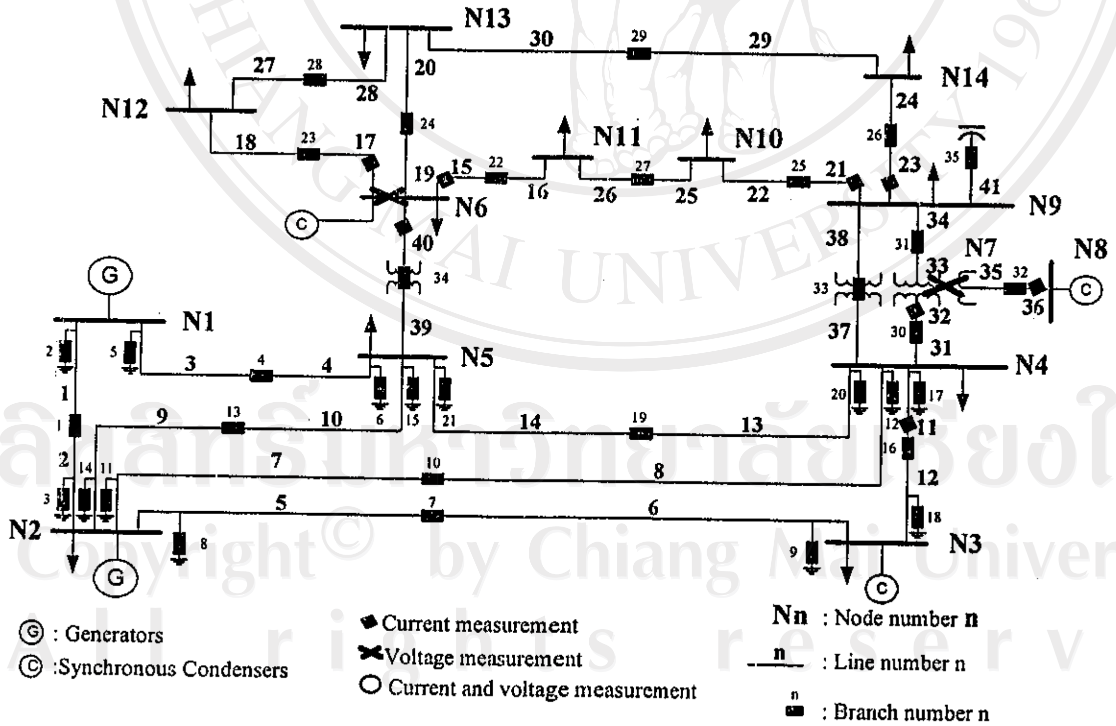

Figure 4.8 Reduced measurement point from Figure 4.7 using the proposed algorithm.

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Table 4.5 shows the performance of the proposed algorithm, which reduce the condition number of measurement matrices. "Fully condition number" in Table 4.5 denotes condition number of fully system that shown in Figure 4.5 and Figure 4.7 of the New Zealand and the IEEE 14-bus test system, respectively. "Reduced condition number" in Table 4.5 denotes condition number of reduced system, such as the reduced system in Figure 4.6 and Figure 4.8.

Table 4.5 Performance of the proposed algorithm to reduce the condition number

Harmonic order	New Zealand		IEEE 14-bus	
	Fully condition number (36 locations)	Reduced condition number (9 locations)	Fully condition number (28 locations)	Reduced condition number (10 locations)
5	5.46×10^9	3.43×10^9	20.21	8.97
7	5.99×10^9	4.28×10^9	16.31	6.29
11	1.42×10^9	8.56×10^8	13.29	5.90
13	1.53×10^8	1.92×10^8	12.77	7.33
17	1.12×10^8	6.40×10^7	11.99	6.46
19	1.87×10^7	1.61×10^7	11.67	6.85
23	1.22×10^7	8.72×10^6	11.24	9.78
25	2.32×10^8	1.52×10^8	11.26	12.14

The condition number of the new measurement matrix of each iteration from the proposed algorithm as shown in Figure 3.1, using the measurement matrix of the each harmonics order of the New Zealand and the IEEE 14-bus test system, could be shown in Figure 4.9 and Figure 4.10, respectively. It was found that, using this proposed algorithm, the condition number of measurement matrix always reduced. In the worst case scenario, such as 13th harmonic order of the New Zealand test system and 25th harmonic order of the IEEE 14-bus test system, the algorithm could not reduced the condition number. However, the algorithm can yield a solution for the measurement placement that makes the power system fully observable. However, to solve HSE correctly, the condition number of measurement matrix is not necessary to minimum. More measurement placements could be added, with addition channels which are relative small cost, to minimize the condition number of measurement matrix, if necessary.

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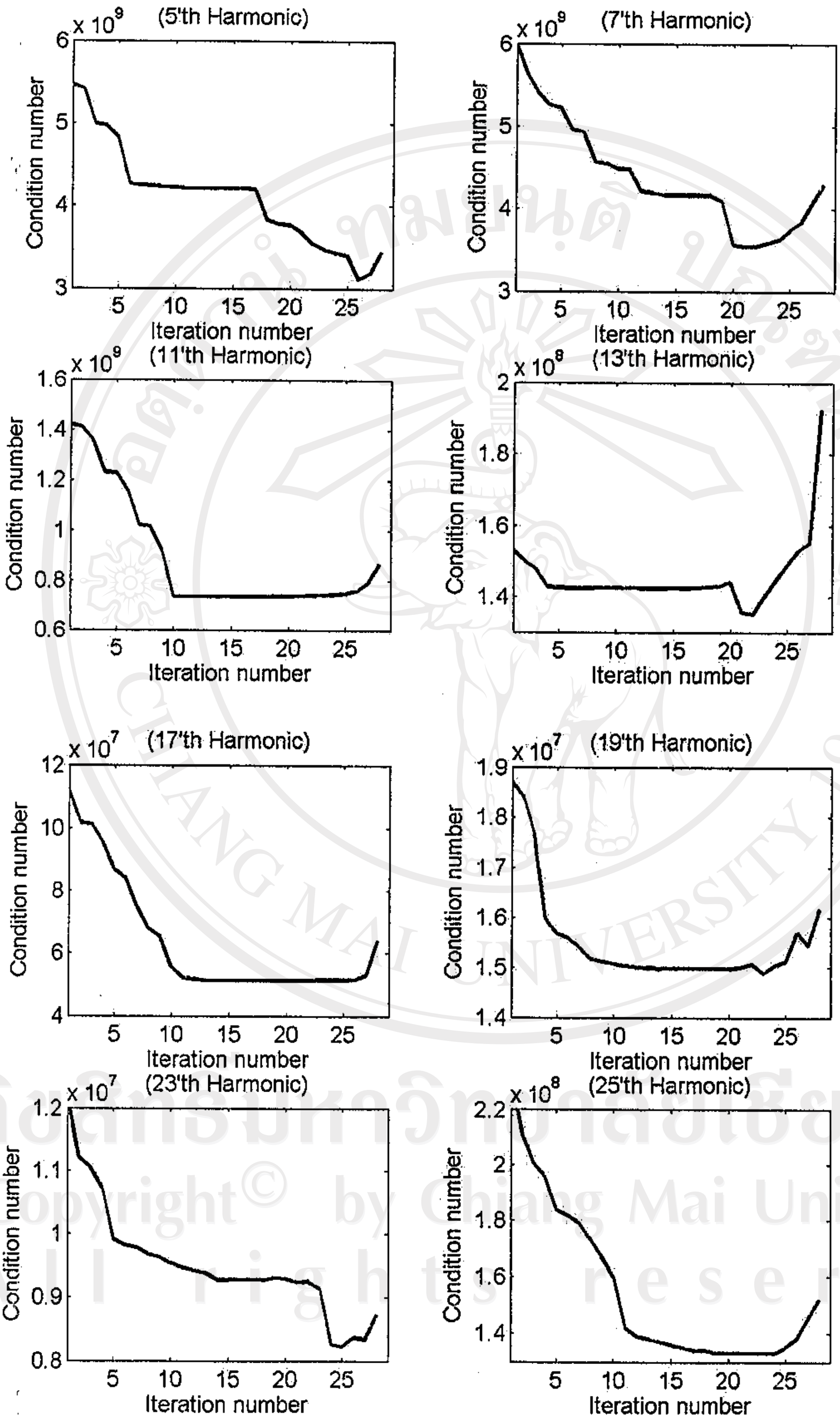

Figure 4.9 The condition number at each iteration using sequential elimination of the New Zealand test system.

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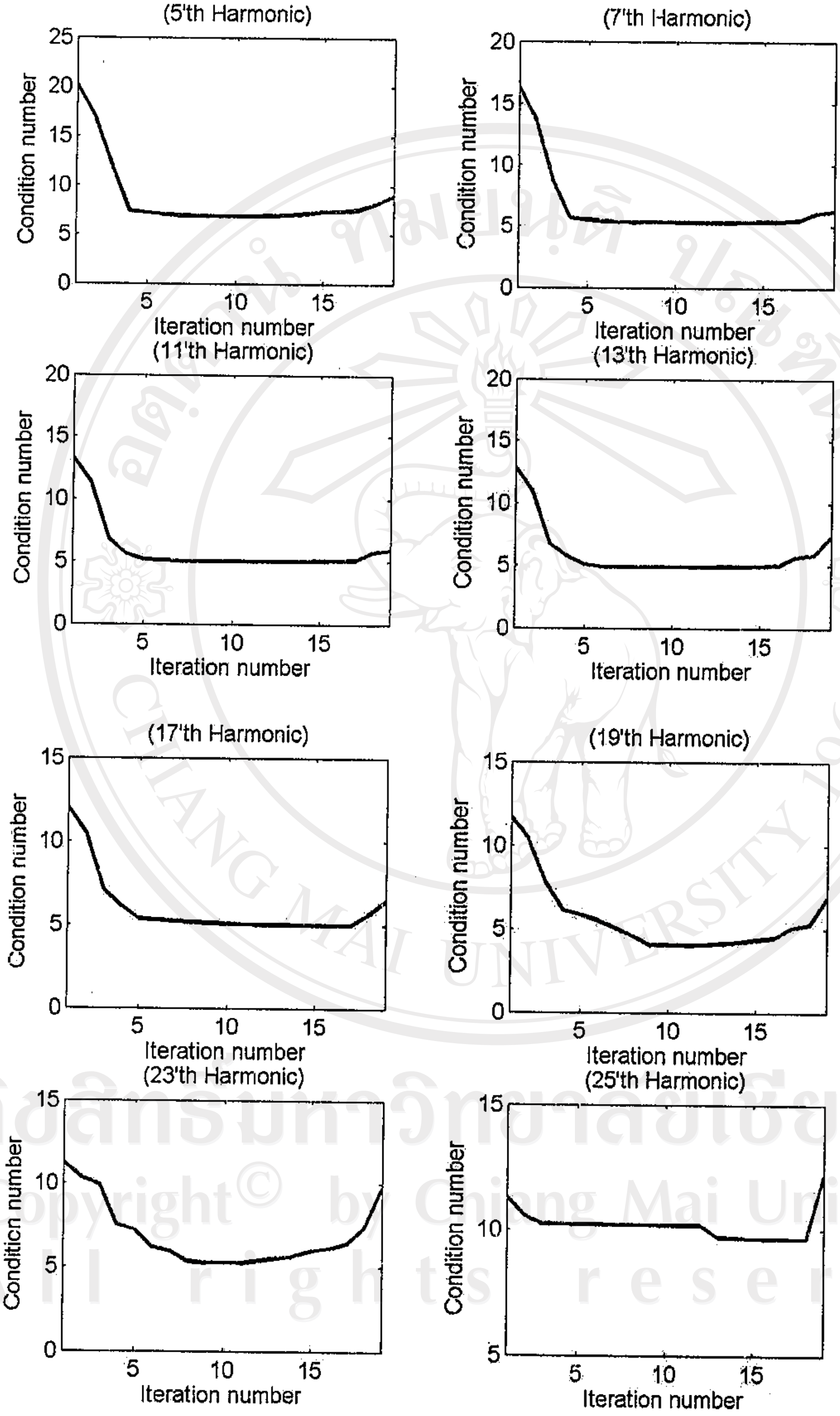

Figure 4.10 The condition number at each iteration using sequential elimination of the IEEE 14-bus test system.

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Reference [1] has been described that the sequential procedure of minimum variance approach has proven itself to be valid in many cases and is always near optimal. To prove the validation, near optimal, of sequential elimination in the proposed algorithm using minimum condition number could be shown in Table 4.6.

Table 4.6 Validation of sequential elimination in the proposed algorithm.

The New Zealand test system

Harmonic order	Fully observable combinations	Condition number			Rank
		Minimum	Maximum	Proposed algorithm	
5	111,600	2.82×10^9	1×10^{12}	3.49×10^9	154
7	80,680	3.50×10^9	1×10^{12}	4.28×10^9	158
11	143,446	1.48×10^8	1×10^{12}	8.65×10^8	22,442
13	96,100	1.38×10^8	1×10^{12}	1.92×10^8	6,872
17	44,117	4.88×10^7	9.82×10^{11}	6.40×10^7	83
19	39,088	1.50×10^7	9.94×10^{11}	1.61×10^7	4
23	68,876	7.17×10^6	9.96×10^{11}	8.72×10^6	88
25	21,435	1.52×10^8	9.83×10^{11}	1.52×10^8	1

The IEEE 14-bus test system

Harmonic order	Fully observable combinations	Condition number			Rank
		Minimum	Maximum	Proposed algorithm	
5	1,121	8.97	5.51×10^5	8.97	1
7	1,642	6.25	1.25×10^5	6.29	2
11	328	5.86	56.76	5.90	2
13	356	5.79	57.47	7.33	17
17	883	6.46	133.77	6.05	7
19	120	6.85	22.44	6.85	1
23	120	9.78	31.49	9.78	1
25	889	9.41	42,846	12.14	13

Two test systems have been used to prove the validation of the proposed algorithm. The complete combinations of the New Zealand test system as shown in Figure 4.5 is $\binom{36}{9}$ or 9.41×10^7. While the complete combinations of the IEEE 14-bus test system as shown in Figure 4.7 is $\binom{28}{10}$ or 13.12×10^6. The complete combinations of the test systems are quite huge for simulation using function "combnk" in MATLAB®, make occasionally insufficient memory. Then, the combinations are changed using the proposed algorithm as shown in Figure 3.1, choosing the last 20 locations, to $\binom{20}{9}$ or 167,960 and $\binom{20}{10}$ or 184,756 for the New Zealand and the IEEE 14-bus test system, respectively.

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The numbers of fully observable combinations of each harmonic order are shown in the 2^{nd} column of Table 4.6. The next column shows the minimum and maximum condition numbers of fully observable combinations and also shows condition number of the proposed algorithm. The last column is the rank of the proposed algorithm against the fully observable combinations. From Table 4.6, it could be claimed that the condition number of the proposed algorithm always optimal or near optimal.

The problem of ensuring global optimum without complete search is almost impossible, normally shows it near optimal by showing any slight variation in any parameter increase the objective function, i.e. is slightly change solution. The parameter which could be changed is the measurement matrix. When the measurement matrix has some error, the measurement placement will be changed and its condition number will be slightly changed as well (as shown in Table 4.7).

Table 4.7 Measurement placement in case of the measurement matrix error using the 5^{th} harmonic order of Figure 4.7 of the IEEE 14-bus test system.

Measurement matrix error	Injection current	Busbars voltage	Line current	Condition number
No error	No	6,7	11,15,17,21,23,32,36,40	8.9725
±5% at busbar 4,6,7-8,9	No	6,7	11,15,17,21,23,32,36,40	8.9725
+5% at busbar 4	No	6,7	11,15,17,21,23,32,36,40	8.9647
-5% at busbar 4	8	6,7	11,15,17,21,23,31,40	8.9794
+5% at busbar 6	No	6,7	11,17,19,21,23,32,36,40	8.9725
-5% at busbar 6	8	6,7	11,15,17,21,23,32,40	8.9725
+5% at busbar 7-8	8	6,7	11,15,17,21,23,31,40	8.9997
-5% at busbar 7-8	No	6,7	11,17,19,21,23,31,36,40	9.3900
+5% at busbar 9	No	6,7	11,15,17,21,23,32,36,40	9.3663
-5% at busbar 9	No	6,7	11,15,17,21,23,32,36,40	8.5831

Typical results obtained by using the HSE algorithm for node or busbar voltages, node or busbar injection currents, and line currents throughout the test system for up to the 25 harmonic order are shown in Figures 4.11–4.22, respectively. Besides, the type of harmonic sources may be identified as well, as described in Chapter 2 section 2.2.5.

Generally the estimation for phase angle is less accurate than the estimation of the magnitudes of the same quantity. However, it does not affect the identification of harmonic source location, since it is able to identify the harmonic source with sufficient magnitude for each harmonic of interest.

The type of harmonic sources can also be identified. In the New Zealand test system, as shown in Figure 4.13, in evident that a six-pulse converter exists at Tiwai busbar (Node 1-3) because the injection currents at the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}, 23^{rd}, and 25^{th} harmonics have been identified. In the IEEE 14-bus test system, as shown in Figure 4.19, the injection currents at the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}, 23^{rd}, and 25^{th} harmonics have been identified at busbar 3 and busbar 8 by performing the HSE. It is found that the harmonic sources exist at busbars 3 and 8.

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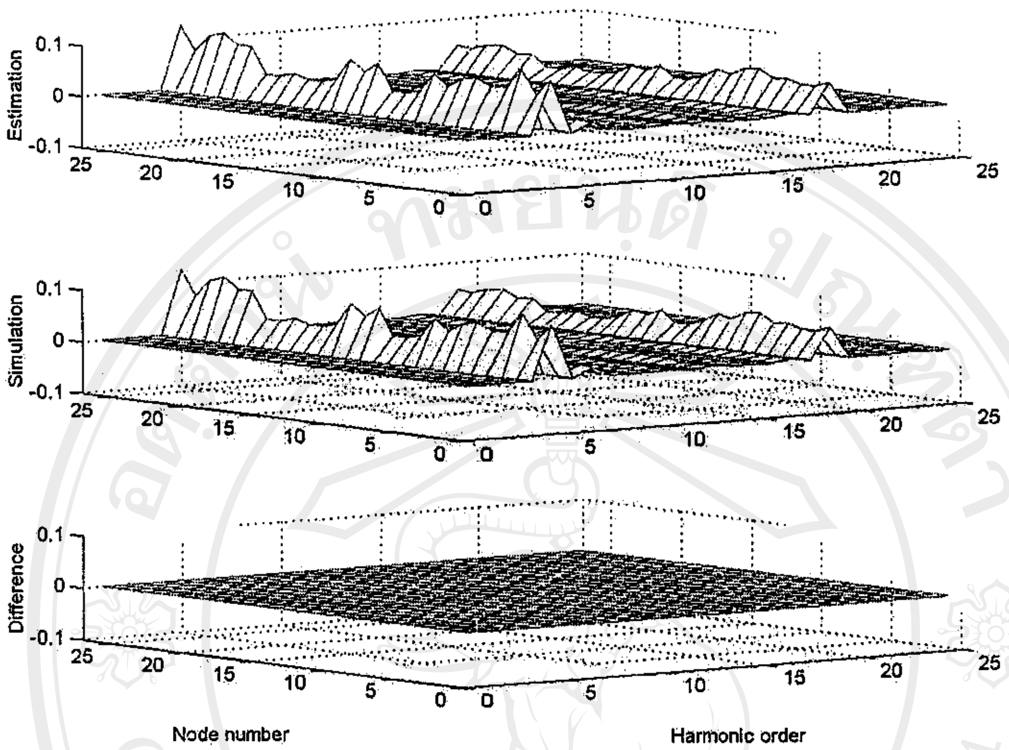

Figure 4.11 Node harmonic voltage magnitudes of the New Zealand test system (p.u.).

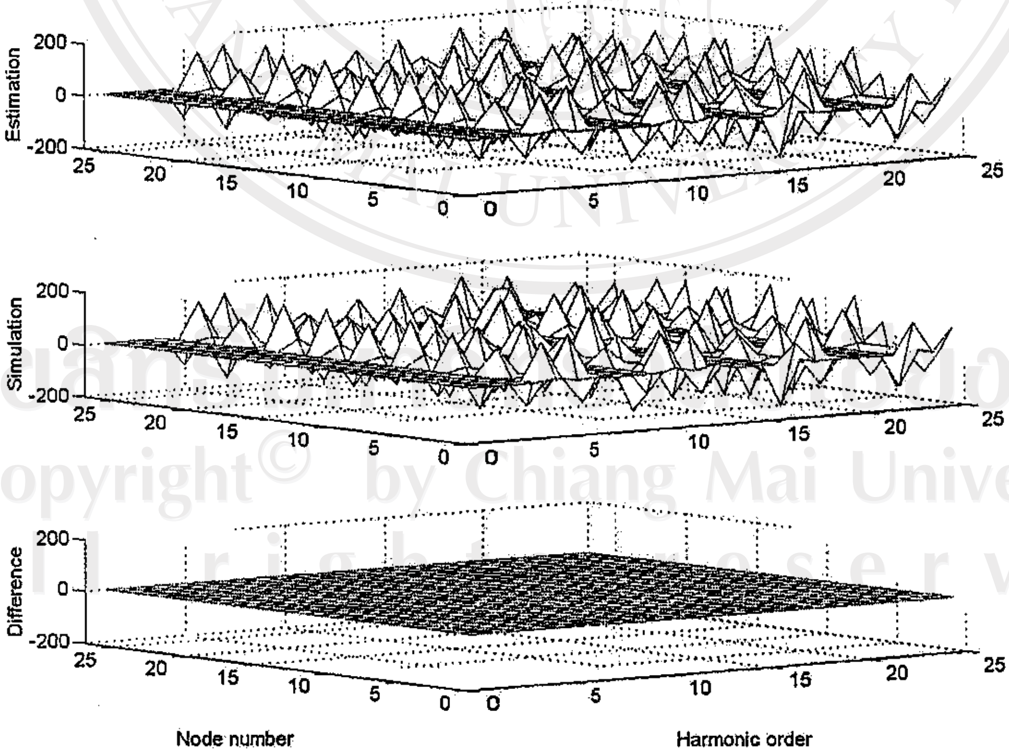

Figure 4.12 Node harmonic voltage angles of the New Zealand test system (degree).

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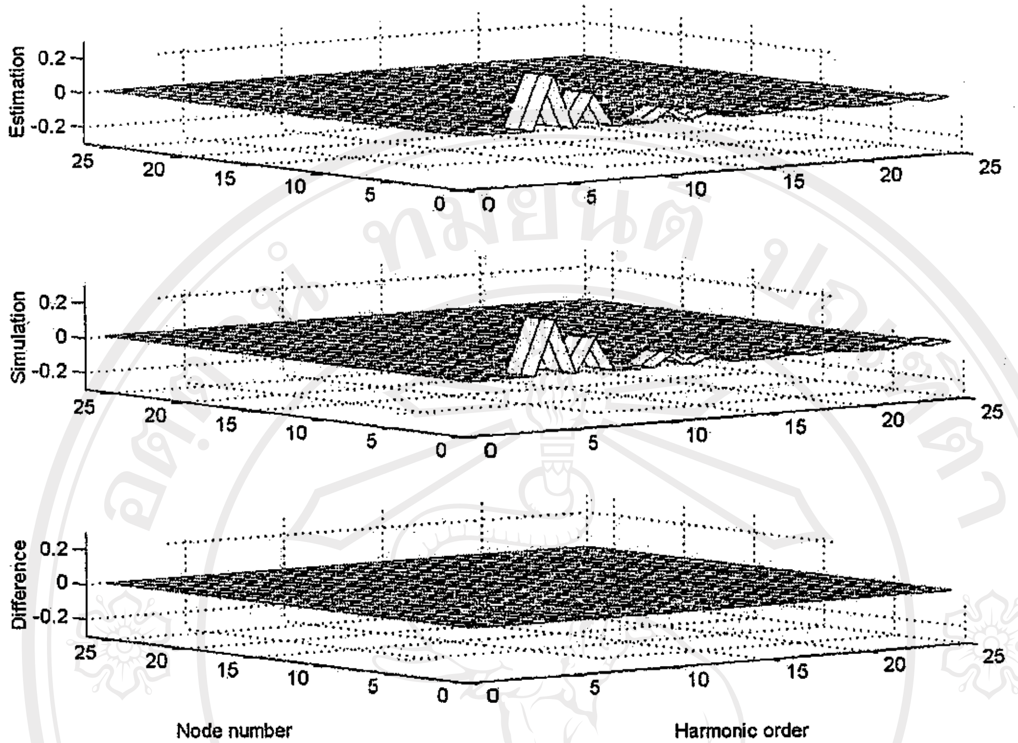

Figure 4.13 Node harmonic injection current magnitudes of the New Zealand test system (p.u

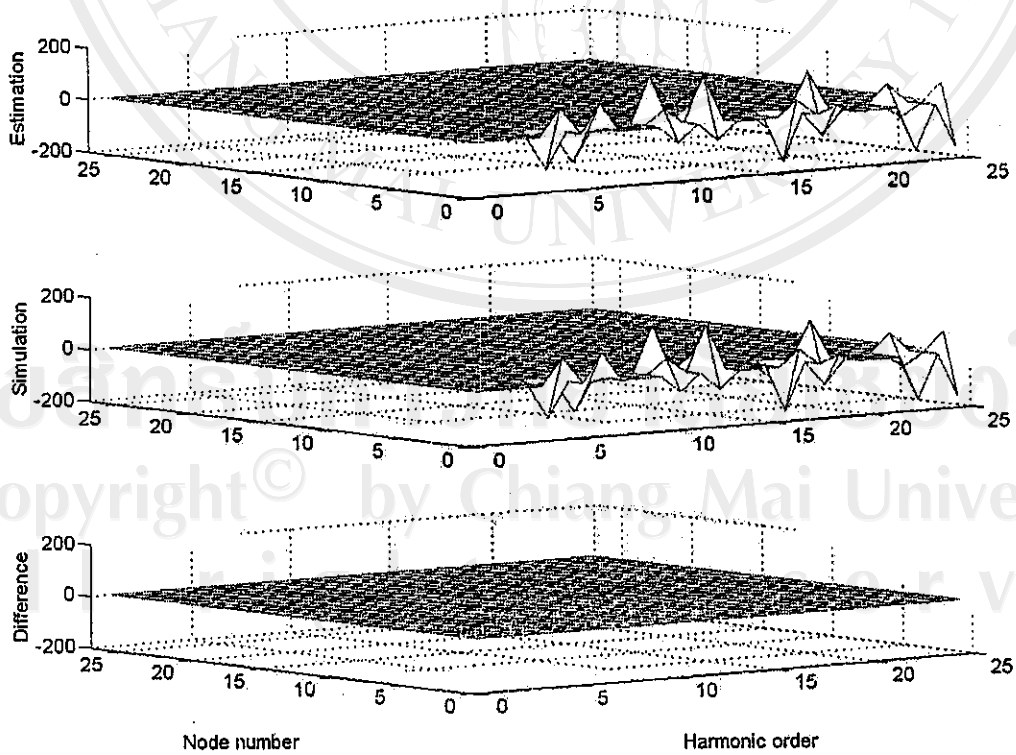

Figure 4.14 Node harmonic injection current angles of the New Zealand test system (degree

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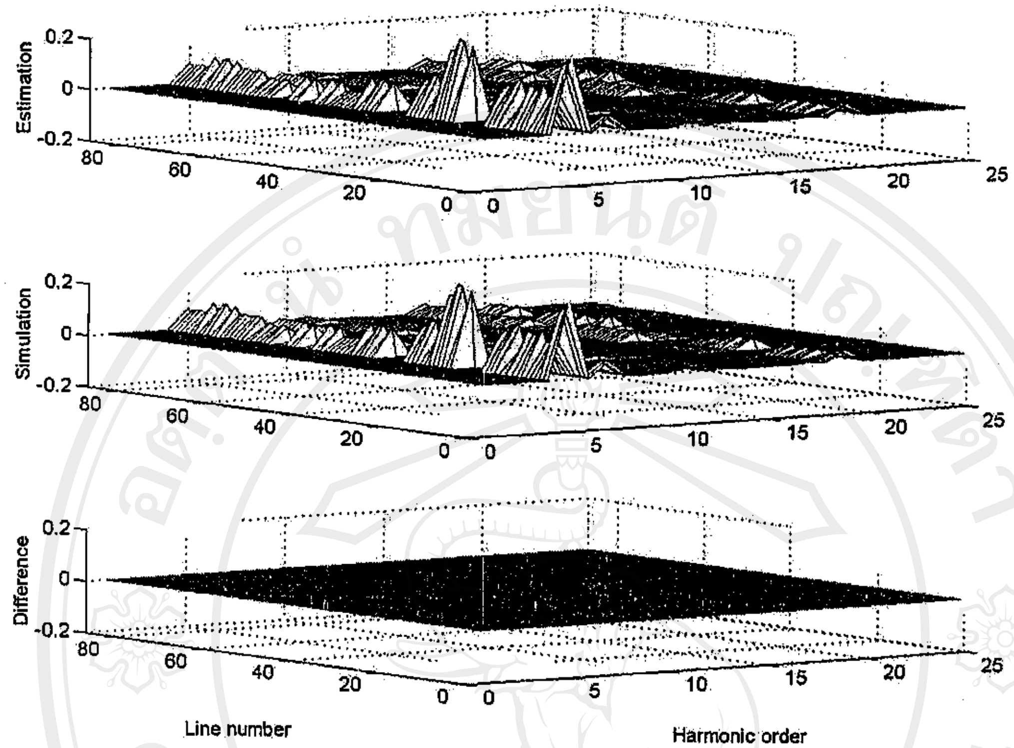

Figure 4.15 Line harmonic current magnitudes of the New Zealand test system (p.u.).

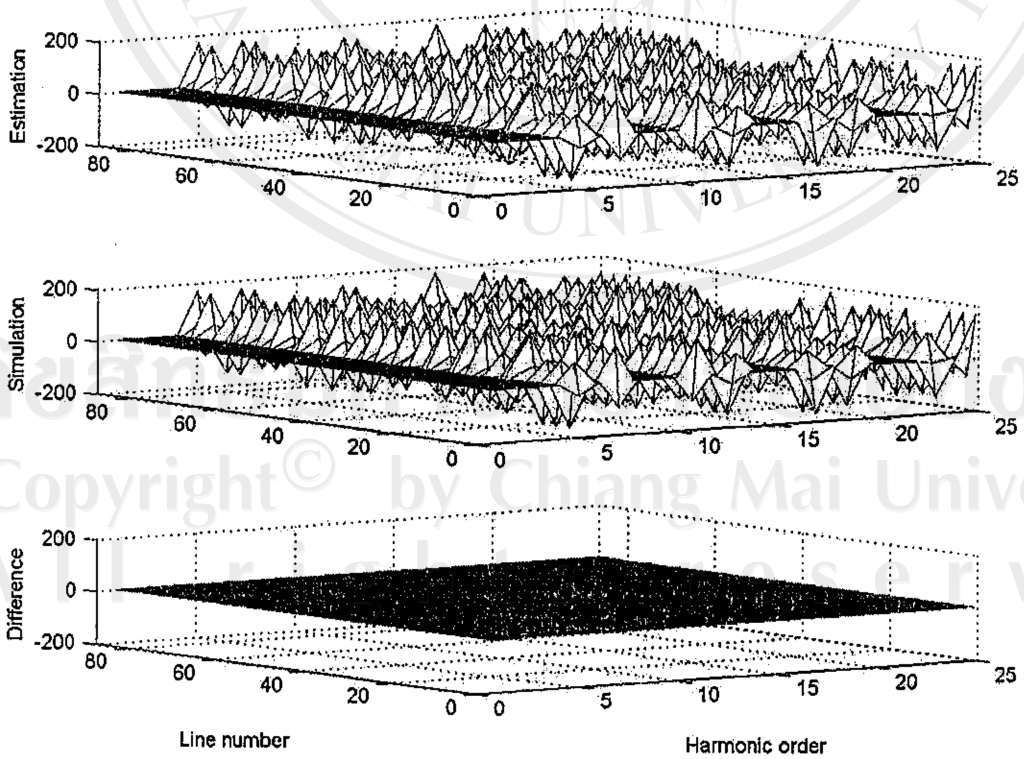

Figure 4.16 Line harmonic current angles of the New Zealand test system (degree).

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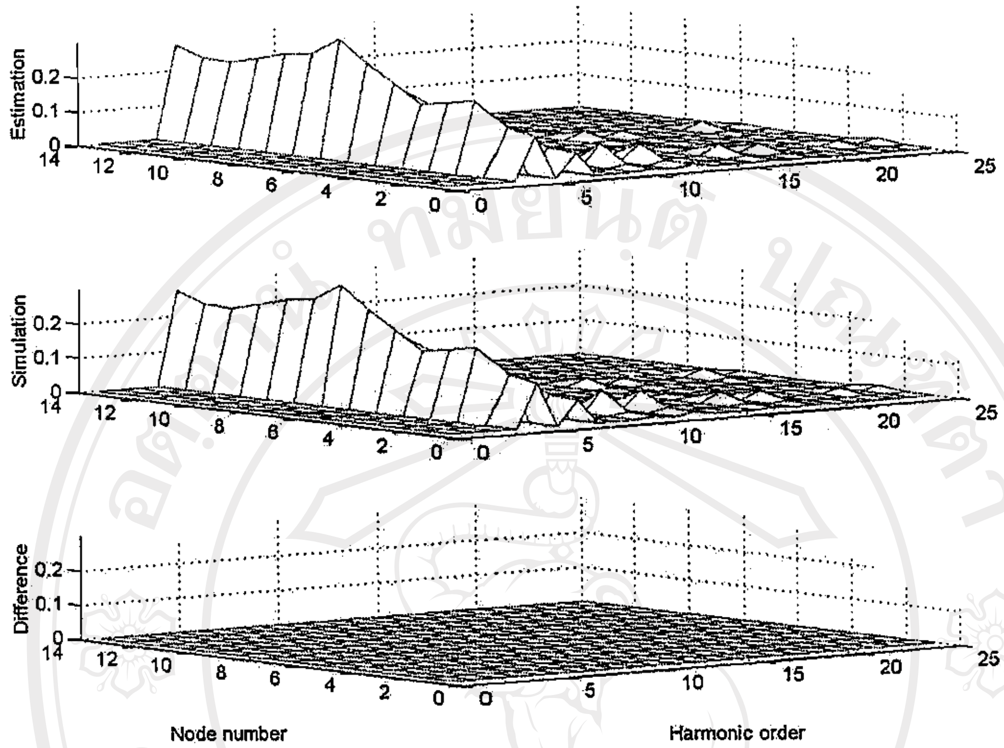

Figure 4.17 Node harmonic voltage magnitudes of the IEEE14-bus test system (p.u.).

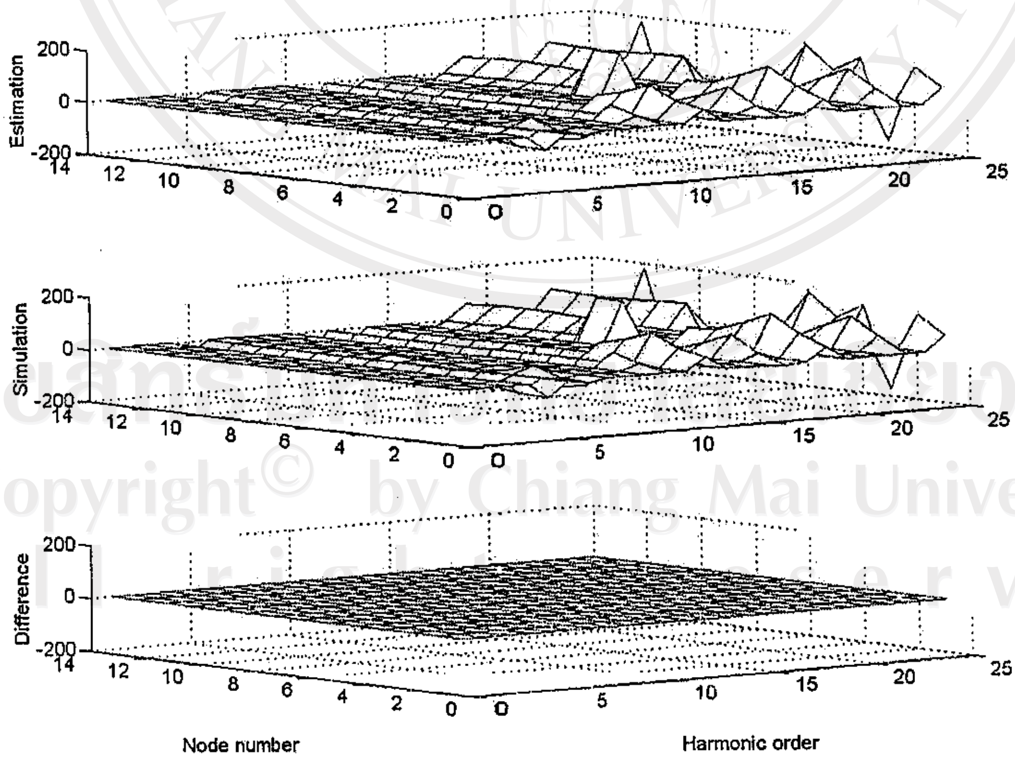

Figure 4.18 Node harmonic voltage angles of the IEEE14-bus test system (degree).

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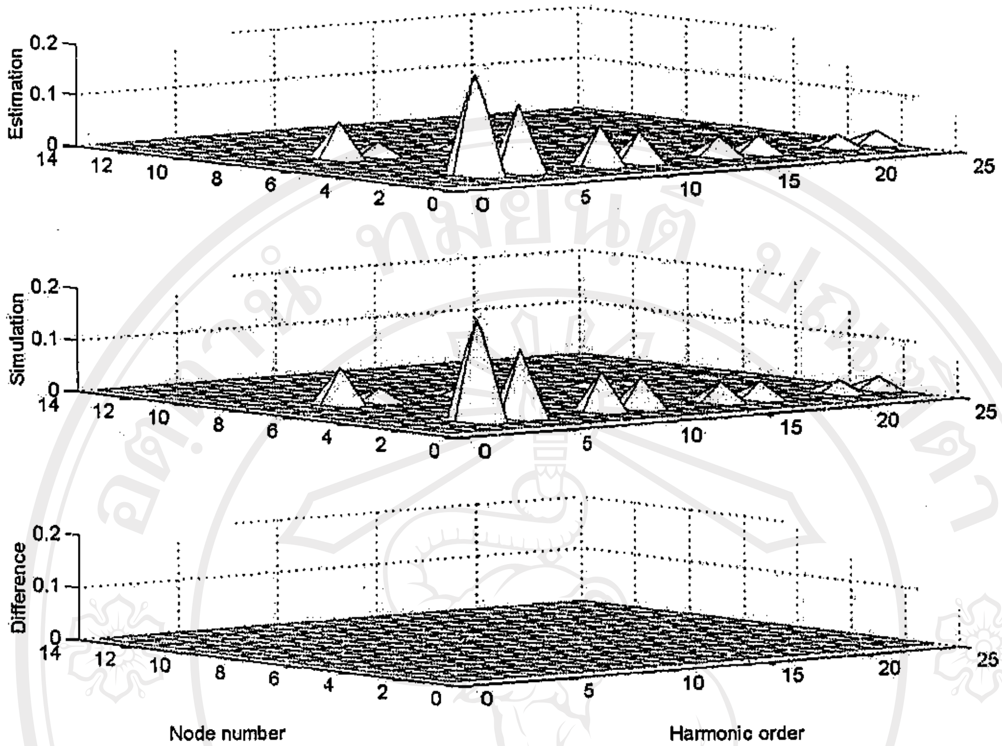

Figure 4.19 Node harmonic injection current magnitudes of the IEEE14-bus test system (p.u

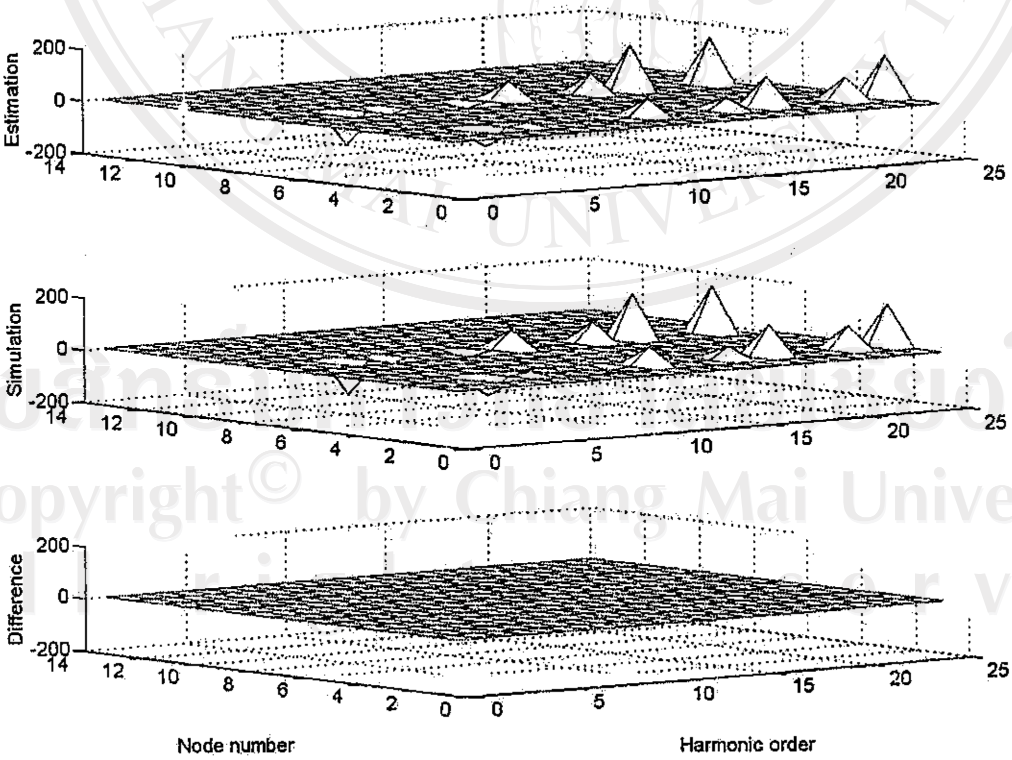

Figure 4.20 Node harmonic injection current angles of the IEEE14-bus test system (degree)

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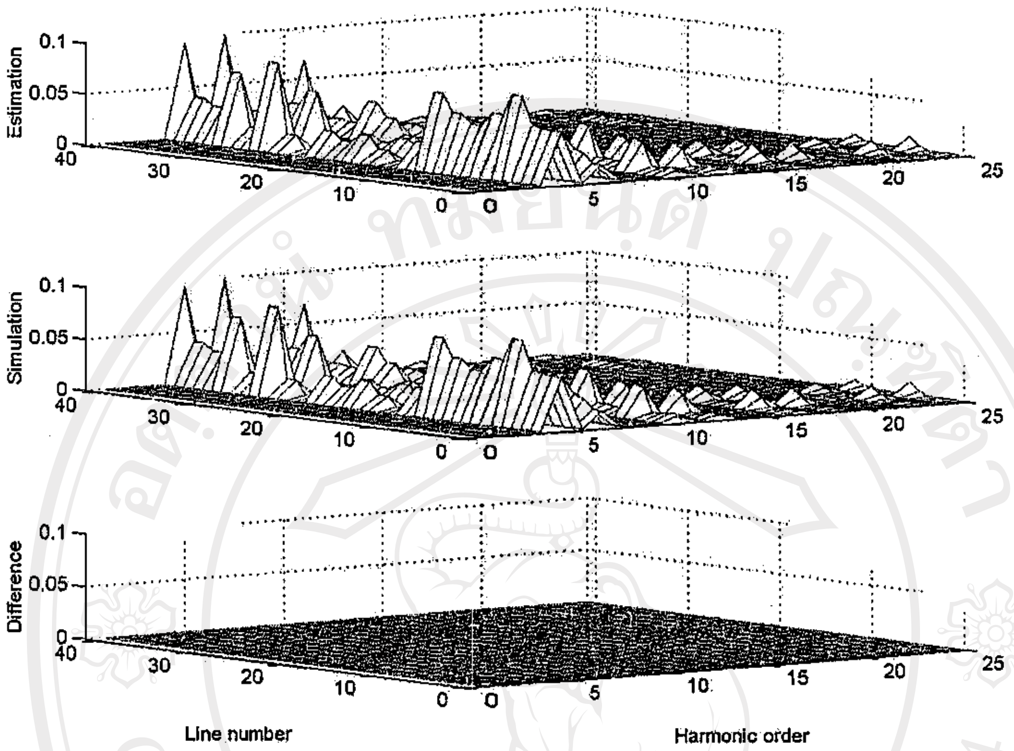

Figure 4.21 Line harmonic current magnitudes of the IEEE14-bus test system (p.u.).

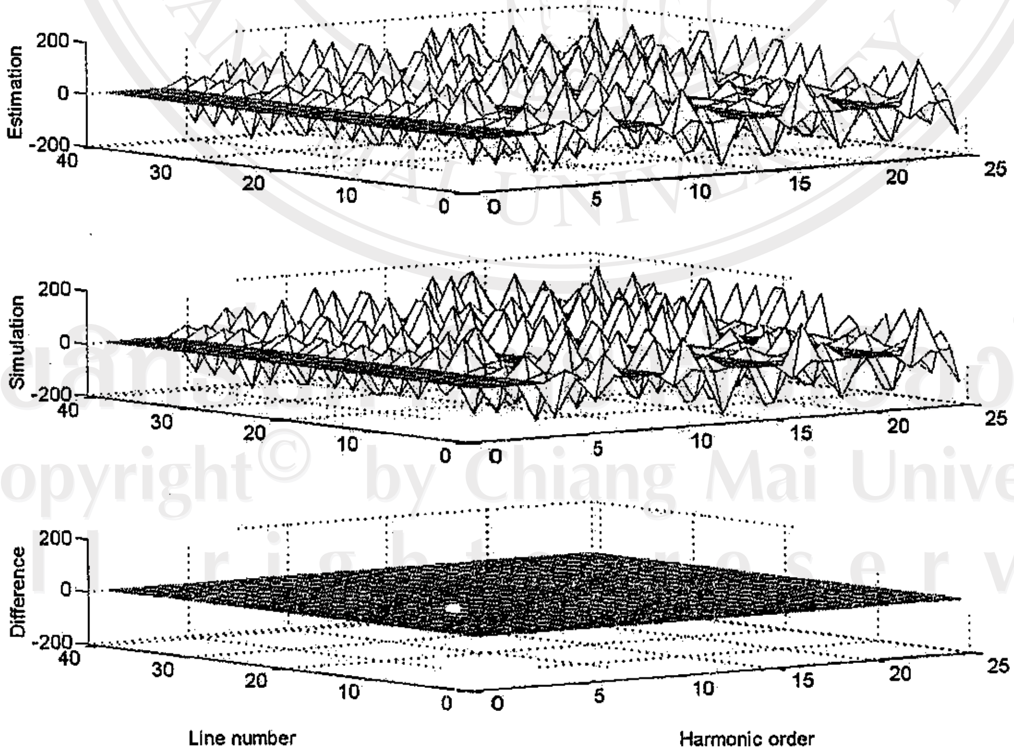

Figure 4.22 Line harmonic current angles of the IEEE14-bus test system (degree).

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