CHAPTER 3

An Optimal Measurement Placement

3.1 Introduction

The placement of measurement points is normally assumed to be symmetrical (e.g., either three or no phase of injection currents of a busbar are measured). However, this requirement restricts the search for the optimal placement of measurement points in three-phase unbalance power systems. Moreover, the implementation of existing algorithms will, in practice, be limited by poor synchronization of conventional instrumentation schemes, lack of continuity of measurements, or lack of processing speed.

The measurement placement can be modified by using observability analysis (OA), which is an essential tool for a system-wide HSE to identify its solvability. A power system is said to be observable if the set of available measurements is sufficient to uniquely calculate all state variables of the system. Therefore, for observability, the number of measurements must not be less than the number of state variables to be estimated. Observability is dependent on the number, locations, and types of available measurements, network topology, as well as the system primitive admittance matrix.

There is a limitation to the number of instruments a utility can afford to place in a power system. The more sensors connected to the system, the more accurate the parameter estimation, but the higher the cost. A proper methodology is needed for selecting optimal placement for the measuring devices.

Any of the following criteria can be used to determine the optimal placement of measurement [23].

- Minimize the number of measurement points for network observability,
- Minimize the sum of the state estimate variances,
- Maximize measurement system reliability,
- Minimize or limit measurement system cost, or
- Minimize the condition number of the gain matrix.

The existing optimal measurement placement algorithms include constrained non-linear optimization, Monte Carlo simulation and perturbation, sequential elimination, and sequential addition. [23]

A rigorous formulation of optimal measurement placement would result in the solution of a 0-1 integer-programming problem (as measurement is either present or not present); that is very difficult to solve exactly for large-scale systems. Therefore, all the approaches, proposed for optimal measurement placement are based on either non-rigorous formulations or heuristic solution techniques, yielding nearly optimal solutions rather than the global optimum. [23]

In practice, minimizing the number of channels does not necessarily result in lower cost because the predominant cost is in the base unit, while the incremental cost of additional channels is relatively small. Therefore, it is the number of locations that should be minimized. [23]

3.2 Review of Measurement Placement Algorithms

3.2.1 Minimum Variance Approach [1]

Minimum variance approach allows developing an expression for expected error that can be minimized. This approach has several major advantages. First, busbar voltages and busbar injection currents can be treated as random variables to incorporate uncertainty in the model. Second, it offers a rigorous framework for the solution. Third, since one selection of buses to be instrumented can be better or worse only in an average sense, a probabilistic setting is naturally endowed with the structure which enables this comparison. The basic ideas of probability theory are fundamental in developing the model for the optimal location of sensors.

The objective is to select the measurement locations (from the set of all possible locations) that will minimize the expected value of the sum of squares of differences between estimated and true parameters variable, as shown in equation (3.1). Then, the minimum variance criterion will be used to estimate current harmonic source.

$$\begin{array}{c} Minimize \\ with\ respect\ to \\ location\ of\ I_o\ and\ V_o \end{array} \left\{ Min\left[E(\hat{I}_u - I_u)^2 \right] \right\} \tag{3.1}$$

Where I_o and V_o denote vectors of measured (observed) quantities, and I_u denote vector of the remaining (unknown) currents, and $\hat{I}_u$ denote estimated I_u.

Equation (3.1) is solved in two steps. First, predictor $\hat{I}_u$ is chosen to minimize the expected value of squares of difference between unknown and true current injection vector I_u. Second, the optimal measurement locations are found, represented by I_o and V_o, that minimize the error due to the best linear predictor $\hat{I}_u$. The theory needed to solve equation (3.1) using two steps is given in [1].

In the worst case scenario, the supreme of the diagonal elements of the covariance matrix is minimized instead of the trace being minimized. In addition, this approach did not prove that it could be equally efficiently for more complex networks.

3.2.2 Modified Symbolic Observability [3, 23]

As described in Chapter 2, the symbolic method seeks to overcome the numerical problems by replacing them with symbolic calculations, where each entry in the measurement matrix used for observability analysis (OA) is either 1 or 0. While being extremely fast and simple, the basic method is not capable of finding all the observable islands and redundant measurements.

Reference [23] shows a flowchart of this OA algorithm. It is based on symbolic reduction of the gain matrix, without the need for numerical computation. The search is not combinatorial and is driven by the structure of the measurement matrix. It uses a step-by-step reduction through the elimination of observable groups (subsystems). The symbolic method starts with the observable state variables and sequentially chooses one as a reference; it then searches through the symbolic measurement matrix to identify the state variables that are linked to the reference state variable as well as the number of state variables linking them.

This method assumes that all voltage measurements contribute to the solution, and identifies how many current measurements are redundant by looking at the number of unknown state variables and the number of equations linking the state variables in each identified group.

It should be noted that symbolic OA cannot detect cases where there are two dependent measurement equations (such as when current at both ends of a line are measured), because the actual values are lost. In addition, although the concept of this OA is simple, it requires complex bookkeeping of the processed, eliminated state variables and equations as well as the observable.

3.2.3 Genetic Algorithms [29]

Genetic Algorithms (GAs) are effective search methods based on the principles of natural selection and genetics. They were developed by John Holland to simulate some of the processes observed in natural evolution. Generally, a GA works on a set of potential solutions to a specific problem encoded into chromosome-like data structures. Some of these solutions, chosen on the basis of their performance in solving the problem, are used to create a new set of potential solutions. A GA uses this process repeatedly until a particular criterion is met. GAs are often described in biological terms. Potential solutions are called chromosomes and are represented by binary strings or floating point numbers. A set of chromosomes is called a population and a problem to be solved is represented by a fitness function. The choice of individuals to reproduce is performed in a process called selection which is based on the fitness values assigned to chromosomes. Genetic operators such as crossover and mutation are operators used to create a new population. Crossover permits the exchange of information among individuals in the population and provides the innovative capability of a GA. Mutation ensures need diversity. [29]

GAs is widely used in areas such as; optimization of the objective function, learning of neural networks, tuning of fuzzy membership functions, machine learning, system identification and control. HSE in [29] has been applied to the New Zealand lower South Island power system for validation of the new HSE algorithm. The study results have indicated an economical and effective method for optimal placement of measurement points.

The objective function is considered as the CHART (Continuous Harmonic Analysis in Real Time) cost and state estimation error to optimize measurement placement, as shown in equation (3.2).

$$Min\left\{J=\sum_{i=1}^{n}I_i+E_{busvolt}+E_{buscurrent}+E_{linecurrent}\right\}$$
$$I_i=\alpha+k\beta \tag{3.2}$$

Where n is the number of buses,
$E_{busvolt}$ is bus voltage error,
$E_{buscurrent}$ is bus or injection current error,
$E_{linecurrent}$ is line current error,
α is standard CHART cost,
k is number of CHART channels, and
β is two extra channels CHART cost.

The results have shown that: (i) GA-HSE model can minimize the number of measurement points for network observability, (ii) GA-HSE model can minimize or limit measurement system cost, and (iii) GA-HSE model is an economical and effective method for optimal placement.

To minimize the expected error and measurement locations, the algorithm of measurement placement and HSE of minimum variance approach and GA approach have to be incorporated at the same time. As a result, it is a very difficult work for more complex networks. In addition, for minimum variance approach, if line harmonic currents that are possible locations in HSE are added, it will affect the algorithm. Therefore, the models will be more complex and consume more computation times. For modified symbolic observability approach, it has some disadvantage as described above.

3.3 Proposed Measurement Placement Algorithm [30]

The new solution technique presented in this thesis provides optimal number and the best positions to place harmonic instruments with a limited number of observations, in order to identify the location and magnitude of harmonic sources. The minimum condition number criterion of the measurement matrix, based on sequential elimination, is utilized to solve this problem.

The condition number of a matrix is the ratio of the largest (in magnitude) to the smallest singular value. A matrix is singular if its condition number is infinite, and it would be considered ill-conditioned if its condition number is too large. A singularity is considered near zero when its value approaches or below the largest singular value times the machine's precision (e.g. 10^{-6} for single precision and 10^{-12} for double precision) [23].

Measurement matrices with small condition numbers are said to be well-conditioned, and make the state variables in equation (2.8) solvable. In addition, using minimum condition number of measurement matrix as the criteria, the algorithm of measurement placement is separated from the algorithm of HSE. As a result, the network size will not affect the basic methodology of the algorithm. While the sequential procedure has proven itself to be valid in many cases and it is always near optimal [1]. Then, the minimum condition number criterion of the measurement matrix, based on sequential elimination, is utilized to solve the optimal measurement placement problem.

A brute-force method may be used to compute a comparative measure for all possible combinations of sensor placement [1]. The procedure exhausts all possibilities and yields the true optimal solution for the problem. For an N-bus system, M possible locations with a limited P measuring devices to be placed, $\binom{M}{P}$ possible combinations must be computed in order to determine the best locations for placing instruments. For example a 27 busbar system, 141 possible locations with 9 measuring devices for 9 suspicious busbars (N_s), the possible combinations are $\binom{141}{9}$ or 4.68×10^{13}. Hence the number of possibilities is usually large. The initial simulations on realistic models of power systems indicate that the location procedure could be performed in a sequential fashion. The methodology for sequential elimination is the best (M+1) measurement locations containing the best M locations (for all M) [1].

The benefits gained from using the sequential procedure are dramatic because of the reduction in the number of possible combinations (as compared to complete enumeration). The sequential procedure need not be repeated from the beginning when increasing or decreasing the number of sensors. In general, for N-bus system, M possible locations with P measuring devices are to be placed. The sequential procedure needs only to compute P(2M+1−P)/2 combinations to determine the best, near optimal instrument locations [1]. Hence the amount of computation required by the sequential procedure is small compared with complete enumeration of a realistic size system. For example, a 27 busbar system, 141 possible locations with 9 measuring device, the sequential procedure requires 1,233 combinations to be computed, instead of the 4.68×10^{13} combinations required by complete enumeration.

The placement of measurement points is normally assumed to be symmetrical (e.g. either three or no phases measured at a location). However, this requirement restricts the search for the optimal placement of measurement points in three-phase asymmetrical power systems. As a result, all possible measurement locations for an N-bus system in this paper include all injection currents (N locations), all node voltages (N locations), and all line currents (L locations, both sending and receiving ends). In fact, the measurement placement at non-harmonic source busbar (N_0 locations) yields less useful information than those of suspicious busbars. However, the proposed measurement placement algorithm will be tested for both the case of all possible locations (2N+L locations) and the case where the injection currents and node voltages at non-harmonic source busbars are not included ($2N+L-2N_0$ locations).

Figure 3.1 shows a flowchart of optimal measurement placement algorithm using sequential elimination. From all possible locations, the measurement matrix can be formulated using Figure 2.6. The objective function in each iteration is the condition number of the measurement matrix.

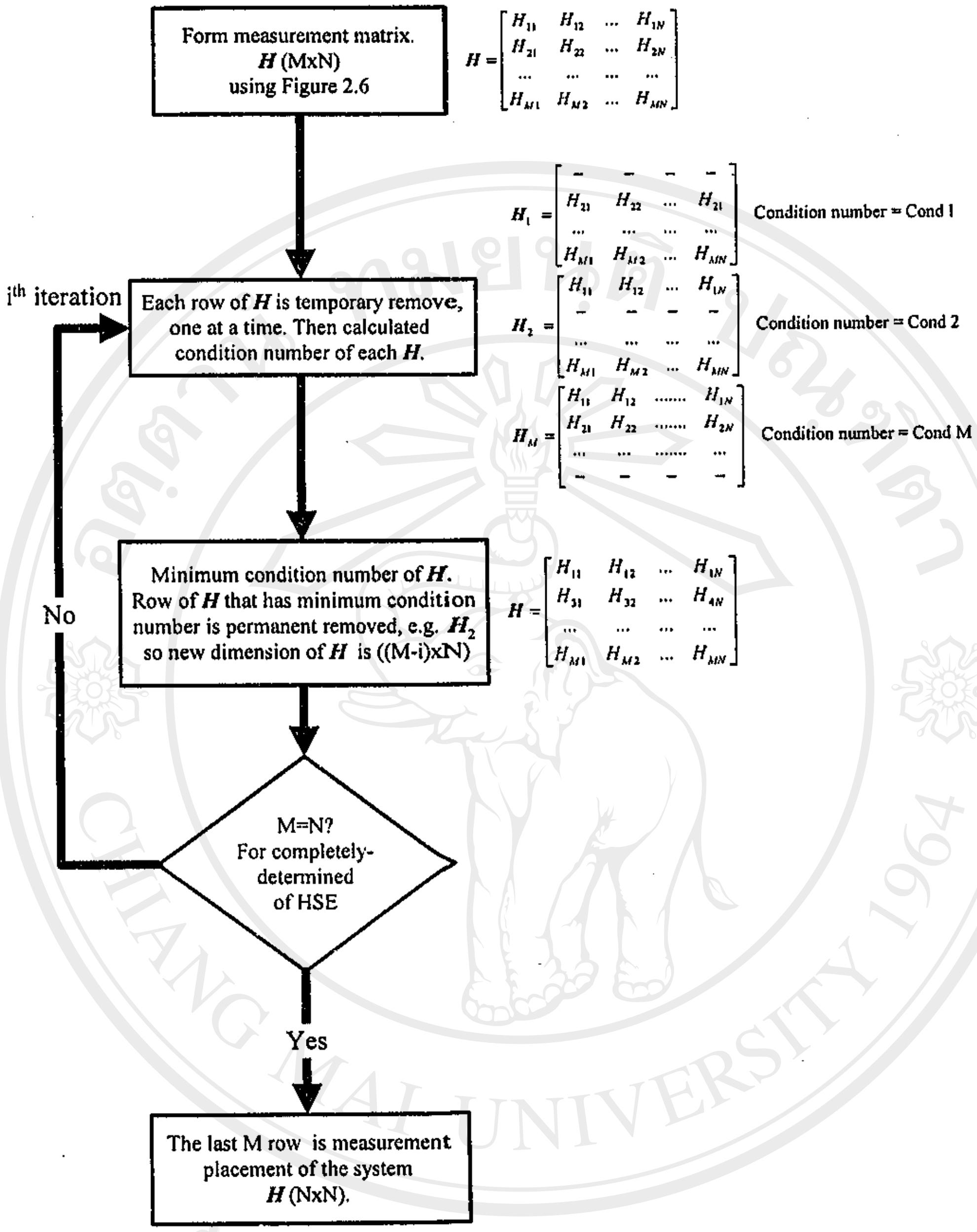

Figure 3.1 Flowchart of proposed measurement placement algorithm.

Due to cost the number of available harmonic instruments is always limited so that the measuring devices (P) have to be minimized. However, to improve the measurement redundancy (which is key to bad data identification), therefore virtual and pseudo measurements should be included in the measurement matrix. Virtual measurements provide the kind of information that does not need metering (e.g. zero harmonic current injections at switching substation and at non-harmonic source bus). To obtain a unique solution (i.e. completely observable system), the minimum required number of harmonic instruments has to be equal to the number of state variables. As a result, for N state variables, in order to minimize P, M has to be minimized as well. Therefore the algorithm needs to iterate until M=N to ensure a completely observable system. It means that the number of computations needed is M–N iterations.

In each iteration each possible location is temporarily eliminated one at a time and then the condition number of the corresponding measurement matrix is calculated (step 2), yield Cond 1 (1^{st} row of $\boldsymbol{H}$ is eliminated), Cond 2,…,Cond M (M^{th} row of $\boldsymbol{H}$ is eliminated). The location that has a minimum condition number from step 2 will be eliminated sequentially to reduce the number of rows for the next iteration (step 3). This means that the condition number of a new measurement matrix in step 3, after eliminating location that has minimum condition number from step 2, will have the best (minimum) condition number (for example, the harmonic instrument in the 2^{nd} row of the corresponding $\boldsymbol{H}$ in Figure 3.1 will be removed). The minimum condition number of the measurement matrix $\boldsymbol{H}$, the ill-conditioned of the measurement matrix, will be minimum as well. As a result, the measurement matrix of this proposed algorithm is always not singular that ensures system solvability. Again, in such a case, all state variables can be obtained when all singular values of the measurement matrix are non-zero [20]. The iterative procedure is performed until M=N (step 4), that is, a row of the measurement matrix $\boldsymbol{H}$ will be eliminated by every iteration. The number of possible locations will be reduced, from M to M–1, M–2,…, M–(M–P). The remaining locations after sequential elimination, base on minimum condition number, should be optimal or near optimal for the measurements [1].

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.

Because load information is not available prior to performing HSE, the loads are not represented in equation (2.9) but their current is part of the estimated (or measured) harmonic current injection. The methodology of HSE, for testing the measurement location is; (i) Assume that the partial 'measured values' from the measurement points are equal to their corresponding 'true values' plus some random noises generated with Gaussian distribution (if necessary), (ii) Estimate the values for all state variables using the estimator from the partial 'measured values', (iii) Compare estimated values with the corresponding 'true values' (results of complete simulation).