CHAPTER 1

Introduction

This introductory chapter contains the motivation and background for the research work presented in this thesis. In addition, a summary of the harmonics is included. Also, a review of the most important investigations that have been done in the last few decades regarding state estimation in power system is presented.

1.1 Motivation

The problem of identifying the location and magnitude of harmonic sources becomes more important in power system analysis. This is essential for designing filters for eliminating and reducing the effects of harmonics in a power system to comply with the standard. The Harmonic State Estimation (HSE) uses harmonic measurement at some certain buses to identify the harmonic sources. The HSE also be able to provide information on harmonic penetration throughout the network.

In particular, the number of available harmonic measurements is always limited due to cost, while the quality of estimation is a function of the number and location of the measurements. Therefore, a systematic procedure is needed to design the optimal measurement placement. Measurement placement algorithm for harmonic component identification is presented in [1-2] based on sequential solution and minimum variance. However, it addressed the problem of how to find the best location to identify the harmonic sources rather than optimizing the number of measurements and estimating the values of harmonic magnitude. A new symbolic method to design the optimal measurement placement is presented in [3]. A disadvantage of this algorithm is that it cannot be applied when there are two dependent measurement equations because the actual value are lost.

Therefore, this thesis mainly focuses on an optimal measurement placement method for HSE in terms of the optimal number of measurements and the best positions to place them in order to identify the locations, magnitudes, and types of harmonic sources.

1.2 Harmonics

Any periodic waveform can be considered to be made up of the sum of components each whose frequency is an integer multiple of the fundamental. Harmonic is a sinusoidal component of a periodic wave or quantity having a frequency that is an integer multiple of the fundamental frequency. Over the past years, there has been a considerable increase in the level of harmonic signals in electric power transmission and distribution systems. This phenomenon has reached substantial levels in many areas in part because of increased penetration of highly rated solid state power processing devices. Electric utilities have paid attention to interest in the analysis of harmonics in power systems since the effect of these signals on power apparatus and measurement devices present many important and serious problems. Those problems include:

(i) Harmonics can interfere with digital timing signals,
(ii) harmonics may be troublesome to communication systems,
(iii) less conservative design for rotating machines and transformers aggravates heating problems associated with harmonics,
(iv) capacitor bank failures or opening of shunt capacitor fuses are frequently caused by harmonics,
(v) induction disk metering accuracy as well as electronic metering methods can be adversely affected by harmonics,
(vi) system resonance at harmonic frequency can cause sharp increases in local voltage levels contributing to the failure of surge arresters, capacitors, and other dielectric system,
(vii) harmonics may cause damaging dielectric heating in cables,
(viii) increasing losses in magnetic components in the distribution and transmission networks, and
(ix) protective relay may be malfunctioning.

At the distribution level, most of these problems can be more severe due to the proliferation of electronic loads, which include static power converters, inverters and rectifiers that generate power system harmonics. A common feature of these electronic type devices is their nonlinearities. The applications of these nonlinear loads cause power systems more often subject to harmonic injections. It is not unreasonable to claim that this trend at the distribution level is expected to be accelerate. As a result, high power/rapid switching semiconductor devices are being developed and being made commercially available for power flow control at the distribution level. At the transmission level, the utilization of high voltage DC systems, many alternative energy sources, and systems with a high percentage of fluorescent lighting loads, may require an analysis of the propagation of harmonic signals. Also, power electronic controllers have been utilized at the transmission level for Flexible Alternating Current Transmission Systems (FACTS).

The importance of the knowledge of harmonic levels and where these signals are being injected is evident from the fact that the IEEE has developed a standard, namely IEEE 519-1992 [4], which gives recommended practices and requirements for harmonic control in electric power systems. The function of this standard, associated with the levels of power system harmonics, results from:

(i) The need to control the distortion levels of power system current and voltage to a level that the system and its components can tolerate.
(ii) There is a necessity that users-connected devices are properly supplied to their particular needs.
(iii) Finally, there is the need to insure that a power system does not interfere with the operation of other systems, such as telephone networks or computer systems.

As a consequence, this IEEE recommended practice is an important motivation for the development of state estimation for harmonic signals. State estimation methodologies offer a practical alternative for implementing the requirements of the IEEE recommended practice.

1.3 Literature Review

Farach *et al.* [1] address the problem of where to take measurements to estimate the location of harmonic sources in a power system. Since there was no guidelines published for choosing the measurements points, they recommend a procedure for placing sensors and identifying sources of harmonics. Sensitivity analysis and the minimum variance criterion based on sequential solution are utilized to solve the problem with under-determined system in linear static problem. Using the minimum variance criterion, they showed that the optimal placement of sensors is not necessarily sequential.

Watson *et al.* [3] propose a new symbolic method of Observability Analysis (OA), which is capable of providing harmonic estimation without the need for the system to be completely observable. The new method is developed for measurement placement in a three-phase unbalance power system, gives the correct identification results as well as information on redundant and additional measurements for improving measurement placement. To solve the under-determined case, where only observable islands exist, Singular Value Decomposition (SVD) needs to be applied, because standard techniques for solving such equations will fail. It should be noted that symbolic OA cannot detect cases where there are two dependent measurement equations because the actual values are lost. The paper also describes the solution process for an under-determined system of HSE using SVD.

Holten *et al.* [5] propose a method to circumvent the ill-conditioned problem in the gain matrix of the classical normal equations approach for state estimation. A comparative study of five methods, normal equation with constraints, method of Peters and Wilkinson, orthogonal transformation, hybrid method, Hachtel's augmented matrix method, is made in terms of their numerical stability, computational efficiency, and implementation complexity. The ill-conditioned may occur in the classical solution method for state estimation when there is a disparity in weighting factors, large number of injection measurements, and connection of short and long transmission lines. The comparison is conducted on three test systems. From simulation results, they find that the performance of each algorithm depends on weighting factor, number of injection measurements and size of network.

Heydt [6] describes a reverse power flow procedure to identify the sources of harmonic signals in electric power systems. Line and bus data at several points in the network are used with a least squares estimator to calculate the injection spectrum at buses suspected of being the harmonic sources. When the energy at harmonic frequencies is found injected into the network at a certain bus, that bus is identified as a harmonic source. Inaccuracies occur due to losses, estimation errors, and modeling errors. As a result, there will be an error in the spectrum of the injected current. Nonetheless, it is possible to identify the harmonic sources. The spectrum bus injection may be used to identify the type of harmonic sources in many cases if the estimation procedure is sufficiently accurate.

Hartana *et al.* [7] apply neural networks to do initial estimates of harmonic sources in a power system with nonlinear loads. Neural networks are used in conjunction with state estimation, not to apply new estimation method. The initial estimates are then used as pseudo-measurements for HSE, which further improves the measurements. This approach permits the measurement of harmonics with relatively few permanent harmonic measurements. Simulation tests show that the trained neural networks are able to yield acceptable estimates of varying harmonic sources and the state estimator will generally pull these estimates closer to the correct values. The process also successfully identifies and monitors the suspect a harmonic sources that has not been measured previously.

Najjar *et al.* [8] study on the application of estimation theory to predict (estimate) harmonic bus voltages and line currents that cannot be measured directly. The present methodology is based on measurements, state estimators, and harmonic system modeling. Specifically, a hybrid of quadratic (Least Square; LS) and non-quadratic (Least Absolute Value; LAV) criterion-based techniques utilizing SVD is used with a feasible application to large-scale problems. In contrary to the fundamental case, the Jacobian matrix of the power system equations at harmonic frequencies is shown to be ill-conditioned; a robust numerical technique, using linear transformations to scale the Jacobian matrix, is suggested to render the estimation problem solvable in a practical environment.

Beides *et al.* [9] use Kalman filter to obtain the optimal estimate of the power system harmonic content. The measurements are simulated by adding gaussian noise to power system voltage and line flows at different harmonics obtained from the harmonic load flow program (HARMFLO). The effect of load variation over a one-day cycle on the power system harmonics and standard are presented. The test results on the IEEE 14 bus system are included. The main difference in this approach from static estimation methods is that this method is dynamic and has a capability of tracking harmonic content versus time.

Du *et al.* [10] present a system-wide continuous harmonic state estimator with under-determined system of three-phase asymmetric power systems, with a development of its reduced mathematical models and algorithm, as well as its application to the New Zealand test system. The complete harmonic information throughout the power system, including location and even type of the harmonic sources, is estimated from a few synchronize, partial, and asymmetric measurements at selected buses and lines which are far from the harmonic sources.

Du *et al.* [11] demonstrate an ability of system-wide HSE to identify remote harmonic sources and the load impedance of a power system from a few synchronize, partial and asymmetric measurements. HSE can be implemented both off-line, with the measurements are stored in advance, and on-line with the measurements continuously provided by the harmonic measurements. It turns multi-point measurements to system-wide measurements in a very economical way. System-wide HSE provides an efficient power quality tool for assessing the impact of hidden harmonic sources on the overall performance of a power system.

Matair *et al.* [12] present a new HSE algorithm, which is based on SVD method with under-determined system. The algorithm does not require the whole network system to be observable prior to estimation. It can give a solution even if the system under consideration is partially observable. Limit measurement data from sites are used only part of the network of interest will be estimated. There is a small difference between the estimated and simulated results. Compare with fully observable, a large number of measurements data are required. There is no difference between the estimated and simulated results. This condition is not practicable/too costly or could be used only for a small network.

Pham *et al.* [13] describe a power system reduction method for use in HSE. The symbolic OA algorithm is applied to determine the system observability from a set of measurement locations. The new method uses harmonic measurements at non-harmonic sources, such as those of generators, without loads or linear loads, to estimate the system-wide harmonic level. The new development allows optimal harmonic measurement locations to be selected and increase the HSE solvability for large and complicated systems. It reduces the cost and time in obtaining harmonic measurement data for HSE purposes.

Baren *et al.* [14] present a new fundamental meter placement method. The method is comprehensive in that all the important aspects of the problem. There are, cost, accuracy, reliability, and bad data processing capability requirements. The problem is solved in three stages. The objective in the first stage is to place a minimum set of measurements to satisfy the desire accuracy requirements. In the second stage, additional meters are placed to incorporate reliability requirements. In the third stage, additional meters are placed to improve the bad data processing ability of the state estimation.

Osowski [15] presents a statistical approach to the estimation of harmonic components in power system from the example waveform of the voltage or current of the power system. Mathematically, it is based on SVD. Three different techniques are investigated: the standard averages SVD, the total LS and double SVD. The total LS has the advantage over the standard LS when both measurement vector and correlation matrix are noisy. The double SVD technique provides additional information on the number of useful harmonic signals of the measured waveform and at the same time gives the estimation results with much better accuracy. The method gives satisfactory results of estimation even in the case when the noise is many times higher than useful harmonic components.

Lobos *et al.* [16] examine the SVD for frequency estimation of harmonics from simulated waveform signals in the presence of high noise. The proposed approach results in a linear LS method. The methods is developed for locating the frequencies, as closely space sinusoidal signals are appropriate tools for the investigation of power system signals containing harmonics and inter-harmonics differing significantly in their multiplicity. For comparison, similar experiments have been repeated using the Fast Fourier Transform (FFT) with the same number of samples and sampling periods. The comparison has proved superiority of the SVD for signals bury in the noise and also possible the estimation of inter-harmonics. However, the SVD computation is much more complex than that of FFT, and requires more extensive mathematical manipulations.

1.4 Purposes of the Study

1.4.1 To develop an optimal measurement placement method for HSE.

1.4.2 To demonstrate the method of HSE using SVD approach comparing with normal equation approach by off-line computer simulation program.

1.4.3 To compare the performance of the two methods: SVD approach and normal equation approach.

1.5 Education/Application Advantages

1.5.1 Propose algorithm of an optimal measurement placement method for HSE.

1.5.2 Improve the performance of HSE in power systems.

1.5.3 Know the performance of the two methods, SVD approach and normal equation approach.

1.5.4 Advanced knowledge in an optimal measurement placement method and HSE.

1.6 Research Scope

1.6.1 An optimal measurement placement algorithm and HSE algorithm will be carried out with computer simulation using computer program. The simulation program will be tested with benchmark test system, part of system in the South Island of New Zealand and the IEEE 14-bus test system.

1.6.2 Compare the performance of the two methods, SVD approach and normal equation approach.

1.7 Research Methodology

1.7.1 Study the algorithm of state estimation.

1.7.2 Study an optimal measurement placement method.

1.7.3 Study the algorithm of HSE using normal equation and SVD approach.

1.7.4 Develop simulation program for optimal measurement placement algorithm and HSE algorithm. The solutions from an optimal measurement placement method will be the measurement locations of HSE.

1.7.5 Part of actual values from the test system will be the measurement values supplied to the HSE algorithm. Then, numerical simulations of the HSE using SVD approach comparing with normal equation approach are performed

1.7.6 Compare the simulated results with the actual values from the test system.

1.7.7 Test the performance of the two methods: SVD approach and normal equation approach.

1.7.8 Test the performance of the algorithm with other test system.

1.8 Research Contributions

First, a new fundamental static state estimation algorithm using weighted least square (WLS) estimation, which is based on SVD rather than the normal equations has been presented. The SVD approach does not require the whole network system to be observable prior to estimation. It can provide a solution even if the system under consideration is partially observable. The simulation study was performed on the IEEE 14-bus test system. The simulation results, both linear and non-linear WLS, have shown that the SVD approach can provide a solution even when ill-conditioned occurred while the normal equation approach failed to give satisfactory results. In addition, the SVD approach can identify which parts of the network are unobservable islands. ([20] and CEPSI2002)

Second, a new algorithm for power system HSE has been presented. The measurement matrix for HSE in previous paper does not included the measurement at non-source bus, while some paper is including at non-source buses only. For an optimal measurement placement, the measurement placement should be anywhere in the network. A new system measurement matrix is obtained which include suspicious bus and non-source bus. HSE algorithm of three-phase asymmetric power systems has been tested with the New Zealand test system. (EECON25)

Third, the number of available harmonic measurements is always limited due to cost, while the quality of estimation is a function of the number and location of the measurements. Therefore, a systematic procedure is needed to design the optimal measurement placement. The new solution provides the optimal number of measurements and the best positions to place them, in order to identify the location and magnitude of harmonic sources. The minimum condition number of the measurement matrix is used as the criteria in conjunction with sequential elimination to solve the problem. Measurement placement in the HSE algorithm for a three-phase unbalance power system has been tested using the New Zealand test system, while the IEEE 14-bus test system has been used for testing a three-phase balanced power system. (IPQC2002 and IEEE Transactions on Power Delivery)

Fourth, the IEEE 14-bus test system for HSE has been presented. Trial and error is used to obtain a physical geometry of the IEEE 14-bus test system that gives, as close as possible, the correct positive sequence impedance and susceptance at fundamental frequency. All parameters for the test system are shown in Appendix A. Harmonic impedance at each frequency of the IEEE 14-bus test system has been calculated by TL (Transmission Line) program as describe in Appendix B.

Finally, the proposed optimal measurement placement for power system HSE has been applied to be measurement placement algorithm of state estimation with linear WLS (IEEE PES2003: General meeting) and non-linear WLS (EECON26). It is found that, the algorithm can give a solution of measurement placement for state estimation that makes the power system observable.

1.9 Thesis Organization

Chapter 2 reviews the state estimation and harmonic state estimation of power system. In Chapter 3, proposed optimal measurement placement algorithm will be developed. Chapter 4 presents two test systems, the real New Zealand test system and the IEEE 14-bus test system and the test results. Finally, conclusions and recommendations for future studies are given in Chapter 5.