CHAPTER 1

INTRODUCTION

1.1 THE NEED FOR STATE ESTIMATION IN POWER SYSTEMS

State estimation in power systems is regarded as the heart of energy control centres. It is becoming a part and parcel of new energy control centres that are being established for large scale power systems. Its purpose is to establish a reliable and complete real time data base for on line monitoring and control.

The main objective of any electric power utility is to ensure reliable and stable power supply at economic price to all the consumers. In order to achieve this, power system engineers utilise all available equipments and the operational facilities. This is not a difficult task so long as the power systems are of small size. System level energy control centres in small power systems rely mainly on speech communication for collection of data. However, with the growth in system size and with the expansion of power systems, it is no longer possible to realise the objective without well equipped energy control centres.

The energy control centre gathers information and measurements on the status and state of a power system through Supervisory Control and Data Acquisition System (SCADA) for
optimum operation and control. The data collected by SCADA are not immediately useful for on line monitoring and control as the measurements and information are corrupted by errors and uncertainties which are inherent in the measurement-data acquisition system. Small errors such as meter calibration errors, transducer inaccuracies, analog-digital conversion errors, communication noise etc and gross errors or bad data such as meter-communication failures, uncertainties in system parameter values, errors in network structure due to faulty switch and circuit breaker status information etc will be present in the gathered data. These errors and uncertainties are to be taken care of to obtain a reliable estimate of the state of the power system. Once the state is known all other electrical quantities of interest, such as line flows, can be computed for on line applications. In a large power system it is uneconomical and sometimes it is not possible to make all possible measurements to determine the state of the system. If the number of measurements are equal to the number of states of the power system, the situation then corresponds to a real time power flow. In this case, the errors and uncertainties present in the measurements are not accounted for. The errors in the state estimate may get amplified in the calculated values of the quantities of interest. If some measurements are lost, the states cannot be computed.

In view of the above considerations, it is necessary to have a method, which processes the raw measurements and
available information to establish a reliable and complete data base for on line monitoring and control. A state estimator in an energy control centre accomplishes this task effectively. A power system state estimator makes use of more number of measurements than the number of states to be estimated. The redundancy which is defined to be the ratio of the number of measurements to the number of states usually lies between 1.2 to 3.0. Even if some measurements are lost, with the remaining measurements the states can be estimated. The small random errors can be filtered out using proper weights to the set of measurements considered. An accurate measurement is weighted more than a less accurate one. Further, redundancy allows detection and identification of bad data to enhance the reliability of the estimates.

1.2 THE STATE ESTIMATION CONCEPT IN POWER SYSTEMS

State estimation programs have become an integral part of the computer system software in modern energy control centres of several major utilities. The static state estimation concept in power systems has evolved rapidly from the pioneering works of Schweppe et al [1-3] in 1968 to the present day on line state estimators. Since then, many researchers and engineers [4-27] have contributed to the evolution of power system state estimator. The first state estimator, the Tokke system, was installed in Norway in the year 1972. This was followed by American Electric Power's (AEP) larger installation
in 1973. A large number of power utilities have developed their own state estimators and successfully implemented them.

A power system static state estimator is a collection of digital computer algorithms which convert redundant, noisy, uncertain measurements and other available information into a reliable estimate of the states of a power system. The static state is the steady value of the phase angles and voltage magnitudes of the buses of a given power system at a particular instant of time.

The state estimator makes use of redundant measurements to obtain a reliable and accurate estimate of the states of a transmission network. The more the redundancy better the filtering and bad data detection properties of the estimator. The overall state estimation process consists of the following steps:

1. Hypothesise mathematical model
2. Estimate the state vector
3. Detect the bad data
4. Identify the bad data
5. Eliminate the bad data or replace them by pseudo-measurements
6. Re-estimate the state vector
The process has to be repeated until all the bad data are either eliminated or replaced.

1.3 THE STATE OF THE ART

The static state estimation problem is characterised by high dimensionality and the need for real time solution with the limited computer time and storage. A survey of literature shows that the basic Weighted Least Squares (WLS) estimator is popular and finds applications in many fields. The basic method, when used in power systems, has good convergence, filtering and bad data processing properties, for a given observable meter placement with sufficient redundancy and yields optimum estimates. But the gain and the Jacobian matrices associated with the basic algorithm require large storage and have to be evaluated at every iteration, resulting in very long computing time. The essential requirements for any on line state estimator are reliability, speed and less computer storage. The computational burden associated with the basic WLS algorithm makes it unsuitable for on line implementation in large scale power systems.

For real time application, in large scale power systems, the basic WLS algoritm is modified [24], using some or all of the following approximations, measures and techniques:
* exploitation of sparsity and symmetry in system matrices
* use of constant gain and/or constant Jacobian matrices
* use of real/reactive power decoupling present in actual power systems
* choice of proper measurement set
* use of decomposition and aggregation methods

Among the algorithms developed and implemented in real time, the AEP's robust Fast Decoupled State Estimator (FDSE) [19] is suitable for on line application and is capable of handling all types of measurements like injections, flows and voltage magnitudes. The state of art is the FDSE.

Any power system state estimator is sensitive to the presence of bad data among the observations. Gross measurement errors result in poor estimates. Many research papers have been published in the area of bad data analysis [28-42]. The erroneous data have to be detected and identified. They have to be either eliminated from the measurement set or replaced by pseudomeasurements [39], to obtain a reliable estimate. The reliable bad data processing have to be implemented in real time, using sparse inverse matrix method [42].
The integrated state estimators like FDSE may not meet the requirements of on line state estimation in terms of computer storage and time for very large scale power systems containing thousand or more, buses. Hierarchical state Estimation (HSE) methods [43-49] have been developed for such very large scale power systems.

Present day power systems are not only large, complex and interconnected, but also have HV dc subsystems embedded in them for better economy and reliability. State estimation algorithms for such large mixed ac/dc interconnected systems have to be developed, if possible, with least modifications of the existing ac state estimators. References [50-64] provide information on ac/dc system modelling, power flow and state estimation.

1.4 THE SCOPE AND AIMS OF THE THESIS

A thorough examination of the present state estimation problems reveals the following:

The rule given by Broussolle [42], to find out the required elements of the estimation error covariance matrix to compute the diagonal elements of the residual covariance matrix is not sufficient. Since this rule forms the basis for bad data processing using sparse inverse matrix method, it
becomes necessary to investigate the rule further to make it perfect.

The HSE algorithm of Van Cutsem et al [48] is the most interesting one. It is based on independent subsystem state estimations and reevaluation of all boundary nodal voltages which are incorporated into the second level procedure of estimating phase angles of all subsystems slack-bus voltages referred to the slack-bus of the overall system. When this HSE algorithm is applied to a large system, the size of the second level estimator can be much greater than that of the biggest subsystem estimator. The reduction of the computation burden associated with the second level algorithm needs further investigation.

It has been claimed by Leita Silva et al [53] that the seven variable steady state model for converter system is more accurate than the five variable model and the ac/dc state estimation results are based on this model. But it is found that the seven variable model is incorrect from the circuit theory point of view. Therefore, it becomes necessary to establish the correct model for ac/dc state estimation. Further, ac/dc state estimation is not well established and hence needs some more investigation. The aims of this thesis for providing solutions to the various problems discussed above are:
to establish necessary and sufficient conditions to flag off the required elements of the estimation error covariance matrix to compute the diagonal elements of the residual covariance matrix for bad data analysis, using the concept of operating point dependent and structural dependent zeros of the gain matrix and to develop sparse inverse matrix method using bifactorization technique for on line application.

* to extend the FDSE for real time state estimation of very large scale power systems employing two level hierarchical state estimation concept.

* to develop steady state model for converter system to be used in ac/dc state estimation.

* to develop an ac/dc state estimation algorithm using a partitioned approach by utilising the FDSE.

* to develop an ac/dc state estimator using a sequential approach with least modifications in the FDSE.

1.5 OUTLINE OF THE THESIS

The contents of the various chapters in the thesis are briefly described below:

In Chapter 1, the need for state estimation, the concept of state estimation, problems of state estimation and the
aims of the thesis are stated. Further, the organisation of the thesis material in the subsequent chapters is briefly outlined.

In the second chapter, in order to introduce the concept and to provide the necessary background required for subsequent discussion, the basic theory of the WLS state estimator and the FDSE is reviewed. The various sources of errors and uncertainties in the measurements are described. Models for estimation problem and noise are explained. The measurements employed for state estimation and their mathematical equations in terms of system state vector are described. The limitations of the basic WLS algorithm for on line implementation for large scale power systems are then discussed. The modifications and techniques required to make the basic algorithm for real time application are also outlined.

Utilising the assumptions made in Fast Decoupled Power Flow (FDPF), the robust AEP's FDSE algorithm is described. The normal equations of the FDSE are solved using sparsity-oriented bifactorization technique with scheme two ordering. The criteria for evaluating the performance of the algorithm are defined and discussed. Simulation procedure, using the results of FDPF, is described. To check the correctness of the program and to use the results of FDSE in some of the subsequent chapters of this thesis, IEEE 14 bus system is considered and the test results are presented.
The third chapter is concerned with bad data processing using sparse inverse matrix method. The statistical tests for bad data detection and identification are outlined. Necessary and sufficient conditions to find out the elements of estimation error covariance matrix required to compute the diagonal elements of the residual covariance matrix are established, based on the dependency of the zero elements of the gain matrix on the operating point and the structure of the network for a given measurement set. The development of sparse inverse matrix method using bifactorization technique is presented. Using the diagonal elements of the residual covariance matrix calculated through sparse inverse matrix method, the error estimate method test (b test) and the bad data replacement are carried out in the robust FDSE to illustrate vital role of the sparse inverse matrix method. Test results are presented and discussed.

Chapter 4 is devoted to the static state estimation using hierarchical approach. The concept of HSE approach of Van Cutsem et al is described. The first level state estimation procedure using the FDSE is described. A modified algorithm, overcoming the limitation of Van Cutsem et al method, is developed for the second level state estimation. The second level algorithm is simple and uses active/reactive decoupling and sparsity technique. It is designed to handle tie-line power flows and estimated states from the first level estimators. The suitability and the main features of the overall
procedure are illustrated on the basis of IEEE 14 bus ac system which is divided into three areas for hierarchical state estimation. The results are compared with the integrated estimator.

Chapter 5 deals with ac/dc static state estimation using a partitioned approach. The integrated ac/dc system is decomposed into three subsystems, namely, ac system, dc system and ac/dc interconnection system for the purpose of state estimation. The steady state model for ac/dc interface and dc system is developed. The seven variable model for converter system is shown incorrect from the circuit theory point of view and the correct equation for the seven variable model is formulated. The solution method for the partitioned approach is described. The expressions for the variances of the pseudo-measurements are derived. The FDSE based on sparsity-oriented bifactorization technique is used for the solution of ac system. Newton-Raphson's method is adopted for the solution of dc and interconnection systems. Test results are presented and discussed for a mesh connected dc subsystem embedded in IEEE 14 bus ac system.

Chapter 6 describes the development of ac/dc static state estimator suitable for dc links as well as multiterminal dc systems using a sequential approach. The ac/dc state estimation problem is formulated. The development of six variable
model is described. The measurements for ac/dc interface and dc systems are systematically classified and the measurement equations are established. The algorithm for ac/dc estimation is described. The performance of the ac/dc state estimator is investigated by incorporating a mesh connected dc network in IEEE 14 bus ac system.

Highlights of the thesis are briefly reviewed in Chapter 7. Suggestions for future research are indicated in this last chapter.