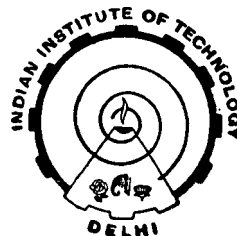


STATIC STATE ESTIMATION ALGORITHMS USING HESSIAN MATRIX APPROACH

by

DURG SINGH CHAUHAN

Thesis Submitted in Partial Fulfilment of the
Requirements for the Award of the Degree of
DOCTOR OF PHILOSOPHY
IN
ELECTRICAL ENGINEERING



Department of Electrical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, DELHI

1985

DEDICATED

TO

LORD AYYAPPA

CERTIFICATE

This is to certify that the thesis entitled, "Static State Estimation Algorithms Using Hessian Matrix Approach", which is submitted by Mr. Durg Singh Chauhan for the award of the Degree of Doctor of Philosophy of the Indian Institute of Technology, New Delhi, is a bonafide record of research work carried out by him over the last three years under our guidance and supervision.

The candidate has fulfilled the requirements of all the regulations relating to the degree. The results obtained in the thesis have not been submitted to any other University or Institute for the award of a degree or diploma.

S. C. Tripathy
Dr. Sarat C. Tripathy

Professor
Centre of Energy Studies
Indian Institute of Technology, Delhi
New Delhi 110 016, India

G. S. S. S. K. Durga Prasad

Dr. G.S.S.S.K. Durga Prasad
Lecturer
Department of Electrical Engineering
Indian Institute of Technology, Delhi
New Delhi 110 016, India

ACKNOWLEDGEMENTS

I am highly indebted to Prof. S.C. Tripathy and Dr. G. Durgaprasad for their constant guidance and encouragement in pursuing this research work. It has been my privilege to have received their help at various stages of the investigation.

I would like to thank the authorities of the Banaras Hindu University, Varanasi, and the Ministry of Education, Government of India, for providing me the QIP scheme facility.

I am thankful to (Late) Prof. A.K. Sinha, Prof. C.S. Indulkar, Prof. B.P. Singh and Dr. R. Balasubramanian for their valuable discussions during the course of this work.

The patience and understanding of my wife, Jyotsna, has been of great source of inspiration and help in the progress of this work.

I wish to thank my colleague Mr. A.K. Wahi and Kailash for their assistance during the preparation of this thesis.

I would like to thank the Head, Department of Electrical Engineering, Indian Institute of Technology, Delhi, for providing me all facilities in the department to carryout my research work.

Finally I would like to thank Mr. P.M. Padmanabhan Nambiar for typing the thesis and Mr. Kapoor for making neat tracings of figures.

DURG SINGH CHAUHAN

ABSTRACT

The thesis presents the results of research carried out by the author in the area of power system state estimation over the period, July 1982 to August 1985, at the Indian Institute of Technology, Delhi, India.

The thesis consists of seven chapters of which the first one is introductory and the last one is the conclusion. The review is described in Chapter II and the results of this investigation are described in Chapters III through VI. The basic theme of the investigation is to develop an algorithm which is computationally efficient and versatile. Specifically, we have utilized the concept of the Hessian matrix approach in the framework of existing WLS estimator. A brief description of the content of chapters is as follows:

Chapter I : This chapter is a brief introductory chapter which attempts to elaborate the importance of the static state estimation in the control room operation with specific features of the present day estimation techniques.

Chapter II : This chapter deals with the detailed mathematical models of estimation algorithms available in the literature. Standard WLS estimator, decoupled estimator in polar coordinate and exact second order estimator in cartesian coordinate are fully derived. Bad data suppression estimators in lumped and decoupled form based on non-quadratic cost function are presented.

Chapter III : This chapter deals with the Hessian matrix approach incorporated in the well known WLS methods in polar as well as cartesian coordinates. Ill-conditioning of information matrix is often a problem in the weighted least square estimation and it could be solved with nominal computational effort using the following methodology.

Using the Hessian matrix approach the information matrix

$$[M] = [M_1] \div [M_2]$$

where

$[M_1]$ = the information matrix of WLS method

$[M_2]$ = the matrix of second order derivative of functions.

If we ignore the second order terms, the algorithm becomes unfit in ill-conditioned or bad conditioned case. Proposed Hessian matrix approach does not affect the sparsity of the information matrix used in the WLS method.

Chapter IV : This chapter completely describes the tracking state estimation algorithm using the proposed approach. Bad data suppression algorithm using the Hessian matrix in decoupled version is described. Prefiltering is incorporated to filter out gross measurement errors. A tracking of states from the nominal base case to final operating condition has been done in 40 samples by using all the aforesaid techniques. The proposed technique tracks the state on the curvature of the cost function.

Chapter V : This chapter deals with the analysis of power system observability. Making use of simple measurement graph and its spanning tree algorithm, critical measurement graph and its spanning tree algorithm, critical measurement algorithm and pseudo measurement placement algorithms are developed. Observability of power system is an essential aspect of processing the measurement vector. The proposed algorithm has computational superiority over other algorithms available in the literature.

Chapter VI : Multiple bad data identification using sensitivity matrix is a new approach. This chapter describes the use of new sensitivity matrix of the proposed Hessian matrix estimator in finding effect of bad data in the residual vector of the estimate. Normalized sensitivity matrix approach is exploited to estimate the random noise vector of suspected bad data, as normalized residual is best judged in identification of single bad data. Bad data effect spread on normalized residual has linear relation with normalized sensitivity matrix. It can give best correction factor. This theme is presented in this chapter with test results conducted on a 30-bus well-conditioned power system.

Chapter VII : This chapter is devoted exclusively to comments on achievements of the investigations reported in earlier chapters and future scope of the research work.

CONTENTS

	Page
Abstract	i
Chapter I Introduction	1
1.1 General Outline	1
1.2 Features and Fundamentals of Estimation	2
1.3 Static State Estimation	4
1.4 Tracking State Estimation	4
1.5 Power System Observability	5
1.6 Multiple Bad Data Identification	5
1.7 Outline of the Thesis	5
Chapter II Review of Static State Estimation	8
2.1 Introduction	8
2.2 Weighted Least Square Estimator	9
2.3 Problem Formulation	10
2.4 The Weighted Least Square Estimation Algorithm Development	13
2.5 Recursive Processing	15
2.5.1 Constant Gain Algorithm	16
2.6 Decoupled State Estimation	17
2.6.1 Decoupled estimation with complete data vector	18
2.6.2 Completely decoupled estimator (Fast decoupled estimator)	21
2.7 Cartesian Coordinate Formulation of Weighted Least Square (WLS) Method	23

	Page	
2.7.1	Fast exact second order state (FESOS) estimator	25
2.8	Bad Data Suppression Estimators	27
2.8.1	The bad data suppression (BDS) algorithm	28
2.8.2	Fast decoupled BDS estimator	31
Chapter III	Static State Estimation Algorithms Using Hessian Matrix Approach	33
3.1	Introduction	33
3.2	Development of Algorithm	36
3.3	Fast Decoupled State (FDS) Estimator using Hessian Matrix Approach	39
3.4	Fast Decoupled Exact Second Order Estimator (FDESOS)	40
3.4.1	FDESOS using Hessian Matrix	41
3.5	Convergence Characteristics	42
3.6	Digital Simulation and Results	43
3.7	Conclusions	64
Chapter IV	A Tracking State Estimation in Power Systems	66
4.1	Introduction	66
4.2	Formulation of Problem	67
4.3	Basic WLS Tracking State Estimator using Hessian Matrix	69
4.4	The Fast Decoupled Model using Hessian Matrix	69
4.5	A Prefiltering Algorithm Formulation	71
4.5.1	The measurements and the state model	72
4.5.2	Loop incidence matrix formulation	74

	Page	
4.6	Fast Decoupled Bad Data Suppression Algorithm using Hessian Matrix	75
4.7	Simulation Description	76
4.8	Numerical Results	99
4.9	Conclusions	99
Chapter V	Power System Observability	100
5.1	Introduction	100
5.2	Relationship between the Measurement Model and the Topology of Network	102
5.2.1	Algebraical and numerical observability	104
5.2.2	Topological Observability	105
5.3	The Measurement Graph	106
5.4	The Spanning Tree Formulation Algorithm	110
5.5	Determination of Critical Measurements	111
5.6	The Pseudo Measurement Placement Algorithm	118
5.6.1	Algebraic concept of pseudo measurement placement	120
5.7	Digital Simulation Description	121
5.8	Conclusions	132
Chapter VI	Multiple Bad Data Identification	
6.1	Introduction	133
6.2	Static State Estimation in Electric Power System - General Formulation and Notations	136
6.2.1	Static state estimation	136
6.2.2	Sensitivity analysis	138

	Page
6.2.3 Sensitivity matrix $\left[\frac{\partial \underline{x}}{\partial \underline{z}} \right]$	138
6.2.4 Sensitivity matrix $\left[\frac{\partial r}{\partial \underline{z}} \right]$	139
6.2.5 Weighted and normalized covariance methods	140
6.2.6 The role of normalized residuals	141
6.2.7 Detection theory of bad data	143
6.2.8 Some interesting properties of r_N -test and r_W -test	144
6.3 The Estimation Identification Approach for Identifying Multiple Bad Data	145
6.3.1 Mathematical description of the approach	146
6.3.2 Correction of the state estimates	150
6.3.3 Identifiability of bad data	151
6.4 Description of Model System and Simulation	151
6.5 Conclusions	163
Chapter VII Conclusions	164
7.1 Scope for Future Research	167
References	168
Appendix 1 Hessian Matrix of the Functionals	179
Appendix 2 Decoupled Hessian Matrix	188
Appendix 3 Decoupled Hessian Matrix (Rectangular)	191
Appendix 4 Proposed BDS Hessian Matrix	196
Appendix 5 Graph theory	198
Appendix 6	203
Curriculum Vitae	214