ON SOME ASPECTS OF OPTIMAL POWER FLOW AND AUTOMATIC GENERATION CONTROL OF INTERCONNECTED POWER SYSTEMS

By
LAKSHMAN HARI
Department of Electrical Engineering

THESIS SUBMITTED
IN FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

to

INDIAN INSTITUTE OF TECHNOLOGY, DELHI
NEW DELHI - 110016, INDIA

February, 1992

DEDICATED

TO

MY PARENTS

DEAR ASHISH, PIYUSH - MY SONS AND

SUDHA - MY WIFE

CERTIFICATE

*This is to certify that the thesis entitled, "**ON SOME ASPECTS OF OPTIMAL POWER FLOW AND AUTOMATIC GENERATION CONTROL OF INTERCONNECTED POWER SYSTEMS**", being submitted by **Mr. Lakshman Hari** to the **Indian Institute of Technology, Delhi**, for the award of the degree of **Doctor of Philosophy in Electrical Engineering**, is a record of bona fide research work carried out by him. He has worked under our joint supervision and guidance and has fulfilled the requirement for submission of the thesis. The thesis, in our opinion, has attained the requisite standard for the award of a Ph.D. degree of this Institute. The results contained in this thesis have not been submitted elsewhere in part or full for the award of any degree or diploma.*

(Dr. M. L. Kothari)
Associate Professor

(Prof. J. Nanda)
Professor

Department of Electrical Engineering,
Indian Institute of Technology, Delhi,
New Delhi-110 016, INDIA.

ACKNOWLEDGMENT

I take this opportunity to express my deep sense of gratitude to my research supervisor Professor J. Nanda and Dr. M.L. Kothari, Department of Electrical Engineering, Indian Institute of Technology Delhi, for their inspiring and stimulating guidance and invaluable thought provoking suggestions at every stage of this research work.

It has been my proud privilege to work with Prof. J. Nanda, a luminary in the field of power system engineering. He has been the principal motivating force behind this research work. Dr. Kothari has always inspired and encouraged me in carrying out this research work and provided all possible help. I shall remain obliged and indebted to these eminent personalities.

I am grateful to Central Electricity Authority/Northern Regional Electricity Board for permitting me to pursue this research work. I am highly grateful to Shri M.K.G. Pillai Member Secretary NREB, Shri S. L. Narasimhan and Dr. S. Mukhopadhyaya, Superintending Engineers NREB for their numerous kind gestures during the course of this work.

I express my sincere thanks to Dr. P.R. Bijwe, Incharge Power System Laboratory for extending all facilities towards the completion of this work.

I sincerely thank Shri A. K. Asthana for his invaluable help at various stages of this work. Thanks are due to all my colleagues and friends who have contributed directly or indirectly to the success of this work.

I humbly acknowledge the help rendered by Mr. Kankar Bhattacharya in preparation of this thesis. I am thankful to all fellow co-researchers S/Shri D. Das, V. Shankar, N.D.R. Sarma, G.G. Bhise, K. Ramalingam and others for their help and cooperation.

I thank the staff of Power Systems and P.G. Machines Laboratories S/Shri Chand Singh, R.P. Sharma, Meharban Singh and Suresh Chandra for their utmost cooperation.

My thanks are also due to M/s. Eagle Computer Centre especially Mr. Sanjay Arora for printing the manuscript.

I am grateful to my wife Sudha and dear little Ashish and Piyush for their excellent understanding, support and cooperation during the course of this work. Infact my wife Sudha has been the main inspiring and deriving force in this endeavour for which no words of thanks would be sufficient.

(Lakshman Hari)

ABSTRACT

This thesis deals with two important aspects of an interconnected power system, i.e. Optimal Power Flow (OPF) and Automatic Generation Control (AGC). The OPF problem considering pollution aspects has been solved using classical techniques based on exact coordination equations and modified coordination equations considering all relevant system constraints. The AGC problem of a typical two equal area reheat thermal system considering generation rate constraint (GRC) has been analysed in the continuous-discrete mode with controllers based on conventional area control error (ACE), new area control error (ACEN) and modified area control error (ACEM).

Chapter-1 introduces the problem of real and reactive power optimization and automatic generation control (AGC) of an interconnected power system in general and presents a critical review of the past work in the areas of real and reactive power optimization and AGC. It lays down the objectives and motivations of the research work carried out.

Second Chapter presents a pioneering attempt to solve the economic emission load dispatch (EELD) problem with line flow constraints using a classical technique based on coordination equations. A concept of total cost of generation and pollution control is introduced to solve the EELD problem for varying degree of compromise factor (α) for cost of generation and cost of pollution control. The inability of classical technique in handling the line flow constraints till date is circumvented in an innovative manner, whereby the line flows are expressed in

terms of real power generations through distribution factors. These distribution factors are elegantly computed from an already available sensitivity information of Newton-Raphson Load Flow (NRLF) using a perturbation technique. The proposed technique is tested on IEEE 14 and 30 bus systems, and the results are compared with those obtained by rigorous techniques.

Investigations clearly show that the utilities should not always go for optimum allocation of generation as per the usual economic load dispatch practice as this may not provide the overall best economy considering all such aspects as cost of generation, emission level, total cost of generation and pollution control, and system transmission loss in totality.

Studies reveal that the algorithm developed for EELD solution based on coordination equations is capable of handling the practical constraints effectively and is envisaged to appeal to the utilities as the most competitive algorithm for on-line application.

In the **Third Chapter** a maiden attempt is made to develop a set of coordination equations based on classical technique for optimal reactive power dispatch in order to minimize system real power loss considering constraints on reactive power generations, OLTC transformers and load bus voltage magnitudes. A set of new loss formulae for active and reactive power losses (P_L & Q_L) are used. The loss coefficients are generated effectively and extremely elegantly from an already available base load flow information using a perturbation technique. An innovative approach considering the concept of fictitious reactive power

injections is used to model OLTC transformers. A pioneering attempt is made to account for the constraints on load bus voltage magnitudes in a novel manner by invoking a search area technique and expressing the bus voltages in terms of reactive power generations through voltage distribution factors which are elegantly computed from an already available base load flow solution using a perturbation technique. The proposed model is tested on IEEE 14 and 30 bus systems. The results obtained show a great promise for practical application of the proposed algorithm for optimal reactive power dispatch.

Chapter-4 presents an unified model based on classical technique for optimal power flow by sequential optimization of real and reactive power scheduling considering environmental and other relevant system constraints. The two subproblems of OPF, i.e. minimization of total cost of generation and/or pollution level control by optimum scheduling of real power generation and minimization of total system real power loss by optimum scheduling of reactive power generation, are solved sequentially till both minimum total cost of generation and/or pollution control and minimum loss figures have converged. The proposed algorithm is tested on IEEE 14 and 30 bus systems. The results obtained by the proposed unified approach are in agreement with those obtained by rigorous technique based on QP method and hence the classical technique for optimal power flow has a tremendous potential (because of its speed, memory and

simplicity) for real time application in practice.

Chapter-5 deals with the development of an innovative computational algorithm for optimal real power scheduling using modified coordination equations. A maiden attempt is made to account for line flow constraints in an innovative manner. The line flows are expressed as a function of real power generations through distribution factors which are generated very efficiently and effectively from an already available Fast Decoupled Load Flow (FDLF) information using a perturbation technique. The penalty factors involved in modified coordination equations are realized extremely elegantly with little computational effort from the knowledge of an already available FDLF solution using a perturbation technique. The economic load dispatch (ELD) / economic emission load dispatch (EELD) solution with line flow constraints are achieved using the concept of search area and augmented modified coordination equations. Proposed algorithm is tested on IEEE 14 and 30 bus systems and results are compared with those obtained by exact coordination equations and other rigorous techniques. Studies reveal that the proposed algorithm based on modified coordination equations is faster than the one based on exact coordination equations particularly for larger systems. It is envisaged that the proposed algorithm would appeal to the utilities as possibly the fastest algorithm for real-time application.

Chapter-6 deals with the optimum selection of governor speed regulation parameter (R) necessary for design of an appropriate governor for continuous-discrete mode automatic generation

control of an interconnected power system considering generation rate constraint (GRC). Investigations reveal that there is no necessity for having a very low value of R as is usually the practice, since under realistic operation of an AGC a larger value of R can be acceptable that can even provide better dynamic responses. A governor designed with larger value of R is envisaged to be simpler in realization and cheaper in cost. Sensitivity analysis for an AGC system with higher value of R reveals that the optimum integral gain setting obtained for nominal system parameters is quite robust for ± 25% change in system parameters such as T_g, T_t, δ_{12}, H, T_r and K_r.

In Chapter-7 the AGC problem of a two equal area reheat thermal system is investigated considering continuous-discrete mode operation of the system with control strategies based on conventional area control error (ACE). The optimum parameters of the controllers are obtained using Integral of the Squared Errors (ISE) technique. The dynamic performances of the system in actual continuous-discrete mode are obtained considering optimum integral controller gain settings evaluated using continuous-time, discrete-time and continuous-discrete time models of the system. This is done to explore the applicability of continuous-time and discrete-time models in a realistic AGC system where the system works in continuous mode and the controller in the discrete mode. Studies reveal that in the presence of GRC optimum value of the integral gain setting (K_i^*) obtained using continuous-time model is acceptable while that obtained using discrete-time model is not acceptable for

the actual continuous-discrete mode operation of the AGC system. Effect of variation of sampling period T on K_i^* and system dynamic performance has also been investigated. Studies reveal that K_i^* and system dynamic performance are hardly affected when T is varied over a wide range. A sampling period of T = 20 seconds is even permissible for the continuous-discrete mode operation of the AGC system in the presence of GRC.

Chapter-8 presents an analysis of continuous-discrete AGC based on new area control error (ACEN) of a two equal area reheat thermal system. The dynamic performance of the system in continuous-discrete mode with controller based on ACEN has been compared with that obtained with controller based on conventional ACE considering GRC. Studies reveal that the dynamic performance of the system with controller based on ACEN is slightly better than the performance based on conventional ACE in terms of settling time. The time error and inadvertent interchange accumulations are effectively regulated to zero by the AGC based on ACEN, while these quantities settle to their finite steady state values with AGC based on conventional ACE. The dynamic performance of the system in actual continuous-discrete mode AGC based on ACEN has also been analysed considering optimum integral gain settings evaluated with continuous, discrete and continuous-discrete time mathematical models of the system in the presence of GRC. The effect of variation of sampling period T on optimum controller parameters (K_i^* and α^*) and system dynamic performance have also been studied. Studies reveal that the optimum value of K_i^* and α^* obtained considering

continuous-time mathematical model are acceptable for the actual continuous-discrete mode AGC based on ACEN as was evidenced with the AGC based on conventional ACE. Investigations show that for the system under consideration it is feasible to choose a large sampling period, to the tune of T = 20 seconds, considering integral controller based on ACEN without jeopardizing the dynamic performance of the system.

Further, the use of a modified area control error (ACEM) for AGC has been proposed. The dynamic performances of the system obtained with controller based on ACEM has been compared with those obtained with controllers based on conventional ACE and ACEN. Studies show that the controller based on ACEM provides the dynamic performance of the system close to that of AGC based on new area control error (ACEN). The former controller, however, is preferable for its comparatively easy realisation and cheaper cost.

Chapter-9 highlights the significant contributions of the present work and identifies the scope for future work.

CONTENTS