Stabilization of Electric Power Systems Through Suboptimal Control(準最適化制御 による電力系統の安定化に関する研究)

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論　文　内　容　要　旨

Chapter I — Introduction:

I−1. Power system structure complexity:

Interconnections have become of vital importance to electric power systems for so many reasons. However, these interconnections increase the degree of complexity of power system operating problems arising from the complexity of the network topology. As the size of a system grows, the efforts required to control it increase very rapidly. This necessitates to find out some reliable control policies to cope with the problems arising in the power systems.

I−2. Stability problem:

System stability is one of the main objectives to be sought in analizing any dynamical system. The linear state feedback is a powerful tool in modern control theory and a stable design is always produced (under reasonable and rather weak conditions) for any choice of the performance index.

This approach has some disadvantages e.g. the design is based on a linearized model of the actual nonlinear system and it is efficient only to damp small oscillations around the operating point. The uncertainties associated with the exact values of the system parameters can not be taken into consideration. Also, it assumes that the sensing and control of the system are done in a centralized way, which is difficulty whether in design or during implementation.

I −3. Closed loop eigenstructure :

It is well known that the closed loop eigenvalues of any controllable system can be arbitrary assigned to any desired self−conjugate set of complex numbers by using the state feedback. The feedback gain matrix F, in this case, is not uniquely defined. To give the dynamical system a certain "time domain characteristic" and "shape of response" the eigenstructure assignment approach has been applied.

Chapter II — Power System Control Problem :

II − 1. Introduction:

The control problem of power systems has different aspects ranging from the optimal allocation of generation and transmission resources to network state estimation, frequency and exchange power control, system stability and dynamic security. Our discussion is limited to control problem from the power system stabilization point of view.

II −2. Review of power system optimal control problem :

Modern control theory has been extensively applied to design power system stabilizers and several attempts in this respect have been appeared in the literature. The theory has been mainly applied to the power system state variable feedback control, megawatt−frequency control and minimum−time control problems. Even the theory has been applied since several years ago but still the relation between Q, and R or the weighting matrices on the system state and control variables respectively, is not quite clear.

II −3. Performance indices :

The nonlinear differential equations describing the power system dynamics are usually linearized at the nominal operating point. A certain performance index is to be chosen and minimized such that some control design requirements are to be satisfied. This leads to the solution of lyapunov equation.

II −4. Approximate solution of Lyapunov equation :

During the solution of optimization problems which appear in the different chap−

ters an efficient solution of Lyapunov equation is needed. Therefore, an approximate solution is derived which is suitable in the case of high order power systems. The solution is based on the non-singular perturbation method. The proposed method has the same convergent condition and rate of convergence as that of Jacob's method for solving large scale linear systems.

Chapter Ⅲ — Closed Loop Eigenstructure Assignment :

Ⅲ-1. Introduction

The relation between feedback gain matrix and the resulting closed loop eigen-structure, and its inverse, can be expressed in terms of maps between the parameters spaces. While the former is called the analysis problem, the later is called the synthesis problem which is treated in this study.

Ⅲ-2. Eigenvalue, eigenvector assignment problem :

The necessary and sufficient conditions for assigning a pair of eigenvalue and eigenvector for closed loop system are given, and the subspace of all the assignable closed loop eigenvectors is defined. The first corollary of the above theorem treates the case of n-pair of eigenvalues, and eigenvectors. Corollary 2 defines the dimension of the assignable subspace in the cases of controllable and uncontrollabe eigen values. Corollary 3 gives a simple proof that the dimension of the assignable subspace equal to the dimension of the column subspace of the input mapping matrix B.

Ⅲ-3. Optimization problem :

The theoretical results obtained in the previous section have been interpreted to a practical version in a form of an optimization procedure. In an attempt to fulfil some control design requirements a cost functional can be formulated and minimized. Th controllable eigenvalues and the assignable parts of the eigenvectors can be considered as optimization parameters, i.e. to iterate the optimization parameters to minimize the chosen cost functional.

Ⅲ-4. Optimization Algorithm:

A general purpose optimization algorithm has been developed based on the eigenstructure assignment approach. All the developed optimization procedures which are given in later chapters follow the same steps. The algorithm considers both the controllable eigenvalues and the components of the assignable part of eigenvectors as an optimization parameters to be iterated such that a cost functional is minimized.

Chapter Ⅳ — Power System Stabilization, A Suboptimal Controller Design:

Ⅳ−1. Introduction :

To design a power system controller, some techniques appeared in the literature are attempting to shift the system's critical eigenvalues to the left in the complex plane. In fact, the system eigenvectors also have an important role in shaping the system response.

Ⅳ−2. Nonlinear system model :

In designing a power system controller by applying the optimal control theory, in almost all of the cases a linearized model is to be derived by linearizing the system dynamics at the nominal operating point. A mathematical model for power system can be derived by approximating the nonlinear relation by two sets of linear equations with the steady state operating point as a matching point between the two sets.

Ⅳ−3. Cost functional choice:

Two cases have been considered. Case 1 : The system eigenvalues are assumed to be assigned to some desired locations in the left−half of the complex plane. Case 2 : It follows the same steps as the algorithm in 3. 4. In both cases the cost functional is to be chosen as a sum of two cost functionals corresponding to the two sets of linear equations representing the nonlinear system.

Ⅳ−4. Power system suboptimal controller design :

The proposed eigenvalue, eigenvector assignment technique has been applied to design power system controllers for some typical power systems.

Ⅳ−4−1. In case 1, an example of a single machine connected to an infinite busbar has been considered.

Ⅳ−4−2. In case 2, two power system examples of a single−machine, and multi−machine power systems have been treated. The designed controllers in both cases have been tested under the influence of different disturbances and compared with the optimal controllers.

Chapter Ⅴ — Eigenvalues Assignment With Minimum Eigenstructure Sensitivity :

Ⅴ−1. Introduction :

Power systems are subject to parameter variations and modeling errors and an accurate mathematical representation of the system is not easily obtained. This results in system performance deterioration due to parameter variations, as long as the controller design is based on nominal value of the system parameters.

V−2. Eigenvalue, eigenvector sensitivities :

The sensitivities, or the differential changes in the system eigenvalues and eigenvectors due to a differential change in a system parameter have been given. The necessary and sufficient conditions to assign the system eigenstructure with zero sensitivities are given in a theorem along with its proof.

V−3. Eigenvalue, eigenvector sensitivity minimization :

From practical point of view the condition stated by the above theorem is difficult to be satisfied. Therefore, the sensitivity problem has been formulated in terms of a cost functional to be minimized. The system eigenvalues have been assigned to some desired pattern in the lefthalf of the complex plane, and the system stability at the nominal operating point is assured. The components of the assignable part of system eigenvectors have been iterated to get minimum sensitivity.

V−4. Power system controller design with minimum eigenstructure sensitivity:

The optimization procedure which has been suggested in the previous section is applied to the example of section 4.4.1 to design a power system controller, with minimum eigenstructure sensitivity. The power system parameters which have been considered are the parameters of AVR & Exciter and Governor control systems. The designed controller has been tested and compared with the corresponding optimal controller.

Chapter Ⅵ—Decentralized Control of Interconnected Power Systems :

Ⅵ−1. Introduction :

A decentralized control schemes can be obtained by assuming constraints on the information transfer between the system local controllers. These different schemes result from the degree of restriction on the information transfer. With complete restriction on information transfer, the local control is the feedback of the local state variables.

Ⅵ−2. Decentralized control approach :

Several approaches have been appeared in the literature to tackle the decentralized control problem. These approaches differe mainly in the degree of information transfer between the different subsystems to be allowed. A brief review of the main approaches has been presented along with the mathematical treatement.

Ⅵ−3. Optimization problem, cost functional choice :

Decentralized control, simply means that the off−diagonal matrices of the feedback gain matrix F have only zero entries. The system closed loop eigenstructure can be assigned such that the resulting feedback gain matrix has such structure. This could be formulated mathematically by chosing a certain cost functional to achieve the required feedback gain matrix with complete restriction on the information transfer.

Ⅵ−4. Interconnected power system example :

The optimization procedure given in 6.3 has been applied in designing a decentralized controller for a power system which consists of four interconnected machines. In this application the system eigenvalues have been assigned to some desired pattern in the left−half of the complex plane, while the components of the assignable part of the system eigenvectors have been iterated in such way that the off−diagonal block submatrices entries of the feedback gain matrix F have been made equal to zero. The designed controller has been tested and compared with the optimal centralized controller.

Chapter Ⅶ— Summary and Conclusions :

Due to the nonlinear nature of power system dynamics and the uncertainties associated with the determination of some parameters of power systems, the optimal solution resulting from the application of the modern control theory is not highly desirable or even attainable especially in the case of large scale power systems. Moreover, the choice of the weighting matrices depends on the engineering sense and experience and in some cases it is of much difficulty to be determined.

Recently, some research works appeared in the literature which based on shifting the system critical eigenvalues to the left in the complex plane. This is not uniquely define the feedback gain matrix F and the extra degrees of freedom can be explored in assigning the closed loop eigenvectors beside the assignment of the corresponding eigenvalues.

In other words this freedom can be explored in satisfying some design requirements such as system nonlinearity, system sensitivity, and system decentralized control. To fulfil such design requirements, some optimization procedures have been developed based on the eigenvalue, eigenvector assignment approach. Those optimization procedures have been used in designing power system controllers. As an application to power systems some typical examples from the power system literature have been employed. The designed controllers, in the different cases, have been tested under the influence of different types of disturbances. For the sake of comparison, the corresponding optimal controllers resulting from the application of the modern control theory have been designed.

From both cases treated in chapter 4, it is clear the improvement which could be achieved by assigning the system eigenvalues and eigenvectors, such that the system nonlinearity could be taken into consideration, in comparison with the optimal case based on the linear model. The design procedure given in this chapter enables the designer to take the nonlinearity effect into consideration, for a single-machine and multi-machine cases.

Power system sensitivity to system parameters change has been considered in chapter 5. A practical optimization procedure to assign the closed loop eigenvalues and to minimize the eigentructure sensitivity has been given. In fact the proposed procedure can take any of the power system parameters into considetion and can be easily applied to multi-machine case.

The power system decentralized control problem has been considered in chapter 6. A decentralized controller for the given system has been designed, based on the proposed procedure, tested and compared with the centralized optimal controller. The proposed procedure keeps only the necessary state variables to be fedback and calculate the required gains, while the others tend to be zero. The given procedure is systematic and can give a good insight to the information flow required, in the case of large scale systems.

Appendices:

There are three appendices. Appendix I is for nomenclature, and Appendix II deals with system operating conditions, and system parameters for the different examples used throughout this report. The detailed electrical machine and network models are discussed in Appendix III.

Finally, the refrences used in all of the chapters are provided at the end of this report.

審査結果の要旨

電力系統の安定度を向上させることは，系統の管理運用上極めて重要であり，近年，最適制御理論を応用した電力系統の安定化制御に関する研究が活発に行われるようになった。しかし，これまでの研究では，電力系統の状態方程式の非線形性やパラメータ変動については十分な考察がなされていなかった。

著者は，電力系統の安定度がその動作点で線形近似された状態方程式の固有値と固有ベクトルに大きく依存することに着目し，固有値・固有ベクトル割当の新しい手法を導入して，非線形性やパラメータ変動を考慮した安定化制御に関して研究を行った。本論文はその成果をまとめたもので全文７章よりなる。

第１章は序論である。第２章では，電力系統の安定化制御に関する従来の研究を概観し，それらの研究の問題点について論じている。

第３章では，固有値・固有ベクトル割当の自由度を詳細に解明して，割当の新しい手法を開発するとともに，この手法を適用して電力系統の安定化に関する最適化問題を解く方法について述べている。これは有用な知見である。

第４章では，状態方程式の非線形性を考慮した局所的な安定化制御を固有値・固有ベクトルの割当に関する最適化問題として定式化し，前章の手法を適用して準最適な安定化制御系を設計する方法を与えている。さらにこの設計法を発電機１機および多機のモデル系統に適用して，その有用性を確めている。

第５章では，固有値および固有ベクトルのパラメータ変動に対する感度解析を行い，その結果に基づいて，電力系統の安定化をはかると同時に固有値および固有ベクトルの感度を最小にする問題を第３章の手法を用いて解くための数値計算法を導き，その適用例を示している。

第６章では，各発電所毎の分散制御によって電力系統全体を安定化する問題を，固有値・固有ベクトルの割当問題に帰着させることにより，第３章の手法を適用して準最適な分散制御系を設計する一方法を与えている。さらに，その適用例を示して，分散制御の得失について論じている。

第７章は結論である。

以上要するに，本論文は固有値・固有ベクトル割当の新しい手法を導入することにより，状態方程式の非線形性やパラメータ変動を考慮した電力系統の安定化制御系の設計法を与えるとともに安定化を目的とした分散制御系の設計指針を示すなど，電力系統の安定化に有用な知見を加えたもので，電力工学および制御工学に寄与するところが少なくない。

よって，本論文は工学博士の学位論文として合格と認める。