称号及び氏名	博士（工学）　張　　建
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論　　文　　名	「**Nonlinear Generator Control Based on Equilibrium Point Analysis and Voltage Stability Considering Dynamic Load for Power System**」 （電力システムの平衡点解析による非線形発電機制御と動的負荷を考慮した電圧安定性）
審　査　委　員	主査　　川本　俊治
	副査　　森本　茂雄
	副査　　小亀　秀己

論文要旨

Modern electric power systems are characterized by extensive system interconnections and increasing dependence. The supply of reliable and economic electric energy is a major determinant of industrial progress and consequent rise in the standard of living.

Moreover, as the deregulation of the electric power industry moves forward, “Decentralized Power Sources” has been a focus of constant attention. Technologies of solar energy, wind power and fuel cells are extensively studied. Although these are the potential for a major portion of the electric power supply, significant issues remain limiting the widespread use of these technologies, including generation control and system stability. Also, because of the complexity of power systems with these distributed generators, the more flexible and overloaded operation of power systems is necessary, and the higher safety and reliability have been strongly required. Therefore, the transient stability of power system and the nonlinear generator control are thought to be important research subjects despite the stability analysis is quite difficult, since the generator has a strong nonlinearity.

Especially, generators play a crucial role in the power systems, which have two important inputs, field voltage and mechanical power. The field voltage is supplied by a generator driven by a motor or by the shaft of the turbine-generator. Rectifier and thyristor units converting ac to dc in various ways are also common. In any case, the units are called exciters, and the voltage control system, including an error detector and various feedback loops, is usually called an excitation system or Automatic Voltage Regulator (AVR). For providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation, Power System Stabilizer (PSS), which is installed in the AVR, can improve the power system stability. This supplementary control is beneficial during line outages and large power transfers.

However, power system instabilities can arise in certain circumstances due to negative damping effects of the PSS on the rotor. The reason is that PSS is always designed around a steady-state operating point: their damping effect is only valid for small excursions around this operating point, but during severe disturbances, power systems are modeled as large nonlinear highly structured systems. Therefore, PSS is limited since it is not available for the swing in the nonlinear region and may actually cause the generator under its control to lose synchronism in an attempt to control its excitation field. The design of a nonlinear controller is a quite important subject.

At the same time, the significance of load modeling for voltage stability studies has been emphasized by several disturbances, which have taken place in the past years. As a result of these disturbances, new investigations have come up to better understand the nature of the load. Actually, accurate models for generators, lines and transformers are available today, whereas load models are usually simplified. Static load models are not accurate enough for capturing the dynamics of the network. Despite power system loads keep being very difficult to model, accurate dynamic load models are indispensable because an accurate one will provide a better understanding of the load dynamics and its representation, making it possible to optimizing the economy and reliability of the system operation by voltage stability analysis.

In this thesis, firstly, an analysis based on equilibrium points has been proposed, and applied to a nonlinear controller design of the Japanese standard one-machine infinite-bus system model by adding a nonlinear complementary control input for the AVR in place of the linear controller PSS. In the analysis, the system model is formulated by the twelfth order nonlinear differential equations, and is analyzed on a basis of the proposed analysis without any approximation, where the limiters are also considered in the numerical simulation.

In the case of PSS, there exists the unstable equilibrium point in the inside of the AVR limiter, and it does not go away from the stable one by changing the variable parameters of the PSS. Therefore, the Critical Clearing Time (CCT) is not improved because the unstable equilibrium point restricts the transient stability.

On the other hand, for the proposed controller, the unstable equilibrium point of the system can be moved or eliminated. So, in this case, the limiter restricts the transient stability since the unstable equilibrium point is eliminated. Here, the unstable point can be eliminated by the feedback of the proposed nonlinear controller, and the excitation current is rapidly increased in comparison with PSS. Thus, the proposed method is valid for the nonlinear region. By adding the complementary control input u_a to the AVR, the unstable equilibrium point goes away from the stable one and disappears depending on the feedback gain, and the CCT and Available Transfer Capability (ATC) are fairly improved.

For the investigation on the voltage stability of the Japanese standard one-machine infinite-bus system model, the dynamic load model is also necessary, and is studied in this thesis. Dynamic load modeling and stability analysis are important subjects under the deregulation of electric power industry and the complexity of power systems with distributed generators. However, it has been said that a realistic dynamic modeling of composite loads is one of the great unsolved (possibly unsolvable) problems of electric power field. On the other hand, the dynamic load model proposed by Ihara, Tani and Tomiyama is constructed on a basis of the measured load characteristics, and is given in the polynomial form with a differential equation.

The Japanese standard one-machine system model with a dynamic load is treated for the derivation of the system P-V curve in this thesis. Next, the load model including a static and a dynamic load terms is introduced, and the measured data of V_2, P_L, and Q_L in Japan and Sweden are expressed by exponential functions. Then, the model can be expressed in an algebraic form. The coefficient parameters are estimated by using the data and the least squares method for the modeling. Therefore, the intersection of the system P-V curve and the load P-V gives an operation point.

The details of this thesis will be discussed in each Chapter.

In Chapter1, the objectives and the backgrounds of this study are introduced simply.

In Chapter2, the basic concepts of power system, e. g., synchronous generator, power system stability are briefly described for an easy understanding.

In Chapter3, the Japanese standard system model used in this thesis is introduced. The models of IEEE are known, and are also used in Japan for the evaluation of a new analytical technique of the electric power system. However, the characteristic phenomena of the Japanese power systems have not been well considered, and sometimes the control system models treated in Japan are also not handled in the system models. Therefore, the technical committee of *the Institute of Electrical Engineers in Japan (IEEJ)* developed the Japanese standard system models to answer the needs of the Japanese electric power engineers. Then, the standard one-machine system model is formulated by the twelfth order nonlinear differential equations, and in the end of the chapter, the power flow is also calculated.

In Chapter4, a nonlinear controller is designed by the equilibrium point analysis. The proposed nonlinear complementary control input based on the analysis for AVR is constructed, and equilibrium points of the model are analyzed in comparison with PSS. Also, CCT, ATC and the simulation results of the system model are discussed. As a result, by using the proposed nonlinear controller, the system transient stability can be quite improved.

In Chapter5, the dynamic load model proposed by Ihara et al. is introduced, and is verified by two types of measured data in Japan and Sweden. The data of terminal voltage, active power and reactive power at a load-bus are expressed by approximated functions. Then, the least squares method is used for the estimation of parameters of the dynamic load model. Since the dynamic load model introduced in this thesis has a form with a differential equation, it is difficult to apply it to the voltage stability analysis. Therefore, the solution of the differential equation is approximated by a simple polynomial form, and then the dynamic load model can be rewritten in a simple polynomial form of the load-bus voltage. So, the load P-V curves can be constructed, and the voltage stability can be analyzed by the system P-V curves derived from the standard system and the load P-V curves.

Finally, in Chapter6, the main results of this thesis are concluded, and a future subject is given by explaining the correlation of generator control and load.

審査結果の要旨

本論文は、電力システムの安全性および信頼性を向上させることを目的として、発電機の非線形制御の方法を新しく提案し、分散型電源が混在する負荷のモデルを構成することにより、電力システムの解析および電圧安定性の向上についての研究をまとめたものであり、次のような成果を得ている。

（１）　標準 1 機無限大系統モデルの動揺方程式を 12 次元の非線形連立微分方程式で定式化し、平衡点解析により近似することなくモデルの平衡点を求め、非線形発電機制御の新しい方法を提案した。
（２）　実電力システムで用いられている線形制御器および提案法について、臨界故障除去時間および制御応答をシミュレーションにより比較し、特性をかなり改善できることを検証した。
（３）　標準 1 機無限大系統モデルの一般的な負荷を取り扱い、実測データに基づいて負荷の電圧低下および負荷脱落を考慮し、分散型電源などによる動的負荷を含む P-V 曲線を導出することにより、実測の負荷の構成を明らかにした。
（４）　系統モデルの P-V 曲線および導出した負荷 P-V 曲線との交点から送電の運転点を求め、負荷の構成に依存する電圧安定度を解析できること、さらに非線形発電機制御により電圧安定度を向上させることができることを示した。

以上の研究成果は、電力自由化および分散型電源が急進展する中で、強く求められている非線形発電機制御および電圧安定度の解析と向上に関する指針と知見を与えるものであり、今後の電力システムの安全性および信頼性の向上に貢献するところは大きい。また、申請者が自立して研究活動を行うために必要な能力と学識を有していることを証したものである。