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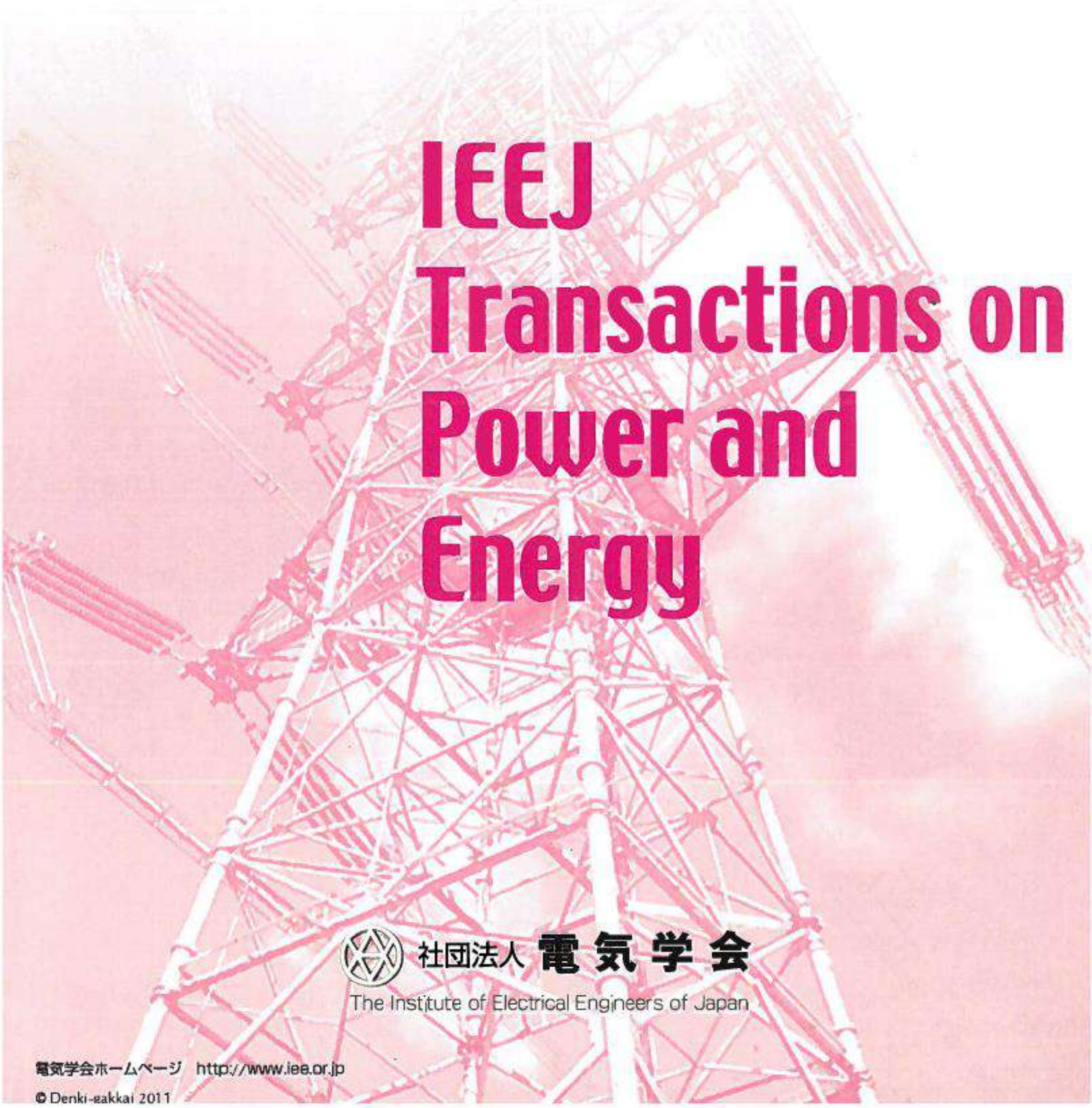

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Paper

Improvement of Transient Voltage Responses using an Additional PID-loop on ANFIS-based Composite Controller-SVC (CC-SVC) to Control Chaos and Voltage Collapse in Power Systems

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Chaos and voltage collapse are qualitative behaviors in power systems that exist due to lack of reactive power in critical loading. These phenomena are deeply explored using both detailed and approximate models in this paper. The ANFIS-based CC-SVC with an additional PID-loop was proposed to control these problems and to improve transient response of the detailed model. The main function of the PID-loop was to increase the minimum voltage and to decrease the settling time at transient response. The ANFIS-based method was chosen because its computational complexity was more efficient than Mamdani fuzzy logic controller. Therefore the convergence of training processes was more rapidly achieved by the ANFIS-based method. The load voltage was held to the setting value by adjusting the SVC susceptance properly. From the experimental results, the PID-loop was an effective controller which achieved good simulation result for the reactive load, the minimum voltage increased and the settling time decreased at the values of $j0.12$ pu, 0.9435 pu and 7.01 s, respectively.

Keywords: transient voltage, chaos, voltage collapse, power system control, ANFIS, PID-loop

1. Introduction

Load demand in a modern power system has grown up rapidly in recent year. However, the increment of power plants and transmission lines being built are very slow due to economical and environmental reasons. This situation will make the systems operate in critical mode at the boundary of stability region. Chaos and voltage collapse are nonlinear phenomena that exist in power systems with critical (heavy) loading condition. Chiang et al.(1) developed the voltage collapse model and described both the physical explanation and computational consideration of this problem. Static and dynamic models were used to know the detailed type of voltage collapse, wherein the static model was used before a saddle-node bifurcation, while the dynamic model was employed after the bifurcation(1)(2). Meanwhile, the Lyapunov exponent which measured how rapidly the two nearby trajectories separate from one to another within the state space and broadband spectrum was used to confirm this observation(3). Within the range of loading conditions, the sensitivity of chaotic behavior made power systems unpredictable after a finite time. In addition, within this range the effectiveness of any control scheme was questionable and should be reevaluated based on state vector information. Furthermore, nonlinear phenomena, including bifurcation, chaos and voltage collapse occurred in a power system model. The presence of various nonlinear phenomena was found to be a crucial factor in the inception of voltage collapse in this model(4)(5). The problems of controlled and suppressed of the presence of nonlinear phenomena in the power systems were addressed in this paper. The bifurcation control approach modified its bifurcation according to the system state equations and controlled chaos in a power system model(4)-(7). The presence of chaotic oscillations in a power system causing seriously unstable problem was studied by Yu et al. and Rajesh and Padiyar(8)-(10). The existence of chaotic oscillations in power systems due to disturbing of energy (DE) at the rotor speed has been found in Ref. (11). In addition, the modeling of chaotic behavior using recurrent neural networks in power systems was previously studied in Ref. (12). Practical techniques for recognizing and classifying chaotic behavior were identified by Parker and Chua(13), while control and anti-control chaos were developed by Chen(14). One scheme of chaos utility was used on electrical systems for smelting which was based on chaos control. Lei et al. demonstrated that chaotic steel-smelting ovens regulated their heating currents according to chaos control theory(15). A control system using a neural-network controller was presumed to be able to stabilize the unstable focus points of 2-dimensional chaotic systems; although, Konishi and Kokame stated that the control system

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did not require this presumption (16).

A fuzzy logic controller (FLC) has been successfully applied to control and stabilize chaotic systems, such as the Lorenz system (17) and the Chua circuit (18). Various studies on controlling transient chaos have been carried out, such as those by Dhamala et al., and Dhamala and Lai attempted to control transient chaos in power systems using a data time-series (19)(20). Strategies for controlling chaos in process plants have been tested on the discrete Henon map chaotic system (21).

A composite controller (CC) that has successfully controlled and suppressed chaos in power systems was reported in Refs. (4), (5). A nonlinear autoregressive moving average neural networks-based CC (NARMA-based CC) has been applied to control and suppress chaos and voltage collapse in power system model (22).

Static var compensator (SVC) placement is an attractive topic of research in power system engineering. There have been many methods applying the SVC placement optimally to maintain voltage stability, such as normal form analysis (23), multi-restart bender decomposition (24), reactive power spot price index (QSPI) (25) and genetic algorithms (GA) (26). An SVC supplementary controller has been applied to improve the damping of inter-area oscillations in small signal stability (27).

Adaptive neuro-fuzzy inference systems (ANFIS) technology is a combination of neural networks and fuzzy inference systems. This technology has been applied on many engineering systems, including on the detection of inter-turn insulation and bearing wear faults in induction motors (28), as well as on supplementary controllers for damping low frequency oscillations in power systems (29) and automatic voltage regulators for generator systems (30). An ANFIS-based CC has been successfully applied to control chaos in power systems (31). Furthermore, an ANFIS-based CC-SVC has been used to control chaos, voltage collapse and control of reactive power in order to maintain the load voltage in power system operation (32). Meanwhile, a PID controller has been proposed in practical engineering such as: a design method for fuzzy PID controller using modified triangular membership functions to improve system performance (33), a fuzzy PID controller using a novel particle swarm optimization-evolutionary programming-based (PSO-EP-based) hybrid algorithm (34), and an intelligent particle swarm optimized fuzzy PID controller for AVR system (35), while ANFIS-based CC-PID has been used to improve transient voltage responses in power systems (36).

In this paper, we focus on improvement of transient voltage responses using additional PID-loop on ANFIS-based CC-SVC to control chaos and voltage collapse in power systems. The PID controller was chosen because it was simple and easy to be implemented. Whilst, the ANFIS method was used in this research because its computational complexity was more effective than Mamdani fuzzy inference system. And, controller parameters were automatically updated by off-line training.

This paper is organized as follows: the detailed and approximate models of power systems are explained in Section 2. Qualitative behavior of power systems in critical mode is described in Section 3. Next, the ANFIS-based CC-SVC with an additional PID-loop design is depicted in Section 4. The simulation results and analysis are presented in Section 5. Finally, the conclusion is provided in the last section.

2. Power System Model

A synchronous machine was modeled as a voltage (E'_{q0}) behind a direct reactance (x'_d). The voltage magnitude was assumed as remaining constant at the pre-disturbance value. De Mello and Concordia, as well as Kundur derived this model of a machine connected to an infinite bus (37). Meanwhile, if saturation and the stator resistance were neglected, the system's condition was balanced with a static load. The machine was connected to the infinite bus and supplied the load. Then the armature current flowed from the machine to the load. This current caused electrical torque on the stator winding, and vice versa. The mechanical torque was produced by the flux through the rotor winding. Meanwhile, when the rotor speed was constant, the rotor speed followed the synchronous speed. When there was imbalanced energy, the rotor speed accelerated or decelerated, which can be expressed by the following equation

$$\dot{\omega}_m = \frac{1}{M}\left(T_m - T_e - D\omega_m\right) \tag{1}$$

where T_m, T_e, ω_m, D and M are the mechanical torque, electrical torque, rotor speed, damping constant and inertia constant, respectively.

2.1 Detailed Model This system model was developed from the work of Chiang et al. (1), as shown in Fig. 1. This model represents the system as one synchronous machine that supplies power to a local dynamic load with a shunt capacitor (Bus 2) connected by a weak tie line to an external system (Bus 3). All parameter values are conveyed to Eqs. (2)–(4):

$$V'_0 = \frac{V_0}{\left(1 + C^2 Y_0^{-2} - 2CY_0^{-1}\cos(\theta_0)\right)^{0.5}} \tag{2}$$

$$Y'_0 = Y_0\left(1 + C^2 Y_0^{-2} - 2CY_0^{-1}\cos(\theta_0)\right)^{0.5} \tag{3}$$

$$\theta'_0 = \theta_0 + \arctan\left(\frac{CY_0^{-1}\sin(\theta_0)}{1 - CY_0^{-1}\cos(\theta_0)}\right) \tag{4}$$

By using the variables and parameters on Table 1, the V'_0, Y'_0, θ'_0 were obtained as follows: $V'_0 = 2.5$ pu, $Y'_0 = 8.0$ pu, $\theta'_0 = -0.209$ rad. Thus, power system equations are defined as follows:

$$\dot{\delta}_m = \omega_m \tag{5}$$

$$\begin{aligned}\dot{\omega}_m = \frac{1}{M}\Big[&-D\omega_m + P_m + V_m{}^2 Y_m \sin(\theta_m)\\ &+ V_m V_L Y_m \sin(\delta_L - \delta_m - \theta_m)\Big]\end{aligned} \tag{6}$$

$$\begin{aligned}\dot{\delta}_L = \frac{1}{K_{q\omega}}\Big[&-K_{qv} V_L - K_{qv2} V_L^2\\ &+ Q - Q_0 - Q_{1d}\Big]\end{aligned} \tag{7}$$

$$\begin{aligned}\dot{V}_L = \frac{1}{TK_{q\omega}K_{pv}}\Big[&K_{p\omega}K_{qv2}V_L^2 + (K_{p\omega}K_{qv}\\ &- K_{q\omega}K_{pv})V_L + K_{p\omega}(Q_0 + Q_{1d} - Q)\\ &- K_{q\omega}(P_0 + P_{1d} - P) + u(\omega_m)\Big]\end{aligned} \tag{8}$$