Controlling Chaos Using ANFIS-Based Composite Controller (ANFIS-CC) in Power Systems

by I Made Ginarsa

Controlling Chaos Using ANFIS-Based Composite Controller (ANFIS-CC) in Power Systems

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Abstract-Chaos appears as nonlinear oscillations in a power system and these phenomena are caused by Disturbing of Energy (DE) when a power system is in critical loading. Chaos causes instability and voltage collapse and must be avoided. The ANFIS-based Composite Controller (ANFIS-CC) is proposed to solve these phenomena. The ANFIS-CC has a more efficient computation than a Mamdani fuzzy logic controller. A three-bus power system with DE and additional reactive load are used to validate the proposed method performance. The proposed method is very effective in the control and suppression of chaos in power systems.

Keywords: Controlling chaos, Disturbing of Energy (DE), power systems, instability, ANFIS-CC.

I. INTRODUCTION

Chaos are complex dynamical behaviors that possess some very special features such as sensitivity to initial condition, having bounded trajectories in the phase space but with a positive Lyapunov exponent, and a fractional dimension [1], [2]. The study of chaos phenomena in power systems is very important to avoid angle instability and voltage collapse [3]–[12]. The chaos appears in power systems due to Disturbing of Energy (DE) has been reported in [3], [4], [8]–[10]. The power systems are very vulnerable to DE, because the DE leads to the loss of stability in the power systems. Observation of chaotic behavior in power systems has been reported in [12] and its model by using recurrent neural networks in [9]. Controlling chaos with many methods have been achieved through: composite controller [5], [7], Ott. Grebogi and Yorke (OGY) [6], [11], [13], neural networks [14], and recurrent neural networks [15]. Other methods such as fuzzy logic [16], [17] and nonlinear autoreggressive moving average-neural networks [10] have been used to control chaos. A scheme of chaos utility is used in the electrical systems for smelting base on chaos control. Lei et al. demonstrated that the chaotic steel-smelting oven regulated its heating current according to the chaos control theory [13]. The ANFIS technology is a combination of neural networks and fuzzy inference systems. The computation of the ANFIS is more efficient than the Mamdani fuzzy logic. This technology has been applied to additive damping on low oscillation power system dynamics [18] and designing of the Automatic Voltage Regulator (AVR) [19].

In this paper, we focused on controlling chaos in power systems using ANFIS-based Composite Controller (ANFIS-CC). The ANFIS method is used because its computation is more efficient than a Mamdani fuzzy logic method. This paper is organized as follows: The power systems and chaos phenomena are described in Section II. The ANFIS-based CC design is detailed in Section III, while the results and analysis are described in Section IV. Finally, the conclusions are given in Section V.

II. POWER SYSTEMS

A. Single Machine Model

Synchronous machine is modeled as a voltage (E') behind a direct reactance. The voltage magnitude is assumed to remain constant at the pre-disturbance value, as shown in Fig.1(a). De Mello and Concordia as well as Kundur, derived this model of a machine connected to infinite bus [20]. The block-diagram for the mechanism of a single machine connected to infinite bus is shown in Fig. 1(b).

The machine is connected to an infinite bus and supplies the load. Armature current flows from machine to the load and causes electric torque on stator winding. When there is imbalanced energy, the rotor speed may accelerated or decelerated, in which case, the swing equation describes the system. The swing equation is presented as follows:

$$\delta = \omega_B \, \Delta\omega, \qquad (1)$$

$$\Delta\omega = \frac{1}{M}\left(T_m - T_e - D\,\Delta\omega\right), \qquad (2)$$

where D, T_m, T_e, δ, $\Delta\omega$ and M are the damping ratio, mechanical torque, electrical torque, rotor angle, rotor speed deviation, and moment inertia, respectively.

B. Three-Bus Power Systems

The system was developed from the work of Chiang et al. [4] and is shown in Fig. 2. 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). The system equations are:

$$\dot{\delta} = \Delta\omega, \tag{3}$$

$$\begin{aligned}\Delta\dot{\omega} = {} & 16.667\sin(\delta_L - \delta + 0.087)V_L \\ & -3.333.D.\omega + 1.881,\end{aligned} \tag{4}$$

$$\begin{aligned}\dot{\delta}_L = {} & 496.872{V_L}^2 \\ & -166.667\cos(\delta_L - \delta - 0.087)V_L \\ & -93.333\,V_L \\ & -666.667\cos(\delta_L - 0.209)V_L \\ & -33.333\,Q_{1d} + 43.333,\end{aligned} \tag{5}$$

$$\begin{aligned}\dot{V}_L = {} & -78.764\,{V_L}^2 \\ & +26.217\cos(\delta_L - \delta - 0.012)V_L \\ & +14.523\,V_L + 104.869\cos(\delta_L - 0.135) \\ & -5.229\,Q_{1d} - 7.033,\end{aligned} \tag{6}$$

where δ, $\Delta\omega$, δ_L, and V_L are the power angle, rotor speed deviation, angle, and magnitude of the voltage at the load bus, respectively. The parameters Q_{1d} and D are the reactive load and damping constants, respectively. Eqs. (3)–(6) can be simplified into a single formula, Eq. (7)

$$\dot{x} = f(x, \lambda), \tag{7}$$

where $x \in \Re^n$, $\lambda \in \Re^p$, and x and λ are the state variable and parameter space, respectively. The state variable is $x = [\delta_m\ \Delta\omega_m\ \delta_L\ V_L]^T$, wherein the superscript T denotes the transpose of the associate vector.

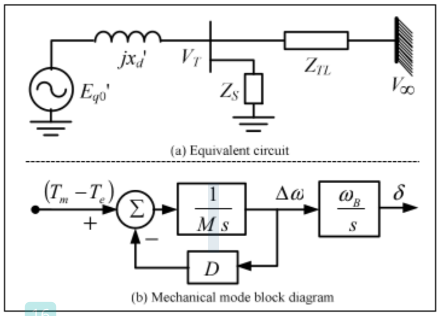


Fig. 1. Synchronous machine connected to infinite bus.

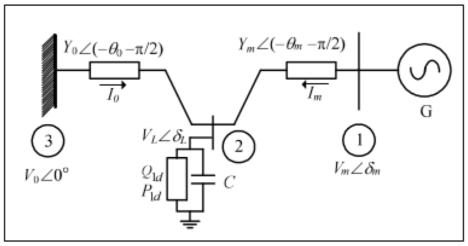


Fig. 2. One-line power system diagram with 3 buses.

C. Chaos in Electrical Power Systems

Chaos refers to one type of complex dynamical behavior that possesses some very special features, such as being extremely sensitive to tiny variations of parameters and initial conditions and having bounded trajectories in the phase-plane, but with a positive Lyapunov exponent and/or a fractional dimension. The definition of chaos, its properties [21], and its applications in engineering systems have been given in [1], [2].

The appearance of chaos can be described by the existing route to chaotic behavior in power systems caused by rotor speed, when the power systems are in critical loading condition. The rotor speed in power systems is affected by Disturbing of Energies (DE). Kinetic energy disturbances are exclusively related to rotor speed [3], [4], [8]–[10].

A disturbance and/or temporal overload cause a shift in a system parameter, such that a boundary crisis occurs, after which the system exhibits transient chaos, leading to voltage collapse. Chaotic behaviors in V_L-δ_L phase-plane trajectories, chaos occur at the rotor speed, and the load voltage time responses in power systems are shown in Figs. 3, 4(a), and 4(b), respectively.

III. ANFIS-BASED COMPOSITE CONTROLLER (ANFIS-CC) DESIGN

Adaptive neuro-fuzzy system is a combination of adaptive neural networks and fuzzy inference system. The ANFIS network under consideration has 2 inputs x, y and 1 output f. Thus for a first-order Sugeno fuzzy model, a common rule set with 2 fuzzy if-then rules is given as follows [22], [23]:

$$\begin{aligned}&1: \text{If } x \text{ is } A_1 \text{ And } y \text{ is } B_1 \text{ Then } f_1 = p_1 x + q_1 y + r_1 \\ &2: \text{If } x \text{ is } A_2 \text{ And } y \text{ is } B_2 \text{ Then } f_2 = p_2 x + q_2 y + r_2.\end{aligned} \tag{8}$$

A step-by-step method of ANFIS-based CC design is presented as follows:

(i) *Choice of input variables:* In this step, the state variables provided as input signals to the controller are chosen. In these designs, rotor speed deviation ($\Delta\omega$) and its derivative ($\Delta\dot{\omega}$) are the input signals for the ANFIS-based CC.

(ii) *Choice of linguistic variables:* The linguistic variables, the alternative approach to modeling human thinking, are characterized by a quintuple set [22]. Five linguistic variables are used to describe of the input variables. The linguistic variables are: Negative High (NH), Negative Low (NL), Zero (ZE), Positive Low (PL), and Positive High (PH).

(iii) *Choice of membership functions:* Gaussian membership functions are used to define the degree of membership of input variables. A Gaussian membership function is specified by two parameters $\{c, \sigma\}$, where c and σ represent the membership function's center and width (spread), respectively. These parameters are obtained automatically through learning processes by a hybrid algorithm [22], [23].

(iv) *Choice of fuzzy model*: A first-order fuzzy model Sugeno (T-S) is chosen in this design because of its computational efficiency.

(v) *Preparation of training data pairs:* There are two sets of data training pairs: Rotor speed ($\Delta\omega$), its derivative ($\Delta\dot{\omega}$), and a control signal (*cs*), as the two inputs and the output, respectively, of the ANFIS-based CC.

The training processes are used in offline methods with 6,000 data points. The training of data pairs was prepared by simulating power systems with a conventional CC. The training results included 75, 75, 20, and 25 for the number of nodes, the number of linear parameters, the number of nonlinear parameters, and the number of fuzzy rules, respectively.

The ANFIS-based CC and its placement in power systems block diagram are shown in Figs. 5 and 6, respectively. The control surface of the tuned ANFIS-Based Composite Controller (CC) is shown in Fig. 7. From Fig. 7 it can be seen that the relationship of the rotor speed and its derivative as inputs and the control signal (cs) as an output were nonlinear.

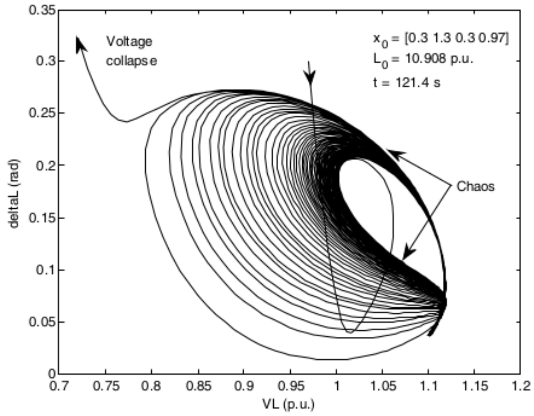
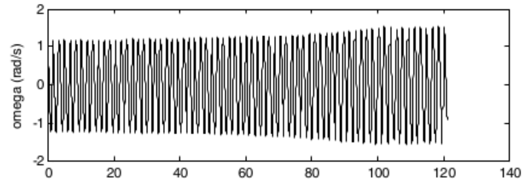
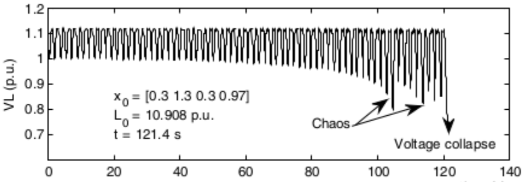


Fig. 3. Chaos in magnitude-angle voltage (V_L-δ_L) phase-plane trajectories.



(a). The rotor speed time response



(b). The load voltage time response

Fig. 4. Chaos is detected in the time responses.

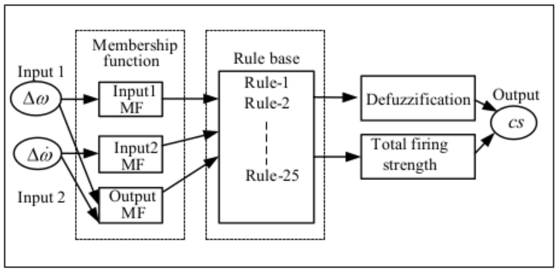


Fig. 5. The ANFIS-based CC block diagram.

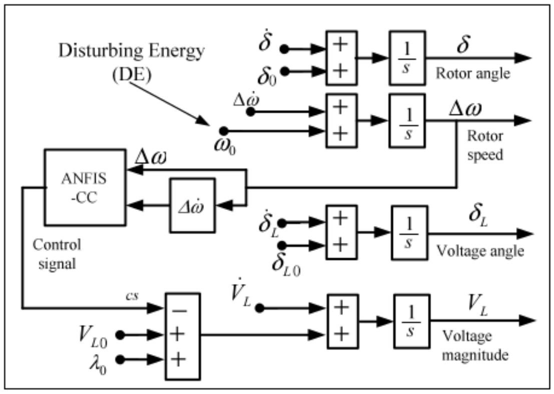


Fig. 6. The ANFIS-CC and power system block diagrams.

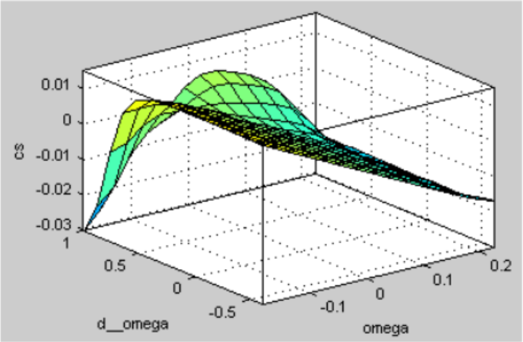


Fig. 7. Control surface of the ANFIS-based Composite Controller (CC).

IV. RESULT AND ANALYSIS

The simulation results show that the power systems for the Eqs. (3)–(6) are in chaotic oscillation. The chaotic oscillations are caused by DE. From Figs. 3 and 4 it can be shown that the chaotic oscilltions occur in duration 121.4 s. Furthermore, the load voltage rapidly declined and then disappeared a phenomenom known as voltage collapse.

A. *Analysis of The ANFIS-CC Device*

The proposed method is used to suppress chaos and voltage collapse inception. The controller was tested when DE (ω_0) affects the rotor speed. The temporal responses of the proposed method when DE values of 0.0, 1.0, 1.1, and 1.3 rad/s are applied to the power systems are shown in Fig. 8. The complete results can be found in Table I. Furthermore, the controller was tested by increasing the reactive loads (λ_1) from 0.0 to 0.14 p.u. The simulation results are shown in Table II and Fig. 9.

The peak rotor speed (ω_{min}) obtained from –0.1011 to –1,0554 rad/s when the DE increased from 0.0 to 1.3 rad/s (Table I). The settling time rotor speeds (ω_{st}, equilibrium point) increase from 12.2 to 21.3 s. In contrast, the minimum load voltages (V_{min}) decrease from 1.1046 to 0.8278 p.u. Furthermore, the steady-state load voltages (V_{ss}) stay at the value of 1.11 p.u.

Control of the load voltage was achieved by injecting signal control (*cs*) to the load bus. The control signal magnitude is dependent on the DE magnitude. When the DE magnitude increases, the control signal magnitude also increases. The maximum control signal is achived at the value of 1.474 when the DE at value of 1.3 rad/s. The control signal with various the DE values are shown in Fig. 9.

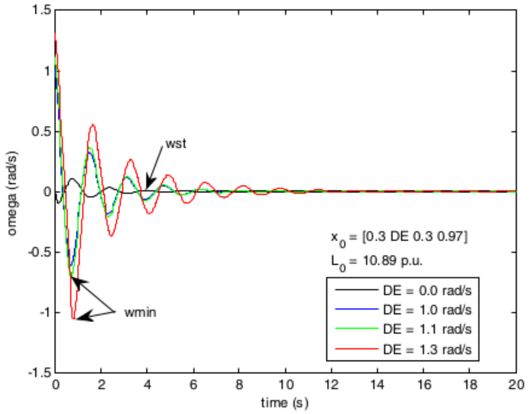


Fig. 8. The rotor speed responses after the proposed method applied.

TABLE I
THE SIMULATION RESULT WITH THE DE (ω_0) INCREASE

ω_0 (rad/s)	ω_{min} (rad/s)	ω_{st} (s)	V_{min} (p.u.)	V_{ss} (p.u.)
0.0	–0.1011	12.2	1.1046	1.1152
0.5	–0.2452	13.4	1.1031	1.1101
1.0	–0.6198	15.6	0.9527	1.1101
1.1	–0.7132	16.9	0.9155	1.1100
1.2	–0.8898	18.0	0.8502	1.1100
1.3	–1.0554	21.3	0.8278	1.1100

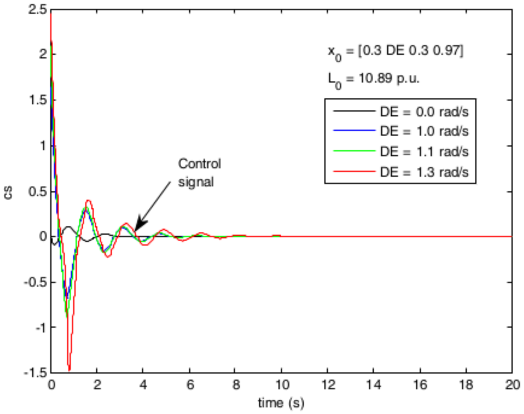


Fig. 9. The control signals necessary to control and suppress chaos in power systems.

B. *Voltage Analysis at Load Bus*

The effectiveness of the proposed method was tested by gradually increasing of the reactive load. According to the simulation results in Table II, the minimum load voltage (V_{min}) increased from 0.8278 to 0.8865 p.u. when the additional reactive load increased from 0.0 to 0.14 p.u. In contrast, the steady-state load voltage (V_{ss}) decreased from 1.11 to 1.0832 p.u. The settling time of the load voltage (V_{Lst}) is obtained at the time of 12.62 s at an initial reactive load. The settling time will be longer be achieved when the reactive load was increased, the systems will be oscillation in a more time. The settling time at 135.8 s was obtained when the additional reactive load increased to 0.14 p.u.

On the basis of results from Table II, the peak rotor speed was obtained from –1.055 to –1.093 rad/s, when the additional reactive load increased from 0.0 to 0.14 p.u. The temporal responses of the proposed method are shown in Fig. 10 when the additonal reactive load at value 0.00, 0.02, 0.06, and 0.1 p.u. were applied. Fig. 10, shows that the voltage oscillation took longer when the additonal reactive load was increased. It can be seen that the load voltage strongly depends on the reactive load. In addition, systems with the proposed method have only control signals for stabilizing deviations in the rotor speed, and do not control the reactive power.

TABLE II
THE SIMULATION RESULT WITH
ADDTIONAL REACTIVE LOAD (λ_1) INCREASE

λ_1(p.u.)	V_{min} (p.u.)	V_{ss} (p.u.)	V_{Lst} (s)	ω_{min} (rad/s)
0.00	0.8278	1.1100	12.62	–1.055
0.02	0.8325	1.1064	13.6	–1.058
0.04	0.8332	1.1032	17.5	–1.060
0.06	0.8461	1.0991	23.8	–1.062
0.08	0.8478	1.0952	33.2	–1.079
0.10	0.8631	1.0912	60.8	–1.084
0.12	0.8742	1.0873	120.3	–1.086
0.14	0.8865	1.0832	135.8	–1.093

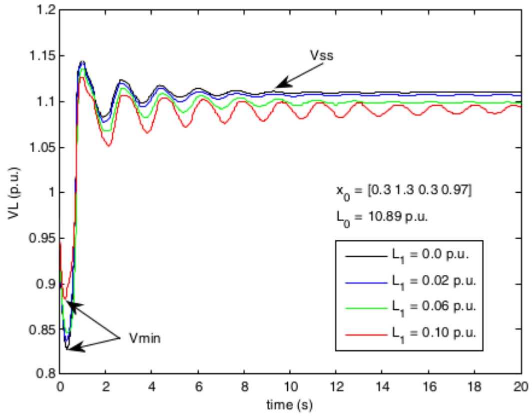


Fig. 10. The load voltage responses with various reactive loads.

V. CONCLUSIONS

Chaos phenomena appear in power systems due to Disturbing of Energy (DE) in a critical (heavy) loading condition. The results show that the proposed method can successfully control and supress chaos. The rotor speed and the voltage can effectively control route to equilibrium point. However, the load voltage cannot be controlled and is dependent on the reactive load change. Future works should aim to control and maintain the load voltage with an ANFIS-based Composite Controler-Static Var Compensator (ANFIS CC-SVC).

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