Optimal Decentralized Excitation Control to Improve Power System Dynamics

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Abstract:
This paper presents an optimal control design for decentralized generator excitation control systems which is suitable for use in power system to damped the oscillation depending on the modern control theory of controllable system by using generator load angle and voltage magnitude behind the quadrature axis transient reactance of generator to represent the interactions among generators, decentralized generator excitation control in multi machine power system can be achieved. Simulation results show that the proposed control improves power system dynamics.

الخلاصة:
يتناول البحث تقديم مسيطر امثل للمولد الكهربائي المتواجد في الشبكة عن طريق التحكم في المثير للمولد وبذلك نحصل على سيطرة مناسبة الاستخدام في انظمة القدرة الكهربائية لاخماد التارجح في نقاط العمل للمولد اعتمادا على نظريات السيطرة الحديثة في نظام قابل للسيطرة باستخدام و تمثيل زاوية الحمل للمولد و قيمة الفولتية بعد المحور العمودي لل(transient reactance) للمولد لتمثيل التداخل بن المولدات. ومن ثم بيان امكانية التنفيذ في نظام قدرة كهربائية يضم عدة مولدات. توضح النتائج للمسيطر المقترح امكانية تحسين استقرارية النظام.

List of symbols and abbreviations:

δ_i: load angle
ω_i: rotor frequency
E_{0qi} : voltage behind the q axis transient reactance of generator
P_{mi}: mechanical power
P_{ei}: reactive power output of generator
D_i: damping coefficient
I_{di}: d-axis current
X_{di}: d-axis synchronous reactance
X_{qi}: q-axis synchronous reactance
T_{0d}: time constant of excitation winding
ODEC: Optimal Decentralized Excitation Controller

1. Introduction

For reliable service, a power system must remain stable and capable of withstanding a wide range of disturbances. Power systems are identified by physical layout of the generators and loads in addition to commercial boundaries. The flow of active and reactive power in the transmission line are independent of each other as the active power depends on the angle by which sending end leads the receiving end, while the reactive power depends on the voltage magnitudes [Songklanakarin J. Sci. Technol. Aug. 2005]. This paper concentrates on active power control by the design a modern controller through the automatic voltage regulator of synchronous machine that is dependent on modern control theory in state space.

2. Dynamic and Generator mechanical model

For a multi-machine interconnected power system, the interaction between the *i*th generator and the rest of the system is shown in Fig. 1.

A dynamic model expresses the active and reactive powers at any instant of time as functions of the bus voltage and frequency at past and present instants of time. The response of most composite loads to frequency and voltage changes is fast, and a steady state response is reached very quickly. The case of static models is justified in such conditions. There are, however, many components of power systems which respond relatively slowly. Studies of inter-area oscillations and long term stability often require load dynamics to be modeled [Noroozian, M., Angquist, L., Ghandhari, M. and Andersson, G., October 1997].

The dynamic behavior of the generators within a power system is of fundamental importance to the overall quality of the power supply. The synchronous generator converts mechanical power to electrical power

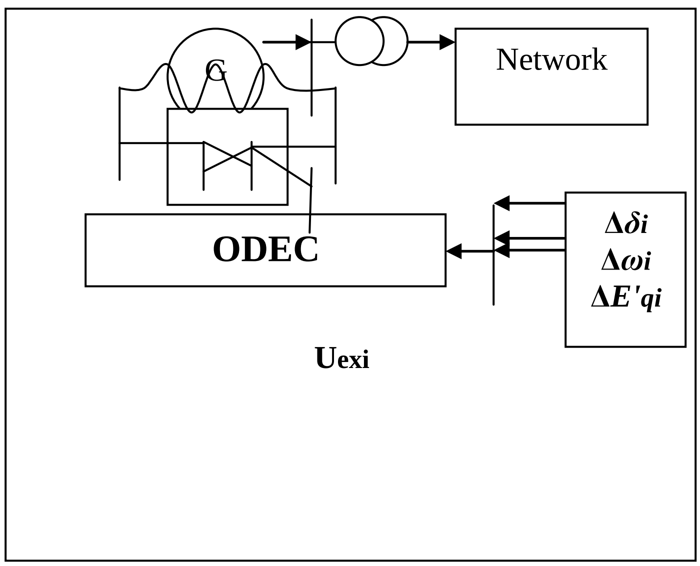

Fig. 1 Structure of Generator Sets with Optimal Decentralized Excitation Controller.

at a specific voltage and frequency. The source of the mechanical power, the prime mover, may be a diesel engine, a steam turbine or a water turbine. Whatever the source, it must have the basic property that its speed is almost constant regardless of the power demand. The analysis of any power system to determine its transient stability involves the mechanical properties of the machines because, after any disturbance, they must adjust the angle of their rotors to meet the conditions of power transfer imposed. The electric dynamics have very short time constant compared to hydrodynamics and can be ignored [Y.Z.Sun X. Li S.Yan Y.H.Song M.M. Farsangi., 4-7 April 2000].

Any imbalance between the torques will cause the acceleration or deceleration of the machine according to the laws of motion of a rotating body.

When fast speed excitation is considered, the excitation control model of the *i*th generator can be described by a set of differential equations as follows [Mohammed Jasim M. September 2007]:

$$\Delta\dot{\delta}_i = \omega_{i0}\Delta\omega_i \qquad \text{……… (1)}$$

$$\Delta\dot{\omega}_i = -\frac{E'_{qi}V_i}{2H_iX'_{di}}\cos(\delta_i)\Delta\delta_i - \frac{D_i}{2H_i}\Delta\omega_i - \frac{V_i\sin(\delta_i)}{2H_iX'_{di}}\Delta E'_{qi} + \frac{1}{2H_i}\Delta P_{mi}$$

$$\Delta\dot{E}'_{qi} = \frac{X_{di}-X'_{di}}{T'_{d0i}X'_{di}}V_i\sin(\delta_i)\Delta\delta_i - \frac{X_{di}}{T'_{d0i}X'_{di}}\Delta E'_{qi} + \frac{1}{T'_{d0i}}U_{exi}(t)$$

The original system can be transformed and linearized into the following equation using the Taylor's series method.

$$\Delta\dot{X} = A\Delta X + BU \qquad \text{…………… (2)}$$

Where:

$$A = diag(A_1,......., A_i,......, A_n).......B = diag(B_1,..., B_i,....., B_n)$$

$$U = [U_1, U_2,........U_n]^T,.........U_i = [U_{exi}]^T$$

$$\Delta X_i = [\Delta\delta_i, \Delta\omega_i, \Delta E'_{qi}]^T$$

$$A_i = [a_{ij}]$$

$$B_i = [b_{ij}]$$

$$a_{12} = \omega_0$$

$$a_{21} = -\frac{E'_{qi0}\cdot V_i}{2H_iX'_{di}}\cos(\delta_{i0})$$

$$a_{22} = -\frac{D_i}{2H_i}$$

$$a_{23} = -\frac{V_{i0}}{2H_iX'_{di}}\sin(\delta_{i0})$$

Other $a_{ij} = 0$ $b_{13} = \dfrac{1}{T'_{d0i}}$ Other $b_{ij} = 0$

$$a_{31} = -\frac{(X_{di}-X'_{di})}{T'_{d0i}.X'_{di}}V_{i0}.\sin(\delta_{i0})$$

$$a_{33} = -\frac{X_{di}}{T'_{d0i}.X'_{di}}$$

3. The Equilibrium Operation

A proper definition of the generic steady-state (or equilibrium) operating condition (i.e., the "working point" at which the system may be required to operate) refers to a well-defined mathematical model of the system itself, as discussed [Kundur, Prabha, 1994].

Let us assume that the "configuration" and the system parameters are constant, as well as the external variables which define, together with parameters concerning users, each load requirement (e.g., braking torques externally applied to electromechanical users). Let us also assume that the three-phase electrical part of the system is "physically symmetrical." Moreover, we may assume that the electrical part of the system is linear with regard to the relationships between *phase* voltages and currents, thus allowing sinusoidal operations of *phase* variables without waveform distortions or production of harmonics [Goran Andersson., March 2007].

We will say that the system is in equilibrium operation if (and only if):

- Excitation voltages of synchronous machines are constant;
- All synchronous machine shafts rotate at the same electrical speed (*"synchronous" operation*), so that electrical angular shifts among rotors are constant;
- Such speed is constant.

4. Studied System

Fig. 2 shows a 5-bus 2-generator test system used in this study. The parameters of the system are obtained in following tables[E. Acha, V. G. Agelidis, O. Anaya-Laa, T.J. E. Miller 2002].

Table.(1)Line data on a base of 100 MVA.

BUS-TO-BUS	Impedence Zik	Line Charging $Y_{IK/2}$
1-2	0.02+j0.06	0.0+j0.030
1-3	0.08+j0.24	0.0+j0.025
2-3	0.06+j0.18	0.0+j0.020
2-4	0.06+j0.18	0.0+j0.020
2-5	0.04+j0.12	0.0+j0.015
3-4	0.01+j0.03	0.0+j0.010
4-4	0.08+j0.24	0.0+j0.025

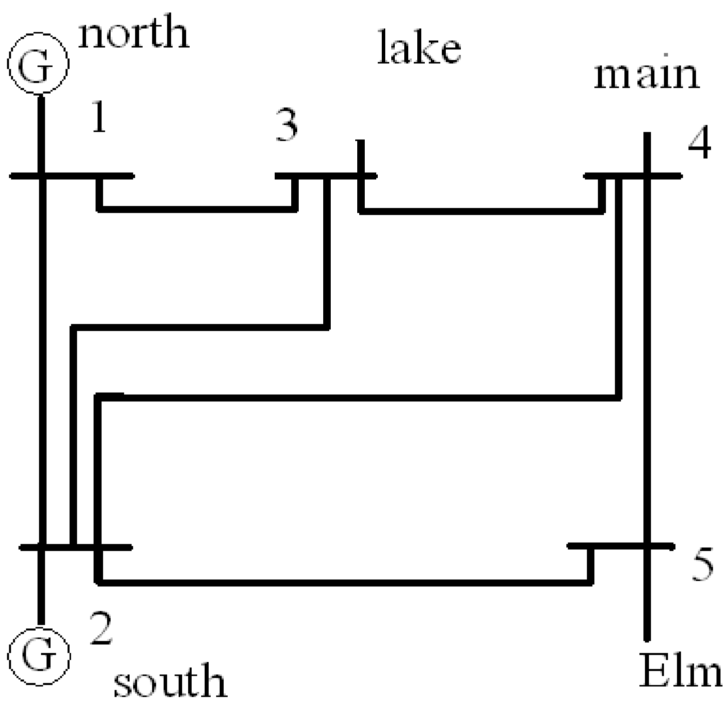

Fig. 2 Single line diagram of 5-bus 2-generator system.

Table (2) Synchronous machines parameters

Machine No.	H KW-sec/(KVA)	X_d' p.u	X_d p.u	T_d' sec
1	50	0.25	1	10
2	1	1.5	3	10

Table (3) load flow calculation results for the system.

Bus NO.	Bus voltage in p.u	Generation M.W	Generation MVAR	Load MW	Load MVAR
1	1.0600+j0.0	129.509	-7.659	0.0	0.0
2	1.04629+j0.05128	40.0	30.0	20.0	10.0
3	1.02043-j0.08922	0.0	0.0	45.0	15.0
4	1.01930-j0.09508	0.0	0.0	40.0	5.0
5	1.01228-j0.10909	0.0	0.0	60.0	10.0

5. Controller design

Optimal control is a branch of modern control theory that deals with designing controls for dynamic system by minimizing a performance index that depends on the system variables. In this section, we will discuss the design of optimal controllers for linear systems with quadratic performance index, the so called *linear quadratic regulator* (LQR) problem. The object of the optimal regulator design is to determine the optimal control law u(x, t) which can transfer the system from its initial state to the final state such that a given performance index is minimized.

The performance index is selected to give the best trade-off between performance and cost of control. The performance index that is widely used in optimal control design is known as the *quadratic performance index* and is based on minimum error and minimum energy criteria [Hadi saadat, 1999].

Consider the plant described by:

$$\dot{X}(t) = AX(t) + Bu(t) \qquad \text{…………. (3)}$$

The problem is to find the vector K (t) of the control law

$$U(t) = -K(t)X(t) \qquad \text{………… (4)}$$

Which minimize the value of a performance index J_x of the form:

$$J_x = \int_{t0}^{tf} (X^T QX + U^T RU)dt \qquad \text{………….. (5)}$$

Subjected to the dynamic plant equation in (3). In (5), Q is a positive semi definite matrix, and R is a real symmetric matrix. Q is a positive semi definite, if all its principal minors are nonnegative, the choice of the elements Q and R allows the relative weighting of individual state variables and individual control inputs.

With the generator control, the control errors of voltage and generator output are expected to settle to zero deviation. Then an integral type multivariable optimal control called a LQR control, which eliminates the control errors under existing applied model error and steady noise, is used. In the design scheme of the LQR control adopted in this research, the integrated control errors are added as a term of state variable.

Since a controller designed with this scheme only feeds back the timing deviation values, the construction of the excitation system is simplified extremely.

6. Simulation results by using MATLAB.

To test the effectiveness of the proposed controller, a three-phase fault was applied to bus 2 at the end close to the busbar (see Fig. 2) when the generator is operating at its rated power level. The fault is cleared in 0.1s. The system responses are simulated using MATLAB R2008a[Duane Hanseman and Bruce Littlefield.,1997]. It can be observed from these figures that the proposed controller can greatly improve the damping of the system. The dynamic oscillations are well damped.

In figure 3 the rotor frequency deviation for generator (1) increases with time as a result for the disturbance and as shown in dash-dot line. The devaition was continously oscillating in case without controller, with controller for the solid line the rotor frequency deviation decreases to reach exactly zero at 6.5 sec. Figure 4 shows the field voltage deviaion for generator (2) although stable behaviour but with continous oscilation as shown in dash line and this line represents the behaviour without contoller, with controller the oscillation reaaches to zero and then damped after 4 sec. In figure 5, the rotor frequency deviation for generator 2 has continuous oscillation with time, with controller the oscillation can be decreased and get improved behaviour.

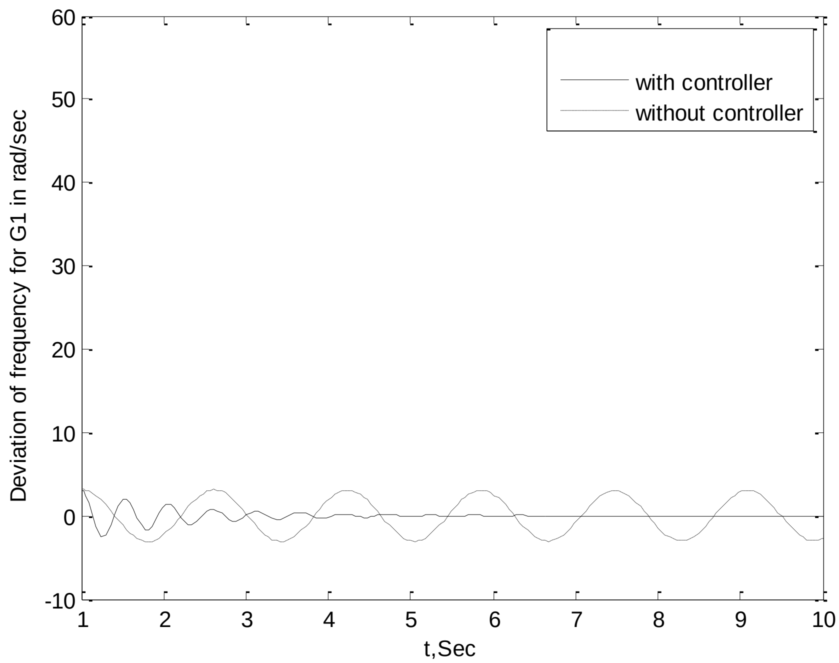

Fig. 3 Rotor frequency deviation for geneator (1) with and without controller.

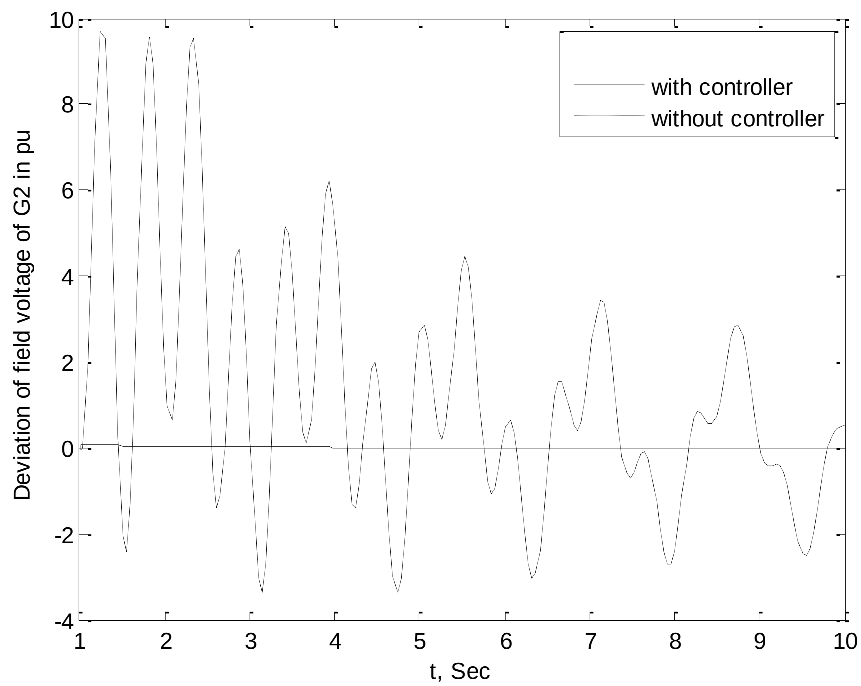

Fig. 4 Field voltage deviation for generator (2) with and without controller.

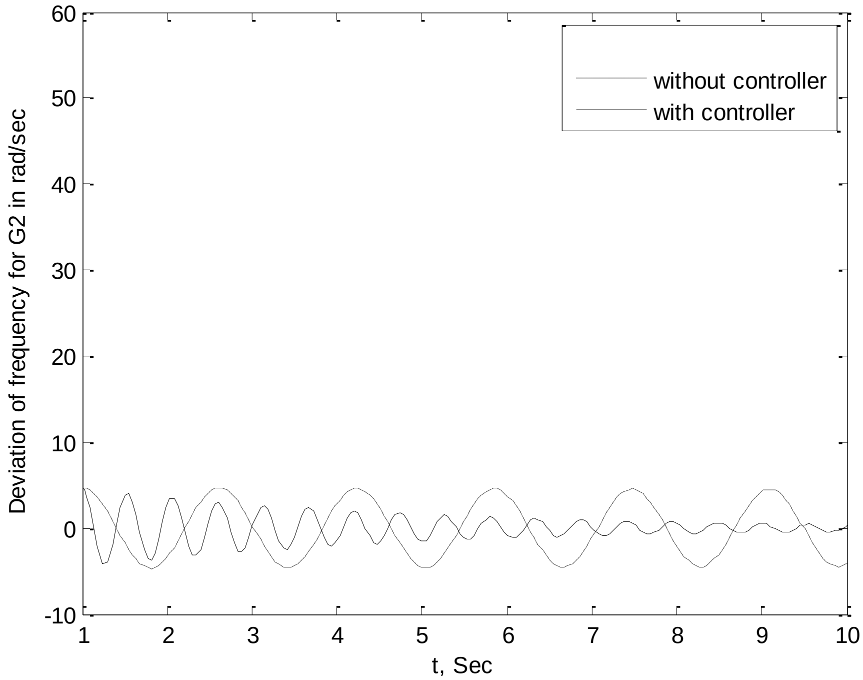

Fig. 5 Rotor frequency deviation for generator (2) with and without controller.

7. Conclusions

In this paper, an optimal controller design for decentralized generator excitation control system to improve power system dynamic is proposed. Since the complex interaction between many generator and the rest of system can be represented simply by load angle, rotor angular frequency and the magnitude of voltage of each generator, the overall power system can be decomposed into separate subsystems conveniently. Each subsystem comprises only one generator. Thus the decentralized control can be realized by designing excitation controllers for each generator respectively and focuses on the generator that is heavily affected by the disturbance. The simulation results and analysis reported indicate the effectiveness of the proposed decentralized excitation control.

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