Design of Stabilizing Controllers for the Nonlinear Power Systems

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Abstract: *The objective here is the development of mathematical model of the non-linear power system which can be utilized for implementing the different class of controller. The controller designed here is to fulfill the stability requirement of the system as well as to make the system transiently stable. The linearization of the power system is done using direct feedback linearization technique andthe model thus obtained has parameters which can be used as controller input. The linear LQ optimal control theory is applied to the model to design an optimal feedback control law,* $v_f(t)$.

Keywords: *Stabilizer, FLC (fuzzy logic controller), DFL (direct feedback linearization).*

I. Introduction

We consider here nonlinear control theory to design controllers for power systems to improve the transient stability and to achieve voltage regulation. The problem of designing controller to prevent an electric power system losing synchronism after a large sudden fault is of great importance in power system design.

In recent years, most of the non-linear excitation controllers have been developed based on the classical third order dynamic generator model. The simulation results showed that such a simplification has very little effect on the performances of the designed controllers.

Establishing a global control structure for general non-linear control systems is preferred, as control of complex system over a wide range of operating conditions can be achieved for a set of control objective. A general global control structure is based on the qualitative analysis of the dynamical systems. Local controllers are designed based on local models and local performance requirements and co-ordination rules are employed to combine the local elements control.

II. Non-Linear Systems

The topic of non-linear control has attracted particular attention during the past few decades as virtually all physical systems are non-linear in nature. Non-linear control analysis and design provides a sharper understanding of real world. For real world systems, large ranges of operation cannot be avoided, and demanding specifications are required by modern technology such as high performance robotics and aircraft which typically involve non-linear dynamics. Therefore use of non-linear control is crucial.

With the development of powerful microprocessor and low cost dedicated digital signal processors, non-linear controllers are becoming easier to implement reliably.

There are numerous examples of large dynamical systems that provide great challenges to control engineers. For example Electrical power systems, aerospace system, process control system in chemical and petroleum industries all require non-linear control.

III. Linear Model Of Synchronous Machine

When system is subjected to a small load change, it tends to acquire a new operating state. During the transition between the initial state and the new state the system behavior is oscillatory. If two states are such that all state variables change only slightly (i.e x_i changes from x_{i0} to $x_{i0}+x_{i\Delta}$ where $x_{i\Delta}$ is small change in x_i), the system is operating near the initial state. The initial state may be considered as a quiescent operating condition for the system.The behavior of the system when it is perturbed such that the new and old equilibrium states are nearly equal, the system equations are linearized about the Q operating condition. First order approximations are made for system equations.The new linear equations thus derived are assumed to be valid in the region near the Q-condition.The dynamic response of a linear system is determined by its characteristic equation.

IV. PID Controllers

Classical and modern methodologies in linear and non-linear control provide powerful design tools for systems modeled by ordinary differential equation. However, linear methods are valid for a small operating region, and many non-linear methods are only effective within a certain operating region due to the non-existence of global geometric structures.

Multiple controllers are widely used in practice where controllers adapt themselves to different operating conditions and are able to co-ordinate various control requirements. Control of a complex system over a wide range of operating conditions to achieve a set of control objectives is called global control.

To achieve the goals of global control, multiple controllers are needed. They are derived from the design method of local control and operate over different operating points during different time periods to fulfill the corresponding primary control requirements. Therefore how to co-ordinate the controllers is the major issue of global control.

A plant model of a physical system that is to be controlled is usually very complex and difficult. Adaptive control is a model-free controller that can be used to control non-linear systems. Most of the adaptive controllers involve certain types of function approximator from input/output experiments. The basic objective of adaptive control is to maintain consistent performance of a control system in the presence of the designed parameters. Traditional adaptive controllers cannot make use of human experience, which is usually expressed in linguistic terms.

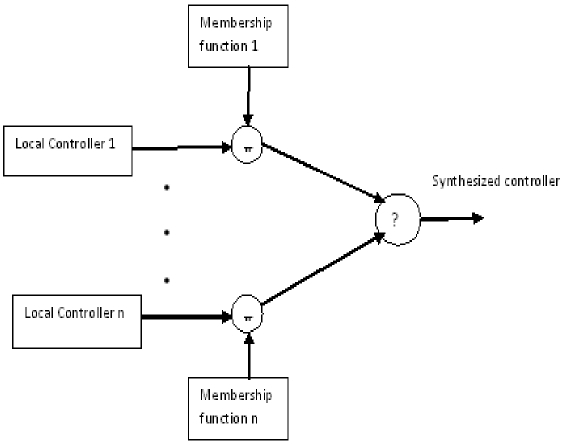

Figure 1. Heterogeneous control law

V. Controller Design Techniques

Since power system are highly non-linear and the operating conditions can vary over a wide range, the conventional PSS (CPSS) performance is degraded when the operating point changes from one to another because of fixed parameters of stabilizers.

Metaheuristic optimization technique like GA, Tabu search, simulated annealing, bacteria foraging, particle swarm optimization.

A. Power system damping controller structure

Power System Stabilizer model consists of:

1. Gain block
2. Washout block
3. Phase compensation block

The input to PSS is rotor speed deviation, output is auxiliary excitation signal given to the generator excitation system.

$$\left[\frac{\Delta U}{\Delta w}\right] = Ks\left[\frac{(1+sT1)}{(1+sT2)}\right]\left[\frac{(sTw)}{(1+sTw)}\right]$$

K_s- PSS gain

T_1, T_2 – PSS time constant

Signal washout function is a high pass filter which removes DC signals. The washout time is in the range of 1-20 sec

Eg. T_w = 15 sec

Eigen value based objective function

$$[J] = Max\{Re[\lambda i]\},\ (\lambda i)\epsilon(\lambda\tau)$$

Where (λi) belongs to the group of electromechanical mode Eigen values $(\lambda\tau)$.

B. Fuzzy controller based design

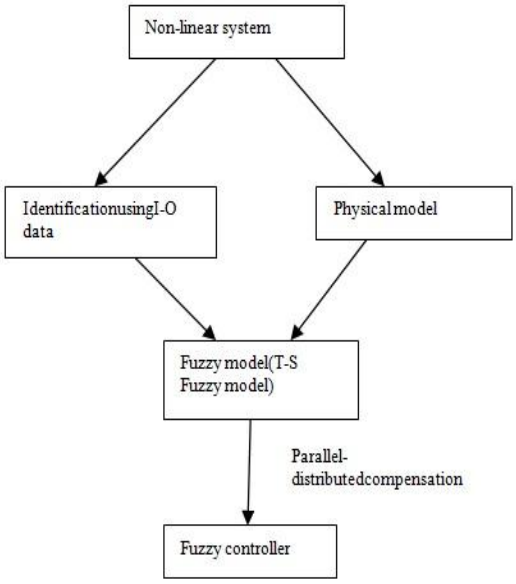

Figure.2 Fuzzy model-based fuzzy control designs

Table 1.Comparisons of different control designs

	Work Range	Simple	Stability
Linear	$\left(-\frac{\pi}{4}\frac{\pi}{4}\right)$	Yes	Local
Non-linear	$\left(-\frac{\pi}{2}\frac{\pi}{2}\right)$	No	Non-local
Fuzzy PDC	$(-\pi\pi)$	No	Non-local

A properly designed voltage regulating system can increase the steady state stability limit of a synchronous machine by a considerable amount.Fast regulator and exciter action and low transient reactance are desirable. The amplification factor of the regulating system must be co-ordinated properly with the machine and system constants are made as large as possible amortisseur windings have little effect on the possible gain in power limit. For maximum gain in power limit, a regulator with broad regulation and rapid response should be used.

C. FLC based on GA

The design employs Sugeno type fuzzy controllers as parameters can be manipulated using GA.Single and two inputs fuzzy controllers are used. The GA manipulates all parameters of the fuzzy controller to find the optimum solution.

Genetic Algorithm (GA) are global, parallel, stochastic search methods founded on Darwinian evolutionary principles. During the last decade GA's have been applied in a variety of areas, with varying degrees of success within each. GA exhibit considerable robustness in problem domain that is not conducive to formal, rigorous, classical analysis. The computational complexity of the GA has proved to be the chief obstruction to real time applications. Hence majority of the applications that use GA's are by nature off-line.

Commonly GA's have been used to optimize both structure and parameter values for both controllers and plant models. Normally Takagi-Sugeno (TS) fuzzy system are employed for control based on GA trying to optimize the parameters of the fuzzy controller.Inputs of the GA will be encoded then cross-over and mutation will be carried out on the population to finally change the centers and variances of the Gaussian membership functions of Sugeno fuzzy controller. The resulting controller will be capable of guiding the system to the desired characteristic with permissible value of error.

After fuzzy controller has been designed, its parameters should be manipulated by G.A, this algorithm should be able to optimize centers, variances and coefficients.

D. Robust controller design

When the parameters in the power system are known, we can design a DFL control law to linearize the plant. But when large sudden fault occurs the reactance of the transmission line x_L changes a lot. These changes are treated as parametric uncertainity. Hinfinity control is closely associated with many robustness problems such as sensitivity minimization and stabilization of uncertain systems. However when there is parameter uncertainity in plant modeling, no robust behavior on Hinfinity performance along with stability can be guaranteed by standard H ∞ control method.

VI. Mathematical Modelling Of The System

The following abbreviations are used while designing the model:

$\Delta\delta(t) = \delta(t) - \delta_0$

$\delta(t)$ = power angle of the generator

δ_0 = power angle of the generator at the operating point;

ω(t) = the relative speed of the generator

$\Delta Pe = Pe(t) - Pm$

Pm= mechanical input power

Pe =active electric power delivered by the generator;

ω_0 = synchronous machine speed; $\omega_0 = 2\pi f_0$

D= per unit damping constant

H = per unit inertia constant

Eq'(t) = the transient emf in the quadrature axis

$E_f(t)$ = the equivalent emf in the excitation coil;

Tdo= the direct axis transient short circuit time;

Qe(t) = the reactive power

If(t) = the excitation current

Iq(t) = the quadrature axis current;

Vt(t) = the generator terminal voltage;

Kc= the gain of the excitation amplifier;

Uf(t)= the input of the SCR amplifier of the generator

$x_{ds} = x_T + \frac{1}{2}x_L + x_d$;

$x`_{ds} = x_T + \frac{1}{2}x_L + x_d`$;

x_T= reactance of the transformer

x_d = direct axis reactance

x_L = the reactance of transmission line;

$x_s = x_T + \frac{1}{2}x_L$

x_{ed} = the mutual reactance between the excitation coil and the stator coil;

V_s = the infinite bus voltage;

Mechanical equation:

$$\Delta\dot{\delta}(t) = \omega(t) \qquad (1)$$

$$\dot{\omega}(t) = \frac{-D}{H}\omega(t) - \frac{\omega_0}{H}\Delta P_e(t) \qquad (2)$$

Generator Electrical Dynamics:

$$\dot{E}q(t) = \frac{1}{T_{do}}(E_f(t) - E_q(t)) \qquad (3)$$

Electrical Equations:

$$E_q(t) = \frac{x_{ds}}{x_{ds'}}E_q'(t) - \frac{x_d - x_d'}{x'_{ds}}V_s cos\delta(t) \qquad (4)$$

$$E_f(t) = K_c u_f(t) \qquad (5)$$

$$P_e(t) = \frac{V_s E_q(t)}{x_{ds}} sin\delta(t) \qquad (6)$$

$$I_q(t) = \frac{V_s}{x_{ds}} sin\delta(t) = \frac{P_e(t)}{x_{ad} I_f(t)} \qquad (7)$$

$$Q_e(t) = \frac{V_s}{x_{ds}}E_q(t)cos\delta(t) - \frac{V_s^2}{x_{ds}} \qquad (8)$$

$$E_q(t) = x_{ad} I_f(t) \qquad (9)$$

$$V(t) = \frac{1}{x_{ds}}\{x_s^2 E_q^2(t) + V_s^2 x_d^2 + 2x_s x_d x_{ds} P_e(t) cot\delta(t)\}^{1/2} \qquad (10)$$

A. Non-linear controller design for the power system

The DFL technique [8] is very useful method for power system non-linear controller design. By employing a non-linear feedback compensating law, a non-linear system can be directly transformed to a system whose closed loop dynamics are linear over a very wide range.

To design a non-linear controller for the power system, since $E_q'(t)$ is physically un-measurable, we eliminate $E_q'(t)$ by differentiating equation (6) and using (1) to (6)

Equation (6) is

$$P_e(t) = \frac{V_s E_q(t)}{x_{ds}} sin\delta(t)$$

$$\frac{dP_e(t)}{dt} = \frac{V_s}{x_{ds}}E_q(t)cos\delta(t)\dot{\delta}(t) + \frac{V_s}{x_{ds}}\dot{E}_q(t)sin\delta(t)$$

$$= \frac{V_s}{x_{ds}}E_q(t)cos\delta(t)\omega(t) + \frac{V_s}{x_{ds}}sin\delta(t)\left[\frac{x_{ds}}{x'_{ds}}\dot{E}_q'(t) + \frac{x_d - x_d'}{x'_{ds}}V_s sin\delta(t)\omega(t)\right]$$

$$= \frac{V_s}{x_{ds}}E_q(t)cos\delta(t)\omega(t) + \frac{V_s}{x_{ds}}sin\delta(t)\left[\frac{x_{ds}}{x'_{ds}}\frac{1}{T_{do}}(E_f(t) - E_q(t)) + \frac{x_d - x_d'}{x'_{ds}}V_s sin\delta(t)\omega(t)\right]$$

We have $T'_{do} = \frac{x'_{ds}}{x_{ds}} T_{do}$

$$= -\frac{1}{T_{do}'} P_e(t) + \frac{1}{T_{do}'} \left\{ \frac{V_s}{x_{ds}} sin\delta(t)[K_c u_f(t) + T_{do}(x_d - x_d') \frac{V_s}{x_{ds}} sin\delta(t)\omega(t)] + T'_{do} \frac{V_s}{x_{ds}} E_q(t) cos\delta(t)\omega(t) \right\}$$

$$= -\frac{1}{T_{do}'} \Delta P_e(t) + \frac{1}{T_{do}'} \left\{ \frac{V_s}{x_{ds}} sin\delta(t)[K_c u_f(t) + T_{do}(x_d - x_d') \frac{V_s}{x_{ds}} sin\delta(t)\omega(t)] + T'_{do} \frac{V_s E_q(t)}{x_{ds}} cos\delta(t)\omega(t) - P_m \right\},$$

As $\Delta P_e(t) = P_e(t) - P_m$

Therefore

$\Delta P_e^{\cdot}(t) = -\frac{1}{T_{do}'}\Delta P_e(t) + \frac{1}{T_{do}'} v_f(t)$

Where

$v_f = \frac{V_s sin\delta(t)}{x_{ds}} [K_c u_f(t) + T_{do}(x_d - x_d') \frac{V_s}{x_{ds}} sin\delta(t)\omega(t)] + T'_{do} \frac{V_s E_q(t)}{x_{ds}} cos\delta(t)\omega(t) - P_m$

or,

$v_f(t) = I_q(t) [K_c u_f(t) + T_{do}(x_d - x_d') \frac{V_s}{x_{ds}} sin\delta(t)\omega(t)] + T'_{do} \left[Q_e(t) + \frac{V_s^2}{x_{ds}}\right] \omega(t) - P_m$

The model (1) to (3) is therefore linearized,

The linearized model is

$$\Delta\dot{\delta}(t) = \omega(t) \quad (11)$$

$$\dot{\omega}(t) = \frac{-D}{H}\omega(t) - \frac{\omega_0}{H}\Delta P_e(t) \quad (12)$$

$$\Delta P_e^{\cdot}(t) = -\frac{1}{T_{do}'}\Delta P_e(t) + \frac{1}{T_{do}'} v_f(t) \quad (13)$$

where $v_f(t)$ is the new input.

After linearization, we can employ linear control theory, such as LQ-optimal control theory, to design a feedback law

$$v_f(t) = f(\delta(t), \omega(t), P_e(t)) \quad (14)$$

To give the desired stability and performance properties, $v_f(t)$ and $P_e(t)$ are the control inputs.

The DFL-LQ optimal controller [10] and the DFL voltage regulator can be obtained by use of DFL techniques and linear optimal control theory.

VII. Simulation Results

The variables $V_t(t)$, w(t) and $P_e(t)$ are to be tracked to their prefault steady values after a fault occurs. An effective feedback control law employed here is

$$v_f(t) = 19.3(\partial(t) - \partial_0) + 6.43(\omega(t)) - 47.6(P_e(t) - P_{m0}) + P_{m0} \quad \textbf{(15)}$$

By employing the control law (15) on the DFL compensated system, the simulation results were obtained for power angle and terminal voltage.

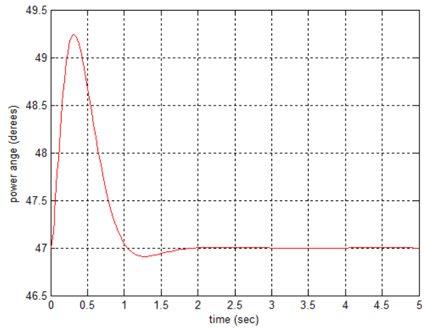

Figure 3a. DFL-LQ optimal controller (Power angle)

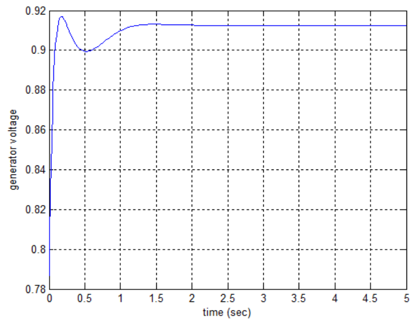

Figure3b. DFL-LQ optimal controller(voltage response)

An electric power plant described in [10], is taken with operating points:

$\delta_0 = 47^0$, ,P_{mo}= 0.45 p.u. and V_{t0}= 1.0 p.u.

The fault considered here is permanent fault, which occurs at 0.1 sec and the fault is removed by opening the breaker of the faulted line at 0.25 sec. The simulation results show that using only DFL-LQ optimal controller or DFL voltage regulator, we cannot achieve both good transient response and good post-fault performances. If we can combine both types of controller then better result is expected. This could be done by the design of DFL co-ordinated controller.

VIII. Conclusion

The linearized mathematical model is obtained for the power system. This model can be utilized for designing different types of controllers for stabilizing the parameters of the power system. Here in this paper, the approach of direct feedback linearization(DFL) is used and the simulation results were obtained for DFL-LQ optimal controller. The new DFL coordinated controller can achieve better transient stability results than the excitation controller irrespective of the operating point of the system and the fault sequence.

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References

[1] Machowski, J.; Bialek, J.W.; Robak, S.; Bumby, J.R.; Excitation control system for use with synchronous generators, IEE Proceedings Generation, Transmission and Distribution, Sep 1998 Vol: 145, p.537 - 546 .

[2] Chapman, J.W.; Ilic, M.D.; King, C.A.; Eng, L.; Kaufman, H.; Stabilizing a multimachine power system via decentralized feedback linearizing excitation control, IEEE Transactions on Power Systems,Aug 1993, Vol. 8 p. 830 - 839 .

[3] Bazanella, A.S.; e Silva, A.S.; Kokotovic, P.V.; Lyapunov design of excitation control for synchronous machines, Proceedings of the 36th IEEE Conference on Decision and Control, 1997., p: 211 - 216 vol.1

[4] Gan D.; Qu Z.; Cai H., Multi machine power system excitation control design via theories of feedback linearization control and nonlinear robust control , Int. Journal of Systems Science, Volume 31, Number 4, 1 April 2000 , pp. 519-527.

[5] Sun, C.; Zhao, Z.; Sun, Y.; Lu, Q.; Design of nonlinear robust excitation control for multimachine power systems, IEE Proceedings- Generation, Transmission and Distribution, May1996,Vol.143,p.253-257.

[6] Schaefer, R.C.; Excitation control of the synchronous motor, IEEE Transactions on Industry Applications,May/Jun 199 ,Vol: 35 Issue:3

[7] Handschin, E.; Hoffmann, W.; Reyer, F.; Stephanblome, T.; Schlucking, U.; Westermann, D.; Ahmed, S.S.; A new method of excitation control based on fuzzy set theory, : IEEE Transactions on Power systems, Feb 1994, vol.9,p.533-539

[8] Gao, L, Chen, L, Fan, Y and Ma, HW ‘ A nonlinear control design for power systems’ Automatica, vol 28, no 5 (1992) pp. 975-979.

[9] Kitauchi, Y.; Taniguchi, H.; Experimental verification of fuzzy excitation control system for multi-machine power system, IEEE Transactions on Energy Conversion, +Kitauchi, Y.+Ta Mar 1997, Vol. 12, p. 94 - 99 .

[10] Wang Y, David J Hill, Richard H. Middleton, transient stability enhancement and regulation of power systems,IEEE Trans.OnPowerSystems,vol.8,no.2,may1993.

[11] Wei-Der Changand Shun-PengShih,PID controller design of nonlinear systems using an improved particle swarm optimization approach, Jan 2010.

[12] Chao-Chung Peng,Chieh-Li Chen, Dynamic controller design for a class of nonlinear uncertain systems subjected to time-varying disturbance,Nonlinear Dyn (2009) 57: 411–423, Nov 2008.

[13] Y. Guo, Member, IEEE, David J. Hill, Fellow, IEEE & Y. Wang, “Global Transient Stability and voltage regulation for power system”, IEEE Trans. On Power Systems, vol.16, no. 4, nov. 2001.