# Different Approaches for the Design of Stabilizing Controller for Non-Linear Power Systems

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## ABSTRACT

The objective of this paper is to study the behavior of the non-linear power systems. The problem of designing controllers for non-linear power system is taken here. The non-linear controller is designed using Direct Feedback Linearization (DFL) technique. The simulation has been carried out taking different values of initial power angles and results were obtained for power angle and terminal voltage. In case of fault in the power system, power angle and the terminal voltage are the parameters which are to be monitored. To overcome the demerits of DFL controller, co-ordinated controller is proposed.

## Keywords

Stabilizer, FLC (fuzzy logic controller), DFL (direct feedback linearization), GA (Genetic Algorithm).

## 1. INTRODUCTION

The problem of designing controller to prevent loss of synchronism of an electric power system due to large sudden fault is of great importance in power system problem. Loss of synchronism may cause or lead to transient instability and the change in terminal voltage. The usual stabilizers designed on approximate linearization models are not adequate for large disturbances. When a large fault occurs, the behavior of the system changes a lot and in many case a linear controller cannot maintain adequate stability. So, to overcome this drawback, several researchers have considered employing nonlinear control theory. Most of the nonlinear controller designs for power system are based on differential geometry approach. Here direct feedback linearization (DFL) approach has been used to design voltage regulator for the power system. The concept of non-linear control theory is considered 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 [6]. 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 [8] is preferred, as control of complex system over a wide range of operating conditions can be achieved for a set of control objective.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 changes a lot. For this type of case robust controller design approach is used. The mathematical formulation for this is done. The simulationsare done by taking different initial power angle and results were obtained for power angle and terminal voltage..

## 2. NON-LINEAR POWER 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 the real world problem. Although linear control has been a mature subject with a variety of powerful methods and a long history of successful industrial applications, it is having limitation that it relies on the key assumption of small range of operation for the linear model to be valid. Whereas for real world systems, large ranges of operation and demanding specifications are required by modern technology such as high performance power system problem which typically involve non-linear dynamics. Therefore the need of non-linear control arises for solving real world problem.As an example of real world complex systems, power systems present a rich source of control problems of practical importance. Power systems are non-linear and have subsystems within a large network. For multi-machine power systems, each generator and its associated control can be viewed as a subsystem, and the transmission network constructs the interconnection through power transfer. The large geographical distances between generators make the transfer of information of system operating inconvenient. Here decentralized control is typically required which employs local feedback signals for ensuring overall system stability. The field of nonlinear control for complex systems is open for continued research and development of design methodologies. The non-linear controller is designed using direct feedback linearization technique. The model obtained by carrying out the linearization is utilized for carrying out the simulation.

## 3. CONTROLLERS

PI and PID controllers are widely utilized in industries. The simplicity and ability of these controllers are the most important advantage and many methods are given in the literature to obtain their parameters.
A unified approach for the design of PI and PID controllers, based on constant –M circles of Nichols chart was presented. The controller parameters are tuned such that the open loop

curve follows the corresponding constant-M circle using predetermined maximum peak resonance. This approach gives the possibility of having the desirable maximum overshoot, the phase and gain margins and the bandwidth of the closed loop system simultaneously.

The main design is first given for PI controller and then easily extended to a PID one.

The process transfer function is

$$G_P(s) = \frac{K_P(1 - T_0 s)\, e^{-\theta s}}{(1 + T_1 s)(1 + T_2 s)}$$

Where θ is the time delay and is considered to be zero for the design of LFC.

The PI controller is then given by

$$G_C(s) = \frac{K_c(1 + T_i s)}{T_i}$$

## 3.1 Fuzzy Controller based design

As fuzzy theory is developed, the research on fuzzy modeling, which describes a real system very successfully with its nonlinear property, is conducted actively. Generally fuzzy models [9] have advantages of excellent capability to describe a given system.

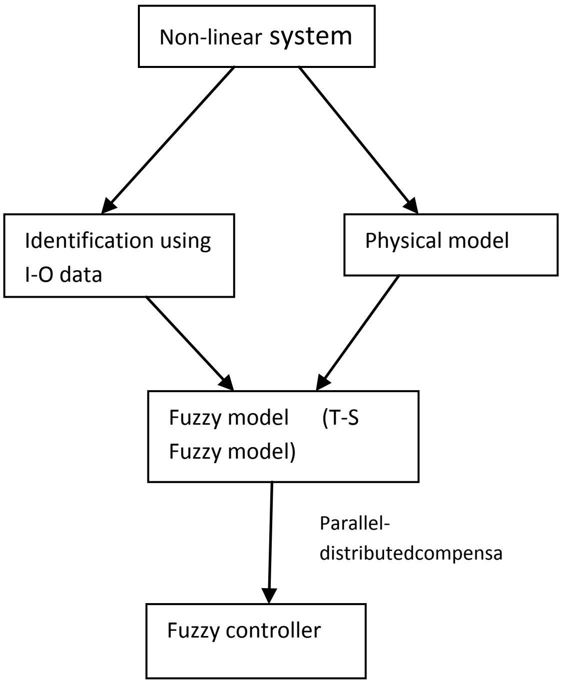


**Fig 1: . Fuzzy model-based fuzzy control designs**

Fig. 1 shows the fuzzy model based control design.Afterfuzzy controller has been designed, its parameters should be manipulated by G.A, this algorithm should be able to optimize centers, variances and coefficients.

## 3.2 Fuzzy Logic Controller based on GA

Updating all the parameters of the fuzzy controller using Genetic Algorithm (GA) will led to a better response than that from previously reported approaches in which parameters of only Sugeno consequents were updated.

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 applications that use GA's are by nature off-line.

The design employs Sugeno type fuzzy controllers as parameters can be manipulated using GA. Single and two inputs fuzzy controllers are used, GA manipulates all parameters of the fuzzy controller to find the optimum solution. The overall average error between the desired and the actual output is to be fed to the GA as a fitness value for evaluating the system. 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.

# 4. MATHEMATICAL MODELLING OF THE SYSTEM

We know that power system model is non-linear. We discuss design principle using DFL technique to design non-linear controllers for a power system. By using this technique linearized model has been obtained

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:

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

Electrical Equations:

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

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

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

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

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

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

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

## 4.1 Non-linear controller design for the power system

The non-linear controller consists of a novel dynamic DFL compensator through the excitation loop to cancel the non-linearities and interactions among generators and a robust feedbackcontroller to guarantee the asymptotes stability of the DFL compensation system considering the effects of dynamic output feedback and plant parameteric uncertainties. The non-linear controller can guarantee the stability of the multi machine non-linear power systems within a whole operating region for all admissible parameters.

The DFL technique [5] 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 $P_e(t) = \frac{V_s E_q(t)}{x_{ds}} sin\delta(t)$

Differentiating the above equation with respect to time and doing the required assumptions, we get the following three equations:

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

We have $T_{do}^{'} = \frac{x^{`}_{ds}}{x_{ds}} T_{do}$

where,

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

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

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

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

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

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

## 4.2 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 uncertainties.

Considering the uncertainty in $x_L$, the plant model becomes

$$\Delta\dot{\partial}(t) = \omega(t)$$

$$\dot{\omega}(t) = -\frac{D}{H}\omega(t) - \frac{\omega o}{H}\Delta Pe(t)$$

$$\Delta\dot{P}e(t) = -\left[\frac{1}{T_{do}^{'}} + \mu(t)\right]\Delta Pe(t) + \left[\frac{1}{T_{do}^{'}} + \mu(t)\right]\left[k_c I_q(t) u_f(t) + T_{do}(x_d - x_d^{'}) I_q^2(t)\omega(t) + (T_{do}^{'} + \Delta T_{do}^{'}) Q_e(t)\omega(t) + (T_{do}^{'} + \Delta T_{do}^{'})\omega(t) - P_m\right]$$

where $\mu(t) = \frac{1}{T_{do}^{'}} - \frac{1}{T_{do}^{'} + \Delta T_{do}^{'}}$ ; $\Delta T_{do}^{'} = \frac{x_{ds}^{'} + \Delta xL}{x_{ds} + \Delta xL} T_{do}^{'}$

$\Delta xL$ denotes the uncertainty in xL, and $T_{do}^{'} = \frac{V_s^2}{x_{ds}} T_{do}^{'}$

Using

$$v_f(t) = \left[k_c I_q(t) u_f(t) + T_{do}(x_d - x_d^{'}) I_q^2(t)\omega(t) + (T_{do}^{'}) Q_e(t)\omega(t) + (T_{do}^{'})\omega(t) - P_m\right]$$

We have

$$\Delta\dot{\partial}(t) = \omega(t) \quad (14)$$

$$\dot{\omega}(t) = -\frac{D}{H}\omega(t) - \frac{\omega o}{H}\Delta Pe(t) \quad (15)$$

$$\Delta\dot{P}e(t) = -\left[\frac{1}{T_{do}^{'}} + \mu(t)\right]\Delta Pe(t) + \left[\frac{1}{T_{do}^{'}} + \mu(t)\right] v_f(t) + \left[\frac{1}{T_{do}^{'}} + \mu(t)\right]\Delta T_{do}^{'} Q_e(t)\omega(t) + \left[\frac{1}{T_{do}^{'}} + \mu(t)\right]\Delta T_{do}^{'}\omega(t) \quad (16)$$

Choosing the states as $x^T(t) = [\Delta\partial(t),\ \omega(t), \Delta Pe(t)]$, then the equations (a), (b), (c) become

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)\, v_f(t) \quad (17)$$

Where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{D}{H} & -\frac{wo}{H} \\ 0 & 0 & -\frac{1}{T_{do}^{'}} \end{bmatrix};\ \Delta A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \beta & -\mu(t) \end{bmatrix}$$

$$B = \left[0,\ 0\ ,\ \frac{1}{T_{do}^{'}}\right]^T;\ \Delta B = [0,\ 0\ , \mu(t)\ \ ]^T;$$

$$\beta = \left[\frac{1}{T_{do}^{'}} + \mu(t)\right][\ \Delta T_{do}^{'} + \Delta T_{do}^{'} Q_e(t)]$$

$\mu(t),\ \Delta T_{do}^{'}$ are bounded, so is $\beta$.

The power system under a symmetrical 3-phase short circuit fault is transiently stable via a non-linear DFL control law

$$u_f(t) = \frac{1}{k_c I_q(t)}\left\{v_f(t) - T_{do}^{'} Q_e(t) w(t) - T_{do}^{'} w(t) - (x_d - x_d^{'}) T_{do} w(t) I_q^2(t) + P_m\right\} \text{ (18)}$$

and $v_f(t) = -R^{-1}(B^T P + E_2^T E_1)x(t)$ (19)

if and only if there exists a stabilizing solution P ≥ 0 for the Riccati equation. The power system problem is transiently stable via the control law (18) and (19) means that the power system under a symmetrical 3-phase short circuit fault can avoid the loss of synchronism. Moreover in the post fault period we have

$$\lim_{t\to\infty}|\Delta\partial(t)| = 0$$

$$\lim_{t\to\infty}|w(t)| = 0$$

$$\lim_{t\to\infty}|\Delta P_e(t)| = 0$$

From [3] and [4], we know that a linear plant in the form derived is quadratically stable if and only if there exists a stabilizing solution P≥0 for the Riccati equation. The suitable feedback law is given by

$$v_f(t) = -R^{-1}(B^T P + E_2^T E_1)x(t)$$

In many cases, the generator terminal voltage is not the same in the postfault state as in the prefault state, which is undesirable in practice. To achieve the postfault regulation of the generator terminal voltage $V_t(t)$, we employ the robust controller proposed in the section to enhance the transient stability of the power system and the DFL excitation controller design [6], to improve the postfault performance of the generator terminal voltage so that we can achieve

$$\lim_{t\to\infty} |\Delta V_t(t)| = 0$$

The design procedure is as follow:

step1: the fault occurs at t= t0 and the robust control law is

$$u_f(t) = \frac{1}{k_c I_q(t)} \{v_{f1}(t) - T'_{do} Q_e(t) w(t) - T'_{do} w(t) - (x_d - x'_d) T_{do} w(t) I_q^2(t) + P_m\}$$

and$v_{f1}(t) = -k_\partial * \Delta\delta(t) - k_w * w(t) - k_p * \Delta P_e(t)$

where$[k_\partial,\ k_w,\ k_p] = R^{-1}(B^T P + E_2^T E_1)$

step2: at t=t1 the feedback law is switched to

$$u_f(t) = \frac{1}{k_c I_q(t)} \{v_{f2}(t) - T'_{do} Q_e(t) w(t) - T'_{do} w(t) - (x_d - x'_d) T_{do} w(t) I_q^2(t) + P_m\}$$

and $v_{f2}(t) = -k_{v1} * \Delta V_t(t) - k_{w1} * w(t) - k_{p1} * \Delta P_e(t)$

## 5. SIMULATION RESULTS

In this section we show the simulation results, how transient stability improvement and postfault performance of the system can be achieved by employing DFL controller. The simulations were carried out the initial angle 72 with mechanical input power of 0.9 p.u. Fig.2 and 3 shows the power angle and terminal voltage response. Next the simulation is carried out for mechanical power of 0.45 p.u and different power angles of 42, 47 and 52 degrees.

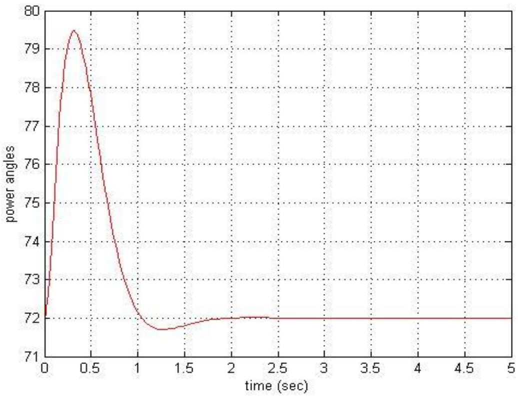


**Fig 2:Power angle response for initial angle 72 and Mechanical power, Pm0=0.9**

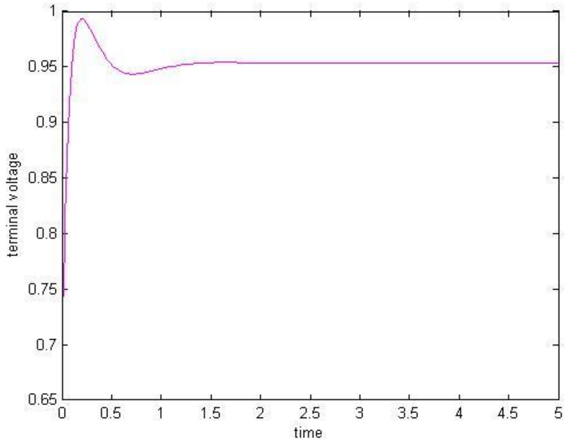


**Fig 3:Terminal voltage for initial angle 72 and Mechanical power, Pm0=0.9**

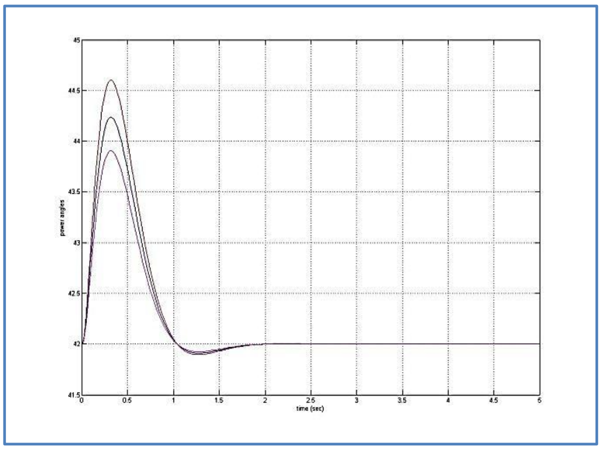

**Fig 4:Power angle response for initial angles 42, 47 and 52 and Mechanical power, Pm0=0.45**

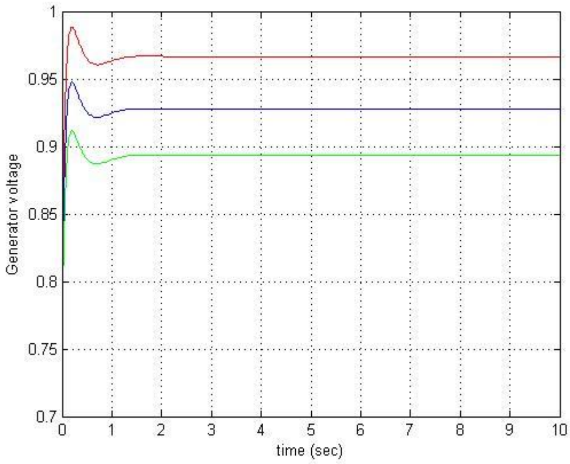


**Fig 5:Terminal voltage for initial angles 42, 47 and 52 and Mechanical power, Pm0=0.45**

# 6. 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. In this paper, the approach of direct feedback linearization (DFL) is used for the design of controller. Next the formulation for the design of robust controller was carried out. From the analysis in this paper, we see that to construct DFL controllers we need to know the parameter $x_L$ in the transient period. The simulation is carried out for two different values of mechanical power.As the DFL controller can not keep the system transiently stable in all fault locations so a nonlinear co-ordinated controller is designed to overcome this difficulty. The coordinated controller could 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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