On Structure Preserving Control of Power Systems

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Abstract—Control designs based on Geometric Feedback Linearization (GFL) and the so-called Direct Feedback Linearization (DFL) technique for power system stability control are presented and compared. The physical integrity of the state space description of a classical single machine infinite bus (SMIB) power system model is preserved with the application of DFL in designing a robust excitation-voltage regulating control system. Firstly, the conflict of simultaneous angle stabilization and voltage regulation is studied. Then linear techniques on the linearized system are applied to design stabilizing feedback gain coefficients for the nonlinear excitation loop. It is shown that GFL results in a coordinate mapping for which the feedback loop stabilizes the angle while the DFL is seen to offer considerable flexibility in designing controllers for all relevant variables. The results emphasize the difference between geometric and direct feedback approaches and provide insights towards nonlinear control theory applications in power systems.

I. INTRODUCTION

System stability is the most important issue for power systems; if stability is lost, network collapse may occur with devastating economical losses and power grid damages. Considerable attention has been given in the literature to excitation control system design and its performance characteristics in enhancing power system stability. Transient (angle) stability and voltage regulation are of major concern in large disturbance dynamic performance assessment of power systems. The basic function of the excitation system is to supply and automatically adjust the field current of the synchronous generator to regulate the terminal voltage. The power system stabilizer (PSS) provides the supplementary signal through the excitation automatic voltage regulator (AVR) loop which damps the power oscillations. The common feature of AVR/PSS controllers is that they are typically based on models established by approximate linearization of the nonlinear equations of a power system at a certain operating point. These kinds of controllers suffer performance degeneracy when operating conditions change due to the highly nonlinear inherent characteristics of power systems [1], [2].

To assess the performance of the excitation system in enhancing stability, the design criteria must take into account operation under realistic power system disturbances and hence the nonlinearities of the plant must be included [3].

The basic foundation of geometric feedback linearization (GFL) arose in control theory and is presented in [4]. A GFL design produces a static state feedback loop and a special nonlinear coordinate change. This is a diffeomorphism mapping which typically changes some physical variables to non physical or unimportant ones corresponding to transformation to a strict canonical Brunovsky form. This form lacks physical integrity and flexibility for control of variables other than angle. In [2], [5], a GFL has been applied to a third order nonlinear power system model to design a nonlinear excitation control loop.

The DFL approach arose from practical concerns, related to power system nonlinearity [6] and was subsequently developed to deal with a number of power system control issues, see [7]–[11]. The theoretical basis is simpler than for GFL. It just uses the Implicit Function Theorem to selectively eliminate specific system nonlinearities.

In this paper, we compare the application of GFL and DFL techniques for the design of power system control. An application of the geometric coordinate mapping changes the original nonlinear state model to a linear and controllable form for which a linear controller is easily obtained. The resulting state feedback achieves angle stability and fails to regulate the terminal voltage of a SMIB power system model. The DFL technique, on the other hand, is used to linearize the plant model over a very wide range. To overcome the effects of parametric uncertainties a robust disturbance attenuating control technique [12], [13] is considered to design a robust nonlinear excitation control for a power system which regulates voltage and angle.

By examining a root locus of a simple linear plant model, an important aspect of power system behavior is observed and used to explain a basic conflict in excitation control of power systems, namely the dynamic conflict between simultaneous generator synchronization and voltage regulation. This knowledge is then used to design an appropriate stability enhancing DFL excitation control structure whose design avoids the specified geometric nonlinear coordinate change and preserves the physical state description of the original plant model.

II. POWER SYSTEM MODEL

The system equations for a large disturbance study are nonlinear. A power system is described by a set of coupled nonlinear DAE of the form

\[
\begin{align*}
\dot{x} &= f(x, \rho, \pi) & f : \mathbb{R}^{n+m+r} &\rightarrow \mathbb{R}^n \\
0 &= \xi(x, \rho, \pi) & \xi : \mathbb{R}^{n+m+r} &\rightarrow \mathbb{R}^m
\end{align*}
\] (1)
where \( x \in X \subset \mathbb{R}^n \), \( \xi \in \Xi \subset \mathbb{R}^m \) and \( \pi \in \Pi \subset \mathbb{R}^r \). In the state space \( X \times \Xi \), \( x \) refers to dynamic state variables and \( \rho \) represents algebraic state variables. The parameters \( \pi \) define a specific system configuration and the operating condition. Typical dynamic state variables are the time dependent generator voltages, rotor angles, controller states; algebraic variables are the transmission line power flow variables (the bus voltage and angles). The dynamics of the generator, control devices, load dynamics, together define the \( f \) equation. A power system stability control goal is to find a feedback loop that satisfies the following condition

\[ \lim_{t \to \infty} (x - x_\ast) = 0 \]  

(2)

where \( x_\ast \) represents desirable values. However the plant model is sometimes transformed such that the developed feedback controller minimizes the error in mapped variables \( z \):

\[ \lim_{t \to \infty} (z - z_\ast) = 0 \]  

(3)

In this case, it is necessary to analyze the impact on asymptotic behavior of \( x \).

We consider a SMIB power system model where the generator is connected to a large network via a transformer and two parallel transmission lines. The third order single axis machine model is found to be a sufficient representation used for the design of excitation control systems \([1],[14]\). The generator is now represented by the transient emf \( e_i' \) behind the transient reactance \( x_d \) defined by the following electromechanical equations \([9]\):

\[ \dot{\delta} = \frac{\omega(t) - \omega_0}{2H} - \frac{\omega_0}{2H} (P_e - P_m) \]  

(4)

\[ \dot{\omega} = \frac{D}{2H} (\omega(t) - \omega_0) - \frac{\omega_0}{2H} (P_e - P_m) \]  

(5)

\[ e_i' = \frac{1}{T_{do}} (E_f - \Delta x_d i_d - e_i') \]  

(6)

and the corresponding electrical equations

\[ E_f = k_e u f(t) \]  

(7)

\[ P_e(t) = \frac{e_i' V_{\infty} \sin \delta(t)}{x_d \Sigma} \]  

(8)

\[ i_d(t) = \frac{e_i' - V_{\infty} \cos \delta(t)}{x_d \Sigma} \]  

(9)

\[ i_q(t) = \frac{V_{\infty} \sin \delta(t)}{x_d \Sigma} \]  

(10)

\[ Q_e(t) = \frac{e_i' V_{\infty} \cos \delta(t) - V_{\infty}^2}{x_d \Sigma} \]  

(11)

\[ V_{L}(t) = \sqrt{e_i'^2 - 2 e_i' x_d i_d + x_d^2 (i_d^2 + i_q^2)} \]  

(12)

where \( \Delta x_d = x_d - x_d' \). The parameters of the system under consideration are: \( \omega_0 = 100 \text{r} / \text{min}; D = 5; H = 4; T_{do} = 6.9; x_L = 0.127; x_d = 1.863; x_d' = 0.657; x_L = 0.4853 \); and the governor is assumed to be slow acting. The physical limit of the plant is taken as \( \text{max} | E_{f_k} | = 6 \). The equivalent system reactance of the whole transmission line is \( x_d \Sigma = x_d + x_L + x_1 \). The fault we consider is a symmetrical 3 phase-to-earth fault that occurs on one of the transmission lines (i.e. fault sequence 1), and a step increase in mechanical input power \( P_m \) at time \( t = t_s \) (fault sequence 2). \( \lambda_f \) is the fraction of the faulted line to the left of the fault location. If \( \lambda_f = 0 \), the fault is at the higher voltage transformer bus, \( \lambda_f = 0.5 \) places the fault in the middle of the line and so on.

III. Linear Case

In this section, we briefly analyze some complexities in the design for voltage regulation and rotor angle control using the familiar linear representation. Using (4)-(12), and assuming a slow acting governor action, the approximately linearized state space description of a simple power plant model is obtained, i.e. \( \dot{x} = Ax + Bu \) such that

\[ A = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{\omega_0}{2H} (Q_e + \frac{V_{\infty}^2}{x_d \Sigma}) & -\frac{D}{2H} & -\frac{\omega_0}{2H} i_q \\ -\frac{1}{T_{do}} \Delta x_d q & 0 & -\frac{1}{T_{do}} (1 + \frac{\Delta x_d}{x_d \Sigma}) \end{bmatrix} \]  

(13)

where \( x = [\Delta \delta, \Delta \omega, \Delta e_i']^T \), the input \( u = \Delta E_f \) and the output \( y = C x \).

Consider the following SISO situations, i.e. \( y = \Delta \delta \), \( y = \Delta \omega \) and \( y = \Delta e_i' \). The corresponding transfer functions relate the input and output variables respectively:

\[ T_{1,2,3}(s) = \frac{N_{1,2,3}(s)}{(s + \beta_1)(s^2 + \beta_2 s + \beta_3)} \]  

(14)

and \( N_1 = -a_1, N_2 = -a_1 s, N_3 = a_2 s^2 + a_3 s + a_4 \) where \( \alpha \) and \( \beta \) represent values for a specific operating point or are directly known from the specified system parameters. It is the dynamic behavior of these values, together with the specified control matrix gains that govern the stability of the plant. The locus of the roots of the feedback system for the gain \( K \in [0, \infty) \) is particularly informative for exploring control issues in a simple power plant model \([14]\).

The inherent dynamic conflict of voltage regulation and transient stability can be further studied from the root locus characteristics for the input to output relationships given in (14), see Fig.1. It can be seen from Fig.1(a)-(Fig.1(b) that the system exhibits stabilizing properties only for a small gain \( K \) using \( \delta \) and \( \omega \), i.e. locus description of \( T_1(s) \) and \( T_2(s) \). Control of \( \delta \) and \( \omega \) in this situation will result in an unstable voltage mode and oscillatory mode respectively.

The proximity of pole-zero pairs in Fig.1(c), i.e. the approximate pole-zero cancellation, frees the voltage mode. In this case, voltage control may be simply enhanced by high gain linear feedback. Combining the feedback signals gives the state feedback form \( \Delta E_f = -k_1 \Delta \delta - k_2 \Delta \omega - k_3 \Delta e_i' \). Although this type of control is not suitable to be implemented for transient stability control directly since it is only valid locally around a specific operating point, it provides valuable insights of limitations and associated design constraints in power plant control.
A more detailed analysis of the detrimental effects of rotor oscillations on voltage mode is reported in [15], where the generator plus exciter model are taken in the following form

\[
\begin{align*}
\delta(s) &= P^{-1}(s)(K_{11}(s + \beta_{11})T_m(s) - K_{12}v_e(s)) \\
V_i(s) &= P^{-1}(s)(K_{21}(s + \beta_{21})T_m(s) \\
&\quad + K_{22}(s^2 + s\zeta_1\sigma_1 s + \omega_1^2)v_e(s))
\end{align*}
\]

such that \(P(s) = (s + \gamma_1)(s + \gamma_2)(s^2 + 2\zeta\omega_0 s + \omega_0^2)\) contains the open loop exciter, field and inertial modes. The inputs \(T_m\) and \(v_e\) represent mechanical torque and exciter voltage. The transfer function reveals the close proximity of zeros and poles. Shifting these poles to improve oscillations on \(\delta\) will expose the voltage mode. It has been shown in [10], that a terminal voltage controller should be combined with an angle stability type controller in the case of a large disturbance. Hence, proper coordination or tuning is needed to achieve satisfactory performance enhancing operation.

IV. NONLINEAR EXCITATION CONTROL DESIGN

This section details the design of a nonlinear excitation control based on the GFL and DFL techniques. The concept of feedback linearization is a very attractive method for designing stabilizing controllers for nonlinear systems. Exact linearization via the geometric approach is one of the most fundamental techniques in the field of nonlinear control [4]. The coordinate transformation employed by the GFL can be written \(z = \Phi(x), x = \Phi^{-1}(z)\) where the new variables are chosen to give a canonical structure to the linearized system. However the geometric approach often changes the physical variables to nonphysical or unimportant ones, and the control objectives become defined via a diffeomorphic transformation from \(x\) to \(z\). As it will be shown in the following section, the resulting state feedback achieves angle stability of a SMIB but fails to regulate the system voltage, causing unacceptable voltage profiles.

In order to preserve the original plant physical integrity, i.e. in the \([\delta, \omega, e_q]\) state space model, the DFL method is used. A full coordinate transformation is not necessary. Only selected variables are affected. The direct linearization technique offers considerable flexibility in designing nonlinear controllers. It uses the Implicit Function Theorem to selectively eliminate specific nonlinearities. This will be illustrated in Section IV(B). The proposed nonlinear DFL excitation controller achieves both voltage regulation and angle stability effectively.

A. GFL Excitation Controller

The GFL technique transforms a nonlinear system to a linear one for which a well known linear control design methods can be applied to obtain stabilizing static feedback gain coefficients. Given the nonlinear power system model with a stable equilibrium point \(x_0\), we find a \(C^\infty\) transformation \(\Phi(x)\) defined on \(\Theta_x\) of \(\mathbb{R}^3\) and scalar fields \(\alpha(x), \beta(x)\) such that \(v(x,u) = \alpha(x) + \beta(x)u, \beta(x) \neq 0 \quad \forall x \in \Theta_x\), and the new transformed state space has the form \(\dot{z} = Az + Bv\) where \(A\) and \(B\) are constant matrices and \((A,B)\) pair is controllable.

The transformation used for feedback linearization was developed in [4] and the details are not repeated here. For a complete GFL design procedure and its application to power systems, readers are referred to [2].

A power plant model (4)-(6) describes a normal affine nonlinear system

\[
\dot{x} = f(x) + g(x)u \quad x(0) = x_0
\]

where \(x = [\delta \quad \omega \quad e_q]^T, g(x) = [0 \quad 0 \quad \frac{1}{2J_{4w}}]^T\) and \(u = E_f\). A new state space is then defined as

\[
z = \Phi(x) = [\Phi_1(x), \Phi_2(x), \Phi_3(x)]^T = [z_1, z_2, z_3]^T
\]

It has been shown [16] that the locally invertible mapping \(\Phi\) must satisfy the following set of partial differential equations:

\[
\begin{align*}
\langle \frac{\partial \Phi_1}{\partial x}, g \rangle &= 0, \quad \langle \frac{\partial \Phi_2}{\partial x}, g \rangle &= 0 \\
\langle \frac{\partial \Phi_1}{\partial x}, f \rangle &= \Phi_2, \quad \langle \frac{\partial \Phi_2}{\partial x}, f \rangle &= \Phi_3 \\
\langle \frac{\partial \Phi_3}{\partial x}, f + ug \rangle &= v
\end{align*}
\]

where \(\langle \cdot, \cdot \rangle\) is the Euclidean inner product, and the linearizing control law is given by

\[
v = \langle \frac{\partial \Phi_3}{\partial x}, f \rangle + \langle \frac{\partial \Phi_3}{\partial x}, g \rangle u
\]
such that \( \frac{\partial \Phi}{\partial x} \neq 0 \) \( \forall x \in \Theta_x \). After some algebraic manipulation, the following linearizing state transformation is obtained: 
\[ z_1 = \Phi_1(x) = \delta, \quad z_2 = \Phi_2(x) = \delta, \quad z_3 = \Phi_3(x) = \delta. \]
The state equations of the GFL-ed system become
\[ \begin{align*}
\dot{z}_1 &= z_2 \\
\dot{z}_2 &= z_3 \\
\dot{z}_3 &= v_f = \alpha(x) + \beta(x)E_f
\end{align*} \]
and the nonlinear excitation controller given as
\[ E_f = \frac{-\alpha(x) + v_f}{\beta(x)} \]
Then using linear state variable feedback on \( z \) gives
\[ v_f = -k_1z_1 - k_2z_2 - k_3z_3 = -k_3\Delta \delta - k_2\Delta \omega - k_1\Delta \dot{\omega} \]
Since the GFL procedure brings the original nonlinear plant model (4)-(6) into a controllable Brunovsky form, we apply a common linear quadratic regulator (LQR) approach to choose coefficients in (27). Selecting the optimal feedback gain \( K = R^{-1}B^TP \) such that \( v = -Kz \), with appropriate \( R \) and \( Q \), the following ARE (Algebraic Riccati Equation) is solved
\[ A^TP + PA - PBR^{-1}B^TP + Q = 0 \]
and a complete GFL nonlinear excitation controller is obtained
\[ E_f = e_q + \Delta x_dq_id - T_{do} e_q \cot \delta \Delta \omega \\
- \frac{D}{\omega_0 q_i} - \frac{2H}{T_{do}} v_f \]
\[ v_f = -28.28 \Delta \delta - 22.64 \Delta \omega - 8.96 \Delta \dot{\omega} \]
The combination of controllers (26) and (30) is a nonlinear excitation controller which has been designed to achieve generator stability subject to a large network disturbance. However, the application of the GFL method results in a specialized stabilizing priority, namely the control structure is designed for achieving angle stability only.

**B. DFL Plant Preserving Nonlinear Compensator**

The direct feedback linearization technique is another idea used to design a nonlinear compensating control law. It has a simple theoretical basis but allows more flexibility in the exact linearization steps. We consider the following 3rd order system
\[ \begin{align*}
\dot{x}_1 &= f_1(x) = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 \\
\dot{x}_2 &= f_2(x) = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 \\
\dot{x}_3 &= f_3(x_1, x_2, x_3, u)
\end{align*} \]
where \( u \) is the input and \( f_3 \) contains the only nonlinear terms. Let the right hand side of nonlinear equation (33) be replaced by a new input \( bv(t) \) as follows
\[ f_3(x_1, x_2, x_3, u) - a_{31}x_1 - a_{32}x_2 - a_{33}x_3 = bv(t) \]
where linear terms have been introduced. These can be used to preserve certain physical features. We require (34) to have a well defined solution of the form
\[ u = g_3(x_1, x_2, x_3, bv) \]
A sufficient condition is given by the Implicit Function Theorem, such that the solution exists if
\[ \frac{\partial f_3}{\partial u} \neq 0 \]
Hence (35) defines a nonlinear feedback control via which the nonlinear plant model becomes linear with respect to an arbitrary new input \( v \in \mathbb{R} \) in the form \( \dot{x} = Ax + bv \) where \( A \) is \( 3 \times 3 \) with elements \( a_{i,j}; \ i,j = 1,2,3 \) and \( b = [0,0,1]^T \). This idea has been applied in various ways [6]–[11] using different variables, i.e. \( (\delta, \omega, \omega_q), (V_1, \omega, P_e) \). To demonstrate flexibility here we use the model based on variables \( (\delta, \omega, \omega_q) \) and allow for physical model uncertainty.

Starting with state model (4)-(12) the following DFL system is obtained
\[ \begin{align*}
\dot{\delta} &= \Delta \omega \\
\dot{\omega} &= \frac{D}{2H} \Delta \omega - \frac{w_0}{2H} i_q \Delta e_q(t) + \eta(t) \\
\dot{e}_q &= \frac{1}{T_{do}} \Delta e_q - \frac{1}{T_{do}} v_f
\end{align*} \]
where \( \Delta \omega = \omega(t) - \omega_0, \Delta e_q = e_q(t) - e_q(0) \) and the input
\[ v_f = E_f - \Delta x_dq_id - e_q(0) \]
Since the current is readily available by measurement, the \( dq \) projections of the current component can be found. The internal steady state generator voltage can be approximated from the \( P_e = e_q_i_q \) equation. Hence the DFL compensating law (40) is simple and practically realizable.

A full description of a disturbance input term \( \eta(t) \) is known since it results from DFL application during the linearization procedure, and is given by
\[ \eta = \frac{\omega_0}{2H} e_q i_q(t) + \frac{\omega_0}{2H} P_m \]
such that \( \eta(0) = 0 \) and during and following the disturbance of a power system it can be approximated by a certain bounded region \( \eta \in [\eta, \bar{\eta}] \) subject to \( i_q \in [\bar{i}_q, i_q] \). When a large fault occurs close to a generator terminal, reactances of transmission lines change and the configuration of the power system varies very quickly. To overcome these parametric uncertainties, robust control techniques can be employed. A bound of \( i_q(t) \) in (38) can be used to estimate the change of the system structure. The relationship between stabilizability and \( H_{\infty} \) control has been considered for uncertainty in the plant [12], [17].

If we let the system uncertainty be defined by \( \Delta A \), then the application of DFL results in a state space description that can be written in the form
\[ \begin{align*}
\dot{x}(t) &= (A + \Delta A)x(t) + Bu(t) + G\eta(t) \\
\varphi(t) &= \Omega x(t) \\
y(t) &= Cx(t)
\end{align*} \]
where $x(t)$ is the state space, $u(t), \eta(t), \varphi(t)$ and $y(t)$ denote the control, the disturbance, the controlled output and the measured output, respectively. A full state measurement is assumed, i.e. $C = I$, with the feedback controller in the form $u = Fx$.

Definition 1.1 The system (42)-(44) is said to be stabilizable with disturbance attenuation if there exists a state feedback matrix $F$ such that the following conditions are satisfied.
1. The pair $(A + \Delta A, B)$ is stable.
2. The closed loop transfer function $H(s)$ from $\eta$ to $\varphi$ satisfies the bound
   \[ \| \Omega(sI + (A + \Delta A) + BF)^{-1}G \|_\infty \leq \gamma^2 I \] (45)
for all realizations in the uncertainty region.

Theorem 1.1 Let $Q \in \mathbb{R}^{n \times n}$ and $R \in \mathbb{R}^{m \times m}$ be positive definite matrices for a given constant $\gamma > 0$, and $\epsilon > 0$ such that ARE has a positive definite solution $P$. Then, the required feedback matrix can be given by
\[ F = -\frac{1}{2\epsilon}R^{-1}B^TP \] (46)
Suppose the uncertainty is expressed as
\[ \Delta A = \sum_{i=1}^{k} A_i \epsilon_i(t) \]
with $|\epsilon_i(t)| \leq \bar{\epsilon}_i, i = 1, 2, \ldots, k; \bar{\epsilon} \geq 0$; and each $A_i$ has a rank one decompositions chosen as $D_iE_i^T$. At present, there is no systematic way of choosing the best rank one decompositions and this would be an important area for a future research [17]. Any variation in the uncertainty bounds can be eliminated by suitable scaling of $A_i$.

For the above power systems problem, $k = 1$ and the linearized system model can be rewritten as
\[ \dot{x} = (\bar{A} + r(t)DE^T)x + Bu + Gy \] (47)
where $\bar{A}$ represents the average value for which the time varying function (represented by $a_{23}$ in (32)) is defined as
\[ f(t) = \frac{\omega_0}{2H}q(t) \] (48)
The uncertainty range can be found by letting the quadrature current component be bounded by $i_{q_{\text{min}}} \leq i_q \leq i_{q_{\text{max}}}$ and the bounds of $f(t)$ are found [9], such that
\[ \bar{f} = \frac{1}{2}(f_{\text{max}} + f_{\text{min}}) \]
\[ r(t) = \psi_3 \frac{f - \bar{f}}{f_{\text{max}} - \bar{f}}; \quad |r(t)| \leq 1; \]
\[ D = \begin{bmatrix} 0 & \psi_1 \end{bmatrix}^T \]
\[ E = \begin{bmatrix} 0 & -\psi_1^{-1}\psi_2^{-1}(f_{\text{max}} - \bar{f}) \end{bmatrix}^T \]
where $\psi_{1,2}$ are scalar. The application of state feedback matrix (46) to (47) results in a closed loop system matrix $A_c = \bar{A} + r(t)DE^T - \frac{1}{2\epsilon}BR^{-1}B^TP$ such that
\[ A_c^TP + PA_c = -\gamma^{-1}PGG^TP - \gamma^{-1}\Omega^T\Omega - \epsilon Q \] (49)
Note that identity
\[ \Sigma^T\Pi + \Pi^T\Sigma \leq \lambda^{-1}\Sigma^T\Sigma + \lambda\Pi^T\Pi \] (50)
holds for any real matrices $\Sigma$ and $\Pi$ of appropriate dimensions, and any scalar $\lambda > 0.\] Expanding the left hand side of (49) and using the above inequality, we obtain
\[ r(t)(PDE^T + ED^T) \leq \lambda^{-1}PDD^TP + \lambda\epsilon T \] (51)
and the following ARE is derived
\[ \tilde{A}^T + \tilde{A} - P(BR^{-1}B^T - DDE^T - GG^T)P \] (52)
If there exists a positive definite stabilizing solution $P$ to the ARE (52), then a stabilizing control law (46) can be obtained and the uncertain DFL compensated plant is stable under this robust control law. A complete excitation controller is obtained as:
\[ E_f = v_f + \Delta \omega_d \psi_d + \epsilon \] (53)
\[ v_f = 15.61\Delta \omega(t) + 15.9\Delta \omega(t) - 64.48\Delta \epsilon_q(t) \] (54)
Rotor angle is required as a state feedback variable. In the simulation, rotor angle excursion is taken with respect to an infinite bus. Since $\delta(t)$ may be hard to measure, an angle detector can be introduced as a possible observer to estimate the power angle [7]. The EMF in the quadrature axis on the other hand can be approximated from the readily available electrical power signal and the quadrature projection of the measurable current.

The proposed nonlinear controller damps out system oscillations and quickly regulates the generator terminal voltage to within its operational limits. The effectiveness of the nonlinear excitation compensator is demonstrated in the following section.

C. Angle Stability and Voltage Control

In the above DFL design we have derived a voltage type controller based on the state space model with variables $\{\delta, \omega, \epsilon_q\}$. In [10], a coordinated control structure is presented such that transient stability control via $(\delta, \omega, P_e)$ feedback and voltage regulation via $(\omega, V_r, P_e)$ feedback can be achieved within a so-called global control law. As proposed in [10], the following static linear feedback is obtained for voltage control $v_f = -k_v \Delta V_r - k_w \omega - k_P \Delta P_e$. Since the voltage is introduced as a feedback variable, the post fault voltage is maintained within its operational limits.

In practice, we want to achieve system synchronization and good post fault performance of the system. In [7], [10] it has been recognized that angle and voltage controllers achieve different objectives in different regions of the state. A switching strategy has been proposed as a way to unify different control actions to achieve synchronization and post fault voltage regulation. In the following section, we show that the proposed DFL type controller (53)-(54) achieves both voltage regulation and enhances dynamic performance of the power system.
V. SIMULATION RESULTS

Following the design procedures given in Section IV, we obtain complete excitation controllers

\[
E_f^{DFL} = v_f + \Delta x_d i_d + \epsilon q_0
\]

(55)

\[
v_f = 15.61 \Delta \delta(t) + 15.9 \Delta \omega(t) - 64.48 \Delta e_q(t)
\]

\[
E_f^{GFL} = e_q + \Delta x_d i_d \frac{\delta}{e_q}\cot \Delta \omega
\]

\[
+ e_q - 2 \omega \Omega i_q
\]

\[
- e_q - 2 \omega \Omega i_q
\]

(56)

The power system responses with different controllers subject to a large disturbance are shown in Fig. 2 and Fig. 3. From the simulation results it can be observed that GFL nonlinear controller stabilizes the disturbed system but the post-fault voltage excessively differs from the pre-fault value. The DFL nonlinear excitation controller achieves post fault voltage regulation and satisfactorily achieves system synchronization at a new operating point.

Thus, we have shown that the new DFL excitation controller improves the transient stability and achieves post-fault performance of the generator terminal voltage \( V_f \). As a result of the fixed coordinate transformation, the GFL excitation controller achieves transient stability for the transformed state space variables and fails to regulate the system voltage to within its limits.

VI. CONCLUSIONS

In this paper, we study some issues in the nonlinear control of power systems via (exact) feedback linearization. The geometric (GFL) and direct (DFL) approaches are compared for their flexibility in design with respect to different choices of state variables and control requirements. As preparation for this, a basic conflict between angle and voltage control via excitation voltage is studied. Such physical limitations are important to preserve in the design. The DFL approach is seen to be very flexible for achieving control of both angle and voltage. The GFL approach naturally leads to angle (and frequency) control. Finally, a novel DFL plus robust control design is presented to achieve coordinated angle and voltage control.

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