Decentralized Nonlinear Control for Power Systems
Using Normal Forms and Detailed Models

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Abstract—This paper proposes a decentralized method for nonlinear control of oscillatory dynamics in power systems. The method is applicable for ensuring both transient stability and small-signal stability. The method uses an optimal control law, which has been derived in the general framework of nonlinear control using normal forms. The model used to derive the control law is the detailed subtransient model of synchronous machines, as recommended by the IEEE. Minimal approximations have been made in either the derivation or the application of the control law. The developed method also requires the application of the dynamic state estimation technique. As the employed control and estimation schemes only need local measurements, the method remains completely decentralized. The method has been demonstrated as an effective tool to prevent blackouts by simulating a major disturbance in a benchmark power system model and its subsequent control using the proposed method.

Index Terms—Decentralized, dynamic state estimation, feedback linearization, lie derivative, nonlinear control, normal form, optimal control, subtransient model, unscented Kalman filtering.

NOMENCLATURE

0 Zero matrix (or vector) of appropriate size
φ Vector field of state-mapping in normal form transformation
B Imaginary part of the bus admittance matrix in p.u.
C(x) Characteristic matrix with (i, j) element = $L_{g_i}^{(i)}(x)$
D(x) Vector $[D_1^{(i)}(x) h_1(x) D_2^{(i)}(x) \ldots D_m^{(i)}(x) h_m(x)]^T$
F Vector of machine-state functions
f Vector of system state functions, $[f_1 f_2 \ldots f_n]^T$
G Real part of the bus admittance matrix in p.u.
gi ith vector of input functions for $i = 1, 2, \ldots, m$
h Vector of output functions, $[h_1 h_2 \ldots h_m]^T$
I Identity matrix of appropriate size
Ig Column vector of current injections at system buses

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Electrical and mechanical torques, respectively, in p.u., \( V_d \) and \( V_q \) are the relative degree of armature resistance in p.u.

Time constants for dummy-rotor coil & AVR filter in s, respectively, in p.u.

Electrical and mechanical torques, respectively, in p.u.

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Electrical and mechanical torques, respectively, in p.u.

Time constants for dummy-rotor coil & AVR filter in s, respectively.

Time constants for dummy-rotor coil & AVR filter in s, respectively.

Armature resistance in p.u.

A VR-control input (from the PSS or other controller)

Machine’s terminal bus voltage in p.u. and is equal to \( V \).

Bus terminal voltage magnitude in p.u.

\( V_d \), \( V_q \) are the relative degree of armature resistance in p.u.

Machine’s terminal bus voltage in p.u. and is equal to \( V \).

Armature leakage reactance in p.u.

**I. INTRODUCTION**

Rotating angle stability is essential for the stability of power systems. It refers to “the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance” [1]. A disturbance to the system can be a large one, such as a three-phase fault, or a small one, such as a small step-change in system load. The ability of a power system to recover from a large disturbance is referred to as transient stability, while its ability to adequately damp all the system-oscillations after a small disturbance is referred to as small signal stability.

Corrective measures should be taken in a timely manner after a disturbance, otherwise it can lead to system separation—a phenomenon in which the system divides into two groups of machines and there is a loss of synchronism between the groups and ultimately to wide scale blackouts and/or islanding in the system. In order to ensure that such a loss in synchronism does not occur, protective and control actions should be taken as soon as a disturbance is detected. For example, a protective action in case of large disturbances is to clear a fault within its critical clearing time. An example of control action for both large and small disturbances is to damp the ensuing system oscillations using power system stabilizers (PSSs) and/or power oscillation dampers (PODs).

Majority of the control actions which are taken after a disturbance in a power system use linear control theory. This requires linearization of power system dynamics at a particular equilibrium point or at a finite set of equilibrium points [2]–[4]. Power systems are nonlinear in nature and a large disturbance (and sometimes even a small one [5]) can alter the operating point of the system quite significantly from equilibrium condition(s) [6]. As linearization is applicable only in the vicinity of equilibrium condition(s), application of linear control methods can prove to be ineffective at the altered condition, and can possibly have an adverse effect on system stability [5], [6]. A logical solution to this problem is to use nonlinear control methods which remain valid for any operating condition and not only for conditions which are close to equilibrium. This solution is the focus of this paper.

The nonlinear control methods which have been proposed in the power system literature can broadly be divided into two categories: methods based on normal forms [7]–[12], and methods based on Lyapunov functions [13]–[17]. In methods based on normal forms, the dynamics of the system are transformed into a new form (called as a normal form) using a curvilinear coordinate system. The transformed system is such that some or all of the transformed states are defined by linear differential equations, and at the same time nonlinearity of the system is exactly preserved in the new form. This transformation process is known as feedback linearization.

In Lyapunov function based methods, a scalar energy-like function of the system states is found (called as Lyapunov function) such that its value is positive at every operating point (except at equilibrium, where it is zero), and the function is non-increasing along any trajectory of the system.

An advantage of normal form based methods over Lyapunov based methods is that a general technique does not exist for finding a Lyapunov function for a system, while the steps for finding a normal form are well established. Moreover, as a normal form is either fully or partially linear, linear control techniques can be used for the linear part of the normal form, whereas linear theory is not applicable in general for Lyapunov based methods. Owing to these advantages, methods based on normal forms have been considered in detail in this paper.

Over the past twenty five years, an in-depth exploration of nonlinear control methods based on normal forms has been conducted for power systems, but almost all of these methods rely on model simplification and approximations [7]–[12]. Specifically, some shortcomings of the existing methods are as follows.

1) Classical model is used in these methods to derive the normal form of power systems. Classical model is a reduced order representation of a synchronous machine, and the transient dynamics of the system are incorrectly reflected in this model. Thus, using a control law which has been derived using this model can have unexpected or unwanted effects on the stability of the system.

2) The final control expression which is obtained in these methods is a function of unmeasurable states of the power system such as rotor angle and transient flux. Approximations are made in order to represent this control expression as a function of measurable quantities, such as stator current and stator terminal voltage. These measurements are acquired from instrument transformers and phasor measurement units (PMUs), and noise, harmonics...
and bad-data are present in them [18]–[22]. Thus, the control expression can become grossly erroneous if it is approximated using these measurements, thereby impacting the stability of the system in a negative manner.

The theory of normal forms has been further explored in this paper in order to address the above shortcomings, and a more robust and practical nonlinear control method has been proposed. The key contributions of this paper are as follows.

1) A detailed subtransient model of machines has been used for developing the control method. This is the recommended model for transient stability analysis as per IEEE Std 1110-2002 [23] (also see [24]) and adequately models transient dynamics in power systems.

2) The aforementioned problem of gross approximation in the final control expression has been eliminated by using estimates of states instead of using directly measured quantities.

3) The proposed method is completely decentralized and only requires local measurements at each generation unit.

4) It has been rigorously shown that the power system remains asymptotically stable under the proposed control.

5) The adverse effects of the aforementioned approximations on the stability of the system have been demonstrated.

Rest of the paper is organized as follows. Section II briefly describes the basics of nonlinear control using normal forms, while Sections III–V develop this theory for power systems. Section VI explains the application of dynamic estimation in the developed nonlinear control. Section VII presents simulations to demonstrate the practical applicability and implementability of the method using a benchmark power system model, and Section VIII concludes the paper.

II. BASICS OF CONTROL USING NORMAL FORMS

A general multi-input-multi-output (MIMO) nonlinear system with an equal number of inputs and outputs can be represented in the following form.

\[ \dot{x} = f(x) + \sum_{i=1}^{m} g_i(x)u_i; \quad y_i = h_i(x), \quad i = 1, 2, \ldots, m \quad (1) \]

It will be shown in Section III that a power system can also be represented as (1) to a normal form as are follows [25].

Definition 1: Lie derivative: The Lie derivative of a differentiable scalar function \( h(x) \) of vector \( x \) along a vector field \( f(x) \), such that \( f \) has same dimension as \( x \), is defined as:

\[ L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) \quad (2) \]

Definition 2: Relative degree: For a MIMO nonlinear system given by (1), the relative degree of output \( y_i \) with respect to the input vector \( u \) at a state \( x \) is the smallest integer \( r_i \) such that \( L_{\phi_j} L_{f}^{r_i-1} h_i(x) \neq 0 \) for at least one \( j \in \{1, 2, \ldots, m\} \).

Definition 3: Relative degree set: A MIMO nonlinear system given by (1) has a relative degree set \( \{r_1, r_2, \ldots, r_n\} \) at a state \( x \) if \( r_i \) is the relative degree of \( y_i, \forall i \in \{1, 2, \ldots, m\} \) and the \( (m \times m) \) characteristic matrix \( C(x) \), with \((i, j)\) element as

\[ C^{ij}(x) = L_{\phi_j} L_{f}^{(r_i-1)} h_i(x) \], is nonsingular. If such a set exists, the system is said to have a well defined relative degree.

With the above three definitions as a base, following results are obtained in order to derive a normal form for a MIMO system described by (1) (as explained in detail in [25]).

Result 1: If a relative degree set \( \{r_1, r_2, \ldots, r_m\} \) exists for a system given by (1), then \( r = r_1 + r_2 + \cdots + r_m \leq n \), where \( n \) is the total number of states of the system.

Result 2: (a) Provided that \( r < n \), where \( r = r_1 + r_2 + \cdots + r_m \), and \( r_i \) is the relative degree of \( i \)th output, define \( r \) new states as \( z_i = \phi_i(x) = L_{f}^{r_i-1} h_i(x) \) where, for each \( i \), \( \phi_i \) is the relative degree set, \( j \leq r_i \). Define \( z^1 = [z_1^T z_2^T \ldots z_r^T]^T \) and \( z = [z_1^T z_2^T \ldots z_m^T]^T \). The dynamics for each state of the new state vector \( z \) are given as follows (for \( 1 \leq i \leq m \), and are known as linearized dynamics of the system)

\[ z_i^1 = h_i(x), \quad z_i^j = L_{f}^{j-1} h_i(x) = z_i^{j+1}, 1 \leq j \leq r_i - 1 \]

\[ z_i^r_j = L_{f}^{r_i} h_i(x) + \sum_{j=1}^{m} L_{\phi_j} L_{f}^{r_i-1} h_i(x) u_j = v_i \]

\[ \Rightarrow v = D(x) + C(x)u; \quad D, C \text{ are as in nomenclature (3)} \]

(b) If \( r < n \), then define another \((n - r)\) new states, \( u_i = \phi_i(x) \), where \((r + 1) \leq i \leq n \), such that the nonlinear differentiable mapping of the original states to the new states, \( \phi(x) = [\phi_1(x) \ldots \phi_r(x) \ldots \phi_{n-r}(x)]^T \), has a corresponding differentiable inverse mapping, \( \phi^{-1} \). That is, if \( \phi(x) = (z, w) \), then \( z = \phi^{-1}(z, w) \). It is always possible to find such a mapping for a nonlinear system of form (1) with well defined relative degree. Define \( w = [u_{r+1} u_{r+2} \ldots u_n]^T \).

The dynamics for each state of the state vector \( w \) can be written as follows (for \((r + 1) \leq i \leq n \) and are known as internal dynamics of the system.

\[ \dot{w}_i = [L_{f} \phi_i(x) + \sum_{j=1}^{m} L_{\phi_j} \phi_i(x) u_j]_{x = \phi^{-1}(z, w)} \]

\[ \Rightarrow \dot{w} = q(z, w) + p(z, w) u; \quad q, p \text{ as in nomenclature (4)} \]

(c) The linearized dynamics and internal dynamics (given by (3) and (4), respectively) represent the system’s normal form.

A simple interpretation of (3) is that the output \( h_i(x) \) is repeatedly differentiated with respect to time \((r_i \) times, to be exact) until the input \( u \) appears. After this, \( h_i(x) \) and its time derivatives \( \frac{d^j h_i(x)}{dt^j} = L_{f}^{r_i-j} h_i(x) \), \( 1 \leq j \leq r_i - 1 \) are denoted as a new state vector \( z_r \) and their dynamics are in a linear form.

Thus, this process is known as feedback linearization and the linearized dynamics can be controlled using a linear gain of \( z_r \) as a state feedback for input \( v_i \). But, in such a feedback, the system’s internal dynamics are unobservable and may be unstable. Thus, for the overall stability of the system, it is necessary that besides the linearized dynamics, the internal dynamics also remain stable for a given feedback control. The following result formally states the stability criterion [25].

Result 3: A MIMO system given by (1), with normal form given by (3), (4), is asymptotically stable for a given initial
condition and a given feedback control if the closed loop linearized dynamics are asymptotically stable (that is the closed loop poles are in the left half plane) and the internal dynamics are asymptotically stable. If the closed loop linearized dynamics are asymptotically stable, the asymptotic stability of internal dynamics is equivalent to the asymptotic stability of zero dynamics, which are derived from (4) by representing $v$ in terms of $u$ using (3), with $v = \phi^{-1}(z, u)$ and by setting $z$ and $v$ equal to zero. Thus, zero dynamics are given as follows.

$$w = \phi(0, w) - p(0, w)(C(\phi^{-1}(0, w)))^{-1} D(\phi^{-1}(0, w))$$  \hspace{1cm} (5)

### III. POWER SYSTEM DYNAMICS AND THEIR NORMAL FORM

The subtransient model of machines with four rotor coils in each machine, known as Model 2.2 [23], has been used to study power system dynamics (as explained in Section I) and to derive their normal form. Model of a static automatic voltage regulator (AVR) is also included with the model of each machine. Also, all the loads in the system are assumed to be modelled as constant impedance loads. The dynamic equations for this model are given as follows [22]–[4] (where $i$ refers to the system’s $i$th machine, $1 \leq i \leq m$).

$$\Delta \dot{\xi} = (\omega^i - \omega_0) = \Delta \omega^i \quad \text{(where, } \Delta \delta^i = \delta^i - \delta_0^i\text{)}$$

$$\Delta \dot{\omega}^i = \frac{\omega}{2H}(T_m^i - T_s^i) - \frac{D^i}{2H\Delta}\Delta \delta^i$$

$$\dot{E}_d^i = \frac{1}{T_{q0}^i} \left[ -E_d^i + (X_q^i - X_m^i) \left[ K_{1d}^i I_d^i + K_{2q}^i \Psi_q^i + E_q^i \right] \right]$$

$$\dot{E}_q^i = \frac{1}{T_{q0}^i} \left[ -E_d^i + (X_q^i - X_m^i) \left[ K_{1q}^i I_d^i + K_{2q}^i \Psi_d^i + E_q^i \right] \right]$$

$$\dot{\Psi}_{1d}^i = \frac{1}{T_{d0}^i} \left[ E_d^i + (X_d^i - X_m^i) I_d^i - \Psi_{1d}^i \right]$$

$$\dot{\Psi}_{2q}^i = \frac{1}{T_{q0}^i} \left[ -E^i_d + (X_d^i - X_m^i) I_d^i - \Psi_{2q}^i \right]$$

$$\dot{E}_{dc}^i = \frac{1}{T_{d0}^i} \left[ (X_d^i - X_q^i) I_d^i - E_{dc}^i \right]$$

$$\dot{V}_r^i = \frac{1}{T_{r0}^i} \left[ V_r^i - V_r^i \right]$$

Using the facts that $R_s << X_d^i$, $R_s << X_d^i$ and it is normally taken as 0 p.u. in power system studies ([2], [26]), the above expression for $I_d^i$ and $I_q^i$ is simplified as follows.

$$I_d^i = (V_d^i - E_d^i K_{1d}^i - \Psi_{1d}^i K_{2d}^i) / X_d^i$$

$$I_q^i = (E_q^i K_{1q}^i - \Psi_{2q}^i K_{2q}^i - V_q^i) / X_q^i$$  \hspace{1cm} (7)

The bus voltages, $(V_i^+, \theta_i)$, $1 \leq i \leq M$ (total number of buses is $M$), are given by the following power flow equations.

$$P_i^i = \sum_{j=1}^{M} V_i^j V_j^i \left[ G_i^j \cos(\theta_i - \theta_j) + B_i^j \sin(\theta_i - \theta_j) \right]$$

$$Q_i^i = \sum_{j=1}^{M} V_i^j V_j^i \left[ G_i^j \sin(\theta_i - \theta_j) - B_i^j \cos(\theta_i - \theta_j) \right]$$  \hspace{1cm} (8)

In order to apply nonlinear control theory to power systems, the differential and algebraic equations (DAEs) of the power system given by (6) and (8) need to be mathematically shown equivalent to the affine ordinary differential equations (ODEs) given by (1). This equivalence can be shown for a well-defined network configuration. Here, a network configuration is considered to be well-defined if the matrix corresponding to the equivalent admittance of the network exists and is non-singular. One example in which the network configuration is not well defined is during a fault in which the line admittance of one or more lines becomes infinite, and hence the line-admittance matrix is undefined and the equivalence fails to hold for the duration of the fault. For a well-defined network configuration, one way to show the equivalence of these DAEs and ODEs is by representing each machine as a current source, $I_d^i$ (defined in (6)), behind a constant admittance, $1/(R_i^i + j X_i^i)$. It should be noted that $I_d^i$ is a function of only the states of $i$th machine and not of any algebraic variables.

The network equations in (8) can be written as follows using basic relation between voltages and current injections.

$$V = Z_A I_y; \quad Z_A = (Y_A)^{-1}; \quad Y_A = Y_N + Y_G + Y_L$$  \hspace{1cm} (9)

Here, $V$ is column vector of bus voltages; $I_y$ is column vector of current injections, with $i$th element equal to $I_y^i$ if $i$ is a machine bus, else it is equal to zero; $Y_N$ is network admittance matrix; $Y_G$ is diagonal matrix of machine admittances, with $i$th diagonal element equal to $1/(R_i^i + j X_i^i)$ if $i$ is a machine bus, else it is equal to zero; similarly, $Y_L$ is diagonal matrix of load admittances, and $Y_A$ and $Z_A$ are augmented matrices of admittance and impedance, respectively. It should be noted that $Y_L$ will change with any change in load, hence, $Y_L$ is a time varying quantity, unless the loads are constant impedance loads. Thus, modelling loads as constant impedance loads is required to represent power system DAEs as ODEs given by (1). Also, $Y_G$ and $Y_N$ can always be found for a given well-defined network [2]–[3]. Thus, as it is assumed that network configuration is well defined, $Y_A$ and $Z_A$ exist and are non-singular.

The differential equations in (6) can be written as follows.

$$\dot{x}^i = F^i(x^i, V^i) + \sum_{i=1}^{m} g_i^i(x^i)u_i$$  \hspace{1cm} (10)
Where, \( x^i \) is column vector of the \( i \)th machine’s states; \( V^i_q \) is the machine’s terminal bus voltage and is equal to \( V^i e^{j\delta^i} \); \( E^i \) is the column vector of differential functions in (6); \( g'_i(x') = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \) and \( u_i = V^{ss}_i \). Consolidating (10) for \( i = 1, 2, \ldots, m \) gives the following equation.

\[
\dot{x} = F(x, V^s_g) + \sum_{i=1}^{m} g_i(x) u_i \tag{11}
\]

Here \( x = [x^1^T x^2^T \ldots x^m^T]^T; F = [F_1^T F_2^T \ldots F_m^T]^T; V^g_g = [V^1_g V^2_g \ldots V^m_g]^T; g_i(x) = [g_{i1}^T g_{i2}^T \ldots g_{im}^T]^T, \) where \( g_{ij}^i \) is defined as before and \( g_{ij}^i = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \forall j \neq i \) as \( V^g_g \). \( g_i(x) \) is a subset of \( V (V^g_g \) only constitutes voltages of machine buses, while \( V \) constitutes voltages of all the buses), and \( V = Z_A I_g \) (from (9)), hence \( V^g_g \) is also a function of \( Z_A I_g \). Thus, (11) can be written as follows.

\[
\dot{x} = F(x, Z_A I_g) + \sum_{i=1}^{m} g_i(x) u_i \tag{12}
\]

The above equation is same as (1), and hence this establishes the equivalence of power system DAES in (6) and (8) and the nonlinear affine ODEs in (1) for a given well-defined network configuration. This idea that DAES and ODEs are equivalent for a given network configuration has also been used to apply nonlinear control theory to power systems in the current literature [7]–[12]. It should be understood that \( f \) changes as soon as there is any change in any line parameter or in network structure, e.g., a change in tap position of a transformer, or if there is any change in load at any bus. Even though \( f \) may change, the above equivalence remains valid for the new \( f \) as long as \( f \) remains well defined, that is the network configuration remains well-defined.

To summarize the above equivalence, with \( V_{1s}^i \) as input and \( \Delta \delta_1 \) as output, the power system model given by (6)–(8) can be represented as (1), with various terms defined as follows.

\[
x = [x^1^T x^2^T \ldots x^m^T]^T,
\]

\[
x^i = [\Delta \delta^i \Delta \omega^i E^i_d E^i_q \Psi^i_{1d} \Psi^i_{2d} E^i_c V^i_r]^T;
\]

\[
f(x) \text{is obtained from (6)–(8)} \text{as described above}
\]

\[
u_i = V_{1s}^i;
\]

\[
g_i(x) = [g_{i1}^T g_{i2}^T \ldots g_{im}^T]^T, \quad g_{ij}^i = \begin{bmatrix} 0 & 0 \end{bmatrix}^T \forall j \neq i;
\]

\[
y_i = h_i(x) = \Delta \delta^i \tag{14}
\]

The normal form for the above MIMO representation of power system dynamics is derived as follows. A. Relative Degree

The relative degree of output \( y_i = \Delta \delta^i \) for the MIMO system given by (1) and (14) is \( r_i = 3 \), as \( r_i = 3 \) is the smallest integer for which \( L_g, L_{f}^{(r_i-1)} \Delta \delta^i \neq 0 \) for at least some \( j \in \{1, 2, \ldots, m \} \). That is,

1) \( L_g, L_{f}^{(r_i-1)} \Delta \delta^i = L_g, L_{f} \Delta \delta^i = 0 \forall j \in \{1, 2, \ldots, m \}, \) but

2) \( L_g, L_{f}^{(2-1)} \Delta \delta^i = L_g, L_{f} L_{f} \Delta \delta^i = L_g, L_{f} \Delta \omega^i = \frac{K^i}{T^i_d} \frac{\partial \Delta \omega^i}{\partial E^i_q} \neq 0 \forall j \in \{1, 2, \ldots, m \}, \) but

3) \( L_g, L_{f}^{(r_i-1)} \Delta \delta^i = L_g, L_{f} L_{f} \Delta \delta^i = L_g, L_{f} L_{f} \Delta \omega^i = \frac{\Delta \omega^i}{2H^i T^i_d}; \)

\( \forall j \in \{1, 2, \ldots, m \}. \) The \((i, j)\) element of the \((m \times m)\) characteristic matrix \( C(x) \) for the system is \( C^{ij}(x) = L_g, L_{f}^{(r_i-1)} \Delta \delta^i = \frac{\Delta \omega^i}{2H^i T^i_d}; \)

Therefore, the system has a well defined relative degree provided that \( C(x) \) is non-singular. But \( C(x) \) is highly complex and depends not only on the states and parameters of all the machines, but also on various loads and line parameters. Thus, it is very difficult to verify the non-singularity of this matrix. But the existence of a non-singular \( C(x) \) is not necessary for the existence of a normal form. In case of power systems, the existence of a relative degree for each individual output is sufficient to derive the normal form (as described below). B. Linearized Dynamics

As \( r_i = 3 \) is the relative degree of \( y_i = h_i(x) = \Delta \delta^i \), hence \( r = r_1 + r_2 + \cdots + r_m = 3m \leq n = 8m \). According to Result 2(a), \( 3m \) new states for the linearized dynamics can be defined, with \( 3 \) states for each of the \( m \) machines. Using (3), the \( 3 \) new states for the \( i \)th machine are defined as follows.

\[
z_1^i = \Delta \delta^i, \quad z_2^i = L_f \Delta \delta^i = \Delta \delta^i, \quad z_3^i = \Delta \omega^i = \frac{\Delta \omega^i}{2H^i T^i_d}; \)

\[
\dot{z}_3^i = L_f^2 \Delta \delta^i + \sum_{j=1}^{m} L_g, L_{f}^j \Delta \delta^i u_j = \Delta \dot{\omega}^i = v_i \tag{15}
\]

C. Internal Dynamics

The total number of states of the power system are \( n = 8m \), and only \( 3m \) new states are defined in the linearized dynamics. Thus, another \( 5m \) states need to be defined for the system in order to completely represent the system’s dynamics, as explained in Result 2(b). One straightforward way to do this is to redefine the states \( [E^i_d \Psi^i_{1d} \Psi^i_{2d} E^i_c V^i_r]^T \) of the \( i \)th machine as its new states \( [v_1^i w_1^i w_2^i w_3^i]^T = w_i \). It should be noted that the state vector \( w = [w_1^1 w_2^1 w_3^1 \ldots w_m^m]^T \) in应在“Result 2(b)” as same as \( w_T = [w_T^1 w_T^2 \ldots w_T^m]^T \) in this redefinition. This definition is not only simple, but it also has an added advantage that the input \( u_i = V_{1s}^i \) does not affect the dynamic equations of these states directly, but only indirectly through...
the linearized dynamics. In other words, the term $L_g \phi_i(x)$ in (4) is zero (as $\frac{\partial E_i}{\partial E_i} = \frac{\partial \Psi_i}{\partial E_i} = \frac{\partial \Psi_i}{\partial \Psi_i} = \frac{\partial \Psi_i}{\partial \Psi_i} = 0$) and hence, the term $p(z, w)u$ in (4) vanishes, and (4) reduces to the following equation.

$$\dot{w}_i = L_f E_i = \dot{E}_i, \quad \dot{w}_2 = L_f \Psi_2 = \dot{\Psi}_2, \quad \dot{w}_3 = L_f \Psi_1 = \dot{\Psi}_1, \quad \dot{w}_4 = L_f E_{d} = \dot{E}_{d} \tag{16}$$

Therefore, the eight new states for the ith machine, including both the linearized dynamics and the internal dynamics, are given by $\left[ z_i^1, z_i^2, z_i^3, w_i^1, w_i^2, w_i^3, w_i^4, w_i^5 \right] = \left[ \delta_i, \delta_i', \omega_i, \omega_i', \delta_i''', \omega_i'''', \delta_i''''', \omega_i''''' \right]$. Also, equation (16) represents the internal dynamics only when the derivatives $E_i', \Psi_2, \Psi_1', E_1'$, and $\dot{V}_i$ are represented in terms of the new states. Substituting the expression for $I_d$ from (7) in the expressions for $E_i'$ and $\Psi_2$ from (6), followed by substituting the values of $K_{1d}$ and $K_{2d}$ (using the nomenclature section), and collecting the coefficients of $E_i'$, $\Psi_{1d}$ and $V_i'$, the following equations are obtained.

$$\dot{E}_i = a_{11} E_i' + a_{12} \Psi_2 + \frac{(X_q - X_i')(X_q - X_i)}{T_{q0} X_q} (X_q - X_i') V_d \tag{17}$$

Similarly, substituting the expressions for $I_q$, $K_{1q}$ and $K_{2q}$ in the expression for $\dot{\Psi}_{1d}$ from (6), and collecting the coefficients of $E_i', \Psi_{1d}$ and $V_i'$, the following equation comes.

$$\dot{\Psi}_{1d} = \frac{X_i}{T_{d0} X_d} E_i' + \frac{-X_i'}{T_{d0} X_d} \Psi_{1d} + \frac{X_i - X_i'}{T_{d0} X_d} V_i' \tag{18}$$

As $E_i'$ is not equal to any of the new states, it should be expressed in terms of the new states in the above equation. Substituting the expressions for $I_d$ and $I_q$ from (7) in the expression for $T_r$ from (6), $T_r$ comes as follows.

$$T_r = \frac{V_i}{w} E_i' K_{q1} - \Psi_2 K_{q2} - V_d' \frac{X_q}{\omega_0} + \frac{V_i}{w} E_i' K_{d1} - \Psi_{1d} K_{d2} \tag{19}$$

Substituting the above expression for $T_r'$ in the expression for $\Delta \omega$ from (6), the following equations are derived.

$$\Delta \omega = \frac{\omega_0}{2H} T_m' - \frac{\omega_0^2 V_i'}{2H \omega^2 X_q} (E_i' K_{q1} - \Psi_2 K_{q2} - V_d') \tag{20}$$

Plugging the above expression for $E_i'$ in (18), and collecting the coefficients of $\Psi_{1d}$ and $V_i'$, the following equation comes.

$$\dot{\Psi}_{1d} = a_{31} E_i' + a_{32} \Psi_2 + a_{33} \Psi_{1d} + \left[ \frac{X_q}{X_d} - \frac{X_i}{X_q} \right] V_i' \tag{21}$$

Finally, using the expressions for $E_i', \Psi_2', \Psi_{1d}', E_1'$, and $V_i'$ (from (17), (20), (21) and (6) in (16), and replacing $\Delta \omega$, $\Delta \omega'$, $E_i'$, $\Psi_2'$, $\Psi_{1d}'$, $E_1'$, and $V_i'$ with $z_i^1, z_i^2, z_i^3, w_i^1, w_i^2, w_i^3, w_i^4$, respectively, the internal dynamics are as follows.

$$w = a' w + b', \forall i \in \{1, 2, \ldots, m\} \tag{22}$$
\[\begin{align*}
\mathbf{u}^i &= [w_1^i, w_2^i, w_3^i, w_4^i]^T, \\
b_1^i &= - \left( X_2^i - X_4^i \right) X_3^i \left( X_d^i - X_1^i \right) \left( X_d^i - X_1^i \right) V_i \sin \left( \delta_0^i + z_1^i - \theta^i \right), \\
b_2^i &= \frac{X_2^i - X_4^i}{X_1^i} V_i \sin \left( \delta_0^i + z_1^i - \theta^i \right), \\
b_3^i &= \frac{-2H^i(\omega_0 + z_2^i)X_1^i X_3^i}{T_i^i T_d^i} V_i \sin \left( \delta_0^i + z_1^i - \theta^i \right) \left( X_d^i - X_1^i \right) \left[ z_3^i + \frac{D_i^i z_2^i}{2H^i} \right] \left( X_2^i - X_4^i \right) V_i \cos \left( \delta_0^i + z_1^i - \theta^i \right), \\
b_4^i &= \frac{X_2^i - X_4^i}{X_1^i} V_i \sin \left( \delta_0^i + z_1^i - \theta^i \right), b_5^i = \frac{1}{T_i} V_i.
\end{align*}\]

Elements of \(\mathbf{a}^i\) are as in (17)–(21); \(V_i\), \(\theta^i\) are as in (8) or (9).

Thus, (15) and (22) completely specify a normal form for the power system dynamics.

IV. ASYMPTOTIC STABILITY OF ZERO DYNAMICS

The power system will be asymptotically stable under a nonlinear control method based on normal form if both its linearized dynamics and internal dynamics are asymptotically stable, as explained in Section II. The asymptotic stability of linearized dynamics can be ensured using any desired control method (provided that the closed-loop linearized dynamics are not already unstable, or the operating condition has not crossed some threshold of stability, for example, any system fault should be cleared before its critical clearing time (CCT)). From Result 3, if the closed-loop linearized dynamics are stable, then the internal dynamics will be asymptotically stable if and only if the zero dynamics are asymptotically stable.

Lemma 1: The zero dynamics for a power system (with normal form given by (15) and (22)) are asymptotically stable irrespective of operating condition.

Proof: Using Result 3, the zero dynamics of a power system for a given initial operating condition are obtained from its internal dynamics (given by (22)) by putting \(z = 0\), that is, by putting \(z_1^i = 0\), \(z_2^i = 0\) and \(z_3^i = 0\) for all \(1 \leq i \leq M\). After substituting \(\Delta \omega^j\) and \(\Delta \omega^j\) with \(z_1^j\) and \(z_2^j\), respectively, the expression for zero dynamics for \(\Delta \omega^j\) from (6) reduces to \(z_1^j = \frac{w_{\omega_0}^j [T_m^j - T_i^j] - D_{\omega_0}^j z_2^j}{T_m^j - T_i^j} \Rightarrow T_m^j - T_i^j = 0\) (as \(z_2^j = 0\) and \(z_1^j = 0\)). Thus, in zero dynamics, \(T_m^j\) and \(T_i^j\) are equal. \(T_m^j\) and \(T_i^j\) can be equal (for all \(1 \leq i \leq M\)) only if the system loads and generations are exactly matched and the line connections and parameters are constant. Thus, \(P, Q, B\) and \(G\) in (8) remain constant in zero dynamics, and hence \(V_i^j\) and \(\theta^i\) also remain constant for all \(1 \leq i \leq M\). The elements of \(b^j\) in (22) also remain constant for zero dynamics, as they are functions of \(z_1^j\), \(z_2^j\), \(V_i^j\) and \(\theta^i\). As \(b^j\) is a constant for all \(1 \leq i \leq M\), the zero dynamics will be asymptotically stable if and only if all the eigenvalues of \(\mathbf{a}^j\) are negative for all \(1 \leq i \leq m\) [27]. The eigenvalues of \(\mathbf{a}^j\) are the roots of its following characteristic polynomial.

\[
\text{determinant}(\mathbf{a}^j - \lambda I) = 0
\]

\[
\Rightarrow \left[ |a_{11}^j - \lambda| |a_{22}^j - \lambda| - a_{12}^j a_{21}^j \right] \left[ |a_{13}^j - \lambda| - \frac{1}{T_i^j} \right] = 0
\]

\[
(23)
\]

Three roots of the above equation are \(\lambda = a_{13}^j, \lambda = \frac{1}{T_i^j}, \lambda = \frac{1}{T_i^j} \), and the other two roots are the solutions of the following equation.

\[
\lambda^2 + b \lambda + c = 0; b = -a_{11}^j - a_{22}^j, c = a_{12}^j a_{21}^j
\]

\[
\Rightarrow \lambda = \frac{-b \pm \sqrt{b^2 - 4c}}{2} = \frac{-b \pm \sqrt{b^2 - 4c}}{2} (24)
\]

Using (17), \(c\) in the above equation is evaluated as follows.

\[
c = -\frac{1}{T_i^j} \left[ 1 - \frac{(X_d^i - X_1^i) (X_d^i - X_1^i) - X_1^i (X_d^i - X_1^i)}{T_i^j T_m^j} \right] \left( X_d^i - X_1^i \right)^2
\]

\[
= \frac{X_d^i}{T_i^j T_m^j} + \frac{(X_d^i - X_1^i) (X_d^i - X_1^i) - X_1^i (X_d^i - X_1^i)}{T_i^j T_m^j} \left( X_d^i - X_1^i \right)^2
\]

\[
\Rightarrow c > 0, b > 0, \sqrt{b^2 - 4c} > 0
\]

\[
\Rightarrow (b \pm \sqrt{b^2 - 4c})/2 > 0 \Rightarrow (b \pm \sqrt{b^2 - 4c})/2 < 0 (26)
\]

From (24) and (26), \(\lambda = -\frac{b \pm \sqrt{b^2 - 4c}}{2} < 0\) are two roots of (23) and the other roots are \(\lambda = a_{13}^j = \frac{-X_d^i X_1^j}{T_i^j} < 0\) (using (20) and (25)). \(\lambda = \frac{1}{T_i^j} < 0\) and \(\lambda = \frac{1}{T_i^j} < 0\). Thus all the five roots of (23) are negative, and \(\mathbf{a}^i\) has negative eigenvalues for all \(1 \leq i \leq m\). , the zero dynamics are asymptotically stable. 

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Finally, using (6), (28)–(30), the optimal \( V_{ss}^i \) comes as follows.

\[
V_{ss}^i = \frac{E_{id}^i}{K_n} - V_{ref}^i + V_r^i, \quad E_{f,d,min}^i \leq E_{f,d}^i \leq E_{f,d,max}^i
\]

\[
E_{f,d}^i = T_e^i \left[ 7.07 \Delta \delta + 13.65 \Delta \omega + \left( \frac{D_i}{2H_i} \right) \Delta \omega^i \right] \frac{2H_i}{\omega_i} - E_q^i
\]

where, \( T_e^i, E_q^i \) are defined in (29), (30), resp. (31)

Remark 1: Although the normal form for power system dynamics, their asymptotic stability and the final control expression have been derived using a static AVR, these can be similarly derived considering other types of AVRs as well.

Remark 2: The control input \( V_{ss}^i \) in (31) is a small-signal input given to a machine's AVR. It should be zero in steady-state, and should be non-zero only for around 10 s–20 s after a disturbance (which is the time-frame of interest for rotor angle stability). Thus, \( V_{ss}^i \) should be passed through a washout filter to filter-out any DC-component in it and then be given as an input to the AVR. The largest time constant which describes the dynamics corresponding to rotor angle stability is given by \( T_{d0}' \), which is around 3–10 s for a thermal unit in a power system [26]. \( T_{d0}' \) for the machines considered in Section VII is around 5 s. Also, the time period of any oscillatory mode which is of interest (including inter-area modes) is not more than 5 s. Thus, time constant of the washout filter is taken as 5 s, so that any dynamic which have time constant higher than 5 s (or any DC components) are filtered out.

As the washout filter removes any DC components in the signal, and as \( \Delta \omega^i = (\dot{\omega}^i - \omega_0^i) \), \( \Delta \omega^i = (\dot{\omega}^i - \omega_0^i) \) and \( \Delta \delta = (\delta^i - \delta_0^i) \) are DC signals in the post-fault equilibrium, when the fault is removed and system stabilizes to a new steady state (and hence to a new topology), these DC components are also filtered-out by the washout filter. Thus post-fault rotor angle and rotor velocity can be different from their pre-fault values, and the post-fault dynamics can easily adjust to any topological changes in the system. Also, due to filtering-out of the DC-components by the washout filter, any initial values of \( \omega_0^i, \omega_0^i, \delta_0^i \) can be taken, and in this paper these are taken as 0 p.u., 1 p.u. and 0 rad, respectively.

Remark 3: The stability criteria given in Sections IV and V will remain valid even if saturation of the unit is considered. This is because saturation in synchronous machines is manifested as changes in its parameters (see (23)), that is, changes in \( X_{d}, X_{q}, \dot{X}_{d}, \dot{X}_{q}, \) and so on. Thus, even if these parameters get altered because of saturation, the relation given by (25) still remains valid, and hence the stability criteria given in Sections IV and V are valid.

VI. DECENTRALIZED NONLINEAR ESTIMATION

The control expression in (31) is a function of unmeasurable system states, and hence these states must be estimated in real-time to implement the control. With the introduction of PMUs in power systems, it is now possible to acquire in real-time various phasor quantities, such as bus voltages and line currents, at very...
high sampling frequencies (> 100 Hz) [20–22]. These phasor
measurements can be utilized for estimation of the unmeasurable
states and this estimation is known as dynamic state estimation
(DSE) [28–33]. In [31] a method was proposed to perform
DSE in a decentralized and nonlinear manner. In this method,
the voltage phasor \( V_i \) acquired at \( i \)th machine’s terminal
bus is treated as an input in order to decouple the dynamic
equations of a machine from rest of the power system, followed
by application of unscented Kalman filtering (UKF, [34])–a
nonlinear method of DSE.

UKF is a discrete and iterative method that has four steps.
First, a set of points, called as sigma points, is generated at each
time sample such that the mean and covariance of the points,
respectively, is equal to the estimated mean and covariance of
the state estimates from the previous time sample. In the second
step, the sigma points are passed through the dynamic state
equations (in this case, the decoupled dynamic equations of the
machine) to get the predicted sigma points and predicted state
estimates. In the third step, the predicted sigma points are used to
generate predicted measurements, and finally, the predicted state
estimates and the predicted measurements are corrected using
the actual measurement(s) (in this case, the actual measurement
is current phasor measured at machine terminal) and the states
estimates are thus generated.

Using the above method, the estimates of \( \Delta \delta_i, \Delta \omega_i, E_q^i, E_d^i, \)
\( \Psi_{21}, \Psi_{11}, V_q^i \) are found for the \( i \)th machine using just the
voltage and current phasors measured at that machine. These
estimates are then used in (31) to find the input \( V_{q_k} \) for the
machine’s AVR at each time sample. The estimate of derivative
of a term used in (31) is found by subtracting the estimate
of the term in the previous sample from its estimate in the
current sample, and dividing the difference by the sampling
period. For example, estimate of \( V_q^i(k) \) is \( V_q^i(k) - V_q^i(k-1) \), where
\( k \) denotes the \( k \)th time sample, \( T_s \) is the sampling period, and
\( V_q^i(k) = V_q^i(k) \cos(\delta(k) + \Delta \delta(k) - \theta(k)) \) (from (6)).

Remark 4: As \( V_q^i \) and \( E_d^i \) are algebraic quantities, their time-
derivatives can have very large magnitudes during switching
events or any other disturbances, and hence these large mag-
nitude derivatives should be detected and filtered-out as they
can jeopardize the stability of the system. In this paper, this is
done by comparing the derivative at the \( k \)th time sample with
the derivative at \((k-1)\)th time sample, and if the difference
between the two is more than a predetermined value, then the
derivative at the \( k \)th time sample is set to zero. In this paper, this
determined value is taken as 0.04, as this value successfully
removes all such large magnitude derivatives, and at the same
time retains other derivatives. This value was found using trial
and error.

VII. CASE STUDY

A model 16-machine, 68-bus test system (Fig. 1) has been
used for the case study and MATLAB-Simulink has been used
for its modelling and simulation. A detailed description of the
system is available in [4] or [35]. The following two cases have
been considered to assess the performance of the proposed
control method for both small signal stability and transient
stability.

| TABLE I
<table>
<thead>
<tr>
<th>MODAL ANALYSIS OF INTERAREA MODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode-1 frequency (Hz)</td>
</tr>
<tr>
<td>Open-loop</td>
</tr>
<tr>
<td>0.39</td>
</tr>
</tbody>
</table>

Case A. Assessment of Small Signal Stability: In this case, the
test system starts from steady state, and at \( t = 1s \) a small-
disturbance takes place in which one of the tie-lines of the
double circuit line between buses 54–53 goes out of service.
The test system has four inter-area modes in the range 0.1–
1.0 Hz and three of these modes are very poorly damped with
damping ratios less than 3% (Table I). Thus, after the small-
disturbance, poorly damped oscillations ensue in the open-loop
system, which need to be controlled using an adequate method of
control. Three different control methods have been considered
to control the oscillations: (1) using PSS control, (2) using de-
centralized linear control, and (3) using the proposed non-linear
control. The employed decentralized linear control is based on
an extended linear quadratic regulator (ELQR), and has been de-
scribed in [36]–[37]. A description of the PSS control method
and its parameters is also available in [37].

The plots of the power flow in the inter-area line between
buses 60–61 for the three control types are shown in Fig. 2 and
the plots for \( \delta, \omega, V \) and \( E_{id} \) of units 1 and 8 are shown in
Figs. 3 and 4. Units 1 and 8 have been chosen for showing the
plots because the disturbance takes close to these units. Also,
the plots for a unit which is not close to the disturbance (unit
13) are shown in Fig. 5. It can be observed in Figs. 2–5 that the
damping provided by the proposed control is better than the other two controls. Also, the voltage regulation
provided by the proposed control is on a par with the other two
methods.
Fig. 2. Small-signal stability comparison: Power flow in interarea line.

Fig. 3. Small-signal stability comparison: $\delta$ and $\omega$ for units 1 and 8.

Fig. 4. Small-signal stability comparison: $V$ and $E_{fd}$ for units 1 and 8.

Fig. 5. Small-signal stability comparison for unit 13.

**Modal and sensitivity analysis**: Table I presents the modal analysis of interarea modes, wherein the frequencies and damping ratios of the three poorly damped inter-area modes have been shown. It can be seen in Table I that the damping ratios for the proposed control are much higher as compared to the other two control methods, while the corresponding frequencies for the proposed control are much lower. To understand the reason behind this, further analysis of the sensitivity of the interarea modes to system states needs to be done.

The sensitivity of a system’s $a$th mode (or eigenvalue) to the system’s $b$th state is given by the participation factor $P_{ba}$, and is equal to the product of the $b$th entry of the $a$th right eigenvector and the $b$th entry of the $a$th left eigenvector [26]. As the interarea modes are the most significant electromechanical modes of the test system, it is logical to see how sensitive these modes are to the various electromechanical states of the system (electromechanical states are the $\delta$ and $\omega$ of various generating units in the system). Table II shows the top three normalized participation factors (NPF) of the electromechanical states in each of the interarea modes for the four control scenarios.

It can be seen that the participation in the three interarea modes from various electromechanical states is among the...
highest for three scenarios: open-loop, PSS control and ELQR control. But this participation is significantly reduced for the proposed nonlinear control. Instead, the highest participating quantities are estimated controller states. This high participation of controller states in the interarea modes is the reason behind relatively low frequencies, and relatively higher damping ratios for the interarea modes.

The overall system damping is decided not only by the frequencies of the dominant modes, but also by the damping ratios of those modes [26]. Thus, the reduction in frequencies of the interarea modes in the case of nonlinear control has no adverse effect on control performance because this reduction is well compensated by a significant increase in damping ratios, and the overall damping provided by the proposed control is better than the other two control methods.

**Remark 5. Performance of other methods of nonlinear control:** Other methods of nonlinear control have also been tested for controlling the oscillations caused by the aforementioned small disturbance in the test system. These methods include control using two methods based on normal forms given in [7] and [8], and control using two Lyapunov based methods given in [13] and [16]. It was found that the methods either destabilize the system or produce unwanted oscillations (power flow in line 60–61 for the methods based on normal forms are shown in Fig. 6). This is because all these tested methods have been derived using classical model of machines and employ gross approximations, and hence have adverse effects on the stability of the test system which is modelled using a detailed subtransient model (IEEE Model 2.2) for machines.

**Case B. Assessment of Transient Stability** In the second case, the system starts from steady state, and at \( t = 1 \) s a three phase fault is simulated at bus 54, followed by clearing the fault after 200 ms by opening of circuit breakers on the line 54–53. Fig. 7 shows the response of the three control methods to this large disturbance. Other nonlinear methods of control have not been used for comparison as they failed to perform properly even for a small disturbance (Remark 5). It can be clearly observed that the proposed method can provide adequate damping to the oscillations occurring after the disturbance, and hence can ensure the transient stability of the system after a large-disturbance. On the other hand, the system destabilizes after the disturbance under either PSS control or ELQR control. As both PSS and ELQR fail to stabilize the system, in Figs. 8–10 only the performance under the proposed nonlinear has been shown.

**Discussion on magnitude of control input and the control performance:** The final control input which is given to a generator is the excitation voltage, \( E_{fd} \), from the corresponding AVR. It can be observed in Figs. 4, 5, 9, and 10 that the control input is larger for nonlinear control as compared to PSS or ELQR. A relatively larger control input in case of nonlinear control is needed in order to ensure that the control can maintain the stability of the system in face of both large and small disturbances. This observation of nonlinear control requiring relatively larger control input has been made in power system literature, such as [7], [8]. It can also be observed that nonlinear control provides a large control input to the generators only for the first four-five seconds after the disturbance, and within around 15 seconds the control inputs, the states and other algebraic variables of generators settle down to their steady-state values. Also, the control input is larger for generators which are electrically close to the

<table>
<thead>
<tr>
<th>State</th>
<th>NPF</th>
<th>State</th>
<th>NPF</th>
<th>State</th>
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</tr>
</thead>
<tbody>
<tr>
<td>State NPF State NPF State NPF</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Open-loop ( \delta^{15} )</td>
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<td>( \omega^{16} )</td>
<td>1.00</td>
<td>( \omega^{13} )</td>
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</tr>
<tr>
<td>( \omega^{14} )</td>
<td>0.99</td>
<td>( \delta^{16} )</td>
<td>0.99</td>
<td>( \delta^{13} )</td>
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<tr>
<td>( \lambda^{14} )</td>
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<td>( \delta^{14} )</td>
<td>0.81</td>
<td>( \omega^{16} )</td>
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</tr>
<tr>
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<td>( \omega^{16} )</td>
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</tr>
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<td>( \omega^{15} )</td>
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<td>( \omega^{14} )</td>
<td>0.73</td>
<td>( \omega^{16} )</td>
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</tr>
<tr>
<td>ELQR control ( \delta^{1} )</td>
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<td>( \delta^{16} )</td>
<td>1.00</td>
<td>( \omega^{13} )</td>
<td>1.00</td>
</tr>
<tr>
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<td>0.25</td>
<td>( \omega^{13} )</td>
<td>0.39</td>
</tr>
<tr>
<td>( \delta^{15} )</td>
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<td>( \omega^{16} )</td>
<td>0.07</td>
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![Performance of other methods of control based on normal forms.](image)

![Transient stability comparison: Power flow in interarea line.](image)
disturbance (generators 1 to 8), as opposed to the generators which are not close (such as generator 13).

PSS and ELQR take longer time to settle down in case of a small disturbance (Case A), and fail to maintain the stability of the system in case of a large disturbance (Case B). This is because the control input from PSS and ELQR is not large enough after the disturbance, and the magnitude of the control input is more-or-less uniform for all the generators (instead of being larger for generators electrically closer to the disturbance and smaller for machines which are electrically farther), as can be observed in Figs. 4, 5, 9, and 10. If larger gains are used for PSS and ELQR then they would also provide large control inputs. But as PSS and ELQR are derived using linear model of power systems and are designed specifically for small disturbances, they may not work for large disturbances since a linear model is not valid for large disturbances. Thus, using large gains for PSS and ELQR (or other tools for small signal stability) may worsen the situation in case of a large disturbance, or jeopardize the stability of the system even in case of a small disturbance. As the proposed nonlinear control is derived specifically for nonlinear model of power systems, it is not dependent on a particular equilibrium point or a linear model evaluated at that point. Hence, it ensures that both the small signal stability and the transient stability of the system are maintained irrespective of whether the disturbance is small or large.

**Computational feasibility:** The complete simulation of the power system, along with the dynamic estimators and the nonlinear controllers at each of the 16 machines, runs in real-time. In the case study, a 30 s simulation takes an average running time of 10.1 s on a personal computer with Intel Core 2 Duo, 2.0 GHz CPU and 2 GB RAM. Hence the computational requirements at one machine can be easily met for both estimation and control.

**VIII. Conclusion**

A nonlinear control scheme has been proposed for decentralized control of power system dynamics. A normal form
has been developed for modelling the subtransient dynamics of power systems, and the proposed control scheme has been subsequently derived using this normal form. Asymptotic stability of the whole system under the proposed control has been proved. It has been demonstrated using simulations that the method can be used to ensure both transient stability and small signal stability. Thus, it is a robust tool for mitigation of blackout which are caused by poorly damped oscillations and other transient instabilities occurring in power systems.

REFERENCES


