Observer-Based Distributed Control Design to Coordinate Wind Generation and Energy Storage

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Abstract—Higher percentages of wind generation are anticipated to reduce effective inertia on the electric power grid, presenting challenges to electromechanical stability. Two technologies will help mitigate these stability problems: (i) advanced control systems on wind turbines, exploiting Phasor Measurement Units (PMUs), and (ii) deployment of controllable energy storage. This paper extends state feedback-based, centrally-coordinated control design for energy storage and wind generation to consider distributed, observer-based implementations. Establishing that a local bus PMU measurement at each controller is inappropriate, we demonstrate the feasibility of limiting each local controller to a very small set of remote PMU measurements. An approach is developed that characterizes the practical degree of observability achieved on a subspace of lightly damped electromechanical modes of interest. In a representative power system model, the measurement selection methodology and local observer design is shown to yield control performance very closely approximating that obtained in the centralized, full state feedback case.

I. INTRODUCTION

Increasing penetration of wind energy generation poses major technical challenges to the reliable and secure operation of the electric grid. These challenges are primarily due to the intermittent nature of wind. Wind generators are increasingly integrated to the electrical grid through power electronic based converters and differ significantly from the conventional synchronous generators, particularly in terms of their impact on the electromechanical stability of the grid. The inertia of synchronous machines plays a significant role in today’s power systems in order to stabilize the grid frequency during transients. However, current designs for wind energy systems do not allow these systems to directly contribute to grid frequency regulation. As the penetration of wind is expected to grow dramatically in the coming decade, researchers are seeking improved designs to allow these technologies to better contribute to grid frequency regulation and stability.

An obvious solution is to add a control loop that would feed (draw) active power in response to a decline (rise) in the time derivative of frequency, thereby seeking to mimic the inherent inertial response of conventional synchronous generators. For example, in [1], it is shown that through the addition of a supplementary control loop, an inertial response characteristic can be added to wind turbines. The implementation of such an additional control loop results in an improved inertial response of wind turbines. Some of the other works that explore similar ideas of inertial emulation using simple control configurations such as the proportional-integral (PI) control can be found in [2], [3], and [4].

However, the idea of inertial emulation neglects two important limitations. Any control loop designed to mimic inertia will inevitably be limited both in bandwidth, and in the magnitude of power change that can be applied. In order to overcome these limitations, a work-around being actively considered is to supplement the control available from a wind generator with that available from energy storage devices, such as batteries. Typically, energy storage devices offer fast control action (high bandwidth) while having narrow limits on the magnitude of power and energy that can be absorbed or supplied. On the other hand, varying the mechanical input power to a wind turbine through changes in its blade pitch is a relatively slow control action (low bandwidth), but one which can have broad limits before saturation is reached. This paper proposes a practically feasible control scheme that exploits the complementary relation between the bandwidth and saturation limits between two classes of actuators for grid frequency regulation. In a previous paper [5], we demonstrate a solution that exploits the actuator requirements through a full state feedback scheme. In this paper, we develop a more practical scheme that uses observer-based state feedback.

The previous paper [5] investigated a modification of the saturation accomodating controller design presented in [6] to exploit the complementary nature of saturation-bandwidth requirements of actuators. One of the main reasons for adopting the design approach of [6] is the inclusion of an exogenous system (“exosystem”) model to represent input disturbances. In particular, typical designs using this method adopt an unforced linear system with all purely imaginary eigenvalues as the exosystem. Over the bounded set of initial conditions, its output then yields families of weighted sinusoidal responses as the disturbance signals; in essence, the choice of the exosystem represents a choice of allowable spectra for periodic disturbances. This is well suited to represent the underlying periodic variation typical in wind turbine studies. In the example to follow in this paper, the exosystem represents the variations in wind turbine shaft power, as driven by wind speed variation, by a truncated Fourier approximation to a periodic square wave.

The centralized full state feedback scheme presented in [5] serves as a good reference case while designing a more practically feasible design scheme. With increasing penetration of PMUs in the system, local controllers utilizing local as well
as remote measurement signals can be practically achievable. In [7], it is shown that a remote measurement feedback controller with PMU measurements in conjunction with or as a replacement for locally available information can improve the damping of low frequency inter-area oscillations present in the system when the proposed controller is included in the generator feedback control loop. In [8], a decentralized state estimation strategy that forms distributed observers is adopted to demonstrate a distributed model predictive control framework for control of large power networks. In [9], the authors propose a $H_\infty$ based fuzzy control method for the design of a delay-independent decentralized controller in the context of large interconnected power systems based on wide-area measurement systems (WAMS).

The remaining part of the paper is organized as follows: In section II, the full state feedback-based method presented in [5] is reviewed. The saturation accommodating control design methods based on material in [6] are briefly discussed. A test system which includes a standard IEEE test power system is developed, along with an exosystem to provide wind speed variation. Low pass filters representing bandwidth limitations of actuators are also developed in the same section. An enhancement to the control methods that uses information on the degree of controllability of individual modes is then introduced. A consolidated state space formulation that includes all these components is developed and results of the control implementation on this system are briefly reviewed. In section III, an observer-based control design technique is presented to make the proposed control technique practically feasible. Results of implementation of this technique are presented and compared with the full state feedback case, and an analytical method to decide on an appropriate measurement signals set to be fed to the local observers is presented. Section IV summarizes the contributions of this paper.

II. FULL STATE FEEDBACK-BASED OUTPUT REGULATION

A. Control Design Methods

We first recall the control design method presented in [5] that utilizes full state feedback. The method is based on an optimal control design method to form a controller for linear systems subject to input amplitude limits (i.e., actuator saturation) presented in [6]. Consider the linear system

$$\dot{x} = Ax + B\sigma(u) + E_w w$$

$$\dot{w} = Sw$$

$$y = Cx$$

Equation (1) describes the plant with state $x \in \mathbb{R}^n$ and control input $u \in \mathbb{R}^m$, subject to the effect of an exogenous disturbance represented by $E_w w$ where $w \in \mathbb{R}^s$ is the state of the exosystem. Equation (2) describes the state space realization of the autonomous exosystem. The output is $y \in \mathbb{R}^p$, and $\sigma$ is a normalized vector-valued saturation function defined as

$$\sigma(s) = [\bar{\sigma}(s_1), \bar{\sigma}(s_2), ..., \bar{\sigma}(s_m)]^T$$

with

$$\bar{\sigma}(s) = \begin{cases} s & \text{if } |s| \leq 1 \\ -1 & \text{if } s < -1 \\ 1 & \text{if } s > 1. \end{cases}$$

Because of the presence of the saturation function, $\sigma$, the system is non-linear. If all the eigenvalues of $A$ lie in the closed left-half plane and the pair $(A, B)$ is stabilizable, then a linear state feedback can be designed by solving the Algebraic Riccati Equation (ARE)

$$P_e A + A^T P_e - P_e B B^T P_e + Q_e = 0$$

where, $Q : \{0, 1\} \rightarrow \mathbb{R}^{n \times n}$ is a continuously differentiable matrix-valued function such that $Q_e > 0$, $\frac{dQ_e}{d\epsilon} > 0$ for any $\epsilon \in (0, 1]$, and $\lim_{\epsilon \rightarrow 0} Q_e = 0$. The solution to (5) is a unique positive definite $P_e$. Typically, $Q_e$ is chosen as $\epsilon I$. The state feedback gain matrix $F_e$ is given by

$$F_e = -B^T P_e$$

Feedback using $F_e$ yields an asymptotically stable undisturbed system for any $\epsilon \in (0, 1]$. As sufficient conditions to ensure regulation in the presence of the exosystem’s disturbance signal, $w$, there should exist matrices $\Pi$ and $\Gamma$ that solve the regulator equation

$$\Pi S = A\Pi + B\Gamma + E_w$$

$$0 = C\Pi$$

The proposed state feedback, termed the “low gain” design, is given by

$$u = F_e x + (\Gamma - F_e \Pi) w$$

For a system subject to input amplitude saturation, this design, with an appropriate choice of $\epsilon$, results in exact output regulation with the system operating in the linear regions of the saturation elements as long as the previously stated conditions hold true.

The authors of [6] go on to modify this design methodology, in what they term a “low-and-high gain” approach, to obtain designs that more fully utilize available control signal amplitudes and yield faster convergence of regulation. This approach introduces an additional degree of freedom, $\mu$, weighting the state feedback term. In particular, define

$$F_{\mu, e} = -(\mu + 1) B^T P_e$$

where, $\mu$ is the high gain control parameter, $\epsilon$ is the low gain parameter.

The feedback control law in this case is given by

$$u = F_{\mu, e} x + (\Gamma - F_{\mu, e} \Pi) w$$

This method offers an improved performance in the output regulation problem over the low gain design method. Following the philosophy of [6]’s “low-and-high gain” improvement, a further enhancement to more fully utilize the available control power when one has actuators of differing saturation limits and bandwidth is offered in [5].

B. System Description

Variation in wind speed gets reflected at the output of the wind generator as variation in power generated, which in turn gets reflected onto the power system as variation in frequency. We seek to construct the autonomous exosystem in
such a way that it approximates periodic wind variation. The control design methods described in the previous section are applied on a standard IEEE 14 bus test system with two of the traditional generators replaced by wind generators, and the performance of the system with the controller under variations in wind speed is studied.

1) Modeling Wind Variations: As a simple proof of principle in modeling periodic variation in wind speed/power, the exosystem is constructed such that it can generate a periodic square wave disturbance. The matrix $S$, governing the dynamics of the exosystem according to (2), is chosen such that it has purely imaginary pairs of eigenvalues. With an appropriate choice of initial conditions, $w_0$, an unforced system that approximates a periodic square wave can be constructed. More specifically, a $S$ matrix of size $10 \times 10$, given by

$$
S = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \cdot \omega_s
$$

is chosen, where, $\omega_s$ is the frequency of the periodic square wave. A disturbance signal with spectrum that overlaps the bandwidth of interest for each of the two classes of actuator channels is desired. Therefore, for the simple proof of concept illustration here, $\omega_s$ is selected such that its fifth harmonic lies between the low pass filter cut-off frequencies on the two classes of actuators. For the specific initial conditions of

$$
w_0 = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T
$$

direct calculation confirms that $w(t)$ trajectories will contain sinusoids at $\omega_s$ and its odd harmonics to order 9. The matrix $E_w$ is chosen such that each row, $E_{wi}$, corresponding to each wind generator, $i$, is of the form,

$$
E_{wi} = \begin{bmatrix} \frac{1}{10} & 0 & \frac{1}{3} & 0 & \cdots & 0 & \frac{1}{9} & 0 \end{bmatrix}.
$$

The remaining rows of $E_w$ are set to zero, so that the periodic square wave affects only the powers of the wind generators.

2) The IEEE 14 Bus Test System: The IEEE 14 bus test system represents a 14 bus power system with 5 generator buses and 9 load buses [10]. Buses numbered 1, 2, 3, 6 and 8 represent the generator buses. The other buses represent the load buses. Buses numbered 2 and 8 are assumed to represent those buses with wind generators. The single line diagram of this system is shown in Fig. 1. The state space formulation of this system is assembled as follows.

The electromechanical behavior of each of the generators in the system can be captured by standard swing equation models [11], with characteristics of the units representing wind generation approximated by choice of very small inertia. The frequency, $\omega$, and the angle, $\delta$, are related by definition

$$
\dot{\delta} = \Delta \omega
$$

The differential equation governing the dynamics of the generator, the swing equation, is given by

$$
M \Delta \omega = P_m - P_e - D \Delta \omega
$$

where,

$M$ - rotational inertia of the generator,
$D$ - damping constant,
$P_m$ - mechanical shaft power input to the generator,
$P_e$ - electrical power output of the generator.

$P_e$ must also balance the power absorbed by the rest of the network at the generator bus and is related to the other network variables through the standard power flow equations. These equations are inherently non-linear in nature. As is typical in power systems practice, the feedback control design is based on a linearization about the operating point.

A state space model of the linearized 14 bus system with the $\Delta \omega$’s and $\delta$’s of each of the generators as states is formed. The inputs to the system are the mechanical input powers, $P_m$, for each of the generating units. A state space representation of the system similar to the one described by (1) and (3) can be formed. The two wind generators of the system are modeled in the same fashion as the traditional generators (using swing equations), but a much smaller rotational inertia, $M$, is chosen in comparison with that of the traditional generators.

C. System Model with Bandwidth Limitation

The bandwidth limitation is imposed by having a low pass filter in front of the actuator as shown in the system block diagram in Fig. 2. A fourth order low pass butterworth filter is considered for each of the input channels. The cut-off frequencies, $\omega_c$’s, of the filters are chosen such that the input channels 1, 3 and 4 have a high bandwidth,

$$
\omega_{c1,3,4} = \max\{|\lambda_A|\}
$$

while the channels 2 and 5 have a lower bandwidth,

$$
\omega_{c2,5} = 0.1 \cdot \max\{|\lambda_A|\}
$$
where, \( \max\{|\lambda_k|\} \) is the absolute value of the eigenvalue of \( A \) with the largest magnitude. To relate these choices to the physical motivation for our problem, one may assume that channels 1, 3 and 4 represent bus locations at which generator power control is supplemented by energy storage device attached to the bus. As per the earlier motivation, these are assumed to be high bandwidth controls, but subject to narrow saturation limits on available power. Conversely, channels 2 and 5 represent bus locations at which variation in generator mechanical shaft power is the available control. These are the locations at which the two wind generators are modeled. These channels have broad actuation limits before saturation is reached, but narrow bandwidth (by filter cutoff being one decade lower, as indicated above). The high bandwidth channels are denoted as \( p_1 \) and the lower bandwidth channels are denoted as \( p_2 \). The overall state space model composed of the filter and the plant (14 bus system) is formed as follows. The states of the net system are given by

\[
\Delta x_{\text{net}} = \begin{bmatrix} \Delta x_{\text{filter}} \\ \Delta x \end{bmatrix}
\]

(14)

The state equations defining the filter are

\[
\dot{\Delta} x_{\text{filter}} = A_{\text{filter}} \Delta x_{\text{filter}} + B_{\text{filter}} \Delta u_{\text{filter}}
\]

(15)

\[
\Delta y_{\text{filter}} = C_{\text{filter}} \Delta x_{\text{filter}} + D_{\text{filter}} \Delta u_{\text{filter}}
\]

(16)

The input to the plant is the output of the filter as shown in Fig. 2. Thus

\[
\Delta e = C_{\text{filter}} \Delta x_{\text{filter}} + D_{\text{filter}} \Delta u_{\text{filter}}
\]

(17)

The resulting system consists of 30 states (20 filter states, 10 power network states) and is given by

\[
\Delta x_{\text{net}} = A_{\text{net}} \Delta x_{\text{net}} + B_{\text{net}} \Delta u + E_{\Delta w} \Delta w
\]

(18)

\[
\Delta y = C_{\text{net}} \Delta x_{\text{net}}
\]

(19)

where

\[
A_{\text{net}} = \begin{bmatrix} A_{\text{filter}} & 0 \\ B C_{\text{filter}} & A \end{bmatrix}
\]

(20)

\[
B_{\text{net}} = \begin{bmatrix} B_{\text{filter}} \\ B D_{\text{filter}} \end{bmatrix}
\]

(21)

\[
C_{\text{net}} = \begin{bmatrix} D C_{\text{filter}} & C \end{bmatrix}
\]

(22)

Fig. 2. Block diagram of the system.

D. Design Improvement Through Modal Decomposition

In order to better exploit the complementary nature of saturation limits and bandwidth limits of actuators, the \( Q_\epsilon \) matrix is partitioned. The \( Q_\epsilon \) matrix is partitioned according to the partitioned input channels, \( p_1 \) and \( p_2 \), by transforming the system into its modal co-ordinates. The transformation square matrix \( P^{-1} \) is formed, such that every real eigenvector, \( q_j \), of the matrix \( A_{\text{net}} \) forms a column of \( P^{-1} \) and every complex eigenvector of \( A_{\text{net}} \), \( q_j \), results in two columns of \( P^{-1} \) such that one column is the real part of \( q_j \) and the other column is the imaginary part of \( q_j \). Then, the state matrix in the modal co-ordinate frame is given by

\[
\overline{A}_{\text{net}} = P A_{\text{net}} P^{-1}
\]

The matrix \( \overline{A}_{\text{net}} \) thus formed has all the real eigenvalues of \( A_{\text{net}} \) on the diagonal, and each of the complex eigenvalues result in blocks of size \( 2 \times 2 \) with the real part of the eigenvalues on the diagonal and the imaginary part appearing as skew symmetric terms on the off-diagonal. For example, for a matrix \( A \) with a real eigenvalue \( \lambda_1 \) and a pair of complex conjugate eigenvalues \( \alpha_1 \pm j \beta_1 \), the corresponding matrix in its modal form is

\[
\overline{A} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \alpha_1 & \beta_1 \\ 0 & -\beta_1 & \alpha_1 \end{bmatrix}
\]

The modal degrees of controllability with respect to each of the input channels are of interest, so that the states can be partitioned according to the corresponding partitions of input channels. For each input channel, \( i \), and each mode of the system, \( k \), the scalar, \( m_{i,k} \), given by,

\[
m_{i,k} = |w_k^T b_i|
\]

(23)

is formed. Where, \( w_k \) is the left eigenvector of \( A_{\text{net}} \) in the modal form corresponding to the mode \( k (||w_k|| = 1) \), \( b_i \) is the \( i^{th} \) column of \( B_{\text{net}} \) in the modal form. This gives blocks of 2 states which are most controllable for each of the input channels.

E. Results of Implementation on 14 Bus System

The full state feedback-based control design method in modal co-ordinates is applied to the IEEE 14 bus system. The most controllable pairs of modes for each input channel are summarized in Table I. Let \( \Delta e_1(t) \) and \( \Delta e_2(t) \) represent the control power signals for each of the partitioned channels \( p_1 \) and \( p_2 \) respectively. Then, the low-high gain method is applied with an appropriately partitioned \( Q_\epsilon \) matrix based on the modal degrees of controllability. \( 2 \times 2 \) diagonal blocks of

<table>
<thead>
<tr>
<th>Input Channel</th>
<th>Modes</th>
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<tbody>
<tr>
<td>1</td>
<td>3, 4</td>
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<td>2</td>
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<td>19, 20</td>
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<tr>
<td>4</td>
<td>21, 22</td>
</tr>
<tr>
<td>5</td>
<td>13, 14</td>
</tr>
</tbody>
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the $Q_1$ matrix are parameterized in two different $\epsilon$'s. The two $\epsilon$'s are chosen as, $\epsilon_1 = 10^{-1}$ and $\epsilon_2 = 10^{-4}$, and $\mu = 1000$ is chosen. The $\epsilon$'s are chosen such that a higher value of $\epsilon$ is chosen for the blocks corresponding to the higher bandwidth input channels, $p_1$. The resulting $||\Delta e_1(t)||$ and $||\Delta e_2(t)||$ are shown in Fig. 3. From the figure it can be seen that for the high bandwidth channels, $p_1$, the norm of the error signals is lesser than that for the lower bandwidth channels, $p_2$. Also, the “effort” required from the actuators while maintaining operation in the linear region is very reasonable. These results are compared with other approaches such as the low-gain design method, and the design methods without partitioning the $Q_1$ matrix in [5] and it is found to be the best in terms of reducing the “effort” required from the actuators.

III. OBSERVER-BASED FEEDBACK FOR OUTPUT REGULATION

In order to make the control technique described in the above section practically feasible, an observer-based feedback control scheme is demonstrated here. This scheme utilizes a small subset of available measurement signals from each of the generator buses to form estimates of the system states that are then fed to each of the local controllers. A schematic of the proposed system is shown in Fig. 4. Decentralized control uses local information available at each sub-system level. This approach overcomes the limitations of traditional centralized control, where large communication bandwidth is required for exchanging information between various sub-systems.

A. Observer Design

The local observers are designed according to the following technique. The technique is described for one of the local observers. The observer-based control design is performed on the system in its modal co-ordinates, $(\overline{A}_{net}, \overline{B}_{net}, \overline{C}_{net}, \overline{E}_w)$, so that the complementary nature of saturation-bandwidth limits of the actuators is exploited. Re-writing (18) and (19) in modal co-ordinates

$$\Delta \hat{x}_{net} = \overline{A}_{net} \Delta \hat{x}_{net} + \overline{B}_{net} \Delta \pi + \overline{E}_w \Delta w \quad (24)$$

$$\Delta \pi = \overline{C}_{net} \Delta \hat{x}_{net} \quad (25)$$

The dynamic equation of the observer is given by

$$\Delta \hat{x}_{net} = \overline{A}_{net} \Delta \hat{x}_{net} + \overline{B}_{net} \Delta \pi + \overline{E}_w \Delta w + L(\Delta \pi - \overline{C}_{net} \Delta \hat{x}_{net}) \quad (26)$$

where

$$\Delta \pi = \lambda \pi + \Delta \hat{x}_{net} \quad (27)$$

and

$$\Delta \hat{x}_{net} = 0 \quad (28)$$

Substituting (25) in (27) and subtracting resulting equation from (24), we obtain

$$\Delta \hat{x}_{net} = (\overline{A}_{net} - \overline{L} \overline{C}_{net}) \Delta \hat{x}_{net} \quad (29)$$

This equation governs the estimation error. The choice of the $L$ matrix determines the eigenvalue/eigenvector placement of this system.

Next, a method to form the $L$ matrix that takes advantage of the degrees of freedom in choosing not only the eigenvalues but also the eigenvectors of this system is described. Given a complex scalar $\lambda$ (such as an eigenvalue), the Hautus matrix is defined as

$$H_\lambda = \left[ \begin{array}{c} \lambda I - \overline{A}_{net} \\ \overline{C}_{net} \end{array} \right] \quad (30)$$

Suppose $(\lambda_k, v_k)$ is an eigenpair of $\overline{A}_{net}$ such that $H_{\lambda_k}$ is full rank, i.e., mode $k$ is observable, the matrix $L$ is chosen such that $(\overline{\lambda}_k, v_k)$ is an eigenpair of $(\overline{A}_{net} - \overline{L} \overline{C}_{net})$ for arbitrarily chosen $\overline{\lambda}_k$. The choice of the $L$ matrix is made as follows.

From the basic definition of eigenpair of a matrix

$$(\overline{A}_{net} - \overline{L} \overline{C}_{net})v_k = \lambda_k v_k - \overline{L} \overline{C}_{net} v_k$$

$$= \overline{\lambda}_k v_k \quad (31)$$

$$\implies \overline{L} \overline{C}_{net} v_k = (\lambda_k - \overline{\lambda}_k) v_k \quad (32)$$

Let $w_k = \overline{C}_{net} v_k$, and $z_k = (\lambda_k - \overline{\lambda}_k) v_k$. Also, let $\overline{C}_{net}$ be of size $r \times n$. Then, $w_k, z_k$ can be formed for $r$ number of
Let
\[ W = \begin{bmatrix} w_k & w_{k+1} & \ldots & w_{k+r-1} \end{bmatrix} \]
\[ Z = \begin{bmatrix} z_k & z_{k+1} & \ldots & z_{k+r-1} \end{bmatrix} \]

Then, (32) leads to
\[ LW = Z \]
\[ \implies L = ZW^{-1} \]

Thus, for each observer, the \( L \) matrix can be formed. This matrix could be different for different observers, since it depends on the choice of the \( C_{net} \) matrix at that particular bus.

The control law (11) is modified such that the state feedback acts on the estimated states, \( \Delta \hat{x}_{net} \). So
\[ \Delta \hat{\pi} = F_{\mu, e} \Delta \hat{x}_{net} + (\Gamma - F_{\mu, e}\Pi)\Delta w \]

Thus, (24), (25), (26) and (35) represent the observer-controller configuration for a particular observer at a generator bus.

B. Results of Implementation on 14 Bus System

The above observer-based technique is adopted to design local observers at each of the generator buses. Here, it is assumed that at each generator bus, the available measurement signals are the generator frequency, \( \omega \), and the generator angle, \( \delta \). Each of the local observers may use locally available signals as well as some of the other signals from the rest of the system. The communication related cost required for the exchange of information between different locations in the system poses a restriction on the number of signals that each observer may use. The key question then is, what choice of measurement signals of the system would lead to a desirable performance. Desirable performance in this context can be set as control performance that comes as close as possible to the full state feedback case. The results of the implementation for a few choices of sets of measurement signals are shown here and compared with the full state feedback case. Then, an analytical approach to arriving at a small subset of available measurement signals of the system that would lead to good control performance is presented.

First, consider a measurement signal set such that each of the observers uses only the locally available signals, i.e., each of the five observers uses the corresponding generator frequency and angle information to form an estimate of the states that then get fed to the local controllers. The resulting \( ||\Delta e_1(t)|| \) and \( ||\Delta e_2(t)|| \) are shown in Fig. 5. The average values of \( ||\Delta e_1(t)|| \) and \( ||\Delta e_2(t)|| \) are 1.7 and 0.88 respectively. Clearly, this measurement set does not lead to good performance as compared to the full state feedback case in Fig. 3. Next, consider a larger set of measurement signals. Consider the measurement signals set at each observer to consist of frequencies of all the traditional generators and angles of all the wind generators. The resulting \( ||\Delta e_1(t)|| \) and \( ||\Delta e_2(t)|| \) are shown in Fig. 6. The average values of \( ||\Delta e_1(t)|| \) and \( ||\Delta e_2(t)|| \) are \( 1.5 \times 10^{-4} \) and \( 1.3 \times 10^{-3} \) respectively. The ratio of these average values is 8.3. This performance is quite satisfactory, both in terms of reducing the “effort” on the actuators as well as in terms of exploiting the complementarity nature of saturation-bandwidth limitations of the actuators. However, this implementation requires a large set of measurement signals and may not be very feasible in terms of the communication costs.

Next, consider a measurement signal set such that the frequency and angle of the generator at bus number 3 are used by all the observers except the one at bus number 2. The frequency and angle of the generator at bus number 1 are used by the observer at bus number 2. The resulting \( ||\Delta e_1(t)|| \) and \( ||\Delta e_2(t)|| \) are shown in Fig. 7. The average values of
as the full state feedback case. The number of measurement signals required in this case is quite small, thus making this implementation practically feasible too.

C. Analytical Approach to Identifying Appropriate Measurement Signals

It is not practically feasible to test each set of measurement signals to arrive at the best set, especially when dealing with a large system. So, we demonstrate an approach based on singular values of the Hautus matrix to arrive at a significantly small subset of signals that can then be tested.

A set of relevant modes of the network can be found by first identifying the lightly damped modes of the network and then comparing the magnitude of the corresponding eigenvalues with the natural frequency of the exosystem. The ones with magnitudes “close” to the natural frequency of the exosystem are considered as relevant modes. For this set of modes, compute the singular values of the Hautus matrix for different choices of $C_{\text{net}}$ (corresponding to different choices of measurement signals at a particular observer). Then, determine the condition number of the Hautus matrix, which is simply the ratio of the largest to smallest singular value of the Hautus matrix. This is repeated for every observer in the system to result in a set of condition numbers for each relevant mode. The most appropriate choice of set of $C_{\text{net}}$ matrices for the system would then be the one which results in small condition numbers over the entire set of observers.

The above algorithm is implemented for some of the choices of $C_{\text{net}}$ matrix. For the case where each of the observers uses only the locally available signals, the resulting condition numbers are shown in Table II. Next, consider the measurement signal set that resulted in performance corresponding to Fig. 7. The resulting condition numbers are shown in Table III. Comparing the results in Tables II and III, it can be seen that the condition numbers are smaller in the latter case. This is also in agreement with the performance results shown in Figs. 5 and 7 respectively. So, we have an analytical approach that can indicate to a relevant measurement signal set, thus avoiding the computation for all the possible combinations of available signals.

### TABLE II

<table>
<thead>
<tr>
<th>Input Channel</th>
<th>Mode 5</th>
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<th>Mode 10</th>
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### TABLE III

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IV. CONCLUSION

Motivated by anticipated control challenges associated with grid integration of very high percentages of wind and other renewable generation sources, this paper considered distributed, observer-based implementations of controllers to coordinate frequency regulation of wind turbines with contributions from controllable energy storage. The work here built upon previous efforts by the authors, that had treated the problem of coordinating high-bandwidth, but saturation limited power control from energy storage devices, with the lower bandwidth control of wind turbines. That approach utilized methods that explicitly treat the saturation limits of the actuators (i.e., power drawn from energy storage), but suffered the practical shortcoming of being a centralized, full state feedback design. Even with the advances in communications and “smart grid” technologies, centralized real-time feedback control on the power grid remains an impractical proposition.

Motivated by this framework, this paper developed a decentralized, observer-based alternative, that adapted the state feedback-based design of earlier work to a more practical implementation. It was first established that the “naïve fix”, that of building an observer based just on a local bus PMU measurement was inappropriate. In the representative example model, using one local bus PMU to drive a controller for a generator or storage element at that bus fails. As a next step, anticipating practical concerns that low latency, highly reliable communication of PMU signals (as is needed for real-time control) remains an expensive propositions, the “two bus” observability problem was examined; i.e., each local controller was assumed to be allowed measurement of its own local frequency and phase angle, along with the frequency and phase angle of a single remote bus. Even with this expanded, two bus measurement set, the sample system failed to be fully observable. The “fix”, which is hoped to represent a useful insight to contribute to power system control, is to adopt a less ambitious objective. Utilizing a “modal perspective”, characterizing observability via the Hautus test applied to individual eigenvalues of the system. The approach utilized then sought a measurement set with the more limited goal of providing observability only of lightly damped oscillatory electromechanical modes, whose improved damping would be the objective for the distributed controllers. In this case, each of the distributed control locations in the example showed the property that just one remote bus measurement provided good observability on the set of modes of concern, where the choice of appropriate measurement signal set was made on the basis of the Hautus test. For the observer construction, rather than adopting the standard textbook approach of placing eigenvalues for the error dynamics, the design methodology here took an eigenstructure assignment approach to the observer design, seeking to maintain the eigenvectors of the error dynamics aligned with the eigenvectors of the observable modes.

The result of this measurement selection methodology and observer design proved very successful in the demonstration case study. Our demonstration system included modeled multiple buses with representative wind machines attached, and multiple buses with representative controllable energy
storage attached. The benchmark was the degree of stability enhancement provided in this system by a centralized, full state feedback design driving each of these local “actuators”. The distributed alternative replicated the channels of the full state feedback matrix appropriate to each bus actuator (generator or energy storage unit), and “fed” the state feedback matrix with a state estimate generated by each local observer, utilizing only a small sub set of the available measurement signals. For the demonstration system studied, the performance very closely replicated that of the full state feedback. In particular, the local control continued to display a key desirable property that will likely be of great practical importance in utilizing energy storage as a controllable power input to the grid. The distributed design (like the full state feedback design) respected the saturation magnitude versus bandwidth tradeoffs of the different cases of controllers: the energy storage devices' power command was a relatively higher bandwidth signal, but remained within the small magnitude saturation limits associated with the devices; the wind turbine power command varied over wider range of magnitude, but was exercised only with a very low bandwidth. Practically speaking, the control design allowed the storage units to offer fast, small magnitude power corrections to regulate and stabilize frequency, while the wind units provided the slower, larger magnitude changes in power supplied to the grid. The authors hope that this demonstration that coordinated, complementary control characteristics can be achieved in a distributed fashion using only a minimum of long distance communication of PMU signals, will provide a useful contribution to increased integration of wind resources.

REFERENCES