An Approach for Power Oscillation Damping Control using DFIG-based Wind Farms to Deal with Communication Dropouts

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***Abstract*—In this paper, a systematic approach is proposed for wide-area oscillation damping control, which can handle data-packet dropout in the communication channels of a smart power grid with large-scale deployment of distributed and networked Phasor Measurement Units (PMUs) and wind energy resources. To that end, a reduced order dynamic equivalent model of the New England-New York power system with replacement of two existing synchronous generators (SGs) by two doubly-fed induction generator (DFIG)-based wind farms (WFs) is considered. One of these SGs was equipped with a power system stabilizer (PSS). The issues with electromechanical oscillation damping control through WFs using locally available signals is identified and a methodical way for appropriate selection of control input and remote feedback signals through modal analysis is presented. The remote feedback signals transmitted through communication channels encounter data dropout which is characterized by the Gilbert-Elliott model. Deterioration in the performance of the oscillation damping control is demonstrated when data-packet dropout takes place in the remote feedback signals from PMUs. An Observer-driven Reduced Copy (ORC) approach is proposed to improve the damping performance under data-packet drop scenarios where conventional feedback would suffer. Nonlinear time-domain simulations following large large disturbances (e.g., faults, line outages, etc.) demonstrate that the ORC gives significantly better performance compared to conventional feedback under higher data drop situations.**

***Index Terms*—Networked Control Systems (NCS), Smart Grid, Phasor Measurement Units (PMUs), Wide-area Measurement, Electromechanical Oscillations, Observer-driven Reduced Copy (ORC), Wind Farm, Data-dropouts, Gilbert-Elliott Model.**

I. Introduction

THE 2010 American Physical Society's Panel on Public Affairs (POPA) reported [1] that land-based wind energy totals more than 8000 GWs of potential capacity. Also, off-shore wind power is in the early stages of development in the US. Although small amount of renewable generation can be easily integrated in the grid, accommodating large penetration from these renewable sources will require new approaches to enable reliable operation of the grid. The Networked Control System (NCS) with distributed networked sensors (i.e. Phasor Measurement Units (PMUs)) has the potential to be a key enabler towards achieving this objective. In a NCS the control and the feedback signals are exchanged amongst a multitude of sensors and actuators through a communication network in the form of data packets. However in a power system with large geographical span, leading to huge separation of the sensors and the actuators, the challenges of maintaining reliability within the NCS in the face of uncertainties such as network congestion, bandwidth limitations, data drop, packet corruption, latency and signal loss increases significantly.

With NCS likely to be more common, the impact of data dropout on power oscillation damping controllers is a matter of concern. Several researchers have attempted to model the impact of data dropouts, BW restriction and delays in the NCS but the significance of combining communication constraints and control specification has not apparently been addressed in the power systems literature. Most of research done on smart grid in the past, oversimplified the physical portion of the grid. In [2] the important consideration towards the coordinated control of doubly-fed induction generator (DFIG)-based wind farms (WFs) for power oscillation damping were analyzed, but communication layer was assumed to be ideal. In [3] the BW restriction in the communication was dealt with in a deterministic framework. Also in [4] a predictor corrector strategy is applied using a reduced-order model of the nominal system (system copy) for damping electromechanical oscillations in power systems under constrained communication BW. However, packet dropout was not considered in both. Singh *et-al* [5] represented packet data transmission process and probability of packet loss using an independent Bernoulli model in NCS for power system control. However, as mentioned in [5], the validity of Bernoulli model is questionable when the communication channel is congested. Moreover, the papers [3]–[5] considered only conventional generators and no inverter-interfaced generation was taken into account. It is therefore important to develop a system-level consideration of the effect of wind generators and identify factors and ways of controlling them for power oscillation damping problem in the networked controlled power system (NCPS) with non-ideal communication situation, which is the focus of this paper.

In this paper, to understand the behavior of the system impact of WF integrations, two conventional synchronous generators (SGs) in the reduced equivalent model of New England-New York power system are replaced by equivalent DFIG-based WFs. A systematic approach for appropriate choice of control input and remote feedback signals through modal analysis is presented. A detailed characterization of the communication process with packet loss probability has been considered in NCS framework for power system control, and an ORC with linear quadratic regulator (LQR) based optimal control scheme is used to damp the inter-area oscillations.

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Moreover, an analysis of the bound on the inter-sample error between the actual and estimated states in presence of data-dropouts and off-nominal operating conditions is presented. Finally, the effectiveness of the proposed ORC approach for damping the inter-area oscillation following faults and line outages is validated.

II. Modeling of NCPS

Three main components of the NCPS, see Fig. 1, are the physical layer (i.e. power system), the cyber layer (i.e. communication network) and the controller, respectively.

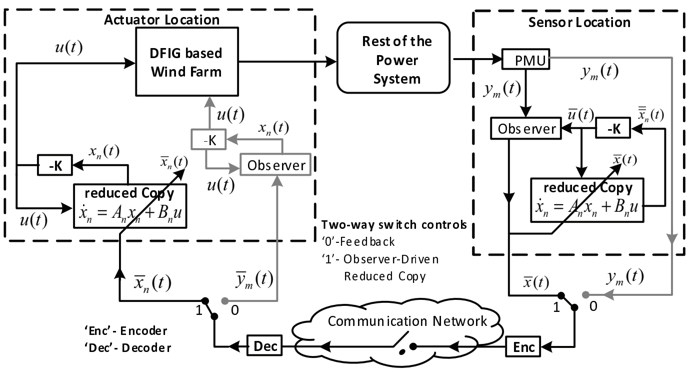

Fig. 1. Overal architecture of the NCPS including feedback control (in gray) and the proposed Observer-driven Reduced Copy (ORC).

A. Power System Model

In this work the nonlinear positive sequence fundamental frequency phasor model of a 16-machine 5-area dynamic equivalent of the New England-New York system is considered, see Fig. 2. The SGs are represented by a sixth-order subtransient model and eight of them (G1-G8) were equipped with IEEE DC1A excitation. The rest of the SGs are under manual excitation control, G9 is equipped with a static exciter with a power system stabilizer (PSS). The active and reactive components of the loads have constant impedance characteristics.

In this paper, we will study the impact of shutting down two conventional plant (G9 and G15) and replacing them with two DFIG-based WFs. Modeling of the WF is described next.

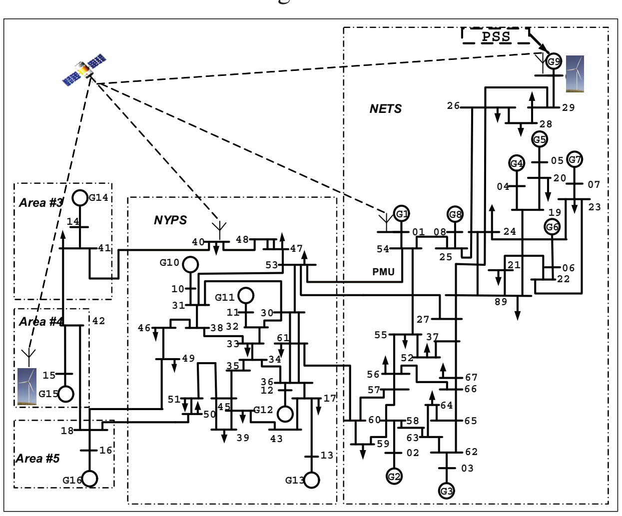

Fig. 2. 16-machine, 5-area equivalent representing New England - New York power system. Wind Farm are connected to bus-9 and bus-15.

B. Wind Farm Modeling and Controls

The overal structure of a DFIG-based WF with its controls is shown in Fig. 3, which is represented by an aggregated model whose turbine-generator rotational dynamics is represented by a two-mass model to include the torsional mode. The generator is modeled using standard differential and algebraic equations as given in [6]. The turbine is assumed to operate in the zone of maximum power point extraction. Also, the blade pitch angle and the wind speed is assumed to be constant. Stator transients of the induction machine are neglected. The tie-reactors of the VSCs, DC-link dynamics and the PLL dynamics are included in the model (Fig. 3). Standard vector control approach was considered for both rotor-side converter (RSC) and the grid-side convertor (GSC) controls [7]. For Maximum Power Point Tracking (MPPT) and the stator terminal voltage control for RSC, the stator flux is aligned with the q-axis. As shown in Fig. 3, for DC voltage control and reactive power control of GSC, the stator terminal voltage is aligned with the q-axis. The modulation signals i_{drmod} or i_{qrmod} is used to damp the inter-area oscillation as will be discussed in Section V.

So far, modeling of the physical layer (power system) in the NCPS is discussed. Modeling of the communication channels (cyber layer) and uncertainties are discussed in the following section.

C. Communication Network and Dropouts

Reliable transmission of a continuous-time signal over a communication network constitutes the following steps: first, the signal must be sampled and encoded in a digital format, then transmitted over the network, and finally the data must be decoded at the receiver side. As shown in the Fig. 1, in the communication network at the transmitting end, the encoder maps the measurements into streams of bits (Analog to Digital Conversion) that can be transmitted across the network and a decoder at the receiving end maps the streams of bits received from the network into continuous signals (Digital to Analog Conversion). In our studies we did not explicitly represent the encoder and decoder-rather these are represented by zero-order-hold (ZOH) and sample and hold (S/H) circuits, respectively. As discussed earlier this work consider the data dropout in the communication. Dropout during the data transmission is always unpredictable. Reliable transmission protocols, such as Transmission Control Protocol (TCP) which provides mechanisms for re-transmission of lost data again, guarantees the eventual delivery of packets. Eventhough, re-transmission of old data is generally not very useful for NCSs [8], in this analysis TCP is assumed only to acknowledge data dropout event to the sending end. This is used to reset both of the reduced copy at the same time instances, but not for the re-transmission as will be elaborated in the next section.

Characteristics of packet dropout over a network usually follows a stochastic process known as burst noise. Stochastic model can be used to model the error process in a communication channel. The most complex and detailed 2-state Markov process called the Gilbert- Elliott model is shown in Fig. 4. The readers are referred to a modeling adequacy analysis of the NCPS that was performed by the authors in [9].

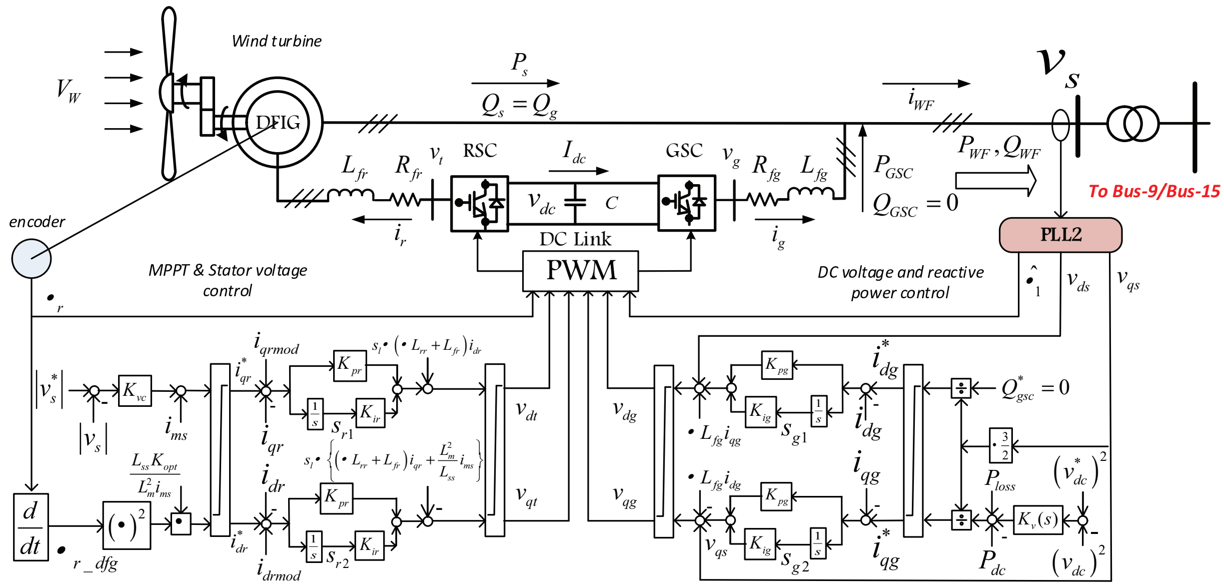

Fig. 3. Schematic of the DFIG-based WFs with its controllers. The WFs are connected to the power system as shown in Fig.2.

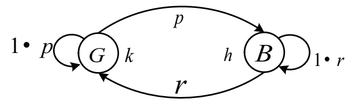

Fig. 4. Gilbert-Elliott data dropout models in the communication link.

This model considers two states: the good (G) and the bad (B) states. Each of them may generate errors as independent events with the state dependent error rates, $1-k$ and $1-h$ in the good and the bad states, respectively. The transition probabilities between the states are defined by, p: G-state to B-state, r: B-state to G-state. The stationary state probabilities P_G and P_B exist for $0<(p,r)<1$ from which the error rate P_E and the packet delivery rate (R) of the transmission channel can be obtained in steady state as:

$$\begin{aligned} P_G &= r/(p+r), P_B = p/(p+r) \\ P_E &= (1-k)P_G + (1-h)P_B \\ R &= (1-P_E)\times 100\% \end{aligned} \tag{1}$$

When $k=1$, $h=0$ and $p+r=1$ gives the Bernoulli model.

As shown in the Fig. 1, the estimated states $(\bar{x}(t))$ of the observer is sampled at times $\{t_k : k \in N\}$ and the samples $\bar{x}(k)=\bar{x}(t_k)$ are sent through the communication network (in the case of ORC approach discussed next). It is often assumed that when the packet containing the sample $\bar{x}(k)$ is dropped the NCS communication network utilizes the previous value of $\bar{x}_n(k)$. This corresponds to replacing the lossless network model by: $\forall k \in N$

$$\bar{x}_n(k) = \theta_k \bar{x}(k) + (I-\theta_k)\bar{x}_n(k-1) \tag{2}$$

where $\theta_k = diag(\theta_k^1, \theta_k^2, ..., \theta_k^n)$ is binary diagonal random matrix, each θ_k^i follows a stochastic random variation with the understanding that $\theta_k^i = 1$ (having a probability of $(1-P_E)$) signifies that the measurement $x_n^i(k)$ sent at time k reaches its destination and that $\theta_k^i = 0$ (having a probability of P_E) when it does not, and I is the identity matrix of same size as θ_k.

III. Proposed ORC Approach

As shown in Fig. 1, if conventional feedback (Grey colored) is employed, the measured signals $(y_m(k))$ from the remote PMUs are communicated to the WFs. Data dropout higher than a threshold could lead to unacceptable system response as illustrated in Section V. When the data packets are dropped out in the communication link, special measures will be needed for oscillation damping control. ORC approach [10], [11] addresses this problem by exploiting the knowledge of the nominal system to predict the dynamic behavior of the system when data-packet drop occurs.

$$G_n = \left[\begin{array}{c|c} A_n & B_n \\ \hline C_n & 0 \end{array}\right] \tag{3}$$

An observer at each sensor location uses the reduced-order linearized model (G_n) of the system to estimate the states $(\bar{x}(t))$ which will be sent over the communication network, instead of $y_m(t)$, to the WF, see Fig. 1. For each feedback signal the corresponding control input at the actuator location $(u(t))$ and the sensor locations $(\bar{u}(t))$ are calculated using two different reduced order models of the power system at each place, (see Fig. 1). We call this model as 'reduced copy of system model' or simply 'reduced copy'. The reduced copy is described by:

$$\dot{x}_n(t) = A_n x_n(t) + B_n u(t) \tag{4}$$

The states of the 'reduced copy' at the actuator locations and the sensor locations are reset by $\bar{x}(t)$. Since data dropout in the communication channel is a stochastic phenomena, the interval between two consecutive resetting $t_{k+1}-t_k = h$ $\forall k = 0,1,...$ will encounter stochastic variations, thereby, resetting the states at unequal interval. When data packets drop out in the communication network and fails to reach the WF, the states of both of the reduced copy are allowed to evolve naturally, otherwise with the knowledge of the TCP, the proposed ORC architecture is switched on to reset the states of both reduced copy, leading to a switched control strategy. This strategy is refereed as an ORC approach in this paper.

A. LQR-based Controller

The linearized system has three poorly damped inter-area modes and the objective of the controller is to damp these inter-area modes. To establish this control function a Linear Quadratic Regulator (LQR) is located at the WF. To that end, a reduced order Luenberger type observer is used (see Fig. 1). The state-space model of the observer is given by:

TABLE I
COMPARISON OF INTER-AREA MODES OF THE SYSTEM WITH SG-PSS, DFIG AND DFIG-PSS.

$Case$	$SG-PSS$		$DFIG$		$DFIG-PSS$	
$mode$	$\xi,\%$	f,Hz	$\xi,\%$	f,Hz	$\xi,\%$	f,Hz
#1	6.50	0.38	2.20	0.42	14.10	0.42
#2	4.40	0.50	4.40	0.51	10.20	0.51
#3	5.70	0.62	4.50	0.62	9.80	0.62
#4	5.00	0.79	–	–	–	–

TABLE II
MODAL CONTROLLABILITY OF DFIG ROTOR CURRENTS.

$Modes$		#1	#2	#3
$G9$	i_{drmod}	0.640	0.026	0.695
$G9$	i_{qrmod}	0.322	0.091	0.010
$G15$	i_{drmod}	0.464	0.018	0.505
$G15$	i_{qrmod}	0.195	0.041	0.012

$$\begin{aligned}\dot{\bar{x}}(t) &= A_n\bar{x}(t) + B_n\bar{u}(t) + L(y_m(t) - \bar{y}(t)) \\ \bar{y}(t) &= C_n\bar{x}(t)\end{aligned} \tag{5}$$

where, L is the observer gain. The state-feedback control law is given by:

$$u(t) = -Kx_n(t) \tag{6}$$

Here $u(t)$ is the modulating signal i_{drmod} or i_{qrmod} in Fig. 3 and K, the state-feedback controller gain vector, is calculated using LQR to minimize the control effect.

B. Overal System Dynamics and Stability

Let us consider the state-space model of the power system under off-nominal operating condition (e.g. line outage) is denoted by:

$$G_i = \left[\begin{array}{c|c} A_i & B_i \\ \hline C_i & 0 \end{array}\right] \tag{7}$$

where, $A_i = A_n + \tilde{A}$, $B_i = B_n + \tilde{B}$, $C_i = C_n + \tilde{C}$ and $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ represent the deviation from the nominal operating condition. The states of G_i is denoted as $x_i(t)$. We define an error $e(t_k) = \bar{x}_i(t_k) - x_n(t_k)$ during the time interval $t \in [t_k, t_{k+1})$, $t_{k+1} - t_k = h$, which is the difference between the observer states and the states of the reduced copy. Including $e(t)$ one can describe the overall system dynamics as:

$$\begin{bmatrix}\dot{x}_i \\ \dot{\bar{x}} \\ \dot{e}\end{bmatrix} = \begin{bmatrix} A_i & -B_iK & B_iK \\ LC_i & A_n - LC_n - B_nK & B_nK \\ LC_i & -LC_n & A_n\end{bmatrix}\begin{bmatrix}x_i \\ \bar{x} \\ e\end{bmatrix} \tag{8}$$

Frequency of inter-area modes usually lie between $0.2 - 1.0$ Hz, therefore according to Nyquist-Shannon sampling theorem the minimum required sampling rate of the system is at least $2Hz$. In this paper, sampling rate of PMUs and the data transmission rate of the communication network are assumed to be $50Hz$ and $10Hz$, respectively.

C. Bound on the Inter-sample Error Norm

Accuracy of estimated states by the reduce copy would go down when the system is under off-nominal condition and the communication channels have large data dropout. Therefore, it would be useful to estimate the state trajectories of the reduced copy during inter-sample interval. From equation (9), assuming that the observers are able to correctly estimate he system states, one can derive an approximated expression for the maximum error norm during the inter-sample interval as:

$$\|E(t^*)\| \propto K_1 \left\|\tilde{A} - \tilde{B}K\right\| + K_2 \|I - \theta\| \tag{9}$$

Due to the space constrains in this paper we report only the final expression . Detailed derivation will be reported in a full paper in future.

It can be seen that from (9) the maximum error bound is proportional to the model mismatch and the data dropout in the communication link i.e there are constant K_1 and $K_2 \in R$. This relation verifies that the performance of the proposed ORC based controller deteriorates with increases in the model mismatch and data drop out.

TABLE III
MODAL OBSERVABILITY OF LOCAL AND REMOTE POWER-FLOW SIGNALS.

$mode$	#1		#2		#3	
P_{line}	SG	$DFIG$	SG	$DFIG$	SG	$DFIG$
P_{G9}	0.078	0.001	0.017	0.001	0.032	0.001
P_{G15}	0.284	0.001	0.229	0.001	0.008	0.001
P_{14-41}	0.191	0.198	0.813	1.000	0.015	0.016
P_{27-37}	0.072	0.028	0.238	0.017	0.069	0.075

IV. CONVENTIONAL FEEDBACK CONTROL

As shown in the Fig. 1 (in grey), a conventional feedback controller is employed to damp the inter-area power oscillation where the measure signals ($y_m(t)$) from the remote PMUs are communicated to the actuator location. The Luenberger type observer (discussed in the Section III-A) at the actuator location uses the decoded signal ($\bar{y}_m(t)$) to estimate the states of the system and the LQR-based controller is used to produce the control input $u(t)$ to the actuator.

V. SIMULATION RESULTS AND DISCUSSION

Here, the frequency domain analysis and the time domain simulation results are presented to analyze the impact of replacing SG-PSS by DFIG-based WF on system modes and the performance of the proposed ORC under different data receiving rates with different operating conditions.

A. Modal analysis and Control Loop Selection

As mentioned in the Section III-A, the linearized system has three inter-area modes with frequencies (f) in the range of $0.4 - 0.7\ Hz$ and several local modes. From the eigenvalue analysis it is observed that when the SG with PSS at G9 and G15 is replaced by DFIGs, the damping ratio (ξ) of two inter-area modes (mode #1 and #3) become poorer while mode #3 is unaffected and mode #4 ceased to exit. Also, the frequency of mode #1 and #3 are increased whereas that of the other mode is mostly unchanged, see Table I. This analysis indicating the need of PSSs at G9 and G15. As discussed in the Section. II-B, the current control strategy is used to control the RSC of DFIG. Therefore the d and q components of the rotor currents are selected as the modulation signals. Table II shows the modal controlability of rotor current. i_{drmod} of G9 i_{qrmod} of G15 is selected as the control inputs.

The control objective of the DFIG-PSS is to damp the inter-area oscillations of the system using modulation signals of the rotor currents. Selection of the feedback signal with better observability for these three inter-area modes is needed for effective control action. Table III compares the normalized modal observability of few line real power flows in the SG-PSS case and DFIG without PSS case. It can be seen that the DFIG stator powers P_{G9} and P_{G15} have significantly less observabilities compare to the case of SG-PSS for all the three modes. This clearly implies that the P_{G9} and P_{G15} are not a better feedback signal for effective damping performance. In this case tie line flows P_{27-37} and P_{14-41} are selected as the feedback signals ($y_m(t)$) based on using residue magnitude-angle criteria as mentioned in [12] for $G9$ and $G15$, respectively. The controller is designed as explained in Section. III-A. As shown in Table I, the DFIG-PSS damps the inter-area modes better than SG-PSS.

Next, the impact of data-packet drop in the communication network is considered and Nonlinear time domain simulation is carried out in MATLAB/SIMULINK to demonstrate the effectiveness of the proposed ORC approach (Section III) over the conventional feedback (Section IV).

B. Performance of ORC

As proposed in Section. III, the ORC is embedded in the system for both of the feedback signals (P_{27-37} and P_{14-41}). The time-domain simulation of the closed-loop system is tested with different operating conditions and data receiving rate (R) in the communication channel, see equation (1).

1) Effect of Communication Data Dropouts on ORC: In this case study, self-clearing fault in the nominal system is considered to avoid any possible deterioration caused by the off-nominal condition. The system responses with ORC, for data receiving rates of 100, 50 and 25% is compared against feedback controller response with 50 and 25% receiving rates following a three-phase self-clearing fault near bus 60, see Fig. 5, which reveals that the system with feedback controller is going unstable below certain data receiving rates. On the other hand the system with ORC for low data receiving rates produces satisfactory damping performance. Also, the performances of ORC is almost similar for 25%, 50% and 100% data receiving rates. Therefore, ORC approach is capable of dealing with the low data receiving rate under the nominal condition.

2) Impact of Operating Condition on ORC: Since the control design and the reduced copy is based on the nominal condition, it would cause poorer behavior of ORC under off-nominal operating condition (e.g. following line outages). To study the effect of the operating condition on the ORC performance, system response after a three-phase fault near bus 40 for 20 ms followed by the outage of one of the tie-lines between buses 40-41 is compared against the conventional feedback controller, Fig. 6, which reveals that the ORC is still produces acceptable response.

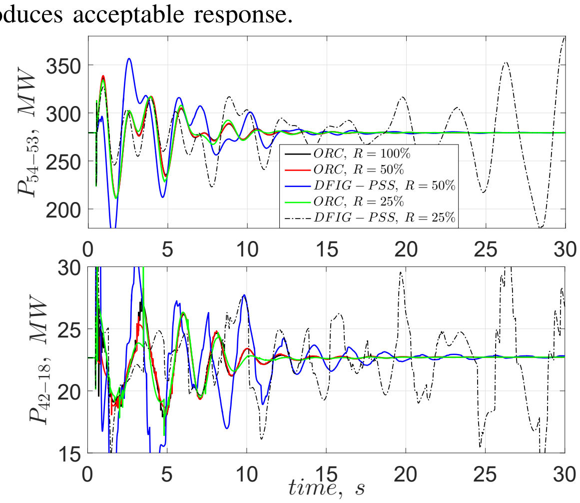

Fig. 5. Dynamic performance of the system for different data receiving rates (R) following a three-phase fault at 0.5 s near bus 60 for 20 ms. ORC: proposed approach. DFIG-PSS: conventional feedback approach.

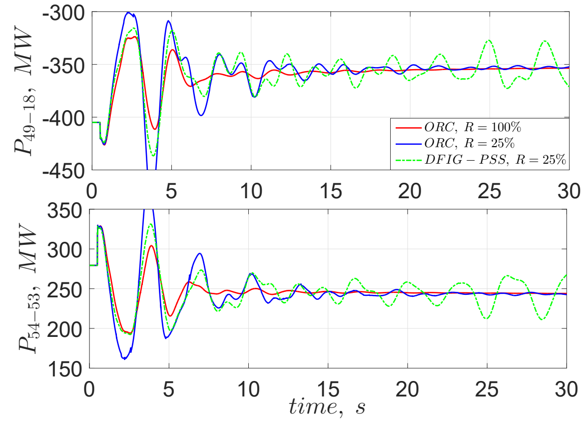

Fig. 6. Dynamic performance of the system after a three-phase fault at 0.5 s near bus 60 for 20 ms following by the outage of one of the tie-lines between buses 40-41. ORC: proposed approach. DFIG-PSS: conventional feedback approach.

VI. Conclusion

In this paper, the effect of replacing SGs in reduced model of New England-New York power system by DFIG-based WFs on system modes is analyzed. A systematic way of choosing remote feedback signals from PMUs is presented. A detailed characterization of communication process with packet loss probability using Gilbert-Elliott model is performed in NCS. An Observer-driven Reduced Copy (ORC) approach with LQR based controller is proposed here to deal with high data drop in the communication. Significantly better performance compared with conventional feedback controller is validated using the nonlinear time-domain simulation. In the future work extensive study on ORC performance will be analyzed.

References

[1] American Physical Society's Panel on Public Affairs (POPA), Tech. Rep. Nov 2010. "Integrating Renewable Electricity on the Grid,".

[2] N. R. Chaudhuri and B. Chaudhuri, "Considerations toward coordinated control of dfig-based wind farms," in *IEEE Transactions on Power Delivery*, vol. 28, no. 3, 2013, pp. 1263–1270.

[3] N. R. Chaudhuri, D. Chakraborty, and B. Chaudhuri, "An architecture for facts controllers to deal with bandwidth-constrained communication," *IEEE Transactions on Power Delivery*, vol. 26, no. 1, pp. 188–196, 2011.

[4] N. R. Chaudhuri, D. Chakrabarty, and B. Chaudhuri, "Damping control in power systems under constrained communication bandwidth: A predictor corrector strategy," *in Early Access in IEEE Transactions on Control Systems Technology*, vol. 20, no. 1, pp. 223–231, Jan 2012.

[5] A. Singh, R. Singh, and B. Pal, "Stability Analysis of Networked Control in Smart Grids," *IEEE Transactions on Smart Grid*, vol. 6, pp. 381–390, 2015.

[6] J. G. Slootweg, H. Polinder, and W. L. Kling, "Dynamic modelling of a wind turbine with doubly fed induction generator," in *IEEE Power Engineering Society Summer Meeting, 2001*, vol. 1, 2001, pp. 644–649 vol.1.

[7] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," *IEE Proceedings on Electric Power Applications*, vol. 143, no. 3, pp. 231–241, 1996.

[8] J. Hespanha, P. Naghshtabrizi, and Y. Xu, "A survey of recent results in networked control systems," *Proceedings of the IEEE*, vol. 95, pp. 138–162, 2007.

[9] Y. Amirthagunaraj, K. Jagdeep, and N. R. Chaudhuri, "Modeling Adequacy for Studying Power Oscillation Damping in Grids with Wind Farms and Networked Control Systems (NCS)," in *IEEE Power Energy Society General Meeting, 2016*, accepted and to be presented, pp. 1–5.

[10] L. A. Montestruque and P. J. Antsaklis, "On the model-based control of networked systems," *Automatica*, vol. 39, no. 10, pp. 1837–1843, 2003.

[11] P. V. Zhivoglyadov and R. H. Middleton, "Networked control design for linear systems," *Automatica*, vol. 39, no. 4, pp. 743–750, 2003.

[12] S. Ray, B. Chaudhuri, and R. Majumder, "Appropriate signal selection for damping multi-modal oscillations using low order controllers," 2008, pp. 1–7.