

# An unknown input observer based framework for wide-area control of inter-area oscillations with local measurement

Abhilash Patel \*, Sandip Ghosh \*\*

\* *Department of Bioengineering, Imperial College London (e-mail: [abhilash.patel@imperial.ac.uk](mailto:abhilash.patel@imperial.ac.uk))*

\*\* *Department of Electrical Engineering, Indian Institute of Technology (BHU) Varanasi (e-mail: [sghosh.eee@iitbhu.ac.in](mailto:sghosh.eee@iitbhu.ac.in))*

**Abstract:** Inter-area oscillations in power system limit the power transfer capability through tie-lines. For stable operation, wide-area power system stabilizers are deployed to provide sufficient damping. However, as the feedback is through a communication network, it brings challenges such as additional communication layers and cybersecurity issues. To address this, a framework for synthesizing remote signals from local measurement as feedback in the wide-area power system stabilizer is proposed. The remote signal is synthesized using different variants of observers in a case study of a two-area benchmark system. The proposed framework can improve the damping of inter-area oscillations for static output feedback controller. The presented framework should help to design attack-resilient controller design in smart grid.

Copyright © 2022 The Authors. This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>)

**Keywords:** wide-area controller, observer, power system stability

## 1. INTRODUCTION

With an increase in power demand and installation of distributed energy sources in the grid, the stability of power transfer to distant geographical locations has evolved into a challenging issue. Oscillations in a power system can limit the power transfer capability between different areas. These oscillations are contributed by different modes of system dynamics. One example of such modes is an electromechanical mode, which is characterized by low frequency. In general, these electromechanical modes are poorly damped, raising a threat to system stability under limiting power transfer. These electromechanical modes are further grouped as local modes and inter-area modes based on their participation in the system states. In local modes, synchronous machines in one area oscillate against the synchronous machines from the same area and in inter-area modes, machines from one area oscillate against machines from another area connected through a tie-line Klein et al. (1991). To damp the local modes, local power system stabilizer (PSS) with feedback of local measurements are used. However, as the inter-area modes are relatively less observable in local signals, a combination of remote and local signals are being used as feedback to design a wide-area power system stabilizer Aboul-Ela et al. (May 1996). The objective of a wide-area power system stabilizer is to increase the damping of inter-area modes using the measurement from both the local area as well as a remote area.

The remote signals are usually measured by the phasor measurement unit of the wide-area measurement system in the grid Phadke and de Moraes (2008). These measurements are used for control, monitor and protection purposes Chakraborty and Khargonekar (2013). The use of the remote signal along with local signal could damp the inter-area oscillations effectively

However, as the sharing of information is through a network, it can be vulnerable to cyber-attack Ashok et al. (2017); Marinovici and Chen (2019). It has been noted that such attack in the communication channel can lead to instability in the system or degraded performances.

In this letter, we aim to develop a framework that can be used to damp inter-area oscillations using local measurement. In this scenario, the remote signals are synthesized from local measurement using observer from control theory. The convergence of error can be ensured using Lyapunov based analysis. Such a framework increases the grid resilience towards attack in communication as well as reduces the requirement of abundant sensors.

## 2. A BENCHMARK SMART GRID

The benchmark two-area system Kundur (2006) (Fig. 1) is considered in this study. The power system network has 11 buses and 4 generators (Fig. 1). Two areas connected by a weak tie-line to transfer power. Each area of the system consists of two generators and Local PSSs are installed at  $G_1$  and  $G_3$  terminals to provide sufficient damping of local modes. However, it is to be noted that Aboul-Ela et al. (May 1996), such local controllers are insufficient to improve inter-area damping without a wide-area signal as feedback. The system is modeled in PST and linearized around an equilibrium point. In general the linearized model of this system can be written as,

$$\begin{aligned}\dot{x} &= Ax + Bu + Ed, \\ y_l &= C_l x, \\ y_r &= C_r x,\end{aligned}\tag{1}$$

where  $x$  is system states,  $u$  is the input,  $d$  is the disturbance,  $y_l$  is the local output and  $y_r$  is the remote output. The matrices  $A$ ,  $B$ ,  $E$ ,  $C_l$ ,  $C_r$  are of appropriate dimensions.

The low-frequency swing modes are identified with participation analysis Kundur (2006). The modes which have higher participation of electromechanical states  $\delta_i$ ,  $\Delta\omega_i$  ( $\delta$  is the rotor angle,  $\Delta\omega$  is the speed deviation of the synchronous machines) states are the swing modes. The swing modes come out to be  $M_1 : -0.037 \pm j3.90$ ,  $M_2 : -1.03 \pm j6.8$ ,  $M_3 : -0.81 \pm j7.2$ . The damping of the  $M_1$  is found out to be 0.009, which needs to be improved. It is to be noted that states of  $G_1$  and  $G_3$  which are farthest from the tie-line have higher participation in the inter-area mode.

To avoid the adverse effect of inter-area damping injection to other modes of the system, the wide-area loop is selected which has higher controllability and observability corresponding to the inter-area mode. This is done by geometrical measures, following Hamdan and Elabdalla (1988), as:

$$LSI_{mm} = \frac{|b_m^T v_l| |c_n v_r|}{\|b_m\| \|v_l\| \|c_n\| \|v_r\|}$$

where  $v_l$  and  $v_r$  are the left and right eigenvector corresponding to the inter-area mode respectively;  $b_m$  represents the column vector of  $m^{th}$  input;  $c_n$  represents the row vector of  $n^{th}$  output. As  $\Delta\omega_{24}$  for feedback signal and  $G_2$  for input has the highest Loop Selection Index (LSI), it is selected as the wide-area loop.

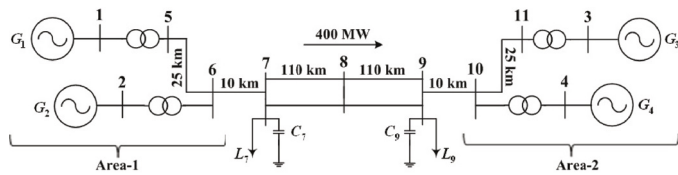


Fig. 1. The 4 Machine 11 Bus study system Kundur (2006)

### 3. REMOTE SIGNAL SYNTHESIS USING OBSERVER

To illustrate the framework, Luenberger observer structure is considered to estimate the states of the system. These estimated states are mapped into the remote signal estimate using the system model. The Luenberger observer with output mapping can be written as,

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + L(y_l - C_l\hat{x}) \\ \hat{y}_r &= C_r\hat{x} \end{aligned} \quad (2)$$

where  $\hat{x}$  is the estimated system,  $\hat{y}_r$  is the estimated remote measurement, and  $L$  is the observer gain. The error is defined between the estimated values and actual values as,

$$e(t) = x(t) - \hat{x}(t). \quad (3)$$

For the system (1) and observer (4), the error dynamics is

$$\dot{e} = (A + LC)e + Ed = A_{cl}e + Ed \quad (4)$$

The qualitative behavior of the error dynamics can be inferred from Lyapunov based analysis Khalil (2002). Consider a quadratic Lyapunov function,

$$V(e) = e^T P e \quad (5)$$

and the time-derivative of Lyapunov function is,

$$\begin{aligned} \dot{V}(e) &= \dot{e}^T P e + e^T P \dot{e} \\ &= e^T (PA_{cl} + A_{cl}^T P + E^T P E + P E) e \\ &= e^T Q e + d^T P E^T E P d \\ &< \lambda_{\min}(Q) \|e\|^2 + \|E P d\|^2 \\ &< \frac{\lambda_{\min}(Q)}{\lambda_{\max}(P)} V + \|E P d\|^2 \end{aligned} \quad (6)$$

In the absence of disturbance, the error converges to zero exponentially. The convergence rate can be increased by increasing the minimum eigenvalue of  $Q$  or decreasing the maximum eigenvalue of  $P$ . Such results termed as exponential stability of error dynamics Khalil (2002). However, in the presence of a disturbance, the error may not be zero, but the stability of the error dynamics retain in the sense of input-to-state stability. The observer gain is designed such that  $A + LC$  meets Hurwitz criterion. This is to ensure the eigenvalues of  $Q$  are negative.

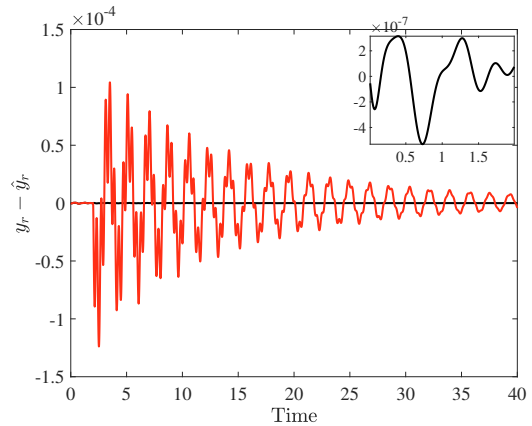


Fig. 2. The difference between the estimated remote signal and the actual remote signal. The black line represents the performance without any disturbance and red line represents the performance in presence of disturbance.

The observer is implemented in the benchmark two-area system. The local measurement  $\Delta\omega_2$  is measured and used to estimate the remote measurement of  $\Delta\omega_4$ . The observer can estimate the remote signal in the absence of disturbance. To verify in simulation, different initial conditions were selected, and error converges to zero as shown in Fig. 2. The disturbance is simulated by changing the mechanical power input as a pulse in the  $G_2$  terminal. In the presence of disturbance, the error does not converge to zero. Perhaps, this is due to the lack of information on disturbance to the observer. This non-zero and prolonged transient in error can deteriorate the performance of wide-area control.

### 4. REMOTE SIGNAL SYNTHESIS USING OBSERVER IN PRESENCE OF DISTURBANCE

To address the shortcoming of Luenberger observer, a different structure of observer is adopted which can undertake disturbance while estimating the states Chen and Patton (2012). The observer structure is,

$$\begin{aligned} \dot{z} &= Fz + T B u + K y \\ \hat{x} &= z - H y \\ \hat{y}_r &= C_r \hat{x} \end{aligned} \quad (7)$$

The error dynamics is

$$\begin{aligned}\dot{e} &= \dot{x} - \dot{\hat{x}} \\ &= (I + HC)(Ax + Bu + Ed) - (Fz + TBu + Ky) \\ &= (MA - KC)x + (MB - TB)u + ME d - F(Mx - e) \\ &= Fe + (MA - KC - FM)x + (MB - TB)u + ME d\end{aligned}\quad (8)$$

From the error dynamics, existence conditions can be noted as follows,

- (1)  $ME = 0 \implies (I + HC)E = 0 \implies H = -E(CE)^{-1}$
- (2) The pair  $(MA, C)$  must be detectable
- (3)  $MB = TB$
- (4)  $MA - KC - FM = 0 \implies F = MA - LC$  where  $L = K + FH$

If these existence conditions are satisfied, the error dynamics reduced to,

$$\dot{e} = (MA - LC)e \quad (9)$$

The convergence of the error dynamics can be exploited using Lyapunov theory. Consider a Lyapunov function

$$V(e) = e^T P e \quad (10)$$

and For the error to be zero in time,  $\dot{V}(e) < 0$ , where

$$\begin{aligned}\dot{V}(e) &= e^T P \dot{e} \\ &= \dot{e}^T P e + e^T P \dot{e} \\ &= e^T (A^T M^T P + PMA - C^T L^T P - PLC)e \\ &= e^T Q e.\end{aligned}\quad (11)$$

The estimation error will converge to zero if  $A^T M^T P + PMA - C^T L^T P - PLC < 0$ . However, this inequality is bilinear in nature and difficult to solve. The inequality can be transformed into a linear form by considering  $R = PL$ . Hence the following equations need to be solved for obtaining the observer gain,

$$\begin{aligned}A^T M^T P + PMA - C^T R^T - R^T C &< 0 \\ L &= P^{-1}R.\end{aligned}\quad (12)$$

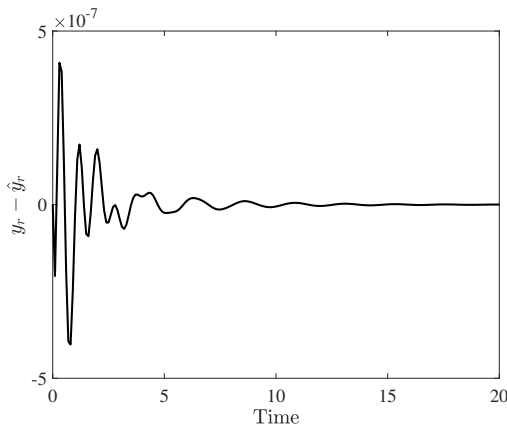


Fig. 3. The difference between estimated remote signal and actual remote signal.

The extended observer is implemented in the same benchmark two-area system. The local measurement  $\Delta\omega_2$  is measured and used to estimate the remote measurement of  $\Delta\omega_4$ . As illustrated in Fig. 3 the observer successfully estimated the remote

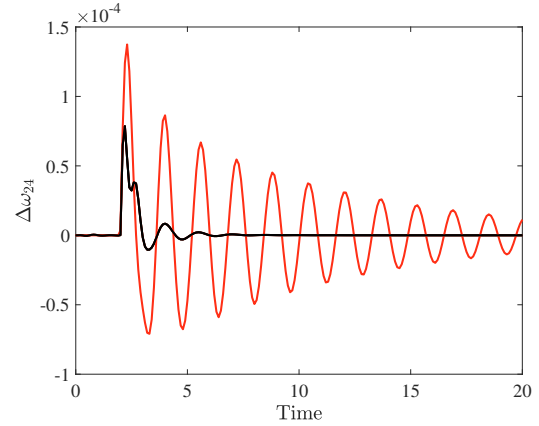


Fig. 4. Performance of wide-area power system stabilizer for local signal measurement and synthesized remote signal as feedback. Red line indicates performance without any wide-area controller and black line indicated performance of wide-area controller with synthesized remote signal.

signal even in the presence of disturbance. The disturbance is simulated by changing the mechanical power input as a pulse in the  $G_2$  terminal. The synthesized remote signal and locally measured signal are fed to a static wide-area controller to validate the ability to damp inter-area oscillations. It can be noted the controller can damp out the oscillations quickly within two cycles.

## 5. REMOTE SIGNAL SYNTHESIS USING OBSERVER IN PRESENCE OF CORRUPTION IN LOCAL MEASUREMENT

In previously described approach, the remote signal synthesis depends on the accuracy of the local signal. The approach may not perform satisfactorily when there is a sensor fault or local signal gets corrupted due to cyber-attack. The system description in this scenario can be,

$$\begin{aligned}\dot{x} &= Ax + Bu + Ed \\ y_l &= C_l x + f\end{aligned}\quad (13)$$

where the  $f(t)$  is the false-data injection attack signal infused to the output measurement. This exogenous signal can be used to model the sensor fault. To address this, we adopted a state augmentation approach where the output signal is passed through a filter as,

$$\dot{x}_a = -ax_a - aC_l x - af. \quad (14)$$

The augmented system can be written as,

$$\begin{bmatrix} \dot{x} \\ \dot{x}_a \end{bmatrix} = \begin{bmatrix} A & 0 \\ -aC_l & -a \end{bmatrix} \begin{bmatrix} x \\ x_a \end{bmatrix} + \begin{bmatrix} 0 \\ B \end{bmatrix} u + \begin{bmatrix} E \\ 0 \end{bmatrix} d \quad (15)$$

## 6. CONCLUSION

In general, to effectively damp inter-area oscillations, a wide-area signal based controller is used. In such a case, remote signals are shared over a communication network. Here, we developed a framework for the smart grid to synthesize the remote signal using local measurement. A standard Luenberger observer lacks the capability to estimate correctly in the presence of disturbance. Hence, another structural observer is applied that can be robust to unknown disturbance. The effectiveness of the proposed framework is validated in a two-area system,

showing the controller can damp out inter-area oscillations rapidly with local measurement only.

#### REFERENCES

- About-Ela, M.E., Sallam, A.A., Mccalley, J.D., and Fouad, A.A. (May 1996). Damping controller design for power system oscillations using global signals. *IEEE Transaction on Power System*, 11(2), 767–773.
- Ashok, A., Govindarasu, M., and Wang, J. (2017). Cyber-physical attack-resilient wide-area monitoring, protection, and control for the power grid. *Proceedings of the IEEE*, 105(7), 1389–1407.
- Chakraborty, A. and Khargonekar, P.P. (2013). Introduction to wide-area control of power systems. In *2013 American Control Conference*, 6758–6770. IEEE.
- Chen, J. and Patton, R.J. (2012). *Robust model-based fault diagnosis for dynamic systems*, volume 3. Springer Science & Business Media.
- Hamdan, A. and Elabdalla, A. (1988). Geometric measures of modal controllability and observability of power system models. *Electric Power Systems Research*, 15(2), 147 – 155.
- Khalil, H.K. (2002). *Nonlinear systems*, volume 3. Prentice hall Upper Saddle River, NJ.
- Klein, M., Rogers, G., and Kundur, P. (1991). A fundamental study of inter-area oscillations in power systems. *IEEE Transactions on Power Systems*, 6(3), 914–921.
- Kundur, P. (2006). *Power System Stability and Control*. McGraw Hill Education (India) Private Limited.
- Marinovici, L.D. and Chen, H. (2019). Framework for analysis and quantification of wide-area control resilience for power systems. *IEEE Transactions on Power Systems*.
- Phadke, A. and de Moraes, R. (2008). The wide world of wide-area measurement. *IEEE Power and Energy Magazine*, 6(5), 52–65. doi:10.1109/MPE.2008.927476.