ELECTRICAL & ELECTRONIC ENGINEERING | RESEARCH ARTICLE

A single machine infinite bus power system damping control design with extended state observer

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Abstract: As an alternative to power system stabilizer, this paper presents a robust controller known as extended state observer (ESO) for synchronous machine connected to an infinite bus (SMIB) power system. The ESO-based control scheme is implemented with an automatic voltage regulator in order to enhance the damping of low frequency power system oscillations so that the deviations in terminal voltage are compensated. The proposed ESO provides the estimates of system state as well as disturbance state together in order to improve the damping as well as compensate system efficiently in presence of parameter uncertainties and external disturbances. The closed-loop poles (CLPs) of the system have been assigned by the symmetrical root locus technique, with the desired level of system damping provided by the dominant CLPs. The performance of the system is analysed through simulating at different operating conditions. The control method is not only capable of providing zero estimation error in steady-state, but also shows robustness in tracking the reference command under parametric variations and external disturbances. Illustrative examples have been provided to demonstrate the effectiveness of the developed methodology.

ABOUT THE AUTHOR

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PUBLIC INTEREST STATEMENT

This paper presents the effect of Extended State Observer-based control scheme to improve the stability and voltage regulation of a SMIB power system through a transmission line. The proposed control scheme is implemented with an Automatic Voltage Regulator (AVR) to enhance the damping of power system low frequency oscillations. The control scheme is simple and inexpensive to implement requiring no additional sensors to measure the power system state variables as well as the state of the external disturbance subjected to the system. By feeding back the disturbance estimate the influence of the disturbance subjected to the system can be compensated. The simulation results show that the control method is capable of providing excellent voltage control and guarantees the stability of the system, thereby supporting the validity of the proposed model. It also shows robustness under different operating points, external disturbances and system parameter variations.
1. Introduction

Stability and control are one of the key elements in modern power system operations. Due to increasing growth in the consumption of electric power and complexity of the power system operations, viz. physical setups, interconnections, etc., a form of instability has emerged in the system in the form of power oscillations of small amplitude and low frequency (Basler & Schaefer, 2008). Such low frequency oscillations often last for long duration of time in the system and sometimes limit the steady state power transfer (Prasertwong, Mithulananthan, & Thakur, 2012). These oscillations are referred to as small signal stability and they are mainly due to the insufficient damping in the system (Kundur, 1994).

To improve the small signal stability and dynamic quality of power system, the effects of excitation system control has been considered by many researchers (Anderson & Fouad, 2003; Jianshun et al., 2015; Lachman & Mohamad, 2009). That is, the excitation system which includes the exciter and AVR must be able to control the system voltage and keep its value within an acceptable threshold. The design of the IEEE Type-I based voltage regulators (Anderson & Fouad, 2003; Bensenouci & Ghany, 2006) are widely accepted and known to be useful for power system operations. However, following a disturbance due to small variations in load or generations in the system dynamics, the synchronous machines equipped with such regulators have the tendency to introduce negative damping into the system and deteriorate its dynamic performance (Kundur, 1994). To improve the dynamic performance of such system, other feedback loops are usually used in conjunction with the AVR (Bensenouci & Ghany, 2006; Chen & Hsu, 1992). However, the regulator design based on feedback loops and other advanced techniques, such as variable structure control (Aggoune et al., 1994), linear quadratic regulator (Ogata, 2010), artificial intelligence (Holland, 1975), etc., have their own limitations and drawbacks.

Power system stabilizer (PSS) excitation control is one of the widely applied methods in the literature and is designed to improve the power system damping characteristics and small signal stability by utilizing supplementary signals through generator excitation. Numerous control techniques have been proposed for the design of PSS (Canales, Torres, & Chavez, 2014; Gurrala & Sen, 2010; Jagadeesh & Veerraju, 2016; Peng, Zhu, & Nouri, 2011; Tayal & Lather, 2015). However, obtaining all the state variable information of the control system is the main problem associated with the design of PSS. The direct measurements of all the system states are not feasible in power system engineering practices due to measurement restrictions of the equipment and its practicability (Wang, Liang, & Tang, 2011). On the other, the use of sensors to acquire the necessary state variable information is a complicated affair in terms of economy and noise. Therefore, the development of state observer to construct the necessary states is required (Hidayat, Babuska, Schutter, & Nunez, 2011; Wang & Gu, 2016). An observer reconstructs the state variable information and feedbacks all the reconstructed states directly, forming a feasible feedback control law (Liu, Liu, Zhang, & Zhao, 2014). As a result, no additional sensors are needed.

The development in the linear observer theory has paved the path for designing linear observers for power systems (Profeta, Vogt, & Mickle, 1990). In addition to state estimation, such observer can be extended to deal with disturbances (external) and parameter or structure uncertainties (internal) that exists in almost all the physical systems and limit its performance (Gao, 2014; Xie & Guo, 2000). The idea is to estimate the disturbance and then using that reconstructed disturbance estimate for feedback, by control action, so as to compensate the influence of disturbance and parameter uncertainties (Chen, Yang, Guo, & Li, 2016). Based on the disturbance estimation and rejection properties, various design methodologies of linear and non-linear observers have been reported in the literature.
under various names, such as unknown input observer (Basile & Marro, 1969; Johnson, 1971), perturbation observer (Kwon & Chung, 2003), equivalent input disturbance (She, Fang, Ohyama, Hashimoto, & Wu, 2008), disturbance observer (Coelingh, Schrijver, de Vries, & Van Dijk, 2000; Kobayashi, Katsura, & Ohnishi, 2007; Schrijver & Van Dijk, 2002), extended state observer (Gao, 2006; Gao, Huang, & Han, 2001; Han, 1995, 2009; Yang & Huang, 2009), etc. Perhaps, the most extensively investigated and widely applied approach to the disturbance estimation is the ESO. It was first proposed by Han (1995) in order to develop an alternative approach to classical PID control method. It was conceived in the context of active disturbance rejection control to estimate the lumped disturbances comprising of unknown uncertainties and external disturbances. In addition to state and disturbance estimation, ESO requires the minimal amount of plant information (Zheng, Gao, & Gao, 2012). Owing to these promising features, ESO is implemented in various engineering applications (Mehta, Jully, & Tapin, 2015; Wang, Guo, & He, 2009; Wang, Li, Yang, Wu, & Li, 2015; Yao, Jiao, & Ma, 2014; Zheng, Dong, Lee, & Gao, 2009; Zheng & Goforth, 2010).

So far various works based on observer schemes have been reported in the literature. For applying observer methods to power system damping control, few or limited works could be seen. For instance, Saleh and Mahmoud (1995) proposed a full order observer as well as reduced-order observer to dampen low frequency oscillations in power system. Lee and Park (1998) described a reduced-order observer-based variable structure PSS for unmeasurable state variables. Liu et al. (2014) and Tabak, Auloge, and Auriol (2008) extended the design of full and reduced order observer to multimachine power systems to improve the small signal stability. In all the cases, they did not consider the ESO for disturbance estimation under external and parametric uncertainties. However, in Wang and Gu (2016) external disturbance has been considered by treating a resilient extended Kalman filter as a real time state estimator for unavailable state variables, but it is based on transient stability of the power system.

In this work, the design of an ESO is presented for a single machine infinite bus (SMIB) power system to improve the small signal stability and voltage regulation of the system. The ESO based full state feedback control scheme act as a damping controller and provides the estimates of the system state as well as the disturbance state. By feeding back the available disturbance estimate, the input disturbance (external disturbance and parametric uncertainties) is compensated. The system performance is analysed through simulating at three different operating points. The proposed control scheme is simple and effective in obtaining controller gain, based on desired closed-loop pole locations and the ESO gain, based on observer pole locations, which are far away from the controller pole locations. The judicious choice of closed-loop poles at desired locations improves the performance of the system, by providing faster and stable response with zero steady-state error and control over peak overshoots, for driving the step response to meet the performance specifications. The performance specifications under consideration in this paper are percent overshoot, settling time and zero steady-state error of the unit step response of the state-space system. Iterative design steps are provided to ensure satisfactory operations of the system. Simulations are graphed and numerical results were presented further to demonstrate the efficacy of the proposed controller. The proposed controller shows robustness under different operating points, external disturbances and parameter variations.

2. Plant model
The system or plant considered in this work is based on linear model of synchronous machine connected to an infinite-bus through a transmission line. The relationship between various quantities; such as electrical power, speed, torque, etc. can be derived depending on the swing equation view point (Kundur, 1994). Figure 1 shows the one-line circuit diagram of a regulated SMIB through a transmission line power system. It includes exciter and voltage regulator which controls the terminal voltage $V_t$ of the synchronous generator whereas, the voltage of the infinite bus $V$ is held at a fixed nominal value. The power system data are given in Appendix 1.
Figure 2 shows the linear-model of the synchronous machine infinite bus power system (Anderson & Fouad, 2003; Ghany, 2008). The model is built in MATLAB/SIMULINK platform. The SMIB power system is based upon the open-loop transfer function model and it will be introduced in the form of state space vector differential equation,

\[
\dot{x} = Ax + Bu
\]

\[
y = Cx
\]  

(1)

where

\[
A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & 0 & 0 \\ 0 & a_{32} & a_{33} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ b_1 \end{bmatrix}
\]  

(2)

\[
a_{11} = -\frac{K_D}{M}, \quad a_{12} = -\frac{K_1}{M}, \quad a_{13} = -\frac{K_2}{M}
\]

\[
a_{21} = \omega_0, \quad a_{32} = -\frac{K_3 K_4}{r_3}, \quad a_{33} = -\frac{1}{r_3}
\]
The state variables and inputs are chosen as

\[
\mathbf{x} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T = \begin{bmatrix} \Delta \omega_r & \Delta \delta & \Delta E' & \Delta E_f \end{bmatrix}^T
\]

\[
\mathbf{u} = \begin{bmatrix} \Delta T_m & \Delta E_{f_0} \end{bmatrix}^T
\]

Also, the electrical torque and terminal voltage are given as

\[
\Delta T_E = K_1 x_2 + K_2 x_3
\]

\[
\Delta V_t = K_2 x_2 + K_3 x_3
\]

where, \( \Delta \) is small deviation around an operating point, \( V_t/E_{f_0} \) is Terminal/Field voltage, \( T_m/E_f \) is Electrical/Mechanical torque, \( \omega_r/\delta \) is Rotor speed/Rotor angle, \((\cdot)^T\) is transpose of a matrix \((\cdot)\)

In order to reduce the deviations in \( \Delta V_t \) due to disturbances, a voltage regulator is incorporated with the excitation system as shown in Figure 3 (Anderson & Fouad, 2003; Ghany, 2008). Then the state model of open-loop AVR system with \( \Delta V_{\text{ref}} \) and \( \Delta T_m \) taken as reference and disturbance input to the plant, the system state-space representation becomes:

\[
\mathbf{x} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T = \begin{bmatrix} \Delta \omega_r & \Delta \delta & \Delta E' & \Delta E_{f_0} \end{bmatrix}^T
\]

\[
\dot{\mathbf{x}} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 \\
0 & a_{22} & 0 & 0 \\
0 & 0 & a_{33} & a_{34} \\
0 & a_{42} & a_{43} & a_{44} \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\
0 \\
0 \\
0 \end{bmatrix} \begin{bmatrix} \Delta T_m \\
\Delta V_{\text{ref}} \end{bmatrix}
\]

where

\[
a_{34} = \frac{K_3}{r_3}, \quad a_{42} = -\frac{K_4 K_5}{r_E}, \quad a_{43} = -\frac{K_5 K_6}{r_E}, \quad a_{44} = -\frac{K_6}{r_E}
\]

For a conventional AVR system, the output in the state-space can be taken arbitrary. From Equation (8), the terminal voltage \( \Delta V_t \) is taken to be the output and can be represented in matrix form as,

\[
\mathbf{C} = \begin{bmatrix} 0 & K_3 & K_6 & 0 \end{bmatrix} \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T
\]

All the values are in per unit (pu) for the convenience of calculation, except that \( H \) and time constants are in seconds while frequency is in hertz. \( K_i \) through \( K_j \) are parameters depending on the operating condition of the power system and their deduction can be found in (Anderson & Fouad, 2003).

**Figure 3.** IEEE Type-I voltage regulator.
3. ESO based control scheme

Figure 4 shows full state feedback based on ESO with disturbance estimation based control scheme. It is assumed that the state variables $x_1 (\Delta \delta)$, $x_2 (\Delta E')$ are available for measurements, while the measurements of rotor speed $x_1 (\Delta \omega_r)$ and field voltage $x_4 (\Delta E_{fd})$ are assumed to be unavailable. Since observer-based state feedback is much stronger than available output feedback (or static output feedback) (Liu et al., 2014), therefore the observer in Figure 4 is of fifth order system to estimate the entire system states ($x_1, x_2, x_3, x_4$) and disturbance input $d$ (external and parametric uncertainties) to provide estimated variables as $\hat{x}_1, \hat{x}_2, \hat{x}_3, \hat{x}_4$ and $\hat{d}$. The design methodology for the construction of ESO is described in detail at the end of Section 3.1.

The state feedback gains (SFGs) $k_1, k_2, k_3$ and $k_4$ are determined by pole-placement technique assuming that the ESO was not present in the system. The algorithm for the selection of CLPs will be discussed in Section 3.1. For now, denoting the desired CLP locations as $s_{1,2} = -a \pm jb$ (faster poles) and $s_{3,4} = -c \pm jd$ (dominant poles). Once $a, b, c$ and $d$ are known, then $k_1, k_2, k_3$ and $k_4$ can be easily determined using MATLAB “place” command. The method of determining $a, b, c$ and $d$ are discussed at the end of Section 3.1.

3.1. Symmetric root locus method

For a SISO system, the simplified version of the LQR problem is to find control such that the performance index (Franklin, Powell, & Emami-Naeini, 2006; Kailath, 1980)

$$ J = \int_0^\infty \left[ \rho y^2(t) + u^2(t) \right] dt $$

(10)

is minimised for the system (1) where $\rho$ in Equation (10) represents the weighting penalties on the state variables and control input and is of designer’s choice. It can be shown that $J$ will be minimised by the control law $u = -Kx$ and the optimal value of $K$ (SFG) is such that which places the closed-loop (LHP) poles at stable roots of symmetric root locus (SRL) Equation

$$ 1 + \rho G(-s)G(s) = 0 $$

(11)

where $G(s)$ is the open loop transfer function from $u$ to $y$

$$ G(s) = \frac{y(s)}{u(s)} = C(sI - A)^{-1}B $$

(12)
The selection of $\rho$ in (11) influences the locations of the closed-loop poles and hence the selection of the gain matrix $K$. The desired closed loop (controller) poles have been decided, considering the dominant pole locations which provide maximum damping on the SRL diagram to meet the desired performance criteria and based on the technique, state feedback gain matrix $K$ is determined.

The system under consideration provides four sets of complex conjugate pairs of poles and four state feedback gains for a chosen value of $\rho$. Two sets out of four complex conjugate pairs of poles are stable (LHP) pairs and they are the desired closed-loop poles for the system considered. In this case, one pairs of complex conjugate poles are dominant poles while other pairs are non dominant poles. Therefore the values of $a$ and $b$ are the magnitudes of real and imaginary parts of the non-dominant pole pairs, similarly $c$ and $d$ are the magnitudes of the real and imaginary parts of the dominant pole pair.

3.1.1. Design methodology of ESO

For the construction of extended observer, the disturbance signals $d$ (Figure 4) can be thought of as being generated by a fictitious autonomous dynamic system. This $d$ is also termed as input equivalent disturbance $\Delta T_m$ (a deviation in prime motor torque). To obtain an estimate of the fictitious disturbance, we build the estimator with the equations of the fictitious disturbance included. In general, the disturbance obeys

$$\dot{x}_d = A_d x_d$$

$$d = C_d x_d$$

This fictitious disturbance generator $x_d$ can be included in the plant, resulting in the augmented plant. For the system under consideration, it is assumed that external disturbance and parametric perturbation are piecewise constant in time. Then from (13), the disturbance dynamic can be given by $\dot{d} = 0$, resulting in $A_d = 0$ and $C_d = 1$. Combining the plant (1) with disturbance generator, the augmented plant in the state-space model is (Franklin et al., 2006; Schrijver & Van Dijk, 2002),

$$\dot{x}_a = A_a x_a + B_a u$$

$$y = C_a x_a$$

where $x_a = [x^T d]^T$. The augmented matrices are

$$A_a = \begin{bmatrix}
a_{11} & a_{12} & a_{13} & 0 & 0 \\
a_{21} & 0 & 0 & 0 & 0 \\
0 & a_{32} & a_{33} & a_{34} & 0 \\
0 & a_{42} & a_{43} & a_{44} & b_1 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$B_a = \begin{bmatrix}
0 & 0 & 0 & b_1 & 0
\end{bmatrix}^T$$

$$C_a = \begin{bmatrix}
0 & K_5 & K_6 & 0 & 0
\end{bmatrix}$$

If the pair $(A_a, C_a)$ is observable and if system $(A_a, B_a, C_a)$ does not have a zero, Equation (14) will be observable (Franklin et al., 2006) and an observer (or ESO) can be constructed that will compute
system state \( x (x_1, x_2, x_3, x_4, x_5) \) along with the disturbance (external and parametric uncertainty) state \( d \) to provide estimated variables as \( \hat{x} (\hat{x}_1, \hat{x}_2, \hat{x}_3, \hat{x}_4) \) and \( \hat{d} \). If the form \( -\hat{d} \) is added to the control scheme (Figure 4), then it will cancel out the effects of the real disturbance.

To construct the fifth-order ESO, the compatible observer equation on the basis of augmented system (14) is describe by

\[
\dot{x}_o = A_o \dot{x}_o + B_o y + L_o (y - \dot{y}) = A_o \dot{x}_o + B_o y + L_o (y - C_o \dot{x}_o) \quad (18)
\]

By taking Laplace transform, Equation (18) reduces to

\[
\hat{x}_o(s) = [sI - A_o + L_o C_o]^{-1} B_o y(s) + [sI - A_o + L_o C_o]^{-1} L_o y(s) \quad (19)
\]

where \( I \) is a \( 5 \times 5 \) identity matrix and \( L_o = [L_{a1} \ L_{a2} \ L_{a3} \ L_{a4} \ L_{a5}]^T \) is the observer gain. The fifth-order observer driven by output \( y(\Delta V) \) and input \( u \) is standard (Franklin et al., 2006; Gupta, 1975), but the control \( u \) has additional form \( -\hat{d} \) and \( r(\Delta V) \), then

\[
u = -(k_1 \hat{x}_1 + k_2 \hat{x}_2 + k_3 \hat{x}_3 + k_4 \hat{x}_4) - \hat{d} + r \quad (20)
\]

It is assumed that the poles of observer system are at \(-\lambda_o, -\lambda_o, -\lambda_o, -\lambda_o\) and \(-\lambda_d\). The value of \( \lambda_d \) is set \( n \) times faster than \( a \), where \( a \) is the magnitude of real part of the non-dominant complex conjugate poles, i.e. \( \lambda_o \). As a rule of thumb, the observer poles can be chosen to be faster than the controller poles by a factor of 2 to 10 (Choi, 2010). The fifth pole \( \lambda_d \) (real) of the observer due to disturbance dynamic has been placed such that the desired performance criteria are satisfied.

From (19), the estimated variables \( \hat{x}_1(s), \hat{x}_2(s), \hat{x}_3(s), \hat{x}_4(s) \) and \( \hat{d}(s) \) are obtained as:

\[
\begin{align*}
\dot{x}_1(s) &= A_o(s) y(s) + B_o(s) u(s) \\
\dot{x}_2(s) &= C_o(s) y(s) + D_o(s) u(s) \\
\dot{x}_3(s) &= E_o(s) y(s) + F_o(s) u(s) \\
\dot{x}_4(s) &= G_o(s) y(s) + H_o(s) u(s) \\
\dot{d}(s) &= I_o(s) y(s) + J_o(s) u(s)
\end{align*} \quad (21-25)
\]

where

\[
\begin{align*}
A_o(s) &= \frac{a_{o5} s^5 + a_{o4} s^4 + a_{o3} s^3 + a_{o2} s^2 + a_{o1} s + a_{o0}}{d_{o5} s^5 + d_{o4} s^4 + d_{o3} s^3 + d_{o2} s^2 + d_{o1} s + d_{o0}} \\
B_o(s) &= \frac{b_{o5} s^5 + b_{o4} s^4 + b_{o3} s^3 + b_{o2} s^2 + b_{o1} s + b_{o0}}{d_{o5} s^5 + d_{o4} s^4 + d_{o3} s^3 + d_{o2} s^2 + d_{o1} s + d_{o0}} \\
C_o(s) &= \frac{c_{o5} s^5 + c_{o4} s^4 + c_{o3} s^3 + c_{o2} s^2 + c_{o1} s + c_{o0}}{d_{o5} s^5 + d_{o4} s^4 + d_{o3} s^3 + d_{o2} s^2 + d_{o1} s + d_{o0}} \\
D_o(s) &= \frac{d_{o5} s^5 + d_{o4} s^4 + d_{o3} s^3 + d_{o2} s^2 + d_{o1} s + d_{o0}}{d_{o5} s^5 + d_{o4} s^4 + d_{o3} s^3 + d_{o2} s^2 + d_{o1} s + d_{o0}}
\end{align*} \quad (26-27)
\]
The expressions for the coefficients in Equations (26 through 30) are obtained using MATLAB (Figure 5).

\[
E_o(s) = \left\{ \frac{e_{o1}s^3 + e_{o2}s^2 + e_{o3}s + e_{o4}}{d_5s^5 + d_4s^4 + d_3s^3 + d_2s^2 + d_1s + d_0} \right\} \tag{28}
\]

\[
F_o(s) = \left\{ \frac{f_{o1}s^4 + f_{o2}s^3 + f_{o3}s^2 + f_{o4}s + f_{o5}}{d_5s^5 + d_4s^4 + d_3s^3 + d_2s^2 + d_1s + d_0} \right\} \tag{29}
\]

\[
G_o(s) = \left\{ \frac{g_{o1}s^4 + g_{o2}s^3 + g_{o3}s^2 + g_{o4}s + g_{o5}}{h_{o1}s^5 + h_{o2}s^4 + h_{o3}s^3 + h_{o4}s^2 + h_{o5}s + h_{o6}} \right\} \tag{30}
\]

\[
H_o(s) = \left\{ \frac{h_{o1}s^5 + h_{o2}s^4 + h_{o3}s^3 + h_{o4}s^2 + h_{o5}s + h_{o6}}{d_5s^5 + d_4s^4 + d_3s^3 + d_2s^2 + d_1s + d_0} \right\}
\]

The expressions for the coefficients in Equations (26 through 30) are obtained using MATLAB (Figure 5).

Figure 5. Block diagram of fifth-order extended state observer.
To obtain the value of $N$ in order to achieve unity steady state gain (with ESO implemented in the loop as shown in Figure 4), the overall transfer function ($G_{cl}$) has to be evaluated as $\Delta V_t/\Delta V_{ref} = NG_{cl}(s)$, $s \to 0$ and the value of $N$ is determined. Another way is to simply multiply the input $r (\Delta V_{ref})$ by a gain factor

$$N = \frac{1}{-C(A - BK)^{-1}B}$$

(31)

5. Simulation and results

With an objective to improve the damping characteristics and no voltage ($\Delta V$) deviations in steady-state, an ESO has been designed for SMIB power system model. The performance studies of ESO are evaluated on MATLAB/SIMULINK platform. The simulations were conducted through three different operating conditions (normal, heavy and light load) of the power system. Table 1 shows the change of the operating conditions (with respective power system constants) in terms of generated power $P_t$ and terminal voltage $V_t$ (Anderson & Fouad, 2003; Bensenouci & Ghany, 2006).

Table 1: Operating conditions with associated power system constants for simulation studies

| Load           | $P_t$ | $V_t$ | $\cos\phi$ | $K_1$   | $K_2$   | $K_3$  | $K_4$  | $K_5$  | $K_6$  |
|----------------|-------|-------|-------------|---------|---------|--------|--------|--------|--------|
| Normal (OP1)   | 1.0   | 1.0   | 0.85        | 1.0751  | 1.2578  | 0.3072 | 1.7124 | -0.0477| 0.4971 |
| Heavy (OP2)    | 1.2   | 0.9   | 0.85        | 0.7021  | 1.2583  | 0.3072 | 1.6881 | -0.1742| 0.4629 |
| Light (OP3)    | 0.8   | 1.2   | 0.85        | 1.4074  | 1.1981  | 0.3072 | 1.6454 | 0.0741 | 0.5487 |

The simulation of SMIB power system is first started with voltage regulator described in Section 2 under normal operating condition with $\Delta V_{ref} = 10\%$. The system eigenvalues are:

$$-a \pm jb = -0.1386 \pm 8.3920i$$

$$-c \pm jd = -0.0148 \pm 2.6410i$$

The system responses are shown in Figure 6. Due to insufficient damping, the system exhibits large oscillations which can be clearly seen from the figures. The performance criteria; namely, settling time and overshoot are more than 100 s and 100%.

From Figure 6, it is clear that some treatment is required to damp out electromechanical oscillations so that the system yields faster response with greater stability. The proposed ESO based control scheme has the capability to limit heavy oscillations under the change of operating conditions, external disturbances and parametric variations. First, the desired closed-loop pole (by dots on the graph) locations have been chosen; with the maximum (desired) level of system damping provided by the dominant system poles ($c$ and $d$) on the SRL plot for the Equation (11), as shown in Figure 7. With the help of four closed loop poles ($a$, $b$, $c$ and $d$) from SRL plot, state feedback gains $k_1$, $k_2$, $k_3$ and $k_4$ are obtained as discussed in Section 3.

Table 2 shows the closed-loop poles for three operating conditions and their corresponding controller gains. The result summarized in Table 2 the controller’s ability to provide good damping of low frequency oscillations under different loading conditions. The ESO pole locations (including the fifth
Figure 6. System responses with AVR only (a) terminal voltage and (b) rotor speed.

![Figure 6](image)

Figure 7. Symmetric root locus diagram with selected closed-loop poles.

![Figure 7](image)
pole due to disturbance dynamic) are made seven times faster than the controller pole locations (obtained from SRL plot). The entire observer poles are chosen to be equal and real (Choi, 2010) including the fifth pole due to disturbance dynamic, i.e. \( \lambda_{od} = 7 \begin{bmatrix} a & a & a & a \end{bmatrix} \). With the observer poles being pushed deeper into the LHP, the observer states track the system state faster. The observer gain \( L_o \) can be determined by first evaluating the values of \( A_o \) and \( C_o \) from Equations (15) and (17) as \( L_o = \text{acker} [ A_o^T, C_o^T, \lambda_{od} ] \). Similarly, the observer estimates \( \hat{x}_1(s), \hat{x}_2(s), \hat{x}_3(s), \hat{x}_4(s) \) and \( \hat{d}(s) \) can be determined from Equation (19).

Figure 8 illustrates the comparison of dynamic responses of the system with proposed ESO in terms of \( \Delta V_t \) and \( \Delta \omega_r \) for normal load (OP1), heavy load (OP2) and light load (OP3) conditions. The simulations are obtained when the system is subjected to a 10% step changes in \( \Delta T_m \) and \( \Delta V_{ref} \). With settling time and overshoot of approximately 1.5 s and 10%, the figures clearly shows that the total electromechanical oscillations in terminal voltage \( \Delta V_t \) and rotor speed \( \Delta \omega_r \) are considerably reduced in comparison with the responses of the system without ESO shown in Figure 6, which is highly oscillatory. The system with proposed controller shows better performance with much lesser oscillations and faster settling time.

To show the stability of the system in presence of parameter related uncertainties and to demonstrate the robustness of the control achieved, a deviation of +50% (OP4) and -50% (OP5) on the nominal values of the inertia constant \( (M = 2H) \) and \( d \)-axis open circuit transient time constant \( (\tau_3 = K_{\tau_d}r_{al}) \) with 10% step changes in \( \Delta T_m \) and \( \Delta V_{ref} \) have been assumed. The perturbed parametric values and prime motor torque deviation \( (\Delta T_m) \) act as a disturbance input to the system. Table 3 shows the closed-loop poles with its associated controller gains under these conditions. The dynamic responses are shown in Figure 9. From the figures, it can be seen that the responses of the perturbed system does not affect the performance of the nominal system. It can be concluded that the system in steady-state under different parametric conditions behaves like a nominal system. Hence, the system is robust to such level of parameter changes.

### Table 2. Selected closed-loop poles with associated controller gains

| Operating point | \( \rho \) | CLP | SFG |
|-----------------|----------|-----|-----|
| OP1 | 80 | \( a = -5.3109 + 5.6176i \) \( k_1 = -12.902 \) | \( k_2 = 0.2696 \) |
| | | \( b = -5.3109 - 5.6176i \) \( k_3 = 4.6042 \) | \( k_4 = 0.1083 \) |
| OP2 | 60 | \( a = -5.6937 + 5.1397i \) \( k_1 = -57.663 \) | \( k_2 = 0.7150 \) |
| | | \( b = -5.6937 - 5.1397i \) \( k_3 = 6.5307 \) | \( k_4 = 0.1288 \) |
| OP3 | 150 | \( a = -5.7806 + 6.7294i \) \( k_1 = 15.771 \) | \( k_2 = 0.3943 \) |
| | | \( b = -5.7806 - 6.7294i \) \( k_3 = 5.5979 \) | \( k_4 = 0.1193 \) |
| | | \( c = -0.3381 + 9.3966i \) \( k_1 = 3.269 \) | \( k_2 = 0.1193 \) |
| | | \( d = -0.3381 - 9.3966i \) \( k_3 = 5.5979 \) | \( k_4 = 0.1193 \) |
Figure 8. System responses with ESO (a) terminal voltage and (b) rotor speed under different operating conditions.

Table 3. Closed-loop poles with associated controller gains

| Operating point | CLP                        | SFG  |
|-----------------|----------------------------|------|
| OP4             | $a = -4.3357 + 4.5866i$    | $k_a = 14.701$ |
|                 | $b = -4.3357 - 4.5866i$    | $k_b = 0.2926$ |
|                 | $c = -0.2043 + 7.0291i$    | $k_c = 4.6551$ |
|                 | $d = -0.2043 - 7.0291i$    | $k_d = 0.0891$ |
| OP5             | $a = -7.5141 + 7.9455i$    | $k_a = 10.516$ |
|                 | $b = -7.5141 - 7.9455i$    | $k_b = 0.2247$ |
|                 | $c = -0.3915 + 12.1691i$   | $k_c = 4.4982$ |
|                 | $d = -0.3915 - 12.1691i$   | $k_d = 0.1510$ |
To test the effectiveness of the proposed ESO to track the reference control values under different operating conditions, the system is subjected to a variation of $\Delta T_m$ and $\Delta V_{ref}$ from $+10\%$ ($0 \leq t \leq 1.5$) to zero ($1.5 \leq t \leq 3$) and from zero to $-10\%$ ($3 \leq t \leq 4.5$). For $\Delta \omega_r$, the system is subjected to the same variations but at an interval of 4 s. The system responses are shown in Figure 10. This test, in addition to the previous results, shows that the system exhibits better performance that is characterized by lower overshoots and faster response. Hence, the proposed ESO based control scheme provides better voltage control, regulates the speed oscillations and guarantees the stability of the system.
Figure 11 shows the estimation results of the system at normal load condition. The estimate of output terminal voltage \( y \) can be obtained by settling Equations (22) and (23) into Equation (6). The simulation results show that the estimations are quite accurate as the estimation error decays quickly to zero as suggested in the literature. Thus, this test shows that the proposed controller ESO is capable of providing zero estimation error in the steady-state.
6. Conclusion
A design methodology for ESO-based control scheme implemented with an AVR for a SMIB power system through a transmission line is presented. The present work aims at enhancing the damping of power system oscillations with a focus on external disturbances and model parametric uncertainties subjected to the system. At the expense of some additional computation burden, the proposed method is easy and inexpensive to implement requiring no additional sensors. The proposed method has the capability of damping the power system oscillations, thereby allowing better voltage control. The Extended Observer estimates the system states as well as the disturbance state simultaneous to implement full state feedback and using this disturbance estimate to compensate the parameter uncertainties and the external constant disturbances. The SRL method has been used to locate closed-loop pole locations such that the dominant CLP have maximum damping in order to minimise the actuator (amplifier) saturation. Such a system equipped with ESO control structure, has
been found to be robust and stable in the face of model parametric uncertainties. It has also been observed that ESO-based control scheme improves the output tracking performance under different operating points.

The present linear analysis does not take into account the effects of non-linearities and delays introduced by sampling and computation. However, control gains obtained by the proposed design may be used as initial guess values in presence of non-linearities.

Acknowledgments
This work is carried out in Control and Instrumentation Laboratory of Electrical Engineering Department at North Eastern Regional Institute of Science and Technology, Nirjuli, Arunachal Pradesh, India. The authors would like to thank Prof. Sarsing Gao for his support and suggestions for the publication of this work.

Funding
The authors received no direct funding for this research.

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Citation information
Cite this article as: A single machine infinite bus power system damping control design with extended state observer, Rittu Angu & R.K. Mehta, Cogent Engineering (2017), 4: 1369923.

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Appendix 1

Power system data

| Parameter                              | Value       |
|----------------------------------------|-------------|
| Line impedance, $R_e + jX_e$           | 0.02 + 0.40 |
| $D$-axis reactance, $x_d$              | 1.7         |
| $Q$-axis reactance, $x_q$              | 1.64        |
| Armature resistance, $r$               | 0.001096    |
| Infinite bus voltage, $V$              | 1           |
| Inertia Constant, $H$                  | 2.37        |
| Rated speed, $\omega_0$               | 314.1593 rad/sec |
| Field circuit time constant, $\tau_{\delta}$ | 8 s       |
| Damping factor, $K_d$                  | 0           |
| Regulator gain, $K_a$                  | 50          |
| Exciter time constant, $\tau_e$       | 0.5         |
| Exciter gain, $K_e$                    | -0.05       |