Observer-Based Stabilizer of A single Machine Power System with Lossy Transmission Line

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Abstract: - This paper proposes a stabilizing controller for single machine power system with nonzero conductance of transmission line. The proposed controller uses a reduced order observer to estimate the power angle of the system. The stability of the reduced order observer and that of the closed loop system incorporating the observer based stabilizer are given based on Lyapunov direct method. Simulation results included in the paper demonstrate the efficacy of the proposed stabilizer. The comparison with a classical type confirms the advantage of the proposed controller.

Key-Words: -single machine power system, lossy transmission, line-reduced order observer, Lyapunov direct method.

1 Introduction

The property of power system stability enables to preserve the stable operation and regain the normal operating conditions after disturbances [1, 2, 3]. The power system transient analysis is considered very important problem for system planning and operation [4, 5]. It is the study of whether the postfault trajectory will converge to an acceptable stable equilibrium point of state. The nature of the problem is described as a nonlinear state model [6, 7]. However, for small disturbances, linearization of power system is acceptable for the analysis purposes [7].

By nature, Power systems switch into an oscillatory mode when they are subjected to perturbations. This mode of operation is detrimental to the goals of system security and the maximum power transfer [8]. If no sufficient damping is available, they may sustain and grow to a level that leads to a loss of synchronism [1]. In order to enhance power system damping, stabilizing controllers are used in the excitation system of the generators to provide the required feedback stabilizing signals.

In recent years, these controllers are undergoing a major reassessment responding to various factors including the introduction of new control technologies [9,10]. In general, the stabilizing controllers function to extend stability boundaries to damp the oscillation of synchronous machine rotor [11,12]. These oscillations occur in the frequency range of 0.2 to less than 3.0 Hz. It provides damping in a form of electrical torque in phase with the reference voltage variations [1,13,14].

The power system is one of the most common applications that require estimation of the states and parameters in order to achieve a stable controller design; the immeasurable states and parameters are generally estimated based on the possible measurements and the system model [15,16,17]. In this paper, the proposed stabilizing controller is designed on the basis of a reduced-order observer for nonlinear dynamic systems. The observer is used to estimate the power angle state.

In this paper, the transient stabilization of single machine infinite bus (SMIB) power systems with nonzero conductance is addressed [18]. The system under study is modelled as one synchronous generator connected through a transmission line to infinite bus. The transmission line is assumed to have a resistance and inductance [19, 20]. Three dimensional models are presented with lossy transmission lines. The proposed controller uses a reduced order observer to stabilize the power system

[21,22, 23]. The stability of the reduced order observer and that of the closed loop system incorporating the observer based stabilizer are designed based on Lyapunov direct method [6,24, 25].

This paper contains five sections beside the introduction. Section 2 presents the dynamic model of a single machine power system. Section 3 provides the reduced order observer and the proof of stability of the observer error model. In section 4 the controller is developed based on the reduced order observer and the stability of the overall closed loop system is derived using Lyapunov direct method. A design of classical controller is presented in section 5 to show the advantage of the proposed controller by comparison. Simulation results and discussion are given in section 6, and finally the conclusions.

2 The Dynamic Model of A single Machine Power System

A SMIB system is considered with a lossy transmission line. Presenting the system dynamic model as follows [25]:

$\dot{\delta} = \omega_M - \omega_0$

$$M\dot{\omega}_M = -D_M\omega_M + P_M - G_M E_q'^2$$

$-E_q' V G_M \cos\delta - E_q' V B_M \sin\delta (1)$

$T_d \dot{E}_q' = -[1 - B_M(x_d - x_d')]E_q' -$

$(x_d - x_d')VE_q'\{G_M \sin(\delta) - B_M \cos(\delta)\} +$

$E_{fs} + u_f$

Where, δ is the power angle δ, ω_M is the rotor angular speed and E_q' is the quadrature axis internal voltage. The control input of the system is the excitation signal u_f. G_M is the conductance and B_M is the susceptance of the generator. E_f is the field voltage (constant component) and P_m is the mechanical input power (constant). x_d, x_d', ω_0 and D_M are the direct-axis synchronous and transient reactances, the synchronous speed and damping coefficient, respectively. The state variables are, ω_M and E_q' , all parameters are assumed to be positive and $x_d > x_d'$ [26,27].

Using trigonometry identity,

$G\cos\delta + B\sin\delta = Y\sin(\delta + \alpha)$

$G\sin\delta - B\cos\delta = -Y\cos(\delta + \alpha)$

The dynamic model of single machine power system is obtained in following form

$\dot{\delta} = \omega$

$$\dot{\omega} = -D\omega + P_m - GE^2 - YEV\sin(\delta + \alpha)$$

$\dot{E} = -aE + bV\cos(\delta + \alpha) + E_f + u (2)$

Where, $Y^2 = G^2 + B^2$,$\alpha = \arctan\frac{G}{B}$ and

$E_f \triangleq \frac{E_{fs}}{T_d}$, $u \triangleq \frac{u_f}{T_d}$, $D \triangleq \frac{D_M}{M}$, $P \triangleq \frac{P_m\omega_0}{M}$, $B \triangleq \frac{B_M\omega_0}{M}$, $G \triangleq \frac{G_M\omega_0}{M}$,

$\omega \triangleq \omega_M - \omega_0$, $a = \frac{1}{T_d}[1 - B_M(x_d - x_d')]$ and $b = \frac{(x_d - x_d')}{T_d}Y$

3 The Reduced Order Observer

The design of a reduced order observer for the dynamic model of a single machine power system described above is based on the assumptions that ω and E are available by direct measurement [21]. The purpose of the reduced order observer is to give an estimate of the power angle δ ; $\hat{\delta}$ such that the error $e = \delta - \hat{\delta}$ tends to zero as time tends to infinity, locally.

Rewriting the model equations in the form

$\dot{\delta}_1 = \omega$

$\dot{\omega} = -D\omega + P_m - GE^2 - YEV\sin(\delta_1) (3)$

$\dot{E} = -aE + bV\cos(\delta_1) + E_f + u$

where $\delta_1 = \delta + \alpha$ and defining $\hat{\delta}_1 = \hat{\delta} + \alpha$.

The steady state equations are obtained by setting $\omega = \dot{\delta}_1 = \dot{E} = 0$

$P_m - GE_*{}^2 - YE_*V\sin(\delta_{1*}) = 0$ (4)

$-aE_* + bV\cos(\delta_{1*}) + E_f = 0 (5)$

$\delta_{1*} = \delta_* + \alpha$. The proposed reduced order observer is

$\dot{z} = f(t)z + l(t)\omega + r(P_m - GE^2)$ (6)

$\hat{\delta}_1 = z - r\omega$ (7)

Where, $f(t)$ and $l(t)$ are to be defined later and $r > 0$ is a positive real number.

Time differentiating $e = \delta - \hat{\delta} = \delta_1 - \hat{\delta}_1$, we obtain:

$$\dot{e} = (1 - rD)\omega - f(t)z + l(t)\omega - r(P_m - GE^2) + r(P_m - GE^2) - rYEsin(\delta_1) = \big(1 - rD + l(t)\big)\omega - f(t)(\hat{\delta}_1 + r\omega) - rYEsin(\delta_1) =$$

$= (1 - rD + l(t) - rf(t))\omega - f(t)\delta_1 + f(t)e - rYEsin(\delta_1)$ (8)

Choosing

$l(t) = 1 - rD - rf(t)$

$$f(t) = f(\hat{\delta}_1) = -rYEV\big(1 - \hat{\delta}_1^2/6\big)$$

With good approximation for $-\frac{\pi}{2} < \delta_1 < \frac{\pi}{2}$, $\sin(\delta_1) = \delta_1 - \delta_1^3/6$ hence Eq. (8) can be re-written as follows:

$\dot{e} = -rYEV\big(1 - \hat{\delta}_1^2/6\big)e - rYEV(\delta_1 - \delta_1^3/6) + rYEV\delta_1\big(1 - \hat{\delta}_1^2/6\big)$(9)

$$\dot{e} = -\tfrac{1}{4}rYEVe - rYEV\left(\frac{3}{4} - \frac{\delta_1^2 + \delta_1\hat{\delta}_1 + \hat{\delta}_1^2}{6}\right)e$$

The term inside the bracket in Eq. (9) is positive definite for $\delta_0 < \hat{\delta}_1, \delta_1 < \delta_0$,

Where δ_0 is to be calculated as follows:

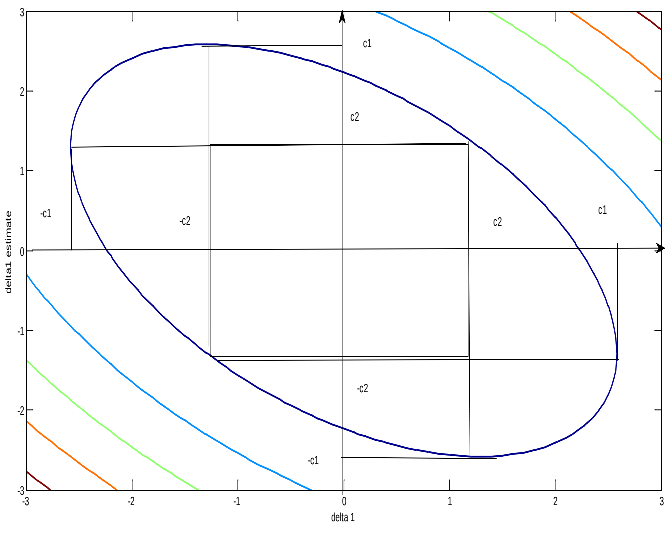


Fig. 1 Contour of constant quadratic term $\delta_1^2 + \delta_1\hat{\delta}_1 + \hat{\delta}_1^2 = c = 9/2$,$c_2 = \delta_0 = \sqrt{3/2} \approx 1.225 < \pi/2$ and $c_1 = 2c_2$

From Eq. (9) it is obvious that for $\delta_1^2 + \delta_1\hat{\delta}_1 + \hat{\delta}_1^2 < 9/2$, $e \to 0$ as $t \to \infty (E > 0)$, the domain of $\hat{\delta}_1, \delta_1$ for which this condition is satisfied as shown in Fig. 1. The internal rectangle represents the admissible domain of δ_1 and $\hat{\delta}_1$ is$-\delta_0 < \hat{\delta}_1, \delta_1 < \delta_0 = \sqrt{3/2} \approx 1.225$. Hence, the estimated angle $\hat{\delta}_1$tends to δ_1 locally as time tends to infinity and the estimated angle $\hat{\delta}$ tends to δ locally as time tends to infinity.

4The Observer-Based Controller

This section presents the proposed controller which stabilizes the single machine power system as modelled in Eq. (1) based on the reduced order observer described in section (3) and the proof that the closed loop system is locally asymptotically stable:

$$u = -k(E - E_*) + \frac{\omega}{\gamma}G(E + E_*) + \frac{\omega}{\gamma}YVsin\big(\hat{\delta}_1\big) - bV\big(cos(\hat{\delta}_1) - cos(\delta_{1*})\big) \quad (10)$$

Where, $\gamma > 0$ is a real number.

It is proved that the closed loop system composed of the power system Eq. (3), observer Eq. (6)-(7) and controller Eq. (10) is locally asymptotically stable using Lyapunov direct method. Consider the Lyapunov function

$W = \frac{1}{2}\omega^2 + \frac{1}{2}\gamma(E - E_*)^2 + \frac{1}{2}\mu e^2 + \big(GE_*{}^2 - P_m\big)(\delta_1 - \delta_{1*}) - YE_*V(cos(\delta_1) - cos(\delta_{1*}))$ (11)

Where W is locally positive definite. This can be shown by evaluating $\frac{d^2V}{d\delta_1{}^2} = cos(\delta_{1*}) > 0$. $\mu > 0$is a positive real and e is the previously defined observer error.

Time differentiating W along the closed loop system trajectories we obtain after some simplification and making use of the steady state equations Eq. (3)-(4)

$\dot{W} = -D\omega^2 - \gamma(a + k)(E - E_*)^2 + \gamma bV(E - E_*)\left(cos(\delta_1) - cos(\hat{\delta}_1)\right) - \omega YV(E - E_*)\left(sin(\delta_1) - sin(\hat{\delta}_1)\right) + \mu e\dot{e}$ (12)

Using the mean value theorem, $\left|cos(\delta_1) - cos(\hat{\delta}_1)\right| \leq |sin(c)||e| \leq |e|$, also $\left|sin(\delta_1) - sin(\hat{\delta}_1)\right| \leq 2$

Hence,

$\dot{W} \leq -D\omega^2 - \gamma(a + k)(E - E_*)^2 + \gamma bV|E - E_*||e| + 2\omega YV|E - E_*| -$

$$\frac{1}{4}\mu rYE \le -\frac{1}{2}D\omega^2 - \gamma\left(a+\frac{k}{2}\right)(E-E_*)^2 - \frac{\mu}{8}rYEVe^2 -$$

$$[|\omega| \quad |E-E_*|]\begin{bmatrix}\frac{D}{2} & -YV\\ -YV & \frac{\gamma k}{4}\end{bmatrix}\begin{bmatrix}|\omega|\\ |E-E_*|\end{bmatrix} -$$

$$[|e| \quad |E-E_*|]\begin{bmatrix}\frac{\mu}{8}rYEV & \frac{\gamma bV}{2}\\ \frac{\gamma bV}{2} & \frac{\gamma k}{4}\end{bmatrix}\begin{bmatrix}|e|\\ |E-E_*|\end{bmatrix} \le 0 \quad (13)$$

For $E > 0, -\delta_0 < \hat{\delta}_1, \delta_1 < \delta_0$,

$\frac{D}{8}\gamma k > (YV)^2$ and $\frac{Yk}{32}\mu\gamma VE > \left(\frac{\gamma Vb}{4}\right)^2$

These inequalities can be satisfied by appropriate selection of μ and k. Hence the closed loop system is locally asymptotically stable. In the next section a simulation example is introduced to demonstrate the effectiveness of the proposed controller.

5 The Classical Power System Stabilizer

To prove the advantage of the proposed controller, a classical power system stabilizer of the dynamic model is applied to the same power system described above. Fig. 2 shows the block diagram of the machine's excitation system that includes the power system stabilizer (PSS) [19, 20]. The PSS representation consists of three major blocks: phase compensation, signal washout, and a gain.

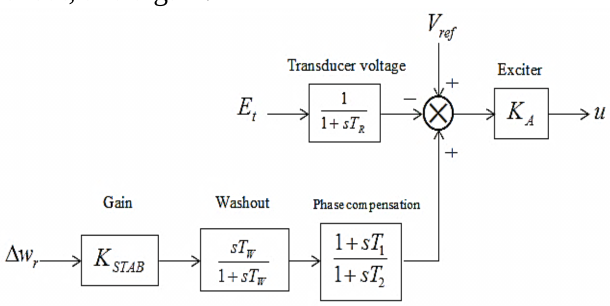


Fig. 2.Thyristor excitation system with power system stabilizer

The phase compensation block provides the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator's electrical torque. The signal washout block serves as a high-pass filter, with time constant T_W high enough to allow signals associated with oscillations in speed w_r to pass unchanged. It allows the PSS to respond only to changes in speed. The stabilizer gain K_{STAB} determines the amount of damping introduced by the PSS.

The lead lag compensatoris one the common and widely used PSS structure.It consists of adjusting the PSS parameters to compensate for the phase lags through the excitation system, and power system such that the torque changes in phase with speed changes.

The main steps for computing the PSS parameters are as follows: obtaining the undamped natural frequency of the mechanical mode is as follows;computingthe phase lag between input and output of the electrical loop to be compensated; the design of phase lead-lag compensator and finally thesetting of the gain. The amount of damping introduced depends on the gain of PSS transfer function at that frequency.

The desired PSS gain K_{STAB} is computed from

$$K_{STAB} = 2\zeta\, w_n M/|Ge||Gc| \qquad (14)$$

Where $\zeta$the desired is damping ratio; w_n is the undamped natural frequency of the mechanical mode; $Ge$is the phase lag transfer function; Gc is transfer function of phase lead compensator.For the full compensation, the phase of $Ge$and Gcshould equal to 180^o [21].

6Results and Discussions

The simulation has been carried out for the single machine power system with lossy transmission line for a value of conductance G = 0.1771 as shown in Table 1, where Table 2 contains the parameters of classical power system stabilizer.

The figures 3 to 6 show the trajectories of the power system state and controller when the system is at steady state and is subjected to fault of short circuit at the end of the transmission line with clearance time of 0.2 sec. after which the proposed controller acts to stabilize the system to the previous equilibrium point.

The short circuit is introduced at t = 0.5 sec. Fig. 3 shows the power angle δ and the estimated power angle $\hat{\delta}$, it is shown that the estimated state converges to the desired state within 3.5 sec.

The behavior of the angular speed ω during the fault is depicted in Fig.4 where it is obvious that it converges to its prefault steady state (settling time $(\leq 2\,\text{sec})$). Fig.5 shows that the generator voltage E comes back to normal state within about 2 seconds after occurrence of the fault and is always positive. Fig.6 depicts the control signal, which confirms the effectiveness of the proposed controller (settling time is 2 seconds).

Table 1The initial conditions and the parameters applied to simulated system

Parameter	Value	Parameter	Value
D	0.1	**B**	34.2900
$\mathbf{E_*}$	0.9824	**G**	0.1777
$\boldsymbol{\delta_*}$	0.9122	**α**	0.0052
$\mathbf{E_f}$	0.2376	**Y**	34.2905
$\mathbf{P_m}$	26.9194	**γ**	5
a	0.3341	**r**	0.1
b	0.1490	**k**	8

Table 2 Parameters of power system stabilizer

Parameter	Value	Parameter	Value
K_{STAB}	2	T_R	0.02
K_A	200	T_1	0.154
T_W	1.4	T_2	0.033

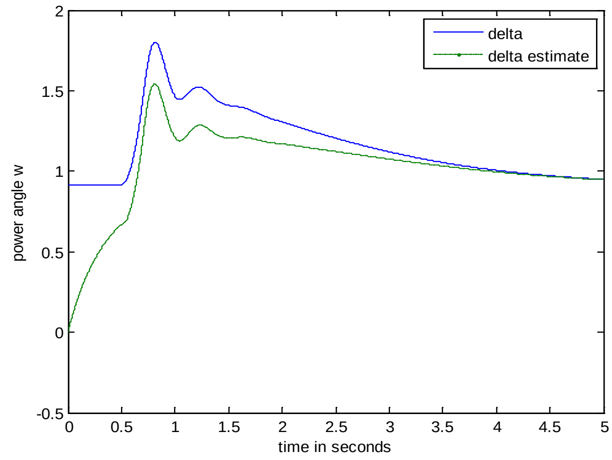


Fig. 3 Behavior of power angles delta δ and delta estimate $\hat{\delta}$

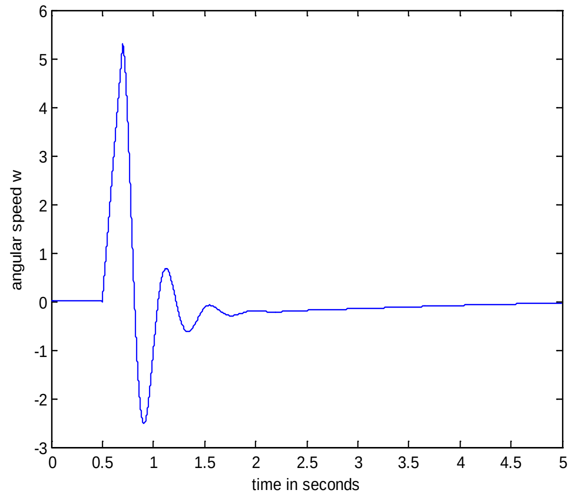


Fig. 4 Behavior of angular speed ω

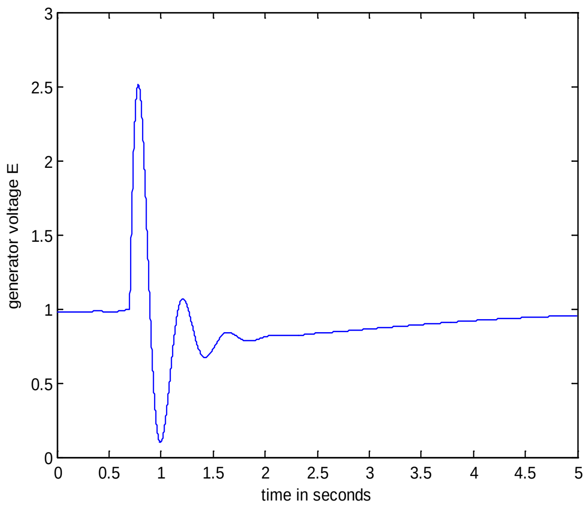


Fig. 5 The behavior of generator voltage *E*.

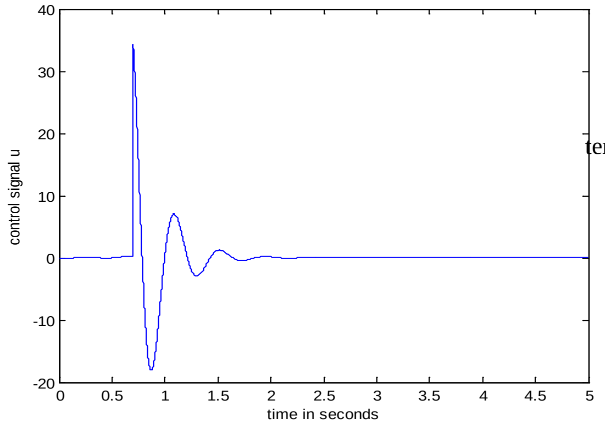


Fig. 6 The behavior of control signal *u*.

The system is simulated for initial the following conditions: $E(0) = 0.8$, $\delta(0) = 0.6$, $\hat{\delta}(0) = 0$, $\omega(0) = 0.2$. The figures (7-9) represent the responses of the system under study using the classical power system stabilizer.

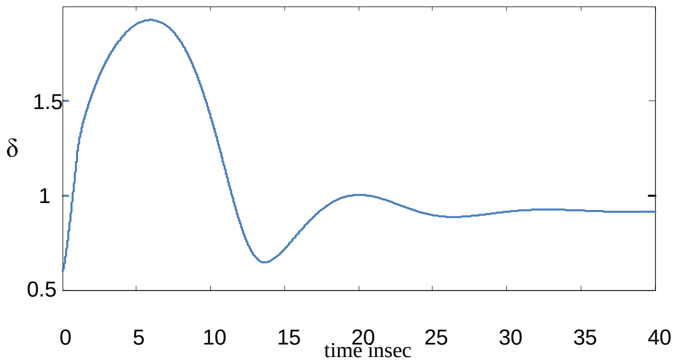
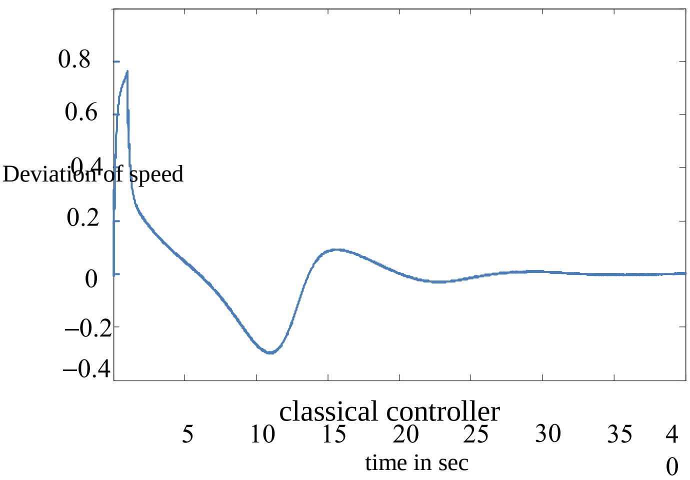


Fig. 7 The behaviour of power angles delta δ with classical controller

Fig. 8Behaviour of synchronous speed ω with classical controller



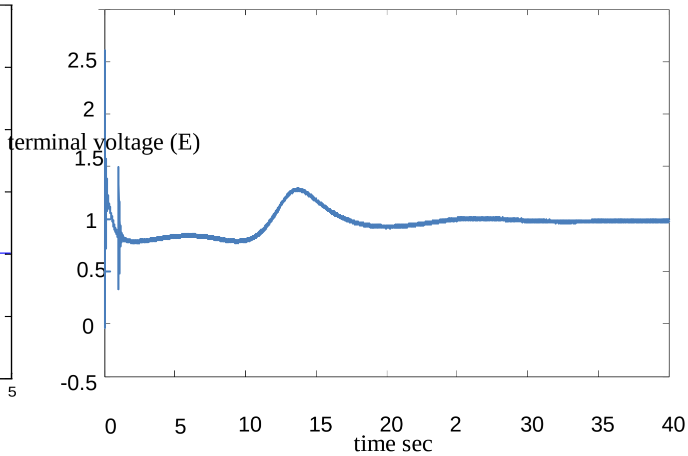


Fig. 9Behaviour of generator voltage *E* with classical controller

Fig.7 shows response of power angle δ, it is clear that it has a slow response with40 sec settling time. Figures 8 showsthe speeddeviationω, it decays to zero in about 35 sec .Fig.9 shows the response of generator voltageE, the curve reaches its steady state in relatively long time (settling time is 40 sec).

7 Conclusions

This paper proposes an observer-based stabilizing controller of single machine power system with non-zero conductance of transmission line. The reduced order observer was designed to estimate the power angle of the system based on measurement of the angular velocity and internal generator voltage. The dynamic range of the proposed nonlinear controller is bigger than the common standard AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizer). Stability of the closed loop system was given based on Lyapunov direct method and simulation results demonstrated the efficacy of the proposed controller.

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