Zero dynamic excitation controller design for power system with dynamic load

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Zero Dynamic Excitation Controller Design for Power System with Dynamic Load

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Abstract—**This paper presents a novel approach of excitation controller design for power system with dynamic load where induction motor is considered as the dynamic load. To design the controller, zero dynamic design approach of feedback linearization is used. The zero dynamic design approach is applicable when the system is partially linearized. The paper also presents the linearizability of power system with dynamic load. Based on the partial linearizability, a zero dynamic excitation control law is derived for power system with dynamic load and the performance of the designed controller on a single machine infinite bus (SMIB) with induction motor load through some simulation results.**

I. Introduction

Power systems are large, complex, and highly nonlinear interconnected dynamic systems. Since the demand for electricity is increasing continuously, the present trends of power system engineers are to operate the power systems closer to their stability limits without sacrificing the reliability. The stability of power system is very important for secure system operation because an unsecured system can undergo non-periodic major cascading disturbances, or blackouts, which have serious consequences. The world power grids are experiencing many blackouts in recent years [1] which can be attributed to special causes, such as equipment failure, overload, lightning stores, or unusual operating conditions. Therefore, it is essential to implement high-performance controller for stable operation of power systems which must be evaluated in order to meet the changing characteristics of the systems.

In order to provide stable operation of power system with its changing nature, power system stabilizer (PSS) is widely used in power industries all over the world. PSS provides some additional damping to the power system through the excitation of the generator by suing the speed deviation of the generator as its input [2], [3]. In a similar way, some improved methodologies of PSS design are proposed in [4], [5] which has large disturbance rejection capacity. A minmax LQG controller is proposed in [6], [7] to stabilize the voltage modes of power systems with dynamic loads. A Fourier-based sliding method is considered in [8] for secure operation of a power system with large disturbance. Recently, a coordinated PSS design approach is proposed in [9]. In these papers [2-9], the nonlinear power systems are linearized at an equilibrium points and the controllers are designed for the linear models of nonlinear power systems. Therefore, these linear controllers provide satisfactory operation over a fixed set of operating regions and cannot properly capture the complex dynamics of the system, especially during major disturbances.

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Nonlinear controllers eliminate the limitations of linear controllers. Feedback linearization is a nonlinear control technique which is widely used in power systems. Feedback linearization technique algebraically transforms the original nonlinear system into a (fully or partly) linear one, so that the linear control techniques can be applied. When the system is fully linearized, then the feedback linearization approach is called exact linearization. In a similar manner, feedback linearization approach for partially linearized system is known as zero dynamic design approach. The feedback linearizability of a system depends on the output function. The same system may become partially or fully linearizable based on the selection of output function. The concept of exact feedback linearization is used in [10], [11], [12] but there is no clear indication about the linearizability of the system. A simple form of feedback linearization called direct feedback linearization is proposed in [13] to design controller for single machine infinite bus system as well as for multimachine power systems and the controller is independent of operating points. In direct feedback linearization approach, the system is transformed into another form by introducing a new state but the main concept of feedback linearization is not used. Recently, the performance of nonlinear excitation controller for SMIB system is also investigated in our previous work [14] by considering the system as fully linearizable. Moreover, the consideration of load dynamics in the design controller is out of the scope of in these literatures [1-14].

The induction motor loads which are considered as dynamic loads, account for a large portion of electric loads, especially in large industries and air-conditioning in the commercial and residential areas. The induction motors used in system studies are aggregates of a large number of different motors for which detailed data are not directly available, therefore it is important to identify the critical parameters for stability studies. The critical parameters for power systems with dynamic loads are investigated in our previous work [15] to determine the effects of dynamic loads on power system stability without any controller. The performance of linear controllers for power systems with dynamic loads is analyzed in our another work [16]. Finally, a feedback linearizing controller using exact linearization in also proposed by us in [17] whose performance is better than than the existing controllers in the sense of operating region. But the control law proposed in [17] is very complex and it is hard to implement practically.

The aim of this paper is to present the zero dynamic excitation controller design for power system with dynamic

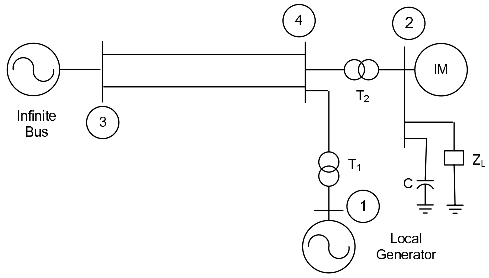

Fig. 1. Test system

load. To get a clear idea about the controller design technique, some preliminary definitions of nonlinear control theory are essential. This paper addresses these preliminary definitions along with the detailed controller design procedure. The performance of this controller is evaluated on an SMIB system with induction motor load.

The rest of the paper is organized as follows. In Section II, the mathematical modeling of a SMIB system with dynamic load is given. Section **??** presents some preliminary definitions. The detailed about zero dynamic design approach is given in Section V. Section VI shows the nonlinear excitation controller design for power system with dynamic load using zero dynamic design approach. Simulation results are shown in VII. Finally, the paper is concluded with future trends and further recommendation in Section VIII.

II. Power system model

Power systems can be modeled at several different levels of complexities, depending on the intended application of the model. Fig. 1 shows an SMIB system with dynamic load which is the focus of this paper. Since SMIB system qualitatively exhibits the important aspects of the behavior of a multimachine system and is relatively simple to study, it is extremely useful in studying general concepts of power system stability.

In this SMIB model, the power is supplied to the load ($P_L = 1500$ MW, $Q_L = 150$ MVAR) from the infinite bus and local generator (approximately, $P_G = 300$ MW, $Q_G = 225$ MVAR). The load at bus-2 is made of three parts: (i) a constant impedance load, (ii) an equivalent large induction motor, and (iii) a shunt capacitor for compensation purposes. The major portion of this loads is the equivalent induction motor.

For a control scheme to be effective, some details of the system must be available. The details of any system can best be described by the mathematical model. Power system can be modeled at several different levels of complexities, depending on the intended application of the model. With some typical assumptions, the synchronous generator can be modeled by the following set of differential equations [2]:

$$\dot{\delta} = \omega \tag{1}$$

$$\dot{\omega} = -\frac{D}{2H}\omega + \frac{1}{2H}(P_m - E'_q I_{qg}) \tag{2}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}[E_f - E'_q(X_d - X'_d)I_{dg}] \tag{3}$$

where δ is the power angle of the generator, ω is the rotor speed with respect to synchronous reference, H is the inertia constant of the generator, P_m is the mechanical input power to the generator which is assumed to be constant, D is the damping constant of the generator, E'_q is the quadrature-axis transient voltage, K_A is the gain of the exciter amplifier, T'_{do} is the direct-axis open-circuit transient time constant of the generator, X_d is the direct-axis synchronous reactance, X'_d is the direct axis transient reactance, $V_t = \sqrt{(E'_q - X'_d I_{dg})^2 + (X'_d I_{qg})^2}$ is the terminal voltage of the generator, I_{dg} and I_{qg} are direct and quadrature axis currents of the generator. The main source of significant nonlinear effects in this model is related to I_{dg} and I_{qg} for which the expressions will be provided at the end of this section.

A simplified transient model of a single cage induction machine is described by the following algebraic-differential equations written in a synchronously-rotating reference frame [18]:

$$\begin{aligned}
(v_d + jv_q) &= (R_s + jX')(i_{dm} + ji_{qm}) + j(e'_{qm} - je'_{dm}) \\
\dot{s} &= \frac{1}{2H_m}(T_e - T_m) \\
\dot{e}'_{qm} &= -\frac{1}{T'_{dom}}e'_{qm} + \frac{1}{T'_{dom}}(X - X')i_{dm} - s\omega_s e'_{dm} \\
\dot{e}'_{dm} &= -\frac{1}{T'_{dom}}e'_{dm} - \frac{1}{T'_{dom}}(X - X')i_{qm} + s\omega_s e'_{qm}
\end{aligned}$$

here $X' = X_s + \frac{X_m X_r}{X_m + X_r}$ is the transient reactance, R_s is the stator resistor which is assumed to be zero, X_s is the stator reactance, X_r is the rotor reactance, X_m is the magnetizing reactance, $X = X_s + X_m$ is the rotor open-circuit reactance, T'_{dom} is the transient open circuit time constant, T_m is the torque drawn by the machine, H_m is the inertia constant of the motor, s is the slip, $T_e = e'_{dm}i_{dm} + e'_{qm}i_{qm}$ is the electrical torque, e'_{dm} and e'_{qm} are the direct and quadrature axis transient voltages, i_{dm} and i_{qm} are the direct and quadrature axis currents. Here, this model represents the induction machine in it own direct and quadrature axes, which is different from the d and q axes of synchronous generator. So axes transformation is used to represent the dynamic elements of both the induction motor and synchronous generator with respect to the same reference frame and to do so we use the following relations:

$$\begin{aligned}
E'_m &= \sqrt{(e'_{dm})^2 + (e'_{qm})^2} \\
\delta_m &= \tan^{-1}(\frac{-e'_{dm}}{e'_{qm}}) \\
(I_{dm} + jI_{qm}) &= -(i_{dm} + ji_{qm})e^{-j\delta_m} \\
V_d + jV_q &= (v_d + jv_q)e^{-j\delta_m}
\end{aligned}$$

Here, the negative sign with i_{dm} and i_{qm} indicates that they are opposite to I_{dm} and I_{qm} when expressed in the same reference frame with synchronous generator.

With these relations, a modified third-order induction motor model can be written as follows:

$$
\begin{aligned}
(V_d + jV_q) &= -(R_s + jX')(I_{dm} + jI_{qm}) + jE'_{qm} \\
\dot{s} &= \frac{1}{2H_m}(T_m - E'_m I_{qm}) && (4) \\
\dot{E}'_m &= -\frac{1}{T'_{dom}}[E'_m + (X - X')I_{dm}] && (5) \\
\dot{\delta}_m &= s - \frac{X - X'}{T'_{dom}E'_m} I_{qm} && (6)
\end{aligned}
$$

To complete the model the equation of I_{dg}, I_{qg}, I_{dm} and I_{qm} can be written as follows:

$$
\begin{aligned}
I_{dg} &= -\frac{E'_q}{X'_d} + \frac{V_{\inf}}{X'_d + X_T + X_e}\cos\delta \\
&+ \frac{E'_m}{X'_d + X_T}\cos(\delta_m - \delta) \\
I_{qg} &= \frac{V_{\inf}}{X'_d + X_T + X_e}\sin\delta - \frac{E'_m}{X'_d + X_T}\sin(\delta_m - \delta) \\
I_{dm} &= -\frac{E'_m}{X'} + \frac{V_{\inf}}{X_e}\cos\delta_m + \frac{E'_q}{X'_d + X_T}\cos(\delta - \delta_m) \\
I_{qm} &= \frac{V_{\inf}}{X_e}\sin\delta_m - \frac{E'_q}{X'_d + X_T}\sin(\delta - \delta_m)
\end{aligned}
$$

where $V_{\inf}$ is the infinite bus voltage, X_T is the reactance of the transformer, and X_e is the reactance of the transmission lines.

III. Preliminary Definitions

In this section some definitions are presented. Though these definitions are very common to those who are working in the area of nonlinear control theory but they are very useful and even may unknown to the power engineering community. All the definitions are taken from [19], [20].

Let, the nonlinear system can be written by equations of the form

$$
\begin{aligned}
\dot{x}(t) &= f(x) + g(x)u && (7) \\
y(t) &= h(x) && (8)
\end{aligned}
$$

where $x \in \mathbf{R}^n$ is the state vector; $u \in \mathbf{R}$ is the control vector; $y \in \mathbf{R}$ is the output vector; $f(x)$ and $g(x)$ are the n-dimensional vector fields in the state space; $h(x)$ is the scalar function of x which needs to select.

In the design of feedback linearizing controller for power system, the definitions of nonlinear coordinate transformation, diffeomorphism, Lie derivative, and relative degree are useful which are defined below:

Definition 1: ***(Nonlinear Coordinate Transformation and Diffeomorphism)***
For the nonlinear system, it is useful to consider nonlinear coordinate transformation for that system which can be written as

$$
z = \phi(x)
$$

where z and x are the same dimensional vector and ϕ is the nonlinear function of x. The above equation will represent the nonlinear coordinated transformation from x-space to z-space, if the following two conditions are satisfied.

Condition 1: There exists an inverse transformation, i.e.,

$$
x = \phi^{-1}(z)
$$

Condition 2: The function of each component of ϕ and ϕ^{-1} has continuous partial derivative up to any order which means the differentiability of the functions.

Definition 2: ***(Lie Derivative)***
For a given differentiable scalar function $h(x)$ of $x = [x_1 \quad x_2 \quad x_3 \quad \cdots \quad x_n]^T$ and a vector field $f(x) = [f_1 \quad f_2 \quad f_3 \quad \cdots \quad f_n]^T$, the new scalar function, denoted by $L_f h(x)$, is obtained by the following operation

$$
L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) = \sum_{i=1}^{n} \frac{\partial h(x)}{\partial x_i} f_i(x)
$$

which is called Lie derivative of function $h(x)$ along the vector field $f(x)$.

Definition 3: ***(Relative Degree)***
If the Lie derivative of the function $L_f^{r-1}h(x)$ along vector field $g(x)$ is not equal to zero in a neighborhood Ω, i.e.,

$$
L_g L_f^{r-1} h(x) \neq 0
$$

then it is said that the system has relative degree r in Ω.

Using these definition, different output functions are considered to prove that the same system can be fully or partially linearized as shown in the following section.

IV. Linearizability of SMIB System with Dynamic Load

The SMIB system with dynamic load as shown in Fig. 1 can be expressed as

$$
\dot{x} = f(x) + g(x)u
$$

where where,

$$
x = \begin{bmatrix} \delta & \omega & E'_q & s & E'_m & \delta_m \end{bmatrix}^T
$$

$$
f(x) = \begin{bmatrix} \omega \\ -\frac{D}{2H}\omega + \frac{1}{2H}(P_m - E'_q I_{qg}) \\ \frac{1}{T'_{do}}[-E'_q - (X_d - X'_d)I_{dg} \\ \frac{1}{2H_m}(T_m - E'_m I_{qm}) \\ -\frac{1}{T'_{dom}}[E'_m + (X - X')I_{dm}] \\ s - \frac{X - X'}{T'_{dom}E'_m} I_{qm} \end{bmatrix}
$$

$$
g(x) = \begin{bmatrix} 0 & 0 & \frac{1}{T'_{do}} & 0 & 0 & 0 \end{bmatrix}^T
$$

and

$$
u = E_f
$$

Now, if the $y = h(x) = \omega$ is chosen as the output function of the system, the the relative degree of the system can be calculated as follows:

$$
L_f^{1-1} h(x) = h(x) = \omega
$$

Therefore,

$$
L_g L_f^{1-1} h(x) = L_g h(x) = \frac{\partial h(x)}{\partial x} g(x) = 0
$$

Again,

$$L_f^{2-1}h(x) = L_f h(x) = \dot{\omega}$$

Hence,

$$L_g L_f^{2-1}h(x) = \frac{\partial(L_f h(x))}{\partial x} g(x) = -I_{qg}\frac{1}{2HT'_{do}} \neq 0$$

Therefore, the relative degree of the system is 2 which is less than the order of the system and the system is partially linearized and zero dynamic design approach can be used to design excitation controller.

V. Zero Dynamic Design Approach

To implement zero dynamic design approach on nonlinear system (7), the following expressions are true.

$$L_g L_f^{1-1}h(x) = L_g L_f^{2-1}h(x) = \cdots = L_g L_f^{r-2}h(x) \quad = \quad 0$$

$$L_g L_f^{r-1}h(x) \neq 0$$

Now the mapping from x space to z space is constructed through nonlinear coordinate transformation by choosing

$$z_1 = y = h(x) = L_f^{1-1}h(x)$$

then we can write

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x}\dot{x}$$

Substituting equation (7) into the above equation for $\dot{x}$, we get

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x} f(x) + \frac{\partial h(x)}{\partial x} g(x)u = L_f^{2-1}h(x) + L_g L_f^{1-1}h(x)u$$

As $L_g L_f^{1-1}h(x) = 0$, from the above equation it can be written that

$$\dot{z}_1 = L_f h(x) = z_2$$

In a similar way

$$\begin{aligned} \dot{z}_2 = &\quad L_f^2 h(x) \quad = z_3 \\ &\vdots \\ &\vdots \\ \dot{z}_{r-1} = &\quad L_f^{n-1}h(x) \quad = z_r \end{aligned}$$

Since $L_g L_f^{r-1}h(x) \neq 0$, finally we can write

$$\dot{z}_r = L_f^r h(x) + L_g L_f^{r-1}h(x)u = v \tag{9}$$

where v is the new control law and determination of v is shown at the end of this section. Here, the first r equation is linearized. Now, let the rest $(n-r)$ equations are

$$\begin{aligned} \dot{z}_{r+1} &= L_f^{r+1}\varphi(x) \\ \dot{z}_{r+2} &= L_f^{r+2}\varphi(x) \\ &\vdots \\ \dot{z}_n &= L_f^n \varphi(x) \end{aligned}$$

which should selected in such a way that they must satisfy

$$L_g \varphi_i(x) \quad = \quad 0 \qquad r+1 \leq i \leq n$$

and the Jacobian Matrix at $x = x_0$

$$J_\varphi \quad = \quad \frac{\partial \varphi(x)}{\partial x}|_{x=x_0}$$

is nonsingular. Finally, the transformed system can be written as

$$\begin{aligned} \dot{z}_1 &= z_2 \\ \dot{z}_2 &= z_3 \\ &\cdots\cdots\cdots \\ \dot{z}_{r-1} &= z_r \\ \dot{z}_r &= L_f^r h(\phi^{-1}(z)) + L_g L_f^{r-1}h(\phi^{-1}(z))u \\ \dot{z}_{r+1} &= L_f \varphi_{r+1}(\phi^{-1}(z)) \\ &\cdots\cdots\cdots \\ \dot{z}_n &= L_f \varphi_n(\phi^{-1}(z)) \end{aligned}$$

Here, $x = \phi^{-1}(z)$ and

$$\phi(x) = \begin{bmatrix} z_1(x) \\ \vdots \\ z_r(x) \\ z_{r+1}(x) \\ \vdots \\ z_n(x) \end{bmatrix} = \begin{bmatrix} h(x) \\ \vdots \\ L_f^{r-1}h(x) \\ \varphi_{r+1}(x) \\ \vdots \\ \varphi_n(x) \end{bmatrix}$$

For the sake of simplicity, we introduce the following notations:

$$\begin{aligned} \zeta &= [z_1 \quad z_2 \quad z_3 \quad \cdots \quad z_r]^T \\ \eta &= [z_{r+1} \quad z_{r+2} \quad z_{r+3} \quad \cdots \quad z_n]^T \end{aligned}$$

Therefore, using the above mentioned notations we can write

$$\begin{aligned} \dot{z}_1 &= z_2 \\ \dot{z}_2 &= z_3 \\ &\cdots\cdots\cdots \\ \dot{z}_{r-1} &= z_r \\ \dot{z}_r &= a(\zeta,\eta) + b(\zeta,\eta)u \\ \dot{\eta} &= q(\zeta,\eta) \end{aligned}$$

where

$$\begin{aligned} a(\zeta,\eta) &= L_f^r h(x)|_{x=\phi^{-1}(\zeta,\eta)} = L_f^r h(\phi^{-1}(\zeta,\eta)) \\ b(\zeta,\eta) &= L_g L_f^{r-} h(x)|_{x=\phi^{-1}(\zeta,\eta)} = L_g L_f^{r-1}h(\phi^{-1}(\zeta,\eta)) \end{aligned}$$

and

$$q(\zeta,\eta) = \begin{bmatrix} q_{r+1}(\zeta,\eta) \\ q_{r+2}(\zeta,\eta) \\ \vdots \\ q_n(\zeta,\eta) \end{bmatrix} = \begin{bmatrix} L_f \phi_{r+1}(\phi^{-1}(\zeta,\eta)) \\ L_f \phi_{r+2}(\phi^{-1}(\zeta,\eta)) \\ \vdots \\ L_f \phi_n(\phi^{-1}(\zeta,\eta)) \end{bmatrix}$$

In general, the output function is chosen in such a way that the output equation $y = h(x) = 0$ at $x = x_0$. Therefore, the output $y = h(x)$ is the actually dynamic deviation of the practical output (dynamic response) from the output at an equilibrium point. Now, if we use the control means to impose on that dynamic deviation of the output of the system keeps zero at any time, i.e.,

$$y = h(x) = 0 \qquad 0 \le t \le \infty$$

then from external dynamics of the control system we can consider that the system is so stable that under the influence of any disturbance as the output of the system does not change.

Since $y = h(x) = Z_1$ has been set to zero at any time, therefore

$$\dot{z}_1 = 0$$

Similarly, the first r components of coordinates z are

$$\zeta = [z_1 \ \ z_2 \ \ z_3 \ \ \cdots \ \ z_r]^T = 0$$

for all $t \ge 0$ and there exists

$$\dot{z}_r = 0$$

Finally, the first r equations will vanish which implies that

$$\dot{\eta} = q(0, \eta) \tag{10}$$

Since external dynamics of the system equals zero under the effect of the control strategy, the above differential equation set describes actually the internal dynamics of the system. Those equations which determine internal dynamics of the system are called the zero dynamics equations of the original system. If the zero dynamics of system is stable, then the whole system must be stable and the output variable $y(t)$ will keep constant under any disturbance. Therefore, it is essential to check the stability of zero dynamics of the system before designing the controller.

If the zero dynamics of a nonlinear system is stable, then the control law can be obtained by using equation (9) which can be written as

$$L_f^r h(x) + L_g L_f^{r-1} h(x) u = v$$

which implies the following control law

$$u = \frac{-L_f^r h(x) + v}{L_g L_f^{r-1} h(x)} \tag{11}$$

and the partially linearized with new coordinates $z = [z_1 \ \ z_2 \ \ \ldots\ldots \ \ z_r]^T$ can be written as

$$z = Az + Bv \tag{12}$$

where,

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

,

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

In the, expression of the control law given by (11), v is not specified yet. To specify this, it is essential to solve the Riccati equation of the linearized system (12) which has the following form:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$

A linear system in the form (12) is quadratically stable [21] if and only if there exists a stabilizing solution $P \ge 0$ for the above Riccati equation. Using LQR principle, the most suitable feedback law is

$$v = -R^{-1}B^T P z = -Kz$$

where $K = R^{-1}B^T P$ is the optimal feedback gain matrix. The main purpose is to seek for a state feedback expression u of the nonlinear system (7)–(8). In terms of new coordinates z, we can write v as

$$v = -k_1 z_1 - k_2 z_2 - \ldots\ldots\ldots\ldots\ldots\ldots\ldots - k_r z_r \tag{13}$$

According to the coordinate transformation, we have

$$\begin{aligned} z_1 &= h(x) \\ z_2 &= L_f h(x) \\ &\ldots\ldots\ldots\ldots\ldots \\ z_{r-1} &= L_f^{r-2} h(x) \\ z_r &= L_f^{r-1} h(x) \end{aligned}$$

Substituting these transformed coordinates into (13), yields

$$v = -k_1 h(x) - k_2 L_f h(x) - \cdots\cdots - k_r L_f^{r-1} h(x)$$

Now substituting this value of v into (11), we can get the expression of nonlinear state feedback u of the system (7)–(8) as follows

$$u = -\frac{L_f^r h(x) + k_1 h(x) + \ldots. + k_n L_f^{r-1} h(x)}{L_g L_f^{r-1} h(x)} \tag{14}$$

This is the final control law for the considered nonlinear system when the system is partially linearized.

VI. Zero Dynamic Excitation Controller for Power System with Dynamic Load

For the considered SMIB system with dynamic load the relative degree of the system is 2. Therefore, using equation (14), the control law for SMIB system with dynamic load can be written as follows:

$$u = -\frac{L_f^2 h(x) + k_1 h(x) + k_2 L_f h(x)}{L_g L_f^{2-1} h(x)} \tag{15}$$

We have,

$$\begin{aligned} h(x) &= \omega \\ L_f h(x) &= \dot{\omega} \\ L_g L_f^{2-1} h(x) &= -I_{qg} \frac{1}{2HT'_{do}} \end{aligned}$$

By solving the Riccati equation k_1 and k_2 as 1 and 2.29, respectively. Now, we need to calculate, $L_f^2 h(x)$ which is shown below:

$$L_f^2 h(x) = \frac{\partial L_f h(x)}{\partial x}$$

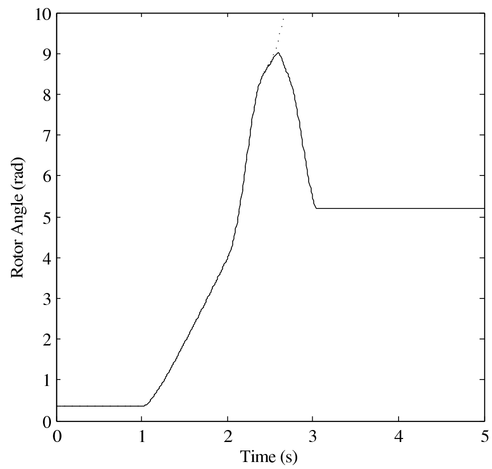

Fig. 2. Generator rotor angle (The solid line represent the rotor angle with proposed controller, whereas the dashed line represents the same without any controller)

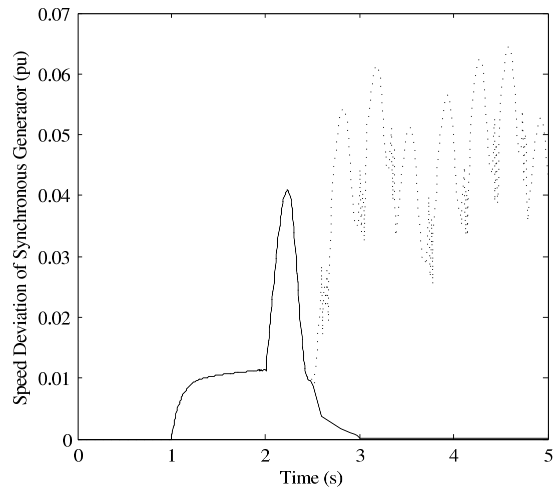

Fig. 3. Generator speed deviation (The solid line represent the speed deviation with proposed controller, whereas the dashed line represents the same without any controller)

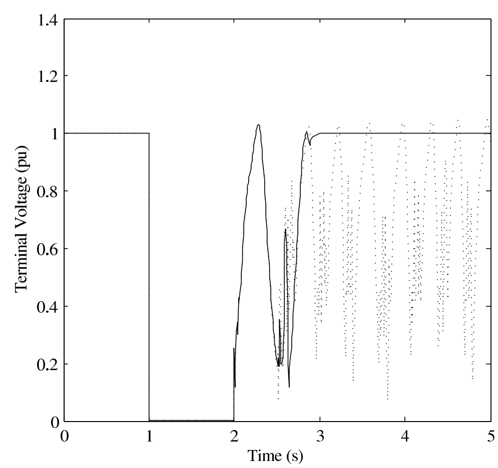

Fig. 4. Generator terminal voltage (The solid line represent the terminal voltage with proposed controller, whereas the dashed line represents the same without any controller)

After doing some manipulation the control law (15) can be written as follows:

$$
\begin{aligned}
u &= E_q - \left(T'_{do}\frac{E_q}{P_e}Q_e + 1\right)\omega - \left(D\frac{E_q}{P_e} + 1\right)\dot{\omega} \\
&- T'_{do}\frac{E_q}{P_e}\frac{T_e}{T'_{dom}} \qquad (16)
\end{aligned}
$$

Here, $E_q = X_{ad}I_f$ where X_{ad} is the mutual reactance between excitation coil and stator coil and I_f is is the per unit excitation current with the no-load rated excitation current as the base value; P_e and Q_e are the active and reactive power supplied by the generator. Equation (16) represents the control input for the considered power system which is expressed in terms of all measured variables and can be implemented through the excitation of SMIB system. Moreover, the control law is much simpler as compared to that which is obtained from exact linearization [17].

VII. Simulation Results

The parameters that are used for simulation are give in Appendix A. The effectiveness of the proposed controller is investigated by applying faults within the system. All the faults are applied in the middle of the transmission line at $t = 1$ s and cleared at $t = 2$ s.

Fig. 2 (dashed) shows that the system goes unstable even the fault is cleared at $t = 2$ s. But with the proposed zero dynamic excitation controller the stable rotor angle of the generator is obtained which is shown by the solid line in Fig. 2. Under the same situation, the generator speed deviation and terminal voltage is shown in Fig. 3 and Fig. 4

In Fig. 2 and Fig. 3, the solid line represents the performance of the zero dynamic excitation controller and the dashed line represent the performance of the system without any controller. Simulation results clearly shows that the system becomes unstable under the disturbances within it. Simulation results also clarify that when there is no controller the performance of the system goes worse at post-fault condition. But the proposed controller provides stable and enhanced performance after post-fault condition.

VIII. Conclusion

A zero dynamic excitation controller is designed for power system with dynamic load. The advantages of this control law over exact linearizing control law is the simplicity for which it is very easy to implement practically. Zero dynamic excitation controller design approach classifies the systems dynamics into external and internal dynamics. The internal dynamics need to be stable only which is the universal truth for power system as power systems are inherently stable. The obtained zero dynamic excitation control law stabilizes the external dynamics of the system, i.e., it provides stable operation under any disturbances. Simulation results justify the performances of the proposed controller under external disturbances. Future works will deal with the implementation of such type of controller for a real power system like Australian test system with dynamic loads.

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APPENDIX A
POWER SYSTEM PARAMETERS

The parameters used for the SMIB system are given below:
Synchronous generator parameters:
$X_d = 2.1\ pu$, $X_{ad} = 1.712\ pu$, $X'_d = 0.4\ pu$, $H = 3.5\ s$, $T'_{do} = 8\ s$, $D = 4$.
Transformer Parameter: $X_T = 0.016\ pu$.
Transmission Line Parameters: $X_e = 0.027\ pu$.
Infinite bus voltage, $V_{inf} = 1.08\ pu$
Induction motor parameters:
$R_s = 0\ pu$, $X_s = 0.1\ pu$, $X_r = 0.18\ pu$, $R_r = 0.18\ pu$, $X_m = 3.2\ pu$, $H_m = 1.5\ s$.

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