Robust Nonlinear Excitation Controller Design for Multimachine Power Systems

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***Abstract*—This paper presents a robust nonlinear excitation controller design for synchronous generators in a multimachine power system to enhance the transient stability. The mismatches between the original power system model and formulated mathematical model are considered as uncertainties and modeled through the satisfaction of matching conditions. To design the controller, the partial feedback linearization is used which transforms the original multimachine power system model into several reduced-order linear subsystems and autonomous subsystems. The control law can be obtained for each subsystem and the proposed scheme can be implemented in a decentralized manner provided that the dynamics of the autonomous subsystem are stable. Finally, the performance of the proposed control scheme is evaluated on a 3 machine 11 bus power system following a large disturbance. The results are then compared with those obtained from a partial feedback linearizing controller with no robustness properties.**

I. INTRODUCTION

IN the modeling of power systems, there exists unavoidable uncertainties due to interconnections, nonlinearities of equipments, unmodeled dynamics, unknown internal or external noises, environmental influences, time-varying parameters, etc., which create a mismatch between a formulated mathematical model and the original power system model in operation. As this mismatch may degrade the performance of the controller and the original power system may also lead to a serious stability problem, the design of robust control strategies that include model uncertainties is of paramount importance.

Some attempts to apply robust nonlinear control techniques have been reported in the literature of power system stability. Adaptive control techniques have been developed for power systems to ensure the robustness with slower variations in the system parameters. An adaptive nonlinear excitation controller is proposed in [1], [2] where exact feedback linearization is used to derive the control law by assuming that power system models are exactly known and an adaptive control approach is considered for the parameter adaptation to enhance the robustness of the nonlinear term cancelation. When a large fault, e.g., a fault at the terminal of a generator occurs, the reactance of the transmission lines in power systems changes a lot and power system configurations change rapidly. In this case, adaptive controllers are unable to adapt the parameter variations and thus, the transient stability of power systems is adversely affected [3], [4].

A Riccati equation-based robust DFL controller for multimachine systems is proposed in [5] where a number of Riccati equations needs to be solved. To ensure the global stability of the Riccati equation-based DFL controller, a fuzzy control technique is used in [6] to integrate the local controller. Based on the developed method as presented in [5]–[7], a robust feedback linearizing controller is designed in [8]–[10] for the excitation system of synchronous generators and static var compensators (SVCs) to enhance the transient stability of power systems considering the interconnection among controllers, variations in the system structure, and parametric uncertainties. In [5]–[10], interconnections with linear bounds are considered for the design of a robust controller which may lead to more conservative results for the global behavior as interconnections in power systems are nonlinear.

To relax the interconnection bound requirements for robust and adaptive controllers based on DFL, an excellent adaptive backstepping controller is proposed in [11]. But the design approach as proposed in [11] is primarily based on the classical adaptive approach. The shortcomings of the classical adaptive backstepping controller are that the estimation error is only guaranteed to be bounded and converge to an unknown constant for which the dynamical behavior may be unacceptable in terms of the transient response of the closed-loop system.

To overcome the shortcomings of the classical adaptive backstepping controller, an alternative approach is proposed in [12], [13] in which the uncertainties do not need to fall within a specific structure, i.e., they do not need to exactly match the system model. However, if a system satisfies the matching conditions, the respective non-adaptive controller robustly and globally stabilizes the system for any fixed estimate of unknown parameter vectors provided that the regressor (i.e., the vector multiplying the unknown parameters) satisfies a structural condition [12]. Moreover, most of the adaptive controllers focus mainly on the parametric uncertainties which is not generally the case for power systems as their uncertainties may be state-dependent if an external fault occurs.

Matching conditions can be used to model the uncertainties in power systems for all given upper bounds on the modeling error which include both parametric and state-dependent uncertainties. To obtain the structure of the uncertainty, the matching condition needs to be satisfied. As the differential geometric approach is used to check the matching of the uncertainties with the structure of the system, an uncertainty can be incorporated using the feedback linearization [14].

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In this case, a feedback linearizing controller guarantees the robustness and improves the performance for all perturbations within the given bounds. Therefore, the design of a nonlinear controller by considering the structured uncertainties, based on the satisfaction of matching conditions, is worthwhile in power system applications which is the main contribution of this paper.

II. Power System Model

It is well-known that a third-order synchronous generator model, represented as the voltage behind direct-axis transient reactance can reliably be used for designing excitation control [15]. Let, in a multimachine power system N numbers of synchronous generators are connected to supply power within the system. The dynamical model of i^{th} machine which is suitable for excitation control can be written as follows [15]:

Generator mechanical dynamics:

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_{0i} && (1) \\ \dot{\omega}_i &= -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H}(P_{mi} - P_{ei}) && (2) \end{aligned}$$

where, $i = 1,\ 2,\ 3, \cdots \cdots N$, δ_i is the power angle of i^{th} generator, ω_i is the rotor speed of i^{th} generator with respect to synchronous reference, ω_{0i} is the synchronous speed of i^{th} generator, H_i is the inertia constant of i^{th} generator, P_{mi} is the mechanical input power to i^{th} generator which is assumed to be constant, D_i is the damping constant of i^{th} generator, and P_{ei} is the active electrical power delivered by i^{th} generator.

Generator electrical dynamics:

$$\dot{E}'_{qi} = \frac{1}{T_{doi}}(E_{fi} - E_{qi}) \tag{3}$$

where, E'_{qi} is the quadrature-axis transient voltage of i^{th} generator, E_{qi} is the quadrature-axis voltage of i^{th} generator, T_{doi} is the direct-axis open-circuit transient time constant of i^{th} generator, and E_{fi} is the equivalent voltage in the excitation coil of i^{th} generator.

The algebraic electrical equations of i^{th} synchronous generator are given below:

$$\begin{aligned} E_{qi} &= E'_{qi} - (x_{di} - x'_{di})I_{di} \\ P_{ei} &= {E'_{qi}}^2 G_{ii} + E'_{qi}\sum_{\substack{j=1 \\ j\neq i}}^{n} E'_{qj}B_{ij}\sin\delta_{ij} \\ Q_{ei} &= -{E'_{qi}}^2 G_{ii} - E'_{qi}\sum_{\substack{j=1 \\ j\neq i}}^{n} E'_{qj}B_{ij}\cos\delta_{ij} \\ I_{di} &= -E'_{qi}G_{ii} - \sum_{\substack{j=1 \\ j\neq i}}^{n} E'_{qj}B_{ij}\cos\delta_{ij} \\ I_{qi} &= E'_{qi}G_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} E'_{qj}B_{ij}\sin\delta_{ij} \\ V_{ti} &= \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2} \end{aligned}$$

where, x_{di} is the direct-axis synchronous reactance of i^{th} generator, x'_d is the direct-axis transient reactance of i^{th} generator, G_{ii} and B_{ii} are the self-conductance and self-susceptance of i^{th} bus, G_{ij} and B_{ij} are the conductance and susceptance between i^{th} and j^{th} bus, $\delta_{ij} = \delta_i - \delta_j$ is the power angle deviation between i^{th} and j^{th} bus, I_{di} and I_{qi} are direct- and quadrature-axis currents of of i^{th} generator respectively, P_{ei} is the real power generated by i^{th} generator, Q_{ei} is the reactive power generated by i^{th} generator, and V_{ti} is the terminal voltage of i^{th} generator.

Substituting the electrical equations into the mechanical and electrical dynamics equation (1)-(3) of the system, the complete mathematical model of multimachine power systems can be written as follows:

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_{0i} \\ \dot{\omega}_i &= -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H}P_{mi} \\ &\quad - \frac{\omega_{0i}}{2H_i}\left({E'_{qi}}^2 G_{ii} + E'_{qi}\sum_{j=1}^{n} E'_{qj}B_{ij}\sin\delta_{ij}\right) \\ \dot{E}'_{qi} &= -\frac{1 + (x_{di} - x'_{di})B_{ii}}{T_{doi}}E'_{qi} \\ &\quad + \frac{x_{di} - x'_{di}}{T_{doi}}\sum_{j=1}^{n} E'_{qj}B_{ij}\cos\delta_{ij} + \frac{1}{T_{doi}}E_{fi} \end{aligned} \tag{4}$$

By considering the uncertainties within this power system model, the robust controller design for a multimachine power system is shown in the following sections.

III. Uncertainty Modeling

A generalized multi-input multi-output (MIMO) system can be expressed in the following form:

$$\begin{aligned} \dot{x} &= f(x) + \sum_{i=1}^{i=N} g_i(x)u_i \\ y_i &= h_i(x) \end{aligned}$$

where $i = 1,\ 2,\ \cdots,\ N$ and feedback linearization linearizes the system in a decentralized manner and therefore, the robust controller design for i^{th} subsystem

$$\begin{aligned} \dot{x}_i &= f_i(x) + g_i(x)u_i \\ y_i &= h_i(x) \end{aligned}$$

can be implemented on a MIMO system. In the presence of uncertainties, i^{th} subsystem can be represented as

$$\begin{aligned} \dot{x}_i &= [f_i(x) + \Delta f_i(x)] + [g_i(x) + \Delta g_i(x)]\,u_i \\ y_i &= h_i(x) \end{aligned} \tag{5}$$

for which the matching condition [16] will be

$$\Delta f_i(x) \ \text{ and } \ \Delta g_i(x) \in \ \text{ span } \{g_i(x)\} \tag{6}$$

which holds if

$$s_i \geq r_i = \rho_i \tag{7}$$

where r_i is the relative degree of i^{th} nominal subsystem, s_i is the relative degree of uncertainty $\Delta g_i(x)$ and ρ_i is the relative degree of uncertainty $\Delta f_i(x)$.

Before designing the robust controller for multimachine power systems, it is essential to express the power system model in terms of uncertainties and this can be expressed as

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_{0i} + \Delta f_1 \\ \dot{\omega}_i &= -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H_i}\left[P_{mi} - P_{ei}\right] + \Delta f_2 \\ \dot{E}'_{qi} &= \frac{1}{T_{doi}}(E_{fi} - E_{qi}) + \Delta f_3 + \Delta g_3 E_{fi} \end{aligned} \tag{8}$$

where Δf_1, Δf_2, and Δf_3 are the uncertainties in $f(x)$; and Δg_3 represents the uncertainties in $g_i(x)$.

$$x_i = \begin{bmatrix}\delta_i & \omega_i & E'_{qi}\end{bmatrix}^T$$

$$f_i(x) = \begin{bmatrix} \omega_i - \omega_{0i} \\ -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H_i}P_{mi} - \frac{\omega_{0i}}{2H_i}P_{ei} \\ -\frac{1}{T_{doi}}\left(E'_{qi} - (x_{di} - x'_{di})I_{di}\right) \end{bmatrix}$$

$$\Delta f_i(x) = \begin{bmatrix}\Delta f_1 \\ \Delta f_2 \\ \Delta f_3\end{bmatrix}$$

$$g_i(x) = \begin{bmatrix}0 & 0 & \frac{1}{T_{doi}}\end{bmatrix}^T$$

$$\Delta g_i(x) = \begin{bmatrix}0 & 0 & \Delta g_3\end{bmatrix}^T$$

and

$$u_i = E_{fi}$$

Since partial feedback linearization technique will be used to derive the control law, the output function of each subsystem is

$$y_i = \omega_i - \omega_{0i}$$

for which the relative degree of each subsystem is 2 [16]. Thus, it can be written that $r_i = 2$.

Now, it is essential to calculate the upper bound of the uncertainties to design and implement the controller and this can be obtained from the satisfaction of matching conditions as represented by equation (7). To satisfy the matching conditions, firstly, we have to consider the following relationships:

$$L_{f_i}^{1-1}h_i(x) = h_i(x) = \omega_i - \omega_{0i} = \Delta\omega_i$$

$$L_{f_i}^{2-1}h_i(x) = L_{f_i}h_i(x) = -\frac{D_i}{2H_i}\Delta\omega_i + \frac{\omega_{0i}}{2H_i}(P_{mi} - P_{ei})$$

In order to match the uncertainty with the structure of the system, the following need to be obtained

$$\begin{aligned} L_{\Delta f_i}L_{f_i}^{1-1}h_i(x) &= \Delta f_2 \\ L_{\Delta f_i}L_{f}^{2-1}h_i(x) &= -\frac{D_i}{2H_i}\Delta f_2 - \frac{\omega_{0i}}{2H_i}Q_{ei}\Delta f_1 \\ &\quad - \frac{\omega_{0i}}{2H_i}\frac{P_{ei}}{E_{qi}}\Delta f_3 \end{aligned} \tag{9}$$

and

$$\begin{aligned} L_{\Delta g}L_{f}^{1-1}h(x) &= 0 \\ L_{\Delta g}L_{f}^{2-1}h(x) &= -\frac{\omega_{0i}}{2H_i}\frac{P_{ei}}{E_{qi}}\Delta g_3 \end{aligned} \tag{10}$$

where L represents Lie derivative. In order to satisfy the matching conditions represented by equation (7), the relative degree (ρ_i) of the uncertainty Δf_i should be equal to the relative degree (r_i) of each nominal subsystem which is possible if Δf_2 in equation (9) is zero and in this case, the uncertainties in Δf can be represented as

$$\Delta f(x) = \begin{bmatrix}\Delta f_1 \\ 0 \\ \Delta f_3\end{bmatrix}$$

In a similar manner, the relative degree (s_i) of the uncertainty (Δg_i) should be equal to or greater than r_i which possible if and only $\Delta g_3 \neq 0$ and the uncertainties in Δg_i can be written as

$$\Delta g(x) = \begin{bmatrix}0 & 0 & \Delta T_{doi}\end{bmatrix}^T$$

where $\Delta f_3 = -\Delta T_{doi}\Delta E_{qi}$ is expressed in terms of the changes within the system which is related to both the parametric and state-dependent uncertainties and Δg_3 is only in terms of parametric uncertainties as $g_i(x)$ has no state dependency. Here, ΔT_{doi} represents the maximum allowable variation in parameter T_{doi} from its nominal value. In this paper, the upper bounds of the uncertainties are considered as a 50 per cent of their nominal values. Since ΔT_{doi} is the function of T_{doi} and by considering a 50 per cent variation of this parameter, the upper bound of ΔT_{do} in terms of T_{doi} can be expressed as follows:

$$\Delta T_{doi} = \left(\frac{1}{T_{doi}} - \frac{1}{T_{doi} + 0.5T_{doi}}\right) = \frac{0.333}{T_{doi}} \tag{11}$$

and that of for Δf_3 is

$$\Delta f_3 = -\frac{1.15}{T_{doi}}E'_{qi} + 0.165\left(\frac{x_{di} - x'_{di}}{T_{doi}}\right)I_{di} \tag{12}$$

Similarly, Δf_1 can be written as

$$\Delta f_1 = 0.5\Delta\omega$$

With these modeled uncertainties, the robust control law can be achieved by using partial feedback linearization. The derivation of the robust control law for a multimachine power system is shown in the following section.

IV. Robust Controller Design

For the considered power system model, the transformed autonomous subsystems do not have any affects on the dynamic stability of power system [16]. Thus, using partial feedback linearization, the control robust control law with the above uncertainties can be written as

$$u_i = \frac{-\left[a_i(x) + \Delta a_i(x)\right] + v_i}{b_i(x) + \Delta b_i(x)} \tag{13}$$

where

$$a_i(x) = L_{f_i}^{r_i}h_i(x) = -\frac{D_i}{2H_i}\Delta\dot{\omega}_i - \frac{\omega_{0i}}{2H_i}Q_{ei}\Delta\omega_i - \frac{\omega_{0i}}{2H_i}P_{ei}$$

$$\Delta a_i(x) = L_{\Delta f_i}L_{f_i}^{r_i-1}h_i(x) = -\frac{\omega_{0i}}{2H_i}Q_{ei}\Delta f_1 - \frac{\omega_{0i}}{2H_i}\frac{P_{ei}}{E_{qi}}\Delta f_3$$

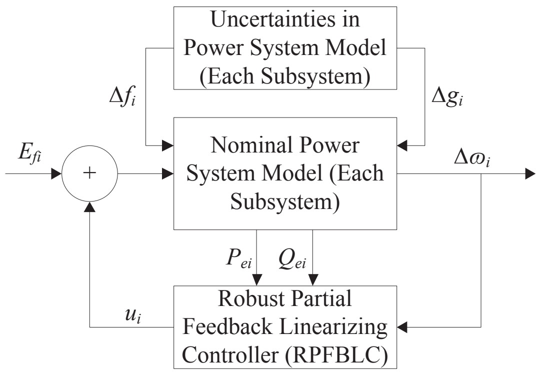

Fig. 1. Control block diagram

$$b_i(x) = L_{g_i} L_{f_i}^{r_i - 1} h_i(x) = -\frac{\omega_{0i}}{2H_i} \frac{P_{ei}}{E_{qi}} \frac{1}{T_{doi}}$$

$$\Delta b_i(x) = L_{\Delta g_i} L_{f_i}^{r_i - 1} h_i(x) = -\frac{\omega_{0i}}{2H_i} \frac{P_{ei}}{E_{qi}} \Delta g_3$$

and v_i is the linear control law which can be achieved by any linear control techniques. If state feedback is used to design the controller, v_i can be written as

$$v_i = -\Delta\omega_i - 1.1732\Delta\dot{\omega}_i$$

Using the above relationships, the robust partial feedback linearizing control law can be derived as follows:

$$\begin{aligned} u_i = 1.62E_{qi} - 1.25T_{doi}\frac{Q_{ei}}{P_{ei}}E_{qi}\Delta\omega_i - 0.75T_{doi}\frac{DE_{qi}}{\omega_{0i}P_{ei}}\Delta\dot{\omega}_i \\ - 0.87(x_{di} - x'_{di})\frac{Q_{ei}}{E_{qi}} + 1.50\frac{H_i T_{doi}}{\omega_{0i}P_{ei}}(\Delta\omega_i + 1.732\Delta\dot{\omega}_i) \end{aligned}$$

This is the partial feedback linearizing excitation control law for a multimachine power system in which $E_{qi} = x_{adi} I_{fi}$ where x_{adi} is the mutual reactance between the excitation and stator coils of i^{th} generator and I_{fi} is the per unit excitation current of i^{th} generator with the no-load rated excitation current as the base value. Therefore, the control law is expressed in terms of all measured variables and the block diagram representation of this controller can be seen in Fig. 1.

V. Simulation Results

In this paper, a two area 3 machine 11 bus test system [15] as shown in Fig. 2 is considered to analyze the performance of the designed excitation controller. The details about the system can be found in [15]. In this simulation, the transient level generator model is used for all synchronous generators connected into the system as shown in Fig. 2. In this paper, the controller is connected to the exciter of G_3 as an alternative of a power system stabilizer (PSS) due to the high participation of G_3 to the instability of the system. To evaluate the performance of the controller a three-phase short-circuit fault is applied at bus 3 where G_3 is connected. The following fault sequence is considered:

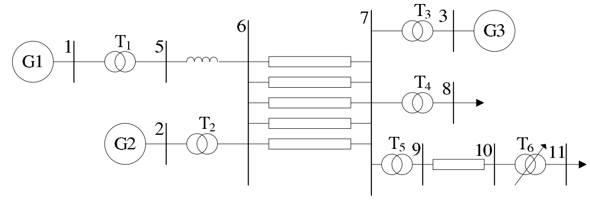

Fig. 2. Test system: 3 machine 11 bus two area system

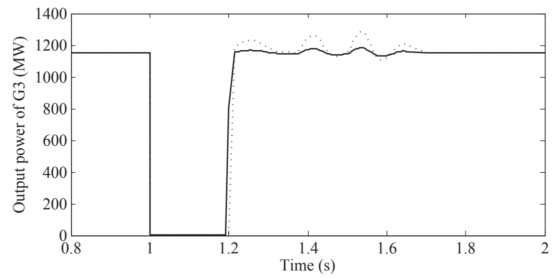

Fig. 3. Output power of G_3 in case of three-phase fault (solid line–RPFBLC and dotted line–PFBLC)

- Fault occurs at $t = 1$ s
- Fault is cleared at $t = 1.2$ s

If a three-phase fault occurs at the terminal of the synchronous generator, the generator will not supply any power during the faulted condition which can be seen from Fig.3. Moreover, the system may become unstable during the post-fault period due to the insufficient damping provided by the excitation system. To enhance the transient stability of the system, the system is simulated using the designed robust partial feedback linearizing excitation controller (RPFBLC). Since the generator supplies constant power as the input mechanical power P_m is considered as constant, the rotor angle of the synchronous generator should be similar to that of the pre-fault steady-state condition after the clearance of a fault. Fig. 4 shows the rotor angle response of the synchronous generator when a three-phase fault is applied on its terminal. From Fig. 4, it is seen that RPFBLC (solid line) responds faster than partial feedback linearizing excitation controller (PFBLC) (dotted line) to maintain the post-fault steady-state condition of the rotor angle. In addition, the partial feedback linearizing excitation controller stabilizes the system within a few cycles by providing sufficient damping.

A synchronous generator operates at a synchronous speed, i.e., the speed deviation is zero under normal operating conditions. But the speed is also disturbed when a fault occurs within the system. Fig. 5 shows the speed deviation response of the synchronous generator with a RPFBLC (solid line) and PFBLC (dotted line) from which zero speed deviation is obtained during the post-fault steady-state operation. However, the proposed RPFBLC ensures the transient stability before the PFBLC.

Another important factor in transient stability analysis is the post-fault steady-state voltage regulation. Since the stability of the considered test system is dominated by the rotor angle and speed dynamics, the voltage stability will be unaffected by external disturbances if the stability issue related to the

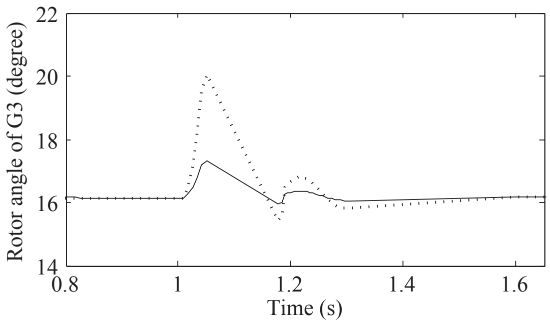

Fig. 4. Rotor angle of G_3 in case of three-phase fault (solid line–RPFBLC and dotted line–PFBLC)

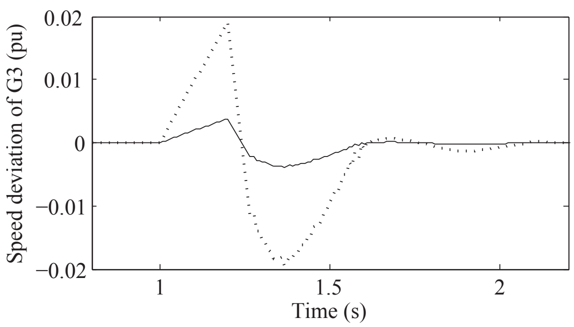

Fig. 5. Speed deviation of G_3 in case of three-phase fault (solid line–RPFBLC and dotted line–PFBLC)

rotor angle and the speed is ensured. As the proposed controller ensures transient stability of the rotor angle and speed deviation within a very short period, the terminal voltage of the generator which is zero during the fault period (1 s to 1.2 s), will reset to the pre-fault voltage during post-fault operation. Fig. 6 presents the terminal voltage response of the synchronous generator.

From the simulation results, it is clear that the designed controller is capable of maintaining stable operation of a multimachine power system in a much better way as compared to PFBLC and this happens due to the inclusion of uncertainties in the processing of designing the robust controller.

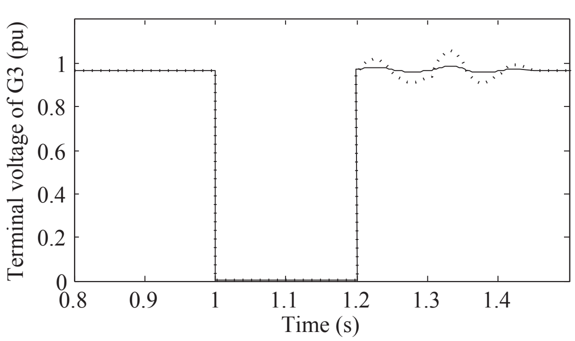

Fig. 6. Terminal voltage of G_3 in case of three-phase fault (solid line–RPFBLC and dotted line–PFBLC)

VI. Conclusion

A robust controller is designed through partial feedback linearization where the uncertainties of power systems are modeled based on the satisfaction of matching conditions. With the designed control scheme, only the upper bounds of the generators' parameters and states need to be known but not the network parameters, system operating points or natures of the faults. The resulting robust controller can enhance the overall stability of a power system considering the admissible network uncertainties. Thus, this controller has good robustness against the generator parameter variations irrespective of the network parameters and configuration and uses local measurements through a simple implementation. The simulation results obtained from the designed controller clearly demonstrate that the designed controller settles the dynamic responses back to their pre-fault steady-state conditions very quickly.

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