NONLINEAR FEEDBACK CONTROL BASED ON A COORDINATE TRANSFORMATION IN MULTI-MACHINE POWER SYSTEMS

Xuecheng Wen
ITMO University
Saint Petersburg, Russia
xuecheng.wen@outlook.com

Igor B. Furtat
Laboratory "Adaptive and intelligent control of networked and distributed systems"
IPME RAS
Saint Petersburg, Russia
cainenash@mail.ru

Article history:
Received 14.04.2023, Accepted 15.09.2023

Abstract

This paper proposes a novel nonlinear feedback control for multi-machine power systems with unknown parameters. There is no need for a state observer and knowledge of the system parameters. The implementation of the control system is therefore more simple. The proposed control algorithm maintains the power angle of each generator within a predetermined restriction for any time and enhances transient stability simultaneously. Simulation results illustrate the effectiveness of the proposed algorithm.

Key words

Power system, excitation controller, coordinate transformation.

1 Introduction

Power systems are considered as large, complex, and nonlinear dynamic networks influenced by various random disturbances. Ensuring safe and stable operation for these systems is a critical challenge. Disturbances can be classified to understand power system stability. Transient stability is an important issue for current research. It is defined as the ability of a power system to remain synchronized during severe disturbances, such as short circuits in transmission lines [Abbadi et al., 2015; Kundur et al., 2004]. The transient stability of the systems can be improved by changing the control quality of the electric generators [Anderson and Fouad, 1977; Furtat et al., 2022; Guo et al., 2000; Patil et al., 2019; Wang et al., 1998; Olmi et al., 2021; Fortuna et al., 2012]. A considerable amount of literature has been published on the excitation control of power system.

In [Guo et al., 2000; Wang et al., 1998], transient stability is ensured by applying a robust control law to a linearized model of a nonlinear multi-machine power system. This approach requires that some of the parameters of the power system are known and the state vector of each generator is measurable. In [Furtat, 2011; Furtat et al., 2019], the robust control strategy that compensates for disturbances and handles parametric uncertainties in power systems is proposed. The control law design is based on the auxiliary loop method. Moreover, an observer is also needed to estimate the mismatch function. In [Liu et al., 2019], a wide-area nonlinear excitation controller (WANEC) based on partial feedback linearization is proposed for power systems. The optimal control law is synthesized by selecting an appropriate wide-area range signal and a voltage regulation objective function in the output function.

However, most methods require knowledge of the parameters. Some algorithms require the measurement of a state vector. In contrast to [Furtat, 2011; Furtat et al., 2019], the algorithm [Furtat and Gushchin, 2021] do not require a state observer. This simplifies the implementation of the control system.

The specific objective of this study is to design a decentralized excitation control law to improve transient stability. It is assumed that parameters of power system are unknown and that only part of state vector of each generator is measurable. Nonlinear feedback control is employed, which provides output within a given set for the systems. The method works by representing an initial problem of restriction on output variables as an unconstrained input-to-state stability analysis problem for a new system through coordinate transformation. Consequently, a feedback control law for multi-machine power systems is developed following this approach. This paper demonstrates that the implemented control law enables the successful synchronization of the power systems with a precision in both normal and post-fault operating conditions. Finally, the effectiveness of the algorithm is verified by simulating a three-machine power system.

2 Model of multi-machine power system and problem formulation

This paper focuses on a power system composed of k generators $\Gamma_i, i = 1, \ldots, k$, which can be described by the following equations:

Mechanical equations:

$$\begin{aligned} \dot{\delta}_i(t) &= \omega_i(t), \\ 2H_i\dot{\omega}_i(t) &= -D_i\omega_i(t) - \omega_0\left(P_{ei}(t) - P_{mi}(t)\right); \end{aligned} \tag{1}$$

Generator electrical dynamics:

$$\begin{aligned} \tau'_{d0i}\dot{E}'_{qi}(t) =& -E'_{qi}(t) - \left(x_{di} - x'_{di}\right) I_{di}(t) \\ &+ k_{ci}u_{fi}(t), \\ \tau'_{q0i}\dot{E}'_{di}(t) =& -E'_{di}(t) + \left(x_{qi} - x'_{di}\right) I_{qi}(t); \end{aligned} \tag{2}$$

Electrical equations:

$$\begin{aligned} I_{qi}(t) =& G_{ii}E'_{qi}(t) + B_{ii}E'_{di}(t) \\ &+ \sum_{j=1,l\neq i}^{k} \left[Y_{G+B}\left(\delta_i(t) - \delta_j(t)\right) E'_{qj}(t)\right. \\ &\left.+Y_{B-G}\left(\delta_i(t) - \delta_j(t)\right) E'_{dj}(t)\right], \\ I_{di}(t) =& G_{ii}E'_{di}(t) - B_{ii}E'_{qi}(t) \\ &+ \sum_{j=1,l\neq i}^{k} \left[Y_{G+B}\left(\delta_i(t) - \delta_j(t)\right) E'_{dj}(t)\right. \\ &\left.-Y_{B-G}\left(\delta_i(t) - \delta_j(t)\right) E'_{qj}(t)\right], \\ V_{ti}(t) =& \sqrt{\left(E'_{qi}(t) - I_{di}(t)x'_{di}\right)^2 + \left(I_{qi}(t)x_{qi}\right)^2}, \\ P_{ei}(t) =& E'_{qi}(t)I_{qi}(t) + E'_{di}(t)I_{di}(t). \end{aligned} \tag{3}$$

Here $\delta_i(t)$ is the power angle of the ith generator with initial value $\delta_i(0)$ (rad), $\omega_i(t)$ and ω_0 are the relative and synchronous speed (rad/s), H_i is the inertia constant (s), D_i is the damping constant (p.u.), $P_{ei}(t)$ is the active electrical power delivered by the ith generator, (p.u.), $P_{mi}(t)$ is the mechanical input power (p.u.), $\tau'_{d0i}\left(\tau'_{q0i}\right)$ is the direct (quadrature) axis transient short circuit time constant (s), $E'_{di}(t)\left(E'_{qi}(t)\right)$ is the transient EMF in the direct (quadrature) axis (p.u.), $I_{di}(t)\,(I_{qi}(t))$ is the direct (quadrature) axis current (p.u.), $x_{di}\,(x_{qi})$ is the direct (quadrature) axis reactance (p.u.), x'_{di} is the direct axis transient reactance (p.u.), k_{ci} is the gain of the excitation amplifier (p.u.), u_{fi} is the input of the excitation amplifier (p.u.), $Y_{G+B}\left(\delta_i - \delta_j\right) := G_{ij}\cos\left(\delta_i - \delta_j\right) + B_{ij}\sin\left(\delta_i - \delta_j\right)$, $Y_{B-G}\left(\delta_i - \delta_j\right) := B_{ij}\cos\left(\delta_i - \delta_j\right) - G_{ij}\sin\left(\delta_i - \delta_j\right)$ $G_{ij}\,(B_{ij})$ is the ith row and the jth column of the conductance (susceptance) matrix of the reduced network (p.u.), V_{ti} is the generator terminal voltage (p.u.).

Consider system (1) – (3) under the following assumptions:

Assumption 1. Unknown parameters $D_i, H_i, \tau'_{d0i}, \tau'_{q0i}, x_{di}, x_{qi}, x'_{di}, k_{ci}, G_{ij}, B_{ij}$ belong to known bounded set Ξ.

Assumption 2. The faults are symmetrical 3-phase short circuit faults occurring on transmission lines.

Assumption 3. In the control system, the measurements of $\delta_i(t),\ i = 1, \ldots, k$ are available.

The objective is to design a continuous control law u_{fi} that meets these requirements:

$$\begin{aligned} &\underline{g}_i < \Delta\delta_i(t) < \bar{g}_i \text{ for all } t, \\ &\text{and } |\Delta\delta_i(t)| < \eta_i \text{ for all } t > T, \end{aligned} \tag{4}$$

for any value parameters of (1)–(3) from Ξ, where $\eta_i > 0$ is prespecified sufficiently required accuracy, $T > 0$ is a transient time, $\Delta\delta_i = \delta_i - \delta_{0i}, \delta_{0i} \in (-\pi/2, \pi/2)$ is the power angle at the operating point of the ith generator, [rad], $\underline{g}_i$ and $\bar{g}_i$ are lower and upper boundaries of the given restrictions accordingly, $\underline{g}_i = -\bar{g}_i$ are constants chosen by a designer. The first inequality is a given restriction on the value of $\Delta\delta_i(t)$, which always lies in the interval $(\underline{g}_i, \bar{g}_i)$. The second inequality is the accuracy of synchronization required for each generator Γ_i after a perturbation.

3 Power system model transformation

According to [Furtat et al., 2022], Eqs. (1)-(3) can be transformed to the input-output form:

$$Q_i(p)\Delta\delta_i(t) = -R_{im}(p)u_{fi}(t) + f_i(t), \tag{5}$$

where

$$\begin{aligned} Q_i(p) :=& p\left(p + \frac{D_i}{2H_i}\right) \\ &\times \left[\left(p + \frac{1 - \left(x_{di} - x'_{di}\right)B_{ii}}{\tau'_{d0i}}\right)\right. \\ &\times \left(p + \frac{1 - \left(x_{qi} - x'_{di}\right)B_{ii}}{\tau'_{q0i}}\right) \\ &\left.+\frac{\left(x_{di} - x'_{di}\right)G_{ii}}{\tau'_{d0i}}\frac{\left(x_{qi} - x'_{di}\right)G_{ii}}{\tau'_{q0i}}\right], \\ \tilde{f}_i(t) =& L_1^4 \operatorname{adj}\left(pI_4 - A_{ii}\left(\zeta_i(t)\right)\right) \\ &\times \left[\sum_{j=1,l\neq i}^{k} A_{ij}\left(\zeta_i(t), \zeta_j(t)\right)\zeta_j(t)\right. \\ &\left.-\left(L_2^4\right)^\top P_{mi}(t)\right], \\ R_i(p,t) :=& pG_{ii}L_3^4\zeta_i(t) \\ &+ \frac{G_{ii}}{\tau'_{q0i}}\left(\left[1 - \left(x_{qi} - x'_{di}\right)B_{ii}\right]L_3^4\zeta_i(t)\right. \\ &\left.+\left(x_{qi} - x'_{di}\right)G_{ii}L_4^4\zeta_i(t)\right), \end{aligned}$$

$$A_{ii}\left(\zeta_i\right) := \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{D_i}{2H_i} & G_{ii}L_3^4\zeta_i & G_{ii}L_4^4\zeta_i \\ 0 & 0 & -\frac{1-\left(x_{di}-x'_{di}\right)B_{ii}}{\tau'_{q0i}} & -\frac{\left(x_{di}-x'_{di}\right)G_{ii}}{\tau'_{d0i}} \\ 0 & 0 & \frac{\left(x_{qi}-x'_{di}\right)G_{ii}}{\tau'_{q0i}} & -\frac{1-\left(x_{qi}-x'_{di}\right)B_{ii}}{\tau'_{q0i}} \end{bmatrix},$$

$$A_{ij}(\zeta_i,\zeta_j) := \begin{bmatrix} 0 & 0 \\ L_3^4\zeta_i & L_4^4\zeta_i \\ 0 & -\frac{x_{di}-x'_{di}}{\tau'_{d0i}} \\ \frac{x_{qi}-x'_{di}}{\tau'_{q0i}} & 0 \end{bmatrix} \times T\left(L_1^4\zeta_i - L_1^4\zeta_j\right)\begin{bmatrix} L_3^4 \\ L_4^4 \end{bmatrix},$$

$$T(\delta_i-\delta_j) := \begin{bmatrix} Y_{G+B}(\delta_i-\delta_j) & Y_{B-G}(\delta_i-\delta_j) \\ -Y_{B-G}(\delta_i-\delta_j) & Y_{G+B}(\delta_i-\delta_j) \end{bmatrix},$$

$$\zeta_i(t) := \left[\delta_i(t), \omega_i(t), E'_{qi}(t), E'_{di}(t)\right]^\top,$$

$$L_i^n = \left[0_{i-1}\ 1\ 0_{n-i}\right] \in \mathbb{R}^{1\times n}, i \in [1,n],$$

$R_{im}(p)$ is the known linear differential operator of the first order such that $R_{im}(s)$ monic Hurwitz polynomial, s is a complex variable, $f_i(t) := \tilde{f}_i(t) - \left[R_i(p,t)\frac{k_{ci}}{\tau'_{d0i}} - R_{im}(p)\right]u_{fi}(t)$ is a new disturbance function representing uncertainties of the ith generator and the impact of the other generators. Let $Q_i(s) = Q_{im}(s) + \Delta Q_i(s)$, where $Q_{im}(s)$ is the monic Hurwitz polynomial of degree 4 (consequently, deg $\Delta Q(s) = 3$). Find the Laplace transform of (5):

$$\Delta\delta_i(s) = -\frac{R_{im}(s)}{Q_{im}(s)}u_{fi}(s) - \frac{\Delta Q_i(s)}{Q_{im}(s)}\Delta\delta_i(s) + \frac{1}{Q_{im}(s)}f_i(s) + \epsilon_i(s), \quad (6)$$

where $\epsilon_i(s)$ depends on nonzero initial conditions of (5) and $\epsilon_i(t)$ is the exponentially decaying function. Finding an inverse Laplace transform for (6) and differentiating $\Delta\delta_i(t)$, we get:

$$\Delta\dot{\delta}_i(t) = -\frac{pR_{im}(p)}{Q_{im}(p)}u_{fi}(t) - \frac{p\Delta Q_i(p)}{Q_{im}(p)}\Delta\delta_i(t) + \frac{p}{Q_{im}(p)}f_i(t) + \dot{\epsilon}_i(t). \quad (7)$$

4 Change of basis and control law

Let us consider a change of the power angle $\Delta\delta(t)$ in the form:

$$\Delta\delta_i(t) = \Phi_i(\varepsilon_i(t), t), \quad (8)$$

where $\varepsilon_i(t) \in R$ is the continuously differentiable function for all t. Let us choose $\Phi_i(\varepsilon_i(t),t) = \frac{\bar{g}_i e^{\varepsilon_i} + \underline{g}_i}{e^{\varepsilon_i}+1}$. Take the derivative of (8) w.r.t. t and rewrite result as $\Delta\dot{\delta}_i(t) = \frac{\partial\Phi_i(\varepsilon_i,t)}{\partial\varepsilon_i}\dot{\varepsilon}_i + \frac{\partial\Phi_i(\varepsilon_i,t)}{\partial t}$. Considering (7), rewrite the dynamics of $\varepsilon_i(t)$ in the form:

$$\dot{\varepsilon}_i = \frac{\left(e^{\varepsilon_i}+1\right)^2}{\left(\bar{g}_i - \underline{g}_i\right)e^{\varepsilon_i}}\left(-\frac{pR_{im}(p)}{Q_{im}(p)}u_{fi}(t) + \varphi_i(t)\right), \quad (9)$$

where $\varphi_i(t) = -\frac{p\Delta Q_i(p)}{Q_{im}(p)}\Delta\delta_i(t) + \frac{p}{Q_{im}(p)}f_i(t) + \dot{\epsilon}_i(t)$. Since power angles $\Delta\delta_i$ are available for measurement introduce control laws of the form:

$$u_{fi}(t) = \frac{Q_{im}(p)}{R_{im}\left(p\left(\mu_i p+1\right)^2 + a_i\mu_i\right)}K_i\varepsilon_i(t), \quad (10)$$

where $K_i > 0$ is constant, chosen by a designer, the sufficiently small number $\mu_i > 0$ and $a_i > 0$ are chosen such that the polynomial $s\left(\mu_i s+1\right)^2 + a_i\mu_i$ is Hurwitz.

Theorem 1. Let Assumptions 1-3 hold, power angle $\underline{g}_i < \Delta\delta_i(0) < \bar{g}_i$. If for given numbers $c_i > 0, \alpha_i > 0$ and $\kappa_i > 0$ there exist $K_i > 0$ and positive coefficients τ_{1i}, τ_{2i} such that the following linear inequalities are feasible

$$\begin{bmatrix} -K_i + \alpha_i + 0.5\tau_{1i} & 0.5 \\ \star & -\tau_{2i} \end{bmatrix} \preceq 0, \quad -c\tau_{1i} + \kappa_i^2\tau_{2i} \leq 0. \quad (11)$$

Then control law (10) ensures the fulfilment of goal (4) and boundedness of all signals in the closed-loop system.

proof. Following [Fradkov and Furtat, 2013], we consider the power system in the pre- and postfault states. We also assume $\underline{g}_i < \Delta\delta_i(t) < \bar{g}_i$ and $f_i(t)$ are bounded. Considering (10), rewrite (5) and (9) as follows:

$$\Delta\delta_i(t) = -K_i\frac{1}{p\left(\mu_i p+1\right)^2 + a_i\mu_i}\varepsilon_i(t) - \frac{\Delta Q_i(t)}{Q_{im}(t)}\Delta\delta_i(t) + \frac{1}{Q_{im}(t)}f_i(t) + \epsilon_i(t), \quad (12)$$

$$\dot{\varepsilon}_i = \frac{\left(e^{\varepsilon_i}+1\right)^2}{\left(\bar{g}_i - \underline{g}_i\right)e^{\varepsilon_i}} \times \left(-K_i\varepsilon_i(t) - K_i\frac{p - p\left(\mu_i p+1\right)^2 - a_i\mu_i}{p\left(\mu_i p+1\right)^2 + a_i\mu_i}\varepsilon_i(t) + \varphi_i(t)\right). \quad (13)$$

Due to $f_i(t)$ and $\Delta\delta_i(t)$ are bounded, the function $|\varphi_i(t)| < \kappa_i$ is bounded. According to [Bauer et al., 2015; Vasilieva and Butuzov, 1973], let us study (13) for $\mu = 0$. Rewrite (13) in the form:

$$\dot{\bar{\varepsilon}}_i = \frac{\left(e^{\bar{\varepsilon}_i}+1\right)^2}{\left(\bar{g}_i - \underline{g}_i\right)e^{\bar{\varepsilon}_i}}\left(-K_i\bar{\varepsilon}_i(t) + \varphi_i(t)\right). \quad (14)$$

For the ISS analysis of (14) consider Lyapunov function $V_i(t) = 0.5\bar{\varepsilon}_i^2(t)$. According to [Nguyen and Furtat, 2023] for any given positive numbers $\alpha_i > 0$: $\dot{V}_i < -2\alpha_i V_i, \forall\bar{\varepsilon}_i \in \mathbb{R} : |\bar{\varepsilon}_i| \geq \sqrt{2c_i}$, if condition (11) holds. According to Theorem 2.2 from [Bauer et al., 2015; Vasilieva and Butuzov, 1973], there exists μ_{0i}, such that for $\mu_i < \mu_{0i}$ the condition $|\bar{\varepsilon}_i(t) - \varepsilon_i(t)| < O(\mu_i)$ holds, where $\lim_{\mu_i\to 0} O(\mu_i) = 0$. As a result, for $\mu_i < \mu_{0i}$ the solution of (13):

$$|\varepsilon_i(t)| < \sqrt{2c_i} + O(\mu_i), t > T. \quad (15)$$

Considering (8) and condition $\underline{g}_i = -\bar{g}_i$, we get following inequality:

$$|\Delta\delta_i| < \frac{\bar{g}_i e^{\sqrt{2c_i}+O(\mu_i)} + \underline{g}_i}{e^{\sqrt{2c_i}+O(\mu_i)}+1}. \quad (16)$$

Table 1: Control system settings

K_i	a_i	μ_i	$\bar{g}_i(t)$[rad]	$\underline{g}_i(t)$[rad]
30	0.1	0.001	1.5	-1.5
30	0.1	0.001	1.5	-1.5
30	0.1	0.001	1.5	-1.5

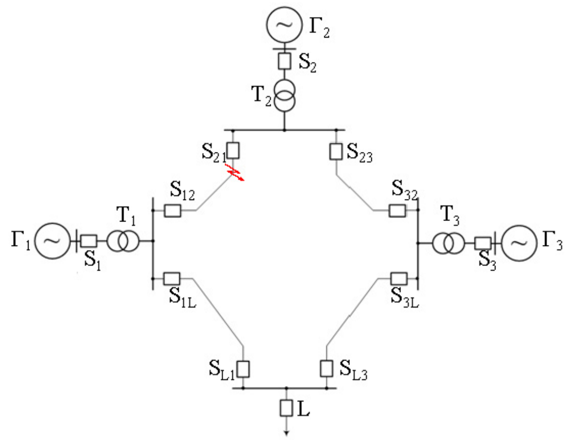

Figure 1: Scheme of three-machine power system.

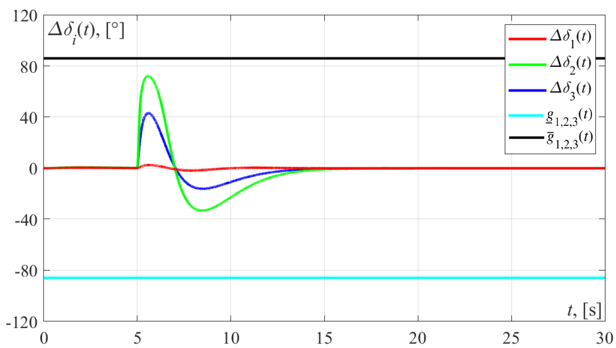

Figure 2: Responses of $\Delta\delta_i$.

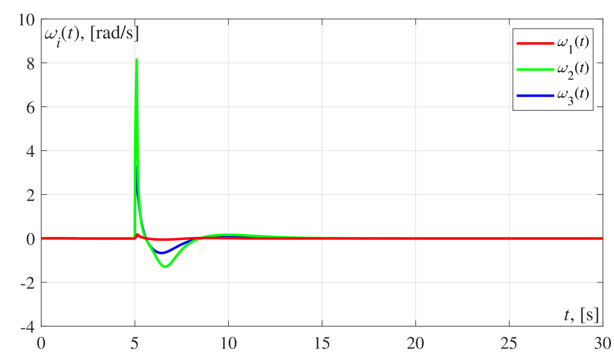

Figure 3: Responses of ω_i over time.

It clearly indicates that by decreasing c_i we can guarantee that $|\Delta\delta_i(t)| < \eta_i$ for all $t > T$. Due to the boundedness of $f_i(t)$, $\varepsilon_i(t)$ and Hurwitz of $Q_i(\lambda)$ and $p\left(\mu_i p + 1\right)^2 + a_i\mu_i$, the signal $\Delta\delta_i(t)$ is bounded from (12). Therefore, the control law $u_{fi}(t)$ is bounded from (10), all signals in the control system are bounded. Let us define the set $\mathcal{Y}_i = \left\{\Delta\delta_i \in \mathbb{R} : \underline{g}_i < \Delta\delta_i(t) < \bar{g}_i\right\}$. According to Theorem 3.1 from [Furtat and Gushchin, 2021], if there exists the control law $u_{fi}(t)$ such that the solutions of (9) are bounded, then $\Delta\delta_i(t) \in \mathcal{Y}_{i\alpha} \subset \mathcal{Y}_i$. Obviously control low (10) guarantees the boundedness of $\varepsilon_i(t)$, thus $\underline{g}_i < \Delta\delta_i(t) < \bar{g}_i$ for all t. Theorem 1 is proved.

5 Simulations

A power system consisting of three electrical generators $\Gamma_i, i = 1, 2, 3$ (Fig. 1), is used to demonstrate the effectiveness of the control scheme described in this paper. The parameters of each generator used in the simulation are detailed in [Furtat et al., 2022].

Let us apply control system (10) to the power system. Choose $Q_{mi}(p) = (p+1)^4$ and $R_{im} = p+1, i = 1, 2, 3$. Table 1 shows the parameters of control laws (10). As in previous work [Furtat et al., 2022], saturations of function u_{fi} are introduced, such as $-40 \leq u_{fi} \leq 40$ p.u., $i = 1, 2, 3$. Consider the following operating states:

1. The system is in the prefault steady state.
2. At $t = 5$ seconds, a symmetrical three-phase short circuit occurs.
3. At $t = 5.1$ seconds the power system enters the postfault state.

Fig. 2 illustrates the response curves for $\Delta\delta_i$ with the given restrictions $\bar{g}_i$ and $\underline{g}_i$. Figs. 3 and 4 show the response curves for the relative speed ω_i and the terminal voltage V_{ti} respectively. The simulation results demonstrate that under the effect of the proposed control low, the power angle, relative speed and terminal voltage of each generator are rapidly approaching the vicinity of the equilibrium state after a large disturbance occurred in the system. Meanwhile, it should be noted that the power angles consistently remain within the specified limits $\bar{g}_i$ and $\underline{g}_i$.

Fig. 5, shows the response curve of $\Delta\delta_i(t)$ when we set $K_i = [0.5, 0.2, 0.6]$. Comparing Fig. 2 with Fig. 5, if we enlarge K_i, it increases robustness to parametric uncertainties and unmoderable dynamics $f_i(t)$.

6 Conclusions

In our present study a nonlinear feedback control algorithm for multi-machine power system under parameter uncertainties is proposed. The algorithm is based on a special coordinate transformation. The proposed algorithm, unlike [Guo et al., 2000; Wang et al., 1998; Furtat et al., 2019; Liu et al., 2019], does not require knowledge of the parameters or a state observer. The implementation of the control system is therefore more simple. The

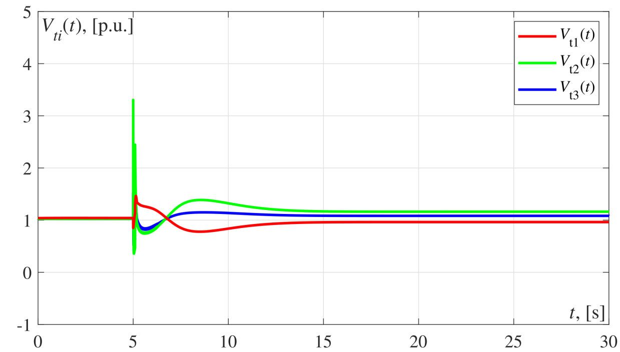

Figure 4: Responses of V_{ti}.

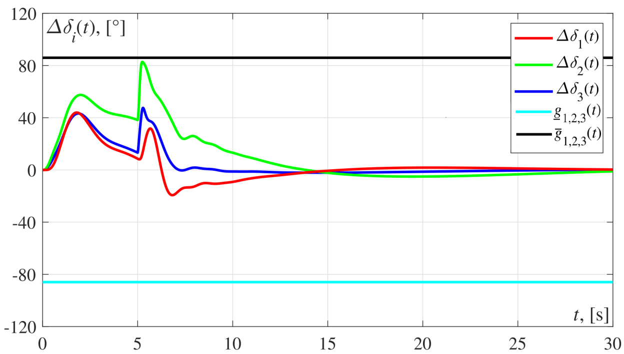

Figure 5: Responses of $\Delta\delta_i(t)$.

proposed control scheme guarantees the synchronization of power systems with a stipulated degree of accuracy during normal and post-fault modes. Additionally, it limits the power angle of each generator to a predetermined constraint at any time. The proposed algorithm is simulated in a power system consisting of three generators, and the simulation results show the correctness of our theory.

Acknowledgements

The study was supported by the Russian Science Foundation grant No. 23-41-00060 at IPME RAS.

References

Abbadi, A., Hamidia, F., Nezli, L., and Boukhetala, D. (2015). Robust Fuzzy-model based controller with sliding mode control for multi-machine power systems. *2015 4th International Conference on Electrical Engineering (ICEE),* Boumerdes, Algeria. pp. 1-6.

Anderson, P. M. and Fouad, A. A. (1977). *Power system control and stability*. Iowa State University Press.

Bauer, S. M., Filippov, S. B., Smirnov, A. L., Tovstik, P. E., and Vaillancourt, R. (2015). Regular perturbation of ordinary differential equations. *Asymptotic methods in mechanics of solids (pp. 89–153).* Springer Nature.

Fortuna, L., Frasca, M., and Fiore, A. S. (2012). Dynamical analysis of the italian high-voltage power grid. *Cybernetics and Physics,* 1(1), pp. 36-41.

Fradkov A. L., Furtat I. B. (2013). Robust control for a network of electric power generators. *Automation and Remote Control,* 74(11), pp. 1851–1862.

Furtat, I. B. (2011). Robust control of electric generator with compensation of perturbations. *Journal of Computer and Systems Sciences International,* 50(5), pp. 785–792.

Furtat, I., Gushchin, P., Tupichin, E., Peregudin, A. (2019). Control study of multi-machine power systems under variations of mechanical input power and communication delay. *Cybernetics and Physics,* 8(4), pp. 235–243.

Furtat, I. B. and Gushchin, P. A. (2021). Control of Dynamical Plants with a Guaranteefor the Controlled Signal to Stay in a Given Set. *Automation and Remote Control,* 82(4), pp. 654–669.

Furtat, I. B., Nekhoroshikh, A. N., and Gushchin, P. (2022). Synchronization of multi-machine power systems under disturbances and measurement errors. *International Journal of Adaptive Control and Signal Processing,* 36, pp. 1272–1284.

Guo, G., Wang, Y., and Hill, D. J. (2000). Nonlinear output stabilization control for multimachine power systems. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications,* 47(1), pp. 46–53.

Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., Hatziargyriou, N., Hill, D., Stankovic, A., Taylor, C., Van Cutsem, T., and Vittal, V. (2004). Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. *IEEE Transactions on Power Systems,* 19(3), pp. 1387–1401.

Liu, S., Li, X., and Chen, D. (2019). Wide-area-signals-based nonlinear excitation control in multi-machine power systems. *IEEJ Transactions on Electrical and Electronic Engineering,* 14(3), pp. 366–375.

Nguyen, B. H. and Furtat, I. (2023). Output Stabilization of Linear Systems in Given Set. *Mathematics,* 11(16), pp. 3542.

Olmi, S., Totz, C., and Schoell, E. (2021). Dynamic control of intermittent renewableenergy fluctuations in two-layer power grids. *Cybernetics and Physics,* 10(3), pp. 143–154.

Patil, B. V., Sampath, L. P. M. I., Krishnan, A., and Eddy, F. Y. S. (2019). Decentralized nonlinear model predictive control of a multimachine power system. *International Journal of Electrical Power and Energy Systems,* 106, pp. 358–372.

Vasilieva, A. B. and Butuzov, V. F. (1973). *Asymptotic expansions of solutions of singularly perturbed equations.* Nauka.

Wang, Y., Hill, D. J. and Guo, G. (1998). Robust decentralized control for multimachine power systems. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications,* 45(3), pp. 271–279.