Received: Added at production | Revised: Added at production | Accepted: Added at production

DOI: xxx/xxxx

ARTICLE TYPE

Synchronization of multi-machine power systems under disturbances and measurement errors†

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Summary

The problem of multi-machine power system synchronization under parameter uncertainties, emergency modes and measurement errors is considered. Only power angles of generators corrupted by bounded measurement errors are available for measurement. Emergency modes are associated with the sudden change of reactance of transmission lines. The proposed control law is based on measurement error filtering and left-differences estimation of power angel derivatives. Differently from some recent control schemes, it makes the obtained control law easier to tune and less sensitive to measurement errors. Under unknown values of reactance, EMF and currents at the initial moment of time the robust-adaptive control law is suggested. The simulations and experiments illustrate the efficiency of the proposed algorithm and confirm theoretical results in comparison with some existing ones.

KEYWORDS:
multi-machine power system, synchronization, measurement error, disturbance, time delay, emergency mode.

1 | INTRODUCTION

The problem of increasing the reliability and efficiency of electric power generation does not loose its relevance[1]. According to[2], overall reliability of the power system is ensured due to the reliability of power supply. It is necessary to maintain the uninterrupted supply of electricity to users and the synchronous interaction of all components of the power system. The reliability and efficiency of power system can be increased by improving the performance of the regulation of its components, in particular, electric generators[3]. Therefore, in the present paper the quality of electric power generation is achieved by control of electrical generators.

There are many methods have proposed to control electric generators in power systems. The decentralized control algorithms[4,5] use feedback linearization and robust control law for linearized model. Papers[6,7] are devoted to synchronization of electric generators by reducing the total energy of the power system. In[8], a synergistic approach is used to design a nonlinear adaptive control law that ensures the desired voltage of each generator by connection or disconnection of some network areas. In[9], an analogy between generators connected to a common bus and coupled pendulums is considered for decreasing the differences between the generator power angles.

Algorithms[4,6,8,9] may be ineffective if only a part of the state vector is available for measurement. On the other hand, additional sensors reduce reliability of the control scheme and increase its cost. In[10,11], this problem is solved by using the control law based on high-gain observer for estimation of the derivatives of power angles or relative speeds.

†The results were developed under support of Russian Science Foundation (grant 18-79-10104) in IPME RAS.

Algorithms [10,11] may loss synchronization in presence of measurement errors. It is well-known that conventional high-gain observers [12,13,14,15,16,17] are sensitive to measurement errors (or also so-called high-frequency measurement noises in [12,13,14,15,16,17]), i.e., an increase of the observer order leads to an increase of the estimation error of derivatives. To overcome this problem there are several modifications of high-gain observer have been proposed. In [12,14,15], the observer gain is adaptively adjusted to reduce the noise influence. A new extended observer [16,17] allows one to improve performance of transients in comparison with [12,14,15]. The extended observer includes a low-pass filter and high-gain observer simultaneously in one equation. The dynamical order of this observer twice more than the conventional one [18]. However, in such observer it is difficult to calculate the filter and observer parameters independently. Therefore, the application of extended observer to multi-agent systems, in particular, to multi-machine power system, becomes complicated.

Differently from [16,17], in the control law [19] the measurement error filtration and the derivative estimation are two independent processes. Also, the derivatives are estimated by using the left differences rather than in high-gain observers. These allow one to reduce the order of the closed-loop system, improve the performance of processes in steady state and simplify calculation and implementation of the control law.

It is worth mentioning that algorithm [19] has been successfully used to synchronize a single generator connected to an infinite bus [20]. Inspired by results from [19,20], in the present paper,

- the multi-machine power systems with unknown parameters of electrical generators and transmission lines are given;
- power angels of each generators with errors are measured;
- emergency modes caused by temporary symmetrical 3-phase short circuits of the transmission lines are considered;
- the control law based on low-pass filter and artificial delays for synchronization of multi-machine power systems is proposed.

The paper is organized as follows. The model of a multi-machine power system and the problem formulation are given in Section 2. Section 3 describes the transformation of the power system model. In Section 4, the low-pass filters and the feedback robust-adaptive control laws are proposed as well as the stability of the closed-loop system is analyzed. Sections 5 and 6 present numerical examples and experiments. Finally, Section 7 collects some conclusions.

Notation. Throughout the paper the superscript $^\top$ stands for matrix transposition; $p = d/dt$ is the differential operator; deg means degree of a polynomial; dist is the distance function; $\overline{\lim}$ denotes the upper limit, $L_i^n = [0_{i-1}\ 1\ 0_{n-i}] \in \mathbb{R}^{1\times n}$, $i \in [1,n]$.

2 | MODEL OF MULTI-MACHINE POWER SYSTEM. PROBLEM FORMULATION

Consider a multi-machine power system consisting of k generators Γ_i, $i = 1,...,k$, described by the following equations [4,9,10,11,21]:

- mechanical equations

$$\begin{aligned} \dot\delta_i(t) &= \omega_i(t),\\ 2H_i\dot\omega_i(t) &= -D_i\omega_i(t) - \omega_0\big(P_{ei}(t) - P_{mi}(t)\big), \quad i = 1,...,k; \end{aligned} \tag{1}$$

- generator electrical dynamics

$$\begin{aligned} \tau'_{d0i}\dot E'_{qi}(t) &= -E'_{qi}(t) - (x_{di} - x'_{di})I_{di}(t) + k_{ci}u_{fi}(t),\\ \tau'_{q0i}\dot E'_{di}(t) &= -E'_{di}(t) + (x_{qi} - x'_{di})I_{qi}(t), \quad i = 1,...,k; \end{aligned} \tag{2}$$

- electrical equations

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

Here the following notations are used for each ith generator:

- $\delta_i(t)$ is the power angle, [rad];
- $\omega_i(t)$ and ω_0 are the relative and synchronous speed, respectively, [rad/sec];

- H_i is the inertia constant, [sec];
- D_i is the damping constant, [p.u.] (per unit);
- $P_{ei}(t)$ is the active electrical power delivered by the ith generator, [p.u.];
- $P_{mi}(t)$ is the mechanical input power, [p.u.];
- τ'_{d0i} (τ'_{q0i}) is the direct (quadrature) axis transient short circuit time constant, [sec];
- $E'_{di}(t)$ ($E'_{qi}(t)$) 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.];
- $u_{fi}(t)$ is the input of the excitation amplifier of the ith generator, [p.u.];
- $Y_{G+B}(\delta_i-\delta_j) := G_{ij}\cos(\delta_i-\delta_j)+B_{ij}\sin(\delta_i-\delta_j)$, $Y_{B-G}(\delta_i-\delta_j) := B_{ij}\cos(\delta_i-\delta_j)-G_{ij}\sin(\delta_i-\delta_j)$;
- G_{ij} (B_{ij}) is the ith row and the jth column of the conductance (susceptance) matrix of the reduced network, [p.u.];
- $V_{ti}(t)$ is the generator terminal voltage, [p.u.]

Although equations (1)-(3) describe a simplified model of multi-machine power system, they are widely used in control law design (see, e.g., [4,6,8,9,10,11,21] and references therein). In [4,6,8,9,10,11], a whole state of each generator is available for measurement without errors. Differently from [4,6,8,9,10,11], we consider a problem when only power angles with errors of each generator are available for measurement in the form

$$y_i(t) = \delta_i(t) + \vartheta_i(t), \quad i = 1, ..., k, \tag{4}$$

where $\vartheta_i(t) \in \mathbb{R}$ is the ith measurement error, ess $\sup_{t\geq 0} |\vartheta_i(t)| \leq \bar{\vartheta}_i < \Delta$.

Before the goal formulation, consider the assumptions for (1)-(4).

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

Assumption 2. Emergency modes in a power system are associated with the temporary symmetrical 3-phase short circuits of the transmission lines.

Assumption 3. The measurement errors $\vartheta_i(t)$ are deterministic functions, $\vartheta_i(t)$ and $\dot{\vartheta}_i(t)$ are uniformly bounded for all t and the lower bound of bandwidth of $\vartheta_i(t)$ is significantly greater than the upper bound of bandwidth of the closed-loop system.

Assumption 4. A digraph associated with a power system has a directed spanning tree [22,23].

The bounded set Ξ in Assumptions 1 is required in Section 4 for the control law design with constant parameters. The kind of emergency modes in Assumption 2 is due to the specific of model (1)-(3) [4,9,10,11,21]. Assumption 3 is needed for implementation of low-pass filters [24]. Assumption 4 is a necessary condition for dynamical network synchronization [25].

The goal is to design the control laws $u_{fi}(t)$ that ensure the practical exponential synchronization of power angles leading to ultimate bound

$$\overline{\lim_{t\to\infty}} |\Delta\delta_i(t)| < \Delta, \quad i = 1, ..., k, \tag{5}$$

where $\Delta\delta_i(t) := \delta_i(t) - \delta_i^0$, $\delta_i^0 \in (-\pi/2, \pi/2)$ is the power angle at the operating point of the ith generator, [rad], $\Delta > 0$ is the required accuracy to be achieved in the steady state and it will be given in Theorem 1 below. Also, all variables in the closed-loop system must be bounded.

3 | POWER SYSTEM MODEL TRANSFORMATION

First we rewrite the power system model (1)-(3) in the form suitable for the control design. Note that the expression for currents I_{qi} and I_{di} can be written in the following forms:

$$\begin{bmatrix} I_{qi}(t) \\ I_{di}(t) \end{bmatrix} = \begin{bmatrix} G_{ii} & B_{ii} \\ -B_{ii} & G_{ii} \end{bmatrix} \begin{bmatrix} E'_{qi}(t) \\ E'_{di}(t) \end{bmatrix} + \sum_{j=1,l\neq i}^{k} T\big(\delta_i(t)-\delta_j(t)\big) \begin{bmatrix} E'_{qj}(t) \\ E'_{dj}(t) \end{bmatrix}, \quad i=1,...,k, \tag{6}$$

where the matrix gain $T : \mathbb{R}\times\mathbb{R} \to \mathbb{R}^{2\times 2}$ is given by

$$T(\delta_i-\delta_j) := \begin{bmatrix} Y_{G+B}(\delta_i-\delta_j) & Y_{B-G}(\delta_i-\delta_j) \\ -Y_{B-G}(\delta_i-\delta_j) & Y_{G+B}(\delta_i-\delta_j) \end{bmatrix}, \quad i=1,...,k.$$

Thus, by introducing the state vector $\zeta_i(t) := [\delta_i(t),\ \omega_i(t),\ E'_{qi}(t),\ E'_{di}(t)]^\top$, one gets

$$\begin{aligned} \dot\zeta_i(t) &= A_{ii}\big(\zeta_i(t)\big)\zeta_i(t) + \textstyle\sum_{j=1,l\neq i}^{k} A_{ij}\big(\zeta_i(t),\zeta_j(t)\big)\zeta_j(t) + (L_3^4)^\top \frac{k_{ci}}{\tau'_{d0i}} u_{fi}(t) - (L_2^4)^\top P_{mi}(t), \\ \delta_i(t) &= L_1^4\zeta_i(t), \quad i=1,...,k, \end{aligned} \tag{7}$$

where the matrix gains $A_{ii} : \mathbb{R}^4 \to \mathbb{R}^{4\times 4}$ and $A_{ij} : \mathbb{R}^4\times\mathbb{R}^4 \to \mathbb{R}^{4\times 4}$ are of the forms

$$A_{ii}(\zeta_i) := \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{D_i}{2H_i} & G_{ii}L_3^4\zeta_i & G_{ii}L_4^4\zeta_i \\ 0 & 0 & -\frac{1-(x_{di}-x'_{di})B_{ii}}{\tau'_{q0i}} & -\frac{(x_{di}-x'_{di})G_{ii}}{\tau'_{d0i}} \\ 0 & 0 & \frac{(x_{qi}-x'_{di})G_{ii}}{\tau'_{q0i}} & -\frac{1-(x_{qi}-x'_{di})B_{ii}}{\tau'_{q0i}} \end{bmatrix}, \quad A_{ij}(\zeta_i,\zeta_j) := \begin{bmatrix} 0 & 0 \\ L_3^4\zeta_i & L_4^4\zeta_i \\ 0 & -\frac{x_{di}-x'_{di}}{\tau'_{d0i}} \\ \frac{x_{qi}-x'_{di}}{\tau'_{q0i}} & 0 \end{bmatrix} T(L_1^4\zeta_i - L_1^4\zeta_j) \begin{bmatrix} L_3^4 \\ L_4^4 \end{bmatrix}.$$

Equation (7) can be represented as follows:

$$Q_i(p)\delta_i(t) = -R_i(p,t)\frac{k_{ci}}{\tau'_{d0i}}u_{fi}(t) + \tilde f_i(t), \quad i=1,...,k, \tag{8}$$

where $Q_i(p) := p\big(p+\frac{D_i}{2H_i}\big)\Big[\big(p+\frac{1-(x_{di}-x'_{di})B_{ii}}{\tau'_{d0i}}\big)\big(p+\frac{1-(x_{qi}-x'_{di})B_{ii}}{\tau'_{q0i}}\big) + \frac{(x_{di}-x'_{di})G_{ii}}{\tau'_{d0i}}\frac{(x_{qi}-x'_{di})G_{ii}}{\tau'_{q0i}}\Big]$, $R_i(p,t) := pG_{ii}L_3^4\zeta_i(t) + \frac{G_{ii}}{\tau'_{q0i}}\big(\big[1-(x_{qi}-x'_{di})B_{ii}\big]L_3^4\zeta_i(t) + (x_{qi}-x'_{di})G_{ii}L_4^4\zeta_i(t)\big)$ and $\tilde f_i(t) = L_1^4\mathrm{adj}\Big(pI_4 - A_{ii}\big(\zeta_i(t)\big)\Big)\Big[\sum_{j=1,l\neq i}^{k} A_{ij}\big(\zeta_i(t),\zeta_j(t)\big)\zeta_j(t) - (L_2^4)^\top P_{mi}(t)\Big]$. Taking into account (4) and that $p^j\Delta\delta_i = p^j\delta_i$ for any $j=1,2,3,4$, we get

$$\begin{aligned} Q_i(p)\Delta\delta_i(t) &= -R_0(p)u_{fi}(t) + f_i(t), \\ y_i(t) &= \delta_i(t) + \vartheta_i(t), \quad i=1,...,k, \end{aligned} \tag{9}$$

where $R_0(p)$ is the known linear differential operator of the first order such that polynomial $R_0(\lambda)$ is Hurwitz, λ is a complex variable, $f_i(t) := \tilde f_i(t) - \Big[R_i(p,t)\frac{k_{ci}}{\tau'_{d0i}} - R_0(p)\Big]u_{fi}(t)$ is a new disturbance function representing uncertainties of the ith generator and the impact of the other generators.

4 | CONTROL LAW DESIGN AND MAIN RESULT

First, it follows from the model (1)-(3) that at the equilibrium point δ_i^0 control laws $u_{fi}(t)$ satisfy the following relations

$$u_{fi}(t) = u_{fi}^0 := \frac{E'_{qi0}+(x_{di}-x'_{di})I_{di0}}{k_{ci}}, \quad i=1,...,k, \tag{10}$$

where E'_{qi0} and I_{di0} are corresponding values of E'_{qi} and I_{di}, respectively, at the operating point δ_i^0.

On the other hand, to meet requirement (5), system (9) has to be asymptotically stable. This can be done, for example, by choosing control laws $u_{fi}(t)$ as some functions $u_{fi}^\Delta(t)$ of the output $\Delta\delta_j(t)$ and its derivatives $p^j\Delta\delta_j(t)$, $j=1,2$. However, it is worth stressing that such a control in general does not satisfy relation (10) since it vanishes at the equilibrium point.

Therefore, these two observations motivate us to define the following control laws

$$u_{fi}(t) = \big(1-c_i(t)\big)u_{fi}^0 + c_i(t)u_{fi}^\Delta(t), \quad i=1,...,k, \tag{11}$$

where $c_i(t) := \max\left\{\frac{|y_i(t)-\delta_i^0|}{\Delta-\bar{\vartheta}_i}, 1\right\}$ is the time-varying gain. One can see that fulfillment of (5) is ensured by means of control $u_{fi}(t) = u_{fi}^{\Delta}(t)$, since $c(t) = 1$ for all $|\Delta\delta_i(t)| \geq \Delta$. Besides, $u_{fi}(t) = u_{fi}^0$ at the operating point δ_i^0 (in its vicinity) if $\vartheta_i(t) \equiv 0$ ($\vartheta_i(t) \neq 0$). In other words, control $u_{fi}^{\Delta}(t)$ is applied during the transient period, meanwhile, u_{fi}^0 operates at the steady state.

To reduce the impact of the high-frequency measurement errors ϑ_i, we consider the low-pass filters of the order $r_i \geq 1$ in the forms

$$\left[\prod\nolimits_{j=1}^{r_i}(\sigma_{j,i}p + 1)\right]\hat{y}_i(t) = y_i(t) - \delta_i^0, \quad i = 1, ..., k. \tag{12}$$

Here $\hat{y}_i(t)$ is the estimate of $\Delta\delta_i(t)$, $\sigma_{j,i} > 0$ are chosen such that $\min\limits_{j=1,\dots,r_i} \sigma_{j,i}^{-1}$ is greater than the cut-off frequency of the closed-loop system and $\max\limits_{j=1,\dots,r_i} \sigma_{j,i}^{-1}$ is smaller than the lower bound of the noise bandwidth. Denoting $\xi := [\xi_{1,i}, \dots, \xi_{1,r_i}]^\top \in \mathbb{R}^{r_i}$, where $\xi_{1,i} := \hat{y}_i$ and $\xi_{j,i} := \dot{\xi}_{j-1,i}$, $j = 2, \dots, r_i$, filters (12) can be rewritten in Brunovsky normal form

$$\begin{aligned} \dot{\xi}_i(t) &= J_i\xi_i(t) + H_i\big(y_i(t) - \delta_i^0\big), \quad \xi_i(0) = 0, \\ \hat{y}_i(t) &= L_1^{r_i}\xi_i(t), \quad i = 1, ..., k, \end{aligned} \tag{13}$$

with the matrices $J_i \in \mathbb{R}^{r_i \times r_i}$ and $H_i \in \mathbb{R}^{r_i \times 1}$ of the forms

$$J_i = \begin{bmatrix} 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \\ -J_{i,1} & -J_{i,2} & \dots & -J_{i,r_i} \end{bmatrix}, \quad H_i = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ J_{i,r_i} \end{bmatrix},$$

where $J_{i,j} := \sum_{1 \leq n_1 < \dots < n_j \leq r_i} \prod_{s=1}^{j} \sigma_{i,n_s}^{-1}$ are the elementary symmetric polynomials obtained by applying Vieta's formulas to (12). Brunovsky normal form of (13) will be used in the proof of Theorem for calculation of the derivatives of $\hat{y}_i(t)$.

According to the problem statement in Section 2, the derivatives of $y_i(t)$ are not available for measurement. Introduce the control law $u_{fi}^{\Delta}(t)$ as follows:

$$u_{fi}^{\Delta}(t) = \alpha_i\big(d_{0,i}\bar{y}_i(t) + d_{1,i}\bar{y}_i^{(1)}(t) + d_{2,i}\bar{y}_i^{(2)}(t)\big), \quad i = 1, ..., k, \tag{14}$$

where $\alpha_i > 0$, the coefficients $d_{0,i}$, $d_{1,i}$, $d_{2,i}$ are chosen such that the polynomial $D_i(\lambda) := d_{2,i}\lambda^2 + d_{1,i}\lambda + d_{0,i}$ is Hurwitz, $\bar{y}_i(t) := \hat{y}_i(t)$ and $\bar{y}_i^{(j)}(t)$ is the estimate of the jth derivative of $\bar{y}_i(t)$, $j = 1, 2$ obtained by using the left differences in the forms

$$\bar{y}_i^{(1)}(t) = \frac{\bar{y}_i(t) - \bar{y}_i(t-h)}{h}, \quad \bar{y}_i^{(2)}(t) = \frac{\bar{y}_i^{(1)}(t) - \bar{y}_i^{(1)}(t-h)}{h}, \quad i = 1, ..., k. \tag{15}$$

Here $h > 0$ is a sufficiently small time delay. Substituting (14) into (9), we get

$$F_i(p)\Delta\delta_i(t) = R_0(p)g_i(t) + R_0(p)D_i(p)\psi_i(t) + \alpha_i^{-1}f_i(t), \quad i = 1, ..., k, \tag{16}$$

where $F_i(p) := \alpha_i^{-1}Q_i(p) + R_0(p)D_i(p)$ is the characteristic polynomial of the closed-loop system, $g_i(t) := d_{1,i}\big(\hat{y}_i^{(1)}(t) - \bar{y}_i^{(1)}(t)\big) + d_{2,i}\big(\hat{y}_i^{(2)}(t) - \bar{y}_i^{(2)}(t)\big)$ is the weighted derivative estimation error, $\psi_i(t) := \Delta\delta_i(t) - \hat{y}_i(t)$ is the filtering error. Since the set Ξ is known and bounded (see Assumption 1), there always exist number α_i and polynomial $D_i(\lambda)$ such that the polynomial $F_i(\lambda)$ is Hurwitz.

Substituting (15) into (14), we obtain feasible output feedback control law in the form

$$u_{fi}^{\Delta}(t) = -\alpha_i\left[\left(d_{0,i} + \frac{d_{1,i}}{h} + \frac{d_{2,i}}{h^2}\right)\hat{y}_i(t) - \left(\frac{d_{1,i}}{h} + 2\frac{d_{2,i}}{h^2}\right)\hat{y}_i(t-h) + \frac{d_{2,i}}{h^2}\hat{y}_i(t-2h)\right]. \tag{17}$$

Rewrite equation (16) in the state-space form

$$\begin{aligned} \dot{\varepsilon}_i(t) &= A_i\varepsilon_i(t) + B_{1,i}g_i(t) + B_{2,i}\psi_i(t) + \alpha_i^{-1}B_{3,i}f_i(t), \\ \Delta\delta_i(t) &= L_1^4\varepsilon_i(t), \quad i = 1, ..., k, \end{aligned} \tag{18}$$

where $\varepsilon_i = [\varepsilon_{1,i}, \varepsilon_{2,i}, \varepsilon_{3,i}, \varepsilon_{4,i}]^\top$, $\Delta\delta_i^{(j)}(t) = \varepsilon_{j+1,i}(t)$, $j = 0, 1, 2$, the matrices A_i, $B_{1,i}$, $B_{2,i}$, $B_{3,i}$ are of corresponding dimensions.

Before formulation of the main result, consider the following notations:

$$
\begin{aligned}
\bar{A}_i &= \begin{bmatrix} A_i + \alpha_i(\kappa B_{1,i} + B_{2,i})L_1^4 + \alpha_i \nu B_{1,i} L_2^4 & \alpha_i B_{1,i}\left[M_i - \left(\frac{d_{1,i}}{h} + \frac{d_{2,i}}{h^2}\right)L_1^{r_i}\right] - \alpha_i B_{2,i} L_1^{r_i} \\ H_i L_1^4 & J_i \end{bmatrix}, \\
F_{1,i} &= \begin{bmatrix} 0 & \alpha_i B_{1,i}\left(\frac{d_{1,i}}{h} + 2\frac{d_{2,i}}{h^2}\right)L_1^{r_i} \\ 0 & 0 \end{bmatrix}, \quad F_{2,i} = \begin{bmatrix} 0 & -\alpha_i B_{1,i}\frac{d_{2,i}}{h^2}L_1^{r_i} \\ 0 & 0 \end{bmatrix}, \quad \nu = \begin{cases} \frac{d_{2,i}}{\sigma_{1,i}}, & \text{if } r_i = 1, \\ 0, & \text{if } r_i \geq 2, \end{cases} \\
\kappa &= \begin{cases} \frac{d_{1,i}}{\sigma_{1,i}} - \frac{d_{2,i}}{\sigma_{1,i}^2}, & \text{if } r_i = 1, \\ \frac{d_{2,i}}{\sigma_{1,i}\sigma_{2,i}}, & \text{if } r_i = 2, \\ 0, & \text{if } r_i \geq 3, \end{cases} \quad M_i = \begin{cases} -\frac{d_{1,i}}{\sigma_{1,i}} + \frac{d_{2,i}}{\sigma_{1,i}^2}, & \text{if } r_i = 1, \\ L_2^2\left(d_{1,i} + d_{2,i}J_2\right), & \text{if } r_i = 2, \\ d_{1,i}L_2^{r_i} + d_{2,i}L_3^{r_i}, & \text{if } r_i \geq 3, \end{cases} \\
\phi_i(t) &= \begin{bmatrix} \alpha_i(\kappa B_{1,i} + B_{2,i}) \\ H_i \end{bmatrix}\vartheta_i(t) + \begin{bmatrix} \alpha_i \nu B_{1,i} \\ 0 \end{bmatrix}\dot{\vartheta}_i(t) + \begin{bmatrix} B_{3,i} \\ 0 \end{bmatrix} f_i(t), \\
\bar{\phi} &:= \operatorname{ess\,sup}_{t\in[0,+\infty)} \chi_i^{-1}\phi_i^{\top}(t)P_i\phi_i(t), \\
W_i &= A_i^{\top}P_i + P_iA_i + (2\chi_i + \gamma)P_i + Q_{1,i} + Q_{2,i}, \\
R_{j,i} &= \chi_i^{-1}F_{j,i}^{\top}P_iF_{j,i} - e^{-\gamma j h}Q_{j,i}, \quad i = 1, ..., k, \quad j = 1, 2,
\end{aligned}
\tag{19}
$$

where $\gamma > 0$ and $P_i, Q_{1,i}, Q_{2,i} \in \mathbb{R}^{3+r_i}$ are positive definite symmetric matrices.

Theorem 1. Let Assumptions 1-4 hold. The signals $\vartheta_i(t)$ and $\dot{\vartheta}_i(t)$ are bounded if $r = 1$ or only $\vartheta_i(t)$ is bounded if $r \geq 2$, $i = 1, ..., k$. Given the exponential decay rate $\gamma > 0$, there exist $\bar{\alpha}_i > 0$, $\chi_i > 0$ and $\bar{h} > 0$ such that for any $\alpha_i > \bar{\alpha}_i$ and $h < \bar{h}$ the conditions $W_i = W_i^{\top} > 0$, $R_{j,i} = R_{j,i}^{\top} > 0$ given by (19) are satisfied. Then the low-pass filters (13) and the control laws (17) ensure the fulfillment of goal (5) with ultimate bound $\Delta = \max\limits_{i=1,...,k}\sqrt{\frac{\bar{\phi}}{\lambda_{\min}(P_i)\gamma}}$.

Proof. Following[10], consider the power system in the pre- and postfault states. For input-to-state stability (ISS) analysis of system (18) use the following Lemma[26].

Lemma 1. Consider the system described by the following equations:

$$
\begin{aligned}
\dot{x} &= f(x, u, \alpha, t), \\
u &= \phi(x, \alpha, t),
\end{aligned}
\tag{20}
$$

where $x \in \mathbb{R}^n$, $f(x, u, \alpha, t)$ is Lipschitz continuous function in x and u, piecewise continuous on t, $\phi(x, \alpha, t)$ is Lipschitz continuous function in x and piecewise continuous on t, $\alpha > 0$ is small parameter.

Consider the reduced system in the form

$$
\begin{aligned}
\dot{\bar{x}} &= \bar{f}(\bar{x}, \bar{u}, t), \\
\bar{u} &= \bar{\phi}(\bar{x}, t),
\end{aligned}
\tag{21}
$$

where $\bar{x} \in \mathbb{R}^n$, $\bar{f}(\bar{x}, t) = f(\bar{x}, \bar{u}, 0, t)$, $\bar{\phi}(\bar{x}, t) = \phi(\bar{x}, 0, t)$. Let system (21) have a bounded closed set of attraction $\Sigma = \{\bar{x}, \bar{u} : F(\bar{x}, \bar{u}) \leq C\}$, where $F(\bar{x}, \bar{u})$ is a smooth, scalar and positive definite function. In addition let there exist some number $C_1 > 0$ such that the following condition holds:

$$
\sup\left[\left(\frac{\partial F(\bar{x}, \bar{u})}{\partial \bar{x}}\right)^{\mathrm{T}} \bar{f}(\bar{x}, \bar{u}, t) \,:\, F(\bar{x}, \bar{u}) \leq C\right] \leq -C_1.
\tag{22}
$$

Then for any $\varepsilon > 0$ there exists $\bar{\alpha} > 0$ such that for $\alpha < \bar{\alpha}$ the condition $\lim\limits_{t\to\infty} \operatorname{dist}(\{x(t), u(t)\}, \Sigma) < \varepsilon$ holds.

According to Lemma, consider (18) under sufficiently small α_i^{-1}. As a result, we have the reduced system in the form

$$
\dot{\bar{\varepsilon}}_i(t) = A_i\bar{\varepsilon}_i(t) + B_{1,i}g_i(t) + B_{2,i}\psi_i(t), \quad i = 1, ..., k,
\tag{23}
$$

Under sufficiently small α_i^{-1} and Hurwitz of polynomials $R_0(\lambda)$ and $D_i(\lambda)$, the polynomial $F_i(\lambda) = \alpha_i^{-1}Q_i(\lambda) + R_0(\lambda)D_i(\lambda)$ is Hurwitz. Therefore, the matrix A_i is also Hurwitz. In[27] it is proven that there exists $\bar{h} > 0$ such that for any $h < \bar{h}$ system (23) is ISS. Since $\psi_i(t)$ and $g_i(t)$ are bounded and A_i is Hurwitz, then there exists smooth, scalar and positive definite function F such that condition (22) holds. Following to Lemma, there exists $\bar{\alpha}_i$ such that for any $\alpha_i > \bar{\alpha}_i$ system (18) is ISS. Thus, all signals are bounded in the closed-loop system. Further, we will show that the closed-loop system (18) is also exponentially stable.

Taking into account (13) and (15), rewrite the functions $g_i(t)$ as follows:

$$
g_i(t) = d_{1,i}\hat{y}_i^{(1)}(t) + d_{2,i}\hat{y}_i^{(2)}(t) - \left[\left(\frac{d_{1,i}}{h} + \frac{d_{2,i}}{h^2}\right)L_1^{r_i}\xi_i(t) - \left(\frac{d_{1,i}}{h} + 2\frac{d_{2,i}}{h^2}\right)L_1^{r_i}\xi_i(t-h) + \frac{d_{2,i}}{h^2}L_1^{r_i}\xi_i(t-2h)\right], \quad i = 1, ..., k.
\tag{24}
$$

Represent derivatives $\hat{y}_i^{(1)}(t)$ and $\hat{y}_i^{(2)}(t)$ as functions of $\vartheta_i(t)$. To this end, consider three cases depending on the order r_i of the low-pass filters (13).

Case 1. $r_i = 1$. Taking the time derivative of (13), one gets

$$\begin{aligned}\hat{y}_i^{(1)}(t) &= \dot{\xi}_i(t) = (\sigma_{1,i})^{-1}\big[-\xi_i(t) + \Delta\delta_i(t) + \vartheta_i(t)\big] = (\sigma_{1,i})^{-1}\big[-\xi_i(t) + L_1^4\varepsilon_i(t) + \vartheta_i(t)\big],\\ \hat{y}_i^{(2)}(t) &= \ddot{\xi}_i(t) = (\sigma_{1,i})^{-2}\big[\xi_i(t) - L_1^4\varepsilon_i(t) - \vartheta_i(t)\big] + (\sigma_{1,i})^{-1}\big[L_2^4\varepsilon_i(t) + \dot{\vartheta}_i(t)\big], \quad i = 1, ..., k.\end{aligned} \tag{25}$$

Case 2. $r_i = 2$. Taking into account (13), we have

$$\begin{aligned}\hat{y}_i^{(1)}(t) &= \xi_{2,i}(t) = L_2^2\xi_i(t),\\ \hat{y}_i^{(2)}(t) &= L_2^2\dot{\xi}_i(t) = L_2^2\big[J_2\xi_i(t) + H_2\big(L_1^4\varepsilon_i(t) + \vartheta_i(t)\big)\big], \quad i = 1, ..., k.\end{aligned} \tag{26}$$

Case 3. $r_i \geq 3$. It follows from (13) that

$$\begin{aligned}\hat{y}_i^{(1)}(t) &= \xi_{2,i}(t) = L_2^{r_i}\xi_i(t),\\ \hat{y}_i^{(2)}(t) &= \xi_{3,i}(t) = L_3^{r_i}\xi_i(t), \quad i = 1, ..., k.\end{aligned} \tag{27}$$

Taking into account (24)-(27), rewrite systems (13) and (18) in the forms

$$\dot{z}_i(t) = \bar{A}_i z_i(t) + F_{1,i} z_i(t-h) + F_{2,i} z_i(t-2h) + \phi_i(t), \quad i = 1, ..., k, \tag{28}$$

where $z_i(t) = col\{\varepsilon_i(t), \xi_i(t)\}$, other notations are given in (19). To analyze the exponential stability of (28) consider Lyapunov-Krasovsky functional $V(t) := \sum_{i=1}^k V_i(t)$, where

$$V_i(t) := z_i^\top(t)P_i z_i(t) + \int_{t-h}^{t} e^{\gamma(s-t)} z_i^\top(s)Q_{1,i} z_i(s)ds + \int_{t-2h}^{t} e^{\gamma(s-t)} z_i^\top(s)Q_{2,i} z_i(s)ds, \quad i = 1, ..., k. \tag{29}$$

Taking the time derivative of (29) along the trajectories of (28), we obtain

$$\begin{aligned}\dot{V}_i(t) = {} & 2z_i^\top(t)P_i\big[\bar{A}_i z_i(t) + F_{1,i} z_i(t-h) + F_{2,i} z_i(t-2h) + \phi_i(t)\big] + z_i^\top(t)(Q_{1,i} + Q_{2,i})z_i(t) - e^{-\gamma h} z_i^\top(t-h)Q_{1,i} z_i(t-h)\\ & - e^{-2\gamma h} z_i^\top(t-2h)Q_{2,i} z_i(t-2h) - \gamma\big[\int_{t-h}^{t} e^{\gamma(s-t)} z_i^\top(s)Q_{1,i} z_i(s)ds + \int_{t-2h}^{t} e^{\gamma(s-t)} z_i^\top(s)Q_{2,i} z_i(s)ds\big], \quad i = 1, ..., k.\end{aligned} \tag{30}$$

Taking into account that $2a^\top b \leq \chi_i a^\top a + \chi_i^{-1} b^\top b$ for any $a, b \in \mathbb{R}^n$, rewrite (30) as follows:

$$\dot{V}_i(t) \leq -\gamma V_i(t) + z_i^\top(t)W_i z_i(t) + z_i^\top(t-h)R_{1,i} z_i(t-h) + z_i^\top(t-2h)R_{2,i} z_i(t-2h) + \phi_i^\top(t)P_i\phi_i(t), \quad i = 1, ..., k. \tag{31}$$

Obviously, there exist α_i, h and χ_i such that matrices W_i and $R_{j,i}$ are negative semidefinite. Therefore, $\dot{V}_i(t) \leq -\gamma V_i(t) + \bar{\phi}$. The latter implies the fulfilment of goal (5). Theorem 1 is proved. □

5 | SIMULATIONS

Consider a multi-machine power system consisting of three ($k = 3$) electric generators Γ_i and one load L (see Fig. 1). Each generator Γ_i is connected to the grid via transformer T_i. The emergencies may occur in transmission lines and it are eliminated by disconnecting the emergency areas by opening the corresponding breakersS_{ij}.

The generators Γ_i are described by equations (1)-(3), where all unknown parameters belong to the set $\Xi = \big\{D_i \in [1,5], H_i \in [1,25], \tau'_{d0i} \in [5,9], x_{di} \in [0.1,1.5], x_{qi} \in [0.05,1.5], x'_{di} \in [0.05,0.2], k_{ci} \in [1,3], G_{il}^m \in [0,1], B_{il}^m \in [-6,2], i,l,m = 1,2,3\big\}$. Unknown parameters of each generator are given in Table 1. The synchronous speed is equal to $\omega_0 = 2\pi \cdot 50 \approx 314.159$ [rad/sec].

Choose the low-pass filter parameters and the feedback gains as $\sigma_{j,i} = 0.01$, $j = 1, ..., 4$, $\alpha_i = 0.4$, $d_{0i} = 2$, $d_{1i} = 3.5$, and $d_{2i} = 1$, respectively.

Consider the following fault sequence:

I. Prefault steady state. The conductance and susceptance matrices of the power grid are equal to

$$G^1 = \begin{bmatrix} 0.846 & 0.287 & 0.21 \\ 0.287 & 0.42 & 0.213 \\ 0.21 & 0.213 & 0.277 \end{bmatrix}, \quad B^1 = \begin{bmatrix} -2.988 & 1.513 & 1.226 \\ 1.513 & -2.724 & 1.088 \\ 1.226 & 1.088 & -2.368 \end{bmatrix}.$$

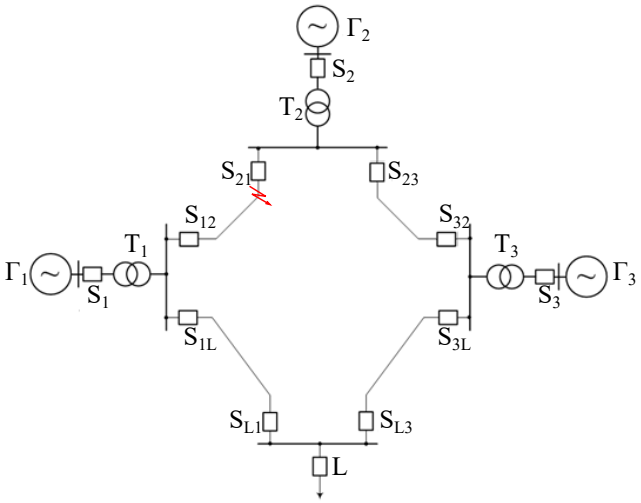


FIGURE 1 Scheme of multi-machine power system.

Parameter [units]	Γ_1	Γ_2	Γ_3	Parameter [units]	Γ_1	Γ_2	Γ_3
D_i [p.u.]	2	2	2	k_{ci} [p.u.]	1	1	1
H_i [sec]	23.64	6.4	3.01	P_{mi} [p.u.]	0.7169	1.6294	0.8506
τ'_{d0i} [sec]	8.96	6.00	5.89	$P_{ei}(0)$ [p.u.]	0.7169	1.6294	0.8506
τ'_{q0i} [sec]	0.001	0.0535	0.0600	$E'_{qi}(0)$ [p.u.]	1.0563	0.7887	0.7688
x_{di} [p.u.]	0.1460	0.8958	1.3125	$E'_{di}(0)$ [p.u.]	0.0242	0.6934	0.6657
x_{qi} [p.u.]	0.0969	0.8645	1.2578	$\delta_i(0)$ [°]	3.5859	61.0532	54.0626
x'_{di} [p.u.]	0.0608	0.1198	0.1813	$\omega_i(0)$ [rad/sec]	0	0	0

TABLE 1 The parameters of the generators Γ_i, $i = 1, 2, 3$.

II. A symmetrical 3-phase short circuit occurs near the generator Γ_2 at the end of the transmission line connecting it with the generator Γ_1 at $t = 5$ [sec]. This fault temporarily splits the network into two subgrids (Γ_1, Γ_3) and Γ_2. The conductance and susceptance matrices of the faulted power system are

$$G^2 = \begin{bmatrix} 0.657 & 0 & 0.07 \\ 0 & 0 & 0 \\ 0.07 & 0 & 0.174 \end{bmatrix}, \quad B^2 = \begin{bmatrix} -3.816 & 0 & 0.631 \\ 0 & -5.486 & 0 \\ 0.631 & 0 & -2.796 \end{bmatrix}.$$

III. The transmission line connecting the generators Γ_1 and Γ_2 is disconnected in nine cycles $(9/50 = 0.18$ [sec]) by opening breakers S_{12} and S_{21}. The conductance and susceptance matrices in the postfault state are equal to

$$G^3 = \begin{bmatrix} 1.181 & 0.138 & 0.191 \\ 0.138 & 0.389 & 0.199 \\ 0.191 & 0.199 & 0.273 \end{bmatrix}, \quad B^3 = \begin{bmatrix} -2.229 & 0.726 & 1.079 \\ 0.726 & -1.953 & 1.229 \\ 1.079 & 1.229 & -2.342 \end{bmatrix}.$$

Consider the measurement errors $\vartheta_i(t)$, $i = 1, 2, 3$ in the forms

$$\vartheta_i(t) = \begin{cases} 0.5\sin(10^5 t) + 0.5\cos(10^5 t) + 0.05\eta_i(t), & \text{for } t \in [0, 20), \\ 0, & \text{for } t \in [20, 25), \\ 0.5\sin(10^5 t) + 0.5\cos(10^5 t), & \text{otherwise}, \end{cases}$$

where $\eta_i(t)$ is the signal simulated in Matlab/Simulink using the "Band-limited white noise" block with the spectral density $\eta_i = 10^{-5} \cdot i$ [rad^2/Hz].

Compare the proposed results with the high-gain observer based control law designed for power systems in [10,11]. According to [10,11], the control scheme is defined by the following equations:

- the high-gain observer with $\mu = 0.01$ in the form

$$\dot{\xi}_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \xi_i - \begin{bmatrix} \frac{2}{\mu} \\ \frac{3.5}{\mu^2} \\ \frac{1}{\mu^3} \end{bmatrix} e_i, \hat{y}_i = [1\ 0\ 0]\xi_i, \quad i = 1, 2, 3;$$

- the control law

$$u_i = 2\xi_{1,i} + 3.5\xi_{2,i} + \xi_{3,i}, \quad i = 1, 2, 3.$$

Figs. 2-5 show the transients of the power angles $\delta_i(t)$, the relative speeds $\omega_i(t)$, the terminal voltages $V_{ti}(t)$ and the control signals $u_{fi}(t)$ of each generator for the proposed control scheme (solid lines) and one from [10,11] (dashed lines). In Figs. 2 and 3 the transients of the power angles $\delta_i(t)$ and the relative speeds $\omega_i(t)$ are almost similar for the proposed algorithm and the one from [10,11]. The terminal voltages $V_{ti}(t)$, obtained by using the high-gain observer based control, more noisy then the terminal voltages, obtained by the proposed algorithm. The advantages of the proposed algorithm is clearly seen in Fig. 5, i.e., the values of the proposed control signals significantly less than the ones from [10,11]. Thus, the proposed control scheme successfully eliminates measurement errors.

Unfortunately, *a priori* it is very difficult to calculate the value of Δ by appropriate choosing of $\sigma_{j,i}$ and r_i in (13) as well as h in (17) due to the complex dependence in (19) and (31). However, the value of Δ can be obtained in simulations. Thus, the simulations show that by decreasing the values of $\sigma_{j,i}$ and h as well as increasing the value of r_i the value of Δ in (5) can be decreased.

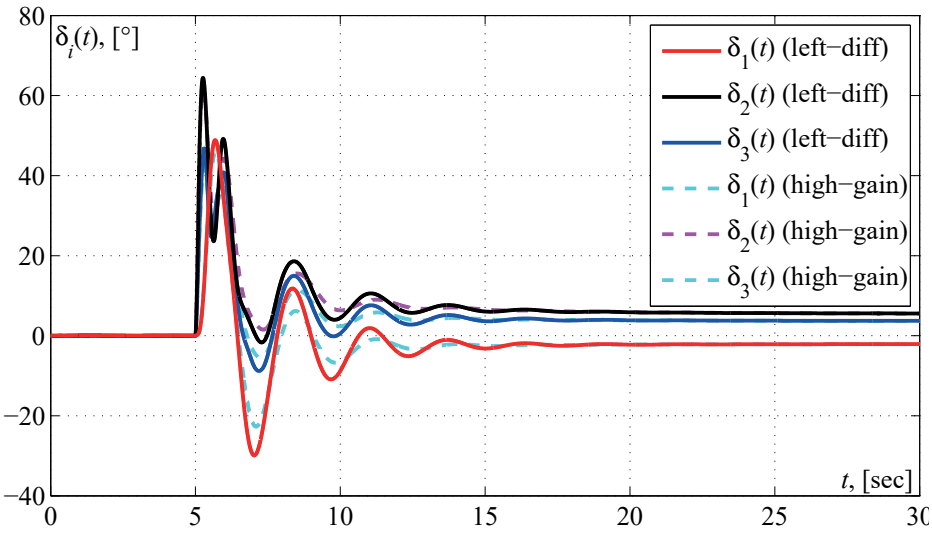


FIGURE 2 The transient of the power angels $\delta_i(t)$.

6 | EXPERIMENTAL RESULTS

We study the performance of the proposed algorithm over the experimental setup located in IPME RAS, consisting of three electrical generators (see Fig. 6). The mechanical input power P_{mi} is generated by AC motors. The power angels δ_i of each generator are measured by the optical encoders (3000 steps per rate) and transmitted to the programmable logic controllers via Matlab/Simulink. The reactance of the transmission lines is changed by the ballast rheostats.

Fig. 7 shows the transients of the relative speed $\omega_i(t)$ of the generators. At $t = 10$ [sec] the reactance of the transmission lines is significantly changed. Clearly, the proposed algorithm allows to synchronize three generators under significant change of the reactance of the transmission line in presence of the measurement errors.

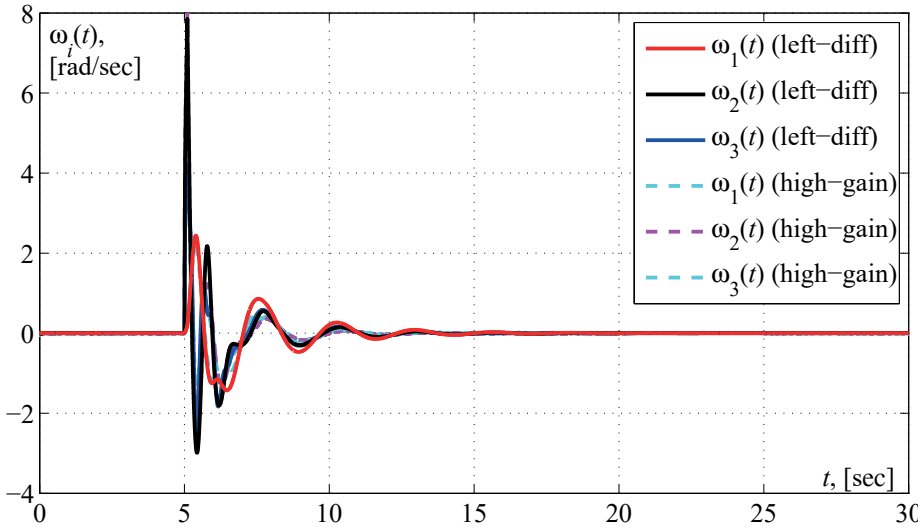


FIGURE 3 The transient of the relative speed $\omega_i(t)$.

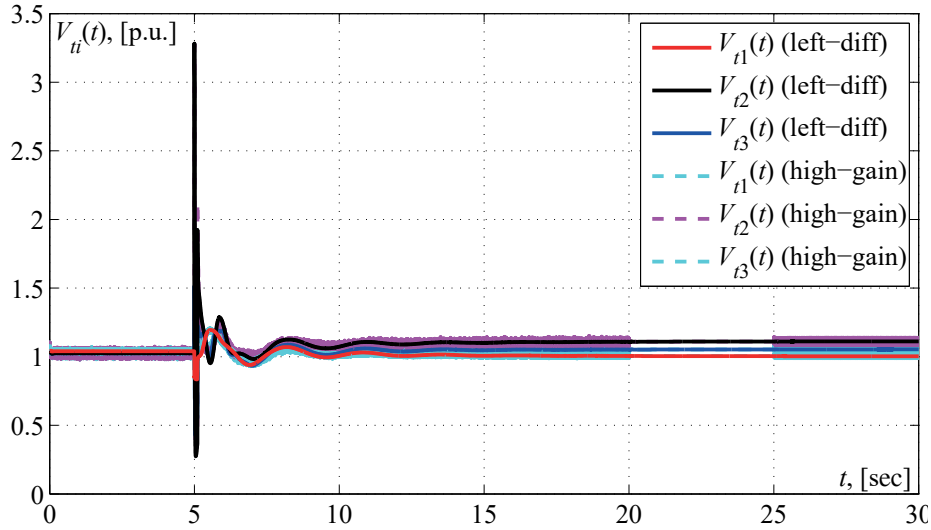


FIGURE 4 The transient of the generator terminal voltage $V_{ti}(t)$.

Differently from simulations the experiments show that by decreasing the values of $\sigma_{j,i}$ and h as well as increasing the value of r_i the value of Δ in (5) does not decrease less than some value. This is due to the fact that in the experiment it is impossible to achieve the exact fulfillment of Assumption 3.

7 | CONCLUSIONS

A novel control law has been designed for synchronization of multi-machine power systems under parametric uncertainty, emergency modes and measurement errors. Differently from [16,17], the proposed control law allows one to independently tune the low-pass filter parameters and the feedback gains. This made it possible to reduce the dynamical order of the closed-loop system and improve the performance in steady state in compassion with [10,11]. The simulations and experimental results illustrate the efficiency of the proposed algorithm and confirm theoretical results.

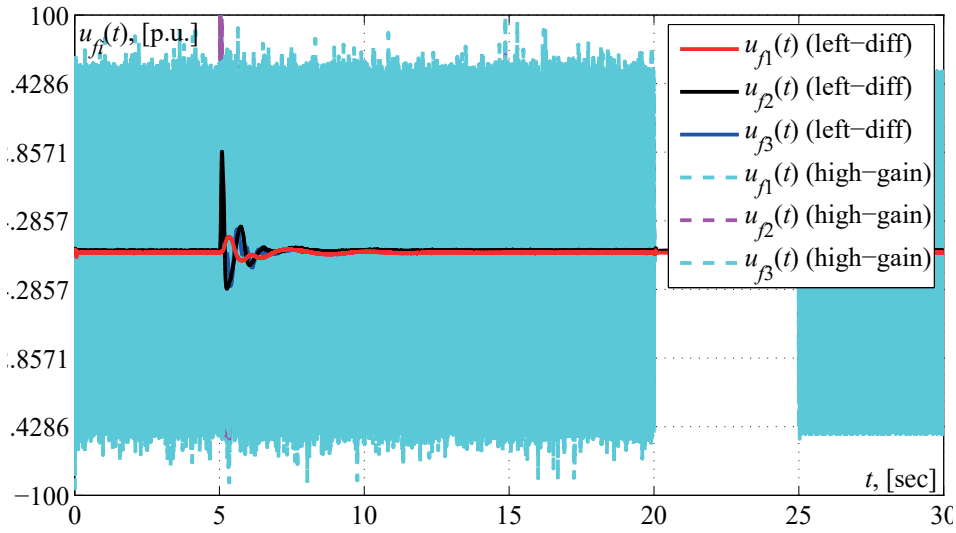


FIGURE 5 The transient of the control signal $u_{fi}(t)$.



FIGURE 6 The experimental setup to study the power system.

References

1. Sadamoto T, Chakrabortty A, Ishizak TI, Imura J-I. Dynamic Modeling, Stability, and Control of Power Systems with Distributed Energy Resources. *IEEE Control Systems Magazine* 2019; 39(2): 34–65.

2. Nowzari C, Preciado V, Pappas GJ. Analysis and Control of Epidemics: A Survey of Spreading Processes on Complex Networks. *IEEE Control Systems Magazine* 2016; 36(1): 24–26.

3. Stoustrup J, Annaswamy A, Chakrabortty A, Qu Z. *Smart Grid Control. Overview and Research Opportunities*. Cham, Switzerland: Springer . 2018. ISBN 978-3-319-98309-7.

4. Gordon M, Hill DJ. Global transient stability and voltage regulation for multimachine power systems. *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century* 2008: 1-8.

5. Psillakis HE, Alexandridis A. Coordinated Excitation and Static Var Compensator Control with Delayed Feedback Measurements in SGIB Power Systems. *Energies* 2020; 13(9): 2181.

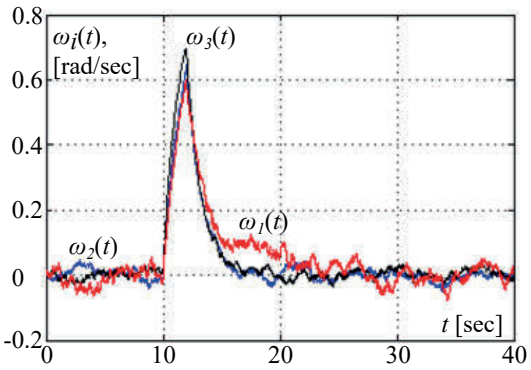


FIGURE 7 The transients of the signals ω_i for the proposed control law

6. Barabanov A, Dib W, Lamnabhi-Lagarrigue F, Ortega R. On transient stabilization of multi-machine power systems: a "globally" convergent controller for structure-preserving models. *17th World Congress, IFAC. Seoul* 2008: 9398–9403.

7. Singh AK, Tripathy M. *Control Applications in Modern Power System: Select Proceedings of EPREC 2020.* Singapore: Springer . 2021.

8. Ghazzali M, Haloua M, Giri F. Modeling and Adaptive Control and Power Sharing in Islanded AC Microgrids. *International Journal of Control, Automation and Systems* 2020; 18: 1229–1241.

9. Dib W, Ortega R, Hill D. Transient stability enhancement of multi-machine power systems: synchronization via immersion of pendular system. *Asian Journal of Control* 2014; 16(1): 50–58.

10. Fradkov AL, Furtat IB. Robust control for a network of electric power generators. *Automation and Remote Control* 2013; 74(11): 1851–1862.

11. Furtat IB, Fradkov AL. Robust control of multi-machine power systems with compensation of disturbances. *International Journal of Electrical Power and Energy Systems* 2015; 73: 584–590.

12. Sanfelice R, Praly L. On the preformance of highgain observers with gain adaptation under measurement noise. *Automatica* 2011; 47: 2165–2176.

13. Boizot N, Busvelle E, Gauthier J. An adaptive high-gain observer for nonlinear systems. *Automatica* 2010; 46: 1483–1488.

14. Ahrens J, Khalil K. High-gain observers in the presence of measurement noise: A switched-gain approach. *Automatica* 2009; 45: 936–943.

15. Prasov A, Khalil H. A nonlinear high-gain observer for systems with measurement noise in a feedback control framework. *IEEE Transaction on Automatic Control* 2013; 58(3): 569–580.

16. Astolfi D, Marconi L. A high-gain nonlinear observer with limited gain power. *IEEE Transaction on Automatic Control* 2015; 60(11): 3059–3064.

17. Wang L, Astolfi D, Hongye S, Marconi L, Isidori A. Output stabilization for a class of nonlinear systems via high-gain observer with limited gain power. *Proc. 1st IFAC Conference on Modelling, Identification and Control of Nonlinear Systems, MICNON 2015, Saint Petersburg, Russia. IFAC-PapersOnLine* 2015; 48(11): 730–735.

18. Esfandiari F, Khalil HK. Output feedback stabilization of fully linearizable systems. *International Journal of Control* 1992; 56(5): 1007–1037.

19. Nekhoroshikh A, Furtat I. Robust Stabilization of Linear Plants under Uncertainties and High-Frequency Measurement Noises. *Proc. of the 25th Mediterranean Conference on Control and Automation, Malta, DOI: 10.1109/MED.2017.7984293* 2017.

20. Furtat IB, Nekhoroshikh AN. Investigation of electric generator robust algorithm under measurement noises. *Cybernetics and Physics* 2018; 7(4): 204–209.

21. Anderson PM, Fouad AA. *Power system control and stability*. Iowa: Iowa State University Press . 1977.

22. Agaev RP, Chebotarev PYu. Spanning Forests of a Digraph and Their Applications. *Automation and Remote Control* 2001; 61(9): 1424–1450.

23. Su A, Lin Z. Distributed Consensus Control of Multi-Agent Systems With Higher Order Agent Dynamics and Dynamically Changing Directed Interaction Topologies. *IEEE Transactions on Automatic Control* 2016; 61(2): 515–519.

24. Williams AB. *Analog Filter and Circuit Design Handbook*. New York: McGraw-Hill Education . 2014.

25. Ren W, Beard RW. Consensus seeking in multiagent systems under dynamically changing interaction topologies. *IEEE Transactions on Automatic Control* 2005; 50(5): 655–661.

26. Furtat IB, Fradkov AL, Liberzon L. Compensation of disturbances for MIMO systems with quantized output. *Automation and Remote Control* 2015; 60: 239–244.

27. Furtat IB. Robust static control algorithm for linear objects. *Automation and Remote Control* 2015; 76(3): 446–457.

How to cite this article: Furtat I., Nekhoroshikh A., and Gushchin P. (2021), Synchronization of multi-machine power systems under disturbances and high-frequency noises, *International Journal of Adaptive Control and Signal Processing*, *2021;00:1–12*.