ROBUST TRANSIENT SYNCHRONIZATION OF POWER NETWORKS

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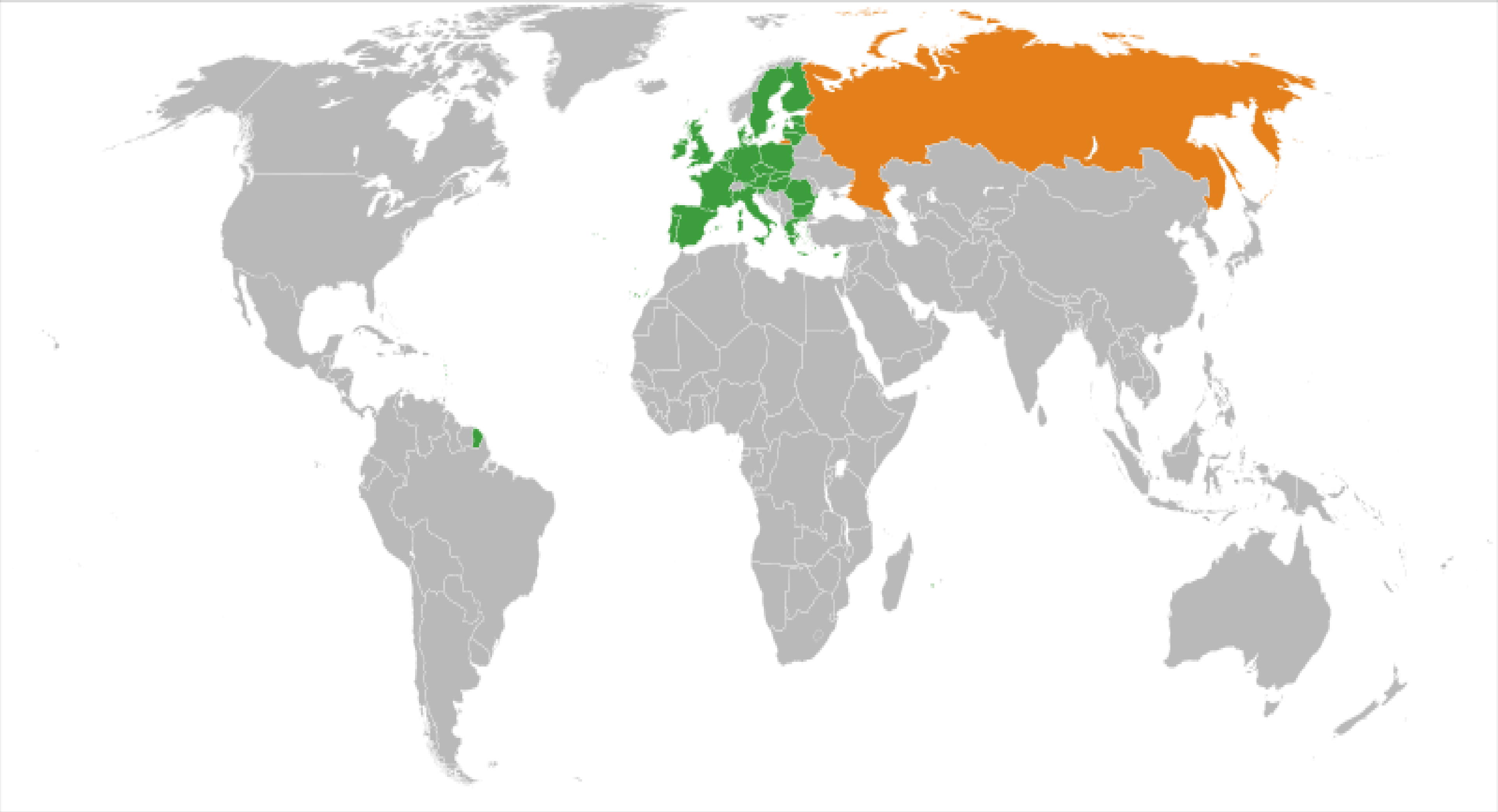
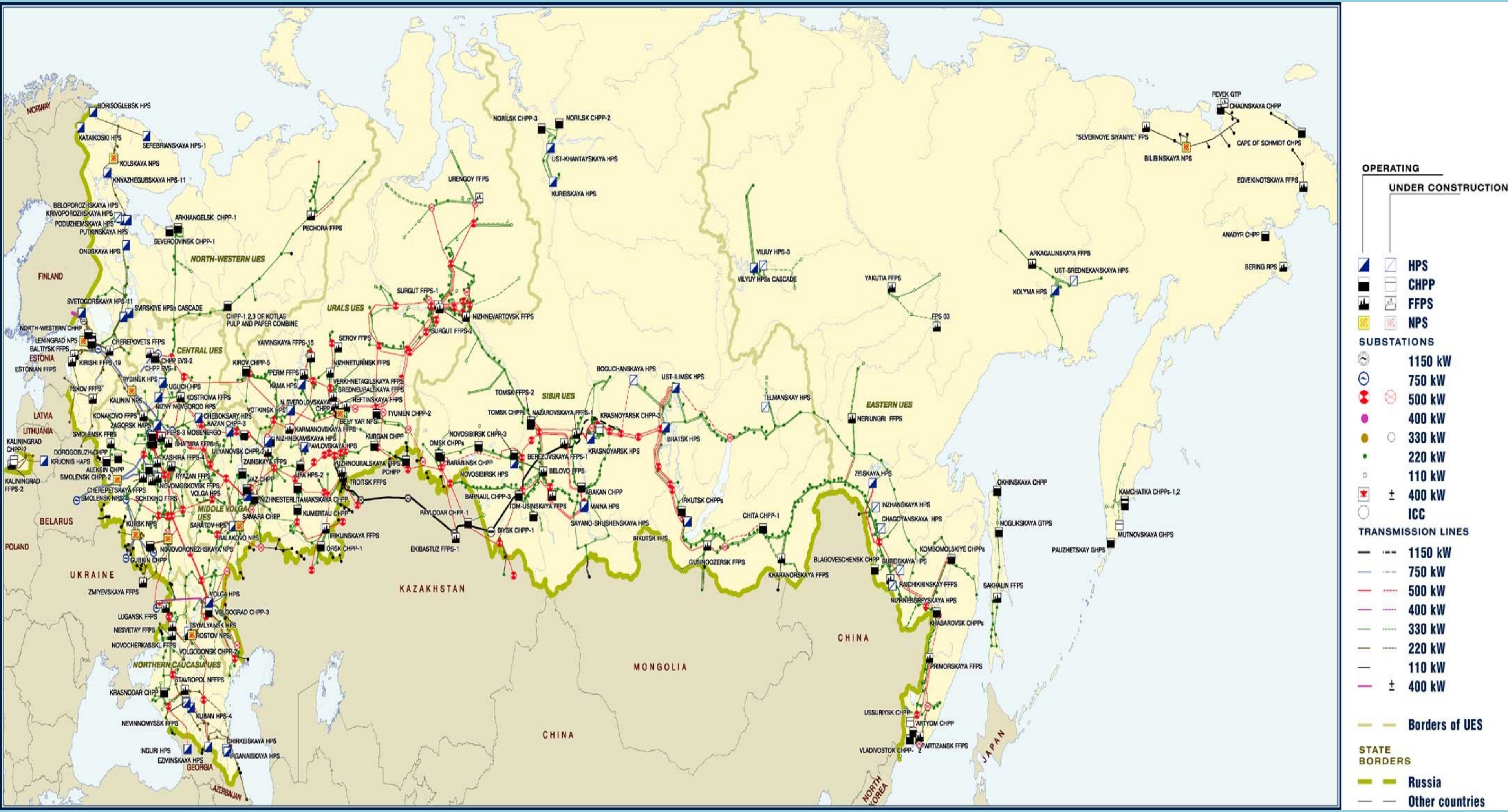
European Union and Russian Federation



European Union
area: **3236, 2** km²

Russian Federation
area: **17 098 246** km²

Energy network of Russia



- More than **600** power stations with power more than **5 MW**
- More than **10 200** transmission lines of **110 - 1150 kW**
- Total power generation capacity **218 235.8 MW** in 2011
- Total generated energy: about **one trillion kilowatt hours** of electricity per year

Emergence of ‘Smart Grid’

Development of ‘smart grid’ area is caused by the following factors:

- technological progress
- growth of customer requirements
- decreasing reliability of electrical networks
- increasing demands for energy efficiency and ecological safety

etc.

- **Butler F.** A call to order a regulatory perspective on the smart grid // IEEE power & energy magazine. March/April, 2009. P. 16-93.
- **Farhangi H.** The path of the smart grid // IEEE power & energy magazine. January/February, 2010. P. 18-28.
- **Jackson J.** Improving energy and smart grid program analysis with agent-based end-use forecasting models // Energy policy, 38, 2010. P. 3771-3780.
- **Liserre M., Sauter T., Hung Y.J.** Future energy systems // IEEE industrial electronics magazine, March, 2010. P. 18-37.
- **Parks N.** Energy efficiency and the smart grid // Environmental science & technology, May, 2009. P. 2999-3000.

Synchronization

Synchronization: - coincidence of the generator rotor speeds,

- reduction to zero the difference between active electrical power and mechanical input power of each generator

$$\begin{bmatrix} \dot{\delta}_i \\ \dot{\omega}_i \\ \Delta\dot{P}_{ei} \\ \vdots \end{bmatrix} = f\left(\delta_1, \ldots, \delta_k, \omega_1, \ldots, \omega_k, \Delta P_{e1}, \ldots, \Delta P_{ek}, \ldots\right), \qquad i = 1, \ldots, k$$

δ_i - deflection of the rotor angle of the *i*th generator from synchronous mode

ω_i - deflection of the speed of the *i*th generator from synchronous mode

$$\Delta P_{ei} = P_{ei} - P_{mi}$$

P_{ei} - the active electrical power delivered by the *i*th generator

P_{mi} - the mechanical input power of the *i*th generator

Transient stability

$$\lim_{t\to\infty} \delta_i = const \qquad \lim_{t\to\infty} \omega_i = 0 \qquad \lim_{t\to\infty} \Delta P_{ei} = 0 \qquad \left(\lim_{t\to\infty}\left(\omega_i - \omega_j\right) = 0\right)$$

Willems J.L. A partial stability approach to the problem of transient power system stability // Int. J. of Control. 1974, Vol. 19. No. 1. P. 1-14.

Existing results

Robust decentralized control

- **Guo G., Hill D.J., Wang Y.** Robust decentralized control of a class of nonlinear systems and applications to multimachine power system stabilization // Proc. of the 36th Conf. of Decision & Control. San Diego. 1997. P. 3102–3107.
- **Wang Y., Hill D.J., Guo G.** Robust decentralized control for multimachine power systems // IEEE Trans. on Circuits and Systems-I: Fundamental theory and applications. 1998. V. 45. № 3. P. 271–279.
- **Guo G., Hill D.J., Wang Y.** Nonlinear output stabilization control for multimachine power systems // IEEE Trans. On Circuits and Systems, part 1. 2000. V. 47.№ 1. P. 46–53.
- **G. Zhang, Y. Wang, D. J. Hill.** Global Control of Multi-Machine Power Systems for Transient Stability Enhancement. IEEE Multi-conference on Systems and Control, 2007, pp. 934-939.

- Network models: sets of nonlinear 3rd order differential-algebraic equations (DAE).
- Measurables: rotor angles and speeds, active electrical power and mechanical power of generators.
- Class of faults: short-term changes in the resistance of the transmission line (short circuits faults, etc).
- Control approach: feedback linearization

- **Qu Z., Dorsey J.F., Bond J., McCalley J.D.** Application of robust control to sustained oscillation in power systems // IEEE Trans. on Circuits and Systems – I: Fundamental theory and applications. 1992. V. 39. № 6. P. 470–476.
- **Jiang H., Dorsey J.F., Bond J.** Transient and steady state decentralized control of large power systems // Proc. of the 32nd Conf. on Decision and control. San Antonio. 1993. P. 3716-3721.

-The results are similar to the results of Hill et. al.
- Network generator models are described by <u>linear</u> DAE of the third order.

Existing results

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 // Proc. of the 17th Word Congress, IFAC. Seoul. 2008. P. 9398–9403.

Guisto A., Ortega R., Stankovic A. On transient stabilization of power systems: a power-shaping solution for structure-preserving models // Proc. of the 45th IEEE Conf. on Decision & Control. San Diego. 2006. P. 4027–4031.

Ortega R., Galaz M., Astolfi A., Sun Y., Shen T. Transient stabilization of multimachine power systems with nontrivial transfer conductance // IEEE Trans. On Automatic Control. 2005. V. 50. № 1. P. 60–75.

Transient stabilization of the power systems

- All network parameters are known.
- Network model: 3rd order DAE model for the generators; load model; the equations of transmission lines; equations of infinite buses.
- Measurables: the power angles, the relative speeds, the transient electromotive force (EMF) of generators.
- Control approach: energy shaping / interconnection and damping assignment (IDA-PBC)

Pogromsky A.Yu., Fradkov A.L., Hill D.J. Passivity based damping of power system oscillations // Proc. of the 35th Confer. On Decision and Control. Kobe. 1996. P. 3876–3881.

Synchronization of electrical generators network

- Models of the generators are described by 2nd order differential equations.
- The power angles and the relative speeds of each generators are available to measurement.
- Control approach: passivity and speed gradient.

I. Speed-gradient-energy approach
Power network model

$$\begin{cases} \dot{\delta}_i = \omega_i, \\ \dot{\omega}_i = -D_i\omega_i + P_{mi} - G_i E_i^2 - \sum\limits_{j=1,\, j\neq i}^{N} \left(\alpha_{ij}\cos\left(\delta_i - \delta_j\right) + \beta_{ij}\sin\left(\delta_i - \delta_j\right)\right), \\ \dot{E}_i = f_i + v_i. \end{cases} \qquad (1)$$

where *i=1,..N*, $\alpha_{ij} = E_i E_j G_{ij},\ \beta_{ij} = E_i E_j B_{ij},\ i \neq j.$

δ_i is the rotor angle,

$\omega_i = \omega_0 - \omega_{Ri}$; ω_{Ri}, ω_0 are the rotor speed and the synchronous speed,

E_i is the internal voltage in the quadrature axis of the *i*th generator,

v_i is the control signal (the field excitation signal),

$f_i = F_i\left(\delta_1, \ldots, \delta_N; E_1, \ldots, E_N\right)$ – the known function,

$D_i, P_{mi}, G_{ii}, G_{ij}, B_{ij}$ – the constant parameters.

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

R. Ortega et al. “Transient stabilization of multimachine power systems with nontrivial transfer conductances”/ *IEEE Trans. on Automatic Control*, vol. 50, no. 1, pp. 60-75, (2005).

Invariant

Let us neglect damping and cancel control:

$$D_i = 0;\ G_{ij} = 0;\ B_{ij} = B_{ji};$$
$$E_i = E_{di} = \sqrt{\frac{P_{mi}}{G_{ii}}},\ (v_i = -f_i). \qquad (2)$$

for all *i,j=1,..,N* . Then the following function is an invariant of (1):

$$H(\delta,\omega) = \frac{1}{2}\omega^T\omega + \sum_{i=1}^{N}\sum_{j=i+1}^{N}\left(\beta_{ij}\left(1-\cos\left(\delta_i-\delta_j\right)\right) + \alpha_{ij}\left(1+\sin\left(\delta_i-\delta_j\right)\right)\right), \qquad (3)$$

where $\omega = \left(\omega_1, \omega_2, \ldots, \omega_N\right)^T\ \delta = (\delta_1, \delta_2, \ldots, \delta_N)^T.$

Control goal: to achieve the desired level of (3) and approximate transient stability of (1):

$$H \xrightarrow{t\to\infty} H_d,\ E_i \xrightarrow{t\to\infty} E_{di},$$
$$\delta_i \in \left(0;\frac{\pi}{2}\right),\quad i = 1,..,N. \qquad (4)$$

Control Algorithm

Introduce a new control

$$u_i = v_i - f_i,\ i = 1,..,N, \tag{5}$$

and a goal function

$$Q = \frac{1}{2}\kappa\left(H - H_d\right)^2 + \sum_{i=1}^{N}\frac{1}{2}\left(E_i - E_{di}\right)^2. \tag{6}$$

Design control according to the speed-gradient algorithm:

$$u_i = -\gamma_i \nabla_{u_i}\dot{Q},\ i = 1,\ldots,N. \tag{7}$$

Finally the control algorithm is

$$v_i = -\gamma_i\kappa\left(Q - Q_d\right)\sum_{j=1,\,j\neq i}^{N} E_j B_{ij}\left(1 - \cos\left(\delta_i - \delta_j\right)\right) - \gamma_i\left(E_i - E_{di}\right) + \eta_i\sum_{j=1}^{N}\omega_j - f_i,\ i = 1,\ldots,N.$$

Simulation results

The system (1) with N=5 and the following parameters is considered

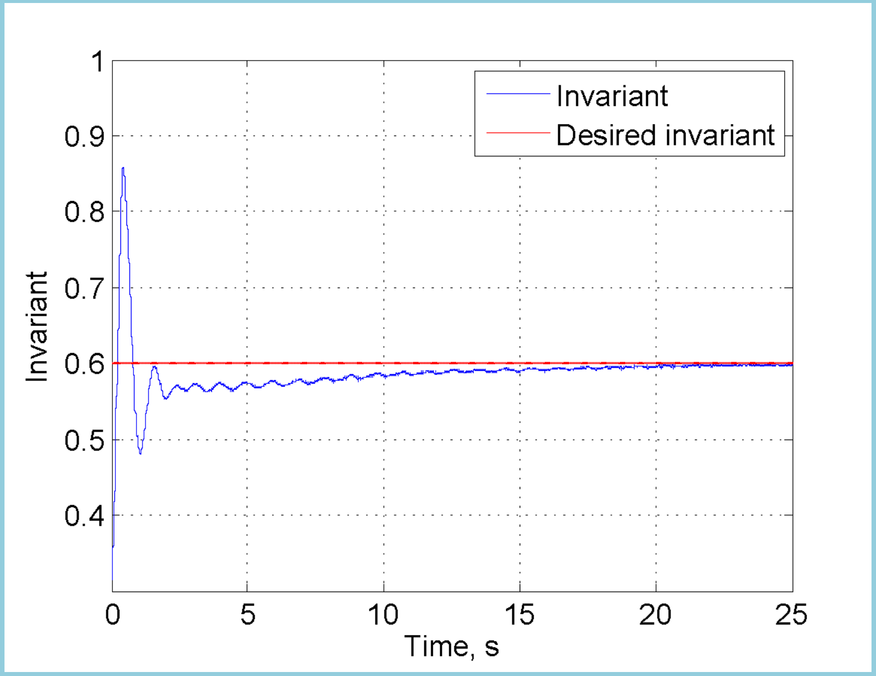
$$\mathrm{D}=[0;0;0;0;0]^{\mathrm{T}};\ \mathrm{P}=[6;5;5.5;5.3;5.8]^{\mathrm{T}};\ \mathrm{G}=\{\mathrm{G}_{\mathrm{ii}}\}_{i=1}^{N}=[3;2;2.5;2.3;2.8]^{\mathrm{T}};$$

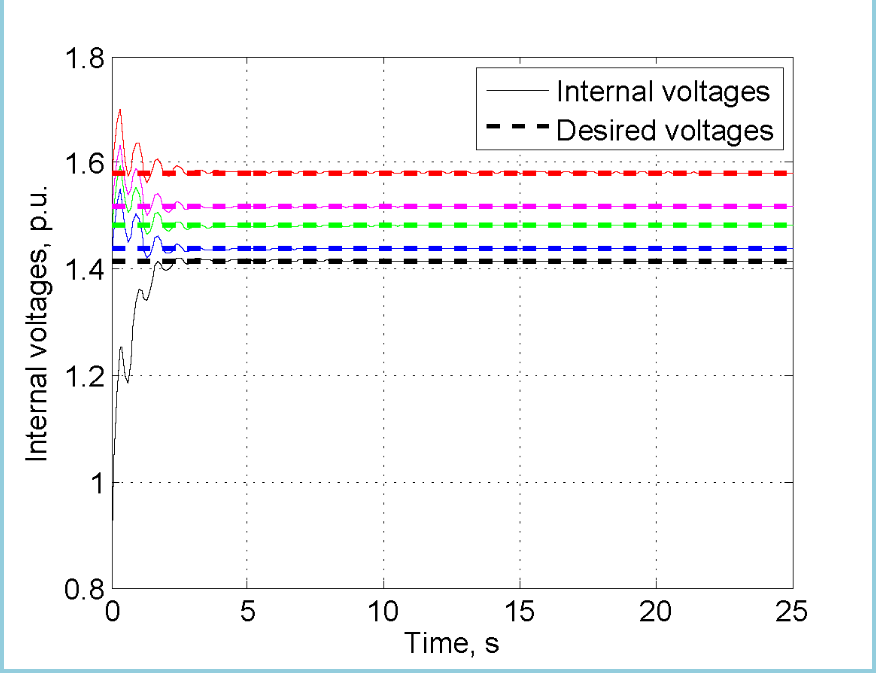
$$\mathrm{G}_{\mathrm{ij}}=0;\ \mathrm{B}_{\mathrm{ij}}=4;\quad \mathrm{Q}_{\mathrm{d}}=0.6;\ \gamma_i=2;\ \eta_i=2;\ \kappa=6.$$

Initial conditions are as follows:

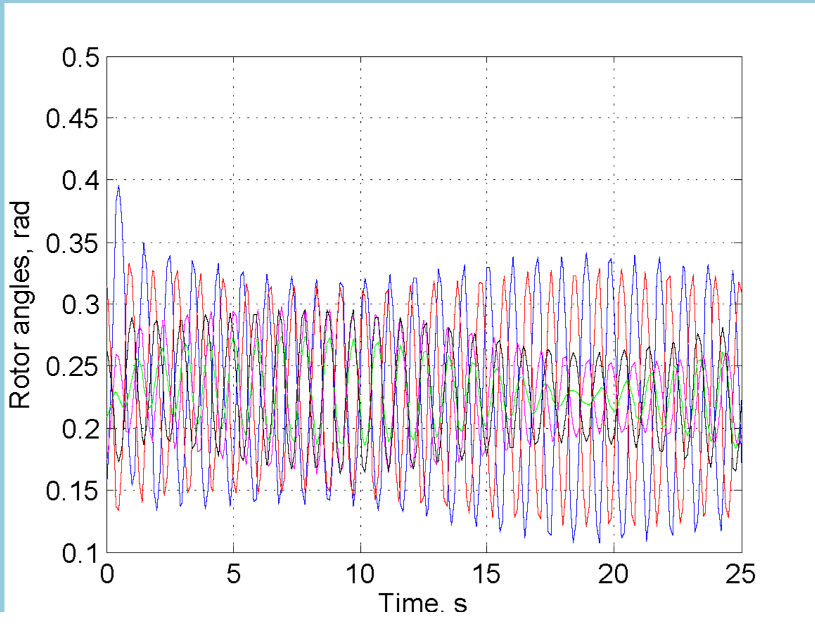
$$\delta=\left(\pi/20;\pi/10;\pi/15;\pi/18;\pi/12\right)^{T};\ \omega=\left(0;0;0;0;0\right)^{T};$$

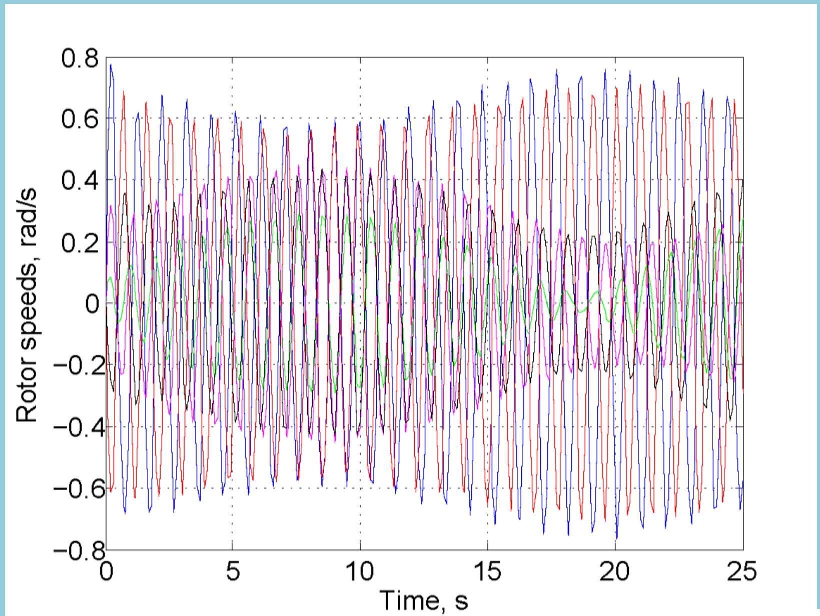
$$E=\left(E_{d1}-0.5;E_{d2};E_{d3};E_{d4};E_{d5}\right)^{T}=\left(0.9142;1.5811;1.4832;1.5180;1.4392\right)^{T}.$$

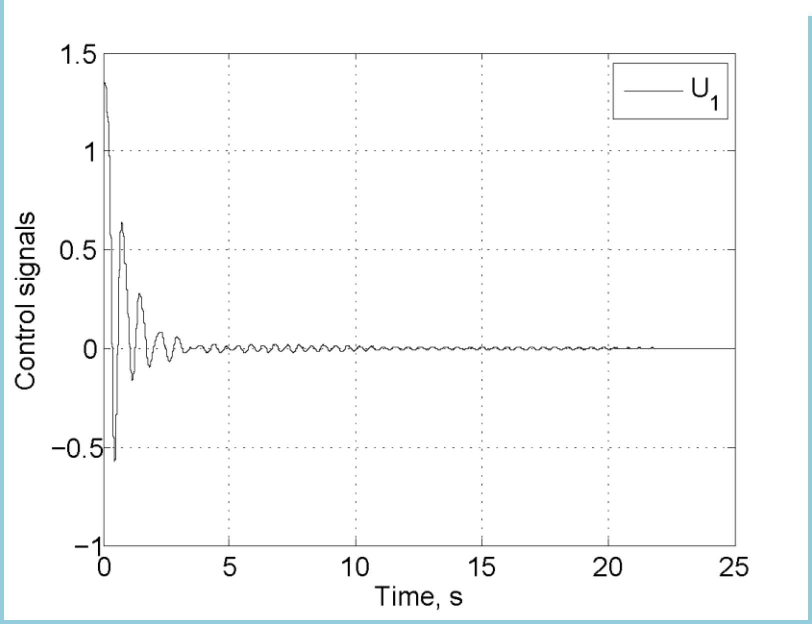


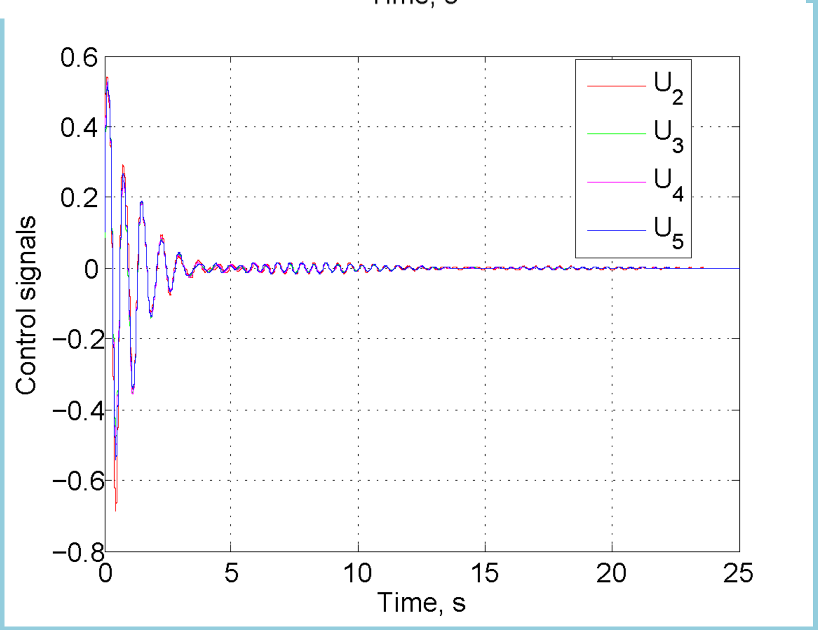


Simulation results









II. Auxiliary loop approach

DAE power network model[*]

Mechanical equations i=1,…,k $$\dot{\delta}_i(t)=\omega_i(t),\quad \dot{\omega}_i(t)=-\frac{D_i}{2H_i}\omega_i(t)-\frac{\omega_0}{2H_i}\Delta P_{ei}(t) \qquad (1)$$

Generator electrical dynamics i=1,…,k $$\dot{E}'_{qi}(t)=\frac{1}{T'_{d0i}}\left(E_{fi}(t)-E_{qi}(t)\right) \qquad (2)$$

Electrical equations i=1,…,k $$E_{fi}(t)=k_{ci}u_{fi}(t)\qquad I_{di}(t)=-\sum_{j\in N_i}E'_{qj}(t)M_{ij}\cos\left(\delta_i(t)-\delta_j(t)\right)$$

$$Q_{ei}(t)=-\sum_{j\in N_i}E'_{qi}(t)E'_{qj}(t)M_{ij}\cos\left(\delta_i(t)-\delta_j(t)\right)\qquad P_{ei}(t)=\sum_{j\in N_i}E'_{qi}(t)E'_{qj}(t)M_{ij}\sin\left(\delta_i(t)-\delta_j(t)\right) \qquad (3)$$

$$E_{qi}(t)=x_{adi}I_{fi}(t)=E'_{qi}(t)-\left(x_{di}-x'_{di}\right)I_{di}(t)\qquad I_{qi}(t)=\sum_{j\in N_i}E'_{qj}(t)M_{ij}\sin\left(\delta_i(t)-\delta_j(t)\right)$$

$$V_{ti}(t)=\frac{1}{x_{dsi}}\sqrt{\left(E'_q(t)-x'_{di}I_{di}(t)\right)^2+\left(x'_{di}I_{qi}(t)\right)^2}$$

Assumptions

1. $\delta_i\in(0;\ \pi)$
2. $\varsigma\in Z$, where ς is the vector of the unknown parameters of the equations (1)-(3);
   Z is known bounded set.
3. The quadratic axis currents signs $I_{qi}(t)$, $i=1,\ldots,k$ are known.
4. Only the rotor speed deflections $\omega_i(t)$, $i=1,\ldots,k$ are measured.

[*] **Zhang G.H., Wang Y., Hill D.J.** Global control of multi-machine power systems for transient stability enhancement // 16th IEEE Int. Conf. on Control Applications. Singapore. 2007. P. 934-939.

Controller design

The goal

$$\lim_{t\to T}\delta_i(t)=const \quad |\omega_i(t)|<\varepsilon_1 \quad |\Delta P_{ei}(t)|<\varepsilon_2 \quad |\omega_i(t)-\omega_j(t)|<\varepsilon_3 \quad |\delta_i(t)-\delta_j(t)|<\pi \qquad (4)$$

for $t>T$, where $\varepsilon_1>0$, $\varepsilon_2>0$, $\varepsilon_3>0$ are small numbers

Control system

Auxiliary loop

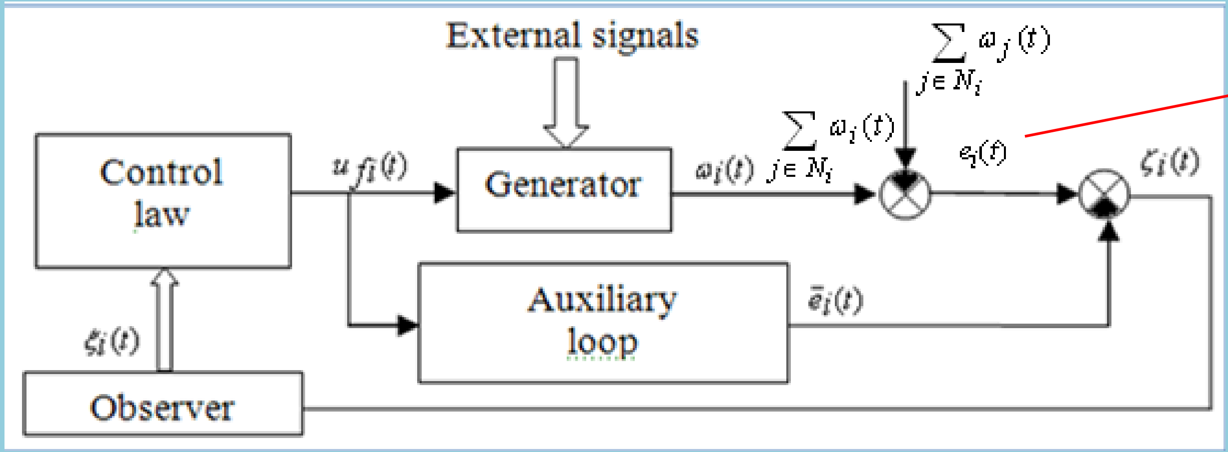
$$Q_m(p)\bar{e}_i(t)=\chi u_{fi}(t), \quad i=1,\ldots,k \qquad (5)$$

Observer [**]

$$\dot{\xi}_i(t)=G_0\xi_i(t)+D_0\left(\bar{\zeta}_i(t)-\zeta_i(t)\right), \quad \bar{\zeta}_i(t)=L\xi_i(t), \quad i=1,\ldots,k \qquad (6)$$

Control law

$$u_{fi}(t)=-\chi^{-1}Q_m(p)\bar{\zeta}_i(t), \quad i=1,\ldots,k \qquad (7)$$



$$e_i(t)=\sum_{j\in N_i}\left(\omega_i(t)-\omega_j(t)\right)$$

[**] Atassi A.N., Khalil H.K. A separation principle for the stabilization of class of nonlinear systems // IEEE Trans. Automat. Control. 1999. V. 44. № 9. P. 1672–1687.

Main theoretical result

For any $\chi > 0$ there is a number $\mu_0 > 0$ such that the control system (5)-(7) ensures the goal (4) for the power network (1)-(3) for $\mu < \mu_0$.

Fradkov A.L., Furtat I.B. Robust control of the electrical generators network // Automation and Remote Control, 2012, submitted.

Simulation results

Network parameters and control system

Set of the network parameters (Z) [**Zhang G.H., Wang Y., Hill D.J.** Global control of multi-machine power systems for transient stability enhancement // 16th IEEE Int. Conf. on Control Applications. Singapore. 2007. P. 934-939]

$$4 \le H_i \le 5{,}5 \qquad 6 \le T'_{d0i} \le 8 \qquad 0{,}2 \le x'_{di} \le 0{,}4$$

$$3 \le D_i \le 5 \qquad 1 \le k_{ci} \le 3 \qquad 1{,}8 \le x_{di} \le 2{,}4$$

$$0{,}3 \le M_{ij} \le 3 \qquad -3 \le E_{fi}(t) \le 6 \qquad i = 1,\, 2,\, 3,\, 4$$

Control system

Auxiliary loop $\left(p^2 + 4p + 4\right)e_i(t) = -u_{fi}(t), \quad i = 1,\, 2,\, 3,\, 4$

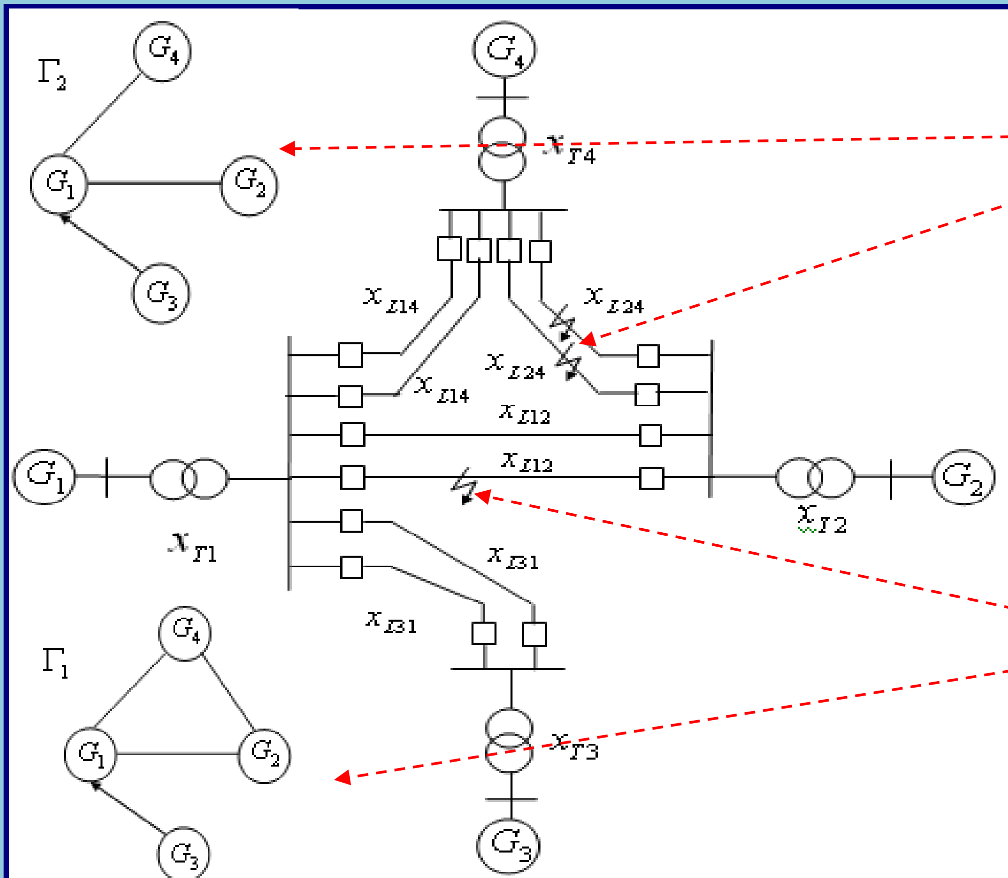
Observer $\dot{\xi}_{1i}(t) = -\xi_{2i}(t) - 4\cdot 100\left(\xi_{1i}(t) - \zeta_i(t)\right), \quad \dot{\xi}_{2i}(t) = -4\cdot 100^2\left(\xi_{1i}(t) - \zeta_i(t)\right),$

$i = 1,\, 2,\, 3,\, 4$

Control law $u_{fi}(t) = \dot{\xi}_{2i}(t) + 4\xi_{2i}(t) + 4\xi_{1i}(t),\, i = 1,\, 2,\, 3,\, 4$

Error $e_i(t) = \sum_{j \in N_i} \left(\omega_i(t) - \omega_j(t)\right)$

Network parameters



Alarm 2) before $t = 10$ s.
$M_{24} = M_{42} = 0{,}95$ p.u., when
$t = 10$ s. fault in line 2-4

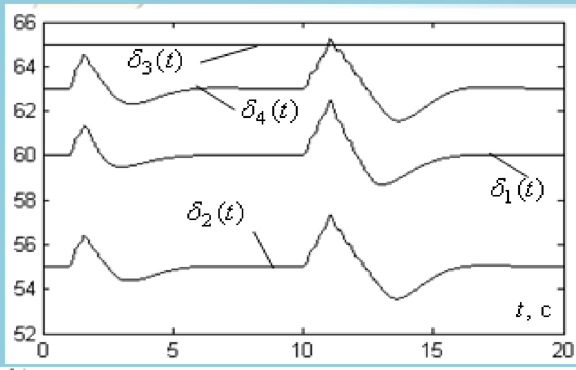
Alarm 1[*]) before $t = 1$ s.,
$M_{12} = M_{21} = 0{,}4853$ p.u., when
$t = 1$ s., $M_{12} = M_{21} = 3$ p.u.,
when $t = 1{,}5$ s.
$M_{12} = M_{21} = 0{,}4853$ p.u.;

$\omega_0 = 314{,}159$ rad/s, $\omega_i(0) = 0$ rad/s, $\Delta P_{ei}(0) = 0$ p.u. [*]

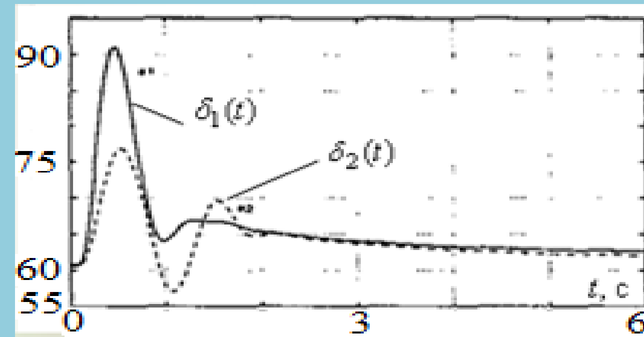
Generator	D_i, p.u.	H_i, s.	T'_{d0i}, s.	x_{di}, p.u.	x'_{di}, p.u.	P_{m0i}, p.u.	V_{t0i}, p.u.	k_{ci}, p.u.	$\delta_i(0)$, rad
G_1	5	4	1,7	1,863	0,257	0,9	1	1	$\pi/3$
G_2	4	5	2	2,17	0,32	0,8	0,9	1	$11\pi/36$
G_3	4	5	2	2,01	0,28	1	1,1	1	$13\pi/3$
G_4	4,5	5,2	2,1	2,07	0,35	0,85	0,87	1	$7\pi/20$

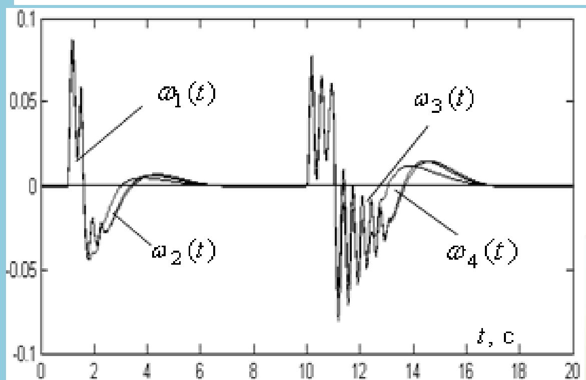
[*] Zhang G.H., Wang Y., Hill D.J. Global control of multi-machine power systems for transient stability enhancement // 16th IEEE Int. Conf. on Control Applications. Singapore. 2007. P. 934-939.

Simulation results

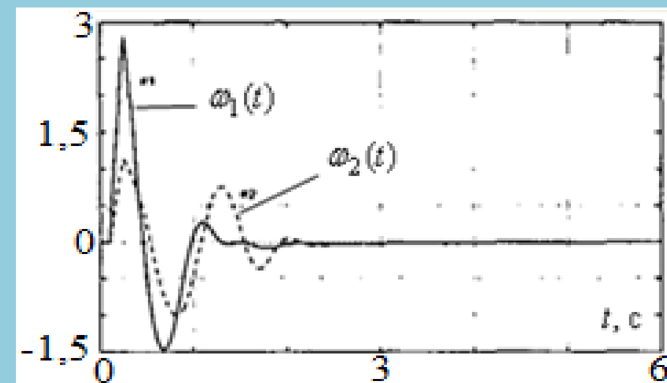


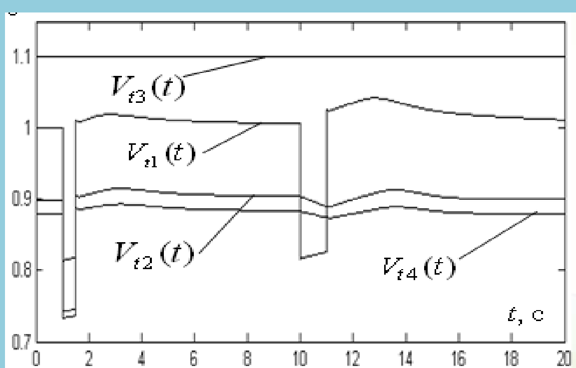
$\delta_i(t)$,
deg



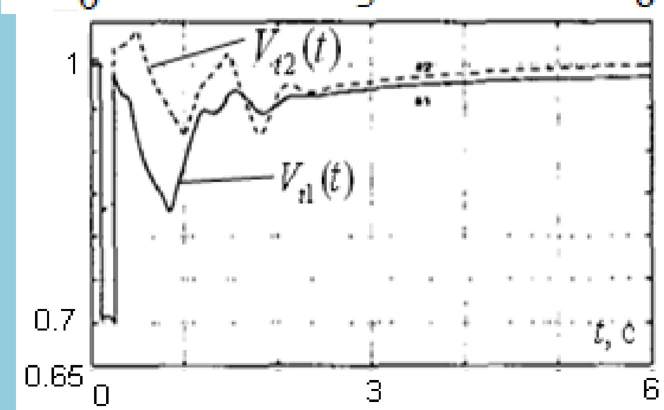


$w_i(t)$,
rad/s





$V_{ti}(t)$,
p. u.



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