Proceedings of the 35th
Conference on Decision and Control
Kobe, Japan • December 1996

Passivity Based Damping Of Power System Oscillations

A.Yu. Pogromsky
Inst. for Problems
of Mech. Engg.
61, Bolshoy, 199178
St. Petersburg, Russia
sasha@ccs.ipme.ru

A.L. Fradkov
Inst. for Problems
of Mech. Engg.
61, Bolshoy, 199178
St. Petersburg, Russia
alf@ccs.ipme.ru

D.J. Hill
EE Dept. Uni of Sydney
NSW 2006 Australia
davidh@ee.usyd.edu.au

Abstract

The aim of the paper is to apply the passification and Speed-Gradient methods to the problem of transient stabilization. A controller is proposed and the stability results are established. It is shown that the proposed controller requires only local on-line measurements of relative velocities, i.e., the suggested control law is decentralized and easy to implement. Simulation results prove the ability of the controller to provide transient stabilization of the overall system.

Key Words–Nonlinear control; adaptive control; speed-gradient methodology; passification; power systems.

1 Introduction

Stabilization of power system operating is one of the most important problems in power system control. Modern electrical power systems become heavily loaded and distributed, and possible sudden faults such as lightning, equipment failure, etc., can result in unstability of the whole system.

Most existing approaches to the control of power systems deal with linearization about some operating point. In the case of large disturbances such methods are no longer valid because the system becomes essentially nonlinear. Several methods based on nonlinear approaches can be found in [11],[15],[16],[17]. In [11] the direct Lyapunov method was employed to design a robust stabilizing controller. Wang and his coworkers [16], [17] investigated controllers based on the feedback linearization technique.

In the present paper we propose passivity based transient stabilizers for power systems. The key idea of the approach is that we do not demand asymptotic stability for overall system rather than some passivity properties. This methodology fits the definitions of transient stability presented in [18] which we will use in the sequel.

One of the interesting features of power systems which is exposed in the power system stability studies is that respective Lyapunov functions are not radially unbounded. In fact this is typical for a great deal of oscillatory systems whose steady state can be characterized by unbounded trajectories (e.g. for a rotating pendulum). To overcome the difficulties due to the essential boundedness of Lyapunov functions for some variables we formulate an intermediate result, namely a Partial Stability Theorem which allows us to establish some kind of set-stability of the system.

Recently certain attention has been drawn to the controller design methods based on providing passivity for the overall system. It turns out that providing passivity can play the role of the independent control task and together with the stabilization problem one can consider the problem of passification [5].

It has been established recently the connection between the so-called Speed-Gradient (SG) method [2],[3],[4] and passivity (see [12],[13]). This fact will be used in the control design. To design the control law for power systems which ensures transient stabilization we combine results following from the partial stability theorem and the speed gradient methodology.

It is worth mentioning that the transient stabilization problem (in the sense of the definition given in [18]) does not coincide with the problem of stabilization of power systems at the *desired* operating point. From a practical point of view the solution of the latter problem is preferable but its realisation just after some fault can cause the large control efforts acting on the system. Therefore, one can use the controller which provides transient stabilization, i.e., prevents the system from loss of synchronism, as an intermediate control law and then solve the problem of power system stabilization at the *desired* operating point which better fits the current electric power demand and supply.

2 Partial stability

Consider the controlled plant equation in the state space form

$$\dot{x} = F(x, u, t),\ t \geq 0, \tag{2.1}$$

[1]Work performed while the authors were with the Sydney University

0-7803-3590-2/96 $5.00 © 1996 IEEE

where $x \in \mathbb{R}^n$ is the plant state vector, $u \in \mathbb{R}^m$ is the input vector and $F(\cdot): \mathbb{R}^{n+m+1} \to \mathbb{R}^n$ is continuously differentiable in x, u vector-function. The input variables may be of a general nature, i.e., real control acting on the plant, adjustable parameters, etc.

System (2.1) is called *passive* with respect to output $y = h(x)$ if there exists a smooth nonnegative function $V(x)$ (*storage function*), such that $V(0) = 0$ and the following *dissipation inequality* (DI) is valid along all the trajectories of (2.1):

$$V(x(t)) - V(x(0)) \leq \int_0^t u(s)^T y(s)\, ds \qquad (2.2)$$

The system is called *state strict passive* (SSP) if there exists a positive definite function $S(x)$ such that:

$$\begin{aligned} V(x(t)) \quad - \quad & V(x(0)) \leq \int_0^t u(s)^T y(s)\, ds \\ - \quad & \int_0^t S(x(s))\, ds \end{aligned}$$

The system is called *output strict passive* (OSP) if the following DI holds for some $\eta > 0$:

$$\begin{aligned} V(x(t)) \quad - \quad & V(x(0)) \leq \int_0^t u(s)^T y(s)\, ds \\ - \quad & \eta \int_0^t y(s)^T y(s)\, ds \qquad (2.3) \end{aligned}$$

One can rewrite the dissipation inequality (2.3) in infinitesimal form, as follows:

$$\dot{V} \leq y(t)^T u(t) - \eta y(t)^T y(t) \qquad (2.4)$$

Local and semiglobal versions of the passivity property are defined in the standard way (see [1]). In the sequel, we also need the following stability results.

Theorem 2.1 (**Partial stability theorem**). Let the system

$$\dot{x} = f(x, t) \qquad (2.5)$$

possess smooth nonnegative function $V(x, t)$ such that

$$W(x, t) = \frac{\partial V}{\partial t}(x, t) + (\nabla_x V(x))^T f(x, t) \leq 0,$$

$$\forall t \geq 0, \quad \forall x \in \mathbb{R}^n, \qquad (2.6)$$

where $W(x, t)$ is the derivative of $V(x, t)$ along trajectories of (2.5). Assume further that boundedness of $V(x,t)$ implies boundedness of $f(x, t)$ and uniform continuity of $W(x, t)$ in x and boundedness of $\partial W/\partial t$. Then $V(x(t),t)$ is bounded and

$$\lim_{t\to\infty} W(x(t), t) = 0 \qquad (2.7)$$

Remark 1. Instead of checking uniform continuity of $W(x, t)$ it is often easier to check the boundedness $\frac{\partial W}{\partial x}$.

Remark 2. Theorem claims that $W(x(t), t)$ approaches zero but says nothing about whether $x(t)$ approaches the set $S_t = \{x: W(x, t) = 0\}$ or not. In the case when S_t is unbounded (which is typical for oscillatory systems), the difference between the two above properties may be significant.

Theorem 2.1 is an important tool for oscillatory systems with unbounded solutions. Moreover, it encompasses some commonly used results and its statement extracts the common part of a number of other concepts related to partial stability, see [18], [9], [10].

3 Speed gradient algorithm and passivity

The general control problem is to find the control law $u(t) = U[x(s), u(s) : 0 \leq s \leq t]$, ensuring the control goal:

$$Q_t \to 0 \quad \text{when} \quad t \to \infty \qquad (3.1)$$

where Q_t is some objective functional $Q_t = Q[x(s), u(s) : 0 \leq s \leq t]$. In this paper we will concentrate on the typical case $Q_t = Q(x(t), t)$ where $Q(x, t) \geq 0$ is scalar smooth objective function.

To design a speed-gradient algorithm determine a function $\omega(x, u, t)$ as the speed of change of Q along the trajectories of the system (2.1): $\omega(x, u, t) = (\nabla_x Q)^T F(x, u, t) + \partial Q/\partial t$. SG-algorithm changes the control action along the gradient of $\omega(x, u, t)$ in u. Its most general combined form looks as follows [4]:

$$\frac{d}{dt}(u + \psi(x, t)) = -\Gamma \nabla_u \omega(x, u, t) \qquad (3.2)$$

where $\psi(x, t)$ satisfies the pseudogradient condition $\psi^T(x, t)\nabla_u \omega(x, u, t) \geq 0$ for all x, u, t and $\Gamma = \Gamma^T > 0$ is $m \times m$ gain matrix. The equation (3.2) can be rewritten in integral form: $u = -\psi(x, t) - \Gamma \int_0^t \nabla_u \omega(x, u, s)\, ds$. The main special cases of (3.2) are the SG-algorithm in differential form:

$$\dot{u} = -\Gamma \nabla_u \omega(x, u, t) \qquad (3.3)$$

and the SG-algorithm in the finite form:

$$u = -\psi(x, t), \qquad (3.4)$$

Note that for the affine time-invariant system

$$\dot{x} = f(x) + g(x)u \qquad (3.5)$$

and time-invariant objective $Q(x)$ the speed gradient is just Lie derivative of $Q(x)$ along vector field $g(x)$:

$$\nabla_u \dot{Q} = (\nabla_x Q)^T g(x) = (L_g Q(x))^T$$

Therefore the well known Jurdjevic-Quinn algorithm [7] is a special case of (3.4) for affine plant (2.1) with $\psi(x, t) = \nabla_u \omega(x, u, t)$ and for $Q(x) = \frac{|x|^2}{2}$.

For the sake of simplicity here we consider affine time-invariant case:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ u &= -\Lambda(L_gQ(x(t))^T - \Gamma \int_0^t (L_gQ(x(s)))^T \, ds \end{aligned} \quad (3.6)$$

In (3.6) we took $\psi(x) = \Lambda(L_gQ(x))^T$, where Λ is positive definite gain matrix. The following theorem can be formulated for system (3.6) and time-invariant objective function $Q(x) \geq 0$. (Nonaffine time variant case is considered in [6]):

Theorem 3.1. Consider the system (3.6) under the following assumptions:

A1. There exist constant $u_* \in \mathbb{R}^m$ and matrix Π such that the inequality $L_fQ(x) \leq (L_gQ(x))\Pi(L_gQ(x))^T - (L_gQ(x))u_*$ holds for all $x \in \mathbb{R}^n$ **(achievability condition)**.

A2. Functions $f(x)$, $g(x)$, $\nabla_x f(x)$, $\nabla_x g(x)$, $\nabla_x Q(x)$, $\nabla_x^2 Q(x)$ are bounded if $Q(x)$ is bounded **(boundedness condition)**.

Then for $\Lambda - \Pi \geq 0$, $u(t)$ is bounded and $\lim_{t\to\infty} L_gQ(x(t)) = 0$, $\lim_{t\to\infty} L_fQ(x(t)) = 0$.

Remark 1 Notice that although condition A1 is restrictive (it is stronger than one in the Arstein theorem on nonlinear stabilization [14]), nevertheless, it makes possible to design regulators which require less information about the plant.

Remark 2 Condition A1 is typical for adaptive systems. In this case u_* plays the role of the unknown paramater. The theorem says nothing about convergence $u(t) \to u_*$ as $t \to \infty$. Moreover, as it will be seen from the example this convergence is undesirable for power systems.

Remark 3 Notice that instead of the goal (3.1) the more weak goal is achieved by the controller but this weakened goal is achieved globally although function $Q(x)$ may not be radially unbounded.

Proof of theorem is based on the following Lyapunov function:

$$V(x, u) = Q(x) + \frac{1}{2}(u - u_* + \psi)^T \Gamma^{-1} (u - u_* + \psi).$$

Now let us discuss links between concepts of speed gradient control and passivity and demonstrate that applicability of the SG algorithms is related to the passivity of the closed-loop system.

System (3.5) is called passifiable (respectively, *strict passifiable, output strict passifiable*) (see [1]; [12], [13]) if there exist a smooth feedback

$$u = \alpha(x) + \beta(x)v \quad (3.7)$$

and a smooth output function $h(x)$ such that closed loop (3.5), (3.7) is passive (resp. strict passive, output strict passive).

Passivity itself may be considered as a control goal whose achievement significantly facilitates stabilization of cascaded and interconnected systems (see [12], [13]; [5]). It is easy to show (see [1]; Proposition 4.14) that system (3.5) is strictly passifiable if and only if it is globally asymptotically stabilizable by smooth feedback, the output function being just the speed-gradient of Lyapunov function $V(x)$ guaranteeing global asymptotic stability:

$$h(x) = \nabla_u \dot{V} = (L_gV)^T$$

Also it was shown in [5] that if system (3.5) is globally asymptotically stabilizable by state feedback with some overboundedness condition near the origin then it may be semiglobally asymptotically stabilized and passified by speed-gradient feedback law $u = -\gamma(L_gV)^T + v$ making the system passive with respect to input v and output $(L_gV)^T$.

The above explanation makes it possible to investigate the passivity properties of the system (3.5) with the control law

$$u(t) = -\Lambda(L_gQ(x(t)))^T - \Gamma \int_0^t (L_gQ(x(s)))^T \, ds + v(t) \quad (3.8)$$

One can extend the state vector x of the system as follows:

$$x' = (x, x_1)^T$$

where

$$\dot{x}_1 = (L_gQ(x))^T \quad (3.9)$$

Then the controller (3.8) makes the system (3.5), (3.9) passive with respect to the input v and output $y = \Lambda(L_gQ(x))^T + \Gamma x_1$.

4 Mathematical model of a power system

In this section the mathematical model of a power system consisting of n synchronous generators is formulated. The following assumptions about the power system model are imposed:

1. Each generator in the power system is represented as a constant voltage behind its transient reactance. Flux decay and voltage regulation are not included in the analysis. This assumption is valid in most practical cases.
2. Damping power is assumed proportional to slip velocity (mechanical damping) and/or to slip velocity differences (asynchronous damping). Moreover, asynchronous damping is symmetric.
3. The inertia constant is assumed constant.
4. The control is implemented by controlling mechanical power supplied to generators.

The above assumptions are common for transient stability studies. Under these assumptions we specify the mathematical model of the power system as follows. The nonlinear differential equations describing the dynamics of the i^{th} machine are

$$\begin{aligned} \dot{\delta}_i &= w_i \\ M_i \dot{w}_i &= -a_i w_i - \sum_{\substack{j=1 \\ j \neq i}}^{n} b_{ij}(w_i - w_j) + \\ & \quad P_{mi} - P_{ei} + u_i \end{aligned} \tag{4.1}$$

where M_i is the inertia constant, δ_i is the angle (measured in electrical degrees) between the rotor shaft and a shaft running at reference speed, P_{ie} is the electrical power delivered by the i^{th} machine, P_{mi} is the nominal mechanical power input and u_i is the control that can be implemented through turbine governor; $a_i \geq 0$ and $b_{ij} \geq 0$, $b_{ij} = b_{ji}$ are damping constants of mechanical and asynchronous damping respectively.

The electrical power outputs P_{ei} are given by

$$\begin{aligned} P_{ei} &= G_{ii}E_i^2 + \sum_{\substack{j=1 \\ i \neq j}}^{n} E_i E_j (G_{ij} \cos(\delta_i - \delta_j) + \\ & \quad B_{ij} \sin(\delta_i - \delta_j)) \end{aligned} \tag{4.2}$$

where E_i is the magnitude of the constant internal voltage, G_{ii} is the short-circuit conductance, $G_{ij} = G_{ji}$ is the mutual conductance between generators i and j and $B_{ij} = B_{ji}$ is the susceptance between the i^{th} and j^{th} machines.

The model of power system can be rewritten in a more convenient matrix notation:

$$\begin{aligned} \dot{\delta} &= w \\ \dot{w} &= M^{-1}Rw + M^{-1}(f(\delta) + u) \end{aligned} \tag{4.3}$$

with $\delta = \mathrm{col}(\delta_1 \ldots \delta_n)$, $w = \mathrm{col}(w_1 \ldots w_n)$, where R is the $n \times n$ matrix with elements

$$\begin{aligned} r_{ij} &= b_{ij} \quad \text{for} \quad i \neq j \\ r_{ii} &= -(a_i + \sum_{j=1}^{n} b_{ij}) \end{aligned}$$

$M = \mathrm{diag}(M_1, \ldots, M_n)$; $u = \mathrm{col}(u_1, \ldots, u_n)$ and elements of vector function $f(\delta)$ are given by

$$f_i(\delta) = f_{i0} - \sum_{\substack{j=1 \\ i \neq j}}^{n} (\alpha_{ij} \cos(\delta_i - \delta_j) + \beta_{ij} \sin(\delta_i - \delta_j)) \tag{4.4}$$

with $f_{i0} = P_{mi} - G_{ii}E_i^2$, $\alpha_{ij} = E_i E_j G_{ij} \geq 0$, $\beta_{ij} = E_i E_j B_{ij} \geq 0$. Further, for the sake of compactness we will use the notation $f_0 = \mathrm{col}(f_{10}, \ldots, f_{n0})$.

In the sequel, we need the following result:

Claim 4.1 Matrix R is negative semidefinite.

Proof: Consider the quadratic form:

$$z^T R z = -\sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} z_i b_{ij}(z_i - z_j) - z^T P z$$

where $P = \mathrm{diag}\{a_1, \ldots, a_n\} \geq 0$. Since $b_{ij} = b_{ji}$ we have

$$z^T R z = -\sum_{i=1}^{n} \sum_{j=i+1}^{n} b_{ij}(z_i - z_j)^2 - z^T P z \leq 0$$

■

5 Problem statement

The purpose of introducing control into the power system is to make it transiently stable with respect to large disturbances.

Definition A Following [18] we say that the trajectory $x(t_0, x_0)$ of the uncontrolled system is *transiently stable* if the initial conditions $x_0 = (\delta_0, w_0)^T$ belong to an open domain of attraction of the set defined by

$$\delta_i - \delta_j = c_{ij}; \quad w_1 = w_2 = \ldots = w_n \tag{5.1}$$

which means that the motions converge to a synchronous motion of all machines. Willems [18] showed that in the case of nonzero damping, this definition is equivalent to the following:

Definition B A trajectory $x(t_0, x_0)$ is transiently stable if its initial conditions x_0 belong to an open domain of attraction of the set $\delta_i - \delta_j = c_{ij}$; $w_i = 0$.

Based on the definition B one can pose the problem of transient stabilization as follows:

For the given initial conditions $x_0 = (\delta_0, w_0)^T$ to provide convergence of the trajectory $\delta(t, \delta_0)$, $w(t, w_0)$ to the set defined by $\delta_i - \delta_j = c_{ij}$; $w_i = 0$.

Notice that in this problem statement we do not specify the constants c_{ij} but for practical purposes it is desirable to achieve an additional control goal: assume that the initial conditions $x_0 = (\delta_0, w_0)^T$ belong to some subset of the following set:

$$|\delta_i - \delta_j| < \bar{\delta} < \pi \tag{5.2}$$

provide transient stabilization of trajectory $x(t, x_0)$ such that this trajectory remains in the set (5.2). This additional constraint is necessary to ensure that during transient time the power system does not lose synchronism.

6 Transient stabilization of the power system

In this section we will implement the theoretical results of Section 3 to solve the problem stated in the Section 4. According to the SG methodology one has to choose an objective function which describes the control task.

Consider the following objective function:

$$Q(\delta, w) = \frac{w^T M w}{2} + \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\beta_{ij}(1 - \cos(\delta_i - \delta_j)) + \alpha_{ij}(1 + \sin(\delta_i - \delta_j))) \quad (6.1)$$

which is the commonly used energy function for power systems [8].

Obviously $Q(\delta, w) \geq 0$. Calculation of the time derivative of Q with respect to the trajectories of (4.3) gives

$$\dot{Q}(\delta, w) = w^T R w + w^T (f_0 + u) \quad (6.2)$$

The SG control law in the combined form looks as follows:

$$u(t) = -\Lambda w(t) - \Gamma \int_o^t w(s)\, ds \quad (6.3)$$

where Λ and Γ are positive definite matrices. The typical choice of these matrices is: $\Lambda = \mathrm{diag}(\lambda_1, \ldots, \lambda_n)$, $\Gamma = \mathrm{diag}(\gamma_1, \ldots, \gamma_n)$, λ_i, $\gamma_i > 0$. To study the stability of power system (4.3) under the control law (6.3) one can apply Theorem 3.1.

Clearly for "ideal" control $u_* = -f_0$ the achievability condition is satisfied for $\Pi = 0$ since R is negative semidefinite (see Claim 4.1). The boundedness condition is valid since boundedness of objective function (6.1) implies boundedness of $w(t)$.

Theorem 3.1 asserts that once control is applied it remains bounded and $\lim_{t\to\infty} \Lambda w(t) = 0$. Since Λ has full rank it means that $w(t) \to 0$. Boundedness of control implies that the integral $\int_0^\infty w(s)\, ds$ exists which, in turn, implies that $\delta(t) \to$ const.

Therefore under the control law (6.3) any trajectory of (4.3) is transiently stable in the sense of Definition B.

Now, recall that according to the problem posed in Section 3, the design controller must preserve all trajectories of the overall system in the set (5.2). In other words, during the transient process differences between all rotor angles must not exceed the threshold value $\overline{\delta}$. To find the conditions under which this additional goal is achieved consider the following Lyapunov function:

$$V(\delta, w, u) = Q(\delta, w) + (u + f_0 + \Lambda w)^T \Gamma^{-1} (u + f_0 + \Lambda w)/2 \quad (6.4)$$

which is a non-increasing function or, in other words,

$$V(\delta(0), w(0), u(0)) \geq V(\delta(t), w(t), u(t)) \quad (6.5)$$

The inequality (6.5) can be rewritten as follows:

$$\begin{gathered} \frac{w(0)^T M w(0)}{2} + \\ \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\alpha_{ij}(1 + \sin(\delta_i(0) - \delta_j(0))) + \\ \beta_{ij}(1 - \cos(\delta_i(0) - \delta_j(0)))) \\ + (u(0) + f_0 + \Lambda w(0))^T \Gamma^{-1} (u(0) + f_0 + \Lambda w(0))/2 \\ \geq \frac{w(t)^T M w(t)}{2} + \\ \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\alpha_{ij}(1 + \sin(\delta_i(t) - \delta_j(t))) + \\ \beta_{ij}(1 - \cos(\delta_i(t) - \delta_j(t)))) \\ + (u(t) + f_0 + \Lambda w(t))^T \Gamma^{-1} (u(t) + f_0 + \Lambda w(t))/2 \end{gathered} \quad (6.6)$$

Substituting $u(0)$ from (6.3) into (6.6) one can write

$$\begin{gathered} \frac{w(0)^T M w(0)}{2} + \frac{f_0^T \Gamma^{-1} f_0}{2} \\ + \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\alpha_{ij}(1 + \sin(\delta_i(0) - \delta_j(0))) \\ + \beta_{ij}(1 - \cos(\delta_i(0) - \delta_j(0)))) \\ \geq \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\alpha_{ij}(1 + \sin(\delta_i(t) - \delta_j(t))) \\ + \beta_{ij}(1 - \cos(\delta_i(t) - \delta_j(t)))) \end{gathered} \quad (6.7)$$

In other words, if the initial conditions $\delta_i(0)$ belong to the set defined by

$$|\delta_i(0) - \delta_j(0)| < \overline{\delta} < \pi \quad (6.8)$$

and if the gain matrix Γ is chosen to satisfy

$$\begin{gathered} \frac{w(0)^T M w(0)}{2} + \frac{f_0^T \Gamma^{-1} f_0}{2} \\ + \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\alpha_{ij}(1 + \sin(\delta_i(0) - \delta_j(0))) \\ + \beta_{ij}(1 - \cos(\delta_i(0) - \delta_j(0)))) \\ < \min\{\alpha_{\min}(1 + \sin\overline{\delta}),\ \beta_{\min}(1 - \cos\overline{\delta})\} \end{gathered} \quad (6.9)$$

where

$$\begin{aligned} \alpha_{\min} &= \min_{i,j} \alpha_{ij} \\ \beta_{\min} &= \min_{i,j} \beta_{ij} \end{aligned}$$

then each difference $\delta_i(t) - \delta_j(t)$ does not exceed the threshold value $\overline{\delta}$ during the system transient response.

7 Simulation results

Simulation results were performed for system of two generators connected to infinite bus without damping with the following parameters: $M = \mathrm{diag}(5,3)$, $P_{m1} - P_{e1} = 0.5 + 0.1\sin\delta_1 - \sin(\delta_1 - \delta_2)$, $P_{m2} - P_{e2} = -0.5 + 0.2\sin\delta_2 + \sin(\delta_1 - \delta_2)$, parameters of controller were chosen to be $\gamma_1 = \gamma_2 = \lambda_1 = \lambda_2 = 1$, with the following initial conditions $\delta_1(0) = 0$, $\delta_2(0) = 0.8$, $\omega_1(0) = \omega_2(0) = 0$. Computer simulation showed good transient process and achieving of the all prespecified goals (see 1).

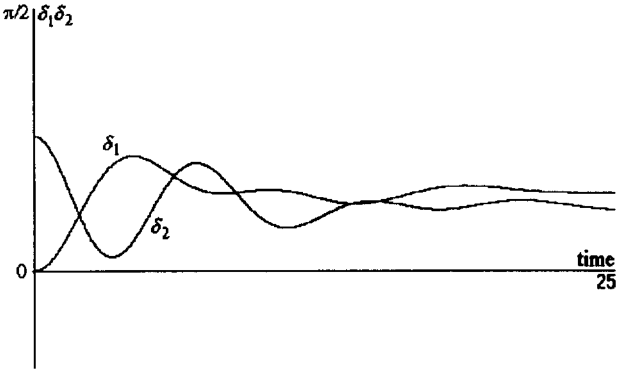

Figure 1: Transient process in controlled system

8 Conclusion

In this paper transient stabilization of a power system with Speed Gradient control law is discussed. Although the proposed controller does not provide asymptotic stability of the overall system the goal of transient stabilization is successfully achieved. The main novelty of the paper is the connection between the transient stabilization problem in the sense of the given definition and passification approach. Indeed as has been discussed in Section 3 the proposed controller solves the problem of passification of the overall system. This control goal may be of interest to damp the oscillations of the power system after some sudden fault and may be considered as an intermediate control step. Once the goal of transient stabilization is achieved one can employ the control law of the next level to stabilize the system at the *desired* operating point and in this case the passivity property of the overall system facilitates the control design of such a controller. The following features of the suggested control law should be emphasised:

1. it depends only on *local* measurements of relative velocities and

2. it does not require the measurement of relative angles.

These features facilitate the possible practical implementation of the controller.

The applicability conditions of the designed control law are given by the formula (6.9) which defines the set of admissible initial conditions for given gain coefficients under which the control goal is approached.

References

[1] Byrnes C., Isidori A. and Willems J.C., (1991) Passivity, feedback equivalence and the global stabilization of the minimum-phase nonlinear systems, *IEEE Trans. Automat. Control.*, V. **36**, pp. 1228–1240.

[2] Fomin V.N., Fradkov A.L. and Yakubovich V.A., (1981) *Objective control of dynamic objects* Moscow: Nauka (in Russian).

[3] Fradkov A.L., (1979) Speed-gradient scheme and its application in adaptive control, *Aut. Remote Control*, V. **40**, pp. 1333–1342.

[4] Fradkov A.L., (1990) *Adaptive control in large-scale systems* Moscow: Nauka (in Russian).

[5] Fradkov A.L., Hill D.J., Jiang Z.-P. and Seron M.M., (1995a) Feedback passification of interconnected systems, *IFAC NOLCOS'95*, pp. 655–659.

[6] Fradkov A.L., Hill D.J., Pogromsky Yu A., (1995b) Speed gradient control and passivity of nonlinear oscillators, submitted to *Automatica*.

[7] Jurdjevich V. and J.P. Quinn (1978) Controllability and stability, *J. Diff. equations*, V. **28**, pp. 381–389.

[8] Pai M.A., (1981), *Power systems stability*, (North-Holland Publishing Company).

[9] Rouche N., Habets P. and Laloy M., (1977) *Stability theory by Lyapunov's direct method*, (New York).

[10] Rumyantsev V.V. and Oziraner A.S., (1987), *Stability and stabilization of the motion with respect to the part of variables*, (Moscow: Nauka), in Russian.

[11] Qu Z., Dorsey J., Bond J. and McCalley J. (1992) Application of robust control to sustained oscillations in power systems, *IEEE Trans. Circ. Syst., I,* V. **39**, pp. 470–476.

[12] Seron M., Hill D.J. and Fradkov A., (1994) Adaptive passification of nonlinear systems, *Proc. 33rd CDC*, pp. 190–195.

[13] Seron M., Hill D.J. and Fradkov A., (1995) Nonlinear adaptive control of feedback passive systems, *Automatica*, V. **31**, pp. 1053–1060.

[14] Sontag E.D., (1989), A universal construction of Artstein's theorem on nonlinear stabilization, *Systems & Control Letters*, V. **13**, pp. 117–123.

[15] Vesely V., Murgas J., Decentralized adaptive stabilization of nonlinear systems, *Int. J. Control* **58**, N6, 1445-1460.

[16] Wang Y., Hill D.J., Gao L and Middleton R.H., (1993), Transient stability enhancement and voltage regulation of power systems, *IEEE Trans. Power Syst.*, PWRS–8, pp. 620–627.

[17] Wang Y., Hill D.J., Middleton R.H. and Gao L., (1994), Transient stabilization of Power Systems with an adaptive control law, *Automatica*, V. **30**, pp. 1409–1413.

[18] Willems J.L., (1974) A partial stability approach to the problem of transient power system stability, *Int. J. Control*, V. **19**, pp. 1–14.