Design of wide-area time-delay supplementary controller for interconnected Network based on Hamilton function method

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Abstract. The transient stability of interconnected network with supplementary time-delay controller for generator excitations and static var compensator (SVC) has been investigated in this paper. Firstly, a delay-dependent stability criterion based on Hamilton function method is derived, and the criterion is in terms of matrix inequalities. Secondly, a nonlinear time-delay Hamilton function model of interconnected network with SVCs is constructed. Thirdly, the wide-area time-delay supplementary controller (WATSC) for the interconnected network is designed and converted into the form of Hamiltonian system. The delay-dependent stability of the closed-loop power system is analysed. The gains of the WATSC are determined by using the theoretical analysis results. It is effective for the designed WATSC installed in the 16-machine, 68-bus power system for damping the inter-area modes. Then simulation results show that the method of the controller is effective.

1. Introduction
Collection and transmission of terminal data, and the remote control technology is widely used in intelligent interconnected grid [1-2]. Damping of inter-area oscillation can be controlled not only rely on local feedback signal generator. Therefore, the main function of the controller is designed to obtain the remote data signal through the device, in order to coordinate the control interval ringing problem [3].

As we all know, the transmission delay of dynamic data is the actual problems existing in the wide-area control [4]. And it will make worse the effect of the controller, and may lead to destabilization of the whole system. Thus, the design of the controller should consider the delays of the transmission signal [5]. Such a method can effectively improve the effect of the wide area controller. Calculate the maximum delay time process is a necessary step of the processing of the controller design. In [6] and [7], proposed a damping controller attached to the SVC device, and it used the data of steady-state voltage of the grid, current and power. In [8], designed damping controller attached to the STATCOM equipment, the use of the data signal from the entire system. A similar method is used in [9], and damping controller attached to the TCSC device is designed. Robust control is a popular method in the nonlinear control system.

Such as a multi-agent $H_{\infty}$ controller [10] and a mixed $H_2/H_{\infty}$ controller [11] are used in wide-area damping controller design. Generator excitation control, while additional control device SVC method

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1 Address for correspondence: G Hailati, Shanghai Polytechnic University Rm513, #16, Lane 2360, Jinhai Road, Pudong, Shanghai (201209), China. E-mail: glzt128@qq.com.
can effectively control the range of problems caused by the ringing signal propagation delay caused by [12]. Wide-area delay controller is predicted based on the prediction method in [13]. Power vibration controller is proposed based on adaptive approach in [14]. Linear controller is designed used by LMI equations in [15]. Practical experience used in the damping controller for HVDC system in [16]. Wide area damping controller is presented based on Lyapunov theory and technical design model simplification, and taking into account the time delay of two different forms: the constant and time-varying in [17]. Factors wide area power controller is based on the prediction method highlight, while using variable delay in [18]. The controller design using varying norm - bounded uncertainty method in [19].

Most wide-area damping controller method is basically a simplified linear model of the power system. However, according to the characteristics of the power system, which are nonlinear and dynamic characteristics. Controller design by using nonlinear dynamics method is proposed in [20-21]. Hamilton function method is an important method for analyzing nonlinear systems [22-23]. This method first used in ordinary nonlinear system, then extended to the study of nonlinear time-delay system. Hamilton is an energy-based approach, to analyze the energy distribution problems and the stability of nonlinear systems. It is significance for design wide-area delay damping controller by using energy stability analysis methods.

A wide area damping controller WATSC is designed in this paper Consider using Hamilton function method and the time delay. Firstly, nonlinear systems Hamilton stable condition is derived. Secondly, Hamilton model is established of the power system, including generators, AVR (auto voltage regulator), PSS (power system stabilizer) and SVC and other major electrical equipment. Finally, calculate the relationship between the delay time and the controller parameters according to the stability condition, and to determine the optimal parameters of the controller.

The remainder of the paper is organized as follows: nonlinear systems Hamilton stable condition is derived in Sec. II. Model of interconnected network based on Hamilton function is established in Sec. III. The designed methodology of WATSC is described in Sec. IV. The simulation results of the test system and the effectiveness of the controller with and without time-delay are presented in Sec.V. Finally, the conclusions are drawn in Sec. VI.

2. Stable condition of Hamilton system

Consider the following Hamilton systems:

\[ \dot{x}_i(t) = (J_{ui} - R_{gi}^\tau) \frac{\partial H_i}{\partial x_i} H_i + g_i u_i(t); \]
\[ \dot{x}_i(t) = (J_{ui} - R_{gi}^\tau) \frac{\partial H_i}{\partial x_i} H_i + g_i u_i(t), \]
\[ \dot{x}_i(t) = (J_{ui} - R_{gi}^\tau) \frac{\partial H_i}{\partial x_i} H_i + g_i u_i(t), \]

let \( x = (x_1^T \ x_2^T \ x_3^T)^T \), and \( \frac{\partial H_i}{\partial x_i} = \frac{\partial H(x(t))}{\partial x_i} \) for \( i = 1, 2 \), where \( x_i(t) \in \mathbb{R}^n \) is the state vector of the system, \( x_i(t) \in \mathbb{R}^n \) is the state vector of SVC installed in the system, \( \dot{x}_i(t) = x_i(t - \tau) \), for \( i = 1, 2 \), \( \tau \) is the signal transmission delay, \( u_i(t) \in \mathbb{R}^m \) is the control input of the system, \( u_i(t) \in \mathbb{R}^m \) is the control input of the SVC, \( H \) is a Hamilton function, \( g_i \in \mathbb{R}^{m \times n} \) and \( g_i \in \mathbb{R}^{m \times n} \) is the port matrix, the anti-symmetric matrix \( J_x \) and \( J_y \) are the interconnection matrix, the symmetric positive semi-definite matrix \( R_x \) and \( R_y \) is the damping matrix.

Consider the problem of dynamic variable delay, state feedback input is expression as:

\[ u_i(t) = -K_{11} \frac{\partial H_i}{\partial x_i} H_i - K_{12} \frac{\partial H_i}{\partial x_i} H_i; \]
\[ u_i(t) = -K_{21} \frac{\partial H_i}{\partial x_i} H_i - K_{22} \frac{\partial H_i}{\partial x_i} H_i; \]
\[ u_i(t) = -K_{31} \frac{\partial H_i}{\partial x_i} H_i - K_{32} \frac{\partial H_i}{\partial x_i} H_i; \]

where \( \tau \) is the time-delay from generator dynamically variable feedback to the controller. Suppose there is a limit of time delay, so that they meet the following criteria:

\[ 0 \leq \tau \leq h. \]
Form Equation (1)-(3) we can get the following closed loop system:

$$
\begin{align*}
\dot{x}_i(t) &= \begin{pmatrix}
J_{ii} - R_{ii} & 0 & 0 \\
0 & J_{ii} - R_{ii} & 0 \\
0 & 0 & J_{ii} - R_{ii}
\end{pmatrix} x_i(t) + \begin{pmatrix}
-g_{K_{1i}} & 0 & 0 \\
0 & -g_{K_{2i}} & 0 \\
0 & 0 & -g_{K_{3i}}
\end{pmatrix} \nabla_{x_i} H_i(t) \\
&+ \begin{pmatrix}
0 & -g_{K_{12}} & 0 \\
-g_{K_{21}} & 0 & 0 \\
-g_{K_{31}} & -g_{K_{32}} & 0
\end{pmatrix} \nabla_{x_{1,2}} H_{i(1,2)}(t),
\end{align*}
$$

where \( \nabla_{x_i} H_i = \frac{\partial H(x(t)}{\partial x_i} \) for \( i = 1, 2 \).

Then Equation (4) can be expressed in the following form:

$$
x(t) = (J - R) \nabla_x H_{1,2} + T_1 \nabla_x H_{1} + T_2 \nabla_x H_{2}.
$$

We can write (5) in a transformed form as

$$
x(t) = (\bar{J} - \bar{R}) \nabla_x H_{1,2} + T_1 \nabla_x H_{1} + T_2 \nabla_x H_{2},
$$

where \( J - R + T_i = \bar{J} - \bar{R} \). \( \bar{J} \) and \( \bar{R} \) are symmetric matrix which satisfies \( \bar{R} \geq 0 \).

**Proposition 1**: Denote \( \Delta := \nabla_x H(x) \). For all \( x \) in an open neighbourhood of the origin, and the system described by Eq. (6) is globally asymptotically stable, and matrices exist as \( 0 \leq P^T = P \in \mathbb{R}^{m \times m}, \quad 0 \leq Q^T = Q \in \mathbb{R}^{m \times m} \), and for any \( 0 \leq \tau \leq h \), such that

\[
\mathcal{Z} = \begin{pmatrix}
M_{11} & Q - S \\
M_{12} & -Q - hT_2 A^T SAT_2
\end{pmatrix} < 0
\]

holds for all \( x \in \mathbb{R}^n \), where

\[
M_{11} = -\bar{R} + (\bar{J} - \bar{R}) A^T P + PA(\bar{J} - \bar{R}) + h^2(\bar{J} - \bar{R}) A^T SA(\bar{J} - \bar{R})
\]

\[
M_{12} = T_1 + PAT_1 + S + h^2 (\bar{J} - \bar{R}) A^T SAT_2,
\]

then the stability of system (6) is local.

**Proof**: Let

\[
V_1(x(t)) = H_i + \nabla_{x_i} H_i^T P V_1 H_i;
\]

\[
V_2(x(t)) = \int_{t - \tau}^{t} \int_{s}^{t} \nabla_{x_i} H_i(x(s)) Q \nabla_{x_i} H_i(x(s)) ds dv;
\]

\[
V_3(x(t)) = h \int_{t - \tau}^{t} \left( \int_{s}^{t} \frac{d}{ds} \left( \nabla_{x_i} H_i(x(s)) \right) \right) ds dv,
\]

then we have

\[
\frac{d}{dt} V_1 = \nabla_{x_i} H_i^T (\bar{J} - \bar{R}) \nabla_{x_i} H_i + \nabla_{x_i} H_i^T T_1 \nabla_{x_{i,2}} H_{i,2} + \nabla_{x_i} H_i^T PA(\bar{J} - \bar{R}) + (\bar{J} - \bar{R}) A^T P \nabla_{x_i} H_i
\]

\[
+ \nabla_{x_i} H_i^T PAT_1 \nabla_{x_{i,2}} H_{i,2} + \nabla_{x_i} H_i^T T_2 A^T P \nabla_{x_i} H_i,
\]

\[
\frac{d}{dt} V_2 = \nabla_{x_i} H_i^T Q \nabla_{x_i} H_i - \nabla_{x_i} H_i^T Q \nabla_{x_{i,2}} H_{i,2},
\]

\[
\frac{d}{dt} V_3 = h \left( \nabla_{x_i} H_i^T (\bar{J} - \bar{R}) A^T SA(\bar{J} - \bar{R}) \nabla_{x_i} H_i + \nabla_{x_i} H_i^T (\bar{J} - \bar{R}) A^T SAT_2 \nabla_{x_{i,2}} H_{i,2} \right)
\]

\[
+ \nabla_{x_i} H_i^T T_1 A^T SA(\bar{J} - \bar{R}) \nabla_{x_i} H_i + \nabla_{x_i} H_i^T T_2 A^T SAT_2 \nabla_{x_{i,2}} H_{i,2} - \nabla_{x_i} H_i^T SV_{x_i} H_i + \nabla_{x_i} H_i^T SV_{x_{i,2}} H_{i,2}
\]

\[
+ \nabla_{x_i} H_i^T SV_{x_i} H_i - \nabla_{x_i} H_i^T SV_{x_{i,2}} H_{i,2}.
\]

Now, choose the following Lyapunov-Krasovskii functional

\[
V(x(t)) = V_1(x(t)) + V_2(x(t)) + V_3(x(t)),
\]

and compute the time derivative along the orbit of system (6), by using the relations (8), (9) and (10), we get
\[
\frac{dV}{dt} = \begin{bmatrix} \nabla H(x) \end{bmatrix}^{T} \begin{bmatrix} \nabla H(x) \end{bmatrix} \geq 0.
\]

From the inequality (7), we can find that \( V(x(t)) < 0 \) for all nonzero \( x(t) \) which proves the system (6) is global asymptotic stable.

3. **Model of interconnected network**

The interconnected network with \( n \) machines, AVR, PSS and SVC equipment can be described as follows:

\[
\begin{align*}
\dot{\delta}_i &= \omega_i - \omega_k; \\
\dot{\omega}_i &= \frac{\omega_b}{M_i} P_m - \frac{D_i}{M_i} (\omega_i - \omega_k) - \frac{\omega_b}{M_i} \sum \left[ E_p^i - E_q^i B_s S_k \right]; \quad (12a) \\
E_p^i &= \frac{-1}{T_{d偶}} \left( E_p^i + (x_d - x'_d) \sum \left[ E_q^i (G_s S_k - B_s C_k) \right] - E_q + u_q^i \right); \\
\dot{v}_{ji} &= - \frac{1}{T_w} (v_{ji} - v_{ji0}) + \frac{1}{T_{sw}} (u_{ji} - u_{ji0}); \\
\dot{v}_{ji} &= - \frac{1}{T_{sw}} v_{ji} + K_s (\omega_i - \omega_k); \\
\dot{v}_n &= - \frac{1}{T_{sw}} v_n + \left( \frac{T_u}{T_{sw}} + \frac{T_u}{T_{sw}} \right) v_n + \frac{T_u}{T_{sw}} K_s (\omega_i - \omega_k) \quad; (12f) \\
B_{nck} &= \frac{1}{T_{nck}} \left[ K_{nck} (V_{ref,nck} - V_{nck} - u_{nck}) \right]. 
\end{align*}
\]

respectively, \( n \) and \( m \) is the number of generators and SVC, \( i=1,\ldots,n \) \( k=1,2,\ldots,m \), \( \delta \) means the rotor angle, \( \omega \) means the angular velocity, \( \omega_k \) means synchronous speed; \( x_d \) means \( d \)-axis synchronous reactance, \( x'_d \) means the \( d \)-axis transient reactance (\( x'_d < x_d \)), \( T_{d偶} \) means \( d \)-axis transient open-circuit time constant, \( E_p \) means \( q \)-axis transient potential, \( M_i \) and \( D_i \) means inertia time constant and damping, \( P_m \) means mechanical input power, supposed as constant; \( u_q^i \) means excitation input, \( u_n \) means generator terminal voltage. Notice \( S_{ki} = \sin(\delta_i - \delta_k) \), \( C_{ki} = \cos(\delta_i - \delta_k) \).

\[ \text{Figure 1. Structure of excitation system with AVR and PSS} \]

\[ \text{Figure 2. Structure of SVC control block diagram with WATSC} \]

The Structure of the system with AVR and PSS is shown in Figure 1 see [28]. \( u_n \) means terminal voltage of generator, \( V_{ref} = const \), field voltage \( E_m = K_{nck} (v_{ref} + v_n - v_0) \), variable \( v_n \) means per unit value, \( v_{lim} \) and \( u_{lim} \) means corresponding initial values, \( K_n \) means the gain coefficient, the AVR means a simple PI regulator, the PSS includes gain link, \( K_n \) and \( K_{nck} \) means the gain coefficients, \( T_{nck} \), \( T_{sw} \), \( T_u \), \( T_{d偶} \), \( T_u \) and \( T_{sw} \) means the time constants in seconds, \( B_{nck} \) represents the equivalent susceptance of the SVC, \( V_{nck} \) means the voltage magnitude of the SVC bus, \( V_{ref,nck} \) means the SVC reference voltage and \( u_{nck} \) means the input of auxiliary control WATSC. The Figure 2 is the SVC control block diagram with WATSC, where \( T_1 = R_s C_i = (R_s + R_2) C_i \), \( T_2 = R_2 C_i \), \( T_u = R_s C_m \), \( T_{nck} = R_n C_{nck} \).

The system with Hamilton function (12) is constructed as follows:
\[
H(x) = \frac{1}{2} \sum_{\alpha=1}^{n} M_{\alpha} \left( \dot{\omega}_{\alpha} - \omega_{\alpha} \right)^{2} - \sum_{i=1}^{n} P_{i} \delta_{i} + \sum_{j=1}^{m} G_{j} \dot{\delta}_{j}^{2} + \sum_{i=1}^{n} E_{p,i}^{\prime} \left( G_{i\alpha} S_{\alpha} - B_{i\alpha} C_{\alpha} \right) - \frac{1}{2} \sum_{i=1}^{n} B_{i} \dot{E}_{p,i}^{\prime} \\
+ \sum_{i=1}^{n} \frac{E_{p,i}^{\prime}}{2(x_{\alpha} - \dot{x}_{\alpha})} + \frac{1}{2} \sum_{i,j=1}^{n} \left( C_{ij} \dot{\omega}_{i}^{2} + C_{i\omega} \dot{\omega}_{i} \dot{\omega}_{j} + C_{j\omega} \dot{\omega}_{i} \dot{\omega}_{j} \right) + \frac{1}{2} \sum_{i=1}^{m} C_{n\omega} B_{n\omega}^{2},
\]

where \( H(x) \) means total storage energy of system. The (13) includes the kinetic energy and the other term define the summation of the potential energy.

By calculation, the partial derivatives of Hamilton function are:
\[
\begin{align*}
\partial_{i} H &= -P_{i} + \sum_{j=1}^{m} E_{p,j}^{\prime} \left( G_{j\alpha} S_{\alpha} - B_{j\alpha} C_{\alpha} \right); \\
\partial_{\alpha} H &= \frac{M_{\alpha}}{\dot{\omega}_{\alpha}} \left( \dot{\omega}_{\alpha} - \omega_{\alpha} \right); \\
\partial_{\omega} H &= 2G_{i} \dot{\delta}_{i}^{2} - \sum_{j=1}^{m} E_{p,j}^{\prime} \left( G_{j\alpha} S_{\alpha} - B_{j\alpha} C_{\alpha} \right) - B_{i} \dot{E}_{p,i}^{\prime} + \frac{E_{p,i}^{\prime}}{x_{\alpha} - \dot{x}_{\alpha}}; \\
\partial_{\delta_{i}} H &= C_{i\omega} \dot{\omega}_{i}; \\
\partial_{\omega_{i}} H &= C_{\omega} \dot{\omega}_{i}; \\
\partial_{\omega_{n\omega}} H &= C_{n\omega} B_{n\omega}.
\end{align*}
\]

Substitute the equations above into Equ. (12), and then the equations above can be simplified as follows:
\[
\begin{align*}
\ddot{\delta}_{i} &= \frac{\partial_{\omega} H}{M_{\omega}}; \\
\dot{\omega}_{i} &= \frac{\partial_{\alpha} H}{M_{\omega}} - \frac{D_{\alpha \omega} H}{M_{\omega}^{2}}; \\
E_{p,i}^{\prime} &= \frac{x_{\alpha} - \dot{x}_{\alpha}}{T_{i\omega}} \partial_{\alpha} H + \frac{K_{i\omega}}{T_{i\omega} C_{\omega}} \partial_{\omega} H + \frac{K_{\omega}}{T_{i\omega} C_{\omega}} \partial_{\omega} H + \frac{1}{T_{i\omega} C_{\omega}} \partial_{\omega} H; \\
\dot{v}_{i} &= \frac{1}{T_{i\omega} C_{\omega}^{2}} \partial_{\alpha} H - C_{\omega} \dot{\omega}_{i}; \\
\dot{v}_{\omega} &= \frac{K_{i\omega}}{M_{\omega}} \partial_{\alpha} H - \frac{K_{\omega}}{M_{\omega}} \partial_{\alpha} H - \frac{1}{T_{\omega} C_{\omega}^{2}} \partial_{\omega} H; \\
\dot{v}_{\omega} &= \frac{-T_{i\omega} K_{i\omega}}{T_{\omega} M_{\omega}} + \frac{T_{i\omega} K_{\omega}}{T_{\omega} M_{\omega}} \partial_{\alpha} H - \frac{T_{\omega}}{T_{i\omega} C_{\omega}} \partial_{\omega} H + \left( \frac{1}{T_{i\omega} C_{\omega}^{2}} - \frac{T_{i\omega}}{T_{\omega} C_{\omega}} \right) \partial_{\omega} H; \\
B_{n\omega} &= \frac{1}{T_{n\omega} C_{n\omega}} \partial_{\omega} H + \frac{K_{n\omega}}{T_{n\omega}} \left( V_{\text{ref} - \omega} - V_{\omega} - \dot{u}_{\omega} \right). \tag{15g}
\end{align*}
\]

Defining \( x = (\delta, \omega, E_{p,i}^{\prime}, v_{i}, v_{\omega}, B_{n\omega})^{T} \), the system (15) rewritten as the following form:
\[
x_{i} = (J_{i} - R_{i}) \nabla_{\omega} H_{i} + g_{i}(x) u_{i}. \tag{16}
\]

where
\[
J_{i}(x) = \begin{pmatrix}
0 & -F_{1} & 0 & 0 & -F_{3} & -F_{5} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -F_{2} & 0 & 0 & 0 & 0 \\
0 & 0 & F_{2} & 0 & 0 & 0 & 0 \\
F_{3} & F_{4} & 0 & 0 & 0 & 0 & 0 \\
F_{5} & F_{6} & F_{7} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix},
R_{i}(x) = \begin{pmatrix}
0 & 0 & 0 & 0 & N_{i} & N_{i} & 0 \\
0 & 0 & 0 & 0 & 0 & N_{i} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & N_{i} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}.
\]
means the port matrix, it is , and the other is be the equilibrium point of the system (16), and it is satisfied , means the damping matrix, if the equilibrium point . of wide-area which an additional input to SVC. The inputs is an extremum of means the interconnection matrix, . and means the state , then the means the control input \( \tau \).

\[
g_i = \begin{bmatrix}
0 & 0 & K_u / T_{du} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -C_v & 0 & 0 & 0 \\
0 & 0 & T_{du} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & K_m / T_{mk} \\
0 & 0 & 0 & 0 & 0 & 0 & -K_m / T_{mk} \\
0 & 0 & 0 & 0 & 0 & 0 & -K_m / T_{mk}
\end{bmatrix}^T, \quad u_i = (v_{ref} \quad u_u \quad u_{fi} \quad v_{ref, udeck} \quad v_{mk} \quad u_{mk}^{eq})^T,
\]

and

\[
F_i = \frac{\sigma_i}{M_i}, \quad F_z = \frac{K_u \sigma_i}{2T_{du}C_u}, \quad F_3 = -\frac{K_u D \sigma_i}{2M_i}, \quad F_4 = -\frac{T_u K_u \sigma_i}{2T_{M_i}} , \quad F_5 = -\frac{T_u K_u D \sigma_i}{2T_{M_i}}, \quad F_6 = -\frac{K_u}{2T_{du}C_u},
\]

\[
F_7 = \left\{ \frac{1}{2T_{M_i} C_u} - \frac{T_u}{2T_{du} T_{M_i} C_u} \right\}, \quad N_1 = \frac{K_u}{2T_{du} C_u}, \quad N_2 = \frac{K_u D}{2M_i}, \quad N_3 = \frac{T_u K_u}{2T_{M_i}}, \quad N_4 = \frac{T_u K_u D}{2T_{M_i}}, \quad N_5 = \frac{T_u K_u}{2T_{M_i}}.
\]

where \( g_i \in \mathbb{R}^{10\times10} \) means the port matrix, \( u_i(t) \in \mathbb{R}^n \) means the control input \( x_i(t) \in \mathbb{R}^n \) means the state vector of the system, the anti-symmetric matrix \( J(x) \) means the interconnection matrix, \( J(x) = -J^T(x) \), the symmetric positive semi-definite matrix \( R_i(x) \) means the damping matrix, \( R_i(x) = R_i^T(x) \geq 0 \).

\( x := [x_1^T \quad x_2^T \quad \cdots \quad x_n^T]^T \) and \( \nabla_i H_i = \{ \partial H(x(t)) \} / \partial x_i \), \( i = 1, \cdots, n \).

Let \( x_0 \) be the equilibrium point of the system (16), and it is satisfied \( (J - R_i)\nabla_i H_i\big|_{x=x_0} = 0 \). It is obvious that \( H(x_0) = 0 \) and \( \nabla_i H_i\big|_{x=x_0} = 0 \). If the equilibrium point \( x_0 \) is an extremum of \( H(x) \), then the equally sufficient condition is

\[
\text{Hess}(H(x_0)) = \frac{\partial^2 H(x)}{\partial x^2}\big|_{x=x_0} > 0.
\]

4. Wide-Area damping coordination controller design

4.1. Coordination Control of Excitation and SVC with delay

To illustrate the idea of coordination controller, the block diagram of coordinated controller WATSC shown in Figure 3. This additional controller includes two outputs: first, an additional input to generator excitation system is \( u_u \), and the other is \( u_{mk}^{eq} \) which an additional input to SVC. The inputs signals of WATSC are dynamic remote measurement information from the other regions or areas. The three parts of WATSC input including: local signal, wide-area signal and the time delay \( \tau \) of wide-area signal.

\[\text{Figure 3. Structure of wide-area damping control scheme with time-delay}\]
There are two control outputs of WATSC, $u'_c$ and $u'_{wc}$, that is to say there are two parts of WATSC, and each part includes a washout links, a lead-lag links and a gain links ($K^i$). The part of structure of wide-area damping coordination controller in this study is illustrated at Figure 4.

![Figure 4. The part of structure of wide-area damping coordination controller](image)

Selection of the input signal $y$ usually is the speed difference signal or tie-line power signal, and the signal contains time delays. When $i = j$, take $\tau_y = 0$. And when $i \neq j$, it is a wide-area signal, take $\tau_y > 0$. The output signals of the WATSC are used as an additional inputs, which $u'_c$ to the excitation system block and $u'_{wc}$ to the SVC device. The main factor affecting the controller effect, here is the relationship between delay margin and the parameters of controller. So, it is necessary to determine the relationship between delay margin and the parameters of controller.

Selection of the installation position and the feedback signal are main problems for the design of WATSC. The geometric controllability/observability analysis method [29] has been used to select the suitable installation position and the feedback signals.

The washout link is $T_s/(1+T_s)$, $T_s$ is the washout constant and chosen as 10s in this paper. The lead-lag link and the gain of the controller is designed by using sisotool function in MATLAB.

4.2. Convert the controller into the form of Hamiltonian system

The transfer function of the WATSC is easily obtained by the method mentioned in the previous section. As we all known, the transfer function model is equivalent to the circuit model. Thus, the energy functions of WATSC are obtained by using the energy of the equivalent circuit [30].

Assuming that the transfer function of the lead-lag link of WATSC is described as

$$
\frac{u'(s)}{u_c(s)} = \frac{h_2s^2 + h_1s + b_1}{a_3s^2 + a_2s + a_1} = d + \frac{\beta_3s + \beta_2}{a_3s^2 + a_2s + a_1} , (d = b_1). \tag{17}
$$

The differential equations of each link of WATSC branch can be written as follows:

$$
u'_c = \frac{1}{T_y} u'_c + K^i y ; \tag{18a}$$

$$u_1 = u_i ; \tag{18b}$$

$$u_2 = -a_3x_1 - a_2x_2 + u'_c ; \tag{18c}$$

$$u' = -\beta_2a_3x_1 + (\beta_1 - \beta_2a_2)x_2 + (\beta_1 - d / T_y)u'_c + dK^i y ; \tag{18d}$$

The circuit energy of controller can be expressed as

$$H^c = \frac{1}{2}C_{u1}u_1^2 + \frac{1}{2}C_{u2}u_2^2 + \frac{1}{2}C_{u3}(u'_c)^2 + \frac{1}{2}C_{u4}(u')^2 ; \tag{19}$$

The energy storage components of each branch of controller are capacitors $C_{u1}$, $C_{u2}$, $C_{u3}$, $C_{u4}$.

Then the differential equations of each link of WATSC can be converted into the form of Hamiltonian system as

$$\dot{u}'_c = -\frac{1}{T_y} \frac{\partial H^c}{\partial u'_c} + K^i y ; \tag{20a}$$

$$u_1 = \frac{1}{C_{u2}} \frac{\partial H^c}{\partial u_2} ; \tag{20b}$$

$$u_2 = -a_3u_1 - a_2u_2 + \frac{1}{C_{u3}} \frac{\partial H^c}{\partial u_3} + \frac{1}{C_{u4}} \frac{\partial H^c}{\partial u'_c} ; \tag{20c}$$

$$u' = -\beta_2a_3u_1 + (\beta_1 - \beta_2a_2)u_2 + (\beta_1 - d / T_y)u'_c + \frac{1}{C_{u4}} \frac{\partial H^c}{\partial u'_c} + dK^i y . \tag{20d}$$
Let $x' = (u', u_1, u_2, u')^T$, thus the system (20) can be rewritten as the following form:

$$
\dot{x}' = (J' - R')y + H' + g' u',
$$

(21)

where

$$
J' = \begin{pmatrix}
0 & 0 & -1 & \frac{d - T_c \beta_i}{2C_{i1}} \\
0 & 0 & \frac{C_{i1} + a_i C_{i2}}{2C_{i1} C_{i2}} & \frac{a_i \beta_i}{2C_{i1}} \\
\frac{1}{2C_{i1}} & -\frac{a_i C_{i2}}{2C_{i1} C_{i2}} & 0 & \frac{\beta_i - \beta_i}{2C_{i2}} \\
\frac{T_c \beta_i - d}{2C_{i1} C_{i2}} & -\frac{a_i \beta_i}{2C_{i1}} & \frac{\beta_i - \beta_i}{2C_{i2}} & 0
\end{pmatrix}, \quad R' = \begin{pmatrix}
1 & 0 & -1 & \frac{d - T_c \beta_i}{2C_{i1}} \\
0 & 0 & \frac{C_{i1} + a_i C_{i2}}{2C_{i1} C_{i2}} & \frac{a_i \beta_i}{2C_{i1}} \\
\frac{1}{2C_{i1}} & -\frac{a_i C_{i2}}{2C_{i1} C_{i2}} & 0 & \frac{\beta_i - \beta_i}{2C_{i2}} \\
\frac{T_c \beta_i - d}{2C_{i1} C_{i2}} & -\frac{a_i \beta_i}{2C_{i1}} & \frac{\beta_i - \beta_i}{2C_{i2}} & 0
\end{pmatrix},
$$

and $g_i = (K' \ 0 \ 
0 \ d K')^T$, $u = y$.

As mentioned above, the WATSC has two control outputs, $u'_i$ and $u'_m$, so the control gain is $K_i$ and $K_m$, respectively, they are the main adjustable parameters to achieve the effect of suppressing the interval damping. The control gain of WATSC is described as $K_i = k_{ii} = -k_{ii}$, $K_m = k_{mm} = -k_{mm}$, $i, j = 1, \ldots, n$.

Then, the Hamiltonian system of controller (21) is added to the original Hamiltonian system (16) of interconnected network to obtain complicate time-delay Hamiltonian system. The delay margin is found for the tolerated capability of power system by using the criterion Eq. (7). The function `feasp` and `gevp` in MATLAB [31] is used to calculate the feasibility problems of matrix inequality. Finally, the relationship between delay margin and the parameters of controller will be found.

4.3. Summary of steps of the controller design

To design the controller proposed in this paper has the six steps as following.

Step 1) Model the system in the toolbox of MATLAB/Sim Power system. To linearize the nonlinear model by using the Linear Analysis Toolbox of MATLAB. And then get the state space model.

Step 2) Calculate the eigenvalues, damping ratios and frequencies of state matrix of the system to determine the inter-area low frequency oscillation mode. Select the installation sites and the feedback input signals of the WATSC by calculating the participation factor of each mode and analysing the controllability and observability [32] of linear model of the system.

Step 3) According to the characteristics of the dominant eigenvalues to design the lead-lag link and determine the gain range of the controller by using the interactive MATLAB GUI called sisotool function.

Step 4) Convert the differential equations of the complicate power system into the form of Hamiltonian system. Obtain the relationships between the delay margins and the gains of WATSC based on the method described in Proposition 1.

Step 5) Choose the gains of WATSC by a trade-off between damping ratios of the inter-area modes and delay margins.

Step 6) Model the WATSC by using MATLAB/Sim Power system and add it on the original nonlinear details models of the studied power system to verify the effectiveness of the designed wide-area controller.

5. Simulation Studies

5.1. System description and WATSC design

The 16-machine, 68-bus power system consists of five areas linked together, shown in Figure 5, and the all data illustrated in [33]. Each generator is equipped with excitation system. This is a prototype
power system using a SVC. The Area#2 is required to import 889MW from Area#5. To facilitate this large amount of power transfer, a 200 Mvar SVC is installed in the middle of the tie-line connecting busses #51 and #52, and the parameters of SVC as \( k_{sc} = 20 \) and \( \tau_{sc} = 0.05 \). Under nominal operating condition, the tie-line power flow from Area#1 to Area#2 is 701.3MW. And the eigenvalues of the state matrix as shown in Table 1.

It is obvious that Mode 1 (vibration frequency is 0.6743Hz) shows the swing of the opposite phase between the G1 and the G13. The largest swing is released on the G1 (participation factor is 0.2). Mode 2 (vibration frequency is 0.8216Hz) is an inter-area mode, and the swing of the opposite phase formed between the G10, G14 and the G16. The largest swing of mode 2 is released on the G16 (participation factor is 0.3). Mode 1 and Mode 2 have the smallest damping ratio. Thus, the intention to design WATSC provides additional damping to Mode 1 and Mode 2 in order to achieve coordinated control.

![Figure 5](image-url) The 16-machine, 68-bus power system with SVC

| Mode No. | Eigenvalue    | Damping Ratio \( \zeta \) | Frequency \( f \) (Hz) |
|---------|--------------|-----------------|------------------|
| 1       | -0.0408+j0.6731 | **0.0604**     | 0.6743           |
| 2       | -0.0539+j0.8198 | **0.0657**     | 0.8216           |
| 3       | -0.5239+j0.5812 | 0.6696         | 0.7825           |
| 4       | -0.5778+j0.5703 | 0.7117         | 0.8118           |
| 5       | -0.6168+j0.6304 | 0.6994         | 0.8820           |

Table 2. Analysis result of maximal geometric controllability/observability of system

| No. | \( \alpha_i \) | Geometric Controllability |
|-----|----------------|--------------------------|
|     |                | Wide-area                 |
|     |                | Input                     |
|     |                | -ility                    |
|     |                | Geometric Observability   |
|     |                | Wide-area                 |
|     |                | Input                     |
|     |                | -ility                    |
|     |                | Geometric Observability   |
|     |                | -ility                    |
|     |                | Geometric Observability   |

9
The control scheme proposed in this paper is illustrated at Figure 3. According to the analysis of eigenvalues and eigenvectors of the test system, we can determine the candidate input signal and the role of place of WATSC by the participation factor of each mode. The installation sites and the feedback input signals of the WATSC are selected by calculating the participation factor of each mode and analysing the controllability and observability of linear model of system. The geometric controllability/observability measures associated with Mode 1 and mode 2 are calculated and then used to choose the feedback signal of the WATSC, as shown in Table 2. As the G1 has the largest geometric joint controllability index, it is chosen as a suitable location to install wide-area feedback control signal \( u_f \). As the rotor angle difference between G1 and G13 has the largest geometric observability index, it is chosen as one of the remote feedback signal of the WATSC. The speed difference signal \( \omega_{16-10} \) has the largest geometric observability index of mode 2, as shown in Table 2, it is chosen as the other one of the remote feedback signal of the WATSC.

The WATSC has two output signals, one is \( c_{svc} \) (acting on SVC), and the other is \( c_{fu} \) (acting on the generator excitation of G1). The WATSC uses remote signals with time-delay to supplement excitation for generator and SVC if we assuming that control time-delay is negligible.

According to the characteristics of the dominant eigenvalues to design the lead-lag link and determine the range of gain of the controller without considering time-delay by using the interactive MATLAB GUI called siso tool function. The control parameters of WATSC with different feedback signals (speed difference signal \( \Delta \omega_{16-10} \), \( \Delta \omega_{16-14} \) and tie line active power \( \Delta P_{42-52} \) have the larger geometric observability index, as shown in Table 2) are computed and given in Table 3, where \( K' \) means the gain range of WATSC which changes from 0 to \( K' \).
and speed difference signals by using WATSC in Table 3, where u
f
 and u
f
\text{vc}
 are selected as input signals of WATSC.

Adding WATSC to the selected machine G1 and SVC as shown in the Figure 3, and we can obtain the gains \( K_f \) and \( K_s \) changed from 0 to \( K' \) of WATSC in Table 3, where \( K_f \) represents \( K_f \), \( K_{d} \) and \( K_{a_d} \). It is clear that the damping ratio is significantly improved as shown in Table 4. And the gain \( K_{d} \) has better damping ratio and the largest frequency than the gains \( K_f \) and \( K_{a_d} \) for the Mode 2. Thus, the speed difference signals \( \omega_{1-1} \) and speed difference signals \( \omega_{3-10} \) are selected as input signals of WATSC.

Convert the WATSC into the form of Hamiltonian system by using the method described in section 4.2. And Hamiltonian system is establishing of the system, then calculate the delay margin \( h \) by using the stability criterion. Calculating the matrix inequalities (6) described in the previous section, and using MATLAB Control Toolbox, the results are shown in Table 3. It can be found that \( h \) decreases with the increase of the gains \( K_f \) and \( K_{d} \).

### Table 3. The control parameters of WATSC

| Output Of WATSC | Gain name | Feedback signal | \( K' \) | Parameters of WATSC | \( a_0 \) | \( a_1 \) | \( b_0 \) | \( b_1 \) |
|-----------------|-----------|-----------------|---------|---------------------|---------|---------|---------|---------|
| \( u_f\text{'} \) | \( K_f \) | \( \Delta \omega_{1-1} \) | 86      | 0.86                | 1.1     | 0.36    | 0.47    |
| \( u_{\text{vc}} \) | \( K_{d} \) | \( \Delta \omega_{3-10} \) | 8469    | 1.96                | 1.4     | 0.81    | 0.49    |
| \( K_{a_d} \) | \( \Delta \omega_{3-14} \) | 8520    | 0.58                | 1.5     | 0.66    | 0.38    |
| \( K_{a_d} \) | \( \Delta \omega_{3-16} \) | 0.0134  | 4.41                | 3.8     | 0.88    | 0.02    |

### Table 4. Inter-area modes and delay margin with different gain of WASC (f/Hz)

| No. | \( h \) | \( \zeta \) | \( f \) | \( \zeta \) | \( f \) |
|-----|--------|-----------|-------|-----------|-------|
| 1   | 0      | 0.060     | 0.674 | 0         | 0.0657| 0.8216 |
| 2   | 473.12 | 0.0938    | 0.682 | 1000      | 0.117 | 0.849  |
| 3   | 1000   | 0.01      | 0.69  | 2000      | 0.14  | 0.887  |
| 4   | 0.001  | 0.0759    | 0.823 | 0.002     | 0.0878| 0.825  |
| 5   | 0.128  | 383.32    | 0.69  | 2000      | 0.156 | 0.832  |
| 6   | 0.156  | 290.18    | 0.679 | 2000      | 0.149 | 0.917  |
| 7   | 2000   | 0.165     | 0.698 | 3000      | 0.197 | 0.841  |
| 8   | 0.003  | 0.101     | 0.828 | 0.005     | 0.123 | 0.838  |
| 9   | 4000   | 176.94    | 0.706 | 4000      | 0.154 | 0.94   |
| 10  | 0.235  | 4000      | 0.706 | 4000      | 0.235 | 0.853  |
| 11  | 0.111  | 5000      | 0.714 | 5000      | 0.155 | 0.959  |
| 12  | 0.269  | 5000      | 0.714 | 5000      | 0.269 | 0.868  |
| 13  | 0.123  | 5000      | 0.714 | 5000      | 0.269 | 0.868  |
| 14  | 0.005  | 85.74     | 0.725 | 6000      | 0.16  | 0.975  |
| 15  | 0.298  | 85.74     | 0.725 | 6000      | 0.16  | 0.975  |
| 16  | 0.134  | 85.74     | 0.725 | 6000      | 0.16  | 0.975  |
| 17  | 0.145  | 77.61     | 0.737 | 7000      | 0.163 | 0.988  |
| 18  | 0.323  | 77.61     | 0.737 | 7000      | 0.163 | 0.988  |
| 19  | 0.145  | 54.26     | 0.756 | 8000      | 0.166 | 1.0    |
| 20  | 0.342  | 54.26     | 0.756 | 8000      | 0.166 | 1.0    |
Generally, the time delay of wide-area signals between tens to hundreds of milliseconds, therefore, the time delay is afforded by the wide-area controller should be as large as possible. Thus, the picking of the gains of WATSC should be satisfied the time margin and damping ratio as large as possible (15). Form the Table 4, the number 8 with gains $K_f = 30$ and $K_sI = 3000$ should be selected to be as the gains of WATSC.

5.2. Simulation results
The fault which is a 3-phase line to ground occurs at bus 61 followed by tripping one of the lines connecting buses 60 and 61 at $t = 1.1s$, and the fault is cleared at $t = 1.1s$. A time-domain simulation was carried out based on detailed nonlinear model to check the effectiveness of WATSC. And the output of the $u'_f$ is limited by $\pm 0.05$ p.u. and the output of the $u'_svc$ is limited by $\pm 0.1$ p.u.

**Figure 6.** Dynamic response of the system with different gains of WATSC, without considering time-delay

**Figure 7.** Output of the WATSC without time-delay

($u'_f = u'_f, \; u'_svc = u'_svc$)
Figure 8. Dynamic response of the system with different gains of WATSC ($\tau = 100$ms).

Figure 9. Dynamic response of the system with different time-delay ($k_f = 30$ and $k_s = 3000$)

As shown in Figure 6 and Figure 7, the response of the system is compared with and without the WATSC. The Figure 6 (a) shows the rotor speed difference of G1-G15 that the WATSC with different gains are applied to the case. It is means that the inter-area oscillation is caused by the proposed controller. And the damping performance better with the increase of gains of WATSC. It is confirmed that the result shown in Table 3.

The responses of the system with different time delay by adding WATSC are shown in Figure 8 and Figure 9. It is clear that the system performance deteriorates considerably with increasing delays. It is mean that the WATSC ($k_f = 30$ and $k_s = 3000$) is effectively when the time-delay is large as 100ms. Results show that the WATSC ($k_f = 30$ and $k_s = 3000$) has a big delay margin of 290.18ms, and it is better than the WATSC ($k_f = 80$ and $k_s = 8000$) has the delay margin 54.26ms. Thus, the gains $k_f = 30$ and $k_s = 3000$ of the WATSC should be selected to provide damping for the Mode 1 and Mode2 of the test system.

From the simulation results above, the delay margin can provide an effective guide for the design of supplementary controller, and the gain of supplementary controller can be chosen to achieve trade-off between the delay margin and damping performance. It is mean that the wide-area controller mentioned in this paper is effective.

6. Simulation Studies

Wide-area damping controller is designed by using the theory of Hamilton and the affection of time delay from remote signals. The optimal controller parameters are selected of the power system. Coordinated control between the generator excitation and SVC device has certain rationality. Simulation results show that the ringing interval has been effectively suppressed. And the relationship of the delay margin and the gains of WATSC are analyzed. The delay margin can be used as design specifications to guide the selection of different gain of the wide-area damping controller.

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