Control Frame for Synchronous Stability of Interconnected Power Systems in Deregulated Environments

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***Abstract* – Power system restructuring brings about new challenges to power system stability, especially the transient stability (TS) and small-signal stability (SS) of interconnected large-scale power systems under large and cascaded disturbances. This is because of the need to yield more economic benefits in deregulated environments. In order to improve interconnected power system TS and SS in deregulated environments, the development of an effective global control frame is very important. In this paper a preliminary study on the issue is presented. First, nonlinear robust adaptive control (RAC) is applied to excitation system utilizing local measurements. Then, RAC for the supplementary control of HVDC transmission and FACTS device (e.g. TCSC) using the WAMS signal of system center of inertia (COI) dynamics is presented. The computer test results are shown to be very positive. Based on the results, an overall control frame is suggested for enhancing TS and SS of interconnected power systems. Future work in realizing the new control frame is also discussed.**

***Index Terms* -- HVDC transmission, FACTS, power system, transient stability, nonlinear robust adaptive control.**

I. INTRODUCTION

Power system restructuring brings about new challenges to power system stability, especially the transient stability (TS) and small-signal stability (SS) (or jointly the synchronous stability) of interconnected large-scale power systems under large and cascaded disturbances. This is because the system is often heavily loaded and operating at its operation limit in order to yield more economic benefits in a deregulated environment. Moreover some unforeseen operation modes might occur which is far beyond former system design consideration. When cascaded faults appear, the system dynamic behavior will be even worse, which may lead to system blackout. It is well known that the area control centers of interconnected power systems usually exchange rather limited real-time steady-state information such as system frequency, power exchange and tie line flow; while real-time dynamic information exchange is rare and difficult. The control coordination for TS and SS under tie line faults and/or inter-area low frequency oscillations might not be perfect, and the control adaptivity to changeable operation conditions and to unforeseen cascaded faults may be far from satisfactory. In order to improve interconnected power system synchronous stability in deregulated environments, the development of a new effective control strategy or frame is an urgent, important but difficult task.

Various control strategies can be applied to improve the TS and SS of power systems. In recent years, there has been an increasing tendency to apply nonlinear theory in power systems since power systems are highly nonlinear, and traditional linear control based on power system linearized model at a special operation point can't meet the requirements of real power systems. In nonlinear control theory applications in power systems, the most successful ones may be the applications of differential geometric theory and robust control theories. In the application of differential geometric theory, nonlinear power systems are transformed into linear ones, and then mature linear control theories are applied to ensure decent dynamic performance of the closed-loop systems [1]-[3]. However, this method requires exact knowledge of the mathematical model of the studied power systems and any uncertainties such as model errors, parameter errors or other types of disturbances are neglected. In order to solve this problem, various robust control theories have also been proposed to enhance the robustness of the control methods used in power systems [4]-[7].

However, in actual power systems, many parameters are either totally unknown or slowly time-varying, which renders the aforementioned control strategies ineffective. Examples of such parameters include the damping coefficient of generators, which is usually untraceable, and the synchronous reactance and transient reactance, which may vary slowly during system dynamics as a result of generator saturation effects. In such cases, adaptive control methods, which employ dynamic estimation of unknown parameters, tend to be more appropriate in obtaining solutions to problems involving unknown parameters [8]-[10]. It should be pointed out that while adaptive control theories for linear systems are relatively mature, no universal approach has been developed for nonlinear adaptive control theories yet.

The study of robust adaptive control (RAC) for nonlinear systems has been widely conducted in recent years with some rewarding results shown in [11]-[15]. As a result, the study on applying RAC in power systems has become a hotspot in power system stability and control.

In this paper RAC is applied to improve interconnected power system TS and SS under deregulated environments. First, the novel nonlinear RAC proposed in [11] is applied to excitation systems, and then to HVDC transmission and

The work is supported by the National Key Basic Research Special Fund (Project 2004CB217900) of China and the National Natural Science Foundation (Project 50337010) of China.

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FACTS devices (e.g. TCSC) to improve interconnected power system synchronous stability using system center of inertia (COI) dynamic signals from WAMS (wide area measurement system). The designed RAC controllers ensure uniform ultimate boundedness of all system states. Hence, the system is stable in the Lyapunov stability sense. Computer test results show clearly the effectiveness of the RAC as compared with conventional control methods. Based on the results, an overall control frame is suggested. Future work required to realize the new control strategy is also discussed.

It should be pointed out that nonlinear control methods have already been applied to HVDC power controllers in [16]-[17], but the applications are restricted to single machine to infinite bus systems or very simple power systems. It can be seen from those papers that without using COI signal from WAMS, the coordination of various controllers will be a serious problem in large-scale interconnected power systems. On the other hand, it can be seen in this paper that through COI signal application, the detailed topology, parameters and dynamic information of the sending and receiving areas of the interconnected power systems will not be required, and the tough task of controller coordination can be eliminated. Another advantage of using COI signals in control is that the new controller can have better performance under cascaded faults, which will be shown in the paper.

This paper is organized as follows. In Section 2, RAC is applied to excitation systems. In Section 3, RAC is applied to the supplementary control of HVDC transmission system and to a FACTS device-TCSC. Computer simulation results are provided in relevant sections as well. An overall system control frame is suggested in Section 4 with conclusions drawn in Section 5.

II. Nonlinear Robust Adaptive Excitation Control

A. Power System Dynamic Model

The i[th] generator subsystem of a multi-machine power system comprising N generators with proper assumptions can be represented by the third order model below [4], with disturbances and model errors in ω_i and E'_{qi} dynamics represented by ε_{i1} and ε_{i2} respectively.

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_0 \\ \dot{\omega}_i &= \frac{\omega_0}{M_i}(P_{mi} - P_{ei}) - \frac{D_i}{M_i}(\omega_i - \omega_0) + \varepsilon_{i1} \\ \dot{E}'_{qi} &= \frac{1}{T'_{d0i}}(E_{fi} - E'_{qi} - (X_{di} - X'_{di})I_{di}) + \varepsilon_{i2} \end{aligned} \tag{1}$$

where: $P_{ei} \cong E'_{qi} I_{qi}, \quad P_{mi} = const. \quad (i = 1, 2 \ldots N)$

The notation for the above model can be found in [3]. The damping coefficient D_i is an unknown constant, while the d-axis synchronous reactance X_{di} and transient reactance X'_{di} are slowly time-varying parameters as a result of the saturation effect of generators. D_i, X_{di}, X'_{di}, ε_{i1} and ε_{i2} are all assumed to be bounded. The designed controller should be adaptive to the unknown parameters (D_i, X_{di}-X'_{di}) and robust to the dynamic uncertainties of the model errors (ε_{i1}, ε_{i2}).

If the desired operating point of the generator in (1) is given by (δ_{i0}, ω_0, E'_{qi0}) and we define state variables $\mathbf{x_i}$ as:

$$\mathbf{x}_i = [\delta_i - \delta_{i0}, \omega_i - \omega_0, \dot{\omega}_i]^T$$

based on [11]-[15] the normal perturbed exact-feedback form of (1) will be

$$\begin{aligned} \dot{x}_{i1} &= x_{i2} \\ \dot{x}_{i2} &= x_{i3} \\ \dot{x}_{i3} &= v_i + \boldsymbol{\theta}_i^T \boldsymbol{\varphi}_i + \Delta_i(t) \\ y_i &= x_{i1} \end{aligned} \tag{2}$$

where the virtual control input is given by

$$v_i = \frac{\omega_0}{M_i}\left(-\frac{I_{qi}}{T'_{d0i}}E_{fi} + \frac{P_{ei}}{T'_{d0i}} - E'_{qi}\dot{I}_{qi}\right) \tag{3}$$

and

$$\boldsymbol{\theta}_i = [\theta_{i1}, \theta_{i2}]^T, \ \boldsymbol{\varphi}_i = [\varphi_{i1}, \varphi_{i2}]^T, \ \theta_{i1} = X_{di} - X'_{di}, \ \theta_{i2} = D_i$$

$$\varphi_{i1} = \frac{\omega_0 I_{di} I_{qi}}{M_i T'_{d0i}}, \ \varphi_{i2} = -\frac{x_{i3}}{M_i}, \ \Delta_i(t) = \dot{\varepsilon}_{i1} - \frac{\omega_0 I_{qi}}{M_i T'_{d0i}}\varepsilon_{i2}.$$

The ‘differentiability’ issue of certain variables at the instants of system operations/faults and the solution to it will be discussed in section 4.

B. Controller design

Applying the transformation below

$$\begin{aligned} z_{i1} &= x_{i1} \\ z_{i2} &= x_{i2} - \alpha_{i1}(x_{i1}) \\ z_{i3} &= x_{i3} - \alpha_{i2}(x_{i1}, x_{i2}) \end{aligned} \tag{4}$$

given that α_{i1} and α_{i2} are smooth functions where $\alpha_{i1}(0)=0$ and $\alpha_{i2}(0,0)=0$, the equilibrium point of (4) remains unchanged and at the origin.

References [11] and [18] show that the control law v_i for (2) can be given by

$$v_i = -z_{i2} - k_{i3} z_{i3} - \hat{\boldsymbol{\theta}}_i^T \boldsymbol{\varphi}_i + \dot{\alpha}_{i2} - \beta_i \tag{5}$$

and the adaptive law can be taken as

$$\begin{aligned} \dot{\hat{\boldsymbol{\theta}}}_i &= \boldsymbol{\Gamma}_i [z_{i3}\boldsymbol{\varphi}_i - \sigma_{i1}(\hat{\boldsymbol{\theta}}_i - \boldsymbol{\theta}_i^0)] \\ \dot{\hat{\psi}}_i &= \gamma_i [z_{i3} w_i - \sigma_{i2}(\hat{\psi}_i - \psi_i^0)] \\ \beta_i &= \hat{\psi}_i w_i \\ w_i &= \tanh\left(\frac{z_{i3}}{\varepsilon_i}\right) \end{aligned} \tag{6}$$

It has been proven that the designed control can guarantee that $\mathbf{x}_i(t)$, $\tilde{\boldsymbol{\theta}}_i(t)$ and $\tilde{\psi}_i(t)$ are uniformly ultimately bounded while there exists T>0 such that $|y_i(t)| \le \mu_i$ for $T \le t \le \infty$ and any $\mu_i > \mu_i^*$ where

$$\mu_i^* = \left[\frac{\varepsilon_i \psi_i^M + \sigma_{i1} \left| \boldsymbol{\theta}_i - \boldsymbol{\theta}_i^0 \right|^2 + \sigma_{i2}(\psi_i^M - \psi_i^0)}{\min\{2k_{i1}, 2k_{i2}, 2k_{i3}, \sigma_{i2}\gamma_i, \frac{\sigma_{i1}}{\lambda_{\min}(\boldsymbol{\Gamma}_i^{-1})}\}} \right]^{1/2}$$

The notations for the above equations are omitted and can be found in [18], which is similar to [11].

The excitation control law for the i[th] generator based on the inverse transformation of (3) can therefore be found as

$$E_{fi} = \frac{T'_{d0i}}{I_{qi}}\left(-\frac{M_i}{\omega_0}v_i + \frac{P_{ei}}{T'_{d0i}} - E'_{qi}\dot{I}_{qi}\right) \quad (7)$$

The designed controller uses local measurements and is independent of network topology and load conditions. The control law in (7) always holds as $I_{qi} \neq 0$, and E_{fi} can be set to its upper bound in the case when $I_{qi} \cong 0$.

The application of this control law ensures that the state variables of the ith subsystem are uniformly ultimately bounded, while the rotor angle δ_i will be driven to a value within a small neighborhood of the ideal value δ_{i0}.

C. Computer simulation results

Computer simulations were run on a 4-machine interconnected power system [19] as shown in Fig. 1.

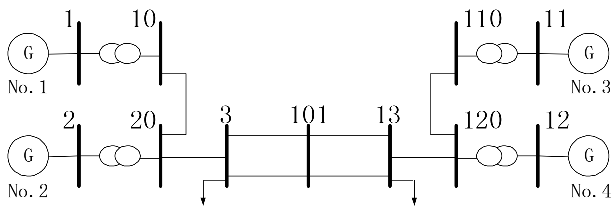


Fig. 1. Single-line diagram for a 4 machine power system

The 6th order practical model is adopted for the generators with (δ_i, ω_i, E'_{qi}, E'_{di}, E''_{qi}, E''_{di}) as the state variables. The saturation effects are considered while the governor dynamics are neglected. The load is modeled as constant impedance. The excitation system output is limited to [0, 6]. Detailed information and data of the test system can be found in [19].

All machines are equipped with the same type of controllers. For RAC, the estimated uncertain parameter values are taken as the initial values of the uncertain parameters, and they may be different from the real values of the parameters. The initial values of these parameters are taken as:

$$\theta_{i1}^0 = 1, \theta_{i2}^0 = 0, \psi_i^0 = 0.001. \ (i = 1 \sim 4)$$

For conventional (AVR+PSS) controllers, the parameters are well designed and the controller parameters are taken as:

$$k_{i1} = 1, k_{i2} = 3, k_{i3} = 5;\ \varepsilon_i = 1, \sigma_{i1} = 1, \sigma_{i2} = 1;\ \gamma_i = 10$$

$$\Gamma_i = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}. \ (i = 1 \sim 4)$$

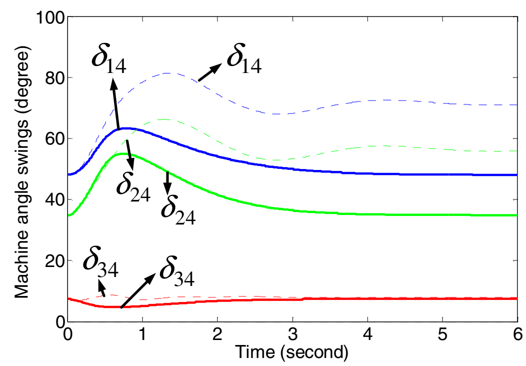
Two fault test cases are used for computer test and comparison. They are:

Case 1: A 3-phase short circuit fault occurs on line 101-3 near bus 101 at 0.1s and the fault line is tripped at 0.2s.

Case 2: Line 13-101 trips at 1s for an unknown reason after the fault and clearing operation of case 1.

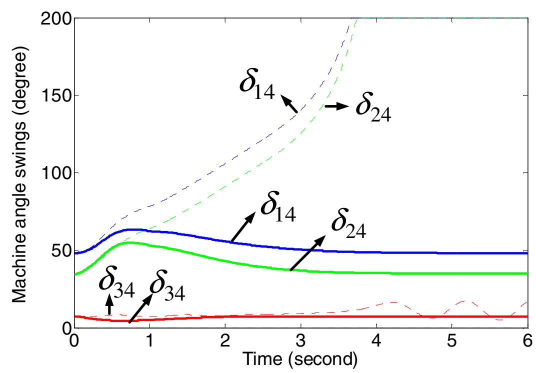
Time simulation is conducted with generator 4 taken as the reference machine. The machine angle swings in both test cases are shown in Figures 2 and 3 respectively.

From Figures 2 and 3, it can be seen that the proposed RAC controller is very effective in improving power system transient stability and has better performance as compared with the conventional ones. It can be seen from Fig. 2 that in case 1, both the first swing stability and the damping of angle swings are improved when the RAC is employed. Moreover, it can be seen from Fig. 3 that the conventional controllers are incapable of ensuring system stability and that the power system collapsed. However, when RAC is employed, the power system can maintain stability well. Through operation limit search, for case 2, power transfer limit can be increased by 15% through RAC in excitation systems. It is clear that the suggested RAC controller is more effective in enhancing power system synchronous stability as compared with conventional ones.



(--- AVR+PSS; — NRAC)

Fig. 2. Machine angle swings for case 1



(--- AVR+PSS; — NRAC)

Fig. 3. Machine angle swings for case 2

III. Nonlinear Robust Adaptive Control for Supplementary Control of HVDC Transmission and TCSC in Interconnected Power Systems

A. Interconnected ac/dc power system model

Consider an interconnected ac/dc power system with 2 areas (area 1 and area 2) connected by parallel ac-dc transmission lines as shown in Fig. 4.

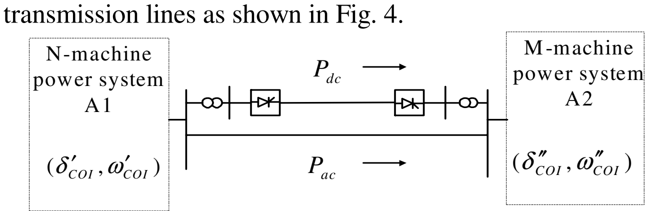


Fig. 4. Circuit diagram of a two area interconnected system

Assuming that there are N generators in area 1, the rotor dynamics of the i[th] generator in area 1 can be given by [19]

$$\begin{aligned} &\dot{\delta}'_i = \omega'_i - \omega_0 \\ &M'_i\dot{\omega}'_i = \omega_0(P'_{m,i} - P'_{e,i}) - D'_i(\omega'_i - \omega_0) \quad (i = 1,2,...,N) \end{aligned} \tag{8}$$

The concept of center of inertia (COI) is adopted, and the COI angle and speed in area 1 are defined as [20]:

$$\begin{aligned} &\delta'_{COI} = \frac{1}{M'_T}\sum_{i=1}^{N} M'_i\delta'_i \\ &\omega'_{COI} = \frac{1}{M'_T}\sum_{i=1}^{N} M'_i(\omega'_i - \omega_0) \qquad M'_T = \sum_{i=1}^{N} M'_i \end{aligned} \tag{9}$$

COI angle and speed definition can also be applied to area 2. The dynamic model of the ac/dc interconnected power system in COI coordinates will take the form below (see Fig. 4) with system errors and disturbances taken into consideration:

$$\begin{aligned} &\dot{\delta}'_{COI} - \dot{\delta}''_{COI} = \omega'_{COI} - \omega''_{COI} \\ &\dot{\omega}'_{COI} - \dot{\omega}''_{COI} = \frac{\omega_0}{M'_T}(P'_{m,\Sigma} - P'_{L,\Sigma} - P_{ac}) - \frac{\omega_0}{M''_T}(P''_{m,\Sigma} - P''_{L,\Sigma} + P_{ac}) \\ &\qquad -(\frac{\omega_0}{M'_T} + \frac{\omega_0}{M''_T})P_{dc} + \tilde{D}_{COI}(\omega'_{COI} - \omega''_{COI}) + \varepsilon_D \\ &\dot{P}_{dc} = \frac{1}{T_d}(-P_{dc} + P_{dc,ref} + u_{dc}) + \varepsilon_P \end{aligned} \tag{10}$$

The notation for (10) is omitted and can be found in [21]. In (10), the equivalent damping coefficient $\tilde{D}_{COI}$ in COI coordinates cannot be measured directly, and is thus taken as an unknown parameter. The constant dc power control is of first order with u_{dc} served as dc power modulation signal to be controlled. The idea of the control is to drive the COIs of interconnected areas to a stable equilibrium point (SEP).

To design RAC for dc power modulation, a coordinate transformation X is defined as:

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} (\delta'_{COI} - \delta''_{COI}) - (\delta'_{COI,0} - \delta''_{COI,0}) \\ \omega'_{COI} - \omega''_{COI} \\ \dot{\omega}'_{COI} - \dot{\omega}''_{COI} \end{bmatrix}$$

so that (10) can be re-written to the normal form for RAC design [11]:

$$\begin{aligned} &\dot{x}_1 = x_2 \\ &\dot{x}_2 = x_3 \\ &\dot{x}_3 = v + \theta^T\phi + \Delta(t) \end{aligned} \tag{11}$$

where the virtual control input is given by

$$\begin{aligned} v = &\frac{\omega_0}{M'_T}(\dot{P}'_{m,\Sigma} - \dot{P}'_{L,\Sigma} - \dot{P}_{ac}) - \frac{\omega_0}{M''_T}(\dot{P}''_{m,\Sigma} - \dot{P}''_{L,\Sigma} + \dot{P}_{ac}) \\ &-(\frac{\omega_0}{T_dM'_T} + \frac{\omega_0}{T_dM''_T})(-P_{dc} + P_{dc,ref} + u_{dc}) \end{aligned} \tag{12}$$

The ‘differentiability’ issue of certain variables at the instants of system operations/faults and the solution to it will be discussed later on.

B. Controller Design

The RAC design for dc power modulation is almost the same as that for excitation system.

First of all, we consider the coordinate transformation below

$$\begin{aligned} &z_1 = x_1 \\ &z_2 = x_2 - \alpha_1(x_1) \\ &z_3 = x_3 - \alpha_2(x_1, x_2) \end{aligned} \tag{13}$$

where α1 and α2 are smooth functions such that $\alpha_1(0)=0$ and $\alpha_2(0,0) = 0$. Applying this transformation to (11), the equilibrium of the new system remains unchanged and at the origin.

The control law for (11) can be derived as:

$$v = -z_2 - k_3z_3 - \hat{\theta}^T\phi + \dot{\alpha}_2 - \beta \tag{14}$$

and the adaptive law as

$$\begin{aligned} &\dot{\hat{\theta}} = \Gamma[z_3\phi - \sigma_1(\hat{\theta} - \theta^0)] \\ &\dot{\hat{\psi}} = \gamma[z_3w - \sigma_2(\hat{\psi} - \psi^0)] \\ &\beta = \hat{\psi}w \\ &w = \tanh(\frac{z_3}{\varepsilon}) \end{aligned} \tag{15}$$

which can ensure that $x(t), \tilde{\theta}(t), \tilde{\psi}(t)$ are uniformly ultimately bounded and there exists T>0 such that $|x_1(t)| \le \mu$ for $T \le t \le \infty$ and any $\mu > \mu^*$ given

$$\mu_i^* = \left[\frac{\varepsilon_i\psi_i^M + \sigma_{i1}\left|\boldsymbol{\theta}_i - \boldsymbol{\theta}_i^0\right|^2 + \sigma_{i2}(\psi_i^M - \psi_i^0)}{\min\{2k_{i1}, 2k_{i2}, 2k_{i3}, \sigma_{i2}\gamma_i, \frac{\sigma_{i1}}{\lambda_{\min}(\boldsymbol{\Gamma}_i^{-1})}\}}\right]^{1/2} \tag{16}$$

The control signal for dc power modulation can finally be found to be:

$$\begin{aligned} u_{dc} = &\frac{T_dM''_T(\dot{P}'_{m,\Sigma} - \dot{P}'_{L,\Sigma} - \dot{P}_{ac}) - T_dM'_T(\dot{P}''_{m,\Sigma} - \dot{P}''_{L,\Sigma} + \dot{P}_{ac})}{M'_T + M''_T} \\ &- \frac{T_dM'_TM''_Tv}{M'_T\omega_0 + M''_T\omega_0} + P_{dc} - P_{dc,ref} \end{aligned} \tag{17}$$

C. Computer simulation results

The system in Fig. 1 is modified to be an ac/dc interconnected power system (see Fig. 5) for computer test.

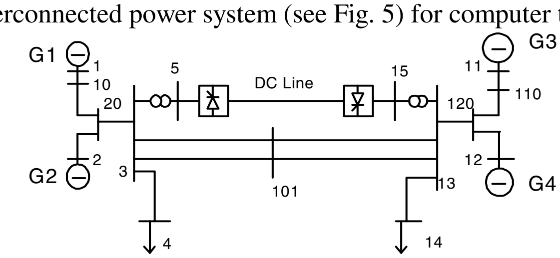


Fig. 5. Single line diagram of a 2-area 4-machine interconnected system

The subtransient model is adopted for generators installed with conventional third-order AVR as well as well designed PSS. The mechanical power of each generator is assumed to be constant, while the loads are represented by constant impedances.

The parameters of robust adaptive dc power modulation control (RAMC) are set as: k_1=1.5, k_2=3, T_d=0.2, ψ^0=0.001,

γ=100, Γ=100, σ_1=0.1, σ_2=0.1, ε=0.01.

The parameters of classical (PSS-like) dc power modulation control (CMC) are set based on the phase compensation method as: T_w=3, K_A=1.0, T_1=0.02, T_2=0.04, T_3=0.02, T_4=0.04.

Three fault cases are tested. They are:

Case 1: The parallel ac lines of 3-101 transfer total power of P_{ac} = 320MW. A temporary three-phase fault occurs at bus 3 at t=5s and disappears at t=5.1s.

Case 2: The parallel ac lines of 3-101 increase transfer power to P_{ac} = 450MW. A three-phase fault occurs on bus 3 at t=5s and one circuit of line 3-101 is tripped at t=5.1s.

Case 3: The parallel ac lines of 3-101 increase transfer power to P_{ac} = 600MW. Apply the same fault as case 2.

For all 3 cases, the dc transmission power is P_{dc}=1000MW, and the HVDC system is temporarily blocked during the fault period and restored upon clearance of the fault. Generator 4 is still taken as the reference generator in time simulation.

Figures 6, 7 and 8 show the rotor relative angle δ_{14} swings in cases 1-3 respectively.

It can be observed from Fig. 6 that at the controller design point where the SEP remains unchanged after the fault, RAMC has similar performance as CMC with only a little improvement. However in cases 2 and 3 where the power transfer increases and the SEP is changed after the fault clearing, it can be seen from Figures 7 and 8 that the new controller can provide better damping to inter-area power oscillations as compared with CMC and can control the system to a better post-fault SEP for further operation. (The bus voltage plots are not given here, but they are also within normal range.) Moreover, it can be seen from Fig. 8 that CMC fails in maintaining first swing stability, while the RAMC is capable of preventing system collapse. It is found that for the fault in case 2 the transfer power limit of the two ac lines using CMC is only 540 MW, while that of using RAMC reaches 620 MW, which is about 15% higher.

D. Implementation of RAMC on FACTS device-TCSC

The RAMC design can be extended to the control of FACTS devices such as the Thyristor Controlled Series Capacitor (TCSC). The TCSC can be represented as variable impedance on an ac tie line in a power system (see Fig. 9). In Fig. 9, one of the ac tie lines makes use of constant series compensation while the other one is installed with TCSC.

Using the COI coordinates, the mathematical model for the system in Fig. 9 is similar to that of ac/dc interconnected power system. The control law and adaptive law for RAMC of the TCSC can be derived similarly. Computer test results, which will not be presented in the paper, show clearly that RAMC is more effective than CMC in damping low frequency oscillations, especially when the real transfer power is much more than that of the designed point and when the SEP changes noticeably after the faults.

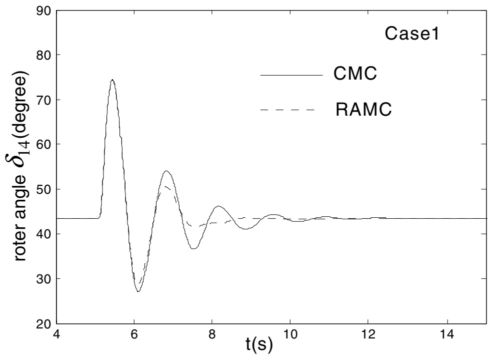


Fig. 6. Fault bus rotor angle δ14 for Case 1

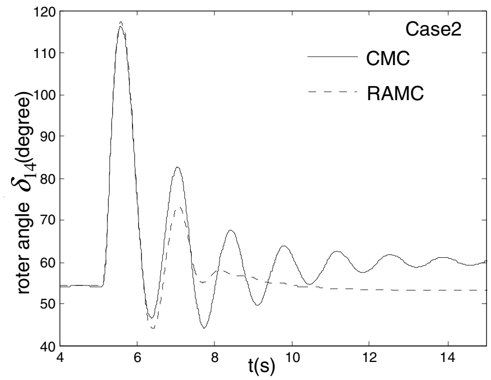


Fig. 7. Fault bus rotor angle δ14 for Case 2

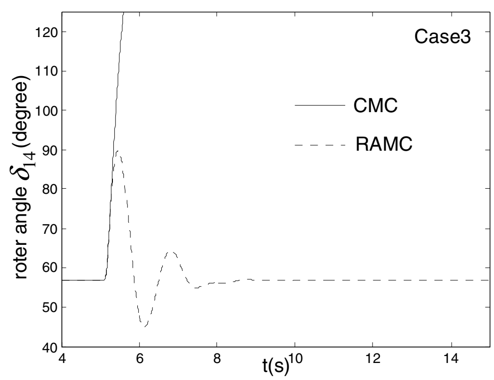


Fig. 8. Fault bus rotor angle δ14 for Case 3

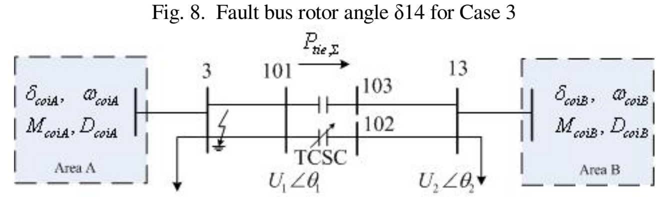


Fig. 9. Equivalent circuit of a multi-machine system with TCSC

IV. Nonlinear RAC for Interconnected Power System Stability– Suggested Frame

Based on the research work reported above, some discussions will be made. Then, an overall control frame for interconnected power system TS and SS enhancement will be proposed.

The observations below are important to the control frame suggestion:

(i) In some cases, power system continuous control of excitation systems, HVDC transmission systems and FACTS devices cannot guarantee the system synchronous stability without the support of bang-bang (discontinuous) control like generator inter-tripping and load shedding. This is because in nonlinear control theory, the stability proof is often based on a well-defined Lyapunov function V. If it is proven that V is positive and its derivative w.r.t. time is non-positive after disturbances the controlled system is said to be stable in Lyapunov stability sense. However, for each real power system there exists a critical value for the defined V-function. For any large disturbance that can cause the V-function to exceed that critical value, the system will not be stable even if dV/dt can be proven to be non-positive. This is a special nonlinear feature of power system rotor dynamics. This is also true for the RAC theory used in this paper. Therefore *we have to combine uncontinuous and continuous control into hybrid control for TS and SS*.

(ii) For cascaded faults, an important issue is the change in SEP after faults, which causes traditional control to have very poor performance; and even for nonlinear control, its effects might be poor if its robustness and adaptivity is unsatisfactory. Therefore *the nonlinear robust adaptive control is highly recommended for various continuous controllers.*

(iii) For interconnected power systems, the low frequency power oscillations along the heavily-loaded long-distance ac tie lines are of great concern. HVDC transmission lines in parallel with ac ties and FACTS devices along the ac ties can provide superior controllability to the damping of oscillations. PSS is another well-known selection but it has drawbacks such as its linear control nature, poor robustness and adaptivity and complex control coordination requests. It can be observed from the research of the paper that *in damping interarea oscillations*, *the efficient way is to make use of area-COI dynamic signals* of the interconnected power systems if they are available from WAMS. Its advantages are apparent: (a) COI dynamics are relatively smooth when compared with individual generator angle dynamics since it 'filters out' rotor relative motions of the area. (b) COI dynamics can reflect global system power and frequency trends and is better than using only local signals in control. (c) Using COI as tracking target in control design is more reasonable and renders it easier to realize synchronous stability, especially when the system is in shortage of generation or with over generation. Our recent test results show that if the COI-tracking concept is used in excitation control (rather than to control the system strictly back to 50Hz as in Section 2 of this paper), the system operation limits can increase noticeably by 15% for the test cases if system COI signal can arrive within 0.1 sec. delay. (d) For interconnected power systems, the use of COI coordinates in control can eliminate the need for coordination of various controllers. It is also not sensitive to the topology, parameters and load conditions of individual areas. It can also be easily extended to multi-infeed HVDC transmission systems and multi-area interconnected power systems. (e) COI tracking strategy can be used for both TS and SS enhancement, since the system will be synchronously stable if all the machines are coherent to the system COI.

(iv) In the study we assume *excitation control can maintain synchronous operation of machines in one area* with the support of PSSs designed for local/plant modes; while *dc system in parallel with ac ties and FACTS devices on ac ties as well as PSSs strongly participating to the interarea-modes are mainly used for damping interarea modes*.

(v) In our study, we didn't mention voltage and frequency viability crisis for their mid-term stability nature. RAC can also be applied for this purpose (still it should be a hybrid control with uncontinuous control included) but with longer time scale and with proper coordination to TS and SS control.

Based on the above observations, the suggested TS and SS control strategies for flexible-ac and multi-infeed-dc interconnected power systems under deregulated environments with consideration of cascaded faults can be worked out without difficulty.

<u>The overall control frame</u> is suggested as follows.

(i) Nonlinear RAC is designed as continuous control of excitation systems (recently saturation/excitation-limit effects can be considered as well), which aims at tracking the local area COI (see section 2 as an example) and realizing synchronous operation of local generators.

(ii) Nonlinear RAC is also designed for interconnected power system synchronous operation (see section 3 as an example) which aims at driving all area COIs to a global SEP.

(iii) The critical values of Lyapunov functions for (i) and (ii) will be predicted respectively and compared with corresponding real system Lyapunov functions, and if necessary, discontinuous control (or say bang-bang control) should be applied to reduce the Lyapunov functions to become lower than the critical values, so that nonlinear RAC can drive the system to an SEP effectively. It is clear that steps (i) and (iii) can form a hybrid control for local area synchronous stability while steps (ii) and (iii) are for interarea synchronous stability.

(iv) Similarly, frequency and voltage mid-term dynamic stability can be controlled by hybrid RAC and bang-bang control as well, which should also consider local area and inter-area situations respectively. COI coordinates can still be applied for mid-term stability, and AGC can be used to enhance mid-term frequency stability of interconnected power systems under deregulated environments.

(v) The TS and SS control should finally be integrated with mid-term stability properly to form hybrid global control of power systems.

(vi) One more issue is the 'differentiability' of certain variables at system operation/faults instants. It can be proven that if the studied system experiences a *limited number* of operations/faults at $t<T$, and if the operations/faults cause sudden but *limited* rise of Lyapunov function where the latter is never beyond the critical value, the system will be stable in Lyapunov stability sense when it installs the RAC designed in

sections 2 and 3. The derivatives of certain variables w.r.t. time at limited system operation/fault instants can be obtained through tracking differentiators [22]-[23] with acceptable accuracy, as tested in time simulation.

Further R&D is required to realize the suggested control strategy. The main tasks are as follows.

(i) RAC parameters should be optimized to yield satisfactory performance and avoid high-frequency trembling of its output.

(ii) COI signal should be available from WAMS and its fast communication is important with bad data issue considered.

(iii) Local measurements for RAC should be accurate. The derivatives of certain variables can be realized through tracking differentiators (TD) [22]-[23], where the input is a certain variable while the output is its derivative. The TD in [23] has very good accuracy and convergence.

(iv) The estimation/prediction of critical Lyapunov function and bang-bang control optimization, if necessary, are tough research topics. They will have significant impacts on final hybrid control system performance.

(v) The issue of coordination of existing excitation systems and PSSs with new RACs should be solved. In addition optimal allocation of new RACs should also be studied.

(vi) The hybrid RAC and bang-bang control for mid-term stability and the coordination of TS and SS control with mid-term stability control are also important tasks.

(vii) Sample system development, system test on real-time digital simulator and field test are challenging.

V. Conclusion

In this paper RAC is applied to improve interconnected power system synchronous stability under deregulated environments. The novel nonlinear RAC proposed in [11] is first applied to excitation systems, and then to HVDC transmission and TCSC to improve synchronous stability of interconnected power systems using COI dynamic signal from WAMS. The designed RAC controllers ensure uniform ultimate boundedness of all system states. Therefore, the system is stable in the Lyapunov stability sense. Computer test results show clearly the effectiveness of the RAC.

Based on the results, a control frame is suggested which is suitable for TS, SS and mid-term stability of large scale interconnected power systems under deregulated environments with special consideration on cascaded faults. The future R&D work to realize the suggested control frame is also discussed.

With fast development of WAMS technology, the suggested control strategy can be realized in the future and will bring about significant progress in power system stability and control.

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VII. Biography

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