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Robust Decentralized Switching Power System Stabilisers for Interconnected Power Grids: Stability using Dwell Time ⋆

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Abstract: This paper addresses the problem of designing decentralized robust power system stabilisers for interconnected power systems by considering effects of parameter variations and interconnections from other generators. To make the controller robust against parameter variations around an operating point, variations in system parameters due to the load change are translated to the uncertainty framework and are represented using Integral Quadratic Constraints (IQCs). The operating range of the generator is divided into several zones with respect to its power output and separate controllers are designed for each zone to achieve robust stabilization in the vicinity of the operating point. As the operating point shifts from one zone to another a suitable controller is selected and switched. The stability of the switched system is achieved by allowing a "dwell time" between consecutive switchings. Jumps in system states during switching are taken into account in the derivation of the dwell time. Interconnection effects due to other machines in the grid are included as the uncertainty in the controller design. The controller design methodology is validated by simulating a two-area power benchmark power system.

Keywords: Power system control design; Decentralized control; Switching control; Dwell time; Power system stabilizers.

1. INTRODUCTION

The primary task of the power system control is to provide reliable and secure electric power supply within a narrow band of voltage and frequency variations. As the demand for electric power is continuously increasing power systems are growing in size and complexity. Also to meet the ever increasing demand, power systems are forced to operate close to their capacity limits without sacrificing the reliability. This reduces the damping of the system making it marginally stable. These issues make the power system control task very difficult and challenging.

In a multi-machine power system, when the steady state condition is disturbed due to load changes or a fault in the system, rotors of the machines comprising the system start oscillating with respect to each other, exchanging energy between them. When oscillations are allowed to grow, the machines are pulled out of synchronization. Most generators have a Power System stabiliser (PSS) to improve the stability margin and to damp out oscillations. A conventional design is generally based on a Single Machine connected to Infinite Bus (SMIB) model and is aimed at achieving the stability of a single operating point. The robustness problems encountered by the conventional design procedures and the modeling limitations were addressed and improved upon by considerable research work in this area as reported in Wang et al. [1998], Jain et al. [1996], Boukarim et al. [2000], Wang et al. [1995], Qiu et al. [2004]. In these works, controllers are designed for multi-machine power systems using modern control techniques like the H_∞ optimisation, μ-synthesis and the Linear Matrix Inequality (LMI) approach.

Generally, a single PSS is designed for the entire operating range of the generator. However the power system parameters vary over a wide range due to variations in load and generation conditions. This makes the conventional PSS design conservative as the PSS must cover a broad range of conditions. To reduce conservatism, several controllers can be designed around different selected operating points and these controllers can be suitably switched as the generator operating conditions change.

Switching controllers are widely used in different areas and considerable research has been carried out in these methodologies, Wang et al. [2006]. Stability of switched controlled systems is also widely investigated and reported in Liberzon [2003], Zhao and Dimirovski [2004], Sun and Ge [2004], Hespanha and Morse [December 1999]. In Liberzon [2003], Hespanha and Morse [December 1999] the concept of allowing a dwell time between two consecutive switchings for switching stability is established. While deriving dwell time, generally, it is assumed that system

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states do not jump at switching instances i.e., trajectories of the system states are continuous everywhere. But to apply the dwell time approach to power systems where controllers are designed for operating points corresponding to different steady state conditions, discontinuous jumps in trajectories have to be considered due to switching of equilibria. In this paper we account for these switching jumps in the states in the derivation of the dwell time.

In our work we divide the entire operating regime of the generator into several zones with respect to power output of the generator and each zone consisting of one Stable Equilibrium Point (SEP). We propose a decentralised output feedback controller designed for a power system linearised around each such SEPs. The controller design methodology is based on the recent work by Li et al. [2007] and Athanasius et al. [2007]. The controller is made robust against parameter variations within the particular zone around the nominal plant corresponding to the selected SEP. These parameter variations due to load change are translated into uncertainty frame work and represented using Integral Quadratic Constraints (IQCs). Along with this, the interconnection effects from other machines in the system and other local uncertainties are also included in the controller design. By this approach the potentially possible perturbations on the system are addressed in the design. This makes the proposed design more robust and less conservative. In the controller design uncertainties are bounded by using IQCs and the H_∞ optimisation problem is solved using rank constrained LMIs Li et al. [2007]. The designed controller guarantees robust performance for load variations within the specified bounds around the SEP.

When the operating point of the generator shifts from one zone to another while the power output of the generator changes, the controller corresponding to the new zone can be selected and switched. Switching stability is achieved by allowing dwell time between consecutive switchings. The proposed controller is validated by designing stabilisers for a test case power system. The performance of the controller is validated through nonlinear simulations. The paper is organised into four parts. First part gives the power system model, the next part covers the controller design, dwell time derivation is given in the third part and in the last part test case and simulation results are presented.

2. POWER SYSTEM MODEL

Mathematical model of a multi machine power system consisting of N generators is considered here. The behavior of a i^{th} generator in a multi-machine power system consisting of N generators, Anderson and Fouad [1994], is described by:

$$\begin{aligned}
\dot{\delta}_i &= \omega_s\omega_i - \omega_s \\
\dot{\omega}_i &= \frac{1}{2H_i}\left(P_{mi} - E'_{qi}I_{qi}\right) \\
\dot{E'}_{qi} &= \frac{1}{\tau'_{do}}\left[K_{ai}(V_{oi} - V_{refi} + V_{si}) - E'_{qi} + (x_{di} - x'_{di})I_{di}\right] \\
\dot{V}_{oi} &= \frac{1}{T_{ri}}\left(V_{oi} - |V_{ti}|\right) \qquad (1)
\end{aligned}$$

where

$$\begin{aligned}
I_{qi} &= \sum_{j=1}^{N} |E'_{qj}|\left[G_{ij}\cos(\delta_j - \delta_i) - B_{ij}\sin(\delta_j - \delta i)\right] \\
I_{di} &= \sum_{j=1}^{N} |E'_{qj}|\left[G_{ij}\sin(\delta_j - \delta_i) + B_{ij}\cos(\delta_j - \delta i)\right] \qquad (2)
\end{aligned}$$

where δ_i is the rotor angle, ω_i is the rotor speed with respect to a synchronous reference frame, E'_{qi} is the quadrature axis transient voltage, V_{oi} is the terminal voltage transducer output and V_{si} is the stabilising signal for the AVR. Detailed description of the parameters in the above equations are given in Anderson and Fouad [1994].

3. CONTROLLER DESIGN

The control design problem considered here is of providing a control algorithm which works for large changes in generator load. The algorithm presented in this paper first divides the entire operating range, i.e., load variations, into several regions, a linear model is obtained about a SEP in that region, and then one controller each is designed for each region of operation. Finally constraints on the frequency of switching between controllers are obtained to preserve system stability.

The controller design in this paper is based on the methodology of rank constrained LMI's and IQC modeling proposed in Li et al. [2007], also see Athanasius et al. [2007] where the results of Li et al. [2007] were utilized in the design of power system stabilisers. Let us consider a generator in a power system with variable power output $\rho(.)$. In Athanasius et al. [2007] each generator connected to the grid is treated as a subsystem and formulated as a system affected by parameter variations and by the interconnection effects. Effects due to parameter variation around the operating point and interconnection effects are treated as uncertainties on the subsystem. IQCs are used to describe the uncertainties and LMI optimization technique is used to solve the optimisation problem.

Following Ugrinovskii and Pota [2005], Ramos et al. [2006] and Athanasius et al. [2007], we consider a large scale system $\mathbb{S}$ comprising of N subsystems $\mathbb{S}_i$ of the following form:

$$\begin{aligned}
\mathbb{S}_i : \dot{x}_i(t) &= A_i(\gamma)x_i(t) + B_iu_i(t) + E_i\xi_i(t) \\
&\quad + \beta_i\phi_i(t) + L_ir_i(t), \\
z_i(t) &= C_ix_i(t) + D_iu_i(t), \\
\zeta_i(t) &= H_ix_i(t) + G_iu_i(t), \\
\hat{\zeta}_i(t) &= \alpha_iIx_i(t), \\
y_i &= C_{y,i}x_i(t) + D_{y,i}\xi_i(t), \qquad (3)
\end{aligned}$$

where $A_i(\gamma)$ is the system matrix corresponding to the power output $\rho(\cdot) = \gamma$, x_i is the state vector and in the case of generator from equation (1) $x_i = [\Delta\delta_i, \Delta\omega_i, \Delta E_{qi}, \Delta V_{oi}]'$, u_i the control inputs which is the PSS output ΔV_{si}, $\xi_i \in \mathbf{R}^{p_i}$ is the perturbation, $\zeta_i \in \mathbf{R}^{h_i}$ is the uncertainty output (made up of both the system states, and the control inputs), $\hat{\zeta}_i$ is the uncertainty output due to parameter variation around operating point, $z_i \in \mathbf{R}^{q_i}$ is the controlled output of the subsystem which consists of both the subsystem states and control inputs, and y_i is output of the system which is $\Delta\omega_i$ feedback to the controller. The input r_i describes the effect of the subsystems S_j, $j \neq i$, on the subsystem S_i. The input ξ_i describes the effect of local uncertain modeling errors in this subsystem.

The variations in $A(\cdot)$ due to load and generation changes around the operating point can be treated as an additional disturbance and the system can be regarded as a perturbation of a linear fixed parameter system. The variations in the matrix $A(\cdot)$ can be regarded as modeling uncertainty and driven by $\phi_i(t)$, Yoon et al. [2007]. Signal $\phi_i(t)$ is defined as:

$$\phi_i(t) := \frac{1}{\beta_i}\left[A_i(\gamma + \Delta\gamma) - A_i(\gamma)\right] x_i(t)$$

where α_i and $\beta_i > 0$ are constants.

Now the designed controller will stabilize the original Linear Parameter Varying (LPV) system provided the parameter $\rho(\cdot)$ varies in a sufficiently small neighborhood Ω_γ of γ. The size of neighborhood is determined by the choice of α_i and β_i.

To design the controllers, let α_i, β_i and $\gamma \in \Gamma$ be so chosen that

$$\sup_{\rho \in \Omega_\gamma} \|A_i(\rho) - A_i(\gamma)\| < \alpha_i \beta_i \quad (4)$$

where $\|\cdot\|$ denotes the largest singular value.

Now we consider the problem of decentralized absolute stabilization via output feedback control. The controllers considered are decentralized linear output feedback controllers of the form

$$\begin{aligned} \dot{x}_{c,i}(t) &= A_{c,i}(\gamma)x_{c,i}(t) + B_{c,i}(\gamma)y_i(t); \\ u_i(t) &= K_{c,i}(\gamma)x_{c,i}(t), \end{aligned} \quad (5)$$

where $x_{c,i} \in \mathbf{R}^{n_{c,i}}$ is the i^{th} controller state vector.

Having the uncertainties, controller structure and load variation parameter defined, we can find the decentralised controllers (5) using the design methodology given in Li et al. [2007] and Athanasius et al. [2007]. In the next section, we describe the method to preserve stability of system when these controllers are switched.

4. SWITCHING SYSTEM AND STABILITY

When the operating point of the generator changes suitable controller need to be selected and switched. The stability of the switched system can be established under slow switching (Liberzon [2003]). In this paper the work in Liberzon [2003] is extended to system states which jump at switching instances.

Now we discuss the stability of a switched system made up of two systems P_1 and P_2:

$$P_1 : \dot{x} = A_1 x, \quad (6)$$

$$P_2 : \dot{x} = A_2 x - A_2 \Psi, \quad (7)$$

where $x \in R^n$ is the state-vector and $\Psi \in R^n$ is a constant vector; the equilibrium point for P_1 is 0 and that of P_2 is Ψ; matrices A_1 and A_2 are stable matrices and further there exist Lyapunov functions $V_1(x)$ and $V_2(x-\Psi)$ for P_1 and P_2 respectively.

We look at the configuration where the system is continuously switching between P_1 and P_2 and determine the stability of this system. The first question is: if both P_1 and P_2 are stable then how is it that switching between the two will make the overall system unstable? For finite number of switchings, stability is guaranteed but the same cannot be said of infinite number of switchings.

Formally we define stability as follows: Given systems P_1 and P_2 and an infinite switching sequence $P_1 \to P_2 \to P_1$, the system is stable if there exists an r-ball

$$B_r = \{z : V_1(z) \leq r\}$$

such that for every P_1-state $x(t_0) \notin B_r$, where t_0 is the instance when system switches from P_1 to P_2, there exists a τ_d such that when the system switches back to P_1 from P_2, at $t_0 + \tau_d$, P_1-state $x(t_0 + \tau_d)$ is in B_r.

Let the system states at the switching instances be denoted as (see Figure 1):

$$x_1 = x(t_0) \quad \text{and} \quad x_2 = x_1 - \Psi \quad (8)$$

$$y_1 = x(t_1) \quad \text{and} \quad y_2 = y_1 - \Psi \quad (9)$$

where the system switches from P_1 to P_2 at t_0 and back to P_2 at t_1.

Note that the definition of stability is satisfied once the system reaches inside a ball and not necessarily as it approaches the origin. There is a good reason for this. Systems P_1 and P_2 have different equilibrium points and when the system switches to P_2, the state approaches Ψ, the equilibrium point of P_2. This means that the ball B_1 has to be large enough to include both equilibrium points (0 and Ψ) (see Figure 1).

To see the motivation for the above stability definition, we define balls B_0 B_1, and B_2, shown in Figure 1:

$$B_0 = \{z : V_1(z) \leq V_1(x(t_0))\} \quad (10)$$

$$B_1 = \{z : V_1(z) \leq V_1(x(t_1))\} \quad (11)$$

$$B_2 = \{z : V_2(z - \Psi) \leq V_2(x(t_0) - \Psi)\} \quad (12)$$

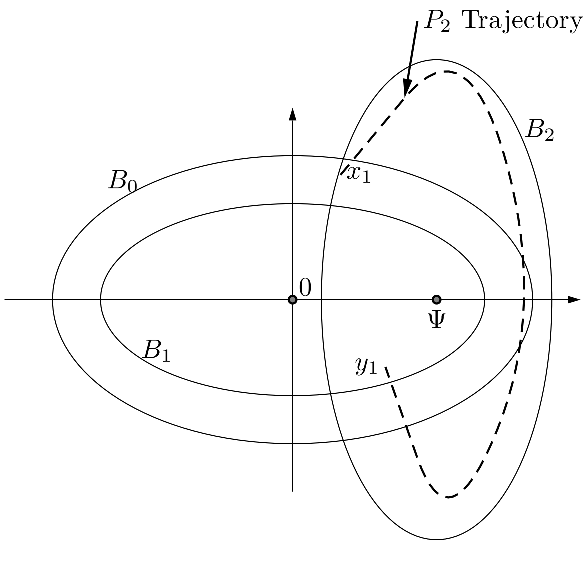

Fig. 1. Balls B_0 and B_1 and system trajectory (dashed)

The interpretation of what these balls are is simple. (Please note that since $V_1(x)$, $V_2(x-\Psi)$ are positive-definite, balls B_0, B_1, and B_2 define closed volumes.) Let t_0 be the time at which the system switches from P_1 to P_2 and then at time t_1, switches back from P_2 to P_1; the two balls B_0 and B_1 correspond to the bound on system states at time instants t_0 and t_1. Ball B_2 gives the bound on the trajectory when the system is switched to P_2.

Our notion of stability is that if $B_1 \subset B_0$, for all switchings $P_1 \rightarrow P_2 \rightarrow P_1$, then the infinite switchings result in a stable system. If such is not the case then every switching may push the state into a larger and larger ball leading to instability.

The condition that B_1 be a subset of B_0 can be ensured by imposing a condition on the minimum time spent in P_2 during every $P_1 \rightarrow P_2 \rightarrow P_1$ cycle. This time is called the dwell time, denoted as τ_d, and our final result is that if the time spent in P_2 is greater than the dwell time, i.e., $t_1 - t_0 \geq \tau_d$, then the switched system is stable.

Next we obtain an expression for the dwell time to ensure the stability of the switched system. Let Lyapunov functions V_1 and V_2 satisfy the following inequalities for some positive constants a_1, a_2, b_1, b_2 and c_1, c_2:

$$a_1 |x|^2 \leq V_1(x) \leq b_1 |x|^2 \tag{13}$$

$$a_2 |x-\Psi|^2 \leq V_2(x-\Psi) \leq b_2 |x-\Psi|^2 \tag{14}$$

$$\frac{\partial V_1}{\partial x} A_1 x \leq -c_1 |x|^2 \tag{15}$$

$$\frac{\partial V_2}{\partial x}(A_2 x - A_2 \Psi) \leq -c_2 |x-\Psi|^2 \tag{16}$$

From equation (13),

$$\frac{V_1(x)}{b_1} < |x|^2,$$

substituting this in (14),

$$\frac{\partial V_1}{\partial x} A_1 x \leq -2\lambda_1 V_1(x) \tag{17}$$

where $\lambda_1 = \frac{c_1}{2b_1}$. This implies that for any positive τ,

$$V_1(x(t_0+\tau)) \leq e^{-2\lambda_1 \tau} V_1(x(t_0)) \tag{18}$$

since $\frac{dV_1(x)}{dt} \leq -2\lambda_1 V_1(x)$ and V_1 decays exponentially. Similarly we have

$$V_2(x(t_0+\tau) - \Psi) \leq e^{-2\lambda_2 \tau} V_2(x(t_0) - \Psi).$$

From (13) and definitions (8) and (9) we have:

$$a_1 |x_1|^2 \leq V_1(x_1) \leq b_1 |x_1|^2 \tag{19}$$

$$a_2 |x_2|^2 \leq V_2(x_2) \leq b_2 |x_2|^2 \tag{20}$$

We find the dwell time, τ_d, by showing that when $t_1 - t_0 \geq \tau_d$ then there exists a ν such that (for x_1 and y_1 defined in (8), (9))

$$V_1(y_1) - V_1(x_1) \leq -\nu |x_1|^2 \tag{21}$$

Since V_1 is a positive definite function, we can substitute an upper bound for $V_1(y_1)$ and lower bound for $V_1(x_1)$ and obtain,

$$b_1 |y_1|^2 - a_1 |x_1|^2 \leq -\nu |x_1|^2 \tag{22}$$

Next we get a bound on $|y_1|$; we know that,

$$V_2(y_2) \leq e^{-2\lambda_2 \tau_d} V_2(x_2) \tag{23}$$

$$\implies a_2 |y_2|^2 \leq b_2 e^{-2\lambda_2 \tau_d} |x_2|^2 \tag{24}$$

$$\implies a_2 |y_1 - \Psi|^2 \leq b_2 e^{-2\lambda_2 \tau_d} |x_1 - \Psi|^2 \tag{25}$$

Using the fact that $2(a-b)^2 \geq a^2 - 2b^2$ with (25), we have,

$$-a_2 |\Psi|^2 + \frac{a_2}{2} |y_1|^2 \leq e^{-2\lambda_2 \tau_d} b_2 |x_1 - \Psi|^2$$
$$\leq e^{-2\lambda_2 \tau_d} b_2 \left(|x_1|^2 + |\Psi|^2\right) \tag{26}$$

Substituting the upper bound on $|y_1|^2$ from (26) into (22) we have,

$$4\frac{b_1 b_2}{a_2} e^{-2\lambda_2 \tau_d} |x_1|^2 + 2\frac{b_1}{a_2} |\Psi|^2 \left(2e^{-2\lambda_2 \tau_d} b_2 + a_2\right)$$
$$-a_1 |x_1|^2 \leq -\nu |x_1|^2 \tag{27}$$

The middle term in the left-hand-side of the above equation (27) is independent of $|x_1|$ and unless x_1, the state at which the system switches from P_1 to P_2, is outside of some region, inequality (27) cannot be satisfied. We ensure that x_1 is outside of some region by constraining it as follows:

$$|x_1|^2 \geq 2\frac{b_1}{a_1} K_\Psi |\Psi|^2 \quad \text{where} \quad K_\Psi > 1. \tag{28}$$

Substituting (28) in (27) we have,

$$4\frac{b_1 b_2}{a_2} e^{-2\lambda_2 \tau_d} |x_1|^2 + \frac{a_1}{a_2 K_\Psi} |x_1|^2 \left(2e^{-2\lambda_2 \tau_d} b_2 + a_2\right)$$
$$-a_1 |x_1|^2 \leq -\nu |x_1|^2 \tag{29}$$

From (29) we have the condition that τ_d should be such that,

$$4\frac{b_1 b_2}{a_2} e^{-2\lambda_2 \tau_d} + \frac{a_1}{a_2 K_\Psi} \left(2e^{-2\lambda_2 \tau_d} b_2 + a_2\right) - a_1 < 0 \tag{30}$$

Thus for stable switching τ_d should satisfy,

$$2e^{-2\lambda_2 \tau_d} \left(\frac{2b_1 b_2 K_\Psi + a_1 b_2}{a_2 K_\Psi}\right) < a_1 \left(\frac{K_\Psi - 1}{K_\Psi}\right)$$
$$2e^{-2\lambda_2 \tau_d} < \frac{a_1 a_2 (K_\Psi - 1)}{2(2b_1 b_2 K_\Psi + a_1 b_2)}$$
$$\tau_d > \frac{1}{2\lambda_2} \log\left[\frac{a_1 a_2 (K_\Psi - 1)}{2(2b_1 b_2 K_\Psi + a_1 b_2)}\right] \tag{31}$$

In the above we have proved that the r-ball into which system trajectories converge is given by:

$$B_r = \{z : V_1(z) \leq 2b_1 K_\Psi |\Psi|^2\} \tag{32}$$

From this it can be seen that there is a trade-off between K_Ψ and τ_d.

So far we have only considered the $P_1 \rightarrow P_2 \rightarrow P_1$ cycle but the development for the $P_2 \rightarrow P_1 \rightarrow P_2$ cycle is symmetrical to this and the dwell time in P_1 can be obtained by commuting the $a_1 \rightarrow a_2$, $b_1 \rightarrow b_2$, and $c_1 \rightarrow c_2$ constants in the above expression (31). In the next section both the dwell times are given for the test case power system.

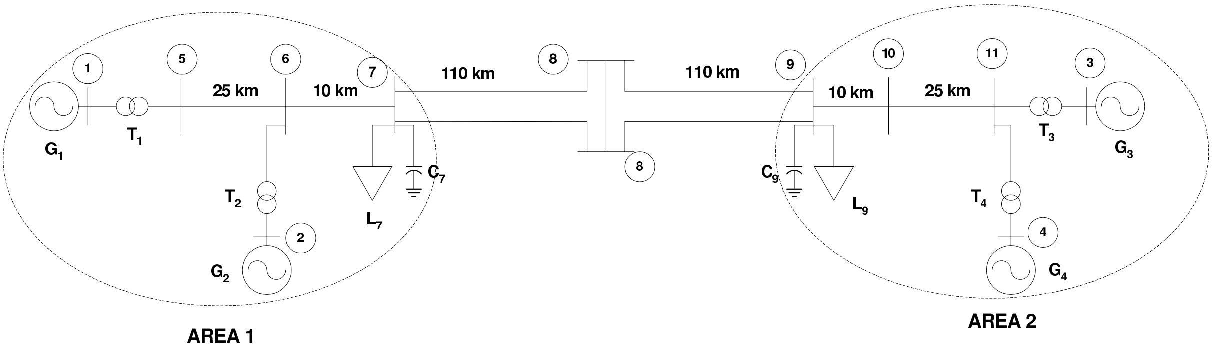

Fig. 2. Two area four machine system.

5. TEST CASE POWER SYSTEM

To apply the controller design methodology, a two area power system consisting of 4 generators and 11 buses is considered. The layout of the power system is given in Figure 2. The generator G_1 bus is considered as the reference slack bus.

Area 1 is connected to Area 2 through a two circuit tie line of length 220 km. The transmission system nominal voltage is 400 kV. Generation voltage is stepped up by the transformers connected to the generators. Load centers are at buses 7 and 9, buses 7 and 9 also have shunt capacitors. Generator, transformer and line parameters for the system are given in Athanasius et al. [2007].

Generators G_1, G_3 and G_4 are base generators and supply a power output of 400 MW each. Hence a single PSS is designed for G_1, G_3 and G_4 for an operating point of 400 MW. Generator G_2 takes up the variation in system load and its power output varies from 0 to 400 MW in increments of 25 MW. The operating region of G_2 is divided into 16 equal zones of 25 MW each and each zone consists of a SEP. Separate controller is designed for each zone with a robust stabilisation over a parameter variation of ± 25 MW as described in Section 3. The stabilisation overlap between the adjacent controllers are so chosen that the adjacent operating points are included in the overlap region.

The dwell time for switching between two controllers is worked out as per the procedure outlined in Section 4. In the dwell time given by the equation (31), the value of K_Ψ is chosen by the user. Larger values of K_Ψ allow a larger size for the ball B_r described in equation (32), which increases the region of convergence for the state trajectories. It can be seen from equation (31) that the value of dwell time τ_d depends not only on K_Ψ but also on the system parameters. We have varied the value of K_Ψ from 1.1 to 100 and observed its effect on dwell time and found that dwell time slightly increases with K_Ψ. For switching from $200MW$ to $225MW$, the dwell time for K_Ψ = 1.1 is 15.88 sec and for $K_\Psi = 100$, dwell time is 21.2698. For the test case system we have selected the value of K_Ψ as 1.5. The dwell time corresponding to switching from $200MW$ to $225MW$ and back given in Case 1 below is $17.1376s$ and from 225 to $200MW$ is $17.4313s$.

To evaluate the performance of controller and controller switching, the following nonlinear simulations are carried out. Case 1 evaluates the performance for back and forth controller switchings around an operating point. Cases 2 and 3 are selected to consider gradual power up and down scenarios.

Case 1: G_2 is initially at 200 MW after the elapse the dwell time, generation of G_2 is increased to 225 MW and corresponding controller is switched in and again after the elapse of dwell time, power and controller are reversed back to 200 MW conditions. Rotor angle response of the generators are given in Figure 3 and the generator speed in Figure 4.

Case 2: The power output of G_2 is initially at 0 MW. Output of G_2 is increased to 400 MW in steps of 25 MW. At each power change corresponding controllers are switched in after the elapse of dwell time. Rotor angle response of the generators are given in Figure 5.

Case 3: Similar to Case 2 above but the output of G_2 is reduced from 400 MW to 0 MW. Rotor angle variations of the generators are given in Figure 6.

6. CONCLUSION

The paper demonstrates a methodology to make the power system controller design less conservative using switching controllers with constrained minimum switching interval. Using IQCs the interconnection effects from other machines in the grid and parameter variation around the operating point are included in the controller design, making the stabiliser robust in the presence of these effects. The switching stability is established using dwell time between consecutive switchings and the effect of jumps in the system states are also included while calculating the dwell time. To validate the controller design and switching stability, two area power system is considered as a numerical example and nonlinear simulations are carried out with wide generation-load variations. Sudden up and down generation changes are simulated in Case 1 and the results of simulation are given in Figures 3 and 4. In Cases 2 and 3 the performance is evaluated for continuous generation up and down conditions the results of simulation are included in Figures 5 and 6. The results of the simulation show the performance and effectiveness of the scheme under different generation conditions.

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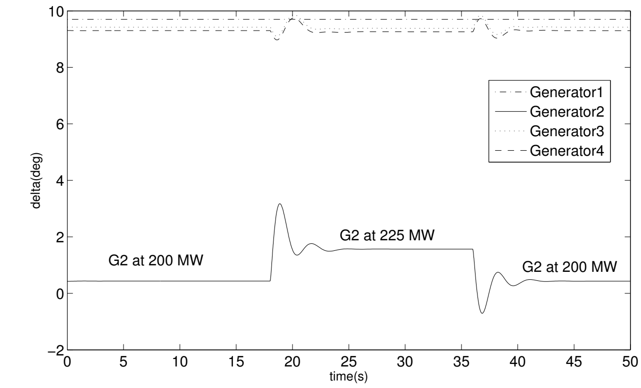

Fig. 3. Case 1: Rotor Angles δ.

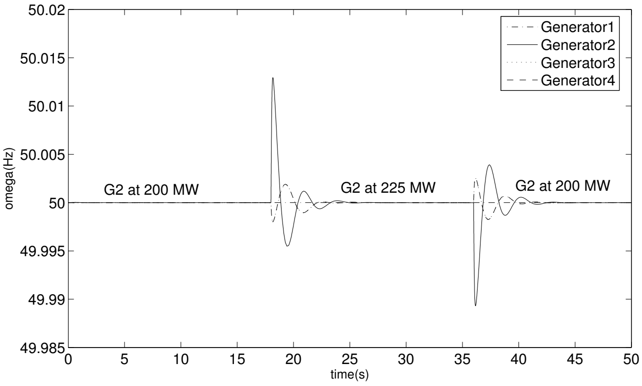

Fig. 4. Case 1: Rotor Speed ω.

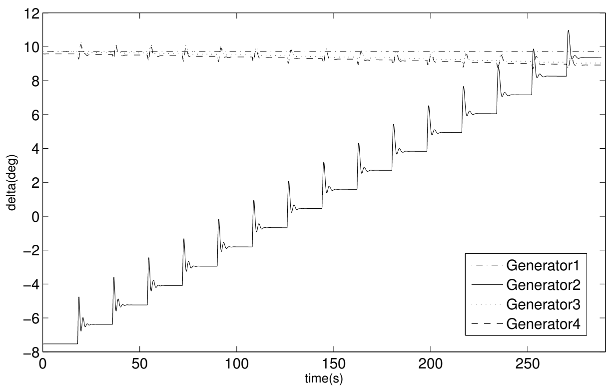

Fig. 5. Case 2: Rotor Angles δ.

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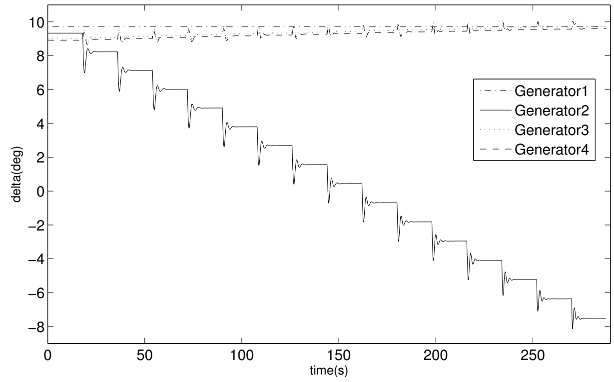

Fig. 6. Case 3: Rotor Angles δ.

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