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Design Of Optimal State Feedback Switching Lqr's For Power System With Upfc At Different Operating Points

Sai Shankar[1] and Yathisha L[2]

[1]Professor, Department of Electronics & Communication Engineering, Akshaya Institute of Technology, Tumkur, VTU Belagavi, Karnataka, India – 572106. Email: saishankar96@gmail.com
[2] Professor, Department of Electronics & Communication Engineering, Akshaya Institute of Technology, Tumkur, VTU Belagavi, Karnataka, India – 572106. Email: yathisha.171@gmail.com
Corresponding Author: Yathisha L, yathisha.171@gmail.com

Abstract:
As a preliminary analysis, this paper presents the design of Bryson, Bouderal and multistage-based Linear Quadratic Regulator (LQR) optimal controllers for the power system with UPFC at light, normal & heavy load conditions. For each load condition, the two best optimized feedback controllers are then selected based on the preliminary analysis and optimal switching strategy is implemented between two candidate controllers to further optimize output energy. The proposed solution is tested for the linearized Single Machine Infinite Bus (SMIB) Phillips-Heffron power system model installed with Uniform Power Flow Controller (UPFC). Simulation was done to verify the hypothesis using MATLAB/SIMULINK platform.

Keywords: Control System, Optimal Control, Linear Systems, Hybrid Systems.

1. Introduction

Power system network will not always operate at a single operating condition. Due to continuous variation of load from minimum to maximum, it always operates at multiple operating conditions. However, conventional approach is to design a single controller and hope for its robustness at all load conditions. Although conventional Power System Stabilizer (PSS) controllers have either been substituted or supplemented with modern Flexible AC transmission Controllers (FACTS) they are not robust enough to take care of all the conditions.

The UPFC device is one of the most popular FACTS based power flow controller and its concept was described in (Gyugyi et al., 1995). The UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system. UPFC is one of the flexible AC transmission system (FACTS) devices, which can control power system parameters such as terminal voltage, line impedance and phase angle. Thus UPFC can be used not only for power flow control, but also for power system stabilizing control.

Besides ensuring stabilization, one would also be interested in minimization of energy of output variables such as rotor angle deviation and rotor speed deviation. Lately, researchers are working for the selection of UPFC control inputs such as (m_E, δ_E, m_B, δ_B) by applying different control techniques. Some of the examples are described in (Ray, Sarker, Ahsan, Israfil, & Seddiqe, 1912), where they proposed a novel approach of PID control scheme with UPFC's for damping of oscillations and they concluded that after incorporating PID controller with UPFC, the damping of oscillation is reduced significantly. The performance of UPFC on controlling of the real/reactive power flow in the line is examined with different control mechanisms based on P, PI, PID and fuzzy controllers in (Saribulut, T¨umay, & Eker, 2008). The results show that, PI and fuzzy controllers provide nearly same performance but there is a low overshoot occurred during the fault when using the fuzzy controller. According to overall results, UPFC improves the system performance under the transient and steady state conditions.

Authors in (Ramesh & MaheshBabu, 2012) presented Artificial Neural Network (ANN) based damping controller for UPFC. Simulation results and comparison showed that the adaptive ANN damping controller has good ability to reduce settling time and reduce amplitude of low frequency oscillations (LFO). Authors in (Shayeghi, Shayanfar, Jalilzadeh, & Safari, 2009) demonstrated robust controller by designing output feedback control for δ_E using particle swarm optimization technique. By applying phase compensation control technique, researchers in (Tambey & Kothari, 2003) have shown that control inputs (δ_E & δ_B) provide robust performance when compared to the other damping controllers. Application of a real-coded genetic algorithm optimization technique and investigation in (Baliarsingh, Panda, Mohanty, & Ardil, 2013) reveals that damping control m_B provides slightly better performance among four alternatives

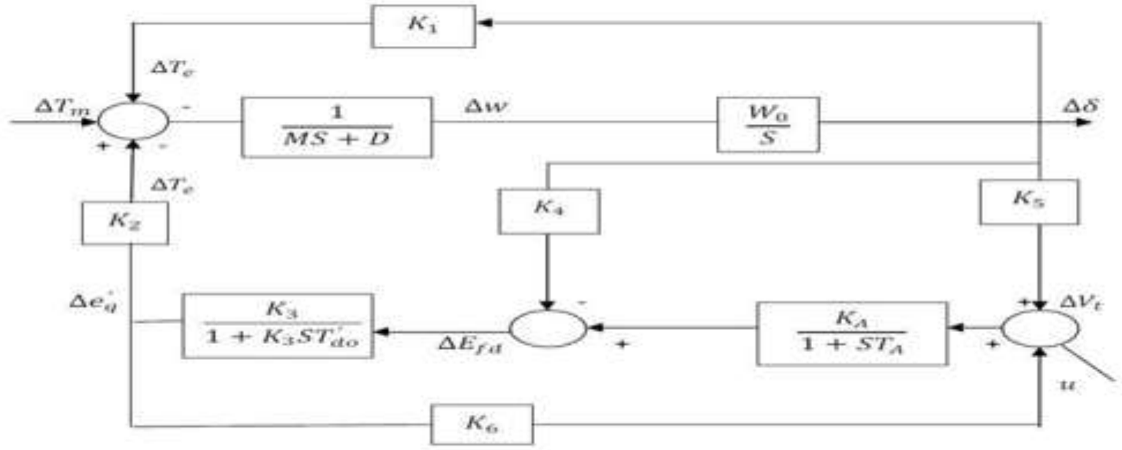
D. Murali & Dr. M. Rajaram et al., [6] compared all the FACTS devices concerning the power system stability enhancement with and without the presence of UPFC in the system in the event of a major disturbance and the experimental results conclude that the performance of UPFC for power system stability improvement is compared with the other FACTS devices such as SVC, TCSC, and SSSC respectively. To evaluate the power quality problems, various FACTS controllers are compared by Budi Srinivasa rao and G. Sreenivasan et. al, [7]. Arthit Sode Yome & Nadarajah Mithulananthan et al,.[8] compared various FACTS devices for exclusive loadability enhancement for the appropriate choice of FACTS device, and the results show that the UPFC FACTS provides better performance compared to all other FACTS devices to all loading conditions.

In summary, for the power system operating over wide range of operating conditions (light, normal & heavy) the FACTS control input UPFC along with the better feedback control technique, play vital role for damping low frequency oscillations as well as power system stability. However, to the knowledge of the authors, no literature addresses the issue of UPFC controller for power system operating at different operating conditions.

In the present work, for each operating loading condition, namely light, normal and high, following experiments are performed:

1. A preliminary analysis is developed for UPFC by designing the feedback control signals using optimal control theory of Linear Quadratic Regulator (LQR) algorithm by tuning the weighting matrices Q & R with different approaches. The approaches used in the current research are Bryson rule (Bryson & Ho, 1975), Boudarel rule (Boudarel, Delmas, & Guichet, 1971) and multistage LQR (Pandey, 2010).
2. The results from preliminary analysis are compared to select the two best candidate optimized feedback control technique based on their ability to minimize overshoot, reduce settling time and minimize output energy.
3. A switching control strategy is developed to switch between two candidate controllers to achieve further improvements in the above parameters.

Paper is organized as follows. In section 2, power system model installed with UPFC is described. It is followed by preliminary analysis, with three different optimal (Bryson, Bouderal & Multistage) LQR approaches in section 3. Switched linear systems, switching algorithm and switching control strategies for each of light load, normal load & heavy load are briefed in section 4. Section 5 describes the results and analysis of research. Discussions and conclusion follow in the subsequent sections.



I. Figure 1. Block diagram of power system

2. Power system modelling with UPFC

A single machine infinite bus (SMIB) system is considered for the present investigations. In (Wang, 2000) the author has presented a linearized Phillips Heffron Model installed with UPFC for single machine infinite bus (SMIB) in power system, where a machine connected to a large system through a transmission line is reduced to a SMIB system, by using Thevenin's equivalent of the transmission network external to the machine (Yousef & El-Sherbiny, 2004), & (Athanasius, Pota, & Ugrinovskii, 2008). SMIB is represented in a block diagram as shown in Fig 1. Its state-space formulation can be expressed as follows (also refer (Alfi & Khosravi, 2012) & (Al-olimat, Farhoud, & Hurtig, 2006):

$$\dot{x}(t) = Ax(t) + Bu(t), \qquad (1)$$

where, the state variables are the rotor angle deviation ($\Delta\delta$), speed deviation $\Delta\omega$, q-axis component deviation ($\Delta E'_q$), and field voltage deviation (ΔE_{fd}). A and B represent the system matrix and control input matrices, given by,

$$A = \begin{bmatrix} 0 & \omega_o & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 \\ -\frac{k_1}{T'_{do}} & 0 & -\frac{k_3}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{k_A k_5}{T_A} & 0 & -\frac{k_A k_6}{T_A} & \frac{1}{-T_A} \end{bmatrix}, \qquad B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{k_{pb}}{M} & -\frac{k_{p\delta b}}{M} & -\frac{k_{pc}}{M} & -\frac{k_{p\delta c}}{M} \\ -\frac{k_{qb}}{T'_{do}} & -\frac{k_{q\delta b}}{T'_{do}} & -\frac{k_{qc}}{T'_{do}} & -\frac{k_{q\delta c}}{T'_{do}} \\ -\frac{k_A k_{vb}}{T_A} & -\frac{k_A k_{v\delta b}}{T_A} & -\frac{k_A k_{vc}}{T_A} & -\frac{k_A k_{v\delta c}}{T_A} \end{bmatrix}$$

3. Preliminary Analysis

Initial Analysis of the optimal control has been done for the phase angle shunt inverter δ_B robust UPFC control input (Yathisha, Davoodi, & Kulkarni, 2017). Numerical Values of A and B matrices for different loading conditions are (Ajami & Asadzadeh, 2011):

Light Load, Normal & Heavy Loads:

$$A_L = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.0232 & 0 & -0.0575 & 0 \\ -0.0172 & 0 & -0.484 & 0.1983 \\ 20.2297 & 0 & -376.98 & -20 \end{bmatrix} \qquad B_L = \begin{bmatrix} 0 \\ 0.20 \\ 0.048 \\ 7.60 \end{bmatrix}$$

For, these three different loading conditions in power system the closed loop control system (A_α, A_β & A_γ)

$$A_N = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.0168 & 0 & -0.1696 & 0 \\ -0.0393 & 0 & -0.484 & 0.1983 \\ 58.80 & 0 & -333.70 & -20 \end{bmatrix} \qquad A_H = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.0157 & 0 & -0.157 & 0 \\ -0.040 & 0 & -0.484 & 0.1983 \\ 66.1087 & 0 & -341.103 & -20 \end{bmatrix}$$

$$B_N = \begin{bmatrix} 0 \\ 0.17 \\ 0.1501 \\ 0.60 \end{bmatrix} \qquad B_H = \begin{bmatrix} 0 \\ 0.20 \\ 0.10 \\ -10.1 \end{bmatrix}$$

are given by,

$$\begin{aligned} A_\alpha &= A_L - B_L K_L, && (2) \\ A_\beta &= A_N - B_N K_N, && (3) \\ A_\gamma &= A_H - B_H K_H, && (4) \end{aligned}$$

where, the feedback controller gains (K_l, K_N & K_H) are derived from optimal control theory of LQR by tuning the weighting matrices with different approaches (Bryson, Boudarel & Multistage).

4. Simulation Experiments & Discussion

To select the better optimized feedback controllers for the specified operating conditions (light, normal & heavy loads), simulations are carried for the three different approaches of optimal LQR's (Bryson, Boudarel & Multistage). Figures 4, 5, shows the responses of deviations in rotor angle (Δδ) and rotor speed (Δω) for light, normal and heavy loads.

Figures 4-5 show the simulation results (MATLAB / SIMULINK) of rotor angle deviation (Δδ) and rotor speed deviation (Δω) for light, normal and heavy loading conditions with three different approaches of LQR. Figures 4-5. The overall results of preliminary analysis reveals that one LQR is better for peak overshoot while other LQR is better for settling time. This situation motivated to design a switching control strategy to achieve optimization between peak overshoots and settling time. Based on the summary of preliminary analysis the two candidate optimized feedback controllers selected for the implementation of switching control strategies (master & alternate controllers) for different operating conditions are as shown in Table 1.

Table 1. Optimized feedback controllers for different loads

Operating Condition	Master Control	Alternate Control
Light Load	Bryson LQR	Multistage LQR
Normal Load	Bryson LQR	Bouderal LQR
Heavy Load	Bryson LQR	Multistage LQR

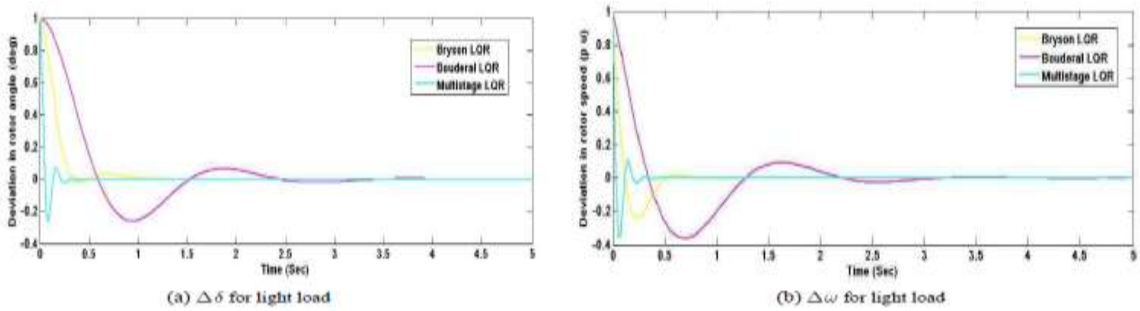


Figure 2. Rotor angle & rotor speed deviation responses

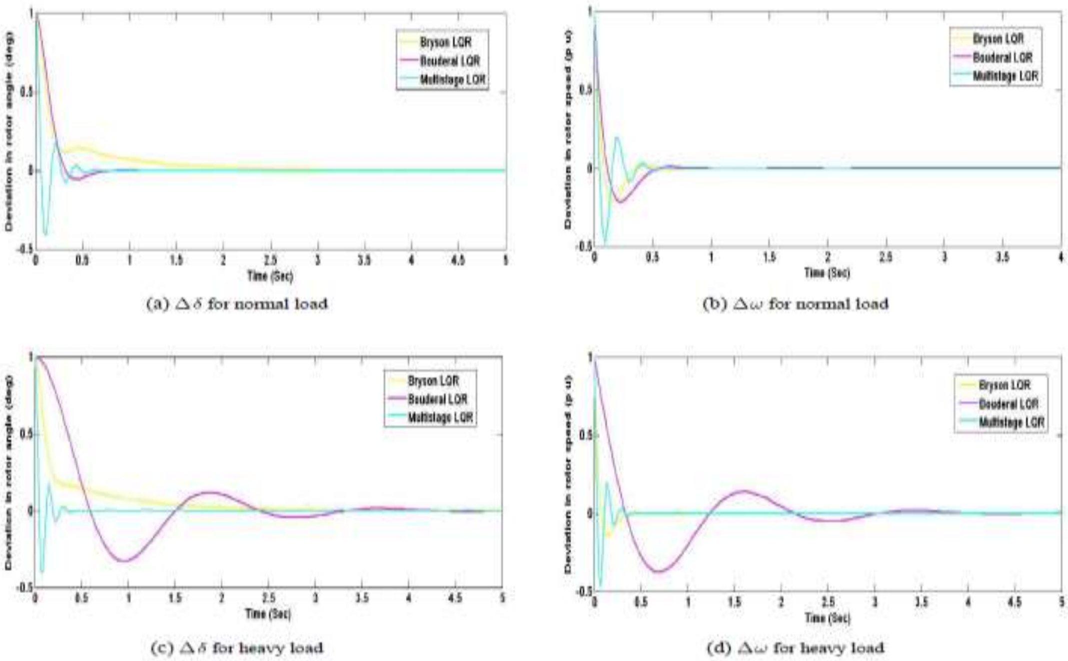


Figure 3. Rotor angle & rotor speed deviation responses

5. Switched Linear System

A switched system is a dynamical system that consists of a finite number of subsystems and a logical rule that orchestrates switching between these subsystems. Hybrid or switching systems, commonly found in control theory which are characterized by a combination of both continuous & discrete systems. The performance of these systems can be realized by switching between relatively two simple linear time invariant (LTI) systems with different control techniques (Santarelli & Dahleh, 2012), (Santarelli & Dahleh, 2009) & (Santarelli & Dahleh, 2010).

The advantage of switching between different feedback structures is to combine the useful properties of each structure and to introduce new properties that are not present in any of the structures used. A necessary and sufficient condition for stability of arbitrarily switched second order LTI systems with marginally stable subsystems is derived in (Huang, Xiang, Lin, & Lee, 2007). It turns out that the condition for the marginally stable case is similar with the one for asymptotically stable except boundary conditions are included. The performance based switching algorithm for LTI systems based on Lyapunov stability criteria was developed by (Aravena & Devarakonda, 2006). An adaptive neural network based Sliding Mode Control (SMC) for a power system stabilizer (PSS) of a single machine power system has been proposed in (Al-Duwaish & Al-Hamouz, 2011). The SMC is essentially a switching feedback control. Simulation results indicate that the controller performance is greatly improved by the use of adaptive SMC. The LTI switched system has found many applications in the areas such as aircraft, robotics, power system, etc. In the context of power system, switched system has very broad applications. Rapid development of cities and industries in the developed and developing countries, increases the demands for energy particularly in electricity. This causes the power systems to be operated near their stability limits. In addition, interconnection between remotely located power systems gives rise to low frequency oscillations in the range of 0.2 to 3.0 Hz. If not well damped, these oscillations may keep growing in magnitude until loss of synchronism results. In order to damp these power system oscillations and increase system oscillations stability, the installation of PSS & UPFC is both economical and effective.

A switched-linear system model for the current research is as follows (refer Figure 6):

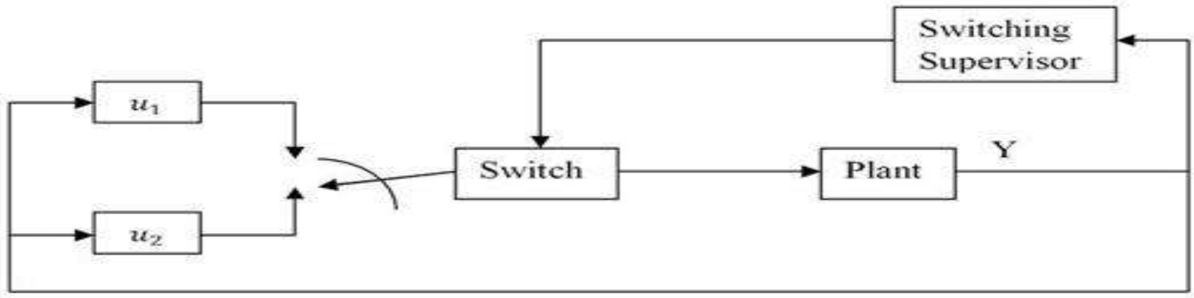


Figure 4. General switched linear system

$$\dot{x} = A_\sigma x(t) \qquad (9)$$

The switching signal $\sigma(t)$ indicates,

$$\begin{aligned} \dot{x}(t) &= A_1 x(t) = \quad if, \quad \sigma = 1 \qquad (10) \\ &= A_2 x(t) = \quad if, \quad \sigma = 2 \end{aligned}$$

$$A_1 = A - BK_1 \qquad (11)$$

$$A_2 = A - BK_2 \qquad (12)$$

The two optimized feedback controller gains K1 and K2 for the closed loop systems A1 & A2 are derived from any of the control theory. In the proposed research these controller gains are selected from the preliminary analysis of previous section (optimal control theory of LQR).

In addition to selecting these optimized controllers, it is proposed to implement an intelligent switching control algorithm that further improves the performance in peak overshoots and settling time along with further optimizes by minimizing the performance index, $J = \int_0^\infty y^2 dt$.

5.1 Switching Control Strategies

The switching control strategies are developed for all the operating conditions (light, normal & heavy loads) is experimented by considering the following cases:

Case I-Light Load- From, the preliminary analysis bryson & multistage LQR optimal feedback controllers provides better performance in peak overshoots & settling time appropriately. Switching between these two optimal feedbacks controllers are proposed for this case. The closed loop systems from Eq. 11 & 12 of K1 & K2 are the feedback controller gains of Bryson and multistage LQR.

Case II-Normal Load- The two closed loop feedback controller gains for this case are Bryson (K1) and Bouderal (K2) LQR (refer preliminary analysis).

Case III-Heavy Load In this case the preliminary analysis of three optimal controllers suggest to switch between Bryson (master control K1) and Bouderal (alternate control K2) optimal based LQR controllers for the proposed switching control strategy.

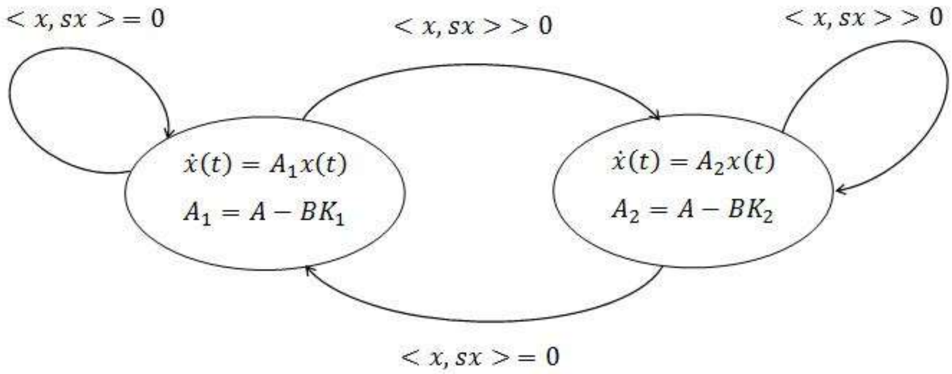
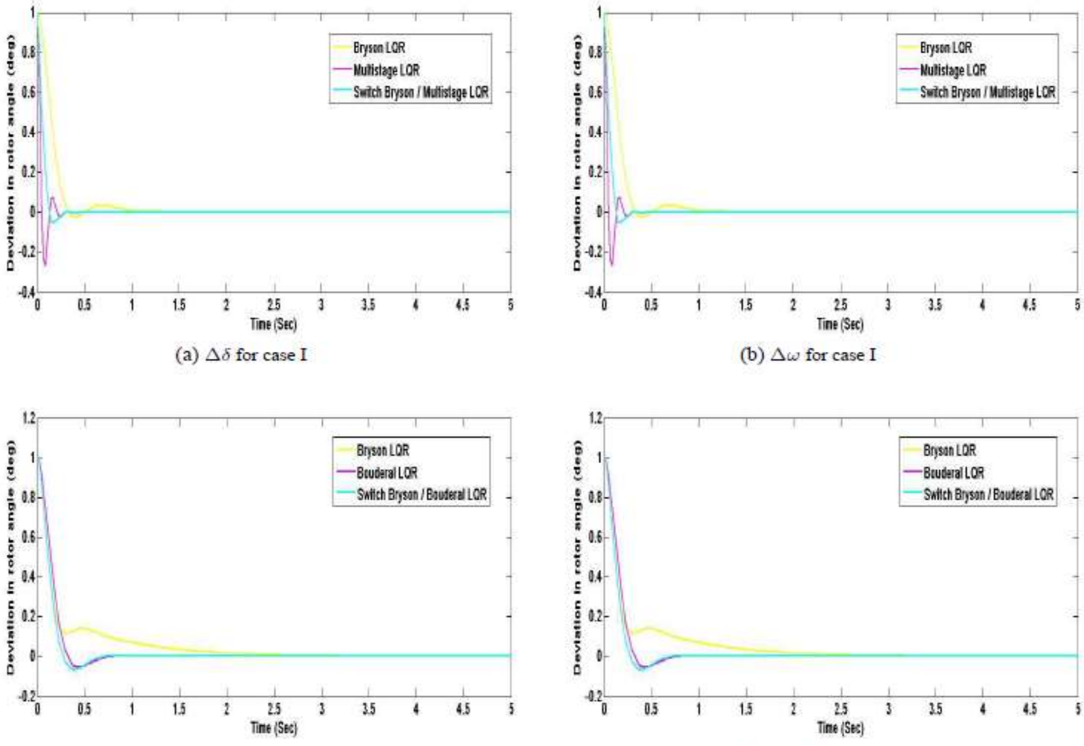


Figure 7. State diagram of switching algorithm between two closed-loop system

6. Simulation results of proposed switching control strategy for UPFC

To, validate the effectiveness of switching between two optimal controllers compared to individual optimal controllers simulations are carried for the state variables rotor angle deviation $\Delta\delta$ and rotor speed deviation $\Delta\omega$ for the operating conditions (light, normal & heavy loads). Figure 8 shows the dynamic response of state variables $\Delta\delta$ & $\Delta\omega$ for the case I and Case II, followed by case III dynamic plots in Fig 9. Switching signal responses for all the three cases are shown in Figures 10 and 11. Tables 5-7, display the comparison of Mp & Ts for all the cases.

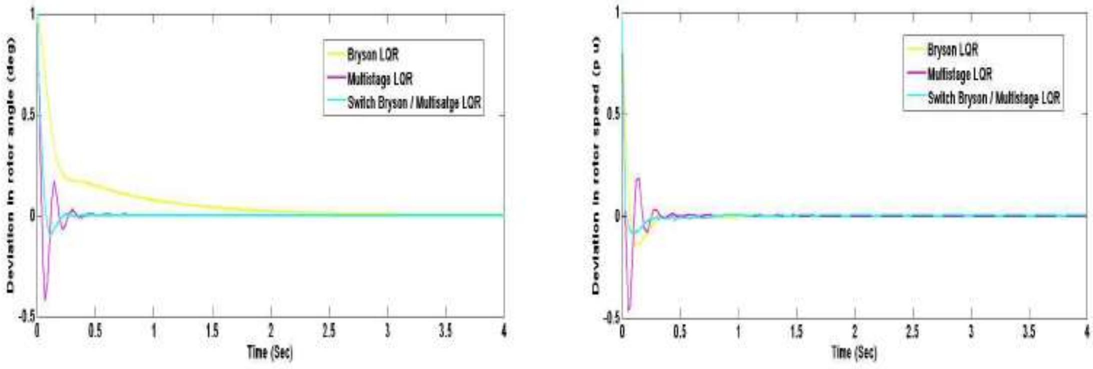
Simulation was done to control the state variables rotor angle deviation $\Delta\delta$ and rotor speed deviation $\Delta\omega$ using the UPFC control input δ_B with switching control concept for all the operating (light, normal & heavy loads) conditions. The discussions of the experimental set up of switching control strategy are explained for three stated cases (light, normal & heavy).



(a) $\Delta\delta$ for case I (b) $\Delta\omega$ for case I

(c) $\Delta\delta$ for case II (d) $\Delta\omega$ for case II

Figure 8. Rotor angle & rotor speed deviation response



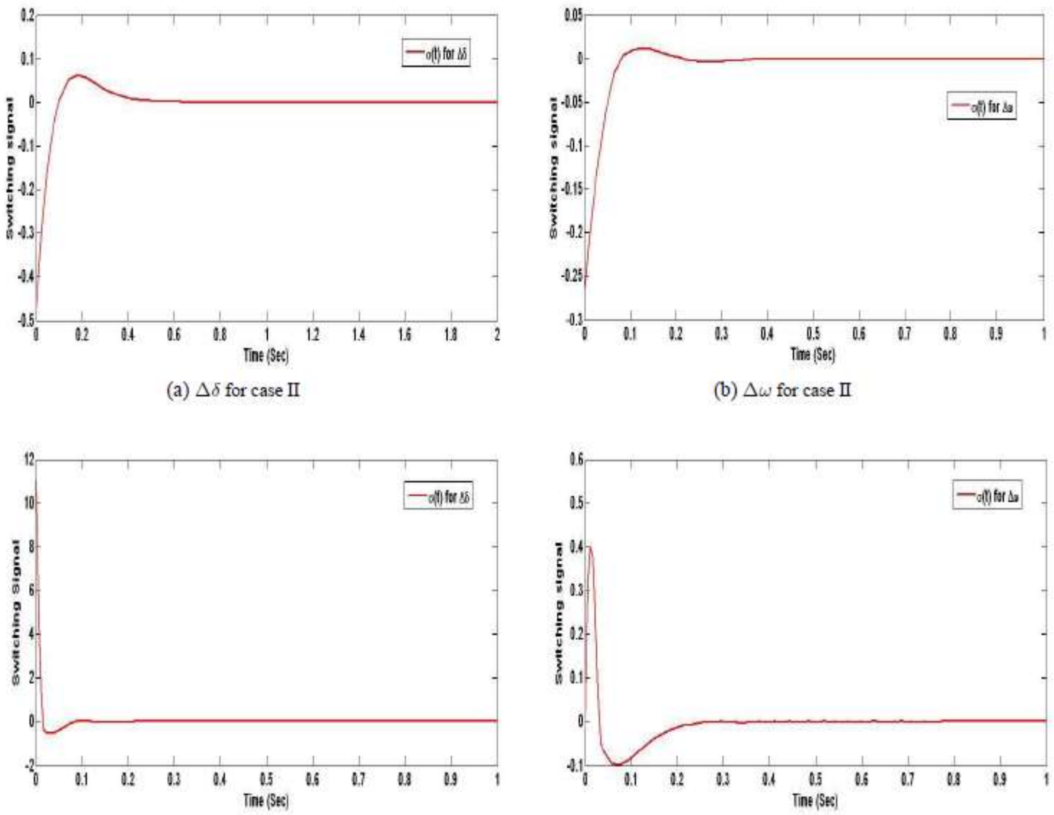
(a) $\Delta\delta$ for case III (b) $\Delta\omega$ for case III

Figure 9. Rotor angle & rotor speed deviation responses for case III

Case I: Fig 8 (a, b), shows the response and comparison of overshoot and settling time (Mp & Ts) for case I and it reveals that the switching between Bryson and multistage LQR optimal controllers provides better performance with respect to peak overshoots and settling time compared to individual Bryson and multistage optimal LQR.

Case II: Dynamic response curves and comparisons of overshoot and settling time (Mp & Ts) are shown in figure 8 (c, d) and Table 6. It concludes that switching between two optimal LQR controllers (Bryson & Bouderal) provides robust output performance compared to without switching control (individual optimal controllers).

Case III: The dynamic plots and comparison tables for overshoot and settling time (Mp & Ts) of case III, are shown in figure 9. It reveals that switching control strategy between two LQR (Bryson & multistage) feedback controllers show improvements in peak overshoots and settling time compared to without switching control strategy of LQR controllers.



(a) $\Delta\delta$ for case II (b) $\Delta\omega$ for case II

(c) $\Delta\delta$ for case III (d) $\Delta\omega$ for case III

Figure 5. Switching signal responses

7. Conclusion

In this paper, a UPFC has been used for dynamic stability improvement and state-space equations have been applied for the design of damping controllers. At each load condition, namely, low, normal and heavy, preliminary experiments have been carried out using three LQR (Bryson, Bouderal multistage) based optimal controllers, with an objective to select the two better candidate optimized feedback controllers. Based on the simulation results, their analysis and comparison the optimized feedback controllers selected at light load condition are Bryson and multistage LQR. Bryson and Bouderal LQR are selected for normal load operating condition. Lastly, for heavy load condition, Bryson and multistage LQR are selected. These optimal feedback controllers are selected in such a way that one is better at minimizing peak overshoots and other is better at minimizing settling time. After selecting the better optimized feedback controllers from the preliminary optimal control analysis, switching control strategy is implemented to switch between selected optimized feedback controller to achieve optimization between peak overshoots and settling time, and hence attaining overall improved output performance compared to individual optimal controllers.

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