

Design of Optimal Feedback Controllers for UPFC with Wide Range of Operating Conditions in Power System

Yathisha L¹ and Nandeesh S P²

¹ECE Department, ATMECE, Mysore

²ECE Department, GEC, K R Pet

Abstract—The following paper is based on the design of a multistage- LQR (Linear Quadratic Regulator) optimal controllers for an UPFC (Unified Power Flow Controller). It is aimed at providing mild, normal & heavy loads with huge range of running situations. The proposed controllers are applied and compared for the existing Phillips heffron model with UPFC installed using MATLAB/SIMULINK software.

Index Terms— Optimal Controllers, UPFC, Operating conditions, Control Strategies, Power System, LQR, FACT devices, Bryson, Bouderal, Multi stage.

I. INTRODUCTION

It may be said that not all Power system networks operate at a single operating condition but some power systems operates at multiple operating conditions because of continually varying load. (Yuang Shung & San Yung Sun et al. 2002) designed a STATCOM controller to damp the electromechanical mode oscillations in power system. The authors in (Anil Kumar Yadav & Hariom Rathaur et al. 2005) designed a STATCOM based stabilizer in order to improve power system oscillation stability of single machine infinite-bus system using MATLAB. (Gh. Shahgholian & S. Eshtehardiha et al. 2008) applied the genetic algorithm for design of LQR controller gains for the STATCOM dynamics to achieve the optimum dynamic response. (Shoorangiz Shams Shamsabad Farahani & Mehdi Nikzad et al. 2012) has shown an application where for using a static synchronous compensator (STATCOM) to provide voltage support and simultaneously damp Low Frequency Oscillations (LFO) in a Single-Machine Infinite- Bus (SMIB) power system that had been incorporated with a STATCOM. The results show that STATCOM can simultaneously control bus voltage and DC voltage. In (A Sagarika & T R Jyothsna et al. 2015) the authors attempted the usage of a single STATCOM incorporating enhanced damping of the low frequency swing mode for three machine system by using supplementary modulation controller to enhance the damping. (J Barati, A Saeedian & (S S Mortazavi et al. 2010) tested power system with severe disturbance for a STATCOM based stabilizers constituting Genetic Algorithms and under different loading conditions. The results of simulations show that the SSSC-based stabilizer provides a better effectiveness than the STATCOM-based stabilizer over damping power system oscillation. Also, both FACTS devices help in improvement of the system stability as well. The LQR feedback controllers designed in the above literature survey, for different loading conditions are with single LQR. In this paper, multi LQRs (Bryson, Bouderal & Multistage) approaches are designed for light, normal & heavy loads of three operating conditions and the consequences are in comparison to pick out the exceptional controllers for the right running circumstance.

II. POWER DEVICE MODELLING WITH UPFC

For the present investigations a Single Machine Infinite Bus (SMIB) system is considered. H. F. Wang (2000) has come up with a linearized Phillips Heffron Model which has UPFC installed for (SMIB) in power system, where a machine connected to a large system through a transmission line is reduced to a SMIB system. Its state-space formulation can be expressed as follows

$$\dot{x}(t) = Ax(t) + Bu(t) \quad [1]$$

Where, the state variables are the rotor angle deviation ($\Delta\delta$), speed deviation ($\Delta\omega$), field voltage deviation (ΔE_f) and q-axis component deviation (ΔE_q). A and B represent the system matrix and control input matrices respectively, given by

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 \\ \frac{k_1}{T'_{d0}} & 0 & -\frac{k_3}{T'_{d0}} & \frac{1}{T'_{d0}} \\ -\frac{k_A k_5}{T_A} & 0 & -\frac{k_A k_6}{T_A} & \frac{1}{T_A} \end{bmatrix}$$

The System has four input variables: modulating index and phase angle for shunt inverter (mE , δE) and the same parameters for series inverter namely (mB , δB).

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{k_{pb}}{M} & -\frac{k_{p\delta b}}{M} & -\frac{k_{pe}}{M} & -\frac{k_{p\delta e}}{M} \\ -\frac{k_{qb}}{T'_{d0}} & -\frac{k_{q\delta b}}{T'_{d0}} & -\frac{k_{qe}}{T'_{d0}} & \frac{k_{q\delta e}}{T'_{d0}} \\ -\frac{k_A k_{vb}}{T_A} & -\frac{k_A k_{v\delta b}}{T_A} & -\frac{k_A k_{ve}}{T_A} & -\frac{k_A k_{v\delta e}}{T_A} \end{bmatrix}$$

The relevant k-constants and also variables with their values which are used in the experiment are explained in the section of appendix at the end of the paper.

A. Problem Formulation

Numerical Values of matrices A and B for one-of-a-kind loading situations are as follows:

Light Load

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

$$B_L = \begin{bmatrix} 0 \\ 0.20 \\ 0.048 \\ 7.60 \end{bmatrix}$$

Normal Load

$$A_N = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.0168 & 0 & -0.1696 & 0 \\ -0.0393 & 0 & -0.484 & 0.1983 \\ 58.80 & 0 & -333.70 & -20 \end{bmatrix}$$

$$B_N = \begin{bmatrix} 0 \\ 0.7 \\ 0.1501 \\ 0.60 \end{bmatrix}$$

Heavy Load

$$A_H = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.0517 & 0 & -0.157 & 0 \\ -0.040 & 0 & -0.484 & 0.1983 \\ 66.1087 & 0 & -341.103 & -20 \end{bmatrix}$$

$$B_H = \begin{bmatrix} 0 \\ 0.20 \\ 0.10 \\ -10.1 \end{bmatrix}$$

TABLE I. LOADING CONDITIONS

Loading conditions	P in pu	Q in pu
Normal	1	0.015
Light	0.3	0.015
Heavy	1.1	0.4

For, those 3 exceptional loading conditions in strength system the closed loop manipulate gadget (A_α, A_β & A_γ) are given by

$$A_\alpha = A_L - B_L K_L \quad [2]$$

$$A_\beta = A_N - B_N K_N \quad [3]$$

$$A_\gamma = A_H - B_H K_H \quad [4]$$

In which, the feedback controller profits (K_L, K_N & K_H) are derived from gold standard manipulate concept of LQR by tuning the weighting matrices with one-of-a-kind methods (Bryson, Bouderal & Multistage).

III. PROPOSED OPTIMAL CONTROLLERS

The three different optimal controllers Bryson, Bouderal & Multistage of LQR are designed. For the sake of clarity, three different approaches of LQR are explained below:

1) **Bryson Rule:** Bryson rule was developed in 1975, where the weighting matrices Q & R are to be chosen as

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R = [1]$$

By applying this rule, the layout of LQR optimized comments controllers obtained for distinct loading situations are:

• **Light Load:**

$$K_L = [1.0730 \quad 63.1563 \quad -4.1411 \quad 0.0980]$$

• **Normal Load:**

$$K_N = [2.3957 \quad 110.9214 \quad -9.9935 \quad -0.0023]$$

• **Heavy Load:**

$$K_H = [2.9017 \quad 119.4919 \quad -12.0624 \quad -0.0877]$$

2) **Bouderal Rule:** Bouderal rule is advanced in 1964, in which the Q & R weighting matrices are to be chosen as

$$Q = C' * C \quad R = B' * B$$

From this rule LQR is designed the optimized feedback controllers are:

• **Light Load:**

$$K_L = [0.0612 \quad 15.1679 \quad -0.1256 \quad -0.0010]$$

• **Normal Load:**

$$K_N = [1.4728 \quad 80.8967 \quad -0.9352 \quad -0.0051]$$

• **Heavy Load:**

$$K_H = [0.0835 \quad 17.7889 \quad -0.3727 \quad -0.0029]$$

3) **Multistage Rule:** The technique of designing LQR is given by R K pandey in 2010. The design process is as follows:

1) **1st stage:** In this level the LQR is designed using Bryson based LQR.

$$[k1, s, e] = \text{lqr}(A, B, Q, R)$$

2) **2nd stage:** Choose Q1 & R1 matrices as

$$Q1 = \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R1 = [1]$$

Select, $A1 = A - (B * k1)$

$$[k2, s, e] = \text{lqr}(A1, B, Q1, R1)$$

3) 3rd stage: Choose $Q2$ & $R2$ matrices as

$$Q2 = \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R2 = [1]$$

Select, $A2 = A - (B * K2)$

$$[k3, s, e] = \text{lqr}(A2, B, Q1, R1)$$

4) 4th stage: Choose $Q3$ & $R3$ matrices as

$$Q3 = \begin{bmatrix} 1000 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R3 = [1]$$

Select, $A3 = A - (B * k3)$

$$[k4, s, e] = \text{lqr}(A3, B, Q1, R1)$$

After, the simulations carried for all the stages (Figures 1- 6), concludes that 4th stage multistage LQR provides better performance compared to the remaining stages of multistage LQR. The optimized feedback controllers of 4th stage for different operating conditions are:

• **Light Load:**

$$K_L = [31.4959 \quad 345.4671 \quad -0.1234 \quad 0.0230]$$

• **Normal Load:**

$$K_N = [24.4860 \quad 208.4555 \quad 0.5622 \quad 0.0216]$$

• **Heavy Load:**

$$K_H = [24.5182 \quad 195.4364 \quad 0.3714 \quad 0.0126]$$

IV. SIMULATION RESULTS OF PRELIMINARY ANALYSIS

To choose the higher optimized remarks controllers for the specified running conditions, simulations are carried for the three optimal LQR's. Figures 7-13, shows the responses of deviations in rotor angle ($\Delta\delta$) & rotor speed ($\Delta\omega$) for light normal and heavy loads. Tables II-VII, shows the contrast of Peak overshoots (M_p) and settling time (T_s).

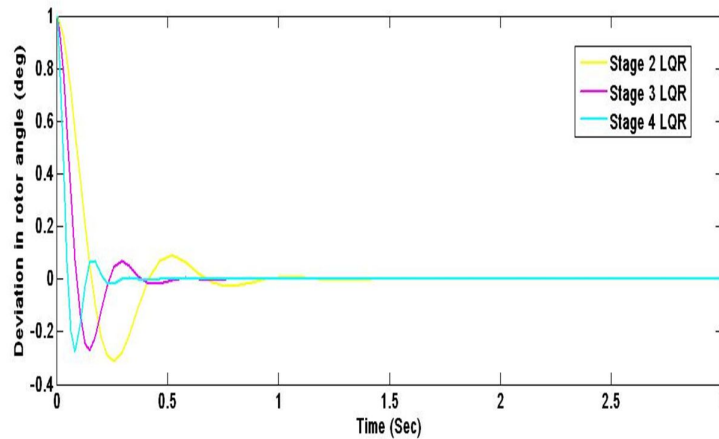


Figure 1. rotor angle deviation responses for light load

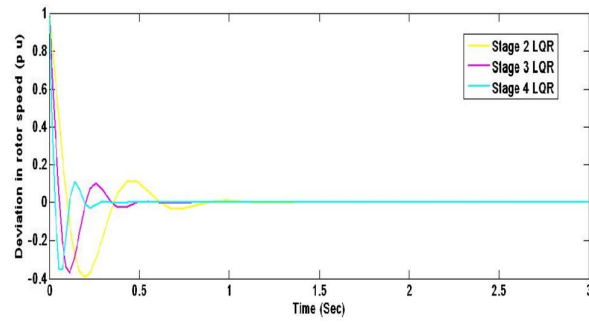


Figure 2. rotor speed deviation responses for light load

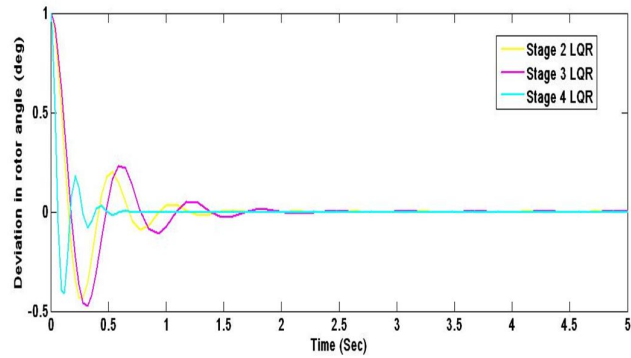


Figure 3. rotor angle deviation responses for normal load

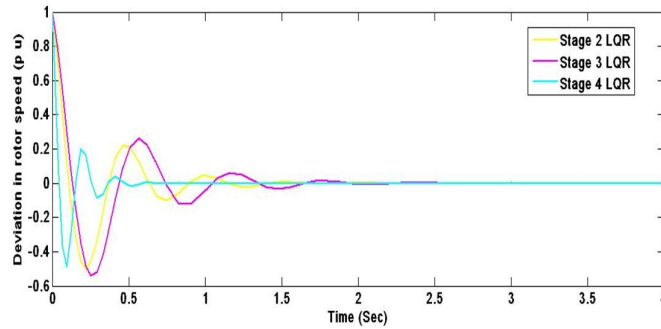


Figure 4. rotor speed deviation responses for normal load

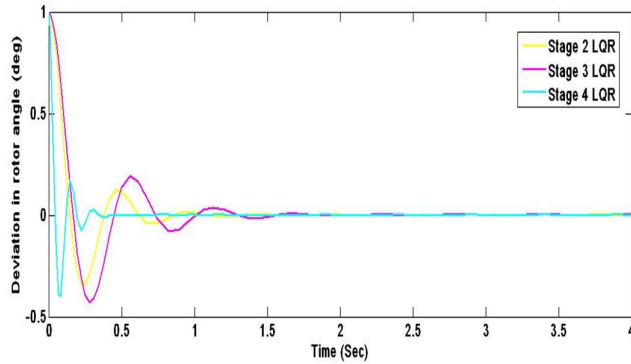


Figure 5. rotor angle deviation responses for heavy load

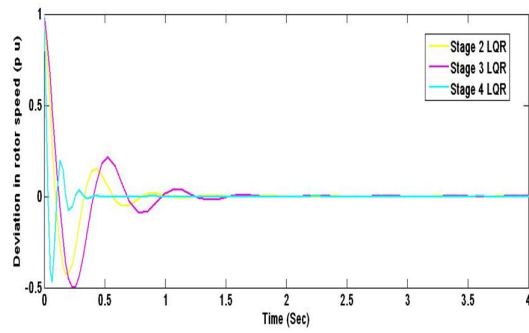


Figure 6. rotor speed deviation responses for heavy load

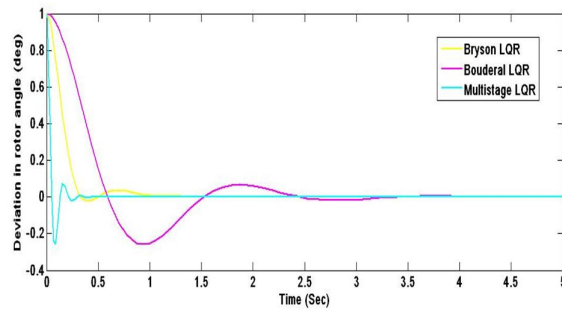


Figure 7. rotor angle deviation responses for light load

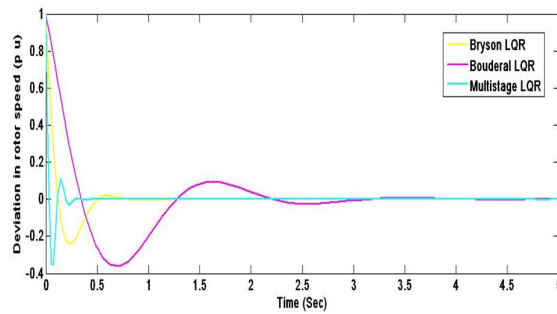


Figure 8. rotor speed deviation responses for light load

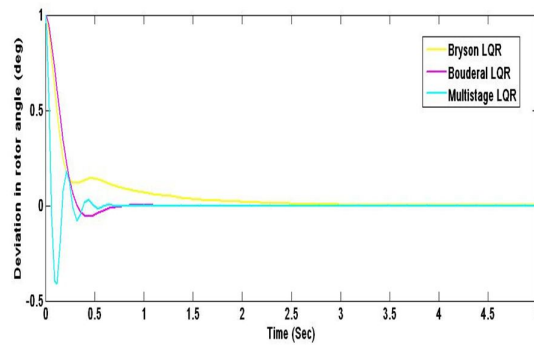


Figure 9. rotor angle deviation responses for normal load

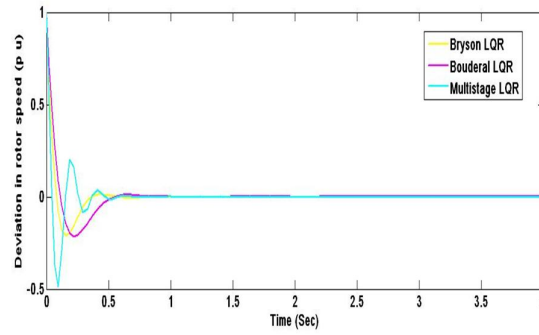


Figure 10. rotor speed deviation responses for normal load

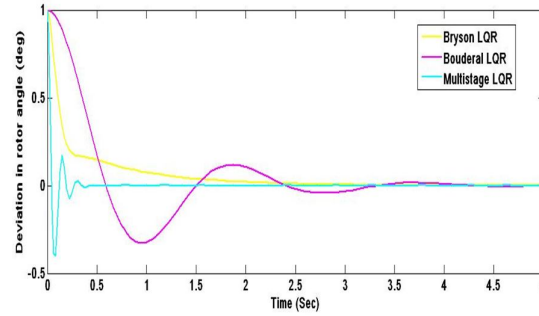


Figure 11. rotor angle deviation responses for heavy load

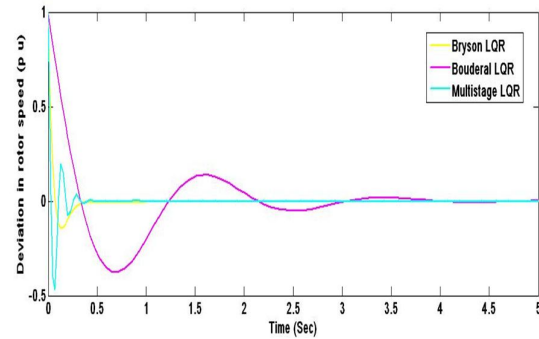


Figure 12. rotor speed deviation responses for heavy load

Figures 7-12 and Tables 2-7, reveals that for the light and heavy load operating conditions Bryson LQR provides properly reaction for peak overshoots (M_p) & multistage LQR gives strong overall performance for settling time (T_s). In normal load operating conditions also the Bryson LQR is better for peak overshoots but for the settling time bouderal LQR provides robust control.

TABLE II. COMPARISON OF M_p & T_s FOR $\Delta\Delta$ WITH DIFFERENT LQR APPROACHES FOR LIGHT LOAD

Optimal LQR controller	M_p	T_s
Bryson rule	-0.001	1s
Bouderal rule	-0.26	3.5s
Multistage rule	-0.25	0.4s

TABLE III. COMPARISON OF M_p & T_s FOR $\Delta\Omega$ WITH DIFFERENT LQR APPROACHES FOR LIGHT LOAD

Optimal LQR controller	M_p	T_s
Bryson rule	-0.25	0.9s
Bouderal rule	-0.38	3.5s
Multistage rule	-0.35	0.45s

TABLE IV. COMPARISON OF Mp & Ts FOR $\Delta\alpha$ WITH DIFFERENT LQR APPROACHES FOR NORMAL LOAD

Optimal LQR controller	Mp	Ts
Bryson rule	0	1.5s
Bouderal rule	-0.005	0.75s
Multistage rule	-0.4	1s

TABLE V. COMPARISON OF Mp & Ts FOR $\Delta\Omega$ WITH DIFFERENT LQR APPROACHES FOR HEAVY LOAD

Optimal LQR controller	Mp	Ts
Bryson rule	-0.2	0.6s
Bouderal rule	-0.2	0.55s
Multistage rule	-0.5	0.7s

TABLE VI. COMPARISON OF Mp & Ts FOR $\Delta\alpha$ WITH DIFFERENT LQR APPROACHES FOR HEAVY LOAD

Optimal LQR controller	Mp	Ts
Bryson rule	0	2s
Bouderal rule	-0.35	4s
Multistage rule	-0.4	0.4s

TABLE VII. COMPARISON OF Mp & Ts FOR $\Delta\Omega$ WITH DIFFERENT LQR APPROACHES FOR HEAVY LOAD

Optimal LQR controller	Mp	Ts
Bryson rule	-0.1	0.5s
Bouderal rule	-0.4	4.5s
Multistage rule	-0.45	0.5s

V. CONCLUSION

In this paper, Unified Power Flow Controller (UPFC) is used for improvement of dynamic stability and state-space equations is applied for the design of damping controllers to the multi operating conditions. Simulation results of three LQR (bryson, bouderal multistage) based optimal controllers has been carried out to pick out the better optimized comments controllers for the specified running conditions.

REFERENCES

- [1] Yang Shung Lee and San Yung Sun, "STATCOM Controller Design for Power System Stabilization with Sub-Optimal Control and Strip Pole Assignment", Electrical Power and Energy Systems, Elsevier Journal, Vol. 24, Issue 1, 2002, pp. 771-779.
- [2] Anil Kumar Y Aadv, Hariom Rathaur and Ambreesh K R, "Static Synchronous Compensator (STATCOM) Modeling for Power Oscillations Damping", International Journal of Scientific and Research Publications, Vol. 1, 2005, ISSN 2250-3153.
- [3] Gh. Shahgholian, S. Eshtehardiha, H. Mahdavi-Nasab, M.R.Yousefi, "A Novel Approach in Automatic Control Based on the Genetic Algorithm in STATCOM for Improvement Power System Transient Stability", 4th International IEEE Conference on Intelligent Systems, 2008.
- [4] Shoorangiz Shams Shamsabad Farahani, Mehdi Nikzad and Mohammad Bigdeli Tabar, "STATCOM Control using a PSO-Based IP Controller", Research Journal of Applied Sciences, Engineering and Technology, Vol. 4, Issue 7, 2012, pp. 768-774, ISSN: 2040-7467.
- [5] A Sagarika and T.R.Jyothsna, "Tuning of PSO Algorithm For Single Machine and Multi-machine Power System Using STATCOM Controller", International Research Journal of Engineering and Technology (IRJET), Vol. 2, Issue 4, 2015, pp. 175-182, ISSN: 2395-0056.
- [6] Damping Power System Oscillations Improvement by FACTS Devices: A Comparison between SSSC and STATCOM", World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering Vol. 4, No.2, 2010.