Application and Comparison of Optimal LQR Controllers for UPFC with wide range of Operating Conditions in Power System

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Abstract*: *This paper presents the design of Bryson, Bouderal & multistage-based totally Linear Quadratic Regulator (LQR) optimal controllers to the Unified Power Flow Controller (UPFC) for mild, normal & heavy loads to cowl 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.

***Keywords*: Optimal Controllers, UPFC, Operating conditions, Control Strategies, Power System.**

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I. Introduction

Power system network not always operate at single operating condition. Power system 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 a 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) presents the application of static synchronous compensator (STATCOM) in order to simultaneous voltage support and damping of Low Frequency Oscillations (LFO) at a Single-Machine Infinite-Bus (SMIB) power system installed with 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 applied a single STATCOM with its supplementary modulation controller to enhance the damping of the low frequency swing mode with three machine systems. (J Barati, A Saeedian & (S S Mortazavi et al. 2010) proposed STATCOM based stabilizers using Genetic Algorithms and tested on power systems with severe disturbance under different loading conditions. The results of simulations show that both FACTS devices help in improvement of the system stability and the SSSC-based stabilizer provides a better effectiveness than the STATCOM - based stabilizer over damping power system oscillation. 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 Modeling 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 systems, 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

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

Where, the state variables are the rotor angle deviation ($\Delta\delta$), speed deviation ($\Delta\omega$), field voltage deviation ($\Delta E\ fd$) and q-axis component deviation ($\Delta E0\ q$).A and B represent the system matrix and control input matrices respectively, given by

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ \frac{-k1}{M} & \frac{-D}{M} & \frac{-k2}{M} & 0 \\ \frac{-k1}{T'_{d0}} & 0 & \frac{-k3}{T'_{d0}} & \frac{1}{T'_{d0}} \\ \frac{-k_A k_5}{T_A} & 0 & \frac{-k_A k_6}{T_A} & \frac{1}{T_A} \end{bmatrix}$$

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).

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

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.

III. Problem Formulation

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

A. *Light Load*

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

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

B. *Normal Load*

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

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

C. *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 1. 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 the gold standard manipulate concept of LQR by tuning the weighting matrices with one-of-a-kind methods (Bryson, Bouderal & Multistage).

IV. 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

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

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

- Light Load:
  K_L = [1.0730 63.1563 −4.1411 0.0980]
- Normal Load:
  K_N= [2.3957 110.9214 −9.9935 −0.0023]
- Heavy Load:
  K_H = [2.9017 119.4919 −12.0624 −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 R=B'*B

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

- Light Load:
  K_L= [0.0612 15.1679 −0.1256 −0.0010]
- Normal Load:
  K_N= [1.4728 80.8967 −0.9352 −0.0051]
- Heavy Load:
  K_H = [0.0835 17.7889 −0.3727 −0.0029]

3. Multistage Rule: The technique of designing LQR is given by R K pandey in 2010. The design process is as follows:
   a. 1st stage: In this level the LQR is designed using Bryson based LQR.
      [k1, s, e] = lqr (A, B, Q, R)
   b. 2nd stage: Choose Q1 & R1 matrices as

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

Select, A1 = A − (B ∗ k1)
[k2, s, e] = lqr (A1, B, Q1, R1)

   c. 3rd stage: Choose Q2 & R2 matrices as

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

Select, A2 = A − (B ∗ K2)
[k3, s, e] = lqr (A2, B, Q1, R1)

   d. 4th stage: Choose Q3 & R3 matrices as

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

Select, A3 = A − (B ∗ k3)
[k4, s, e] = 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 345.4671 −0.1234 0.0230]

• Normal Load:

K_N = [24.4860 208.4555 0.5622 0.0216]

• Heavy Load:

K_H = [24.5182 195.4364 0.3714 0.0126]

V. Simulation Results Of Preliminary Analysis

To choose the higher optimized remark controllers for the specified running conditions, simulations are carried out for the three optimal LQR's. Figures 7-13, shows the responses of deviations in rotor angle (Δδ) & rotor speed (Δω) for light normal and heavy loads. Tables II-VII, shows the contrast of

Peak overshoots (M_P) and settling time (T_S).

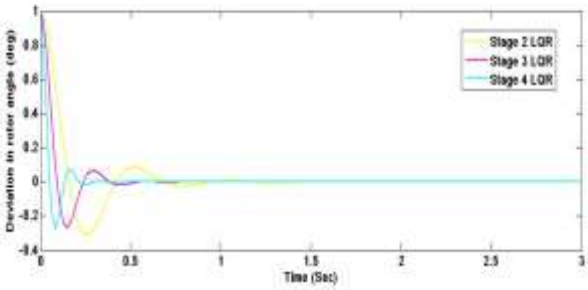

Figure 1. Rotor angle deviation responses for light load

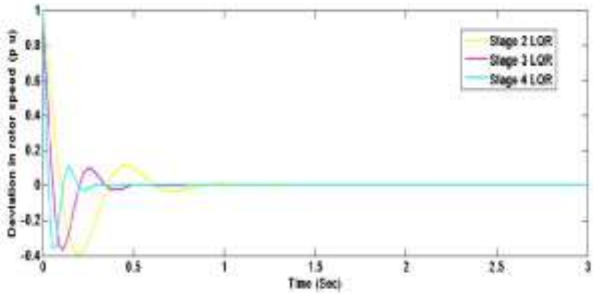

Figure 2. Rotor speed deviation responses for light load

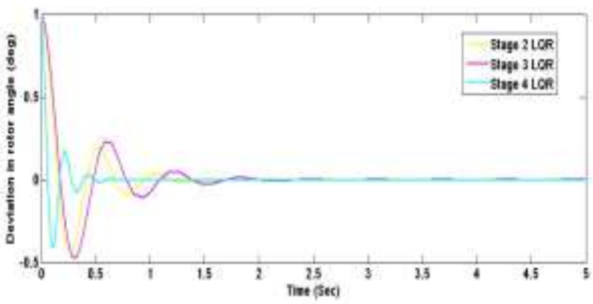

Figure 3. Rotor angle deviation responses for normal load

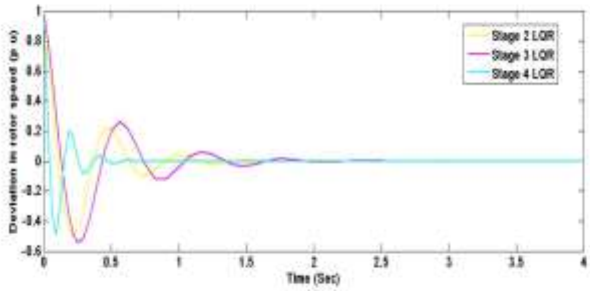

Figure 4. Rotor speed deviation responses for normal load

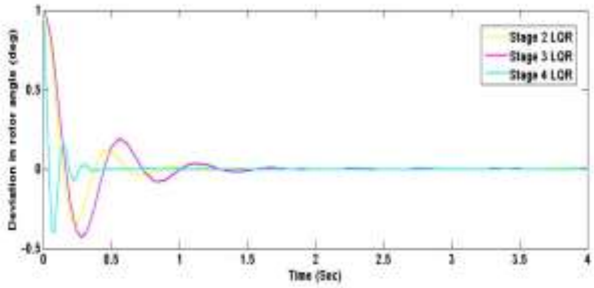

Figure 5. Rotor angle deviation responses for heavy load

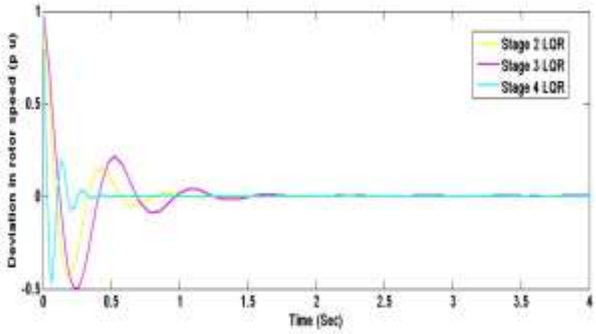

Figure 6. Rotor speed deviation responses for heavy load

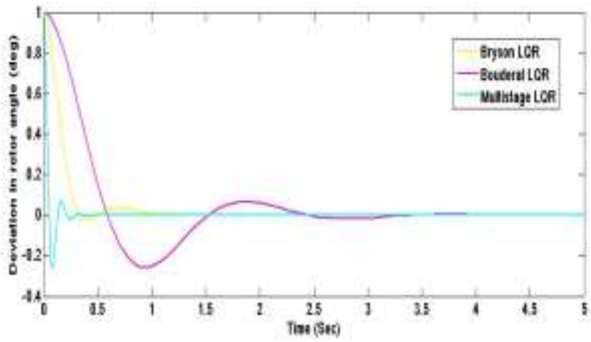

Figure 7. Rotor angle deviation responses for light load

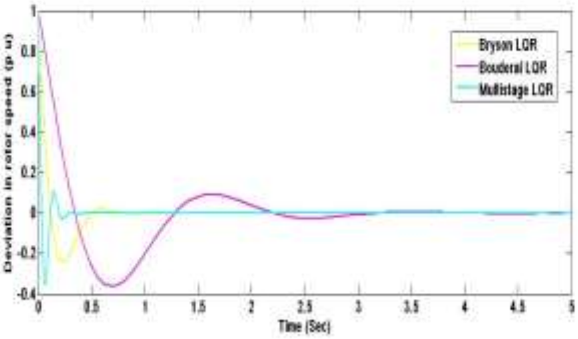

Figure 8. Rotor speed deviation responses for light load

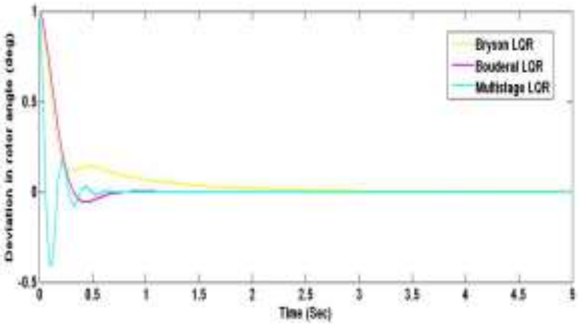

Figure 9. Rotor angle deviation responses for normal load

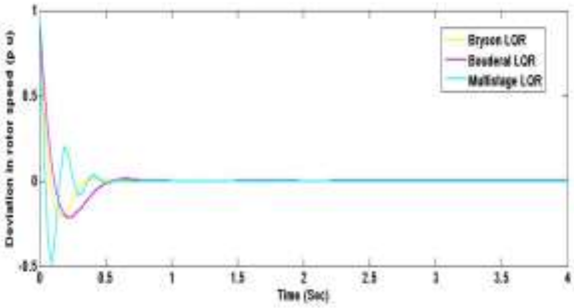

Figure 10. Rotor speed deviation responses for normal load

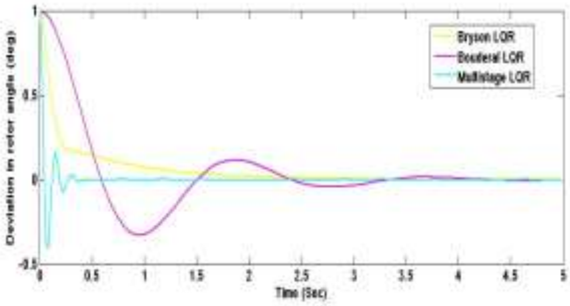

Figure 11. Rotor angle deviation responses for heavy load

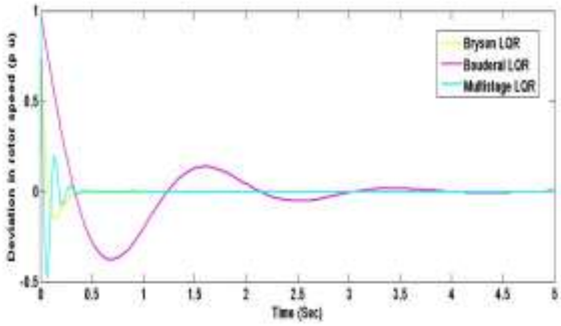

Figure 12. Rotor speed deviation responses for heavy load

Figures 7-12 and Tables 2-7, reveals that for the light and heavy load operating conditions Bryson LQR provides proper reaction for peak overshoots (Mp) & multistage LQR gives strong overall performance for settling time (Ts). 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 2. Comparison of *Mp* & *Ts* for Δδ with different lqr approaches for light load

Optimal LQR controller	*Mp*	*Ts*
Bryson rule	-0.001	1s
Bouderal rule	-0.26	3.5s
Multistage rule	-0.25	0.4s

Table 3. Comparison of *Mp* & *Ts* for Δω with different lqr approaches for light load

Optimal LQR controller	*Mp*	*Ts*
Bryson rule	-0.25	0.9s
Bouderal rule	-0.38	3.5s
Multistage rule	-0.35	0.45s

Table 4. Comparison of Mp & Ts for Δδ 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 5. Comparison of Mp & Ts for Δω 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 6. Comparison of Mp & Ts for Δδ 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 7. Comparison of Mp & Ts for Δω 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

VI. 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.

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