Modelling and Simulation: A Comparison of LQR Control and Unified Power Flow Controller for Dynamic Stability Improvement

Rahmaniar[1], Agus Junaidi[2], Rudi Salman[3], Ganefri[4], Abd. Hamid K[5], Jalius Jama[6], Nizwardi Jalinus[7]

[1] Department of Electrical Engineering Faculty of Engineering, Universitas Pembangunan Pancabudi (UNPAB), Indonesia.

[2,3,5] Faculty of Engineering, Universitas Negeri Medan (UNIMED) Indonesia.

[4,6,7]Faculty of Engineering, Universitas Negeri Padang (UNP), Indonesia.

[1]ORCID: 0000-0001-6667-4030, [2]ORCID 0000-0002-2681-864X

Abstract

Improved dynamic stability of the Single Machine Infinite Bus (SMIB) system can be done with UPFC control and LQR Control. This study examines the use of optimal control and Unified Power Flow Controller (UPFC) devices to improve the stability of the SMIB system. The SMIB system is a single generator connected to an infinite-bus. The SMIB system model is made in the form of a state-space variable equation, then compiles the Riccati matrix equation to determine the gain optimal in the Linear Quadratic Regulator (LQR) control system. The input of the optimal gain amplifier is obtained from the angle of swing ($\Delta\delta$) and the rotor speed ($\Delta\omega$), as well as the internal voltage (Vt) and the voltage change at the anchor. The output of the LQR control is injected on the excitation system of the SMIB model. The LQR control system is compared to the UPFC control system. The UPFC device is installed on the transmission line. UPFC was formed in a new mathematical equation model of injection. The UPFC injection model controls the Pi and Pj power parameters (Power injected on bus-i and bus-j). Installation of the UPFC device is used to test the repair of oscillation of the electric power system. Comparison between systems in an open loop and closed loop state (using LQR and UPFC controls) is made using Simulink. The performance of the open-loop and closed loop systems, namely the observation of oscillation changes in the rotor angle is used in determining the level of repair of system oscillation attenuation. From the tests conducted, it can be seen that the use of UPFC is better than the LQR control in reducing over-shoot and reducing oscillation changes in the rotor angle to reach the steady state.

Keyword: LQR, UPFC, SMIB, Dynamic Stability

1. INTRODUCTION

 The electric power system is an electrical element structure consisting of generating units, transmission lines and loads. In operating a network of electric power systems often experience interruptions that are transient or permanent disturbances [1]. Unit Generators can be interrupted due to sudden changes in load or shut-down generating units that affect changes in system variables such as voltage and frequency. These variable changes will affect stability in the electric power system [2,3]. Dynamic stability in electric power systems can be defined as the state of the electrical power system to maintain synchronization or balance of the system due to interference. Stability studies are needed for analysis of the system to work effectively. To study dynamic stability in electric power systems, mathematical modelling of components such as generators, transmission lines and loads is used. Mathematical modelling is formed from the linear differential equation to represent system dynamics [4-6]. Various studies have been carried out to reduce dynamic stability with the device and the Power System Stabilizer (PSS) and optimal control method to repair system oscillations effectively and economically [7,8].

The implementation of the LQR control system applied to the SMIB system can correct system oscillations when experiencing interference. The SMIB model is formed to determine the weighting matrix at an optimal gain. The concept of LQR control can be applied to dynamic stability studies [9]. Utilization of the Unified Power Flow Controller (UPFC) is used to control dynamic oscillations on the SMIB system. The proposed concept with the control algorithm is separated from the two UPFC series voltage variables, which are quadrature and phase by current injection for each with active and reactive power. The paper submitted presents beneficial information about how to use the UPFC to improve the dynamic stability of the power system. Relationships that inherently imply a coordinated control system of active and reactive power. Implementation of UPFC in the SMIB system with a choice of input signals from active power and reactive power. Feedback control of UPFC to test engine speed oscillation and rotor angle [10].

In this paper, the LQR control test is proposed compared to the UPFC injection model in the electric power system. The comparison is intended to obtain results from the use of LQR controls with the UPFC injection model in improving the dynamic power system oscillation

2. LQR MODEL

Linear time invariant system can be expressed by the variable vector state x (t), vector variable input u (t), observation vector y (t), matrix state variable (A) and input variable matrix (B), while variable observation matrix (C) stated in the equation [8]:

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

$$y\,(t) = Cx(t) \qquad (2)$$

The effort to optimize a system is to find the price of a performance index with the least value, written in the equation:

$$J(t_0) = \Phi(x(T), T) + \int_{t_0}^{T} L(x, u, t) dt \qquad (3)$$

The equation for controlling optimal feedback is:

$$-\dot{S} = A^T S + SA - S BR^{-1}B^T S + Q \qquad (4)$$

Gain Kalman, written in the equation:

$$K(t) = R^{-1}B^T S(t) \qquad (5)$$

With Control Signals

$$U(t)^o = -K(t)x(t) \qquad (6)$$

For problems with a steady state (Steady-state), then the value of S (t) will go to one point so that the price is zero. In this case, the Riccati solution will be the Riccati algebraic equation

$$0 = A^T S + SA - SBR^{-1}B^T S + Q \qquad (7)$$

If A and B are controlled parametric, A and C are observed then Q > 0, and R > 0, the system will be asymptotically stable. In the form of a block diagram, the LQR system can be shown in figure 1.
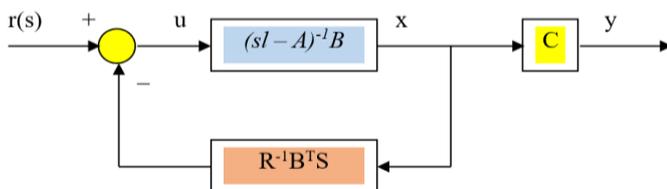

Fig 1. LQR feedback system modelling

3. UPFC MODEL

UPFC is reliable equipment because it can control the voltage of a bus and the power flow for optimal system operation. The advantages of UPFC because there are two switching converters. Two converters are connected using DC links, while Series inverters are connected to a transmission line through a series of transformer devices, while a shunt inverter is connected to a bus that wants to be controlled through a shunt transformer. Shunt inverters can generate or absorb reactive power and can provide active power to series transformers. While the functions of the series inverter in the UPFC circuit are related to voltage regulation.

The control system based on the system control function is divided into two parts, namely, internal control (converter) and functional operational control (function operation). Internal controls provide performance to both converters to produce the desired voltage injection and parallel reactive currents. Internal controls produce a gate signal to the converter valve so that the inverter's output voltage will respond to the ipRef frequency variable and by the first control structure.

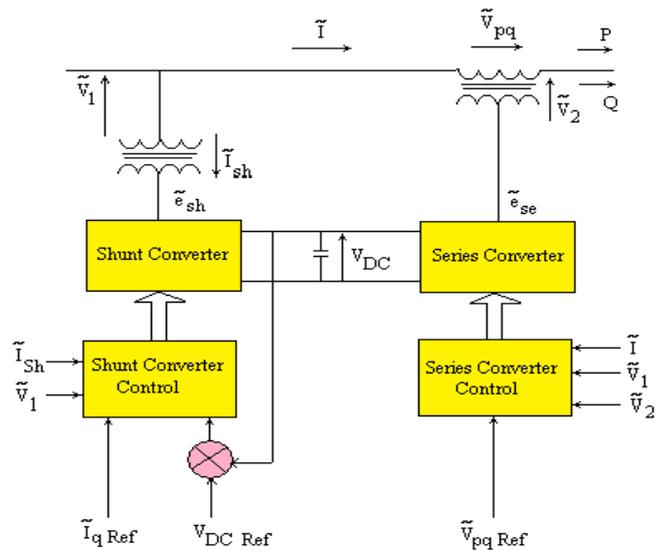The UPFC control structure is shown in figure 2

Fig. 2. UPFC Basic Control Model

In the series converters respond to requests for voltage vector injection, while parallel converter circuits operate on a closed-loop control structure that can control the active and reactive power parameters in the transmission network in electricity. Parallel reactive power responds directly to DC input requests. Parallel active power received by another control loop serves to maintain the voltage level of the dc capacitor and provides the active power needed to inject series voltage into the controlled system. The overall control structure shows internal controls and functional operation controls for the UPFC tool shown in Figure 3.
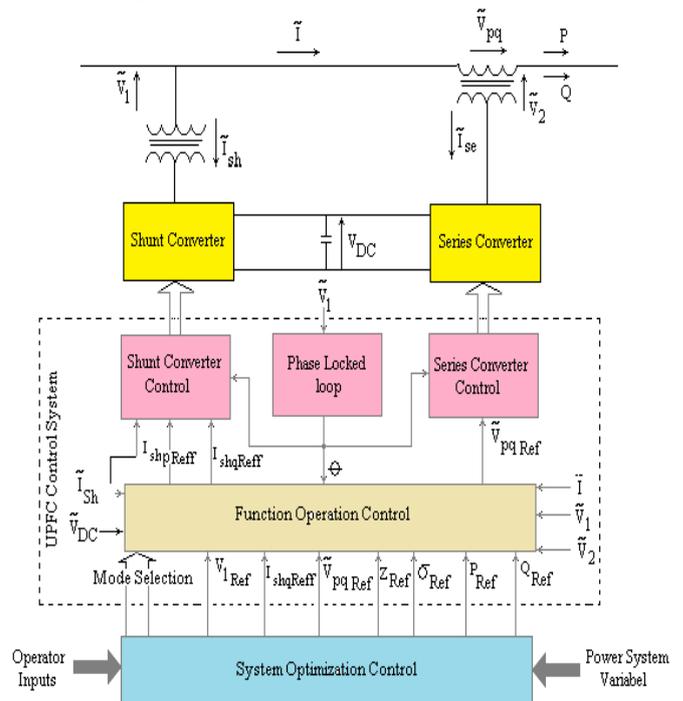

Fig. 3: UPFC Control Structure

Functional control is the operating mode of the UPFC function and the response to generate V_{pqRef} and Iq_{Ref} current internal

voltage references as part to compensate for series and parallel that meet the requirements of the transmission system. Functional operation modes and compensation requirements are explained by external reference inputs, can be done manually by the operator or can be done automatically through an optimal control system.

4. UPFC injection model

The control unit of the UPFC device on the power system begins with an analysis of the series voltage converter (VSC) injection model as the primary function of UPFC control. The concept of the equivalent circuit of the UPFC injection model is shown in Figure 4.
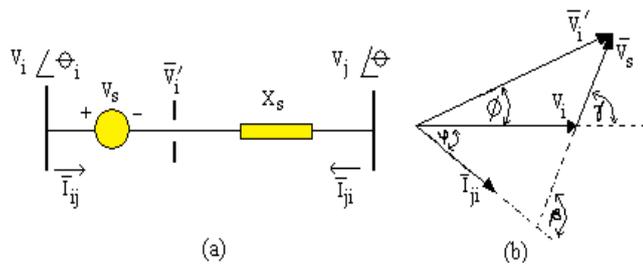

Fig 4.a: Representation of series VSC, b. Vector Diagram of VSC equivalent circuit

V_S voltage is placed between bus-i and bus-j on the power system. The UPFC series voltage converter can be modelled with the ideal series voltage with reactance Xs, as shown in Figure 5.a. On the bus-i side with a voltage equal to $V_i \angle \theta_i$, while on the j-bus, the voltage is $V_j \angle \theta_j$, [11].

$$\overline{V}_i{}' = \overline{V}_s + \overline{V}_i \qquad (8)$$

Series voltage sources that can be controlled for magnitude and phase angles are written in the equation

$$\overline{V}_s = r\overline{V}_i e^{j\gamma} \qquad (9)$$

The magnitude and phase angle settings are influenced by the time constants and reinforcement, as given in Figure 5 [8].
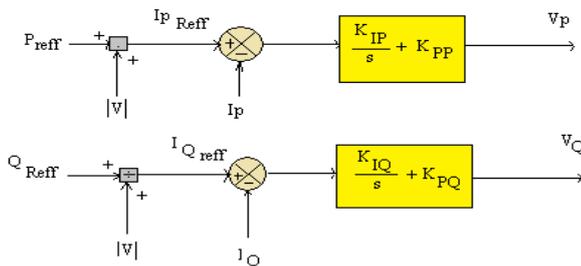

Fig. 5. Block Inverter power control of the UPFC series.

The limit of r as the voltage between the stresses on the i-bus (V_i) and the inject voltage (V_s) is $0 < r < r_{maks}$ and the controlled phase angle is $0 < \gamma < 2\pi$. The injection model is equipped with a voltage source with parallel The injection model is equipped with a voltage $\overline{V}_s$ in the current sources $\overline{I}_s = -jb_s\overline{V}_s$ and parallel with $b_s = \dfrac{1}{X_s}$ is given in fig. 6
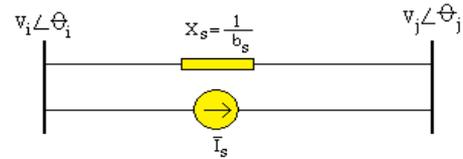

Fig 6: Voltage equivalent circuit with current source.

The current source ($\overline{I}_s$) is related to the injection power $\overline{S}_{is}$ and $\overline{S}_{is}$:

$$\overline{S}_{is} = \overline{V}_i(-\overline{I}_s)^* \qquad (10)$$

$$\overline{S}_{js} = \overline{V}_j(\overline{I}_s)^* \qquad (11)$$

Power injection $\overline{S}_{is}$ and $\overline{S}_{js}$ written in the form of the equation as:

$$S_{is} = \overline{V}_i[jb_s r\overline{V}_i e^{j\gamma}]^*$$
$$= -b_s r\overline{V}_i{}^2 \sin\gamma - jb_s r\overline{V}_i{}^2 \cos\gamma \qquad (12)$$

if it is defined $\theta_{ij} = \theta_i - \theta_j$, it will be obtained;

$$S_{sj} = \overline{V}_j[-jb_s r\overline{V}_i e^{j\gamma}]^*$$
$$= b_s r V_i V_j \sin(\theta_{ij}+\gamma) + jb_s r \cos V_i V_j \sin(\theta_{ij}+\gamma) \qquad (13)$$

The injection model of a series connected voltage source can be seen as two interconnected loads as shown in figure 7
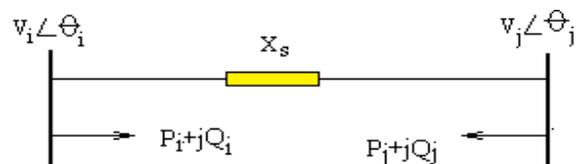

Fig. 7. Injection model for VSC series connection

Mathematically equations power injection on bus-i and bus-j;

$$P_{si} = rb_s V_i^2 \sin\gamma \qquad (14)$$

$$Q_{si} = rb_s V_i^2 \cos\gamma \qquad (15)$$

$$P_{sj} = -rb_s V_i V_j \sin(\theta_{ji}+\gamma) \qquad (16)$$

$$Q_{sj} = -rb_s V_i V_j \sin(\theta_{ij}+\gamma) \qquad (17)$$

P_{si} and Q_{si} are each Active and Reactive power of the bus-i injection while the P_{sj} and Q_{sj} are the Active and Reactive power of the bus-j injection, respectively.

Single Machine Infinite Bus (SMIB)

Single Machine Infinite Bus (SMIB) is a model of an electric power system consisting of a simultaneous machine connected to an infinite bus through a transmission line. G simultaneously

symbolizes the machine, the value of resistance and reactance (R and X) with the value of the bus voltage (Vb) shown in figure 8
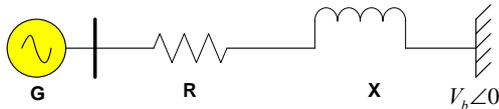

Fig. 8. SMIB Model

The SMIB model is structured in state space equations [12]

$$\begin{bmatrix} \Delta \dot{\delta} \\ \Delta \dot{\omega} \\ \Delta \dot{E_q} \\ \Delta \dot{E} fd \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\dfrac{K_1}{M} & -\dfrac{D}{M} & -\dfrac{K_2}{M} & 0 \\ -\dfrac{K_4}{T'_{d0}} & 0 & -\dfrac{1}{T'_{d0}K_3} & \dfrac{1}{T'_{d0}} \\ -\dfrac{K_A K_5}{T_A} & 0 & -\dfrac{K_A K_6}{T_A} & -\dfrac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{K_A}{T_A} \end{bmatrix} [u_E]$$

The state space equation, described in the block diagram scheme as a model for the SMIB model simulation in the experiment. The SMIB model is shown in figure 9[13].
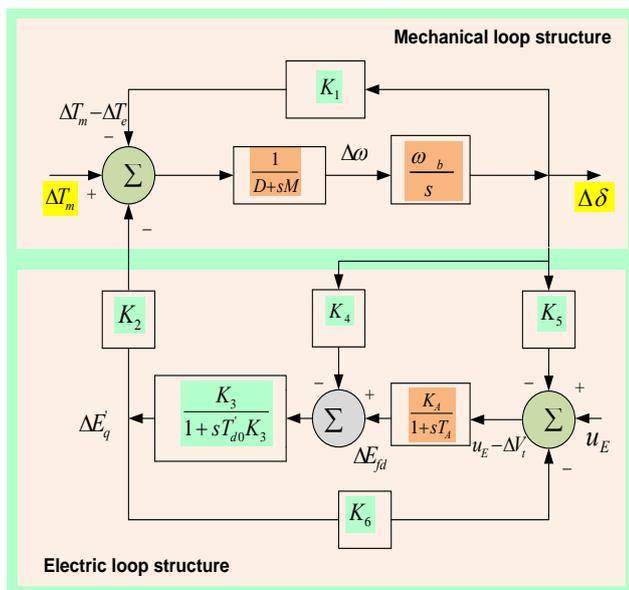

Fig. 9. SMIB Model Diagram

5. EXPERIMENT SIMULATION
5.1.SMIB System Using LQR Control

The LQR Control Model is designed to obtain optimal gain. Optimal amplifiers with amplifiers G1, G2, G3 and G4 applied to the excitation system with the model shown in Figure 9, and the model shows a generator connected to an infinite bus controlled with an optimal amplifier. The simulation uses the Matlab Simulink tool to observe the system's performance when experiencing interference.

The state-space model in the SMIB system for the values of A and B matrices is used to solve the magnitude of the gain in LQR. Calculation of K values using the m-file program. In calculating the K value, it is necessary to determine the

weighting matrix Q, and R. After the tuning process of Q and R is done, the weighted values of Q and R are obtained with the best output. The matrix values Q and R for the SMIB model are [2.4755, -0.9697, 0.6416, 6.0585]. The optimal gain value is the output of the LQR controller to enter on the SMIB system described in the Simulink model, figure 10.
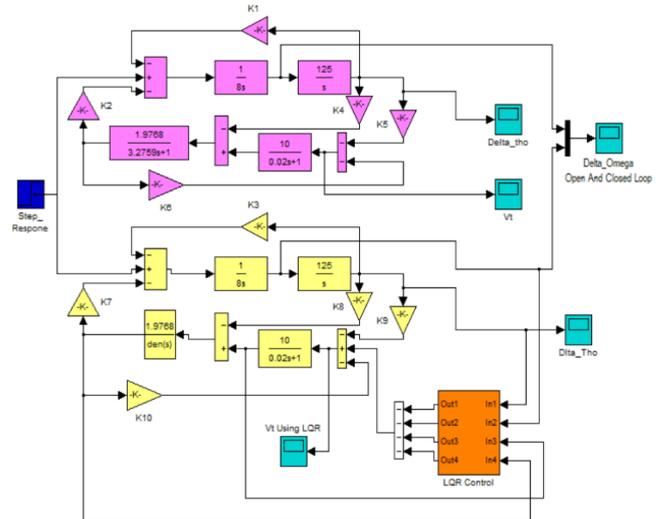

Fig. 10. The LQR Control Model

5.2. Simulation Using Injected UPFC Model

The UPFC injection parameters are given on the transmission line, with the injection block model as shown in figure 11
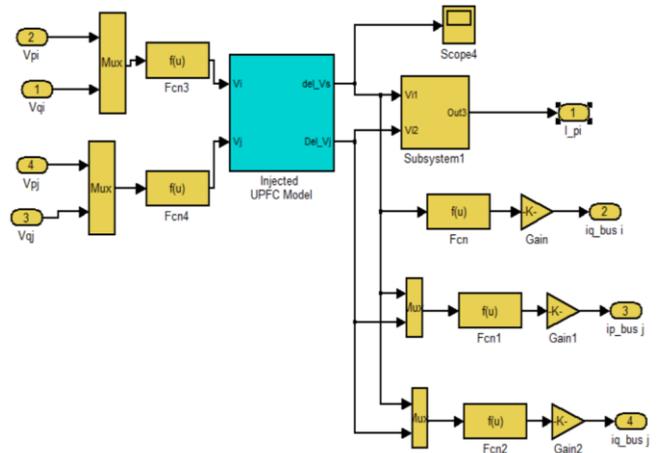

Fig. 11. Injected UPFC Model

6. SIMULATION RESULTS AND DISCUSSION

The simulation results using the Matlab software were carried out to test the performance of the power system when given a step response as a dynamic system disturbance. Simulations carried out at several stages include: (1). The system is in an uncontrolled condition (Open loop) (2) The system is controlled with LQR control and (3) Controlled System with UPFC Injection model. When given interference with the step response in the simulation. There is an open loop state of the electric power system experiencing oscillation and reaches a

stable state (steady state) at 25 seconds. Installation of UPFC, swings due to interference can be dimmed at 4 seconds, while the use of LQR controls, system dynamic oscillation can be muted at 20 seconds, as shown in figure 12.
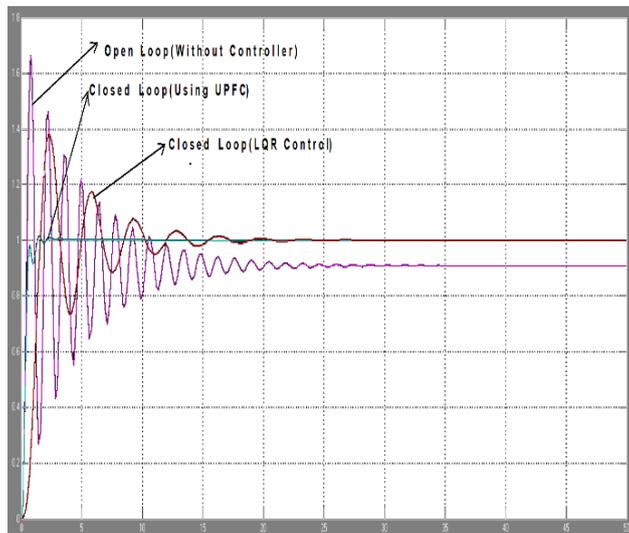
Fig. 12. Comparison of simulation results

The simulation results to observe the performance between the use of LQR controls with UPFC Control are shown in figure x. From the simulation results can be found the system performance. Use of LQR controls Oscillation changes Δω stable at 15 seconds when using UPFC oscillation oscillations Δω stable at 5 seconds, as shown in figure 13
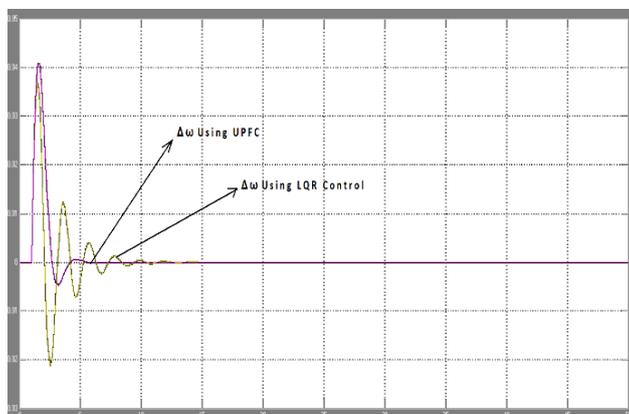
Fig. 13. Comparison of Response of Δω Using UPFC Controls and LQR Controls

Dynamic improvement of the electric power system as studied [14]. FACTS devices such as the UPFC including STATCOM on electric power systems have the ability to maintain the reliability of electric power systems, through the installation of these devices on the transmission line [15]. LQR Control Systems have the ability to control unstable system oscillations [16]. The use of LQR can improve the performance of the electrical power system. The test was carried out on the two areas of the Phillips-Heffron model system. From the trials conducted using LQR models can control the dynamic power system oscillations.

6. CONCLUSION

From the results of experiments and simulations using the Matlab Simulink device, it can be seen that the utilization of LQR and UPFC controls can reduce the oscillation of the electric power system due to interference. An open-loop electrical power system when given a step response as a dynamic disturbance, results in a damped oscillation at 25 seconds. LQR control is installed to reduce oscillation. LQR control can correct system oscillations, and from the system testing it reaches a stable state in 15 seconds, while the UPFC control, the method returns to stable at 4 seconds. The simulation results it can be concluded that UPFC has reliability in reducing the oscillation of electric power systems when the system is disrupted. Oscillation reduction where the system can be stabilized with UPFC installation is better than LQR control.

REFERENCE

[1]. Jan Machowski, Janusz W. Bialek, James R. Bumby, Power System Dynamic, Stability and Control, ISBN 978-0-470-72558-0John Wiley & Sons, Ltd ©. 2008

[2]. P.M. Anderson, A.A Fouad "Power System Control and stability" The Iowa State University Press, © 1977.

[3]. Agus Junaidi, Abd Hamid, K, "Design of Simulation Product for Stability of Electric Power System Using Power System Stabilizer and Optimal Control", IOP Conf. Series: Journal of Physics: Conf. Series 970, 2018

[4]. Prabha Kundur," Power System Stability and Control" Mv. Graw-hill ©, 1994.

[5]. Fuhaid Basheer, Mohamed I. El-Sayed, El-Saied Othman, Improving Dynamic Stability of Power Systems by Using AVR, Power System Stabilizer, International Journal of Electrical Engineering & Technology, 10(2), 2019

[6]. Rahmaniar, The Simulation Computer Based Learning (SCBL) for Short Circuit Multi-Machine Power System Analysis" IOP Conf. Series: Journal of Physics: Conf. Series 970, 2018

[7]. P.K. Padiyar, "Power system stability and control," EPRI Power System Series, 1994.

[8]. Sanjeeva Rao V, Sanker Ram B V, Design of LQR-PSS to Enhancement of Stability of SMIB as Affected by Excitation Control, International Journal of Electrical, Electronics and Computer Systems (IJEECS), Volume -4, Issue-9, 2016

[9]. Dasari Siva, S.Shailaja, G.N.S Vaibhav, Implementation of Optimal Control Methods for Modeling of A Power System Stabilizer in Single Machine Infinite Bus System, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2017.

[10]. Mihalic, R., Zunko, P. and Povh, D., "Improvement of Transient Stability Using Unified Power Flow Controller", IEEE Transactions on Power Delivery, Vol. 11, No. 1, January 1996, pp. 485-491.

[11]. Frank Lewis, Optimal Control, John Wiley &Sons, Inc, 1986. G. I. R. H. I. Shaheen, S. J. Cheng, *"Optimal Location and Parameters Setting of UPFC based on GA and PSO for Enhancing Power System Security under Single Contingencies,"* IEEE, 2008.

[12]. Padiyar, K.R., 1996, *Power System Dynamis Stability and Control*, pp. 191 – 268, John Wiley & Sons, Singapore.

[13]. Frank Lewis, Optimal Control, John Wiley &Sons, Inc, 1986.

[14]. Pandey, R.K. Analysis and Design of Multi-Stage LQR UPFC, 978-1-4244-8542-0 IEEE 2010

[15]. Masdi H, Mariun N, Mohamed A,Yusuf S, 2004, Design of a prototype D-STATCOM for voltage sag mitigation, IEEE Explore, DOI. 10.1109/PECON.2004.1461617.

[16]. An improvement in LQR controller design for TLIP systemvia model order reduction, International Journal of Engineering Research and Technology.ISSN 0974-3154 Volume 11, Number 12 (2018), pp. 1891-1900.