State Feedback LQR & Pole Placement Switching Control for the Power System Stabilizer

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***Abstract*—In order to improve damping during low frequency oscillations in a power system, this work provides a state feedback switching control method for the power system stabilizer (PSS). Extensive research has been conducted by examining the possibility of switching between two static gain vectors: one for the Linear Quadratic Regulator (LQR) controller and another for the Pole Placement controller. The goal is to combine the structures of both controllers and create a new structure that ensures both the desired performance and stability of the closed loop system. Using MATLAB/SIMULINK, the suggested feedback switching model is evaluated on the modified SMIB linearized Phillips heffron model of a power system. By the end of the study, stabilization and improved performance over the two individual controllers are achieved using the suggested feedback switching control between two static controller gains.**

***Index Terms*—SFSC, PSS, LQR, SMIB, Phillips-Heffron Model**.

1 Introduction

In the study of control systems, state feedback switching control is the study of switching between various controllers in accordance with a set of rules. By alternating between several feedback systems, one can combine the beneficial aspects of each structure and add additional characteristics that are absent from any of the others.

An adaptive neural network-based Sliding Mode Control (SMC) for a single machine power system's PSS has been proposed by Hussain N. and Al-Duwaish [1]. In essence, the SMC is a switching feedback control. The findings of the simulation show that using adaptive SMC significantly improves controller performance. The authors of [2] present a methodology that uses switching controllers with limited minimum switching intervals to make the power system controller design less conservative. The architecture of PSS for SMIB power system based on fuzzy logic and output feedback sliding mode controller (SMC) is proposed by Vitthal Bandal and B. Bandyopadhyay [3]. It is discovered that the controller's design offers good damping enhancement. A self-tuning regulator (STR) with multi-identification models and a minimum variance was proposed by the authors in [4].

Power system instability is discussed by Michael J. Basler Richard and C. Schaefer, along with the significance of quick fault clearing in order to provide dependable power output [5]. The use of additional excitation control signals to increase the dynamic stability of power systems has drawn a lot of interest in recent decades. The modest signal stability, line loading, high gain, rapid acting excitation devices, and high impedance transmission lines are all explained by the k-constant model that was created by Phillips and Heffron. The power system stabilizer is a supplementary control system, which is often applied as part of excitation control system. The basic function of the PSS is to apply a signal to the excitation system, creating electrical torques to the rotor, in phase with speed variation, that damp out power oscillations.

PID-PSS and traditional PSS have been compared for effectiveness, according to Balwinder Singh Surjan and Ruchira Garg [6]. A method for fine-tuning a fixed structure PSS's parameters is developed in [7] using particle swarm optimization. The method provides designers with the adaptability to strike a balance between opposing design goals, overshoot, and control constraint. The power system stabilizer (PSS) was devised by M K Ei-Sherbiny and Ali M. Yousef [8] using the LQR Approach. Robustness control property with power system parameters is possessed by the suggested PSS. For the modified Heffron-Phillips model, several power system stabilizer design methodologies are presented in [9]. The proposed IPSO algorithm in [10] was utilized to find the optimize parameters of PSS for SMIB system by minimizing the fitness function. Using the proposed algorithm, the Load frequency oscillations can be reduced appropriately. In [11] the free model approach for system identification and its application to design a power system stabilizer is presented. The free model is transformed to a linear state-space model and the linear quadratic regulator technique is used to design a PSS. The free model thus developed is shown to be controllable,

This paper's goal is to present a switching approach that will allow the power system stabilizer to alternate between two separate controllers, known as the primary and secondary. The pole placement approach is used to construct the secondary controller, which is made to follow the switching rule of the closed loop eigenvalues, while the primary controller is generated from the optimum control theory of LQR.

The structure of the paper is as follows. The linearized Phillips-Heffron model for the PSS is explained in Section II. The proposed switching rule in Section III and the switching model for the Philips-Hefron plant with PSS follow. The proposed method's simulation results are explained in Section IV. The next sections that follow contain the discussions and conclusion.

2 SMIB power system model

For the purposes of these studies, a single machine-infinite bus (SMIB) system is taken into consideration. By applying Thevenin's analog of the external transmission network to the machine, a machine linked to a larger system via a transmission line can be reduced to a SMIB system. Figure 1 depicts a block diagram of the linearized model of the power system under study, which included a synchronous machine connected to an infinite bus bar via a transmission line. The following can be used to express its state space formulation [8,12]:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = \frac{1}{M}(-K_1\Delta\delta - D\Delta\omega - K_2\Delta E_q^{'}) \tag{2}$$

$$\Delta\dot{E}_q^{'} = \frac{1}{T_{do}^{'}}(-K_4\Delta\delta - \frac{\Delta E_q^{'}}{K_3} + E_{fd}) \tag{3}$$

$$\Delta\dot{E}_{fd} = \frac{1}{T_A}(-K_AK_5\Delta\delta - K_AK_6\Delta E_q^{'} - \Delta E_{fd} + K_Au) \tag{4}$$

In a matrix form as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{5}$$

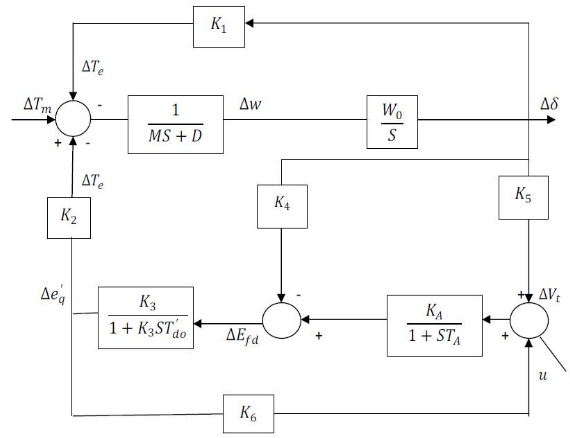

Figure 1: Block Diagram of Power System

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

$$A = \begin{bmatrix} 0 & \omega_o & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 \\ -\frac{k_4}{T'_{do}} & 0 & -\frac{k_3}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{k_Ak_5}{T_A} & 0 & -\frac{k_Ak_6}{T_A} & \frac{1}{-T_A} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & \frac{K_A}{T_A} \end{bmatrix}^T$$

The appendix section at the end of the paper contains descriptions of all the pertinent variables and k-constants that were utilized in the experiment, along with their respective values.

3 Proposed PSS as state feedback switching control

This section will present the suggested switching technique and mathematical modeling of the Philips-Heffron system using PSS devices as switched linear systems.

3.1 Switched Linear Systems

For more than fifty years, the systems and control literature has focused heavily on the topic of studying switched linear systems. A switching law that controls the transitions between various subsystems makes up a switched system, which consists of a collection of subsystems. It has been demonstrated that the performance of a system with proper switching control outperforms that of a system without switching control.

A switched-linear system model (refer Fig.2) for the current problem is as follows [13]:

$$\dot{x}(t) = A_{\sigma(t)}x(t) \tag{6}$$

$$\begin{aligned} \dot{x}(t) &= A_{-1}x(t) \qquad x^{'}Sx \leq 0 \\ &= A_{1}x(t) \qquad x^{'}Sx > 0 \end{aligned} \tag{7}$$

The Switching Signal $\sigma(t)$ is given by

$$\sigma(t) = sgn(x(t)^{'}Sx(t)) \tag{8}$$

The switching signal $\sigma(t)$ indicates which of the matrices A_{-1} or A_1 is being used at any given time; when $\sigma(t) = 1$, $A_1 = (A + BK_1)$, while when $\sigma(t) = -1$, $A_{-1} = (A + BK_2)$.

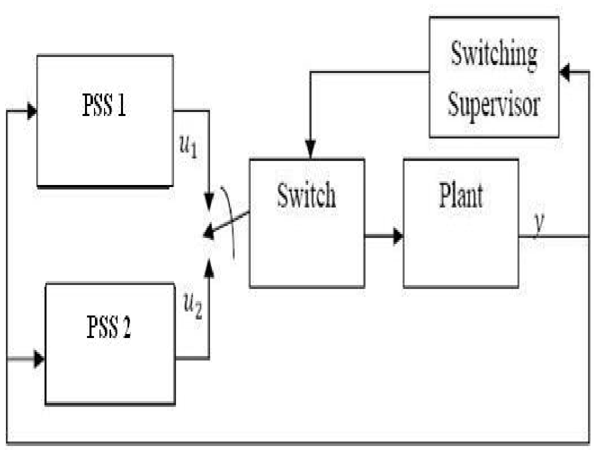

Figure 2: General implementation of switched linear systems

For the proposed algorithm based on [13,14] following definitions and conditions are required:

A. Switching matrix is given by $S = F_1^{'}F_2$.

B. The Switching Boundary Vectors F_1 & F_2 are normal vectors to the stable invariant subspace of the matrices $A + BK_1$ and $A + BK_2$ respectively. i.e., $F_1 \perp V_1$ & $F_2 \perp V_2$.

C. Let,

$$Eig \quad (A + BK_1) = (s + \alpha_1)(s + \alpha_2)(s + \dot{\beta_1})(s + \dot{\beta_2})$$

$$Eig \quad (A + BK_2) = (s + \alpha_1)(s + \alpha_2)(s + \beta_1)(s + \beta_2)$$

where, $\beta_1 = -\beta_2$ and $\dot{\beta_1} = \bullet\dot{\beta_2}$

The optimal control theory of the Linear Quadratic Regulator (LQR) and the Pole Placement approach, respectively, yielded the two controller gains, K_1 & K_2. For the purpose of completeness, a brief explanation of the LQR and Pole placement control mechanisms is provided.

3.2 Linear Quadratic Regulator Control

When the dynamic equations are linear and the objective function is a quadratic function of x and u, there is a unique situation of an optimum control issue that is especially significant. In this instance, the feedback law that results is referred to as the linear quadratic regulator (LQR). The LQR controller minimizes the error criteria in Eqn.(9) to get the gain parameters. Let us consider a linear system where (A, B) is stabilizable and is characterized by Egn. (5). Next, the matrix K of the LQR vector is determined by the cost index, which is

$$J = \frac{1}{2}\int_0^\infty (x^TQx + u^TRu)dt \tag{9}$$

Where Q and R are the real symmetric or positive-definite Hermitian matrices. Using the equations above,

$$K = -R^{-1}B^TP \tag{10}$$

and hence the control law is,

$$u(t) = -Kx(t) = -R^{-1}B^TPx(t) \tag{11}$$

In which P must satisfy the reduced Riccati equation:

$$PA + A^TP - PBR^{-1} + B^TP + Q = 0 \tag{12}$$

With the LQR function, you can select two parameters, R and Q, that together determine how important each input and state are to the overall cost function you're seeking to optimize. In essence, all outputs are controllable with the LQR approach.

3.3 Pole Placement Control

The foundation of pole placement control design is the placement of the closed loop system's poles at any desired location using state feedback via the proper state feedback gain matrix. The first step in the design process is to identify the appropriate closed loop poles based on the steady state requirements as well as the transient response and/or frequency response requirements, such as speed, damping ratio, or bandwidth.

The gain matrix K is designed in such a way that:

Step 1: Check whether the system is controllable

$$M = \begin{bmatrix} A & AB & A^2B - - - A^{N-1}B \end{bmatrix}$$

$$|M| \neq 0$$

Step 2: Find $(SI - A) = s^n + a_1 s^{n-1} + - + a_{n-1}s + a_n$

Step 3: Locate the matrix of transformation T

Step 4: Decide where the poles should be placed $(s+\alpha_1)(s+\alpha_2) + - + (s+\alpha_n) = s^n + \alpha_1 s^{n-1} + -\alpha_n$

Step 5: Solve for K using,

$$K = \begin{bmatrix} \alpha_2 - a_2 & \alpha_1 - a_1 - - - \alpha_n - a_n \end{bmatrix} T^{-1}$$

3.4 Switching Algorithm

Design of a stabilizing switching control law is equivalent to finding switching boundary vectors F_1 & F_2. This can be achieved by carrying out the following steps[13,14]:

Determining the switching boundary vectors F_1 & F_2 is the same as designing a stabilizing switching control law. The following actions can be taken to accomplish this[13, 14]:

1. Design a secondary controller K_2 in such a way that it has $n - 1$ closed loop real eigenvalues located at the left half of the s-plane.

2. Select a gain vector K_1 (primary controller) such that the closed loop eigenvalues of $(A + BK_1)$ has $n - 2$ common eigenvalues of $(A + BK_2)$ and the remaining eigenvalues are not real.

3. To design F_1, multiply the left side eigenvalue polynomials of $(A + BK_1)$ and select the coefficients of expanded polynomial in ascending powers of s.

4. To design $F_2 = [F_1 + \mu\omega_2]$, ω_2 is calulated by multiplying the polynomial that is removed while designing the vector F_1(right side eigenvalue) with other $(n - 2)$ left eigenvalues by selecting $\mu < 0$.

4 Simulation Results

A and B matrices below explain the linearized Phillps-Heffron model of SMIB installed with PSS, which serves as the experimental setup used to evaluate the suggested algorithm. LQR and the pole placement technique are used to obtain the controllers K_1 and K_2, respectively. Depending on the state variables, the matrix C is a vector with zeros and one in any one location. Below are also the suggested state feedback switching control vectors, F_1 and F_2.

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -.1317 & 0 & -.1104 & 0 \\ -.2356 & 0 & -.463 & .1667 \\ 15.47 & 0 & -194.81 & -16.667 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & \frac{25}{0.06} \end{bmatrix}^T$$

4.1 Primary Controller Design:

The matrix A_1 has $n-2$ common eigenvalues of A_{-1}, and the other two eigenvalues are not real, according to the switching algorithm K_1.

Using LQR control Algorithm,

$$[K, S, E] = lqr(A, B, Q, R, N) \tag{13}$$

According to the current methodology in [15], the assumptions in Equation (13) are as follows: matrix $N = 0$, matrix $R = 50$, and Q

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & .001 \end{bmatrix}$$

Solving Egn. (13), the Riccati equation S is

$$S = \begin{bmatrix} 1.8 & 0 & 1.5 & 0 \\ 0 & 5329 & -34.4 & 0 \\ 1.5 & -34.4 & 1.9 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Furthermore, K_1 is the optimal gain matrix that is computed.

$$K_1 = \begin{bmatrix} 0.1217 & -0.1090 & 0.1292 & 0.0015 \end{bmatrix}$$

The eigenvalues are as follows

$$P = \begin{bmatrix} -14.3968 \\ -2.8719 \\ -0.2429 + 7.0208i \\ -0.2429 - 7.0208i \end{bmatrix}$$

4.2 Secondary Controller Design:

The matrices A_{-1} and A_1 contain real $n-1$ stable eigenvalues and are required to share $n-2$ eigenvalues, as per the switching algorithm. In this study, we will (arbitrarily) "move" the eigenvalues of the matrix A_1, which are located at $-0.2429+7.0208i$ and $-0.2429-7.0208i$, to the eigenvalues of $+1$ $\& -1$ for the matrix A_{-1}.

Using pole placement technique, place poles at $P = \begin{bmatrix} -14.3968 & -2.8719 & -1 & 1 \end{bmatrix}$

.

$$K = place(A, B, P)$$

$$K_2 = \begin{bmatrix} -0.1654 & 112.7865 & -0.7135 & 0.003 \end{bmatrix}$$

4.3 Switching boundary vectors Design:

A normal vector to a stable invariant subspace of the matrix $A + BK_2$ is the switching boundary vector F_1:

$$(s + 14.3968)(s + 1)$$

(s+2.8719)

Stacking the co-efficients of the resulting expanded polynomial into the vector F_1 in ascending powers of s:

$$F_1 = \begin{bmatrix} 41.3461 & 58.6148 & 18.268 & 1 \end{bmatrix}$$

Recall, $F_2 = \omega_1^{'} + \mu\omega_2^{'}$ where, $\omega_1^{'} = F_1$

ω_2 corresponds to the left eigenvector with the eigenvalue that is removed form $(A+BK_2)$ to form the characteristic polynomial of $(A + BK_1)$, which in this case is the left eigenvector corresponding to the eigenvalue -1. i.e., $(s + 14.3968)(s + 2.8719)(s - 1)$.

$$\omega_2 = \begin{bmatrix} -41.346 & 24.0771 & 16.2687 & 1 \end{bmatrix}$$

According to the procedure, $\mu < 0$ to achieve a stable closed loop interconnection. If, we choose $\mu = -1$, the switching boundary vector F_2 is given by

$$F_2 = \begin{bmatrix} 82.6922 & 34.5377 & 2 & 0 \end{bmatrix}$$

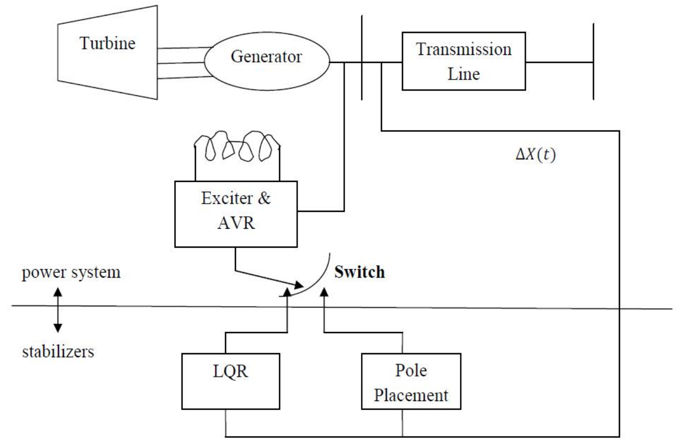

Figure 3: PSS as Switching control for power system

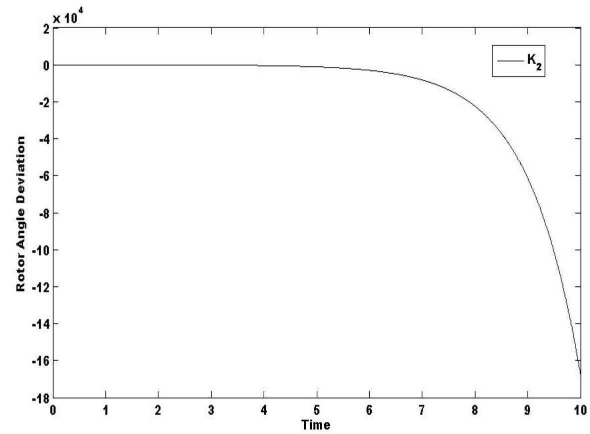

Figure 4: rotor angle deviation response

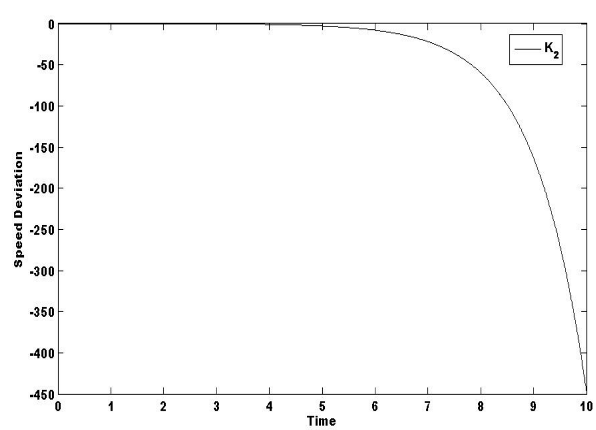

Figure 5: speed deviation response

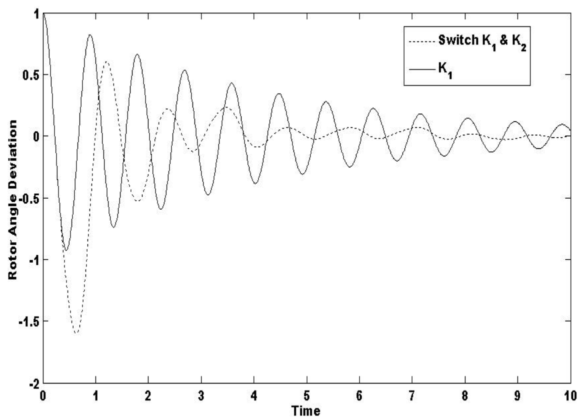

Figure 6: rotor angle deviation response

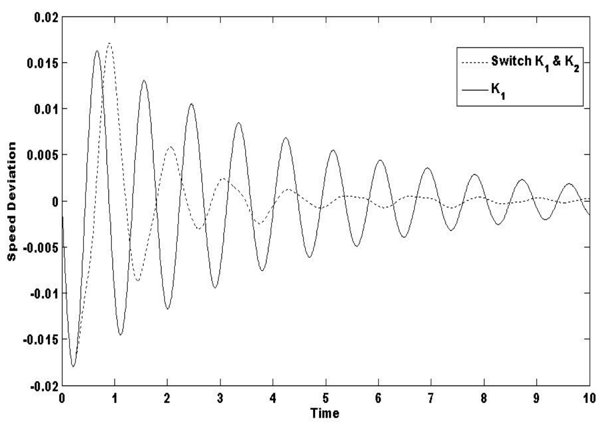

Figure 7: speed deviation response

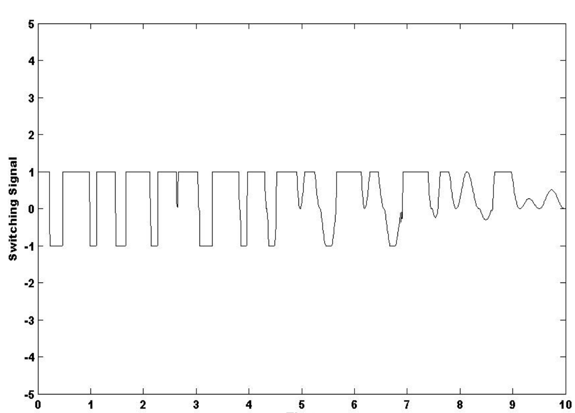

Figure 8: switching signal response

5 Discussions

Plotting the dynamic response curves for the state space variables, Rotor angle deviation ($\Delta\delta$) and Speed deviation ($\Delta\omega$), using the legends K_1, K_2, and Switch K_1 and K_2 for the proposed state feedback switching control for the PSS are displayed in Figs. 4-7. Figure 8 also displays the Switching Signal $\sigma(t)$ as a Function of time.

Figures 4–7 indicate that, in comparison to the system response with individual controllers K_1 (which makes the system stable) and K_2 (which makes the system unstable) with respect to settling time, the proposed state feedback switching control between LQR and pole placement method offers better performance along with the stabilization in the Rotor angle and Rotor speed deviations.

6 Conclusion

Using Heffron Phillip's model, the power system stabilizer (PSS) is introduced to the state feedback switching control approach. The control law alternates between two separate controllers (pole placement & LQR). When compared to the pole placement approach and individual LQR [15] controllers, the suggested switching control offers both improved performance and stabilization. The digital results demonstrate how well switching control can improve the damping of oscillations in the power system.

Appendix

Choosing the machine parameters at nominal operating point as

$X_d = 1.6$, $X_q = 0.32$, $X_e = 0.4p.u.$

$M = 10$, $\omega_0 = 377$, $T_{d0}^{'} = 6$

$D = 0$, $P = 1p.u$, $Q = 0.25p.u$

$K_A = 25$, $T_A = 0.06s$.

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