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Modern Control Design of Power System

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Abstract: Modern control design of isolated power system is introduce in this paper using two techniques. Pole-placement and optimal control design, these two methods concentrate on the way by which frequency deviation and terminal voltage step response can be reduced by shifting the dominant poles to a desired location gives a significant improvement on the isolated power system performance. Modern control design is especially useful in multivariable systems. One approach in modern control systems accomplished by the use of state feedback is known as *pole-placement design*. The pole-placement design allows all roots of the system characteristic equation to be placed in desired locations. This results in a regulator with constant gain vector *K.* The state-variable feedback concept requires that all states be accessible in a physical system. For systems in which all states are not available for feedback, a state estimator (observer) may be designed to implement the pole-placement design. The other approach to the design of regulator systems is the *optimal control*, where a specified mathematical performance criterion is minimized in which the eigenvalues of the system are shifted to a prespecified vertical strip to gives a significant improvement in the dynamic performance of the isolated power system.

Key words:

Pole-Placement Design:

The control is achieved by feeding back the state variables through a regulator with constant gain. Consider the control system presented in the state-variable form:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t)\\ y(t) &= Cx(t) + Du(t)\end{aligned} \tag{1}$$

Now consider the block diagram of the system shown in Figure 1 with the following state feed back control:

$$u(t) = -Kx(t) \tag{2}$$

Where K is a (1* n) vector of constant feedback gain. The control system input r (t) is assumed to be zero. The purpose of this system is to return all state variables to values of zero when the states have been perturbed

Substituting equation 2 into 1, the compensated system state-variable representation becomes:

$$\dot{x}(t) = (A - BK)\times(t) = A_f x(t) \tag{3}$$

The compensated system characteristic equation is:

$$|sI - A + B\,K| = 0 \tag{4}$$

Assume the system is represented in the phase variable canonical form as follows

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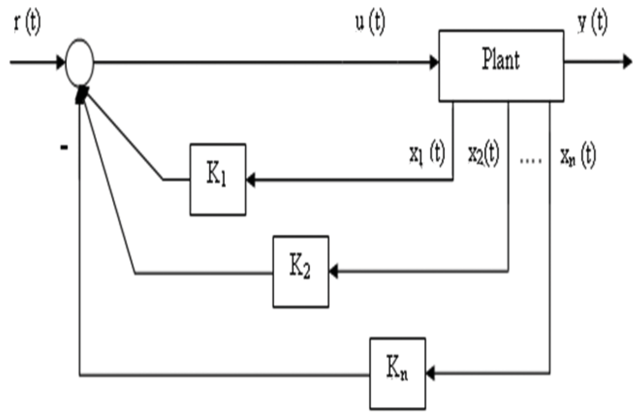

Fig. 1: Control system design via pole placement

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_{n-1} \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & & & & \\ 0 & 0 & 0 & \dots & 1 \\ -a_0 & -a_1 & -a_2 & \dots & -a_{n-1} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n-1} \\ x_n \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} u(t) \tag{5}$$

Substituting for A and B into equation 4, the compensated characteristic equation for the control system is found:

$$\begin{gathered} \left| sI - A + BK \right| = s^n + (a_{n-1} + k_n)s^{n-1} \\ + \dots\dots + (a_0 + k_1) = 0 \end{gathered} \tag{6}$$

For the specified closed-loop pole locations $-\lambda_1 \dots -\lambda_n$, the desired characteristic equation is:

$$\begin{gathered} \alpha c(s) = (s + \lambda_1)\dots\dots\dots(s + \lambda_n) \\ = s^n + \alpha_{n-1}s^{n-1} + \dots\dots + \alpha_1 s + \\ \alpha_0 = 0 \end{gathered} \tag{7}$$

The design objective is to find the gain matrix K such that the characteristic equation for the controlled system is identical to the desired characteristic equation. Thus, the gain vector is obtained by equating the coefficients of equations 6 and 7, and for the *i*th coefficient we get:

$$k_i = \alpha_{i-1} - a_{i-1} \tag{8}$$

To obtain the state variable representation of the isolated power station mentioned as in fig. 2, with ΔP_L = 0.2 pu, and V_{ref} =1 pu.

Using *MATLAP CONTROL SYSTEM TOOL BOX* we can obtain the frequency deviation response and voltage deviation.

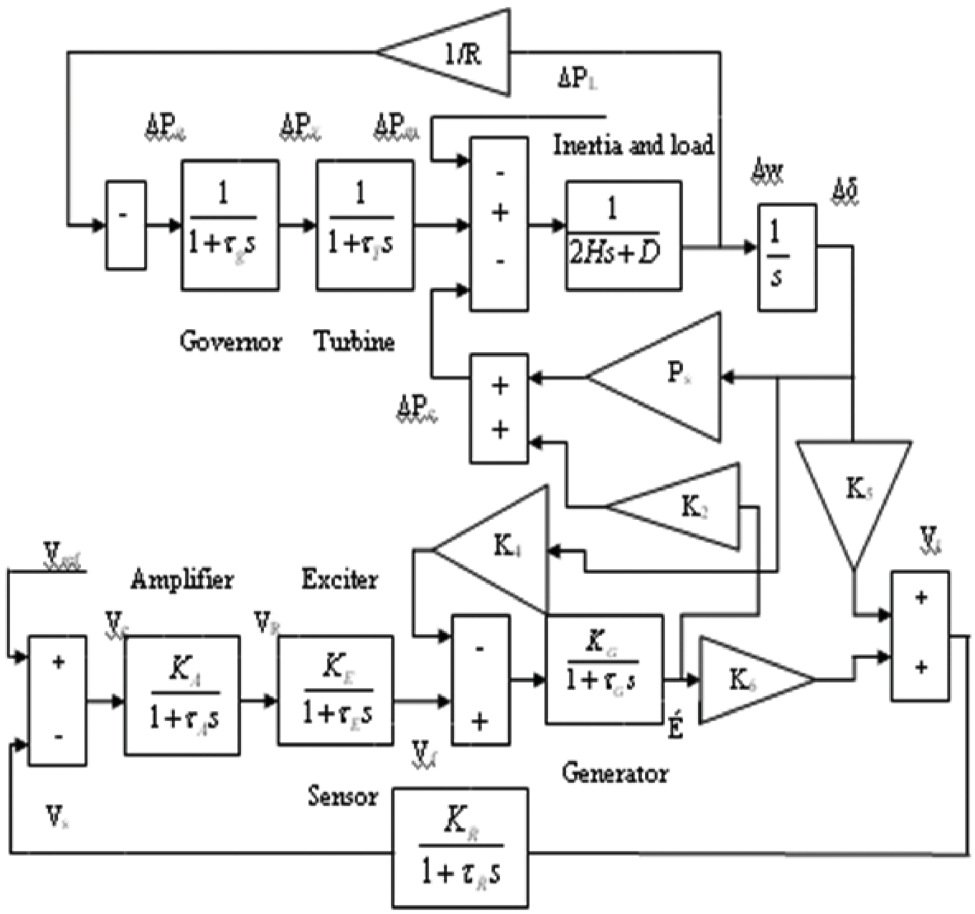

Fig. 2: Isolated power station block diagram.

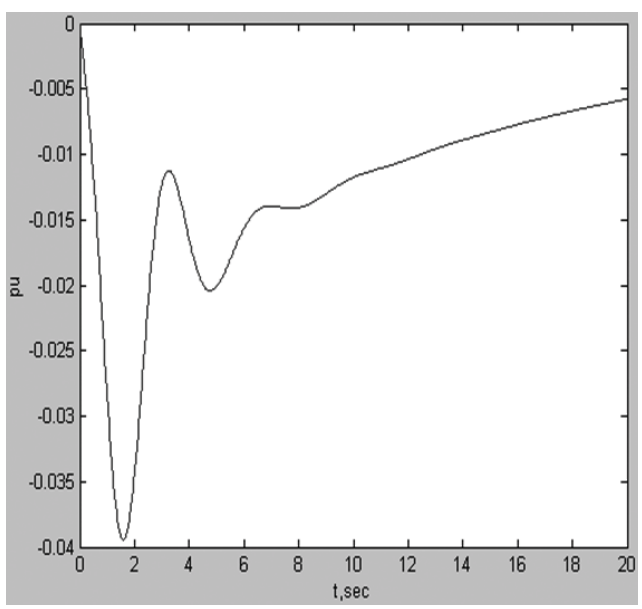

Fig. 3: Uncompensated frequency deviation step response for state- space model.

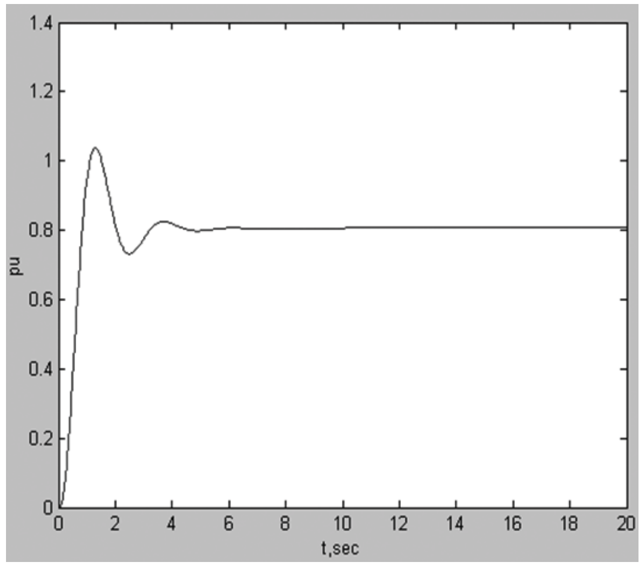

Fig. 4: Uncompensated terminal voltage step response of state-space model

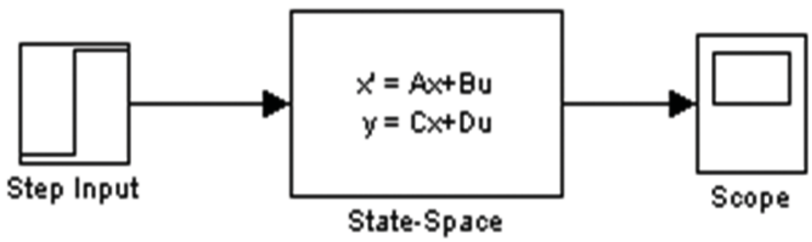

Fig. 5: Simulation block diagram for state-space model.

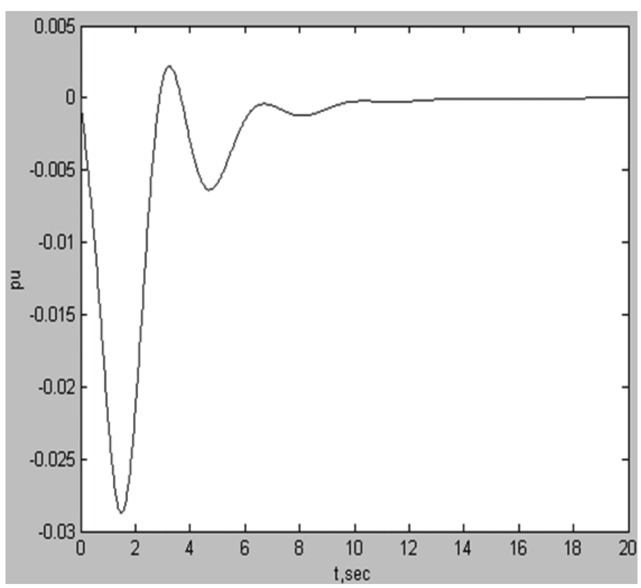

Fig. 6: Compensated frequency deviation step response for state-space model.

Optimal Control Design (Strip Eigenvalue Assignment):

Optimal control is a branch of modern control theory that deals with designing controls for dynamic systems by minimizing a performance index that depends on the system variables. In this section, we will discuss the design of optimal controllers for linear systems (such the system we deal with) with quadratic performance index, the so-called *linear quadratic regulator*. The object of the optimal regulator design is to determine the optimal control law *u*(x, t)* which can transfer the system from it is initial state to the final state such that a given performance index is minimized. The performance index is selected to give the best trade-off between performance and cost of control. The performance index is known as the *quadratic performance index* and is based on minimum-error and minimum-energy criteria.

Consider the plant described by

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{9}$$

The problem is to find the vector *K (t)* of the control law

$$u(t) = -K(t)x(t) \tag{10}$$

which minimum the value of a quadratic performance index ***J*** of the form

$$\mathrm{J} = \int_{t_o}^{t_f} (x'Qx + u'Ru)dt \tag{11}$$

subject to the dynamic plant equation in 18. In 20, *Q* is a positive semi definite matrix, and *R* is a real symmetric matrix.

To obtain a formal solution, we can use the method of *Lagrange multipliers polynomial.* The constraint problem is solved by augmenting equation 18 into 20 using an n-vector of Lagrange multipliers, λ. The problem reduces to the minimization of the following unconstrained function.

$$\begin{aligned} &\mathrm{L}(x,\lambda,u,t) = \left[x'Qx + u'Ru\right] + \\ &\lambda'\left[Ax + Bu - \dot{x}\right] \end{aligned} \tag{12}$$

The optimal values (denoted by the subscript *) are found by equating the partial derivatives to zeros.

$$\begin{aligned} &\frac{\partial \mathrm{L}}{\partial \lambda} = AX^* + Bu^* - \dot{x}^* = 0 \\ &\Rightarrow \quad \dot{x}^* = AX^* + Bu^* \end{aligned} \tag{13}$$

$$\begin{aligned} &\frac{\partial \mathrm{L}}{\partial u} = 2Ru^* + \lambda B = 0 \\ &\Rightarrow \quad u^* = -\frac{1}{2} R^{-1} \lambda' B \end{aligned} \tag{14}$$

$$\begin{aligned} &\frac{\partial \mathrm{L}}{\partial x} = 2x'^* Q + \dot{\lambda}' + \lambda' A = 0 \\ &\Rightarrow \quad \dot{\lambda} = -2Qx^* - A'\lambda \end{aligned} \tag{15}$$

Assume that there exists a symmetric, time-varying positive definite matrix *p (t)* satisfying

$$\lambda = 2p(t)x^* \tag{16}$$

Substituting equation 19 into 25 gives the optimal closed-loop control law

$$u^*(t) = -R^{-1}B'p(t)x^* \tag{17}$$

Obtaining the derivative of equation 25, we have

$$\dot{\lambda} = 2(\dot{p}x^* + p\dot{x}^*) \tag{18}$$

Finally, equating equation 24 with 27, we obtain

$$\dot{p}(t) = -p(t)A - A'p(t) - Q + p(t)BR^{-1}B'p(t) \tag{19}$$

The above equation is referred to as the matrix *recite equation*. The boundary condition for equation 28 is p (t_f) = 0.Therefore, equation 28 must be integrated backward in time. Since a numerical solution is performed forward in time, a dummy time variable $\tau = t_f - t$ is placed for time t. Once the solution to equation 28 is obtained, the solution of the state equation 22 in conjunction with the optimum control equation 26 is obtained.

The optimal controller gain is a time-varying state-variable feedback. Such feedback is inconvenient to implement, because they required the storage in computer memory of time-varying gains. An alternative control scheme is to replace the time-varying optimal gain *K (t)* by it is constant steady-state value. In most practical applications, the use of steady-state feedback gain is adequate. For linear time-invariant systems, since $\dot{p} = 0$, when the process is of infinite duration, that is $t_f = \infty$, equation 28 reduces the algebraic recite equation

$$pA + A'p + Q - pBR^{-1}B'p = 0 \tag{20}$$

The *LQR* design procedure is in stark contrast to classical control design, where the gain matrix *K* is selected directly. To design the optimal *LQR*, the design engineer first select the design parameter weight matrices *Q* and *R*. Then, the feedback gain *K* is automatically given by matrix design equations and the closed loop time response are found by simulation. If these responses are unsuitable, new values of *Q* and *R* are selected and the design is repeated. This has the significant advantages of allowing all the control loops in a multiloop system to be closed simultaneously, while guaranteeing closed-loop stability.

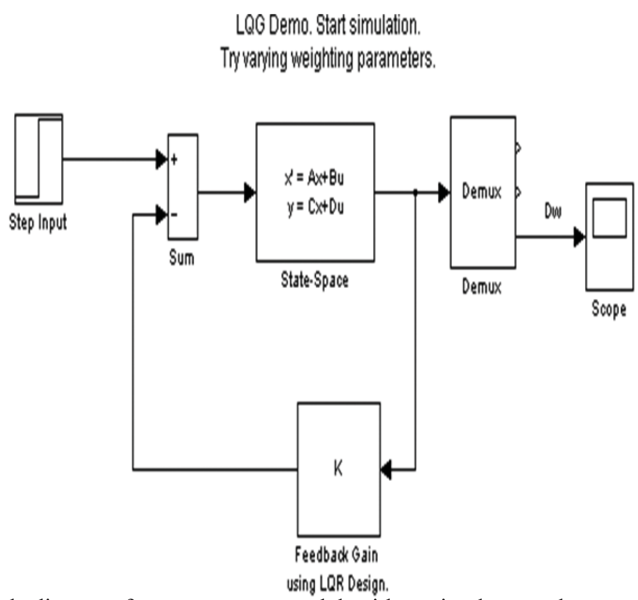

Fig. 7: Simulation block diagram for state-space model with optimal control.

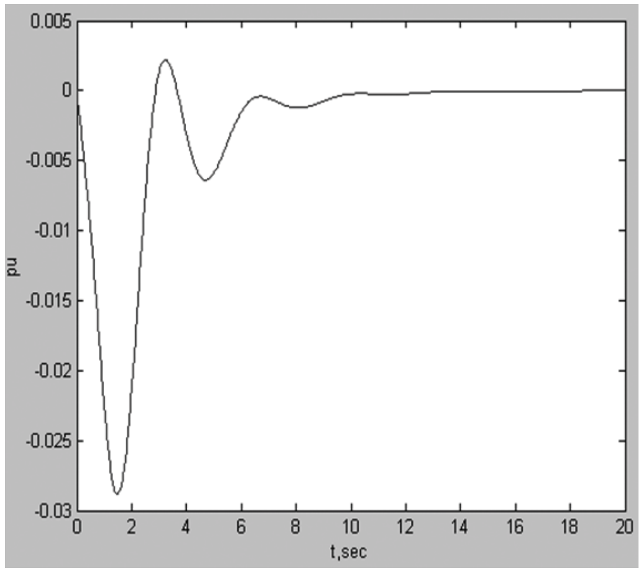

Fig. 8: Frequency deviation step response for optimal control design.

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