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# PI-Observer Based Optimal AGC Regulator for Interconnected Power System

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***Abstract:*** *In this paper PI-Observer based optimal automatic generation control regulator for two area interconnected power system is presented. PI-Observer has been realized in areas of robotic and mechanical system. The PI-Observer is used to estimate the actual states and the unknown inputs generally disturbances, modeling errors or the other non-line arities present in the system. The estimation error of the PI-Observer is gradually reduced by the proportional and integral feedback loop that appreciably improves the observer dynamics. A two area interconnected power system model is considered as a test case to implement the proposed methodology which is then compared with Luen berger observer based state feedback control for automatic generation control problem of power system. The robustness of the proposed scheme is tested for linear and non-linear power system model. The dynamic responses are compared and discussed on the basis of peak overshoot, settling time and oscillations. Lastly it was found that the performance of PI-observer based optimal AGC regulator is quite appreciable as compared to Luen berger observer based state feedback schemes.*

***Keywords:*** *Automatic generation control, optimal LQR, PI-Observer, pole placement, state feedback control, output feedback states.*

## I. Introduction

In the complex structure of geographically distributed and interconnected power system, the generation and load within each area is to be matched and the scheduled power interchange and system frequency should be close to their nominal values for the stable operation of power system. The general idea of controlling the frequency is to maintain the balance between the generated power and the consumed power. Since the existence of alternating current power systems, different philosophies have been applied to maintain the supply frequency. The most common control modes are the isochronous control, Droop control and Automatic Generation Control. In the isochronous control mode, a big generator will be assigned the task of maintaining the frequency and the rest of generators will be running at constant power output. However in droop control mode, all generators will respond to the frequency deviation. However automatic generation control (AGC) is achieved by adding a supervisory control loop to the droop control loop for better performance. The main aim of AGC is to regulate the frequency deviation and to track the load demand. The design of a good performance automatic generation controller has attained considerable importance out of which many novel control strategies have been emerged for AGC problem **[1]**. In modern control theory, the linear quadratic regulator (LQR) have many desirable properties like good robustness and sensitivity. Among observers based control scheme, PI-Observer has the simplest structure and design process. Although there are numerous applications based on the PI-Observer and were initially applied for systems having single input output by Wojciechowski followed by others for its application in multivariable system. The structure of PI-observer has proportional and integral control loop inserted in the estimation error loop which improves robustness in the estimation of states and disturbances. In this paper PI-observer based optimal automatic generation regulator for interconnected linear and non-linear power system is implemented and the performance of the regulator is compared with the Luenberger observer based optimal AGC regulator.

## II. General Design of Observer

In practice all the states of the system cannot be measured due to number of reasons including cost or that state may not be physically measurable therefore a method for reconstructing states of actual system by measuring inputs and outputs of the system. The design basis of observer technique is presented and implemented by Luenberger **[2]**. However with the development of observer technique, research in the design of advanced observer based control for known and unknown inputs have taken a long step forward. Here the known inputs are input signal and system states that cannot be measured directly from system output and the disturbances or modeling errors are the unknown inputs considered for the design of observer. The observer technique is being continuously upgrading and different types of observers are designed such as optimal and nonlinear. On the basis of different pattern or structure of observers for different engineering applications they can be classified as below in fig 1.

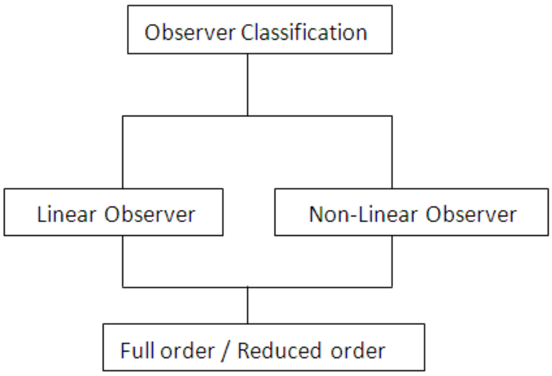


**Figure 1.** Classification of Observer

The basic use of observer is to estimate the unmeasured states and can also be used as disturbance estimation by augmenting an additional state in the basic state space equation of the system **[3].**

**2.1 Structure of Luenberger Observer**

State reconstruction and estimation are used in different types of applications like signal processing, telecommunications and fault detection. The gains of the observer is the main parameter to estimate unmeasured states from the known inputs and the outputs of the system. An observer estimates the state variables of the system and has same mathematical model with the same input signal as that of real system. The observer reproduces an estimate of the actual state variable but due to unknown initial conditions of the actual system, the observer dynamics mismatch the actual system dynamics and there is an error in the estimated and actual state variable that can be minimized by the optimal tuning of observer gain. The basic arrangement of the Luenberger observer is shown in fig 2. Here the power system mathematical model is considered for observer design. The Luenberger observer that has two parts (i) an exact model of the power system dynamics (A,B,C) (ii) plus an error correcting part $K_o(y- y_{est})$ . The $K_o$ is called the observer gain and the observer has same internal states $x_{est}$ as that of power system. If L is optimally chosen then the observer estimates closely matches with power system states.

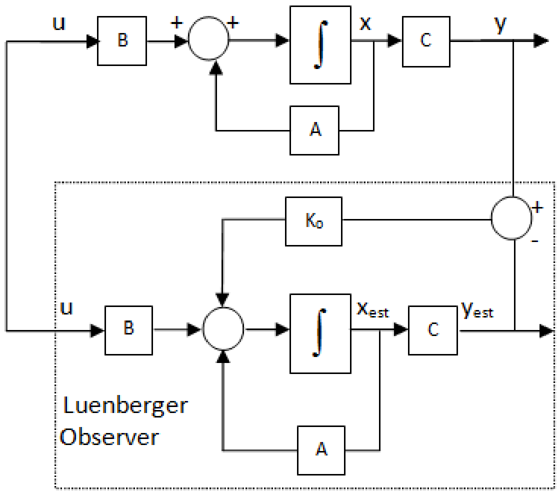


**Figure 2.** Structure of Luenberger Observer.

For the system which is expressed as below

(1) $$\frac{dx}{dt} = A\,x(t) + B\,u(t)$$

(2) $$Y = C\,x(t)$$

For the estimate $\hat{x}$ of the state vector is in given below.

(3) $$\frac{dx_{est}}{dt} = A x_{est} + B u + K_o \left( y - C x_{est} \right)$$

Where $K_o$ is the observer gain matrix.
From equation 1-3 error dynamic is given below.

(4) $$e = x - x_{est}$$

$$\frac{de}{dt} = (A - K_o)\, e \qquad (5)$$

And the equation for Luenberger observer is given below

$$\frac{dx_{est}}{dt} = (A - K_o)\, x_{est} + B u + K_o y \qquad (6)$$

The dynamic behavior of the error depends on the eigenvalues of equation 7 usually called as observer eigenvalues located in the left half of complex plane for observer to be stable.

$$(A - K_o C) \qquad (7)$$

The values for $K_o$ is designed by the pole placement technique by the analogy of state feedback design so that the observer transient response should be more rapid than the system itself. Therefore the observer poles are placed around six times the dominant pair of the actual system.

### 2.2 Structure of PI-Observer

Basically it is a modified Luenberger's observer structure with an extended additional state and have been introduced by Wojciechowsky for linear time invariant systems having single input output. However application has been extended to multivariable systems by Kaczore, shafai and caroll for robustness against disturbances, modeling error and parameter variations. Some successful applications have been implemented in fault detection and loop transfer recovery problems **[4].** There are many non-linear systems that cannot be modeled by equation 1 however due to inherent non-linear effects the dynamics of system is represented as below

$$\frac{dx}{dt} = A\, x(t) + B\, u(t) + N\, f(x,u,t) \qquad (8)$$

The vector function *f (x, u, t)* describes the nonlinearities, unknown inputs and un-modeled dynamics of the system. It is the nonlinear function of states, control inputs and time. The matrix N is the corresponding distribution matrix with full column rank. It was discovered by Ackermann and soffker that by assuming the disturbance as piecewise constant the PI-observer finely reconstruct the states and in combination with controls gives a very good compensation effects. However the performance of the PI-observer defined by Luenberger in equation 4 can only be achieved by the optimum gains of PI loop used in the observer. Since PI-observer is an extension of the Luenberger observer and not only uses the information proportional to estimation but also an integral of the estimation error that gives a better estimation performance. Fig 3 shows the basic structure of PI-Observer for the system expressed by equation 1-2.

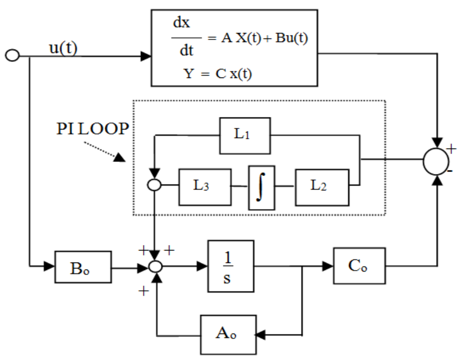


**Figure 3.** Block diagram of PI-observer

The dynamics of the PI-observer can be expressed as

$$\frac{dx_{est}}{dt} = A x_{est} + L_3 f_{est} + B u(t) + L_1 (y - y_{est}) \quad (9)$$

$$f_{est} = L_2 ( y - y_{est} ) \quad (10)$$

Where $y_{est} = C x_{est}$ and writing equation 9-10 in matrix form

$$\begin{bmatrix} \frac{dx_{est}}{dt} \\ \frac{df_{est}}{dt} \end{bmatrix} = \begin{bmatrix} A & L_3 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{est} \\ f_{est} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} ( y - y_{est} ) \quad (11)$$

The state estimation error $y$-$y_{est}$ and the estimation error of unknown inputs $f_{est}$ are considered separately. The optimum selection of gains $L_1$ , $L_2$ and $L_3$ will give the approximate estimate of the original states by the observer. The LQR technique is used for the optimum selection of observer gains and the below cost function is used for the selection of Q and R matrices. The convergence of the estimation error, values of $L_3$ is calculated from equation given below:

$$C A^{k-1} L_3 = 0 \quad with \quad k = 2, \ldots, n, \quad (12)$$

$$J = \int_0^t e(t) e'(t) \, dt \quad (13)$$

Where *e* is the observer error.

## III. Power System Model for AGC

For the stable operation of power system the total power generation should be matched with the load demand including associated system losses. However power system operating point changes continuously, resulting the systems experiences variation in nominal system frequency and scheduled tie line power exchanges between the interconnected control areas, which may yield hazardous effects if not controlled at an appropriate time .The governor control logic includes the supplementary control formulated as a signal proportional to the frequency difference algebraically added its integral, constitutes the classical approach for the AGC problem of power systems. The classical overview of the automatic generation control loop that is used as secondary control loop adjusts power set points of the generators to compensate for frequency error that is not corrected by the primary control where as primary control are done locally at the power plant control center based on the optimum set points for power and frequency is shown in Fig 4.

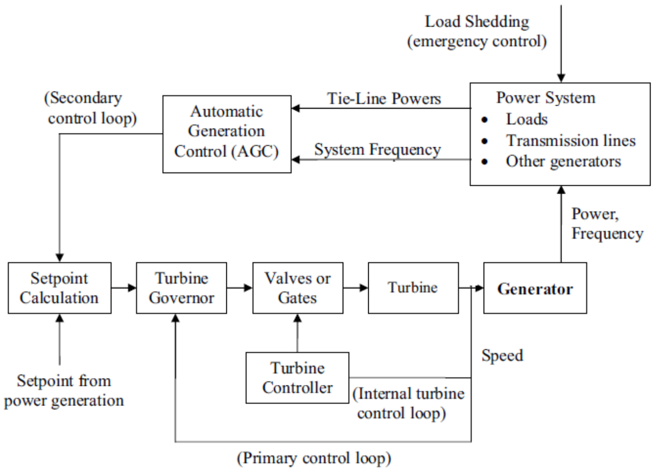


**Figure 4.** Control Structure for frequency control system

The complex AGC problem has been extensively dealt for more than three decades and most of the work reported has been performed by considering linearized model of single and multi-area power system model. But researchers also uses non-linearities such as generation rate constraints (GRC) ,dead band present in governor and dynamics of boiler for different AGC schemes **[5].** The power system model under investigation is considered as continuous time linear dynamic system that can be represented by the standard state space model as-

$$\frac{dx}{dt} = A\ X\ (t) + B\ U\ (t) + \Gamma\ P_d \quad (14)$$

$$Y = C\ X \quad (15)$$

Where $X$, $U$, $P_d$ and $Y$ are the state variables, control input, disturbance and output matrix respectively. These matrices are of appropriate dimensions and depend on the system parameters and the operating point **[6-8].** The state space model for two area interconnected power system is given below:

$$A = \begin{bmatrix} \frac{-1}{Tp_1} & \frac{Kp_1}{Tp_1} & 0 & 0 & 0 & 0 & \frac{-Kp_1}{Tp_1} & 0 & 0 \\ 0 & \frac{-Kt_1}{Tt_1} & \frac{Kt_1}{Tt_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1 * Tg_1} & 0 & \frac{-1}{Tg_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{Tp_2} & \frac{Kp_2}{Tp_2} & 0 & \frac{Kp_2}{Tp_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-Kt_2}{Tt_2} & \frac{Kt_2}{Tt_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{R_2 * Tg_2} & 0 & \frac{-1}{Tg_2} & 0 & 0 & 0 \\ T_{12} & 0 & 0 & -T_{12} & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & B_2 & 0 & 0 & -1 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{Tg_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{Tg_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \tau = \begin{bmatrix} \frac{-Kp_1}{Tp_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-Kp_2}{Tp_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

where state vector $A$ is (9×9), Control Vector $B$ is (9×2) and the Disturbance Vector τ (9×2) and all the values are given in Appendix A. The state vector is given below:-

$$[X]^T = [\ \Delta f_1\ \ \Delta P_{m1}\ \ \Delta P_{v1}\ \ \Delta f_2\ \ \Delta P_{m2}\ \ \Delta P_{v2}\ \ \Delta P_{tie}\ \ \int ACE_1\,dt\ \ \int ACE_2\,dt\ ] \quad (16)$$

The system state vector $X$ have nine states and have been defined in the Nomenclature.

## IV. Optimal Control gains for Power System model

The optimal state feedbacks are evaluated based on the output state feedback in accordance with optimality criterion. The output control law, state equation and the performance index is given as:-

$$U = -K\ y \quad (17)$$

$$\dot{x} = (A - BKC)\ x = A_c\ x \quad (18)$$

$$J = \frac{1}{2}\int_0^{\infty} (\ x^T\ (Q + C^T K^T R\ KC)\ \ x)\ dt \quad (19)$$

The gain matrix K is designed subject to minimization of state equation and solving the Lyapunov equations which are given below:-

$$A_c^T P + P A_c + C^T K^T RKC + Q = 0 \quad (20)$$

$$A_c S + S A_c^T + X = 0 \tag{21}$$

$$K = R^{-1} B^T PSC^T (CSC^T)^{-1} \tag{22}$$

Where P is the solution of the Lyapunov equation and X = I for the initial states assumed to be uniformly distributed on unit sphere. Now from the initial value problem the optimal cost function $J_0$ is given in equation 23 and the optimum value of K is obtained which minimizes cost function.

$$J_0 = \frac{1}{2} tr\,(P\,x) \tag{23}$$

The selection of Q and R is selected subject to below designed criterion:

1. Minimization of ACEs values near their steady state value.
2. Minimization of ∫ ACEs dt values near their steady state value.
3. Minimization of control vector near steady state values.

## V. Simulation and Discussion of Results

The referenced model is developed and simulated in Matlab to observe the dynamics of PI-observer based optimal AGC scheme. Different cases are considered to test the robustness of the proposed scheme.

### 5.1 Performance of PI-observer for linear power system model.

In this case a two area thermal-thermal interconnected linear power system model is considered with step load perturbation of 1% in area-1.

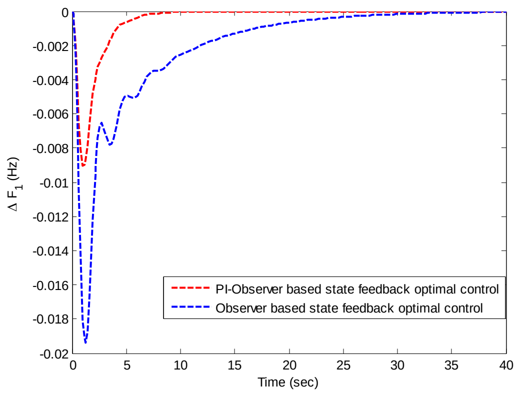


**Figure 5.** Response of $\Delta F_1$ for 1% load disturbance in area 1

It is quite clear from the frequency response of area-1 as shown in fig 5, the first peak overshoot is -0.009 in case PI-observer which is quite low as compared to Luenberger observer which has maximum first peak overshoot of -0.018. As far as the settling time is concerned the error in PI-Observer settles around 12 sec as compared to Luenberger observer which takes more than 26 sec to converge to zero. The oscillation are also quite less in case of PI-observer has quite less oscillation as compared to Luenberger observer.

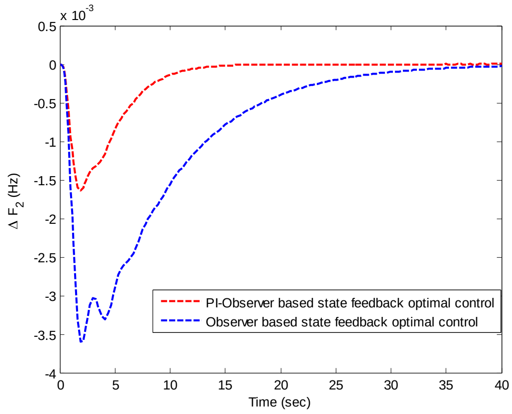


**Figure 6.** Response of $\Delta F_2$ for 1% load disturbance in area 1

The frequency dynamics in area-2 is shown in fig 6 is also disturbed and the deviation in frequency is -0.0015 with settling time 12 sec in case of PI-observer where as frequency deviation is -0.0035 and settling time is around 26 sec in Luenberger observer case. The oscillation is less as compared to area-1 frequency for Luenberger observer and non-oscillatory in case of PI-observer.

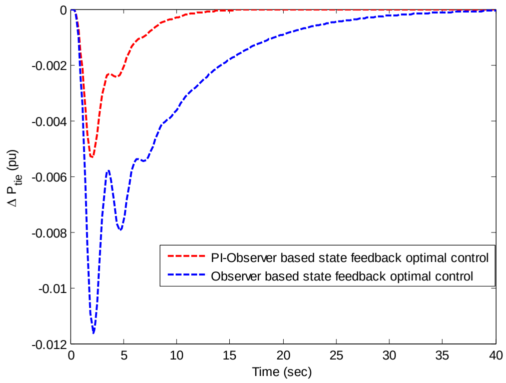


**Figure 7.** Response of $\Delta P_{tie}$ for 1% load disturbance in area 1

The tie-line deviation is shown in fig 7,the PI-observer based optimal control have less peak overshoot and faster settling time as compared to Luenberger observer based optimal control scheme.

### 5.2 Performance of PI-observer for Non-linear power system model.

In this case a two area thermal-thermal interconnected non-linear power system model is considered with step load perturbation of 1% in area-1.The governor deadband is inserted as non-linearity in power system model and the proposed control scheme is simulated.

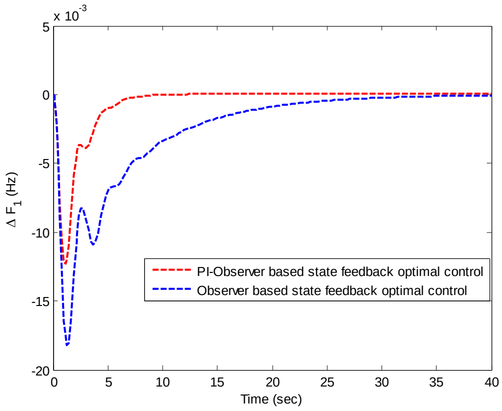


**Figure 8.** Response of $\Delta F_1$ for 1% load disturbance in area 1

The frequency response in area-1 and area-2 is shown in fig 8-9 respectively. Since the disturbance is in area-1, therefore the frequency excursion is more in the same area and due to weak tie-line between

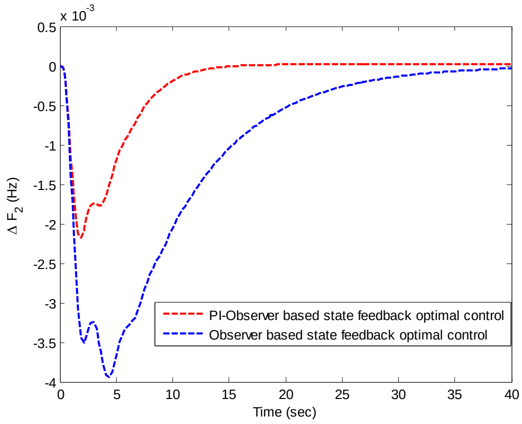


**Figure 9.** Response of $\Delta F_2$ for 1% load disturbance in area 1

the areas , the other areas are also disturbed. However the peak overshoot in both the areas are quite less for PI-observer based optimal scheme and the settling time is also improved by 11 sec in comparison to Luenberger observer based optimal control scheme. The oscillations in the response are also improved.

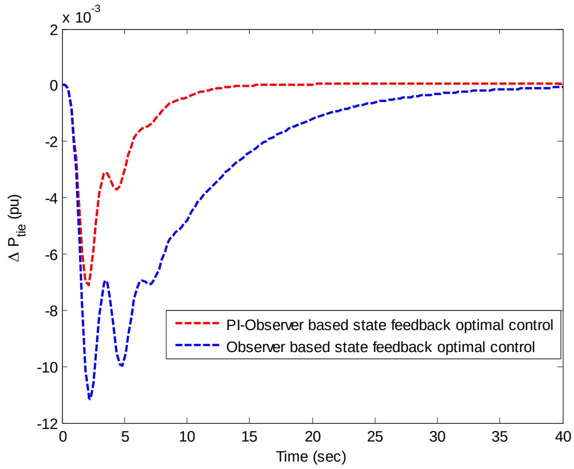


**Figure 10.** Response of $\Delta P_{tie}$ for 1% load disturbance in area 1

The tie-line power deviation is shown in fig10, the deviation will converge to zero as soon as the power imbalances settles in the area of disturbance. The performance of the proposed control scheme displays the remarkable reduction in peak overshoot, settling time and oscillations during the course of disturbance in an interconnected power system.

## VI. Conclusion

The study of PI-Observer based optimal AGC regulator for two area power system model has been carried out. Modern control theory is used in the development of power system model, observer model and finding the optimal gains via LQR technique for observer and state feedbacks. The Q and R for the observer gains and the controller gains are also selected optimally for the desired stable closed loop response of the system. From simulation of the proposed scheme it is inferred that response of PI-observer is appreciable fast as compared to Luenberger observer with an remarkable reduction in peak overshoot , settling time and oscillations while systems tends to achieve steady state conditions. Due to the proportional and integral components the convergence of estimation error of the PI-Observer is faster than Luenberger observer therefore system responses are also improved for the former scheme. Moreover from the time response plot it is also concluded that the performance of the proposed control scheme are also robust against the non-linearity present in the system.

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**Appendix-A:**
**List of symbols and Abbreviations**

**Table 1**

| Sr. No. | Symbol for $i^{th}$ (i=1,2) area | Numerical value |
|---|---|---|
| 1 | $B_i$ | 0.4249 |
| 2 | $R_i$ | 2.4 Hz/puMW |
| 3 | $K_{ii}$ | - |
| 4 | $T_{gi}$ | 0.08 s |
| 5 | $T_{ti}$ | 0.3 s |
| 6 | $T_{Pi}$ | 20 s |
| 7 | $T_{12}$ | 0.0868 MW |
| 8 | H | 5 MW-s/MVA |
| 9 | $F_r$ | 60 Hz |
| 10 | D | 0.8 |
| 11 | $P_{ri}$ | 2000 MW |

**NOMENCLATURE**

**Table 2.**

| | |
|---|---|
| Bias constant | $B_i$ |
| Regulation Constant | $R_i$ |
| Gain of controller | $K_{ii}$ |
| Steam turbine governor time constant | $T_{gi}$ |
| Steam turbine time constant | $T_{ti}$ |
| Time constant of power system | $T_{Pi}$ |
| Tie line power coefficient | $T_{12}$ |
| Inertia constant | H |
| Rated frequency | $F_r$ |
| Damping constan | D |
| Power rating of control area | $P_{ri}$ |