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Multi-area Load Frequency Control using IP Controller Tuned by Particle Swarm Optimization

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Abstract: In this study an optimal load frequency controller for multi area electric power systems is presented. In multi area electric power systems if a large load is suddenly connected (or disconnected) to the system, or if a generating unit is suddenly disconnected by the protection equipment, there will be a long-term distortion in the power balance between that delivered by the turbines and that consumed by the loads. This imbalance is initially covered from the kinetic energy of rotating rotors of turbines, generators and motors and, as a result, the frequency in the system will change. Therefore The Load Frequency Control (LFC) problem is one of the most important subjects in the electric power system operation and control. In practical systems, the conventional PI type controllers are carried out for LFC. In order to overcome the drawbacks of the conventional PI controllers, numerous techniques have been proposed in literatures. In this paper a IP type controller is considered for LFC problem. The parameters of the proposed IP controller are tuned using Particle Swarm Optimization (PSO) method. A multi area electric power system with a wide range of parametric uncertainties is given to illustrate proposed method. To show effectiveness of the proposed method, a PI type controller optimized by PSO is incorporated in order to comparison with the proposed IP controller. The simulation results on a multi area electric power system emphasis on the viability and feasibility of the proposed method in LFC problem.

Key words: IP controller, load frequency control, particle swarm optimization, multi area electric power system

INTRODUCTION

For large scale electric power systems with interconnected areas, Load Frequency Control (LFC) is important to keep the system frequency and the inter-area tie power as near to the scheduled values as possible. The input mechanical power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. A well designed and operated power system must cope with changes in the load and with system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits.

Many control strategies for Load Frequency Control in electric power systems have been proposed by researchers over the past decades. This extensive research is due to fact that LFC constitutes an important function of power system operation where the main objective is to regulate the output power of each generator at prescribed levels while keeping the frequency fluctuations within pre-specifies limits. A unified tuning of PID load frequency controller for power systems via internal mode control has been proposed by Tan (2010). In this paper the tuning method is based on the Two-Degree-of-Freedom (TDF) internal model control (IMC) design method and a PID approximation procedure. A new discrete-time sliding mode controller for load-frequency control in areas control of a power system has been presented by Vrdoljak *et al*. (2010). In this study full-state feedback is applied for LFC not only in control areas with thermal power plants but also in control areas with hydro power plants, in spite of their non minimum phase behaviors. To enable full-state feedback, a state estimation method based on fast sampling of measured output variables has been applied. The applications of artificial neural network, genetic algorithms and optimal control to LFC have been reported by Kocaarslan and Cam (2005), Rerkpreedapong *et al*. (2003) and Liu *et al.* (2003). An adaptive decentralized load frequency control of multi-area power systems has been presented by Zribi *et al*. (2005). Also the application of robust control methods for load frequency control problem has been presented by Shayeghi *et al*. (2007) and Taher and Hematti (2008).

This study deals with a design method for LFC in a multi area electric power system using a IP type controller whose parameters are tuned using PSO. In order to show effectiveness of the proposed method, this IP controller is

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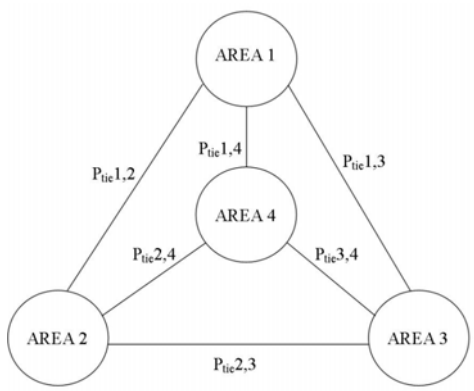


Fig. 1: Four-area electric power system with interconnections

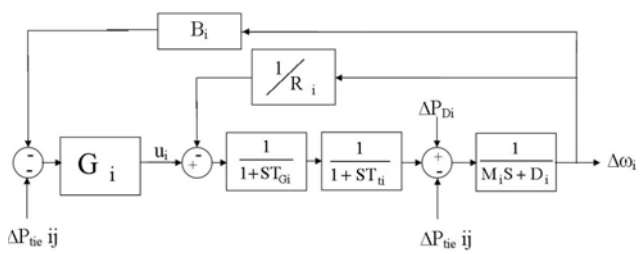


Fig. 2: Block diagram for one area of system (i^{th} area)

compared with a PI type controller whose parameters are tuned using PSO too. Simulation results show that the IP controller guarantees robust performance under a wide range of operating conditions and system uncertainties.

PLANT MODEL

A four-area electric power system is considered as a test system and shown in Fig. 1. The block diagram for each area of interconnected areas is shown in Fig. 2 (Wood and Wollenberg, 2003).

The parameters in Fig. 2 are defined as follow:

Δ	: Deviation from nominal value
$M_i = 2H$	: Constant of inertia of ith area
D_i	: Damping constant of ith area
R_i	: Gain of speed droop feedback loop of ith area
T_{ti}	: Turbine Time constant of ith area
T_{gi}	: Governor Time constant of ith area
G_i	: Controller of ith area
P_{di}	: Load change of ith area
u_i	: Reference load of ith area
$B_i = (1/R_i)+D_i$	: Frequency bias factor of ith area
P_{tie} ij	: Inter area tie power interchange from i^{th} area to j^{th} area.

where, i = 1, 2, 3, 4, j = 1, 2, 3, 4 and $i \neq j$

The inter-area tie power interchange is as (1) (Wood and Wollenberg, 2003):

$$P_{tie}ij = (\Delta\omega_i - \Delta\omega_j)\times(T_{ij}/S). \quad (1)$$

where, $T_{ij} = 377\times(1/X_{tie}ij)$ (for a 60 Hz system); $X_{tie}ij$: Impedance of transmission line between i and j areas

The ΔP_{tie} ij block diagram is shown as Fig. 3. Figure 2 shows the block diagram of ith area and Fig. 3 shows the method of interconnection between i^{th} and j^{th} areas. The state space model of four-area interconnected power system is as (2) (Wood and Wollenberg, 2003):

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX \end{cases} \quad (2)$$

where,

$U = [\ \Delta P_{D1}\ \Delta P_{D2}\ \Delta P_{D3}\ \Delta P_{D4}\ u_1\ u_2\ u_3\ u_4]$

$Y = [\ \Delta\omega_1\ \Delta\ \omega_2\ \Delta\omega_3\ \Delta\ \omega_4\ \Delta\ P_{tie}1,2\ \ \Delta P_{tie}1,3\ \ \Delta P_{tie}1,4\ \ \Delta P_{tie}2,3\ \Delta P_{tie}2,4\ \ \Delta P_{tie}3,4]$

$X = [\ \Delta P_{G1}\ \ \Delta P_{T1}\ \ \omega_1\ \ \Delta P_{G2}\ \ \Delta P_{T2}\ \ \omega_2\ \ \Delta P_{G3}\ \ \Delta P_{T3}\ \ \omega_3\ \ \Delta P_{G4}\ \ \Delta P_{T4}\ \Delta\omega_4\ \Delta P_{tie}1,2\ \Delta P_{tie}1,3\ \Delta P_{tie}1,4\ \Delta P_{tie}2,3\ \Delta P_{tie}2,4\ \ \Delta P_{tie}3,4]$

The matrixes A and B in (2) and the typical values of system parameters for the nominal operating condition are given in appendix. As refereed before, the IP type controller is incorporated to LFC problem. IP type controller is introduced in the next section.

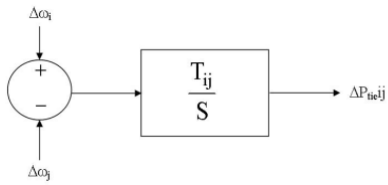


Fig. 3: Block diagram of inter area tie power ($\Delta P_{tie}ij$)

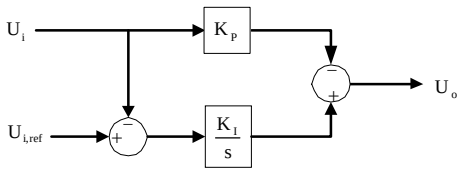


Fig. 4: Structure of the IP controller

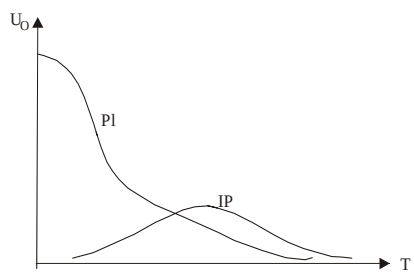


Fig. 5: Output of IP and PI regulators with the same damping coefficient ($\xi = 1$) and the same band width at the same step input signal command

IP controller: As referred before, in this study IP type controllers are considered for LFC problem. Fig. 4 shows the structure of IP controller. It has some clear differences with PI controller. In the case of IP regulator, at the step input, the output of the regulator varies slowly and its magnitude is smaller than the magnitude of PI regulator at the same step input (Sul, 2011). Also as shown in Fig.5, If the outputs of the both regulators are limited as the same value by physical constraints, then compared to the bandwidth of PI regulator the bandwidth of IP regulator can be extended without the saturation of the regulator output (Sul, 2011).

DESIGN METHODOLOGY

The proposed IP controller performance is evaluated on the proposed test system given in section 2. The parameters of the IP controllers are obtained using PSO. In the next subsection a brief introduction about PSO is presented.

Particle swarm optimization: PSO was formulated by Edward and Kennedy in 1995. The thought process behind the algorithm was inspired by the social behavior of animals, such as bird flocking or fish schooling. PSO is similar to the continuous GA in that it begins with a random population matrix. Unlike the GA, PSO has no evolution operators such as crossover and mutation. The rows in the matrix are called particles (same as the GA chromosome). They contain the variable values and are not binary encoded. Each particle moves about the cost surface with a velocity. The particles update their velocities and positions based on the local and global best solutions as shown in (3) and (4) (Randy and Sue, 2004):

$$V_{m,n}^{new} = w \times V_{m,n}^{old} + \Gamma_1 \times r_1 \times (P_{m,n}^{local\ best} - P_{m,n}^{old}) + \Gamma_2 \times r_2 \times (P_{m,n}^{global\ best} - P_{m,n}^{old}) \quad (3)$$

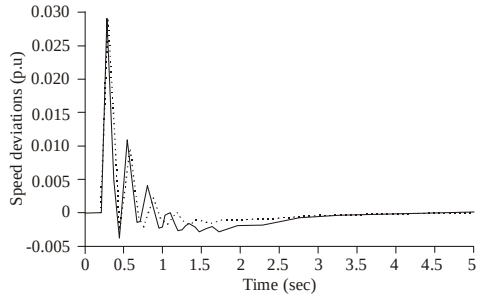
$$P_{m,n}^{new} = P_{m,n}^{old} + \Gamma V_{m,n}^{new} \quad (4)$$

where,

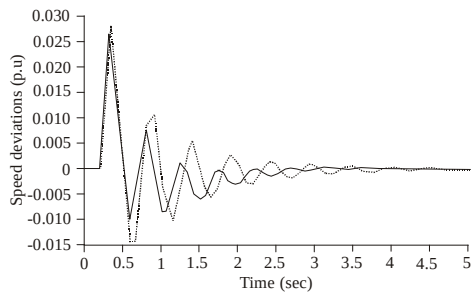
$V_{m,n}$ = particle velocity
$P_{m,n}$ = particle variables
W = inertia weight
r_1, r_2 = independent uniform random numbers
$\Gamma_1 = \Gamma_2$ = learning factors
$P_{m,n}^{local\ best}$ = best local solution
$P_{m,n}^{global\ best}$ = best global solution

The PSO algorithm updates the velocity vector for each particle then adds that velocity to the particle position or values. Velocity updates are influenced by both the best global solution associated with the lowest cost ever found by a particle and the best local solution associated with the lowest cost in the present population. If the best local solution has a cost less than the cost of the current global solution, then the best local solution replaces the best global solution. The particle velocity is reminiscent of local minimizes that use derivative information, because velocity is the derivative of position. The advantages of PSO are that it is easy to implement and there are few parameters to adjust. The PSO is able to tackle tough cost functions with many local minima (Randy and Sue, 2004).

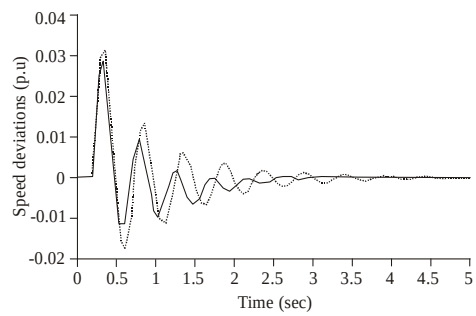
IP controller tuning using PSO: In this section the parameters of the proposed IP controllers are tuned using PSO. The IP controller has two parameters denoted by K_P and K_I and for each area there is one IP controller. Therefore in four-area electric power system with four IP controllers, there are 8 parameters for tuning. These K parameters are obtained based on the PSO. In section 2, the system controllers showed in Fig. 2 as G_i. Here these controllers are substituted by IP controllers and the optimum values of K_P and K_I are accurately computed using PSO. In optimization methods, the first step is to



(a)



(b)



(c)

Fig. 6: Dynamic response $\Delta\omega_1$ following step change in demand of first area (ΔP_{D1})a: Nominal b: Heavy c: Very heavy Solid (IP controller), Dashed (PI controller)

define a performance index for optimal search. In this study the performance index is considered as (5). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE).

$$ITAE = \int_0^t t|\Delta\omega_1|dt + \int_0^t t|\Delta\omega_2|dt + \int_0^t t|\Delta\omega_3|dt + \int_0^t t|\Delta\omega_4|dt \quad (5)$$

The parameter "t" in ITAE is the simulation time. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 10% step change in DP_{D1} is assumed

Table 1: Optimum values of K_p and K_I for IP controllers

	K_p	K_I
First area IP parameters	2.8052	6.8480
Second area IP parameters	3.1648	0.0100
Third area IP parameters	3.8596	2.5493
Fourth area IP parameters	4.5105	0.0100

Table 2: Optimum values of K_p and K_I for PI controllers

	K_p	K_I
First area PI parameters	2.2246	4.6662
Second area PI parameters	2.9728	3.4242
Third area PI parameters	0.5257	1.3945
Fourth area PI parameters	0.1966	1.6119

Table 3: 5% Step increase in demand of 1st area (P_{D1})

	The calculated ITAE	
	PI	IP
Nominal operating condition	0.0159	0.0119
Heavy operating condition	0.0219	0.0148
Very heavy operating condition	0.0237	0.0155

Table 4: 5% Step increase in demand of 1st area (P_{D1}) and 10% step increase in demand of 3rd area (P_{D3})

	The calculated ITAE	
	PI	IP
Nominal operating condition	0.0328	0.0277
Heavy operating condition	0.0459	0.0368
Very heavy operating condition	0.0491	0.0379

and the performance index is minimized using PSO. In order to acquire better performance, number of particle, particle size, number of iteration, Γ_1, Γ_2 and Γ are chosen as 24, 8, 40, 2, 2 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4. It should be noted that PSO algorithm is run several times and then optimal set of parameters is selected. The optimum values of the parameters K_P and K_I are obtained using PSO and summarized in the Table 1.

RESULTS AND DISCUSSION

In this section the proposed IP controller is applied to the system for LFC. In order to comparison and show effectiveness of the proposed method, another PI type controller optimized by PSO is designed for LFC. The optimumvalueofthe IP controllers Parameters are obtained using genetic algorithms and summarized in the Table 2.

In order to study and analysis system performance under system uncertainties (controller robustness), three operating conditions are considered as follow:

- Nominal operating condition
- Heavy operating condition (20% changing parameters from their typical values)
- Very heavy operating condition (40% changing parameters from their typical values)

In order to demonstrate the robustness performance of the proposed method, The ITAE is calculated following step change in the different demands (ΔDP_D) at all

Table 5: Typical values of system parameters for the nominal operating condition

1st area parameters			
$T_{T1} = 0.035$	$T_{G1} = 0.08$	$M_1 = 0.1667$	$R_1 = 2.4$
$D_1 = 0.0083$	$B_1 = 0.401$	$T_{12} = 0.425$	$T_{13} = 0.500$
$T_{14} = 0.400$	$T_{23} = 0.455$	$T_{24} = 0.523$	$T_{34} = 0.600$
2nd area parameters			
$T_{T2} = 0.025$	$T_{G2} = 0.091$	$M_2 = 0.1552$	$R_2 = 2.1$
$D_2 = 0.009$	$B_2 = 0.300$	$T_{12} = 0.425$	$T_{13} = 0.500$
$T_{14} = 0.400$	$T_{23} = 0.455$	$T_{24} = 0.523$	$T_{34} = 0.600$
3rd area parameters			
$T_{T3} = 0.044$	$T_{G3} = 0.072$	$M_3 = 0.178$	$R_3 = 2.9$
$D_3 = 0.0074$	$B_3 = 0.480$	$T_{12} = 0.425$	$T_{13} = 0.500$
$T_{14} = 0.400$	$T_{23} = 0.455$	$T_{24} = 0.523$	$T_{34} = 0.600$
4th area parameters			
$T_{T4} = 0.033$	$T_{G4} = 0.085$	$M_4 = 0.1500$	$R_4 = 1.995$
$D_4 = 0.0094$	$B_4 = 0.3908$	$T_{12} = 0.425$	$T_{13} = 0.500$
$T_{14} = 0.400$	$T_{23} = 0.455$	$T_{24} = 0.523$	$T_{34} = 0.600$

operating conditions (Nominal, Heavy and Very heavy) and results are shown at Table 3-4. Following step change, the IP controller has better performance than the PI controller at all operating conditions (Table 5).

Figure 6 shows $\Delta\omega_1$ at nominal, heavy and very heavy operating conditions following 10 % step change in the demand of first area (ΔDP_{D1}). It is seen that the IP controller has better performance than the other method at all operating conditions.

CONCLUSION

In this study a new PSO based IP controller has been successfully carried out for Load Frequency Control problem. The proposed method was applied to a typical four-area electric power system containing system parametric uncertainties and various loads conditions. Simulation results demonstrated that the IP controllers capable to guarantee the robust stability and robust performance under a wide range of uncertainties and load

Appendix: The typical values of system parameters for the nominal operating condition are presented in Table 5. Also the matrixes A and B in (2) are as follow:

$$A = \begin{bmatrix}
\frac{-1}{T_{G1}} & 0 & \frac{-1}{R_1 T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{T_{T1}} & \frac{-1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{M_1} & \frac{-D_1}{M_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{M_1} & \frac{-1}{M_1} & \frac{-1}{M_1} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{T_{G2}} & 0 & \frac{-1}{R_2 T_{G2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{T_{T2}} & \frac{-1}{T_{T2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{M_2} & \frac{-D_2}{M_2} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{M_2} & 0 & 0 & \frac{-1}{M_2} & \frac{-1}{M_2} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{G3}} & 0 & \frac{-1}{R_3 T_{G3}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{T3}} & \frac{-1}{T_{T3}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{M_3} & \frac{-D_3}{M_3} & 0 & 0 & 0 & 0 & \frac{1}{M_3} & 0 & \frac{1}{M_3} & 0 & \frac{-1}{M_3} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{G4}} & 0 & \frac{-1}{R_4 T_{G4}} & 0 & 0 & 0 & 0 & 0 & 00 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{T4}} & \frac{-1}{T_{T4}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{M_4} & \frac{-D_4}{M_4} & 0 & 0 & \frac{1}{M_4} & 0 & \frac{1}{M_4} & \frac{1}{M_4} \\
0 & 0 & T_{12} & 0 & 0 & -T_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & T_{13} & 0 & 0 & 0 & 0 & 0 & -T_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & T_{14} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -T_{14} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & T_{23} & 0 & 0 & -T_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & T_{24} & 0 & 0 & 0 & 0 & 0 & -T_{24} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{34} & 0 & 0 & -T_{34} & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$B = \begin{bmatrix}
0 & 0 & \frac{1}{M_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{M_2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{M_3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{M_4} & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{T_{G2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{G3}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{G4}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

conditions. Also, the simulation results showed that the IP controller is robust to change in the system parameters and it has better performance than the PI type controller at all operating conditions.

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