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Multi-area Load Frequency Control using IP Controller Tuned by Simulated Annealing

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Abstract: 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 Simulated Annealing (SA) 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 SA 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: Multi Area Electric Power System · Load Frequency Control · Simulated Annealing · IP Controller

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 in [1]. 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 in [2]. In this paper 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 in [3-5]. An adaptive decentralized load frequency control of multi-area power systems has been presented in [6]. Also the application of robust control methods for load frequency control problem has been presented in [7-8].

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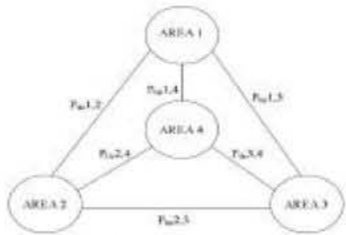

Fig. 1: Four-area electric power system with interconnections

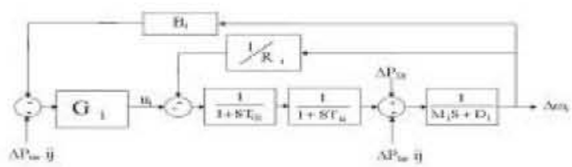

Fig. 2: Block diagram for one area of system (ith area)

This paper deals with a design method for LFC in a multi area electric power system using a IP type controller whose parameters are tuned using SA. In order to show effectiveness of the proposed method, this IP controller is compared with a PI type controller whose parameters are tuned using SA too. Simulation results show that the IP controller guarantees robust performance under a wide range of operating conditions and system uncertainties.

Apart from this introductory section, this paper is structured as follows. The system under study and system modeling are presented in section 2. IP type controller is presented in section 3. The design methodology is developed in section 4 and the simulation results are presented in section 5.

Plant Model: A four-area electric power system is considered as a test system and shown in Figure 1. The block diagram for each area of interconnected areas is shown in Figure 2 [9].

The parameters in Figure 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

ΔP_{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

ΔP_{tie} ij: Inter area tie power interchange from ith area to jth area.

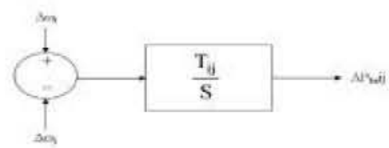

Fig. 3: Block diagram of inter area tie power (ΔP_{tie}ij)

Where:
i=1, 2, 3, 4 j=1, 2, 3, 4 and iΔj

The inter-area tie power interchange is as (1) [9].

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

Where:

$$T_{ij}=377\times(1/X_{tie}ij) \text{ (for a 60 Hz system)}$$

X_{tie}ij: impedance of transmission line between i and j areas

The ΔP_{tie}ij block diagram is shown as Figure 3.

Figure 2 shows the block diagram of ith area and Figure 3 shows the method of interconnection between ith and jth areas. The state space model of four-area interconnected power system is as (2) [9].

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

Where:

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

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

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

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.

IP Controller: As referred before, in this paper IP type controllers are considered for LFC problem. Figure 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

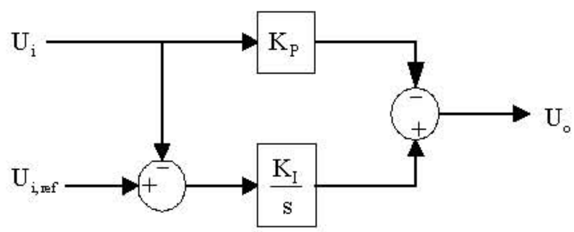

Fig. 4: Structure of the IP controller

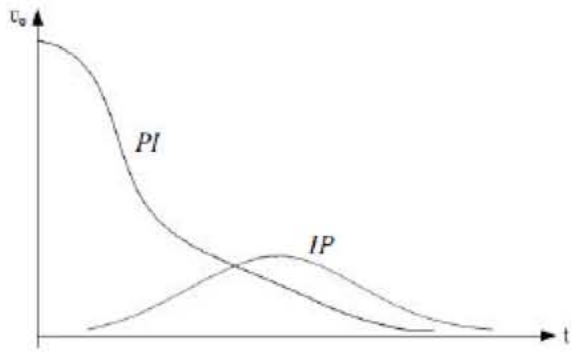

Fig. 5: Output of IP and PI regulators with the same damping coefficient ($\xi = 1$) and the same band width at the same step input signal command

and its magnitude is smaller than the magnitude of PI regulator at the same step input [10]. Also as shown in Figure 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 [10].

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 SA. In the next subsection a brief introduction about SA is presented.

Simulated Annealing: In the early 1980s the method of simulated annealing (SA) was introduced in 1983 based on ideas formulated in the early 1950s. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes its energy probability distribution. This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithmic analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, f, associated with a set of variables. If the output decreases, then the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

$$r \le e^{[f(p_{old}) - f(p_{new})]/T} \tag{3}$$

Where, r is a uniform random number and T is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability. The new variable set is found by taking a random step from the old variable Set as (4).

$$P^{new} = dP^{old} \tag{4}$$

The variable d is either uniformly or normally distributed about p^{old}. This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point the value of T and d decrease by a certain percent and the algorithm repeats. The algorithm stops when $T \to 0$. The decrease in T is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is T_0 and the ending temperature is T_N, then the temperature at step n is given by (5).

$$T_n = f(T_0, T_N, N, n) \tag{5}$$

Where, f decreases with time. Some potential cooling schedules are as follows:

- Linearly decreasing: $T_n = T_0 - n(T_0 - T_n)/N$
- Geometrically decreasing: $T_n = 0.99\, T_{n-1}$
- Hayjek optimal: $T_n = c/\log(1+n)$, where c is the smallest variation required to get out of any local minimum.

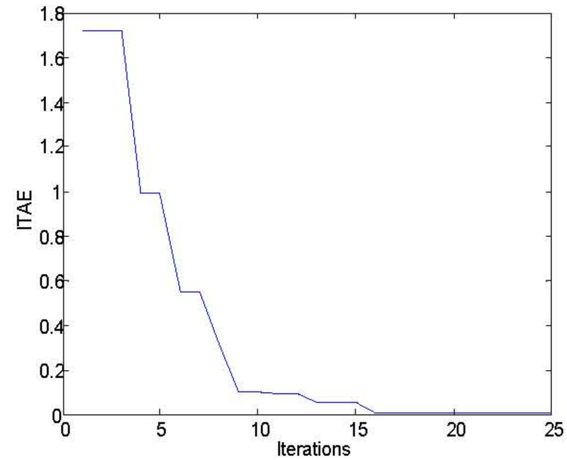

Fig. 6: Convergence of SA algorithm

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems [11].

IP Controller Tuning Using SA: In this section the parameters of the proposed IP controllers are tuned using SA. 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 SA. In section 2, the system controllers showed in Figure 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 SA. In optimization methods, the first step is to define a performance index for optimal search. In this study the performance index is considered as (6). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (*ITAE*).

$$ITAE = \int_0^t t|??_1|dt + \int_0^t t|??_2|dt + \int_0^t t|??_3|dt + \int_0^t t|??_4|dt \quad (6)$$

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 ΔP_{D1} is assumed and the performance index is minimized using SA. It should be noted that SA algorithm is run several times and then optimal set of parameters is selected. Initializing the values of the parameters for this paper is as follows:

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

	K_P	K_I
First area IP parameters	3.2484	7.1910
Second area IP parameters	4.9104	0.0121
Third area IP parameters	5.9110	0.0307
Fourth area IP parameters	4.7779	0.0103

- Population size – 100
- Initial Temperature- 1500
- Decrement Temperature- 10
- Termination temperature- 0.001
- Multiplication Factor – (Ti - Td)/ Ti = 0.995

The optimum values of the parameters K_P and K_I are obtained using SA and summarized in the Table 1. The convergence of SA algorithm is depicted in Figure 6.

RESULTS AND DISCUSSIONS

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 SA is designed for LFC. The optimum value of the 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)

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

	K_P	K_I
First area PI parameters	2.4326	5.1652
Second area PI parameters	2.7418	3.1236
Third area PI parameters	0.4268	1.4247
Fourth area PI parameters	0.1773	1.1639

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

	The calculated ITAE	
	IP	PI
Nominal operating condition	0.0105	0.0150
Heavy operating condition	0.0136	0.0219
Very heavy operating condition	0.0138	0.0235

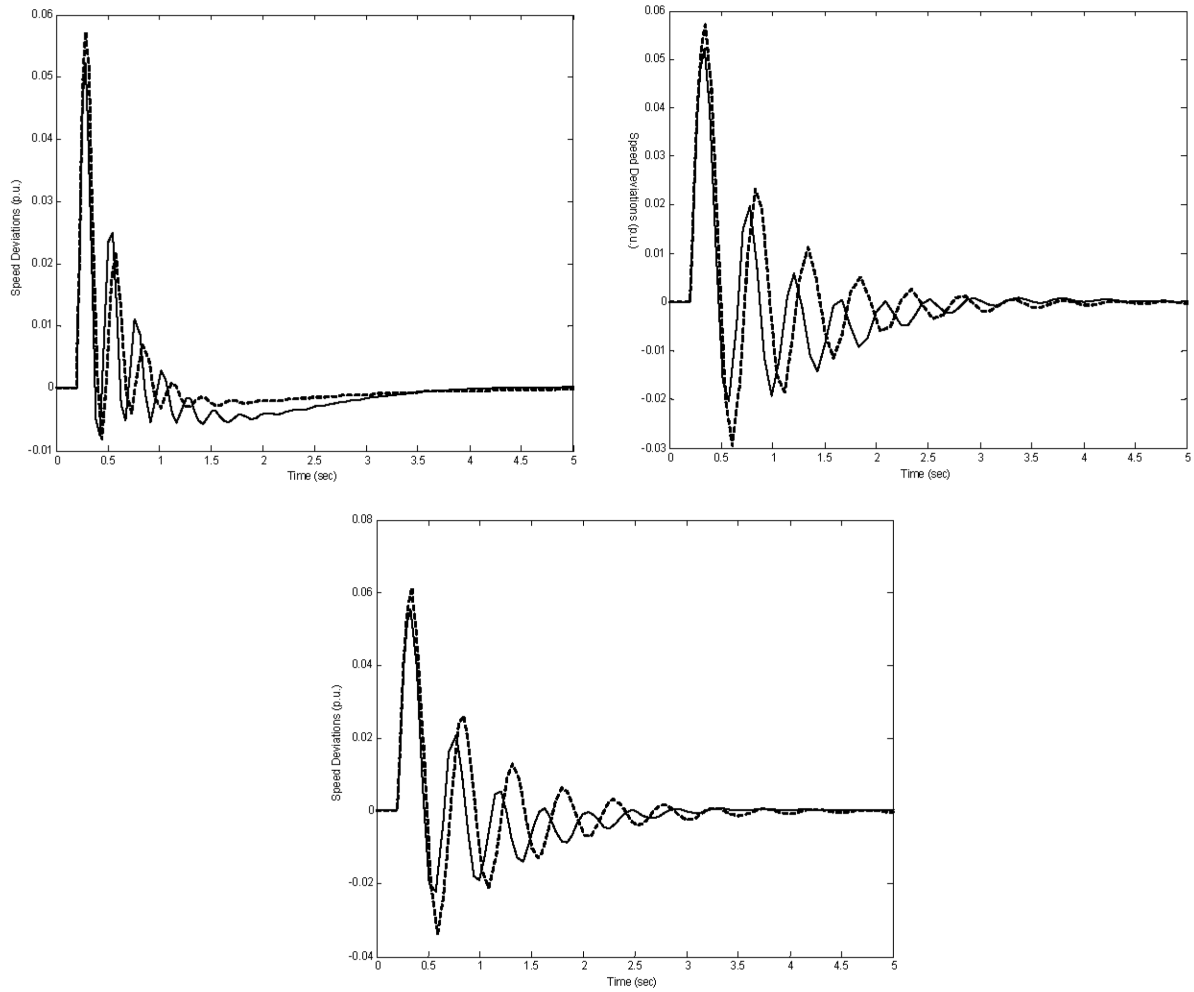

Fig. 7: Dynamic response Δω1 following step change in demand of first area (ΔP_{D1})
a: Nominal b: Heavy c: Very heavy
Solid (IP controller), Dashed (PI controller)

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

	The calculated ITAE	
	IP	PI
Nominal operating condition	0.0277	0.0332
Heavy operating condition	0.0368	0.0464
Very heavy operating condition	0.0378	0.0495

In order to demonstrate the robustness performance of the proposed method, The *ITAE* is calculated following step change in the different demands (ΔP_D) at all operating conditions (Nominal, Heavy and Very heavy) and results are shown at Tables 3-4. Following step change, the IP controller has better performance than the PI controller at all operating conditions.

Figure 7 shows $\Delta\omega_1$ at nominal, heavy and very heavy operating conditions following 10 % step change in the demand of first area (ΔP_{D1}). It is seen that the IP controller has better performance than the other method at all operating conditions.

CONCLUSIONS

In this paper a new SA 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

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

performance under a wide range of uncertainties and load 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.

Appendix

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

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

$$A=\begin{bmatrix}
\frac{-1}{T_{G1}}&0&\frac{-1}{R_1T_{G1}}&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
\frac{1}{T_{T1}}&\frac{-1}{T_{T1}}&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&\frac{1}{M_1}&\frac{-D_1}{M_1}&0&0&0&0&0&0&0&0&0&\frac{-1}{M_1}&\frac{-1}{M_1}&\frac{-1}{M_1}&0&0&0\\
0&0&0&\frac{-1}{T_{G2}}&0&\frac{-1}{R_2T_{G2}}&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&\frac{1}{T_{T2}}&\frac{-1}{T_{T2}}&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&\frac{1}{M_2}&\frac{-D_2}{M_2}&0&0&0&0&0&0&\frac{1}{M_2}&0&0&\frac{-1}{M_2}&\frac{-1}{M_2}&0\\
0&0&0&0&0&0&\frac{-1}{T_{G3}}&0&\frac{-1}{R_3T_{G3}}&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&\frac{1}{T_{T3}}&\frac{-1}{T_{T3}}&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&\frac{1}{M_3}&\frac{-D_3}{M_3}&0&0&0&0&\frac{1}{M_3}&0&\frac{1}{M_3}&0&\frac{-1}{M_3}\\
0&0&0&0&0&0&0&0&0&\frac{-1}{T_{G4}}&0&\frac{-1}{R_4T_{G4}}&0&0&0&0&0&00\\
0&0&0&0&0&0&0&0&0&\frac{1}{T_{T4}}&\frac{-1}{T_{T4}}&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&\frac{1}{M_4}&\frac{-D_4}{M_4}&0&0&\frac{1}{M_4}&0&\frac{1}{M_4}&\frac{1}{M_4}\\
0&0&T_{12}&0&0&-T_{12}&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&T_{13}&0&0&0&0&0&-T_{13}&0&0&0&0&0&0&0&0&0\\
0&0&T_{14}&0&0&0&0&0&0&0&0&-T_{14}&0&0&0&0&0&0\\
0&0&0&0&0&T_{23}&0&0&-T_{23}&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&T_{24}&0&0&0&0&0&-T_{24}&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&T_{34}&0&0&-T_{34}&0&0&0&0&0&0
\end{bmatrix}$$

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