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Improvement of the Load Frequency Control Using Pole-Placement Technique

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Abstract

The classical design techniques that used for load frequency control are based on the root-locus that utilizes only the plant output for feedback with a dynamic controller. In this paper ,a new control technique known the pole-placement design is used to control the frequency and require the use of all state variables to form a linear static controller. The pole placement design allows all root of the characteristic equation to be placed in the desired location. This result will be in a regulator with constant gain vector K .The poles in this technique refer to the root of the characteristic equation and this poles are chosen arbitrary in order to find the best frequency deviation response . Different techniques of the load frequency control such as integral controller, PID controller and the pole placement controller are used and compared with each other to find the best techniques. Due to this comparison the pole placement design is the best technique for load frequency control. The programs are written using matlab package.

تحسين السيطرة على تردد الحمل بأستخدام طريقة تنسيب القطب

ملخص

تستخدم تقنيات التصميم التقليدية في السيطرة على تردد الحمل وتعتمد على مكان الجذر (Root- locus) الذي يستعمل فقط ناتج المحطة (plant station output) للمتعلقات (feedback) مع مسيطر متحرك (dynamic controller). أن هذا البحث يستخدم تقنية حديثة للسيطرة على التردد تعرف بطريقة تنسيب القطب **(pole placement design)** *التي تستخدم كل متغيرات الحالة (state variables) لتكوين مسيطر خطي ثابت (linear static controller). تسمح طريقة تنسيب القطب لكل جذور معادلة الخصائص (characteristic equation) بأن توضع بالمكان المصمم لها .ان هذه النتيجة ستكون بشكل منظم (regulator) مع موجه ثابت المكسب (constant gain vector (k)). تشير الاقطاب (poles) في هذه التقنية الى جذر معادلة الخصائص ويتم اختيارها بشكل عشوائي لايجاد افضل تاثير لانحراف التردد (frequency deviation response). تم استعمال عدة تقنيات للسيطرة على تردد الحمل كالمسيطر التكاملي (integral controller) والمسيطر PID ومسيطر تنسيب القطب (pole placement design) وتم المقارنة مع بعضها البعض لايجاد افضل تقنية للسيطرة على تردد الحمل ومن*

خلال هذه المقارنة فان طريقة تنسيب القطب هي افضل طريقة للسيطرة على تردد الحمل الكهربائي حيث تم الحصول على افضل تاثيرلانحراف التردد (frequency deviation response). تم كتابة البرنامج بلغة ماتلاب.

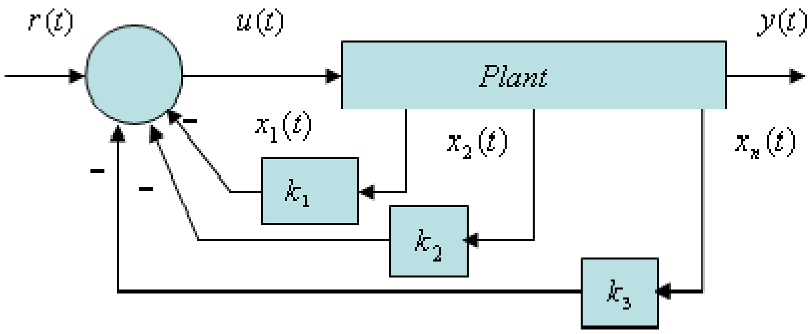
1. Introduction.

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

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$
$$y(t) = Cx(t)$$

Where x(t) is an n*1 state vector and u(t) is the scalar controller. Now consider the block diagram of the system shown in the figure(1) [1]

$$u(t) = -Kx(t) + r(t) \qquad (2)$$



Figure(1) Control system design via pole placement [2]

where K is 1*n vector of a constant feedback gain and the control system input r(t) is assumed to be zero. The purpose of this system is to return all state variables to value of zero when the states have been perturbed. Substituting equation (2) into equation(1), the compensated system state variable representation becomes

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

The compensated system characteristic equation is

$$|sI - A + BK| = 0 \qquad (4)$$

It will be shown in the following that if the pair ***[A,B]*** is completely controllable ,then a matrix ***K*** exists that can give an arbitrary eigenvalues of ***(A-BK)*** ;that is the n root of the characteristic equation in equation(4) can be arbitrary placed. Assume the system represented in the phase variable canonical(CCF) form as follow [2]:

$$A = \begin{bmatrix} 0 & 1 & 0 & .....0 \\ 0 & 0 & 1 & .....0 \\ . & & & \\ . & & & \\ -a_0 & -a_1 & -a_2 & .....-a_{n-1} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ . \\ 0 \\ 1 \end{bmatrix} \qquad (5)$$

The feedback gain matrix K is expressed as

$$K = [k_1 \quad k_2 \quad ....k_n]$$

Where ***k1,k2,……..kn*** are real constants .Then

$$A\text{-}B*K = \begin{bmatrix} 0 & 1 & 0 & .....0 \\ 0 & 0 & 1 & .....0 \\ . & & & \\ . & & & \\ -a_0 - k_1 & -a_1 - k_2 & & .....-a_{n-1} - k_n \end{bmatrix} \qquad (6)$$

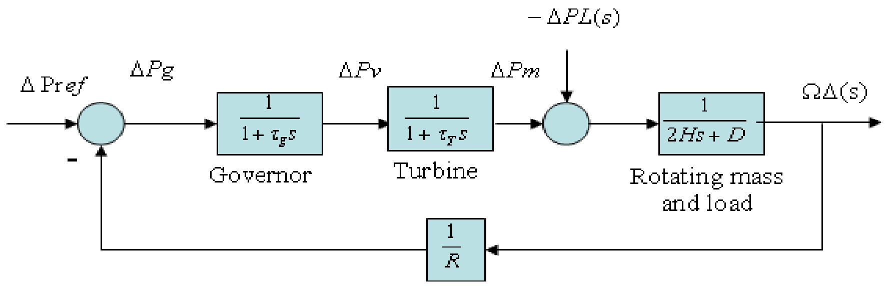
The eigen values of A-B*K are then found from the characteristic eq.

$$|sI - (A - B*K)| = s^n + (a_{n-1} + k_n)s^{n-1} + (a_{n-2} + k_{n-1})s^{n-2} + ...+ (a_0 + k_1) = 0 \qquad (7)$$

The eigenvalues can be arbitrarily assigned, since the feedback gains k1,k2,.kn are isolated in each coefficient of the characteristic equatio**.**

2. The Application of the Pole Placement Design on the Load Frequency Control.

The load frequency control (LFC) loop of an isolated power system is s shown in figure(2) . where each part of the power system is represent by its transfer function ,[3][4] where



Figure(2):Load frequency control(LFC) of power station system[4]
Δf or Δw or ΔΩ(s) is frequency deviation of the station .

D is expressed as percent change in load divided by percent change in frequency. For example if load change by 1.6 percent for 1 percent change in frequency, then D=1.6 .

R is the speed regulation factor($R = \frac{\Delta w}{\Delta P}$).

H is the inertia constant.

ΔPL is the change in the load.

ΔPm is the change in the mechanical power(input to the generation)

ΔPv is the change in the steam value position(input to the turbine).

ΔPref is the reference set power .

ΔPg is the difference between the reference set power ***ΔPref*** and the power (1/R* Δw) .

τg is the governor time constant .

τt is the turbine time constant . ***ΔPtie*** is the tie line power.

The s-domain equations describing the block diagram in figure(2) are

$$(1+\tau_g s)\Delta Pv(s) = \Delta \Pr ef - \frac{1}{R}\Delta\Omega(s)$$

$$(2Hs + D)\Delta\Omega(s) = \Delta Pm - \Delta P_L \qquad (8)$$

$$(2Hs + D)\Delta\Omega(s) = \Delta Pm - \Delta P_L$$

Solving for the first derivative term, yields

$$s\Delta Pv(s) = -\frac{1}{\tau_g}\Delta Pv - \frac{1}{R\tau_g}\Delta\Omega(s) + \frac{1}{\tau_g}\Delta \Pr ef(s)$$

$$s\Delta Pm(s) = \frac{1}{\tau_T}\Delta Pv - \frac{1}{\tau_T}\Delta Pm \qquad (9)$$

$$s\Delta\Omega(s) = \frac{1}{2H}\Delta Pm - \frac{D}{2H}\Delta\Omega(s) - \frac{1}{2H}\Delta P_L$$

Transforming into time-domain and expressed in matrix form, the state equation becomes [5][6].

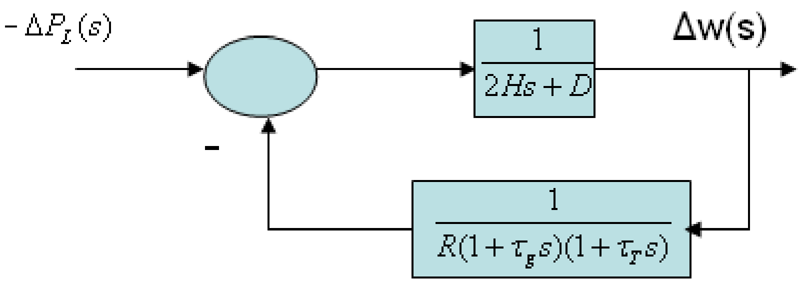
$$\begin{bmatrix} \Delta \dot{P}v \\ \Delta \dot{P}m \\ \Delta \dot{w} \end{bmatrix} = \begin{bmatrix} \frac{-1}{\tau_g} & 0 & \frac{-1}{R\tau_g} \\ \frac{1}{\tau_T} & \frac{-1}{\tau_T} & 0 \\ 0 & \frac{1}{2H} & \frac{-D}{2H} \end{bmatrix} . \begin{bmatrix} \Delta Pv \\ \Delta Pm \\ \Delta w \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{2H} \end{bmatrix} .\Delta P_L + \begin{bmatrix} \frac{1}{\tau_g} \\ 0 \\ 0 \end{bmatrix} .\Delta \Pr ef$$

$$A=\begin{bmatrix} \frac{-1}{\tau_g} & 0 & \frac{-1}{R\tau_g} \\ \frac{1}{\tau_T} & \frac{-1}{\tau_T} & 0 \\ 0 & \frac{1}{2H} & \frac{-D}{2H} \end{bmatrix} \qquad B=\begin{bmatrix} 0 \\ 0 \\ \frac{-1}{2H} \end{bmatrix} \qquad x=\begin{bmatrix} \Delta Pv \\ \Delta Pm \\ \Delta w \end{bmatrix} \tag{11}$$

and the output equation is y=Δw ,where C=[0 0 1] D=[0] (12)
Where A,B,C,D are the state space matrix.

2.1 The Calculation of the Load Frequency Control Using the Pole Placement Design

Figure(2) can be represented in other form as shown in figure(3) below



Figure(3) Load frequency control of input ΔPL(s) and output Δw(s) [5]

2.1.1 The parameters of the load frequency control

Let take arbitrary the parameters of the system in the figure(2) as follow:
Turbine time constant τ_T =0.5 sec. Governor time constant τ_g =0.2 sec.
Generator inertia constant H=5 sec. The speed regulation factor R=0.05.
Frequency sensitive load coefficient D=0.8.
The change in the load ΔPL=0.2 per unit & ΔPref=0, frequency f=50 Hz.

2.1.2 Load frequency control using the pole placement design

Using the state space equations in (10)(11)(12) and the data in the section 2.1.1 to find the frequency deviation response of the figure(2) where ：

$$A=\begin{bmatrix}-5 & 0 & -100\\ 2 & -2 & 0\\ 0 & 0.1 & -0.08\end{bmatrix} \qquad B=\begin{bmatrix}0\\ 0\\ -0.1\end{bmatrix} \qquad C=\begin{bmatrix}0 & 0 & 1\end{bmatrix} \qquad D=0\ .$$

In order to find the uncompensated closed loop transfer function of figure(2) ,This paper used the following commands in matlab pakage :

[num,den]=ss2tf(A,B,C,D) ***sys=TF(num,den)***

Where A,B,C,D is the above state space equation **.**

The uncompensated closed loop transfer function of figure (2)

$$sys=T(s)=\frac{\Delta w(s)}{-\Delta PL(s)}=\frac{-0.1s^2-0.7s-1}{s^3+7.08s^2+10.56s+20.8}$$

The eigenvalues which is the root of the characteristic equation are calculated using the command ***r=eig(A)*** of matlab package where

r=(-5.886 , -0.5968+1.7825 , -0.5968-1.7825i) .

The root locus of this system will be in the figure(4).The root locus intersect the jw axis at s=±j3.23 for gain k=73 (feed back gain).

Note that the speed regulation factor R is equal to R=1/k , that's mean R= 1/73=0.0137 , which it is the critical value of R and thus the system is stable for k < 73 (R>0.0137) .The data that took in this paper in section 2.1.1 is in the limit of stability where the speed regulation factor R=0.05, that's mean the feed back gain k=1/R=1/0.05 =20 and it is less than the critical value of k=73.The advantage of the root locus in this paper is to satisfied the stability limit of the system only and not to comparison between the different methods of control system to choose the best method , therefore this paper took the frequency deviation (**Δ*f*** or **Δ*w or* Δ*Ω(s)***) to satisfied the best method of the load frequency control system. The frequency deviation step response ΔΩ(s) or Δw(s) of uncompensated system of the figure(2) will be in the figure(5) without using any control .

Now in order to apply the pole placement design on the load frequency control in the figure(2),let take the pole or the root of the system characteristic which is chosen arbitrary at ***Pole=(-3 , -2-j6 ,-2+j6)***

Then using the matlab command ***K=place(A,B,P)*** to find a linear static gain K ,where A,B are the state space matrix of the uncompensated system of figure(2)and P is the pole that chosen arbitrary.

Due to this command, the linear static control K is ***(4.2 ,0.8 ,0.8)***

The compensated system closed loop transfer function is AA=(A-B*K)

-5	0	-100
2	-2	0
0.42	0.18	0

Then using the same commands

[num,den]=ss2tf(AA,B,C,D) ***sys=TF(num,den)***

to find the transfer function of compensated system ,where
Where AA is the above compensated matrix AA=(A-B*K)

$$sys = T(s) = \frac{\Delta w(s)}{-\Delta PL(s)} = \frac{-0.1s^2 - 0.7s^2 - 1}{s^3 + 7s^2 + 52s + 120}$$

The eigenvalues of the compensated matrix AA is r=(-3 ,-2+j6 ,-2-j6)
Which is the pole or the root of the characteristic equation that chosen arbitrary as before, and the frequency deviation response of figure(2) with pole placement design at pole(-3 ,-2-j6 ,-2-j6) will be in figure(6).The same process of pole placement can be return for different poles until getting the best frequency deviation response as in the figures (6)(7)(8)

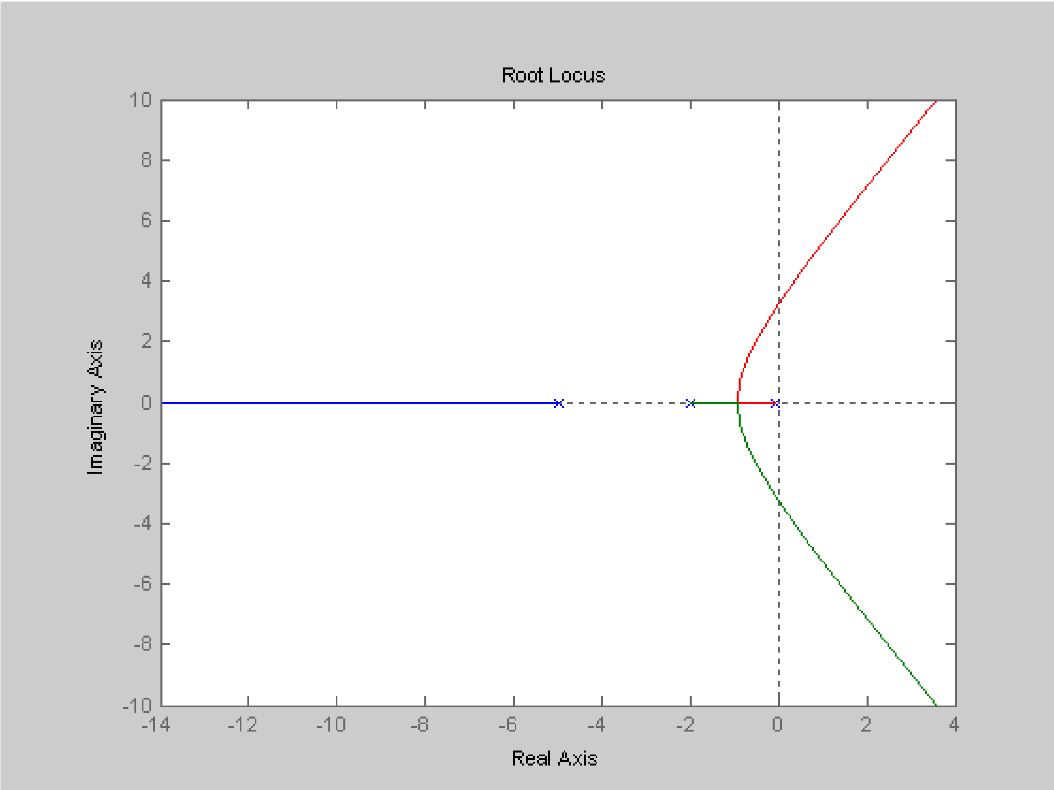
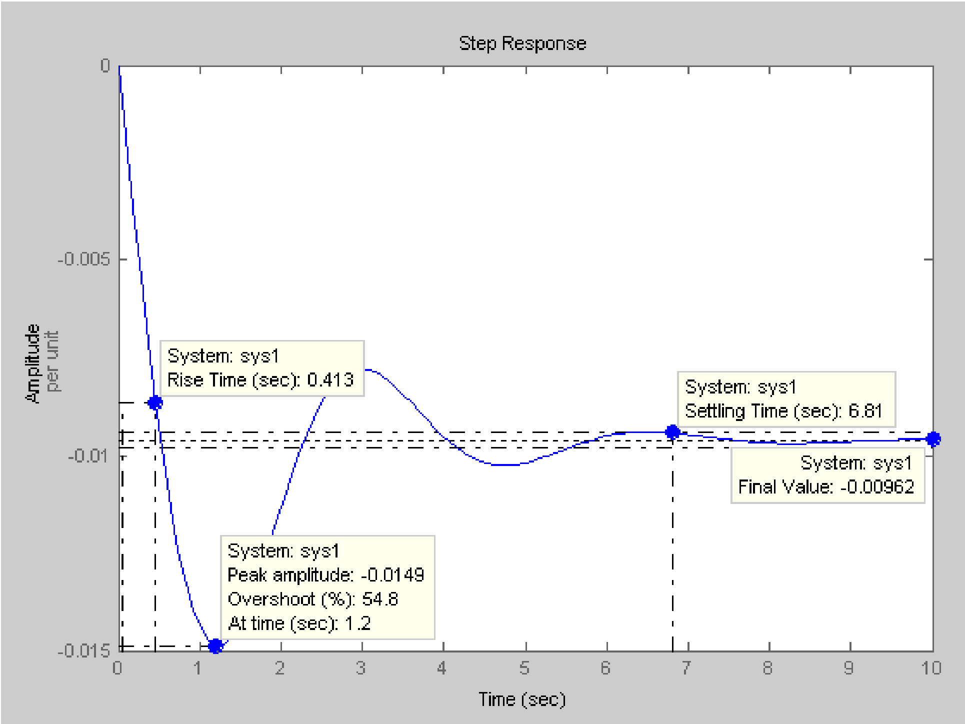
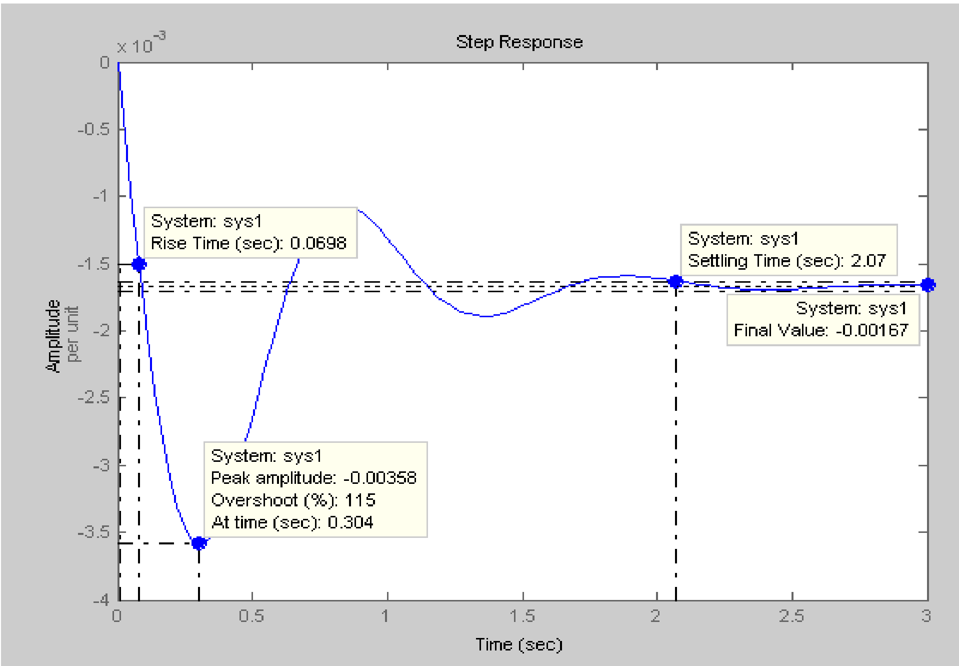


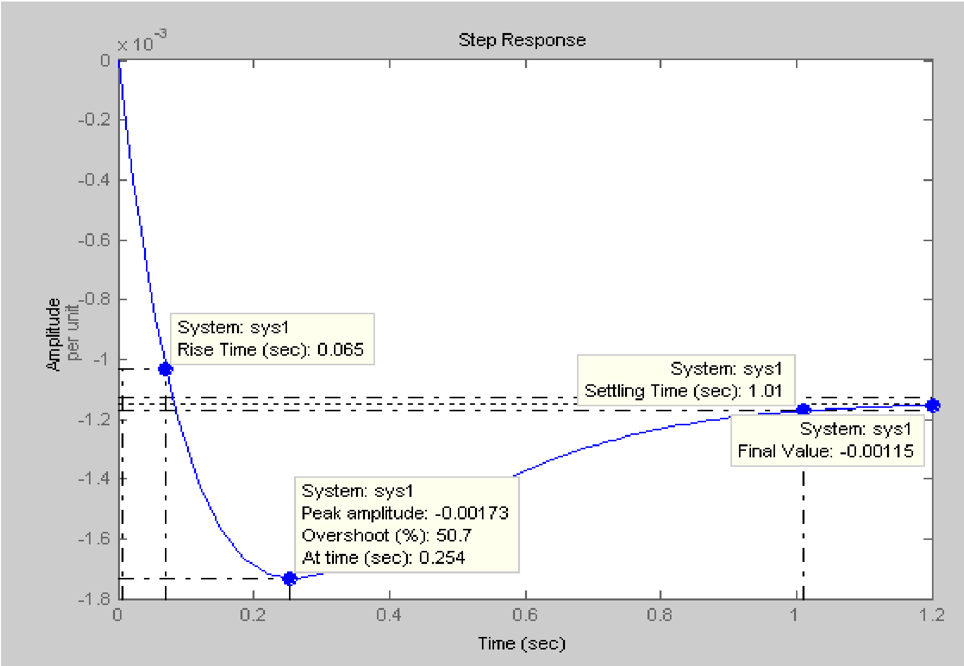
Figure (4) the root locus of uncompensated system



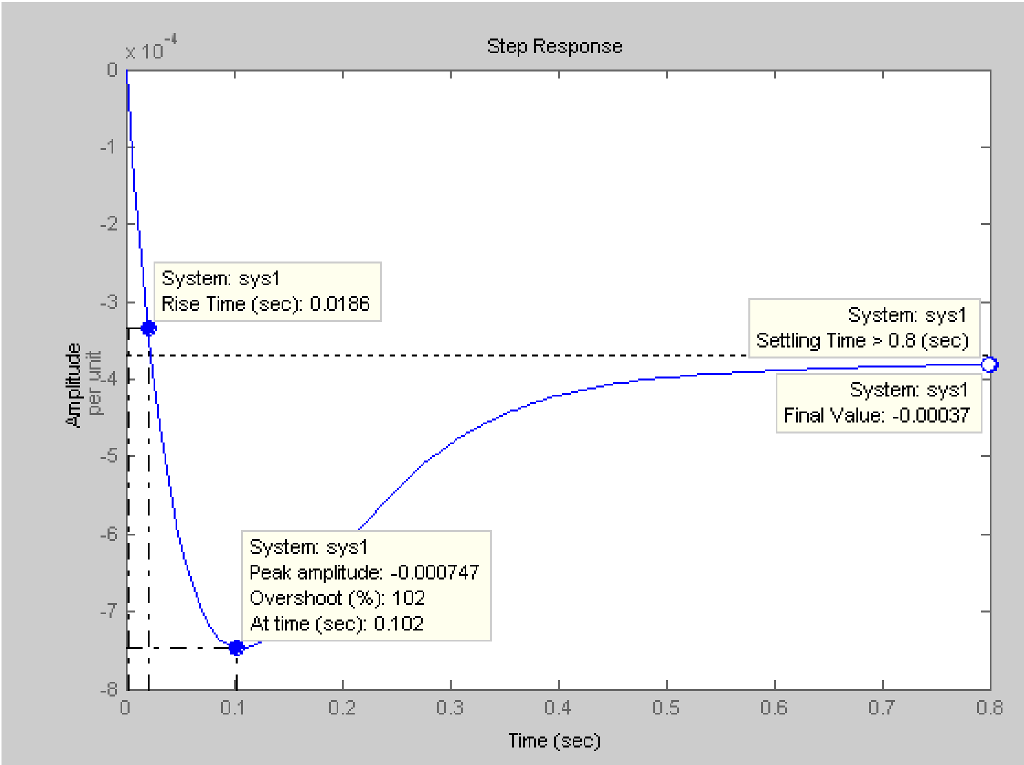
Figure(5) Uncompensated frequency deviation step response



Figure(6)Frequency deviation of pole placement at pole(-3,-2-j6,-2+j6)



Figure(7)Frequency deviation of pole placement at pole(-6,-5-j2,-5+j2)



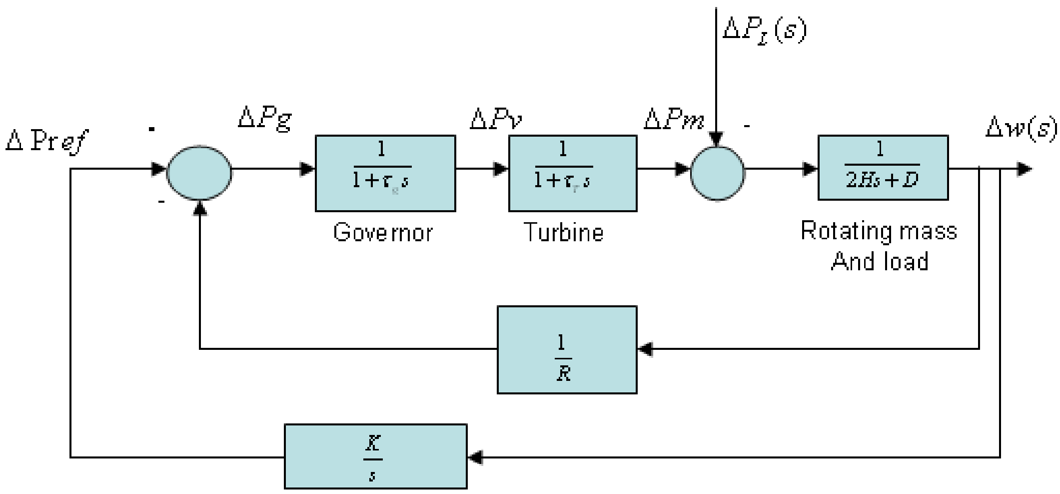
Figure(8)Frequency deviation of pole placement at pole (-3,-12-j6,-12+j6)

3. Comparison between the Pole Placement Design and Different Techniques for controlling the Load Frequency

In this section of paper a different techniques such as the integral controller ,PID controller are used to control the load frequency and comparison with the pole placement design to find the best technique .

3.1 Load frequency control using integral controller

In order to make the frequency deviation equal to zero ,a reset action must be provided. The reset action can be achieved by introducing an integral controller(***(k/s)*** where k is a constant)to act on the load reference setting to change the speed set point. Integral controller increased the system type by one which forces the final frequency deviation to zero[7]. The load frequency control system with integral control and its equivalent block diagram is shown in the figures(9)(10) respectively



Figure(9) Load frequency control using integral controller(k/s)[7]

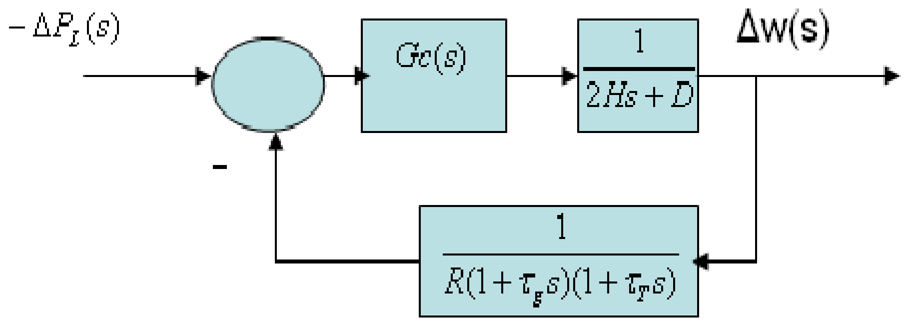


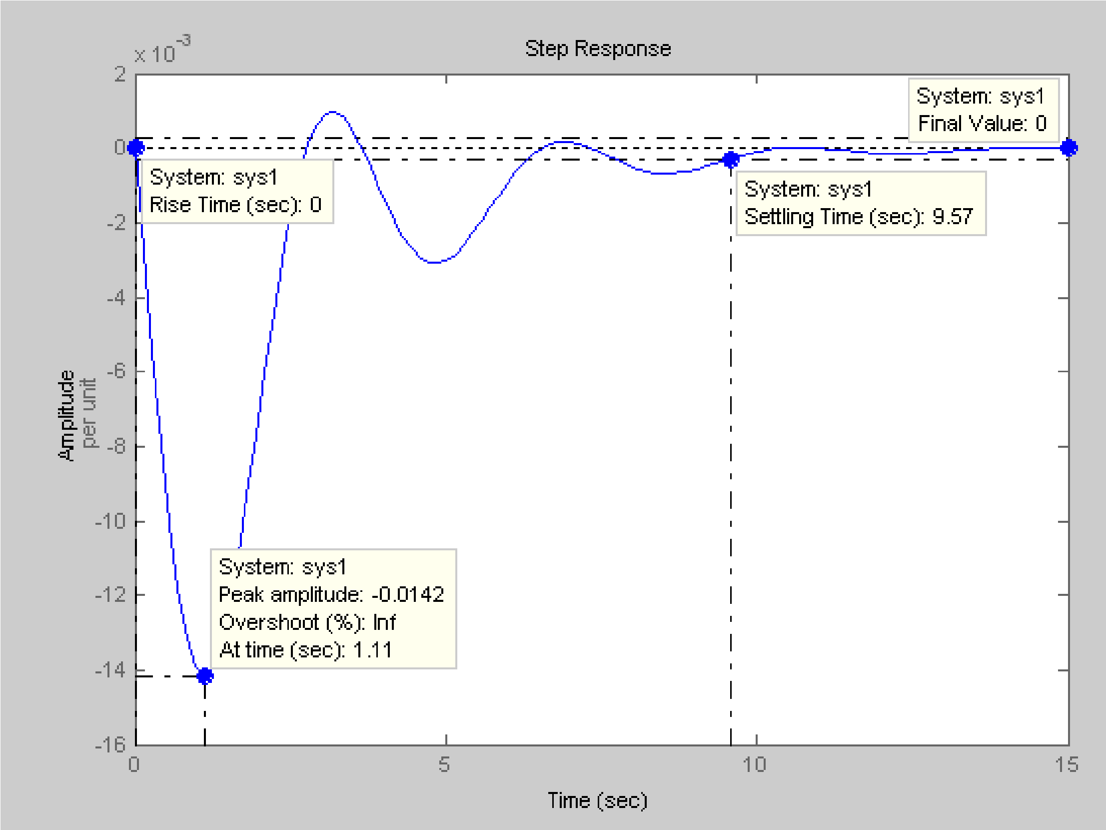
Figure (10).The equivalent block diagram of the load frequency control using integral controller as in the figure(8)[7]

Due to figure(10) and for the same parameters in section 2.1.1 with integral gain K=7 . The transfer function of this closed loop is [8][9].

$$T(s) = \frac{\Delta w(s)}{-\Delta PL(s)} = \frac{s(1+\tau_g s)(1+\tau_T s)}{s(2Hs+D)(1+\tau_g s)(1+\tau_T s)+K+s/R}$$

$$= \frac{-0.1s^3 - 0.7s^2 - s}{s^4 + 7.08s^3 + 10.56s^2 + 20.8s + 7} \quad (13)$$

The integral gain K is chosen arbitrary for the best frequency deviation response as in the figure(11)



Figure(11) Frequency deviation step response with integral controller

From this figure the simple integral controller return the system to the zero steady-state(Δw_{ss} =0) at time 15 sec after the transient characteristic

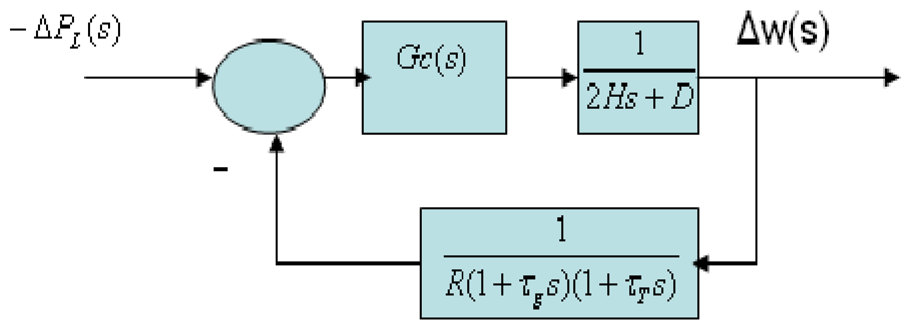
3.2 Load frequency control using PID controller

The PID controller is used to improve the dynamic response as well as to reduce or eliminate the steady state error .Consider that the PID controller consists of a PI portion ($K_P + \frac{K_I}{s}$) connected in cascade with a PD ($K_D s$) portion .The transfer function of the PID controller is written as[10][11]

$$Gc(s) = K_P + K_D s + \frac{K_I}{s} \qquad (14)$$

Where K_P , K_D and K_I are constants and are chosen arbitrary in order to give the best frequency deviation step response .

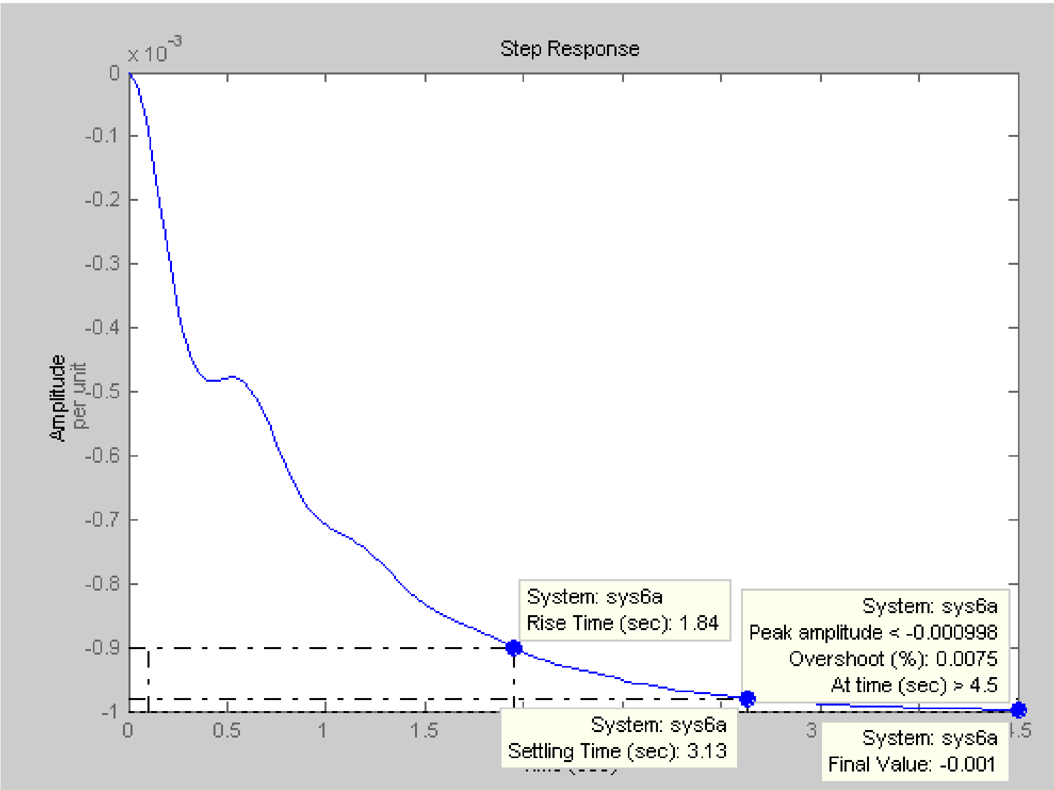
The block diagram of the load frequency control using PID controller is the same in the figure(2) with adding the PID controller as shown in the figure(11) bellow [12]



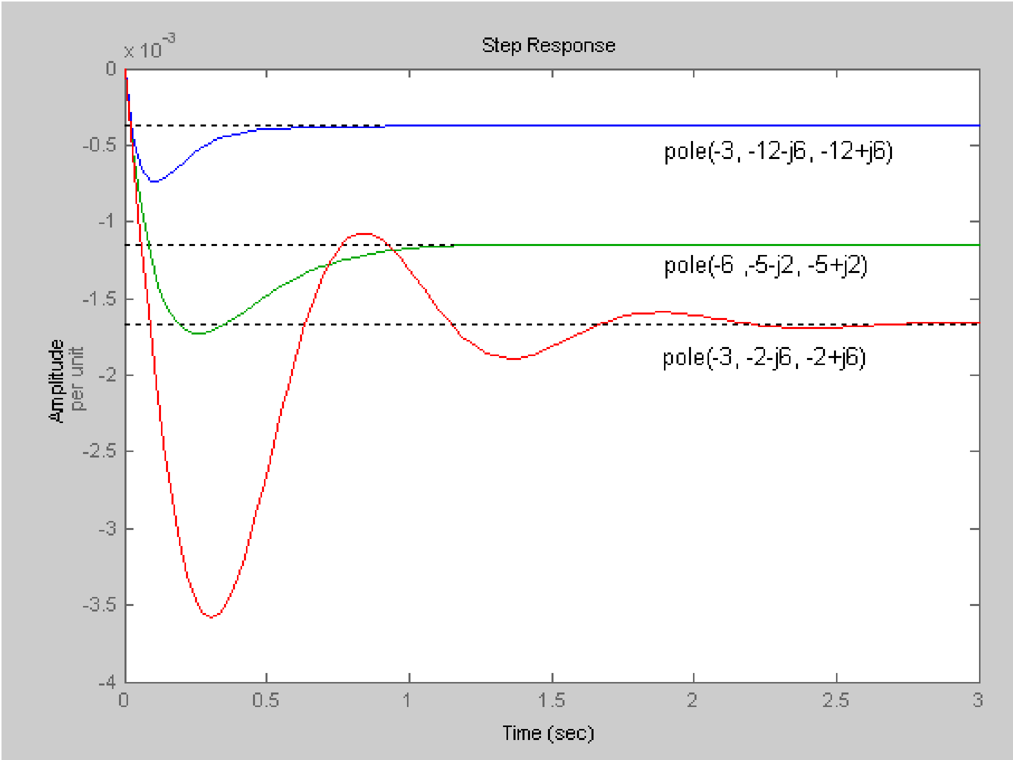
Figure(12)Block diagram of load frequency control with PID [12]

Due to figure(12) and for the same parameters in section 2.1.1 but with PID controller ,the constant of the PID controller are

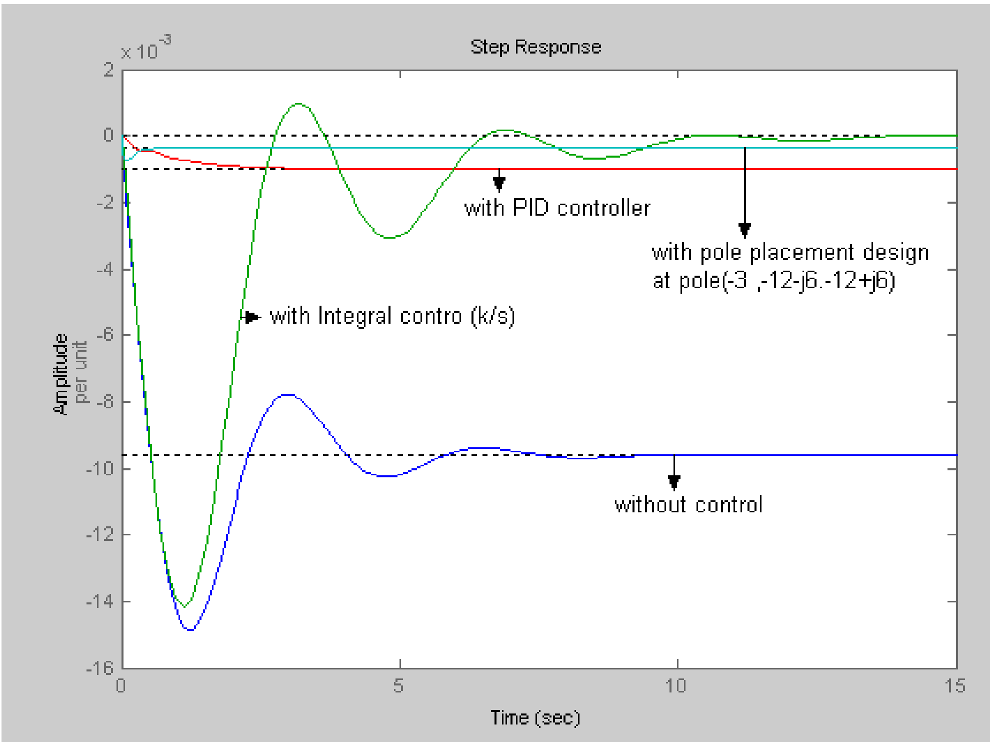
K_P=15 , K_D=6 ,and K_I=10 .These constants are chosen arbitrary in this paper through a number of trying in order to give the best step response of frequency deviation as in the figure(13).It is necessary to explain that this figure and the other figures(4,5,6,7,8,11,13,14,15,16) are the work of this paper and not take from any specific reference



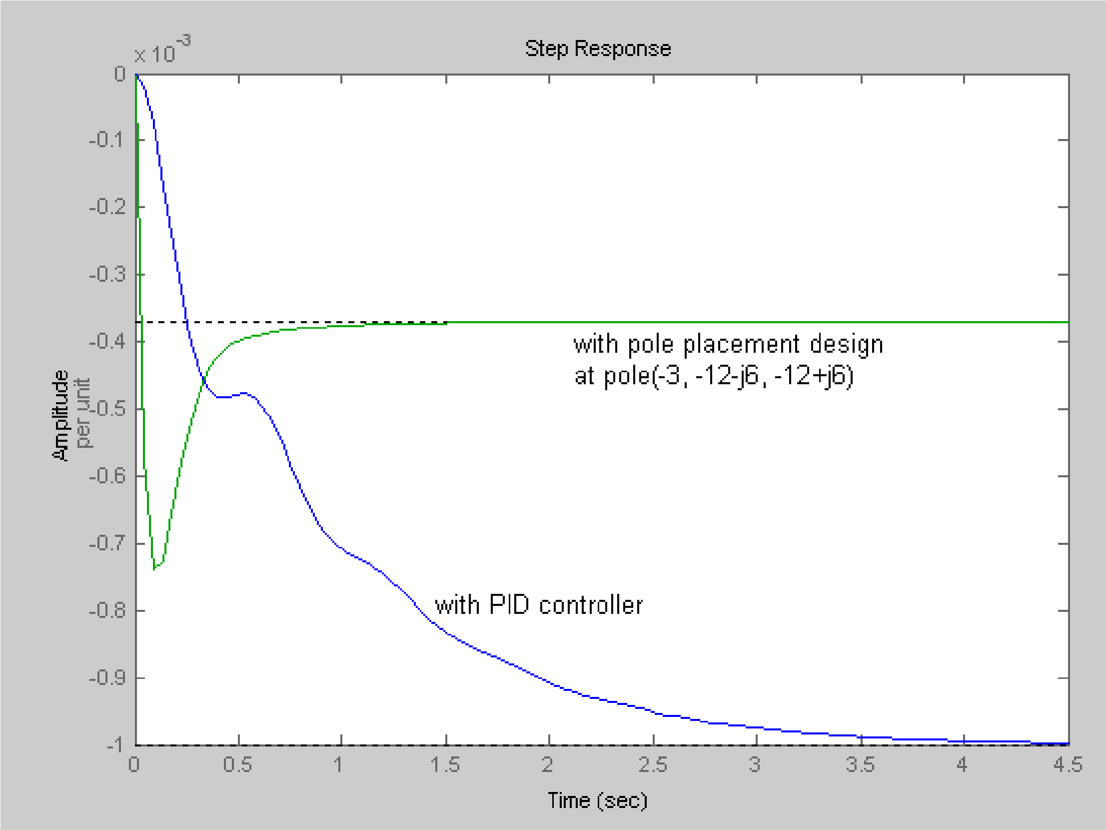
Figure(13) frequency deviation step response with PID controller



Figure(14) Frequency deviation due to the pole placement design at different poles



Figure(15) frequency deviation due to the different type of controllers



Figure(16) Frequency deviation due to PID controller and pole placement design at pole (-3 ,-12-j6 ,-12+j6)

Table(1) Compare between frequency deviation using pole placement design at different poles due to figure(13)

Pole of placement design	***At pole (-3,-2-j6,-2+j6)***	***At pole (-6,-5-j2,-5+j2)***	***At pole (-12+j6 ,-12-j6 ,-3)***
Rise time (sec)	0.0698	0.065	0.0186
Peak time (sec)	0.304	0.254	0.102
Settling time (sec)	2.07	1.01	Less than 0.8
Overshoot %	115	50.7	102
Peak Amplitude(pu)	-0.00358	-0.00173	-0.000747
Steady state value(pu)	-0.00167	-0.00115	-0.00037
Time of steady state value(sec)	3	1.2	0.8

Table(2)Comparison between different methods of load frequency control due to figure(14)

Type of System	*Without control*	*With integral controller*	*With PID controller*	*With pole Placement design at (-12+j6,-12-j6, -6)*
Rise time (sec)	0.413	0	1.84	0.0186
Settling time (sec)	6.81	9.57	3.13	Less than 0.8
Peak time (sec)	1.2	1.11	4.5	0.102
Overshoot %	54.8	Inf	0.0075	102
Peak Amplitude(pu)	-0.0149	-0.0142	-0.000998	-0.000747
Steady state value(pu)	-0.00962	0	-0.001	-0.00037
Time of steady state value(sec)	10	15	4.5	0.8

4. Conclusion

1. This paper used the pole placement design for load frequency control of a power system as in the figures(2)(3).This technique depend on choosing the poles or the root of the characteristic equation to find the control system gain (linear static control system) as in the figure(1) instead of the other control techniques that used the dynamic control system such as the integral control as in the figure(9) and the PID control as in the figure(12)
2. These poles or the roots of the characteristic equation are chosen arbitrary depending of getting the best frequency deviation response as in the figures(6)(7)(8).Due to the figure(14) which represent the comparison between these figures(6,7,8) ,the pole (-3, -12-j6, -3+j6) gives the best frequency deviation response.
3. In order to compare the pole placement design with other techniques, the integral control in figures(9)(10) is used for the same load frequency control in the figure(2) and the data in section 2.1.1. The transfer function of the integral controller is (k/s) and the gain of the integral controller (k) is 7 which is chosen arbitrary to get the best frequency deviation response as in the figure(11).
4. Also the PID controller in figure(12) are used for the same load frequency control in figure(2) and data in section 2.1.1 .The transfer function of PID controller is(

$Gc(s) = K_P + K_D s + \frac{K_I}{s}$) and the constants of this transfer function are(K_P =15, K_D =6, and K_I =10) which are chosen arbitrary to get the best frequency deviation response as in the figure(13).

5. Figure(15) represent the comparison between the frequency deviation response of the different techniques as follow

a-Integral controller of figure(11)

b-PID controller of figure(13)

c-Pole placement design of figure(8) at best pole choosing.

d-Load frequency control without using any control as in figure(5)

For more explainer ,figure(16) represent the same relation between the PID controller in part (b) and the pole placement design in part (c) above. Due to this comparison ,the pole placement design at the best pole choosing (-3 ,-12-j6 ,-12+j6) gives the best frequency deviation response.

6. For more details about the comparison between the different techniques of load frequency control ,table(1) represent the parameters of the frequency deviation response of pole placement design at different poles that chosen arbitrary ,where the data of this table is taken from figure(6) for pole(-3, -12-j6,-12-j6) and from figure(7) for pole(-6,-5-j6, -5+j6) and from figure(8) for pole(-3,-12-j6, -12+j6) .This table show that the pole(-3 ,-12-j6 ,-12+j6) has minimum value of rise time, peak time, settling time, peak amplitude ,steady state value and time of the steady state from the other poles and therefore, this pole is the best choice for frequency deviation response using pole placement design .Table (2) represent the parameters of the frequency deviation response of the different method of control that used in this paper .The data of this table is taken from :

a-Figure(5) for un compensated method (without control) ,where this technique has a high rise time of 0.413 sec,a high settling time of 6.81sec, a high peak time of 1.2 sec ,a high steady state time of 10 sec ,a higher peak amplitude of 0.0149 per unit ,a high steady state value of 0.00962 per un unit ,normal overshoot of 54.8% , therefore it can be a bad method of control

b-Figure(11) for integral controller method, where although this method has a zero rise time ,a zero steady state values but it has ,a higher settling time of 9.57 sec, a higher a steady state time of 15 sec and infinity overshot, therefore it can be a good method of control.

c-Figure(13) for PID controller method ,where although the PID controller has a minimum overshot of 0.0075 % and a low peak amplitude of 0 .000998 but it has a higher a rise time of 1.84 sec and a higher peak time of 4.5 and higher a steady state value of 0.001 per unit, also it has a normal settling time of 3.13 sec and therefore it can be a very good method of control.

d-Figure(8) for pole placement design at pole(-3 ,-12-j6, -12+j6) where, this method has a low rise time of 0.0186 sec ,minimum settling time less than 0.8 sec ,minimum peak time of 0.102 sec , minimum peak amplitude of 0.000747 per unit ,minimum steady state value of 0.00037 per unit and minimum time of the steady state of o.8 sec ,and all these parameters are near to the zero. also this technique has a normal value of overshot of 102% , therefore it can be an excellent method of control .

From the above discussion ,the pole placement design at pole (-3,-12-j6 ,-12+j6) is the best techniques for load frequency control then the PID controller then the integral controller then the uncompensated method (without control).

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