Abstract—the large-scale power systems are liable to performance deterioration due to the presence of sudden small load perturbations, parameter uncertainties, structural variations, etc. Due to this, modern control aspects are extremely important in load frequency control (LFC) design of power systems. In this paper, the LFC problem is illustrated as a typical disturbance rejection as well as large-scale system control problem. For this purpose, simple approach to LFC design for the power systems having parameter uncertainty and load disturbance is proposed. The approach is based on two-degree-of-freedom, internal model control (IMC) scheme, which unifies the concept of model-order reduction like Routh and Padé approximations, and modified IMC filter design, recently developed by Liu and Gao [24]. The beauty of this paper is that in place of taking the full-order system for internal-model of IMC, a lower-order, i.e., second-order reduced system model, has been considered. This scheme achieves improved closed-loop system performance to counteract load disturbances. The proposed approach is simulated in MATLAB environment for a single-area power system consisting of single generating unit with a non-reheated turbine to highlight the efficiency and efficacy in terms of robustness and optimality.

I. INTRODUCTION

With the rapid progress in electric power technology, the whole power system has become a complex unit. Generation, transmission, and distribution systems are installed in various areas which are generally interconnected to their neighboring areas through transmission lines called tie-lines. In such web of interconnected power systems, both area frequency and tie-line power interchange fluctuations occur frequently just because of randomness in power load demand, system parameter uncertainties, modeling errors, and disturbance due to varying environmental conditions. So, the stability of power system is essential to maintain synchronism and prescribed voltage levels, in case of any transient disturbances like faults, line trips, or any overload. In this context, load frequency control (LFC) is responsible for providing efficient and reliable power generation in an electrical energy system and tie-line power interchange. The principle roles of LFC for power systems are:

a. maintaining zero steady state errors for frequency deviations,
b. counteracting sudden load disturbances,
c. minimizing unscheduled tie-line power flows between neighboring areas and transient variations in area frequency
d. coping up with modeling uncertainties and system nonlinearities within a tolerable region, and
e. guaranteeing ability to perform well under prescribed overshoot and settling time in frequency and tie-line power deviations

Thus, LFC can be considered as an objective optimization and robust control problem. Many control strategies like integral control, discrete time sliding mode control, optimal control, intelligent control, adaptive and self-tuning control, PI/PID control, IP control, and robust control, have been reported in the literature as an existing LFC solution. It is observed in power systems that the parameter values in the various power generating units like governors, turbines, generators, etc.,
fluctuate depending on system and power flow conditions which change almost every minute. Therefore, parameter uncertainty is an important issue for the choice of control technique. Hence, a robust strategy for LFC is required which takes care of both the uncertainties in system parameters and disturbance rejection.

II. AUTOMATIC LOAD FREQUENCY CONTROL

2.1 INTRODUCTION
The topic of maintaining the system frequency constant is commonly known as AUTOMATIC LOAD FREQUENCY CONTROL (ALFC). It has got other nomenclatures such as Load Frequency Control, Power Frequency Control, Real Power Frequency Control and Automatic Generation Control. The basic role of ALFC is:

1. To maintain the desired megawatt output power of a generator matching with the changing load.
2. To assist in controlling the frequency of larger interconnection.
3. To keep the net interchange power between pool members, at the predetermined values.

The ALFC loop will maintain control only during small and slow changes in load and frequency. It will not provide adequate control during emergency situation when large megawatt imbalances occur. We shall first study ALFC as it applies to a single generator supplying power to a local service area.

2.2 REAL POWER CONTROL MECHANISM OF A GENERATOR
The real power control mechanism of a generator is shown in Fig. 1.1. The main parts are:
1) Speed changer
2) Speed governor
3) Hydraulic amplifier
4) Control valve.

They are connected by linkage mechanism. Their incremental movements are in vertical direction. In reality these movements are measured in millimeters; but in our analysis we shall rather express them as power increments expressed in MW or p.u. MW as the case may be. The movements are assumed positive in the directions of arrows. Corresponding to raise command, linkage movements will be: A moves downwards; C moves upwards; D moves upwards; E moves downwards. This allows more steam or water flow into the turbine resulting incremental increase in generator output power. When the speed drops, linkage point B moves upwards and again generator output power will increase.

2.3 SPEED GOVERNOR
The output commend of speed governor is \( \Delta P_g \) which corresponds to movement \( \Delta x_C \). The speed governor has two inputs:

1) Change in the reference power setting, \( \Delta P_{ref} \)
2) Change in the speed of the generator, \( \Delta f \), as measured by \( \Delta x_B \).

It is to be noted that a positive \( \Delta P_{ref} \) will result in positive \( \Delta P_g \). A positive \( \Delta f \) will result in linkage points B and C to come down causing negative \( \Delta P_g \). Thus

\[
\Delta P_g = \Delta P_{ref} - R_1 \Delta f \quad (2.1)
\]

Here the constant \( R \) has dimension hertz per MW and is referred as speed egulation of the governor.

Taking Laplace transform of eq\(1.1 \) yields

\[
\Delta P_g(s) = \Delta P_{ref}(s) - R_1 \Delta f(s) \quad (2.2)
\]

The block diagram corresponding to the above equation is shown in Fig. 1.2.

![Fig.2.2 Block diagram of speed governor](image)

Hydraulic time constant \( TH \) typically assumes values around 0.1 sec. The block diagram of the speed governor together with the hydraulic valve actuator is shown in Fig. 2.3.

![Fig. 2.3 Block diagram of speed governor together with hydraulic valve actuator](image)

### 2.7.1: PRIMARY ALFC LOOP – UNCONTROLLED CASE

The primary ALFC loop in Fig. 2.5 has two inputs \( \Delta P_{ref} \) and \( \Delta PD \) and one output \( \Delta f \).
For uncontrolled case, (i.e. for constant reference input) $\Delta P_{\text{ref}} = 0$ and the block diagram shown in can be simplified as shown below

III. INTERNAL MODEL CONTROL (IMC)

3.1 INTRODUCTION

Internal Model Control (IMC) refers to a systematic procedure for control system design based on the Q-parameterization concept that is the basis for many modern control techniques. What makes IMC particularly appealing is that it presents a methodology for designing Q-parameterized controllers that has both fundamental and practical appeal. As a consequence, IMC has been a popular design procedure in the process industries, particularly as a means for tuning single loop, PID-type controllers. The IMC design procedure is quite extensive and diverse.

It has been developed in many forms; these include single-input, single-output (SISO) and multi-input, multi-output (MIMO) formulations, continuous-time and discrete-time design procedures, design procedures for unstable open-loop systems, combined feedback-feedforward IMC design, and so forth. The focus of this chapter is on the feedback-only SISO design procedure for open-loop stable systems, with particular emphasis on its relationship to PID controller tuning.

Aside from controller design, IMC is helpful in assessing the fundamental requirements associated with feedback control, such as determining the effect of non-minimum phase elements (delays and Right-Half Plane (RHP) zeros) on achievable control performance. Since the sophistication of the IMC controller depends on the order of the model and control performance requirements, the IMC design procedure is also helpful in determining when simple feedback control structures (such as PID controllers) are adequate.
3.2 INTERNAL MODEL CONTROL
In the subject area of control theory, an internal model is a process that simulates the response of the system in order to estimate the outcome of a system disturbance. The internal model principle was first articulated in 1976 by B. A. Francis and W. M. Wonham as an explicit formulation of the Conant and Ashby good regulator theorem. It stands in contrast to classical control, in that the classical feedback loop fails to explicitly model the controlled system (although the classical controller may contain an implicit model).

The internal model theory of motor control argues that the motor system is controlled by the constant interactions of the plant and the controller. The plant is the body part being controlled, while the internal model itself is considered part of the controller. Information from the controller, such as information from the central nervous system (CNS), feedback information, and the efference copy, is sent to the plant which moves accordingly.

Internal models can be controlled through either feed-forward or feedback control. Feed-forward control computes its input into a system using only the current state and its model of the system. It does not use feedback, so it cannot correct for errors in its control. In feedback control, some of the output of the system can be fed back into the system’s input, and the system is then able to make adjustments or compensate for errors from its desired output. Two primary types of internal models have been proposed: forward models and inverse models. In simulations, models can be combined together to solve more complex movement tasks.

3.3 IMC Background
In process control applications, model based control systems are often used to track set points and reject low disturbances.

The internal model control (IMC) philosophy relies on the internal model principle which states that if any control system contains within it, implicitly or explicitly, some representation of the process to be controlled then a perfect control is easily achieved.

In particular if the control scheme has been developed based on the exact model of the process then perfect control is theoretically possible.

\[
\text{Output} = G_c \cdot G_p \cdot \text{Set-point} \quad (\text{multiplication of all three parameters})
\]

\[
G_c = \text{controller of process}
\]

\[
G_p = \text{actual process or plant}
\]

\[
G_p^* = \text{model of the actual process or plant}
\]

A controller \( G_c \) is used to control the process \( G_p \). Suppose \( G_p^* \) is the model of \( G_p \) then by setting:

\[
G_c = \text{inverse of } G_p^* \quad (\text{inverse of model of the actual process})
\]

And if \( G_p = G_p^* \) (the model is the exact representation of the actual process).

\[\text{Fig 3.1 Open loop Control strategy}\]
It shows that if we have complete knowledge about the process (as encapsulated in the process model) being controlled, we can achieve perfect control.

This ideal control performance is achieved without feedback which signifies that feedback control is necessary only when knowledge about the process is inaccurate or incomplete.

Although the IMC design procedure is identical to the open loop control design procedure, the implementation of IMC results in a feedback system.

Thus, IMC is able to compensate for disturbances and model uncertainty while open loop control is not. Also IMC must be detuned to assure stability if there is model uncertainty.

**IV. IMC DESIGN**

4.1 INTRODUCTION

The IMC design procedure is exactly the same as the open loop control design procedure. Unlike open loop control, the IMC structure compensates for disturbances and model uncertainties. The IMC tuning (filter) factor “lem” is used to detune for model uncertainty. It should be noted that the standard IMC design procedure is focused on set point responses but good set point responses do not guarantee good disturbance rejection, particularly for the disturbances that occur at the process inputs. A modification of the design procedure is developed to improve input disturbance rejection.

In the above figure, d(s) is the unknown disturbance affecting the system. The manipulated input u(s) is introduced to both the process and its model.

The process output, y(s), is compared with the output of the model resulting in the signal d*(s). Hence the feedback signal sent to the controller is

\[
d^*(s) = [G_p(s) - G_p^*(s)].u(s) + d(s)
\]  

(4.1)

In case d(s) is zero then feedback signal will depend upon the difference between the actual process and its model.

If actual process is same as process model i.e G_p(s) = G_p*(s) then feedback signal d*(s) is equal to the unknown disturbance.
So for this case $d^*(s)$ may be regarded as information that is missing in the model signifies and can be therefore used to improve control for the process. This is done by sending an error signal to the controller.

The error signal $R'(s)$ incorporates the model mismatch and the disturbances and helps to achieve the set-point by comparing these three parameters. It is send as control signal to the controller and is given by

$$R'(s) = r(s) - d^*(s) \text{ (input to the controller)}$$

And output of the controller is the manipulated input $u(s)$. It is send to both process and its model.

$$u(s) = R''(s) \cdot G_c(s) = [r(s) - d^*(s)] G_c(s)$$

$$u(s) = [r(s) - [G_c(s) \cdot G_p(s) - G_p^*(s)] \cdot u(s) + d(s)] \cdot G_c(s)$$

But

$$y(s) = G_p(s) \cdot u(s) + d(s)$$

Hence, closed loop transfer function for IMC scheme is

$$y(s) = \frac{[G_c(s) \cdot G_p(s) \cdot r(s) + [1 - G_c(s) \cdot G_p^*(s)] \cdot d(s)]}{1 + [G_p(s) - G_p^*(s)] G_c(s)}$$

Now if $G_c(s)$ is equal to the inverse of the process model and if $G_p(s) = G_p^*(s)$ then perfect set point tracking and disturbance rejection can be achieved.

Also to improve the robustness of the system the effect of model mismatch should be minimized since mismatch between the actual process and the model usually occur at high frequency end of the system frequency response. A low pass filter $G_f(s)$ is usually added to attenuate the effects of process model mismatch.

Thus the internal model controller is usually designed as the inverse of the process model in series with the low pass filter i.e

$$G_{imc}(s) = G_c(s) \cdot G_f(s)$$

Where order of the filter is usually chosen so that the controller is proper and to prevent excessive differential control action. The resulting closed loop then becomes

$$y(s) = \frac{G_{imc}(s) \cdot G_p(s) \cdot r(s) + [1 - G_{imc}(s) \cdot G_p^*(s)] \cdot d(s)}{1 + [G_p(s) - G_p^*(s)] G_{imc}(s)}$$

Tolerance of model uncertainty is called robustness.

Like open loop control the disadvantage compared with standard feedback control is that IMC doesn’t handle integrating or open loop unstable systems

4.2 IMC DESIGN PROCEDURE

Consider a process model $G_p^*(s)$ for an actual process or plant $G_p(s)$. The controller $Q_c(s)$ is used to control the process in which the disturbances $d(s)$ enter into the system. The various steps in the Internal Model Control (IMC) system design procedure are:

4.2.1 Factorization

It means factoring a transfer function into invertible (good stuff) and non invertible (bad stuff) portions. The factor containing right hand plane (RHP) or zeros or time delays become the poles in the inverts of the process model when designing the controller. So this is non invertible portion which has to be removed from the system.

Mathematically it is given as $G_p^*(s) = G_p^*(+)(s) G_p^*(-)(s)$ Where
Gp*(+)(s) is non-invertible portion Gp*(-)(s) is invertible portion Usually we use all pass factorization

4.3. BLOCK DIAGRAM

![Diagram](image)

Fig 4.2: Internal model control

4.4. PROGRAM

```matlab
clear all;

% Area One
R1=0.4;
Tq1=0.05;
Tc1=0.3;
Tp1=20;
Rq1=120;

% Plant
step('f1')
G1=exp([1, Tq1 1])
Gc=1/(1+G1)
Gm=G1*(1+Gq1/Gc)
G1=1/(1+G*p1*Gq1/Rq1)
Gp=1/(1+G*p1*Gq1/Rq1)

% Om
Gm1=tf(250, [1.15.88 62.46 106.2])
Gm_paste=[(-1.191 18.92), [1 2.708 3.048]]
Gm_round=[1.191 18.92], [1 2.708 3.048]
Gm_sod=exp(-0.07578)
Gm_sod1=exp(-0.0578)
Gm_sod2=Gm_sod1*Gm_sod2

% Q1
Qd_paste=[0.0057 0.1241 1.503 4.065 0.943, 0.000895 0.03355 0.6491 5.732 18.82]
Qd_round=[0.005796 0.03548 0.2134 0.419 0.6251, 0.0016 0.032 0.24 0.8 1]
Qd_sod=exp(-0.07578)
Qd_sod1=exp(-0.0578)
Qd_sod2=Qd_sod1*Qd_sod2
```
4.5. GRAPHS

Fig 4.3: Response of a system when frequency suddenly varies and maintain constant

Fig 4.4 Response of a power system using TDF-IMC design with various reduced order models for nominal parameters

Fig 4.5.: Effect of disturbance at output for nominal and uncertain models

Fig 4.6: Robust stability plot for parameter uncertainty
Fig 4.7: variation of multiplicative error with frequency

REFERENCES

1. P. Kundur, Power System Stability and Control. New York, NY, USA: McGraw-Hill, 1994.
2. H. Shayeghi, H. A. Shayanfar, and A. Jalili, “Load frequency control strategies: A state-of- the-art survey for the researcher,” Energy Convers.
3. A. Khodabakhshian and N. Golbon, “Unified PID design for load frequency control,” in Proc. IEEE Int. Conf. Control applications (CCA), Taipei, Taiwan, 2004, pp. 1627–1632.
4. K. Vrdoljak, N. Peric, and I. Petrovic, “Sliding mode based load-frequency control in power systems,” Elect. Power Syst. Res., vol. 80, no. 5, pp. 514–527, May 2009.
5. R. K. Cavin, M. C. Budge, and P. Rasmussen, “An optimal linear system approach to load- frequency control,” IEEE Trans. Power App.Syst., vol. PAS-90, no. 6, pp. 2472–2482, Nov. 1971.
6. I. Kocaarslan and E. Cam, “Fuzzy logic controller in interconnected electrical power Systems for load-frequency control,” Int. J. Power Energy Syst., vol. 27, no. 8, pp. 542–549, Oct. 2005.
7. D. Rerkpreedapong, A. Hasanovic, and A. Feliachi, “Robust load frequency control using genetic algorithms and linear matrix inequalities,” IEEE Trans. Power Syst., vol. 18, no. 2, pp. 855–861, May 2003.
8. C. T. Pan and C. M. Liaw, “An adaptive controller for power system load-frequency control,” IEEE Trans. Power Syst., vol. 4, no. 1, pp. 122–128, Feb. 1989.
9. M. A. Sheirah and M. M. Abd-El-Fattah, “Improved load-frequency self-tuning regulator,” Int. J. Control, vol. 39, no. 1, pp. 143–158, Jan. 1984.
10. Y. H. Moon, H. S. Ryu, J. G. Lee, and S. Kim, “Power system load frequency control using noise-tolerable PID feedback,” in Proc. IEEE Int. Symp. Industrial Electronics (ISIE), Jun. 2001, vol. 3, pp. 1714–1718.
11. S. M. S. Boroujeni, B. K. Boroujeni, H. Delafkar, and A. S. Boroujeni, “A new IP type controller for load frequency control problem,” J. Basic. Appl. Sci. Res., vol. 1, no. 9, pp. 1078–1083, 2011.
12. G. Ray, A. N. Prasad, and G. D. Prasad, “A new approach to the design of robust load- frequency controller for large scale power systems,” Elect. Power Syst. Res., vol. 51, no. 1, pp. 13–22, Jul. 1999.
13. A. S. Taher and R. Hematti, “Robust decentralized load frequency control using multi variable QFT method in deregulated power systems,” Amer. J. Appl. Sci., vol. 5, no. 7, pp. 818–828, Jul. 2008.
14. M. Morari and E. Zafiriou, Robust Process Control. Englewood Cliffs, NJ, USA: Prentice Hall, 1989.
15. L. Harnefors and H. Nee, “Model-based current control of AC machines using the internal model control method,” IEEE Trans. Ind. Appl., vol. 34, no. 1, pp. 133–141, Jan./Feb. 1998.
16. A. Petersson, L. Harnefors, and T. Thiringer, “Evaluation of current control methods for wind turbines using doubly-fed induction machines,” IEEE Trans. Power Electron., vol. 20, no. 1, pp. 227–235, Jan. 2005.
17. M. Karimi-Ghartemani and F. Katiraei, “An adaptive internal model control for reactive power compensation,” in Proc. 2005 IEEE Conf. Control Applications, Toronto, ON, Canada, August 28–31, 2005, pp. 1668–1673.
18. X. Wei, K. M. Tsang, and W. L. Chan, “DC/DC buck converter using internal model control,” Elect. Power Compon. Syst., vol. 37, no. 3, pp. 320–330, Feb. 2009.
19. Y. Tian and F. Gao, “Double-controller scheme for control of processes with dominant delay,” IEE Proc. Control Theory Appl., vol. 145, no. 5, pp. 479–484, 1998.
20. M. Shamsuzzoha and M. Lee, “Design of robust PID controllers for unstable processes,” in Proc. IEEE 2006 SICE-ICASE Int. Joint Conf., pp. 3324–3329.