LFC in interconnected power system via Internal Model Control Scheme and Model-Order Reduction

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Abstract

An interconnected power systems are subjected to performance gradual decline due to sudden small load perturbations, structural variations, parameter uncertainties, etc. The LFC objective is to maintain the balance of the area generation-demand by adjusting the obtained outputs on regulating units in response to the frequency and tie line power deviations. The state of the system changes, as the demand varies from its normal operating value. The internal model control (IMC) scheme, which includes the concept of model-order reduction and modified IMC filter design is discussed. For model reduction, the combination of Particle Swarm Optimization (PSO) and Dominant Pole Retention technique is proposed. The concept is that a lower order is placed in place of full order of the system for internal model control. In this the performance to counteract load disturbances can be achieved by using improved closed loop system.

Keywords

Load Frequency Control, Internal Model control (IMC), model order reduction (MOR), Particle Swarm Optimization (PSO), Dominant Pole RetentionTechnique.

1. Introduction

WITH the rapid progress in electric energy, the total energy system has become a complicated one. Generation, transmission, and distribution systems are installed in different locations which are interconnected through the transmission lines are known as tie-lines. By this sort of connections, both area frequency and tie-line power interchange fluctuates frequently because of random variations in power load demand, parameter variations, modeling errors, and disturbance due to climatic conditions. By this, to regain stability it is essential to maintain synchronism and prescribed voltage levels in case disturbances like faults, line trips, overload conditions. In this context, load frequency control (LFC) is in a position to provide a healthy frequency and tie line power interchange. The significance of LFC is to 1) balancing frequency deviation to be zero, 2) Unexpected load disturbances to be neutralized, 3) reduce the unscheduled tie-line power flows among neighboring areas and transient variations in area frequency, 4) Regain from modeling uncertainties and system nonlinearities within a endurable region, and 5) the ability to provide well under prescribed overshoot and settling time in both the frequency and tie-line power deviations. From this, LFC can be considered as robust control problem as well as objective optimization.

Wide range of control methods 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 are present to provide LFC optimized results. It can be observed that variation of parameters such as turbines, governors, generators etc., fluctuations depends upon system and power flow conditions which can vary every minute. By this, uncertainty in parameter is a major problem for the concern of control technique. Hence, the LFC provides robust control which concerns uncertainties in system parameters as well as disturbance rejection.

While viewing the power system, one issue is that the large size power system results in enormous increase in both the number of controllers and order of the system. As ever-growing complexity of power systems in the generation industry, providing reduced-order models of these large-scale systems plays a significant role. By this view, the design and implementation of the control systems model order reduction plays a pivotal role. Next to this, size of system reduces its computational complexity, size, and costs are also minimized. By viewing all the circumstances the IMC based controller using model-order reduction scheme for internal-model of a plant proposed. IMC consists of IMC controller, model order reduction and IMC filter. By this it can control plant/model mismatches and parameter uncertainties. Superiority of this approach is provides faster disturbance rejection, and provides robust and optimal performance.
The specific aim is to accomplish the following objectives:

1) Reducing the order of the system by using model-order reduction scheme which consists of Particle Swarm Optimization (PSO) and Dominant Pole Retention technique are applied. These reduced order models are treated as internal (predictive) models for IMC structure.

2) TDF-IMC structure is used provide the system to free from load disturbance. The structure and the implemented scheme, which is effective for utilizing the reduced order models

3) Provide a robust study by injecting 50% disturbance uncertainty in each parameter, simultaneously. The optimal robustness can be presented in terms of multiplicative uncertainty (error), respectively.

2. IMC Theory and Model Order Reduction

The layout of IMC structure is as shown in Fig.1. The structure of the control device consists of the feedback controller Q(s), the real plant to be controlled G(s), and a predictive model of the plant, i.e., the internal-model$G_M(s)$. The internal-model loop to employ the distinguish between outputs of G(s) andG_M(s). The difference considered as error, represents the effect of disturbance D(s) and plant/model mismatch if exits.

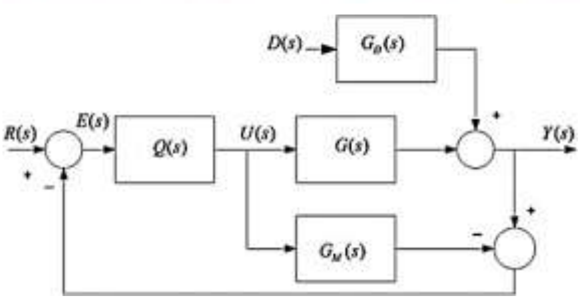

Fig1. Basic IMC structure.

The two-step scheme for producing IMC controller is

1) Factorize the model as shown

$$G_M(s) = G_{M+}(s)G_{M-}(s) \quad (1)$$

Such that is a non-minimum phase part and is a minimum phase part

2) Define the IMC controller as

$$Q(s) = G_{M-}^{-1}(s)F(s) \quad (2)$$

Where F(s) is a low-pass filter, commonly of the form

$$F(s) = (1 + \lambda s)^{-n} \quad (3)$$

In (3), λ is a tuning parameter, which varies the control of the closed loop system, and removes mismatches at the high frequency, thus responsible for robustness. *n* is an integer, chosen such that becomes proper/semi-proper for physical realization.

3. Two-Degree-of Freedom IMC Controller

The groundwork on IMC scheme is on pole-zero cancellation. It offers very good tracking ability; however, the disturbance rejection response may be indisposed to action. So, a trade-off is required, where the execution for load disturbance rejection appear by sacrificing set-point tracking. To keep away from this problem, two different controllers as shown in Fig. 2, are introduced in basic IMC structure. At present the set-point response and disturbance response of the modified IMC structure namely TDF-IMC, can be improved, and each controller can be tuned independently.

In present task, we considered the TDF-IMC structure presents in Fig 2, from this define $Q_D(s)$ as a disturbance rejection filter (feedback controller) and $Q_1(s)$ as a set-point filter. The closed-loop supplementary sensitivity function T(s) and multiplicative error ε(s) which is a

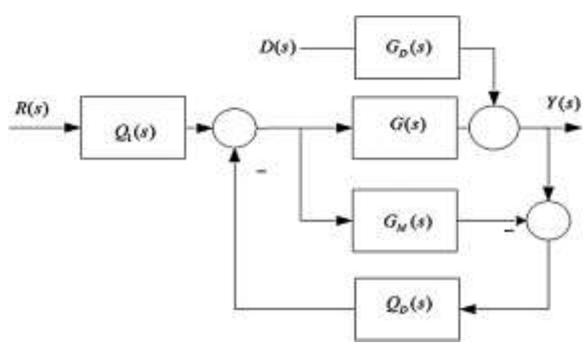

Fig. 2. TDF-IMC structure

measure of plant/model mismatch can be defined, respectively, by

$$T(s) = Q_D(s)G_M(s) \quad (4)$$

$$\varepsilon(s) = \frac{(G(s) - G_M(s))}{G_M(s)}. \quad (5)$$

thus a proper IMC filter is subjected to design IMC based controller for second-order internal-model of a system, therefore, F(s) of the form (3) is replaced by a modified filter F'(s) such that

$$F'(s)=\frac{\psi s^2+\theta s+1}{(\lambda_f+1)^x} \qquad (6)$$

Where x=3 or 4, depends on the requirement to make controller proper. By replacing (6) into (2), the TDF-IMC controller can be provided as

$$Q_D(s) = \frac{G_{M-}^{-1}(s)(\psi s^2+\theta s+1)}{(\lambda_f s+1)^x} \qquad (7)$$

Where ψ, Θ should satisfy the following condition for each pole, p_1 and p_2 of the second order system

$$\lim_{s\to -p_i}(1-T(s)) = 0 \qquad (8)$$

Substituting (1) and (7) in (4), we get

$$T(s) = \frac{G_{M+}(s)(\psi s^2+\theta s+1)}{(\lambda_f+1)^x} \qquad (9)$$

Now, from (9), this cases arises for $G_{M+}(s)$:

Case: When $G_{M+}(s)$ contains non-minimum phase terms, then factorize $G_M(s)$ such that $G_{M+}(s)$ has only all-pass terms, i.e., $G_{M+}(s)$ = (1-as)/ (1+as), then put x=3, and by substituting (9) into (8), we get (10) and (11) at shown below.

Thus, it is clear that controller $Q_D(s)$ expressed by (7) does not require heavy computational burden. Hence, the simplicity and the practical implementation are the major advantages of the scheme. Here, considered with disturbance rejection problem, i.e., effect of D(s) on Y(s), we need not to evaluate set-point filter $Q_1(s)$ since R(s) = 0 is assumed.

4. Particle Swarm Optimization

Let us consider the transfer function of the higher order system of the order 'n' can be of the form

$$G_n(s) = \frac{N(s)}{D(s)} = \frac{a_0+a_1s+a_2s^2+\cdots a_{n-1}s^{n-1}}{b_0+b_1s+b_2s^2+\cdots+b_{n-1}s^{n-1}+s^n} \qquad (12)$$

And consider the lower order system of the order 'r' synthesized is:

$$G_r(s) = \frac{c_0+c_1s+\cdots+c_{r-1}s^{r-1}}{d_0+d_1s+d_2s^2+\cdots+d_{n-1}s^{n-1}+s^n}, r<n \qquad (13)$$

The variation of the lower order system from the original system response can be represented as error index 'E' is known as Integral Square Error (ISE) which is represented as follows

$$E = \int_0^\infty [y(t)-y_r(t)]^2 dt \qquad (14)$$

Where y(t) & $y_r(t)$ are the step responses of the original and reduced order models

The PSO method is a population based search algorithm where each and every individual can be noted as a particle and presents in a candidate solution. In PSO, compete to perform by reproducing from their achieved peers. And then, each particle has a memory to recall the best in the search space. The area where it corresponds to best fitness is considered as pbest and the overall particle from the population can be considered as gbest.

In d-dimensional search space, the velocity and the position of the particles can be updated as follows:

$$v_{id}^{n+1} = wv_{id}^n + c_1r_1^n(p_{id}^n - x_{id}^n) + c_2r_2^n(p_{gd}^n - x_{id}^n) \qquad (15)$$

$$x_{id}^{n+1} = x_{id}^n + v_{id}^{n+1} \qquad (16)$$

Where,

W = inertia weight,

$c_1, c_2 =$ cognitive and social acceleration, respectively.

$r_1, r_2 =$ random numbers uniformly distributed in the range (0,1).

The dimensional vector of the swarm can be represented by $X_i = (x_{i1}, x_{i2}, \ldots\ldots x_{id})$ and the velocity can be represented by $V_i = (v_{i1}, v_{i2} \ldots., v_{id})$. The previous best values as $P_i = (p_{i1}, p_{i2}, \ldots.p_{id})$.

$$\psi = \frac{a^2\lambda_f p_1p_2(p_1+p_2)+\left(a\lambda_f^3+3a^2\lambda_f^2\right)p_1p_2+a\lambda_f\left(p_1^2+p_2^2+p_1p_2\right)+\left(\lambda_f^3+3a\lambda_f^2\right)(p_1+p_2)+3\lambda_f^2}{a^2p_1p_2+a(p_1+p_2+1)} \qquad (10)$$

$$\theta = \frac{a\lambda_f^2p_1^2p_2^2+\left(3a\lambda_f^2+3a^2\lambda_f\right)p_1p_2-3a\lambda_f(p_1+p_2)+a\lambda_f p_1p_2(p_1+p_2)+\left(\lambda_f^3+3a\lambda_f\right)p_1p_2-3\lambda_f}{a^2p_1p_2+a(p_1+p_2+1)} \qquad (11)$$

In PSO, each particle can move in search space as its own best previous values. The velocity update can consists in particle swarm as: namely momentum, cognitive and social parts.

Particles moves among the space with a d-dimesnsional problem. This absorbs new solutions along with their fitness, and measures the quality. The particles represents the speed of each by one. The cognition only component treats individual as isolated beings. The sum of the previous best positions and the new velocity will provide the new one.

The values of c_1 and c_2 represents the relative pull of pbest and gbest and the values of r_1 and r_2 supports in varying the pulls. From the equations (15) & (16), subscripts represent the iteration number. Fig. 3 represents the position updates of a two-dimensional parameter space.

In this, the PSO is subjected to minimize the objective function 'E' as given in (14), parameters to be considered are the coefficeints of numerator and denominatorpolynomials of the lower order system as from subjests to the conditions as follows:

i) To provide a reduced order model, it follws the condition

$d_i>0$; I = 0,1,2,….,(r-1) (17)

ii) To nully any steady state error from the approximation, the condition is :

$$d_0 = \frac{b_0}{a_0} c_0 \qquad (18)$$

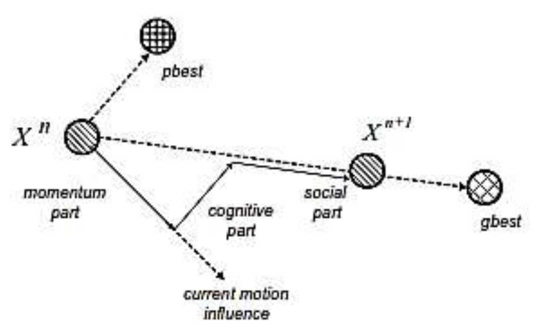

Fig. 3. Position updates in a PSO for a two dimensional parameter space.

The proposed algorithm represents in flowchart as shown below

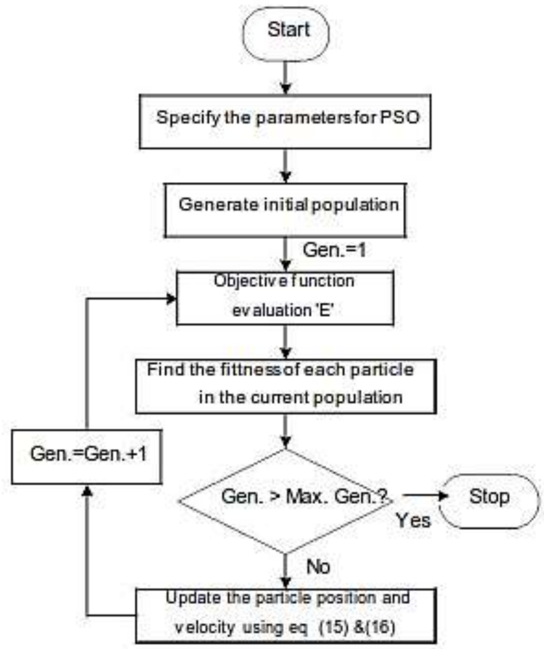

Fig. 4 Flowchart of PSOAlgorithm.

5. Dominant Pole Retention Technique

Frequency compensation is introduced by maintaining the characteristics such as gain and phase of the amplifier's open loop output or of its feedback network, or the two, which oppose the conditions that provides to oscillation. This can be done normally by the internal or external use of resistance-capacitance networks. This method commonly called dominant-pole compensation, which is of the structure of lag compensation. The amplifier gain is set to one (0 dB), when a pole is placed at an appropriate low frequency in the open loop response The least frequency pole considered as dominant pole since it decreases all the higher frequency poles. The solution of the concept is the difference between the open loop output phase and the phase response of a feedback network having no reactive elements never fall below −180° while amplifiers gain is one or more, securing stability.

By boosting this, dominant-pole compensation provides maintain of overshoot and ringing in the amplifier step response, which provides demand requirement more than the easy required for the stability.

6. Transfer Function Model

An interconnected two area Load Frequency Control system with different controllers are considered .The composite block diagram and state space model of the system is shown below. The dynamic behavior of the LFC system is described by the linear vector matrix form

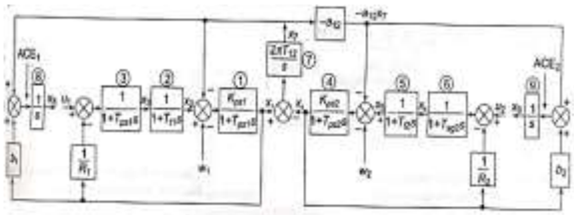

Fig.5. Two Area system with controllers

A. MATHEMATICAL MODELLING:

For the above system:

$$\dot{x}_1 = -\frac{1}{T_{ps1}}x_1 + \frac{K_{ps1}}{T_{ps1}}x_2 - \frac{K_{ps1}}{T_{ps1}}x_7 - \frac{K_{ps1}}{T_{ps1}}w_1 \quad (19)$$

$$\dot{x}_2 = -\frac{1}{T_{t1}}x_2 + \frac{1}{T_{t1}}x_3 \quad (20)$$

$$\dot{x}_3 = -\frac{1}{R_1T_{sg1}}x_1 - \frac{1}{T_{sg1}}x_3 + \frac{1}{T_{sg1}}u_1 \quad (21)$$

$$\dot{x}_4 = -\frac{1}{T_{ps2}}x_4 + \frac{K_{ps2}}{T_{ps2}}x_5 + \frac{a_{12}K_{ps2}}{T_{ps2}}x_7 - \frac{K_{ps2}}{T_{ps2}}w_2 \quad (22)$$

$$\dot{x}_5 = -\frac{1}{T_{t2}}x_5 + \frac{1}{T_{t2}}x_6 \quad (23)$$

$$\dot{x}_6 = -\frac{1}{R_2T_{sg2}}x_4 - \frac{1}{T_{sg2}}x_6 + \frac{1}{T_{sg2}}u_2 \quad (24)$$

$$\dot{x}_7 = 2\pi T_{12}x_1 - 2\pi T_{12}x_4 \quad (25)$$

$$\dot{x}_8 = b_1x_1 + x_7 \quad (26)$$

$$\dot{x}_9 = b_2x_4 - a_{12}x_7 \quad (27)$$

The nine equations (19) to (27) can be organized in the following vector matrix form

$$\dot{x} = Ax+Bu+Fw \quad (28)$$

Where

x = $[x_1\ x_2 \ldots\ldots x_9]^T$ = state vector

u = $[u_1\ u_2]^T$ = control vector

w = $[w_1\ w_2]^T$ = disturbance vector

While the matrices A, B and F are defined as follows:

$$A = \begin{bmatrix} -\frac{1}{T_{ps1}} & \frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 & -\frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1T_{sg1}} & 0 & -\frac{1}{T_{sg1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{ps2}} & \frac{K_{ps2}}{T_{ps2}} & 0 & \frac{a_{12}K_{ps2}}{T_{ps2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{t2}} & \frac{1}{T_{t2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_2T_{sg2}} & & -\frac{1}{T_{sg2}} & 0 & 0 & 0 \\ 2\pi T_{12} & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 & 0 & 0 \\ b_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & b_2 & 0 & 0 & -a_{12} & 0 & 0 \end{bmatrix}$$

$$B^T = \begin{bmatrix} 0 & 0 & \frac{1}{T_{sg1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{sg2}} & 0 & 0 & 0 \end{bmatrix}$$

$$F^T = \begin{bmatrix} -\frac{K_{ps1}}{T_{ps1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_{ps2}}{T_{ps2}} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

7. Simulation Studies

A. Application of Model-Order Reduction

Using particle swarm optimization technique for numerator and dominant pole retention technique for denominator, the second-order reduced models is as shown below

$$G_{MR}^{t}(s) = \frac{(-2.628s-0.3041)}{(s^2+1.026s+0.208)} \quad (29)$$

$$G_{MR}^{f}(s) = \frac{(-0.1571s-0.104)}{(s^2+1.025s+0.208)} \quad (30)$$

The original model step response i.e., full-order model G(s) and the reduced order model (29) and (30). From this the third order model is equal to the second order model. Thus the two models are suitable.

B. Application of Proposed Controller Design

1) Controller for Tie-line power deviation:

Since (29) has RHP zero at s=15.89, and therefore in order to factorize (29), $G_{MR}^{t}(s)$ can be written as

$G^t_{MR}(S) = G^t_{MR+}(S)\, G^t_{MR-}(S)$ Rearrange $G_{MR}(s)$ as

$$G^t_{MR}(s) = \frac{(2.628s+0.3041)}{(s^2+1.206s+0.208)} \frac{(-2.628s-0.3041)}{(2.628s+0.3041)} \qquad (31)$$

Where $G^t_{MR}(s)$ is a minimum phase part

$$G^t_{mr-}(S) = \left(\frac{2.628s+0.3041}{s^2+1.206s+0.208}\right) \qquad (32)$$

and $G^t_{mr-}(S)$ is a non-minimum phase part:

$$G^t_{mr+}(S) = .\left(\frac{-2.628s-0.3041}{2.628s+0.3041}\right) \qquad (33)$$

Consider $\lambda_f =$ and employ (10) and (11), the TDF-IMC of the form (7) is shown as

$$Q_d(s) = \frac{(s^2+1.026s+0.208)(-0.0355s^2+0.3878s+1)}{(2.628s+0.3041)(0.08s+1)^3} \qquad (34)$$

Where φ, ϴ and x are -0.0654, 1.8488 and 3 respectively

2) Controller for frequency deviation:

Since (30) has RHP zero at s=15.89, and therefore in order to factorize (30), $G^f_{MR}(s)$ can be written as $G^f_{MR}(s) = G^f_{MR+}(S) G^f_{MR-}(S)$. Rearrange $G^f_{MR}(s)$ as

$$G^f_{MR}(S) = \frac{(0.1571s+0.104)}{(s^2+1.206s+0.208)} \frac{(-0.1571s-0.104)}{(0.1571s+0.101)} \qquad (35)$$

Where $G^f_{MR+}(S)$ is a minimum phase part

$$G^f_{MR+}(S) = \frac{(0.1571s+0.104)}{(s^2+1.206s+0.208)} \qquad (36)$$

and $G^f_{mr-}(S)$ is a non-minimum phase part:

$$G^f_{MR-}(S) .= \frac{(-0.1571s-0.104)}{(0.1571s+0.101)} \qquad (37)$$

Considering $\lambda_f = 0.08$, and using (10) and (11), the TDF-IMC controller of the form (7) is given by

$$Q_d(s) = \frac{(s^2+1.026s+0.208)(-0.0355s^2+0.3878s+1)}{(0.1571s+0.104)(0.08s+1)^3} \qquad (38)$$

Where φ, ϴ and x are 0.4138, -8.679 and 3 respectively

As noted before, the robust and optimal controller specified for particular type of disturbance (e.g., for an input of the plant step load will acts).
The results of the two-area system (ΔP_{tie}, change in tie line power and Δf, change in frequency) obtained through the digital computer is as shown below

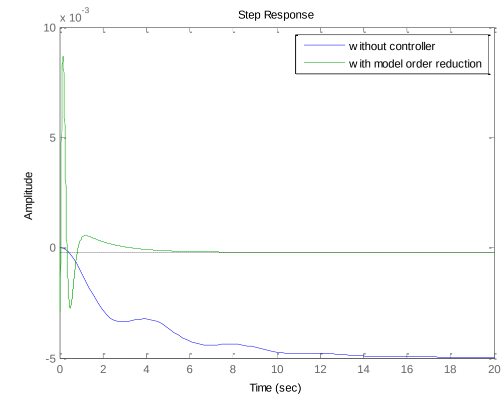

Fig.5. change in tie-line due to step load (0.01p.u) change in area 1

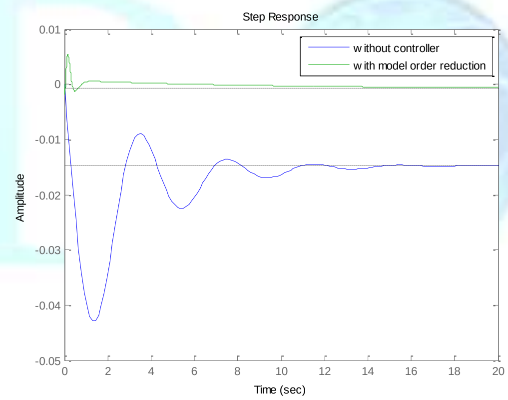

Fig.6. change in frequency due to step load (0.01p.u) change in area 1

The main theme of developing a controller is its ability to perform well under uncertain condition. In IMC design model, the stability can be done by choosing the value of G(s) and Q(s). The previous section clearly states that IMC scheme via reduced order model surely creates plant mismatch which can forms into instability, limit operation of the control system. To obtain this it needs to concentrate on parameters. Thus the designed compensator achieves very good stability by providing the robust techniques.

8. Conclusion and Future Work

In power systems, there is need to provide effective LFC techniques to counter the complexity of large scale systems and robustness against uncertainty in parameters and external conditions. In this, Particle Swarm Optimization and Dominant pole retention are combined to model order reduction techniques. It provides good performance in case of disturbances, removes plant mismatch as well as uncertainty in system parameters. This model removes any redundant information and provides computational efficiency.

The work in progress is for the application of multi-area power systems, and to examine the effective model-order reduction for better approximation to the full-order model.

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