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Frequency Regulation of Two-area Power System Using LFC-DR Model

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***Abstract*— Demand response (DR) is the necessary part of future grid. The benefits and impacts of DR have been reported literally in many research works. The impacts of DR on the load frequency control (LFC) problem are reported in some research works. To fill this gap, the DR control loop is added in the traditional LFC model (called LFC-DR) for a two-area power system. The model consists of optimal operation feature, so the optimal power shared between DR and supplementary control. The communication delay in the controller design is also considered, which is because of DR control loop. Due to DR control loop the stability margin of the system increased and the system dynamic performance effectively improved. Simulation studies are carried out for two-area power systems to verify the effectiveness of the proposed method.**

***Index Terms*— Demand response (DR); linear quadratic regulator (LQR); sensitivity; smart grid; stability; steady-state error; two-area power system model.**

1) Introduction

Frequency regulation in power system is calculated by balancing generation and demand through load following [1]. In future, there will be renewable energy (RE) with high penetration power generation in the power grid, which is highly variable. In those cases for balancing demand and generation, responsive loads and energy storage show great effort, and also avoid the use of schemes with traditional generation techniques, which are costly and/or environmentally unfriendly.

For balancing power with real time smart responsive load participation with low efficiency, limited availability, and high cost of large storage devices, Demand response (DR) is considered. DR manages the uncertainty and variability of some renewable resources by increasing the system flexibility and reliability, intensifies system efficiency and reduces cost of operation. Furthermore, DR can be used to provide ancillary services (AS), which helps to momentarily respond to the area control error (ACE). AS are called frequently than traditional load shedding events, annual total hours of curtailment are less, and individual events are shorter [2]. Thus, AS programs can appeal to retail customers, because they may find frequent and short on-off switching of their end use loads more acceptable than long curtailments and infrequent.

The parameter which indicates the balance of consumption and generation in a power system is frequency. AS are referred to voltage control and frequency, which are crucial parts of a power system. In conventional AS, controlled parameter is frequency by adjusting the resources at generation side including extra capacities from interconnection and large generators.

From the last five decades, the power system basically consists of a governor, a turbine and a generator with feedback of regulation constant. The system includes the step load change input to generator. These are the models help to study small variations in generation and load, and in controller design. In this paper we are introducing a DR control loop, to the LFC model called "LFC-DR". By using this control loop we are modified the small signal model of power system used in LFC studies.

To include the associated communication delay is the further goals of the paper i.e. , joined with DR between the end use consumers devices and load aggregator companies (Lagcos) to build the model as general as possible. This is an important parameter in the system dynamic performance of LFC-DR. The communication delay between the balancing authority (BA) and the load aggregators (Lagcos), and between the generation companies (Gencos) and BA generation companies (Gencos) are assumed to be same [3]. The main focus of this paper is on the assessment of the DR loop in the LFC model when the above delays are not considered. By considering the real time market price, the proposed LFC-DR gives an opportunity to the system operator to choose the DR option or spinning/non-spinning reserve, or a combination of the two. To estimate the value of the required responsive load manipulation of the disturbance is not known to the system operator. The LFC-DR model will help the operators investigates the effect of DR on the dynamic performance of the system.

In chapter II, the model is developed for two area power system by using the concept of LFC-DR. In chapter III, these models are evaluated analytically. In chapter IV, the controller design is presented, and in chapter V, simulation results are pretended. In chapter VI, the conclusion of this paper is presented

2) Two-Area Power System Problem Formulation

For the purpose of frequency control synthesis and analysis a general low order linearized power system model is given by the power balancing equation in the frequency-domain.

$$\Delta P_{T_1}(s) - \Delta P_L(s) = 2H.s.\Delta f_1(s) + D.\Delta f_1(s)$$
$$\Delta P_{T_2}(s) = 2H.s.\Delta f_2(s) + D.\Delta f_2(s)$$
$$\Delta f(s) = \Delta f_1(s) - \Delta f_2(s) \quad (1)$$

Whereas,

$\Delta P_{T_1}(s) - \Delta P_L(s)$	incremental power mismatch in first area;
$\Delta f_1(s)$	deviation in first area frequency;
$2H$	equivalent inertia constant;
D	damping co-efficient of load;
s	Laplace transform operator;
$\Delta P_{T_2}(s)$	Deviation in second area turbine power;
$\Delta f_2(s)$	deviation in second area frequency;
$\Delta f(s)$	frequency deviation in two-area power system.

Since DR for AS performs like spinning reserve in power flow direction and magnitude, i.e., if once frequency deviation is positive (negative), it is required to turn ON (or OFF) a portion of the responsive loads (i.e., DR), can be simply modified as follows to include DR:

$$\Delta P_{T_1}(s) - \Delta P_L(s) + \Delta P_{DR_1}(s) = 2H.s.\Delta f_1(s) + D.\Delta f_1(s)$$
$$\Delta P_{T_2}(s) - \Delta P_{DR_2}(s) = 2H.s.\Delta f_2(s) + D.\Delta f_2(s) \quad (2)$$

The effect of Demand response (DR) has been included in the load damping coefficient D. where D is an inherent parameter and also not controllable, but whereas DR is a controllable signal of the system so the effect of DR should be divided. In addition, the above equations will consent to have a separate control loop for Demand response,

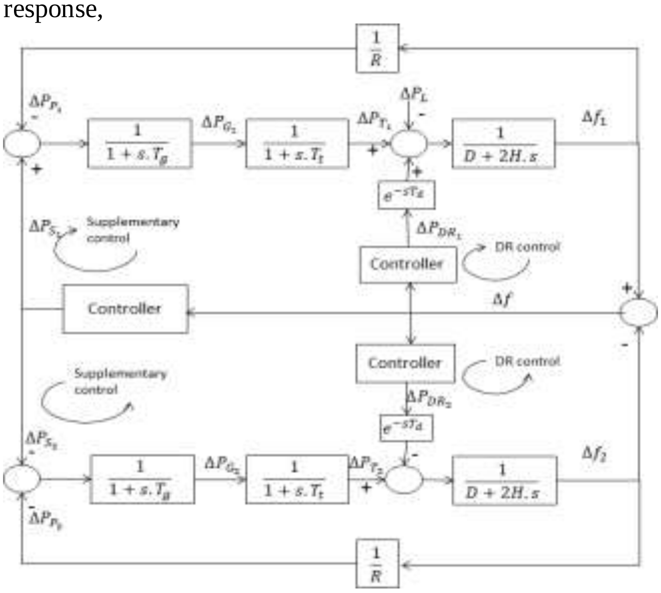

Fig.1. Block diagram representation of a two-area power system model

which provide a better structure for controller design and is more realistic [3]. The block diagram for two-area power system with a simplified non-reheat is shown in Fig.1, feedback control loop for DR is also shown. Where T_g is the equivalent speed governor and T_t is turbine time constant respectively, R is equivalent droop value, and T_d is equivalent DR delay. The parameters of the system can be equivalent of load damping of same area and all generation assets. The main concept of this paper is expressed by using this model.

A. State-Space Dynamic model for LFC-DR

A dynamic model of the power system which is included with DR in the state-space representation is used to study the effect of Demand response (DR) on controller design and LFC performance [4]. A power system model with a non-reheat turbine the proposed LFC-DR model of Fig. 1 analyses, same analysis and conclusions can be extended to the turbines with other models, such as reheat-steam and hydro turbine.

The state-space representation of a two-area power system with DR (shown in Fig. 1) is given by

$$\dot{x}(t) = A.x(t) + B.u(t) + \Gamma.w(t)$$
$$y(t) = C.x(t) \quad (3)$$

Where A is the system matrix, B is the control input matrix, Γ is the disturbance matrix, x is the state vector, $u(t)$ is the input vector, $w(t)$ is the disturbance variable, C is the observation matrix, and $y(t)$ is the system output. A linear model of the system is required to derive the linear state-space model of the system. The system consists of only one nonlinear element i.e. the time delay in the DR control loop it is shown in fig.1. Therefore, we need to linearize the time delay to derive state-space model. In following subsection linearizing of DR time delay is explained using Pade approximation.

B. Pade Approximation

To linearize systems with time delays having very strong convergent results the Pade approximation is widely used. By quotients of polynomials it basically approximates time delays. Specifically, the Pade function is defines as follows:

$$e^{-s.T_d} \approx R_{pq}(-s.T_d) \quad (4)$$
$$R_{pq}(e^{-s.T_d}) = D_{pq}(e^{-s.T_d})^{-1}.N_{pq}(e^{-s.T_d}) \quad (5)$$

where

$$N_{pq}(e^{-s.T_d}) = \sum_{k=0}^{p} \frac{(p+q-k)!p!}{(p+q)!k!(p-k)!}.(-s.T_d)^k \quad (6)$$
$$D_{pq}(e^{-s.T_d}) = \sum_{k=0}^{q} \frac{(p+q-k)!q!}{(p+q)!k!(q-k)!}.(s.T_d)^k \quad (7)$$

The order of the polynomials N_{pq} and D_{pq} are p and q respectively [5]. Usually we will take same order for the denominator and numerator of the approximation fractional function, generally the order varies between 5 and 10. Here T_d is the DR communication latency with the approximation of time delay. The low pass filters cut off frequency, i.e., turbine and speed-governor in the power system are usually less than 15rad/sec. So, here 5th order Pade approximation has been compared to that of pure time delay [1]. They are all at 0dB and not shown here.

3) ANALYTICAL EVALUATION OF THE MODEL

In this section, the steady-state error evaluation, sensitivity analysis, and stability of the system by using LFC model with and without the DR control loop are presented.

A. Steady-State Error Evaluation

The primary control loop is the fastest intentional control action in a power system but it is not enough to make the frequency deviation go to zero at steady-state [6]. Due to this reason, the supplementary frequency control loop is necessary for the further control. Therefore, it is

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necessary to examine the impact of the DR control loop on the steady-state error of the given power system. Later in this subsection, based on optimal sharing between DR and supplementary control loops, a synthesis of controller design will be derived from the steady-state error evaluation [7].

The system frequency deviation, after adding the DR control loop to the conventional LFC model can be expressed as follows:

$$\Delta f_1(s) = \frac{1}{2H.s+D}\left[\Delta P_{T_1}(s) - \Delta P_L(s) + G(s).\Delta P_{DR_1}(s)\right] \quad (8)$$

$$\Delta f_2(s) = \frac{1}{2H.s+D}\left[\Delta P_{T_2}(s) - G(s).\Delta P_{DR_2}(s)\right] \quad (9)$$

Where

$$\Delta P_{T_1}(s) = H(s).\left[\Delta P_{S_1}(s) - \frac{1}{R}.\Delta f_1(s)\right] \quad (10)$$

$$H(s) = \frac{1}{(1+s.T_g)(1+s.T_t)} \quad (11)$$

$$\Delta P_{T_2}(s) = H(s).\left[-\Delta P_{S_1}(s) - \frac{1}{R}.\Delta f_1(s)\right] \quad (12)$$

Any type of power system model with equivalent turbine and governor can be represented by modifying $H(s)$. G(S) is the 5[th] order Pade approximation [8]. In the LFC analysis, it is common to use a step load disturbance for $\Delta P_L(s)$ as

$$\Delta P_L(s) = \frac{\Delta P_L}{s} \quad (13)$$

Based on the final value theorem, the steady-state value of the system frequency deviation can be obtained as follows:

$$\Delta f_{1_{SS}} = \frac{\Delta P_{S_1,SS} + \Delta P_{DR_1,SS} - \Delta P_L}{D+\frac{1}{R}} \quad (14)$$

$$\Delta f_{2_{SS}} = \frac{-\Delta P_{S_2,SS} - \Delta P_{DR_2,SS}}{D+\frac{1}{R}} \quad (15)$$

$$\Delta f(s) = \frac{(\Delta P_{S_1,SS} + \Delta P_{DR_1,SS}) + (\Delta P_{S_2,SS} + \Delta P_{DR_2,SS}) - \Delta P_L}{D+\frac{1}{R}} \quad (16)$$

Where $\Delta P_{S_1,SS}, \Delta P_{DR_1,SS}, \Delta P_{S_2,SS}, \Delta P_{DR_2,SS}$ are the steady-state values. It can be seen from (15) and (16) that the frequency deviation will not be zero unless the supplementary and/or DR controls exist. Also, DR control loop gives an extra degree of freedom for system frequency regulation.

If $\Delta P_{S_1,SS} + \Delta P_{S_2,SS} = \Delta P_L$, the frequency error will be zero at steady-state. It means during disturbance, the required spinning and/or non-spinning reserves are provided by the supplementary control [9]. The required control effort is split between two control loops based on real time electricity market cost when DR available in the LFC. Where 0< α <1 and 0< β<1 is the share of traditional regulation services for the required control effort. The steady-state values of two inputs should be

$$\Delta P_{S_{1,SS}}(s) = \frac{\alpha}{2}\Delta P_L, \quad \Delta P_{DR_{1,SS}}(s) = \frac{1-\alpha}{2}\Delta P_L$$

$$\Delta P_{S_{2,SS}}(s) = \frac{\beta}{2}\Delta P_L, \quad \Delta P_{DR_{2,SS}}(s) = \frac{1-\beta}{2}\Delta P_L$$

(17)

B. Sensitivity Analysis for the Feedback System With and Without DR

To study the impact of the DR control loop on the overall sensitivity of closed-loop system with respect to open loop system an analytical method is utilized. It is to measure the closed-loop system sensitivity with respect to the co-efficient α and β [10]. The robustness of the closed-loop system performance when system performances are subjected to any variations is shown in the first sensitivity analysis, it is quite important. Since then α and β are also very important parameters in the performance of LFC-DR model, second sensitivity analysis is also necessary.

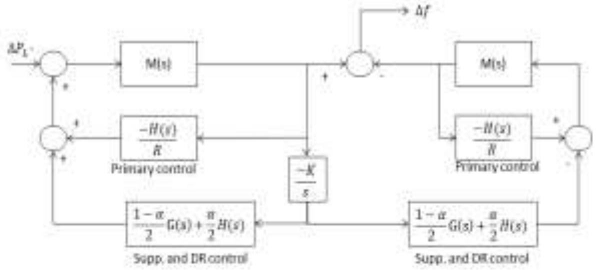

Fig.2. Modified power system model with integral controller for DR and supplementary control loops

The power system model in Fig.1 is modified and a single integral controller (with gain K) is added for both supplementary and DR control loops. For rest of this paper Fig.2. is used. This modification helps to split the required controller effort between the DR and supplementary control loops. The closed-loop transfer function for the power system shown in Fig.2, is relating the system frequency deviation to a step change in the load is derived as follows:

$$\left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_{DR} = \frac{-M(s)}{1+\frac{H(s).M(s)}{R}+\frac{K}{s}\frac{\alpha}{2}H(s).M(s)+\frac{K}{s}\frac{1-\alpha}{2}G(s).M(s)+\frac{K}{s}\frac{\beta}{2}H(s).M(s)+\frac{K}{s}\frac{1-\beta}{2}G(s).M(s)}$$

$$\left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_S = \frac{-M(s)}{1+\frac{H(s).M(s)}{R}+\frac{2K}{s}H(s).M(s)} \quad (18)$$

Where K is integral feedback gain of the system

$$M(s) = \frac{1}{D+2H.s} \quad (19)$$

These are the closed-loop transfer functions, first equation is for both control loops available and second equation is for conventional LFC. The open loop transfer function for only primary control loop exists, can be derived as follows:

$$T_{OL}(s) = \left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_{OL} = \frac{-M(s)}{1+\frac{H(s).M(s)}{R}} \quad (20)$$

The sensitivity function of the closed-loop system w.r.t. the open loop system, for systems with and without DR is follows:

$$\mathbb{S}_{OL}^{DR} = \frac{(T_{OL}(s))^{-1}}{(T_{OL}(s))^{-1}-\frac{K}{s}.\frac{\alpha}{2}.H(s)-\frac{K}{s}.\frac{1-\alpha}{2}.G(s)-\frac{K}{s}.\frac{\beta}{2}.H(s)-\frac{K}{s}.\frac{1-\beta}{2}.G(s)}$$

$$\mathbb{S}_{OL}^{S} = \frac{(T_{OL}(s))^{-1}}{(T_{OL}(s))^{-1}-\frac{K}{s}.H(s)} \quad (21)$$

Form the above equations it is clear that the closed-loop system is highly sensitive to the changes in the open loop system. i.e., small change in the value of T_{OL} will have a large effect on $\mathbb{S}_{OL}^{DR}$ and$\mathbb{S}_{OL}^{S}$. By using a single integral controller for both DR control loop and supplementary control loop the power system is modeled. This will helps to split the control effort between the two control loops (i.e., DR and supplementary control loops). For example when $\alpha = 0.8$ and$\beta = 0.8$, 80% of required regulation is provided by the supplementary control loop and remaining 20% by using the DR control loop.

A simulation study was carried out to compare the sensitivity function for an arbitrary integral feedback gain [11]. The sensitivity values for both closed-loop systems are shown in Fig.3. The values of the parameters for this simulation study are given in Table II.

The simulation study is carried for an arbitrary integral feedback gain to compare the sensitivity function [12]. As α and β are the important parameters to evaluate the sensitivity function as follows:

$$S_{\alpha}^{DR} = \frac{\frac{\partial T_{DR}}{\partial \alpha}}{\frac{T_{DR}}{\alpha}} = \frac{\frac{K}{s}.\frac{\alpha}{2}.[H(s) - G(s)]}{(T_{OL}(s))^{-1} - \frac{K}{s}.\frac{\alpha+\beta}{2}.H(s) - \frac{K}{s}.\left(1 - \frac{\alpha+\beta}{2}\right).G(s)}$$

$$S_{\beta}^{DR} = \frac{\frac{\partial T_{DR}}{\partial \beta}}{\frac{T_{DR}}{\beta}} = \frac{\frac{K}{s}.\frac{\beta}{2}.[H(s) - G(s)]}{(T_{OL}(s))^{-1} - \frac{K}{s}.\frac{\alpha+\beta}{2}.H(s) - \frac{K}{s}.\left(1 - \frac{\alpha+\beta}{2}\right).G(s)}$$

(22)

TABLE I. POWER SYSTEM PARAMETER FOR THE SIMULATION STUDY

T_g	T_t	R	2H	D	T_d	ΔP_l	K
0.08 sec	0.4 sec	3.0 Hz/p.u.	0.1667 p.u.sec	0.015 p.u./HZ	0.1 sec	0.01 p.u.	0.2

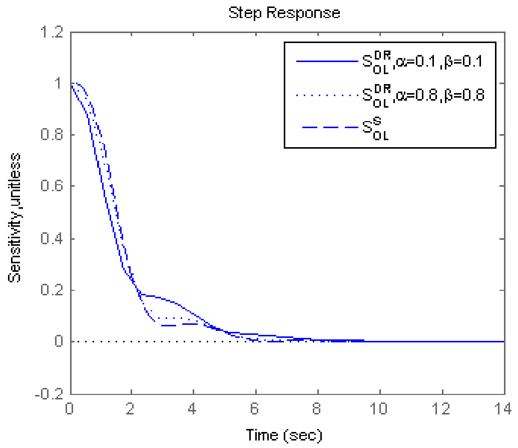

Fig.3.Closed-loop system w.r.t the open loop system sensitivity values of a simulation study for LFC with and without DR

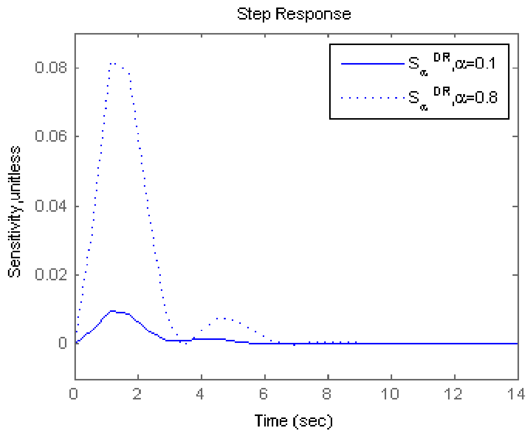

Fig.4. Closed-loop system w.r.t. α sensitivity values for the LFC-DR model, $\alpha = 0.1$ and $\alpha = 0.8$

The previous simulation study was utilized for different values of α and β. Sensitivity results are shown in Fig.4 and Fig.5. The closed-loop system is less sensitive to α and β when DR control loop takes higher share in the frequency regulation, i.e., smaller α and β.

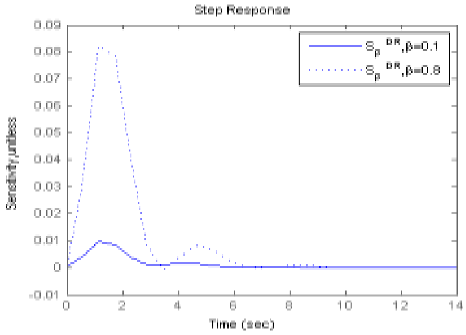

Fig.5. Closed-loop system w.r.t. β sensitivity values for the LFC-DR model, $\beta = 0.1$ and $\beta = 0.8$

C. Stability Analysis of the Closed-Loop Systems

Stability analysis is necessary for a satisfactory control of feedback control system; the commonly used two criteria's for the evaluation of stability are gain and phase margins. This can be obtained from the open loop and closed-loop transfer functions.

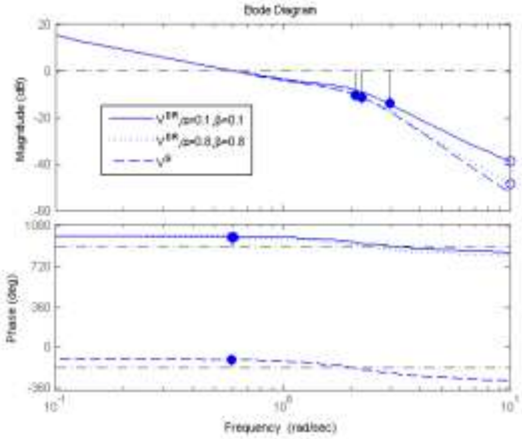

Fig.6.Bode plot of the closed-loop systems for stability analysis

The control characteristics of closed-loop system are obtained by taking the feedback gain as variable parameter. Using the load disturbance, $\Delta P_L(s)$ as the system input, the open-loop transfer functions are

$$1 + \underbrace{K.\frac{R.\left[\left(\frac{\alpha+\beta}{2}\right).H(s).M(s) + \left(1 - \frac{\alpha+\beta}{2}\right).G(s).M(s)\right]}{s.[R + H(s).M(s)]}}_{\vartheta^{DR}} = 0$$

$$1 + \underbrace{K.\frac{R.H(s).M(s)}{s.[R + H(s).M(s)]}}_{\vartheta^{S}} = 0 \qquad (23)$$

TABLE II. PHASE AND GAIN MARGINS FOR THE OPEN LOOP TRANSFER FUNCTION ASSOCIATED WITH EACH CLOSED-LOOP SYSTEMS

	ϑ^{DR}, $\alpha = 0.1$	ϑ^{DR}, $\alpha = 0.8$	ϑ^{S}
Gain margin, dB	14.1	11.3	10.3
Phase margin, degree	83.5	74.8	72.2

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From the above matlab figure, we can observe that the both systems with and without DR are relatively stable. High share of control loop smaller α and β values will provide higher gain and phase margin, which indicate a more stable system [13]. The above table shows that there are no negative impacts on stability due to 5th order Pade approximation.

4) Controller Design For LFC-DR Model

Linear quadratic regulator (LQR) is used for designing the controller. The simplified version of the LQR problem is to design the controller for the system is

$$\Im = \int_0^{\infty} [x^T.Q.x + \rho.u^T.R.u]dt$$
(24)

Where ρ is the weighting factor chosen by the designer, considering trade-off between control effort and system transient performance. Q is nXn semidefinite symmetric state cost matric (n is the number of system states), R is an mXm positive definite symmetric control cost matrix (m is the number of control inputs), and $x^T = [x_1, \ldots, x_{61}]$ (where $x_1 = \Delta f_1$, $x_2 = \Delta P_{T_1}$, $x_3 = \Delta P_{G_1}$, $x_9 = \Delta f_2$, $x_{10} = \Delta P_{T_2}$, $x_{11} = \Delta P_{G_2}$, x_4 to x_8 and x_{12} to x_{16} are the states associated with the 5th order Pade approximation). The controller input to the supplementary controller ($u_1 = \Delta P_{S_1}$ and $u_3 = \Delta P_{S_2}$) and DR controller ($u_2 = \Delta P_{DR_1}$ and $u_4 = \Delta P_{DR_2}$) are related as follows:

$$u_1 = \frac{\alpha}{1-\alpha}.u_2 \text{ or } u_2 = \frac{1-\alpha}{\alpha}.u_1$$
$$u_3 = \frac{\beta}{1-\beta}u_4 \text{ or } u_4 = \frac{1-\beta}{\beta}u_3$$
(25)

For the system with unified control inputs, all the state-space matrices will remain unchanged, except the control input matrix B, where it is modified to include $u_2 = F(u_1)$ and $u_4 = F(u_3)$ as follows:

$$\bar{B}^T = \begin{bmatrix} \frac{\alpha-1}{2H.\alpha} & 0 & \frac{1}{T_s} & \frac{16(1-\alpha)}{\alpha} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1-\beta}{2H.\beta} & 0 & \frac{-1}{T_s} & \frac{16(1-\beta)}{\beta} & 0 & 0 & 0 & 0 \end{bmatrix}$$
(26)

It is also possible to use $u_1 = F(u_2)$ and $u_3 = F(u_4)$. However, it will be shown in simulation results, the system performances in two cases are nearly identical. An integral controller is used to ensure zero steady-state error in system frequency [14]. The modified state-space model after including integrator, the augmented state equations become

$$\begin{bmatrix} \dot{x} \\ \dot{x}_I \end{bmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix}.\begin{bmatrix} x \\ x_I \end{bmatrix} + \begin{bmatrix} \hat{B} \\ 0 \end{bmatrix}.\hat{u} + \begin{bmatrix} \Gamma \\ 0 \end{bmatrix}.w$$
$$y = [C \quad 0].\begin{bmatrix} x \\ x_I \end{bmatrix}$$
(27)

Where $\hat{u} = \begin{bmatrix} u_1 \\ u_3 \end{bmatrix}$. The augmented state-space equation can be written as follows:

$$\dot{\hat{x}} = \hat{A}.\hat{x} + \hat{B}.\hat{u} + \hat{\Gamma}.w$$
$$\hat{y} = \hat{C}.\hat{x}$$
(28)

Where the states are defined as $\hat{x}^T = [\Delta f_1 \ \Delta P_{T_1} \ \Delta P_{G_1} \ x_4 \ldots x_8 \ \Delta f_2 \ \Delta P_{T_2} \ \Delta P_{G_2} \ x_{12} \ldots x_{16} \ \int \Delta f.dt]$.

The matrices for the modified system are

$$\hat{A} = \begin{bmatrix} A & 0_{16X1} \\ [1 \quad 0_{1X15}] & 0 \end{bmatrix}, \hat{B}^T = [\hat{B} \quad 0],$$
$$\hat{\Gamma}^T = [\Gamma \quad 0], \hat{C} = [C \quad 0]$$
(29)

If the augmented system matrix is controllable, then control law and state feedback can be defined as

$$\hat{u} = -[K \quad K_I].\begin{bmatrix} x \\ x_I \end{bmatrix} = -\hat{K}.\hat{x}.$$
(30)

To employ LQR method, we need to define the state and control weighting matrices, Q and R (scalar quantity), respectively. The weighting matrices after considering requirements [1] are

$$Q = diag(1 \quad 0_{1X15} \quad 1), R = [1].$$
(31)

Simulation results for the LFC-DR model of a two area power system are presented to verify the effectiveness of the proposed model.

5) Simulation Results For Two-Area Power System

In order to show important features of the proposed LFC-DR model, the results of different simulation studies are shown for a two area power system. To make a fair comparison, similar LQR design procedure has been employed for designing controller for both with and without DR systems. It is validated using MATLAB/Simulink.

In the first simulation study, a 0.01p.u load disturbance was applied to the two area power system with conventional LFC and the proposed LFC-DR model. The system frequency deviation is shown in below figure.

The supplemenatry and DR control inputs are shown in above Figure, for the same simulation. The steady-state values of the control inputs are based on the share between the supplementary and DR control loops.

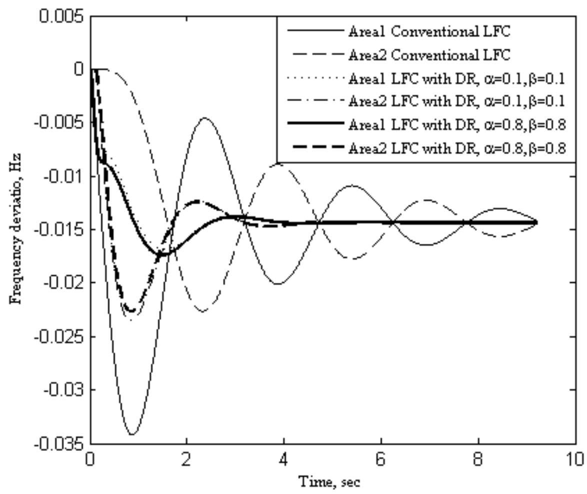

Fig.7. Frequency deviation for conventional LFC and LFC-DR models

The steady-state value calculations also shown in figure. It can be seen that when α=0.1 and β=0.1 (i.e., 10%(area1 5% and area2 5%) of the required regulation is provided by the supplementary control and 90%(area1 45% and area2 45%) from DR), the LFC-DR model has a superrior performance over the conventional LFC during the transient period.The results show that there is a improvement in the settiling time as well. Same simulation was repeated for α=0.8 and β=0.8. As expected, the lower DR control effort resulted in less improvement in the system dyamic performance. It can bw observed that the dynamic performance of the system approaches that of conventional LFC for higher values of α and β.

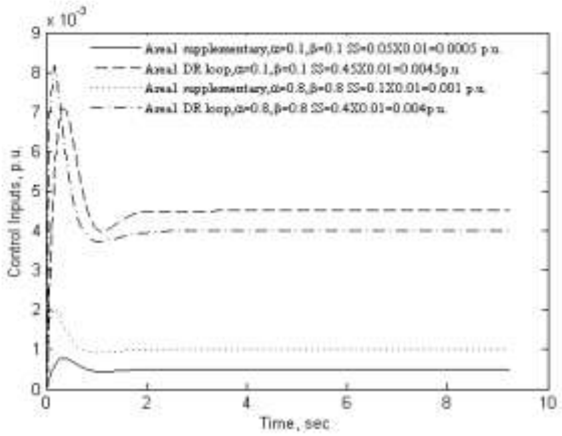

Fig.8. Steady-state values of the control inputs for the LFC-DR model, Area1

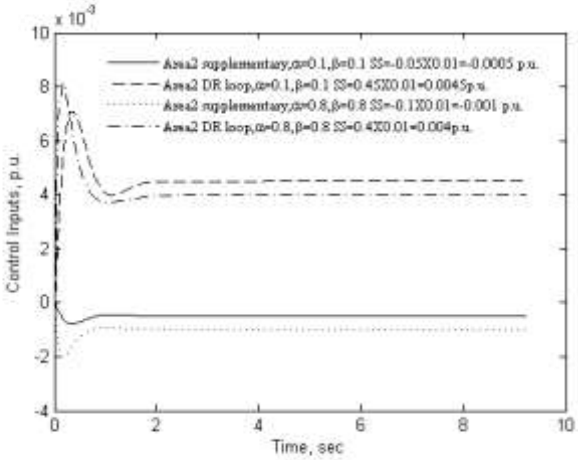

Fig.9. Steady-state values of the control inputs for the LFC-DR model, Area2

A simulation study was carried out to show the imapact of the order of Pade approximation on the performance of the system, the results of which are shown in Fig.10. 2nd and 5th order Pade approximations are considered in the proposed LFC-DR model and compared with the conventional LFC, for α=0.1 and β=0.1. It can be seen from figure that the results from the 2nd and 5th order Pade approximation are almost identical. It is because of simplified governor and turbine models are low pass filters which restrict the system response to lowr frequency ranges, whre Pade approximation is exactly the same as pure time delay. Therefore, for simplicity, 2nd order Pade approximation can be employed for more complicated power systems without negative impacts on the final results.

From the total four controller inputs, we used two control inputs for the controller design as a function of α and β. We can use

$$u_1 = \frac{\alpha}{1-\alpha}.u_2 \text{ or } u_2 = \frac{1-\alpha}{\alpha}.u_1$$
$$u_3 = \frac{\beta}{1-\beta}u_4 \text{ or } u_4 = \frac{1-\beta}{\beta}u_3$$
(32)

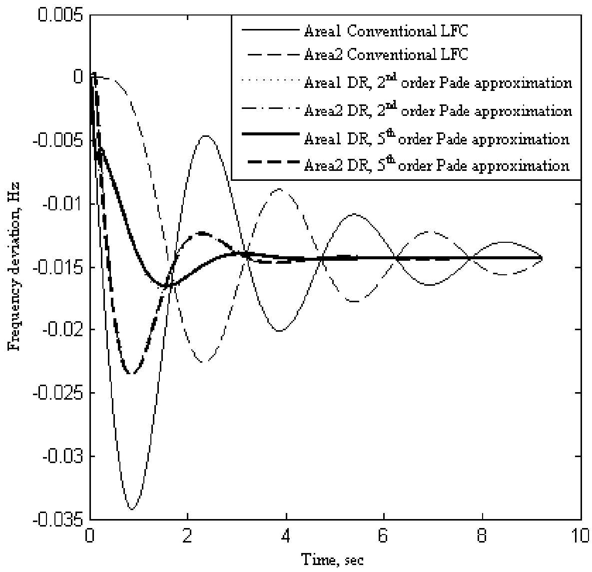

Fig.10. Controller performance for different order of Pade approximation

A simulation study was carried out to comapre the performance of the system for both cases and results are shown in Fig.11. It can be observe that the difference between the two approaches is negligible. In other words, the control input can be chosen arbitarily without any negative impact on the performance of the LFC-DR model.

Another simulation study was proposed to evaluate the imapct of communication delay of the DR control loop on the system performance for frequency stabilization. Simulation resutls ar shown in Fig.12 for α=0.1 and β=0.1. The lowest communication delay is for a small power system with fast two-way communication link. It can be seen that the LFC-DR model gives a better performance compared to the conventional LFC.

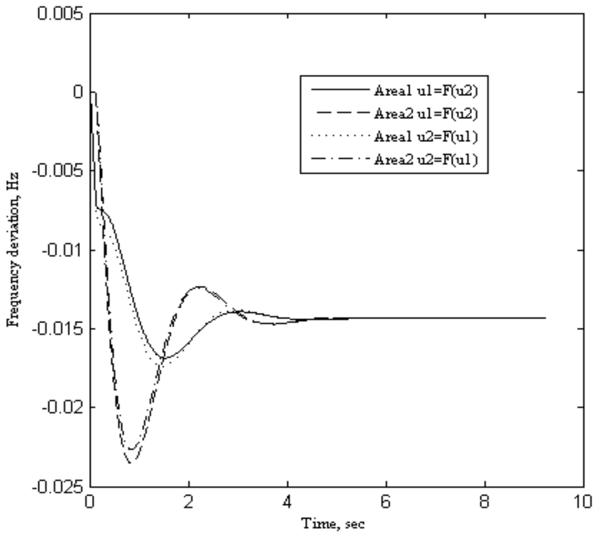

Fig.11. Impact of different unified inputs on the performance of the LFC-DR model

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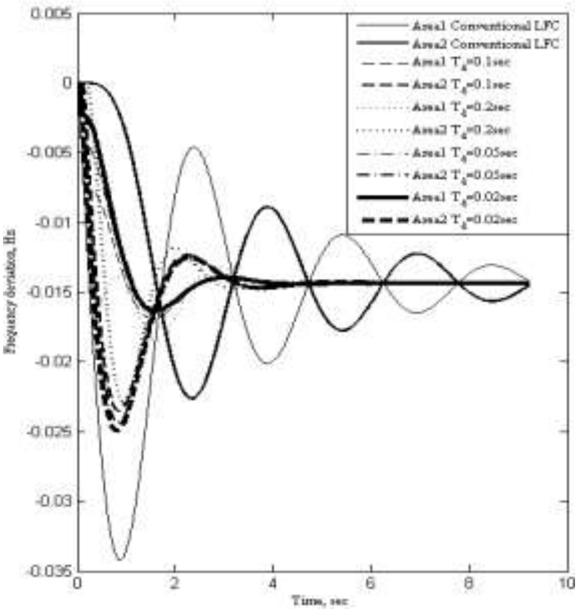

Fig.12. Impact of latency on the performance of the LFC-DR model

6) Conclusion

In this paper, a general framework is proposed to include DR into the LFC problem (LFC-DR). This formulation can expand easily for different types of power systems having various size and characteristics. The proposed formulation balances the power between demand and generation. By utilizing available controllable loads, it stabilizes the system frequency. For controller design it uses communication latencies in DR and Pade approximation. The proposed LFC-DR framework improves the stability margins in the conventional LFC model, such as changes in the open loop transfer function. Similar results have also been obtained for the sensitivity of closed-loop system w.r.t. the parameter α and β. Finally, LQR design is applied for full state feedback controller design for a two area power system. Simulation results shows that the effectiveness of LFC-DR model in iproving stabilization of the system frequency.

References

[1] S. Ali Pourmousavi and M. Hashem Nehrir , "Introducing Dynamic Demand Response in the LFC Model", IEEE Trans. Power Syst., vol. 29, no. 4, july 2014.

[2] A. Brooks, E. Lu, D. Reicher, C. Spirakis, and B. Weihl, "Demand dispatch: Using real-time control of demand to help balance generation and load ," IEEE Power Energy Mag., vol. 8, no. 3, pp. 20–29, May/Jun. 2010.

[3] M. Parvania and M. Fotuhi-Firuzabad, "Integrating load reduction into wholesale energy market with application to wind power integration," IEEE Syst. J., vol. 6, no. 1, pp. 35–45, Mar. 2012.

[4] K. Dietrich, J.M. Latorre, L. Olmos, and A. Ramos, "Demand response in an isolated system with high wind integration," IEEE Trans. Power Syst., vol. 27, no. 1, pp. 20–29, Feb. 2012.

[5] S. A. Pourmousavi and M. H. Nehrir, "Demand response for smart micro grid: Initial results," in Proc. 2nd IEEE PES Innov. Smart Grid Technol. (ISGT), Anaheim, CA, USA, 2011, pp. 1–6.

[6] [6] S. A. Pourmousavi, M. H. Nehrir, and C. Sastry, "Providing ancillary services through demand response with minimum load manipulation," in Proc. 43rd North Amer. Power Symp. (NAPS), Boston, MA, USA, 2011, pp. 1–6.

[7] D. Trudnowski, M. Donnelly, and E. Lightner, "Power-system frequency and stability control using decentralized intelligent loads," in Proc., IEEE PES Conf. Exhib. Transm. Distrib., Dallas, TX, USA, 2005, pp. 1453–1459.

[8] A. Molina-García, F. Bouffard, and D. S. Kirschen, "Decentralized demand-side contribution to primary frequency control," IEEE Trans. Power Syst., vol. 26, no. 1, pp. 411–419, Feb. 2011.

[9] D. Jay and K. S. Swarup, "Dynamic demand response and control in smart grid environment," in Proc. Annual IEEE India Conf. (INDICON), Hyderabad, 2011, pp. 1–4.

[10] Introducing Dynamic demand response in LFC Model IEEE 2014 pp. 1924–1929, Nov./Dec. 2008.

[11] H. Bevrani, *Robust Power System Frequency Control*. New York, NY, USA: Springer, 2009, ch. 1–3.

[12] P. Kundur, *Power system Stability and control*. New York, NY, USA: McGraw-Hill, 1994, ch. 11.

[13] T. Hiyama, "Design of decentralized load-frequency regulators for interconnected power systems," *Proc. IEE Generation, Transmission, Distribution Conf.*, vol. 129, no. 1, pp. 17–23, 1982.

[14] C. Dorf and R. H. Bishop, *Modern Control Systems*, 7th ed. New York, NY, USA: Addison-Wesley, 1995, p. 807.