Stability and Sensitivity analysis of LFC model by introducing Demand Response

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Abstract - The strong inspiration to increase the saturation of renewable energy in power systems, particularly at the distribution level, introduces new challenges for frequency and voltage regulation. Thus, increased attention has been given to demand response (DR), especially in the smart grid environment, where two-way communication and customer sharing are part . Demand Response (DR) is becoming an basic part in the power system and market operations. Much research work is going on the impact of demand response on power system dynamic performance, especially on Load Frequency Control (LFC) problem. The objective of this paper is introducing a DR control loop in the traditional LFC model (LFC-DR) for given power system. The effect of communication delay and optimal operation through optimal power sharing between DR and supplementary control is considered in controller design. The DR control loop increases the stability margin of the system and effectively improves the system dynamic performance. The proposed method simulation studies will be carried out for a single area power system to verify its effectiveness in MATLAB/ Simulink.

Keywords — Demand response (DR), linear quadratic regulator (LQR), Single-area power system model, smart grid, stability, steady-state error.

I. Introduction

Traditionally, frequency regulation in power system is achieved by balancing generation and demand through load following, i.e., spinning and non-spinning reserves [1]. The future power grid, is foreseen to have high saturation of renewable energy (RE) power generation, which can be highly variable. In such cases, energy storage and responsive loads show great secure for balancing generation and demand, as they will help to avoid the use of the traditional generation schemes, which are costly and/or environmentally unfriendly. In the last five decades, traditional LFC models have been revised and modified to include the different types of power plants, including RE power generation with actual limitations, such as ramp-up/down limits, in the traditional and de-regulated power market. These models are useful in small disturbance studies such as small variations in load and generation, and in controller design. However, so far in the literature, the concept of control in the LFC model has only focused on the generation side and DR has not been included in these studies. In this paper we change the general small-signal model of a power system used in LFC studies by introducing a DR control loop to the LFC model (called LFC-DR).

Demand response (DR) plays a very important role in the electricity market by introducing load flexibility instead of adjusting only generation levels, at all the operation time scales to maintain the balance between supply and demand. There are many players in the market who benefit from DR, like the TSO, DSOs, retailers and end customers themselves. The recent arrival of smart grid technologies by providing the needed information and communication infrastructure to the existing grid advanced the addition of DR. **"Changes in the electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices."**

Other aims of the paper is to make the model as general as possible and to include communication latency related with DR between the load aggregator companies (Lagcos) and the end-use customers devices.We have assumed the communication delay between the balancing authority (BA) and the Lagcos to be the same as that between the BA and generation companies (Gencos). We have not considered these delays in our study since the focus of this paper is on the evaluation of the DR loop in the LFC model. The proposed LFC-DR also gives an opportunity to the system operator to select the DR option or spinning/non-spinning reserve, or a combination of the two, based on the real-time market price. The idea of DR for ancillary services (AS) used in this paper, has been fully explored in our previous work [2] . In such a model, the Lagcos will work with the customers and inform the utilities, e.g., independent system operators, of the amount of DR available. An example of such a model is the PJM electricity market [8].

II. Problem Formulation

The general low-order linearized power system model for the purpose of frequency control synthesis and analysis is given by the power balance equation in the frequency-domain [3], [4]:

$$\Delta P_T(s) - \Delta P_L(s) = 2H.s.\Delta f(s) + D.\Delta f(s) \qquad (1)$$

where

$\Delta P_T(s) - \Delta P_L(s)$ Incremental power mismatch; D equivalent load damping coefficient;

$\Delta f(s)$ frequency deviation; s Laplace transform operator;

$2H$ Equivalent inertia constant;

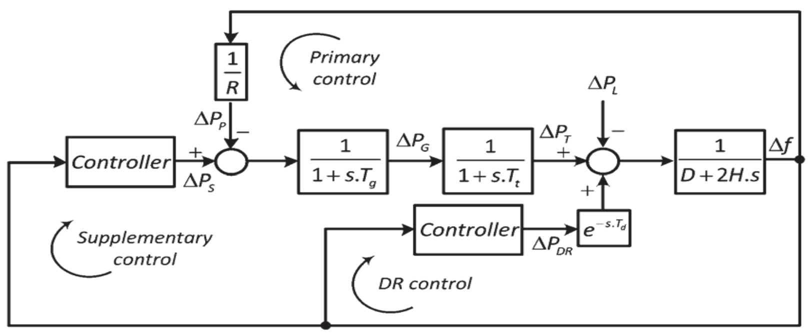

Fig. 1. Block-diagram representation of a single-area power system model

Since DR is used as AS(ancillary services) performs like spinning reserve in magnitude and power flow direction, i.e., once frequency deviation is negative (positive), it is required to turn OFF (ON) a portion of the responsive loads (i.e., DR), (1) can be simply modified as follows to include DR:

$$\Delta P_T(s) - \Delta P_L(s) + \Delta P_{DR}(s) = 2H.s.\Delta f(s) + D.\Delta f(s) \qquad (2)$$

In some previous works the effect of DR has been included in the load-damping coefficient, D. We think the effect of DR should be separated because D is an inbuilt parameter of the system and is not a controllable one, whereas DR is an intentional control signal. In adding, (2) will allow to have a separate control loop for DR, which is more realistic and gives a improved structure for controller design. The block diagram for the power system with a simplified non-reheat steam turbine is shown in Fig. 1, the feedback loop for DR is also shown. T_g and T_t are the equivalent speed-governor and turbine time constants, respectively, R is the equivalent droop value, and T_d is the equivalent DR delay. The parameters of the system can be the equivalent of all generation assets and load damping of the same area.

III. Analytical Evaluation of the Model

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

A. Pade Approximation: Pade approximation is one of the techniques used to lineariz e systems with time delays in control engineering with very strong convergent results [5]. Specifically, the pade approximation is defined as follows

$$e^{-s.T_d} \approx R_{pq}(-s.T_d) \quad (3)$$

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

Where

$$N_{pq}(e^{-s.T_d}) = \sum_{k=0}^{p} \frac{(p+q-k)!\,p!}{(p+q)!\,k!(p-q)!}.(-s.T_d)^k \quad (5)$$

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

P and q are the order of the polynomials of N_{pq} and D_{pq}, it is very common to use the same order for numerator, denominator of the approximation fractional function, the order generally varies between 5 to 10. As the cut-off frequency of the low pass filters, i.e., speed-governor and turbine in the power system model is usually less than 15 rad/sec. So, 5th order pade approximation is used. T_d is the DR communication latency, which is non-linear element, with the above approximation the time delay element is linearized.

B. Steady-State Error Evaluation

The primary control loop in Fig. 1, known as frequency droop control, is the fastest intended control action in a power system but it is not sufficient to make the frequency deviation go to zero at steady-state. For this reason, the supplementary frequency control loop it is shown in Fig.1. However, the DR control loop is also added to the problem in this study. It is essential to investigate the impact of the DR control loop on the steady-state error of the given power system in Fig. 1. Later the synthesis of controller design, based on optimal sharing between DR and supplementary control loops, will be derived from the steady-state error evaluation. The conventional LFC steady-state equations are well-documented, e.g. [3], [4]. Adding the DR control loop to the conventional LFC model, the system frequency deviation can be expressed as follows:

$$\Delta f(s) = \frac{1}{2H.s+D}\left[\Delta P_T(s) - \Delta P_L(s) + G(s).\Delta P_{DR}(s)\right] \quad (7)$$

Where

$$\Delta P_T(s) = H(s).\left[\Delta P_S(s) - \frac{1}{R}.\Delta f(s)\right]$$

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

(8)

$$G(s) = \frac{-s^5 + \frac{30}{T_d}.s^4 - \frac{420}{T_d^2}.s^3 + \frac{3360}{T_d^3}.s^2 - \frac{15120}{T_d^4}.s + \frac{30240}{T_d^5}}{s^5 + \frac{30}{T_d}.s^4 + \frac{420}{T_d^2}.s^3 + \frac{3360}{T_d^3}.s^2 + \frac{15120}{T_d^4}.s + \frac{30240}{T_d^5}} \quad (9)$$

For any type of power system model with equivalent turbine and governor can be represented by modifying $H(s)$. Substituting (8) into (7) yields

$$\Delta f(s) = \frac{1}{2H.s+D}\left[H(s).[\Delta P_S - \frac{1}{R}.\Delta f(s)] - \Delta P_L(s) + G(s).\Delta P_{DR}(s)\right] \quad (10)$$

Solving (10) for $\Delta f(s)$ will result in the frequency deviation equation as follows :

$$\Delta f(s) = \frac{1}{\psi(s)}.\left[H(s).\Delta P_S(s) + G(s).\Delta P_{DR}(s)\right] - \frac{1}{\psi(s)}.\Delta P_L(s) \tag{11}$$

Where $\psi(s) = 2H.s + D + \frac{H(s)}{R}$

(12)

In the LFC analysis, it is common to use a step load disturbance for ΔP_L. $\Delta P_L(s) = \frac{\Delta P_L}{s}$ (13)

Based on the final value theorem, and substituting (13) into (11), the steady-state value of the system frequency deviation can be obtained as follows:

$$\Delta f_{SS} = \lim_{s \to 0} s.\Delta f(s) = \frac{\Delta P_{S,SS} + \Delta P_{DR,SS} - \Delta P_L}{\psi(0)}$$

(14) Where , $\Delta P_{S,SS} = \lim_{s \to 0} s.H(s).\Delta P_S(s)$

(15)

$$\Delta P_{DR,SS} = \lim_{s \to 0} s.G(s).\Delta P_{DR}(s)$$

(16)

$$\psi(s) = D + \frac{H(0)}{R} = D + \frac{1}{R} \approx B$$

(17)

Therefore, $\psi(0)$ is equivalent to the system frequency response characteristics, B, and the steady-state frequency deviation can be written as follows :

$$\Delta f_{SS} = \frac{\Delta P_{S,SS} + \Delta P_{DR,SS} - \Delta P_L}{D + \frac{1}{R}} \tag{18}$$

From (18) the frequency deviation will not be zero unless the supplementary and/or DR controls exist. DR control loop gives an further degree of freedom for system frequency regulation. The following conclusions can be observed from (18):

- The steady-state error is independent on the delay and the order of its approximation.
- With DR existing in the LFC, a higher reliability of frequency regulation can be achieved, as the DR control loop can balance the supplementary control loop. When the supplementary control is not existing , the performance of the frequency regulation can be guaranteed by the DR loop, if adequate DR resources are available.
- For zero frequency deviation at steady-state, the required control effort can be split between the supplementary and DR control loops. In other words, an ISO/RTO will have the chance to perform the regulation services in a cost effective way and analyze the frequency response of the system quickly. This is achieved only in the proposed formulation with the DR control loop (Fig. 1).

The final conclusion is : consider a situation where no DR available. The frequency error will be zero at steady-state if $\Delta P_{S,SS} = \Delta P_L$. It means that the supplementary control should provide sufficient spinning and/or non-spinning reserve at the time of disturbance .With DR available in the LFC, the required control effort, called Ω in this study, can be split between the two control loops based on their cost at real-time electricity market as follows:

$$\Delta P_S(s) = \alpha.\Omega$$

$$\Delta P_{DR}(s) = (1-\alpha).\Omega \tag{19}$$

where $0 < \alpha < 1$ is the share of conventional regulation services in the required control effort. $\alpha = 1$ means that the total required regulation will be provided by the traditional regulation services, i.e. spinning and non-spinning reserve, and $\alpha = 0$, all the required control would be provided by DR. The decision on the value of a should be made by the ISO/RTO, based on the price of DR and the traditional regulation services in a real-time market, explored by the authors in [2]. Then, it is possible for the ISO/RTO to efficiently and quickly assess the various scenarios of LFC to estimate the system performance under various situations. At last, the steady-state value of the two inputs should be

$$\Delta P_S(s) = \alpha.\Delta P_L$$

$$\Delta P_{DR}(s) = (1-\alpha).\Delta P_L \tag{20}$$

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

In this subsection, an analytical method is utilized to study the impact of the DR control loop on the overall sensitivity of the closed-loop system w.r.t the open-loop system. It is also required to measure the sensitivity of the closed-loop system w.r.t the coefficient α .The first sensitivity analysis is quite significant because it shows the robustness of the closed-loop system performance when the system parameters are subjected to any change or any variation. The second sensitivity analysis is also necessary since α is an important parameter in the performance of the LFC-DR model.

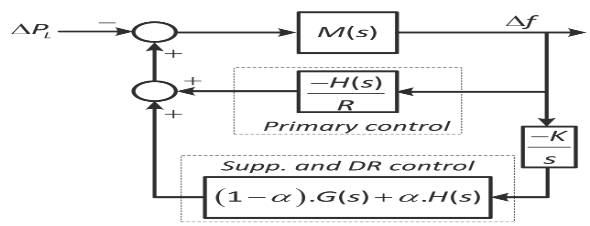

Fig.2. Modified power system model with integral controller for DR and supplementary control loops.

The power system model shown in Fig. 1 is modified for this part with a single integral controller (with gain K) for both the supplementary and DR control loops, and also for the remaining of this paper, as shown in Fig. 2. This modification will also allow us to split the required control effort between the DR and supplementary control loops, as was discussed in Section III-B. From Fig.2 the closed-loop transfer function relating the system frequency deviation to a step change in the load can be expressed as follows:

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

$$\left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_{S} = \frac{-M(s)}{1+\frac{H(s).M(s)}{R}+\frac{K}{s}.H(s).M(s)} \tag{21}$$

Where K is integral feedback gain of the system and $M(s)$ is given by

$$M(s) = \frac{1}{D + 2H.s} \tag{22}$$

In (21), the first expression is the closed-loop transfer function when both DR and supplementary control loops are presented, whereas the second equation shows the closed-loop transfer function for conventional LFC (when no DR). The open-loop transfer function, where only the primary control exists, can be derived as follows:

$$T_{OL}(s) = \left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_{OL} = \frac{-M(s)}{1 + \frac{H(s).M(s)}{R}} \tag{23}$$

In order to derive the sensitivity function of the closed-loop system w.r.t. the open-loop system, (21) can be simplified and rearranged using (23) : p

$$T_{DR} = \left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_{DR} = \frac{1}{(T_{OL}(s))^{-1} - \frac{K}{s}.\alpha.H(s) - \frac{K}{s}.(1-\alpha).G(s)}$$

$$T_S = \left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)_S = \frac{1}{(T_{OL}(s))^{-1} - \frac{K}{s}.H(s)} \tag{24}$$

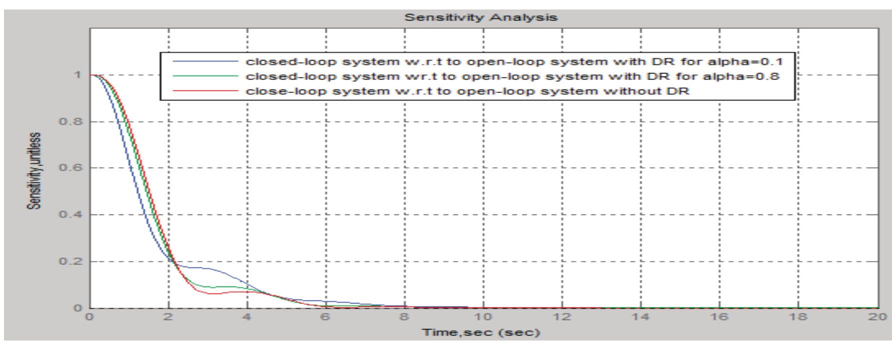

Fig.3 Closed-loop system w.r.t the open-loop system sensitivity values of a simulation study for LFC with and without DR

The unit less sensitivity function of the closed-loop system w.r.t the open-loop system, for systems with and without DR, can be written as follows:

$$S_{OL}^{DR} = \frac{\partial T_{DR}}{\partial T_{OL}} / \frac{T_{DR}}{T_{OL}} = \frac{(T_{OL}(s))^\wedge -1}{(T_{OL}(s))^\wedge -1 - \frac{K}{s}.\alpha.H(s) - \frac{K}{s}.(1-\alpha).G(s)}$$

$$S_{OL}^{S} = \frac{\partial T_{S}}{\partial T_{OL}} / \frac{T_{S}}{T_{OL}} = \frac{(T_{OL}(s))^\wedge -1}{(T_{OL}(s))^\wedge -1 - \frac{K}{s}.H(s)} \tag{25}$$

It is observed from (25) that the closed-loop system is highly sensitive to the changes in the open-loop system, i.e., any change in the value of T_{OL} will have a large effect on S_{OL}^{DR} & S_{OL}^{S}. From (25), the ratio of sensitivity functions can be expressed as

$$\frac{S_{OL}^{DR}}{S_{OL}^{S}} = \frac{(T_{OL}(s))^{-1} - \frac{K}{s}.H(s)}{(T_{OL}(s))^{-1} - \frac{K}{s}.\alpha.H(s) - \frac{K}{s}.(1-\alpha).G(s)} \quad (26)$$

Equation (26) can be rearranged as follows:

$$\frac{S_{OL}^{DR}}{S_{OL}^{S}} = \frac{(T_{OL}(s))^{-1} - \frac{K}{s}.H(s) - \frac{K}{s}.\alpha.H(s) + \frac{K}{s}.\alpha.H(s)}{\underbrace{(T_{OL}(s))^{-1} - \frac{K}{s}.\alpha.H(s)}_{\Phi} - \underbrace{\frac{K}{s}.(1-\alpha)}_{\Psi}.G(s)} == \frac{1-\frac{\Psi}{\Phi}.H(s)}{1-\frac{\Psi}{\Phi}.G(s)} \quad (27)$$

Therefore, it can be observed from (27) that the closed-loop LFC-DR is slightly less sensitive than the system without DR only if H(s) > $G(s)$, assuming Φ and Ψ have the same sign. In order to compare the sensitivity functions, a simulation study was carried out for an arbitrary integral feedback gain. The sensitivity values for both closed-loop systems are shown in Fig.3.The values of the different parameters for this simulation study are given in Table I.

Two different values for α are used in Fig.3 to show that a higher DR share (smaller α) will result in less sensitivity of the closed-loop system w.r.t the open-loop system. That is, the closed-loop system becomes less sensitive to the variation of uncertain parameters of the open-loop system. When α = 0.8 (i.e., 80% of the required regulation would be provided by the supplementary control and 20% is from DR), the sensitivity values for both the closed-loop systems, with and without DR, are almost similar. This is a good indication that the 5th-order pade approximation, used for linearizing the time delay in the DR loop, doesn't have any negative impact on the system performance. A similar study has been carried out to investigate the sensitivity of the closed-loop system w.r.t. the integral feedback gain, and similar results have been obtained.

As α is an important parameter to evaluate the sensitivity of closed loop system. The sensitivity function is written as follows:

$$S_{\alpha}^{DR} = \frac{\partial T_{DR}}{\partial \alpha} / \frac{T_{DR}}{\alpha} = \frac{\alpha.\frac{K}{s}.(H(s)-G(s))}{(T_{OL}(s))\wedge -1 - \frac{K}{s}.\alpha.H(s) - \frac{K}{s}.(1-\alpha).G(s)} \quad (28)$$

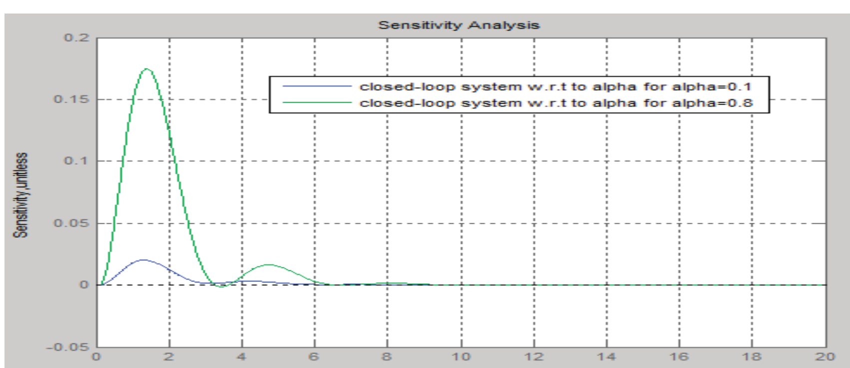

Fig.4 Closed-loop system w.r.t to alpha sensitivity values for the LFC-DR model, alpha=0.1 and alpha=0.8

It can be seen from fig.4 that the closed-loop system is less sensitive to α when the DR control loop higher share in the frequency regulation i..e, smaller α values

TABLE I

POWER SYSTEM PARAMETERS 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 pu.sec	0.015 p.u/Hz	0.1 sec	0.01 p.u	0.2

C.Stability Analysis of the Closed-Loop Systems

Analysis of stability 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. By using the load disturbance, $\Delta P_L(s)$ as the system input, the open loop transfer functions.

$$1+\underbrace{\frac{H(s).M(s)}{R}+\frac{K}{s}.\alpha.H(s).M(s)+\frac{K}{s}.(1-\alpha).G(s).M(s)}_{\nu^{DR}}=0$$

$$1+\underbrace{\frac{H(s).M(s)}{R}+\frac{K}{s}H(s).M(s)}_{\nu^{S}}=0 \quad (29)$$

By taking the feedback gain as variable parameter the control characteristics of closed loop system (29) is obtained ,the above equations contains the open loop transfer function for the closed loop system with and without DR. From (29) new open loop transfer functions having the same root-locus properties as of ν^{DR} & ν^{S} are calculated.

$$1+K.\underbrace{\frac{R.[\alpha.H(s).M(s)+(1-\alpha).G(s).M(s)]}{s.[R+H(s).M(s)]}}_{\hat{\nu}^{DR}}=0$$

$$1+K.\underbrace{\frac{R.H(s).M(s)}{s.[R+H(s).M(s)]}}_{\hat{\nu}^{S}}=0 \quad (30)$$

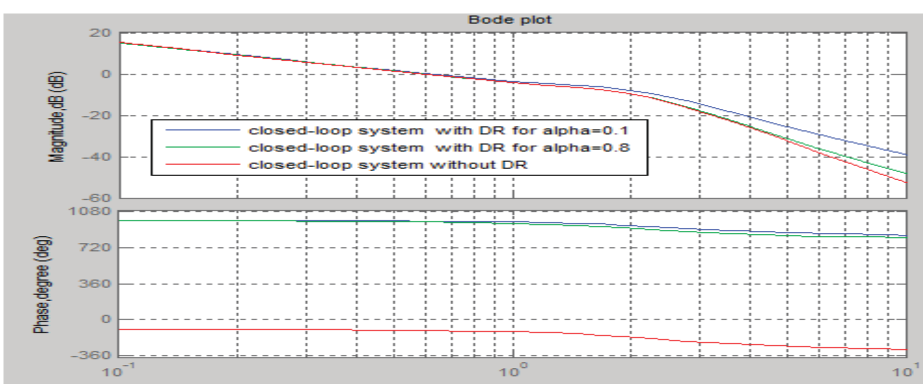

Fig.5 Bode plot of closed loop system for stability analysis, both magnitude and phase plot

The Bode plots of the systems of (30) are shown in Fig. 5. The parameters of the case study are given in Table I. From Fig. 5 that both systems (with and without DR) are relatively stable. however, larger gain and phase margins have been achieved when the DR control loop is present in the system. The phase and gain margins are given in Table II. It can be observed from the table that a higher share of control effort for the DR control loop, i.e., smaller α will provide a higher gain and phase margin, indicating a more stable system. . And the table shows that the 5th-order $Pade$ approximation has no negative impacts on the stability of the system.

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

	closed-loop system with DR for alpha=0.1	Closed-loop system with DR for alpha=0.8	Closed-loop system without DR
Gain margin, dB	14.1	11.3	10.3
Phase margin, degree	83.5	74.8	72.2

IV.SIMULATION RESULTS

Some important description of the proposed LFC-DR model and the results of different simulation studies are shown for the given power system. For the comparison, LQR design procedure has been employed for controller design for both systems, with and without DR. In order to prove the proposed topology, simulation is carried out using the MATLAB/Control system toolbox. In the first simulation study, 0.01 pu load disturbance was applied to the power system with conventional LFC and proposed LFC-DR models. The system frequency deviation is shown in Fig.6

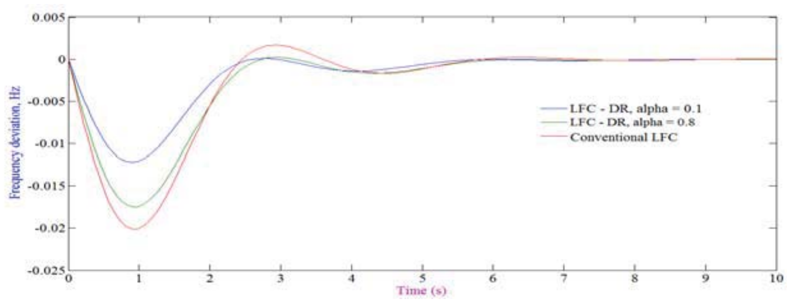

Fig.6 Frequency deviation for conventional LFC and LFC-DR

From Fig.6, it is observed when (i.e., 10% of the required regulation is provided by the supplementary control and 90% from DR), the LFC-DR model has better performance over the conventional LFC during the transient period. The overshoot in the system frequency deviation is decreased by 42.5%.The settling time is also improved. The same simulation was repeated for α =0.8.

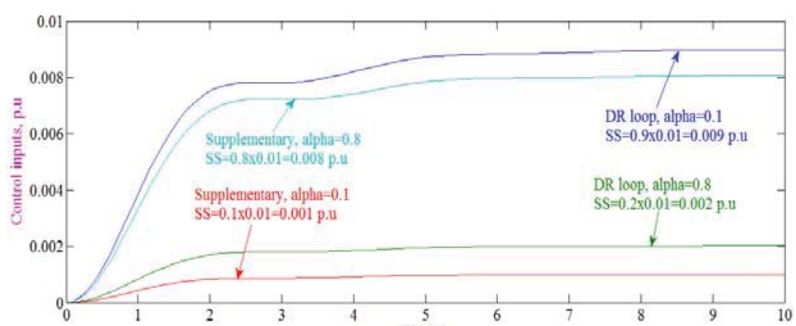

Fig.7 Steady-state values of the control inputs for LFC-DR

The supplementary and DR control inputs are shown in Fig.7. The steady-state values of the control inputs are based on the share between DR and supplementary control loops, i.e., the value of α , which is decided by ISO/RTO based on the real-time electricity market. The steady-state value calculations are shown in Fig.7

The simulation study was carried out to show the impact of the order of pade approximation on the performance of the system, the results are shown in Fig.8. 2nd and 5th order pade approximations are used in proposed LFC-DR model and compared with convectional LFC model for α =0.1 . Both orders of approximations are almost identical it is mainly due to governor and turbine models are low pass filters which restrict the system response to lower frequency ranges, where pade approximation is exactly same as pure time delay. Therefore, 2nd order pade approximations are employed for complicated power systems without negative impacts on results.

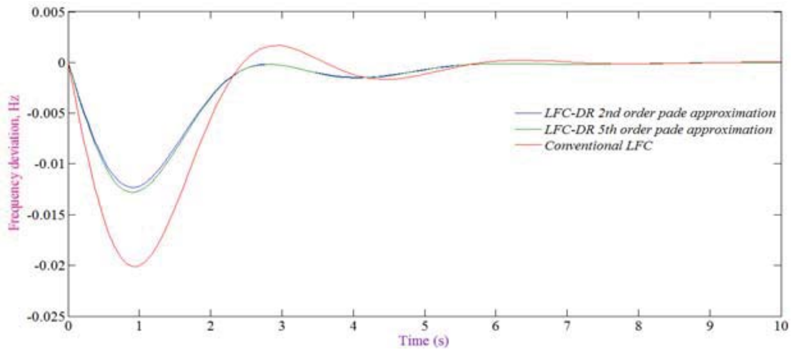

Fig. 8 Controller performance on different orders of pade approximation

The two control inputs are unified as a single input for the controller design as a function of α . The unification can be done in two ways: unifying $u_1(t)$ as a function of $u_2(t)$ or vice versa [$u_1 = (\alpha / (1-\alpha)).u_2$ or $u_2 = ((1-\alpha)/\alpha).u_1$]. To know the impact of unification simulation study was carried out to compare the performance of the system for both cases, results are shown in Fig.9. The difference between two unifying approaches is negligible. The inputs can chosen arbitrarily without any negative impact on LFC-DR.

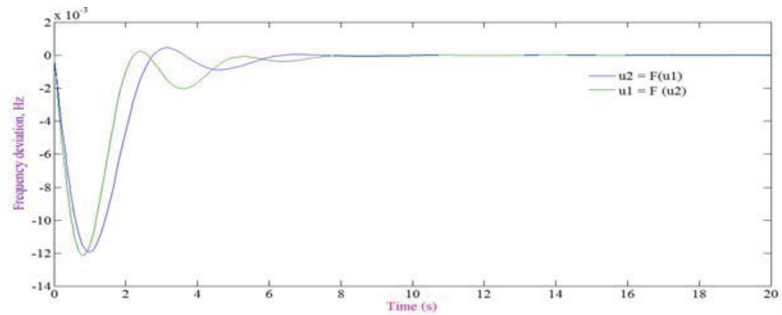

Fig.9 Impact of unified inputs on LFC-DR

The important feature of the LFC-DR model is the possibility for the ISO/RTO to evaluate the impact of communication delay of the DR control loop on system performance for frequency stabilization. To show the impact of latency, a simulation is done for different values of communication latency for α =0.1. The results are shown in Fig.10. The lowest communication delay (lowest) is for a small power system with fast two-way communication link, such as wireless communication, between the Lagcos and individual loads. It can be seen that the LFC-DR model gives a better performance compared to the conventional LFC when $T_d < 0.2\ sec$.

When the time delay exceeds 0.2 sec, it deteriorates the performance of the LFC-DR, and the response is even worse than that of conventional LFC for T_d =0.4. In the large power systems with generation rate limiters and slow turbine-governor systems, a slower dynamic behaviour would be expected from the supplementary control. The LFC-DR will give the superior performance even for higher communication latencies.

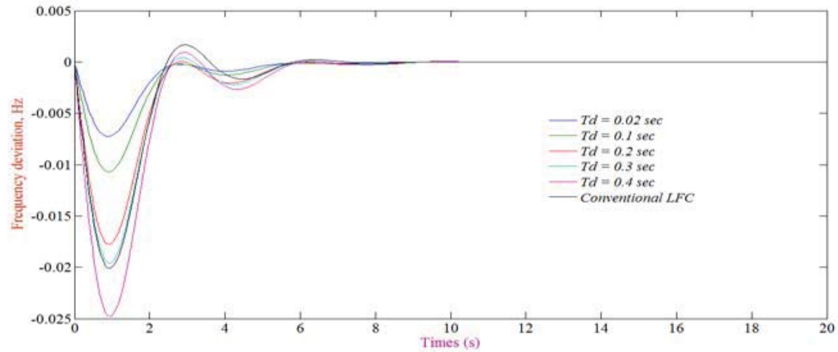

Fig.10 Impact of latency on the LFC-DR model

The proposed method is explained and compared with the conventional method using simulation results. The proposed method validated through simulation results for different cases.

V. CONCLUSION

The proposed LFC-DR model responds to all frequency deviations as same as of conventional LFC model. However, LFC-DR model is desired to prevent the respond to small frequency deviations and keep the linearity of the model, a dead band is added to input, ΔP_L could include the variation in any renewable generation that might be available in power system as negative load. This is due to fast dynamics of the common variable generation like wind, solar PV compared to those of traditional power plants in LFC model

REFERENCES

[1] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity ," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 587–595, May 2005.

[2] S. A. Pourmousavi and M. H. Nehrir, "Real-time central demand response for primary frequency regulation in micro grids," *IEEE Trans.Smart Grid*, vol. 3, no. 4, pp. 1988–1996, Dec. 2012.

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

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

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

[6] G. H. Golub and C. F. Van Loan, *Matrix Computations*, 3rd ed. Baltimore, MD, USA: Johns Hopkins Univ. Press, 1996, pp. 572–574.

[7] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*, 3rd ed. New York, NY, USA: Addison-Wesley, 1994, p. 778.

[8] R. Walawalkar, S. Blumsack, J. Apt, and S. Fernands, "An economic welfare analysis of demand response in the PJM electricity . *Energy Policy*, vol. 36, no. 10, pp. 3692–3702, Oct. 2008

[9] C. E. Fosha and O. I. Elgerd, "The megawatt-frequency control problem: A new approach via optimal control theory," *IEEE Trans. Power App. Syst.*, vol. PAS-98, no. 4, pp. 563–577, Apr. 1970

[10] D. Jay and K. S. Swarup, "Frequency restoration using dynamic demand control under smart grid environment," in *Proc. IEEE PES Innovative Smart Grid Technologies—India (ISGT India)*, Kerala, 2011, pp. 311–315