Robust Load-Frequency Control Technique for Distributed Multi-Area Power System

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Abstract: *A basic task in power system process is to control reliability and quality power supply, and major activity which support the accomplishment of this task is the load frequency control (LFC). Mainly, LFC is an automatic activity which intended to restore system frequency and the total tie line power between a control area and its neighbors to their scheduled values, these parameters fluctuate when there is an imbalance between supply and active power demand in a synchronous connection. This paper investigates a model predictive control (MPC) based on linear quadratic regulator (LQR) technique for load frequency control (LFC) issues in a deregulated power system environment that has become a challenging task for researchers. The simulation result shows there is advantage of using LQR technique and it causes better performance due to the more sustained saturation.*

Keywords: *Load-Frequency Control, Distributed Power System, Multi-Area Network, Linear Quadratic Regulator.*

I Introduction

Electrical power interconnections comprise of a wide range of components systematically coupled together to form a large-scale, complex and high-order multivariable dynamical system that can generate, transmit and distribute electrical energy over a large geographical area [1]. Despite the complexity of interconnected power systems, reliability, economy and quality supply (stable voltage and frequency) are of utmost importance, and these make the operation of power systems very challenging; reliability, economy and quality supply can be achieved through strategic planning, modeling, analysis and design of suitable control systems [2–4]. In power system operations, load fluctuations and other forms of disturbance result in a number of dynamic phenomena which present themselves at different timescales due to the difference in characteristics of the components that made up the interconnection [5]. Figure 1 shows the basic schematic of load-frequency control, typical a dynamic phenomena exhibited by power networks and some important controls, adapted from power system.

Lightning propagation in high voltage transmission lines as depicted in the schematic diagram of Figure 2 is observable in the timescale of typically a fraction of a microsecond to few milliseconds and exhibits the fastest dynamics. Moreover, over-voltages from switching operations in transmission and distribution lines exhibits dynamics in the timescale of a fraction of tens of microseconds to tens of milliseconds [6]. Much slower phenomena are boiler actions and daily load cycles with dynamics spanning a few minutes to several hours, typically.In terms of controls, flexible alternating current transmission system (FACTS) control schemes are one of the fastest as they act in the timescales of a millisecond to less than a second, typically. FACTS controllers are mainly used to influence the electrical characteristics of power transmission networks in order to improve power transfer capabilities [7–9].

Protection systems are also considered to be fast and their function is to isolate faulty components from the network; their timescale of operation, typically, is few milliseconds to around a second. Automatic voltage control (AVC) operates in a timescale of several milliseconds to a few seconds [10]. The role of the AVC is to maintain the terminal voltage of a generator at the set value via the automatic control of the current fed to the generator field winding by a field exciter, and this is one of the most important mechanism for voltage control in most power networks [11–13]. Furthermore, frequency deviations in power systems, which occur when there is an imbalance between the total active power generated across the network and power consumed (including active power losses), is mainly addressed in three control levels, namely, primary frequency control (PFC), secondary frequency control (SFC) and tertiary frequency control (TFC) [14–18].

A primary frequency control (PFC) scheme, which typically operates in a timescale of a second to tens of seconds, is essentially the local action of turbine governing systems in power plants and its function is to quickly, if it is within its ability, reject unacceptable disturbances and keep the frequency close to the nominal value (e.g 50 Hz in India). PFC

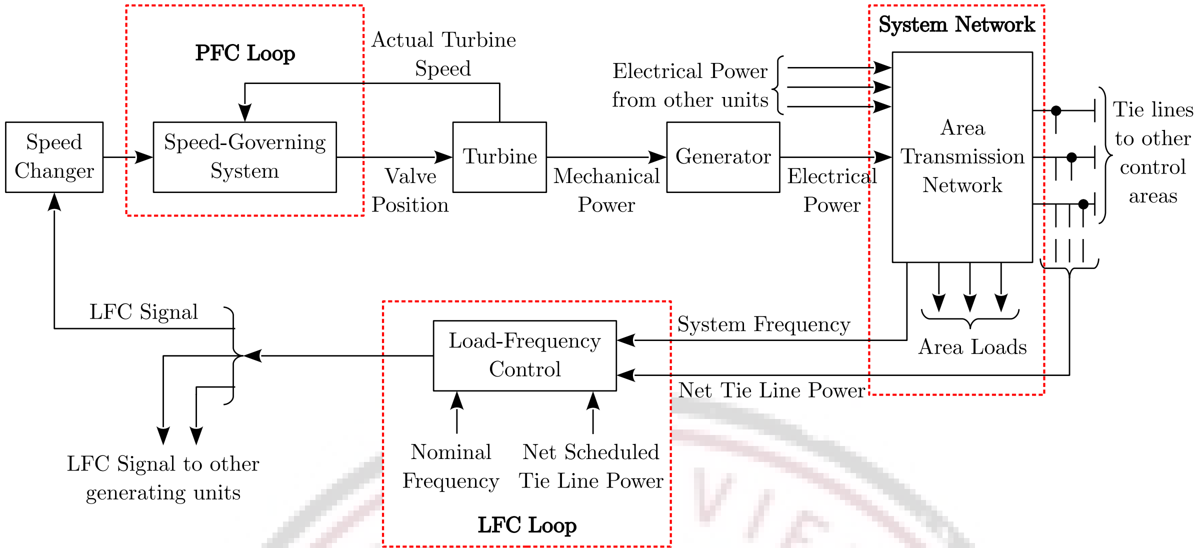

Figure 1: The Basic Schematic of Load-Frequency Control in Power System

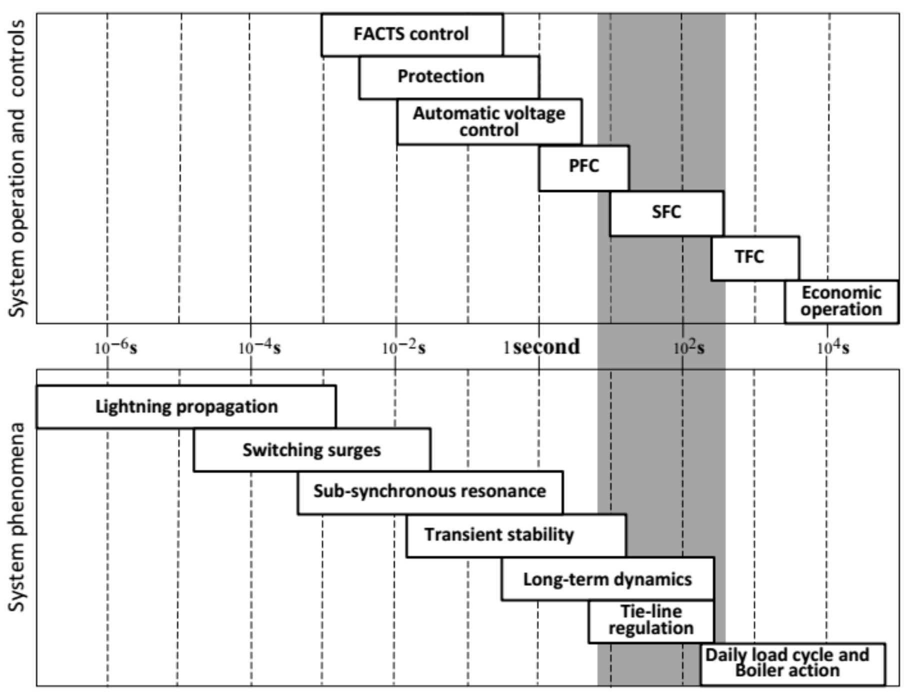

Figure 2: Time Scale of Dynamic Phenomena in Power System Control

is a proportional control strategy and thus leaves some frequency offset behind [19, 20]. Secondary frequency control (SFC) which is the subject of this report, operates in the timescale of few seconds to around ten minutes, and it plays the important role of eliminating the frequency offset left behind by PFC schemes. It restores system frequency to the nominal value by regularly adjusting load reference settings of the turbine governing system of selected power plants, and therefore their output power. Secondary frequency control (SFC) is traditionally an integral control scheme [21–25].

II Literature Survey

II-A Load-Frequency Control in Microgrids using Target-Adjusted MPC

Banis *et al.* [26] presented an alternative optimal control and model predictive control (MPC) formulation for the load-frequency control (LFC) problem. To the best knowledge of the author, these control law formulations are applied to this control problem for the first time. The formulation is compared with a classical MPC. The approaches incorporate an approximated system equilibrium into the controller objective and gain from an estimated lumped disturbance. We show that the derived MPC controller can be used to stabilize the frequency using a three-actor system and that it can be used to track input references. The proposed MPC formulations may be utilized within existing control hierarchy concepts.

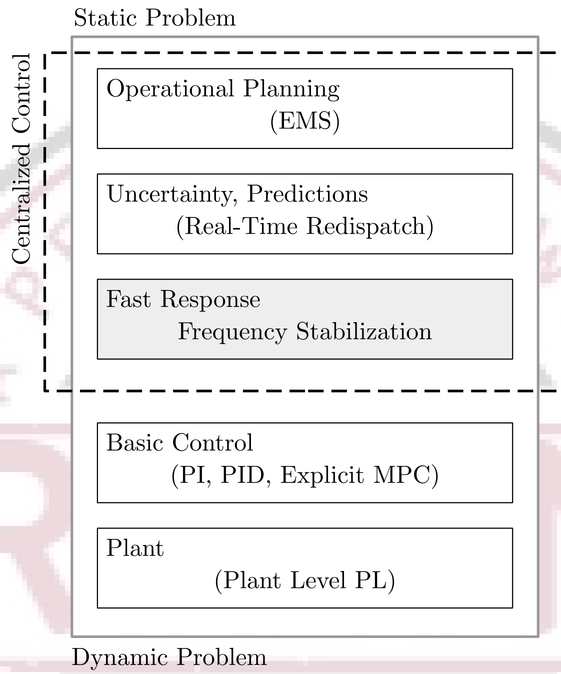

Figure 3: Hierarchy of Controllers in Centralized Control Scheme

Designing controls for virtual power plants involves the setup of a control structure with consideration to complexity and system dynamics. Incorporation of predictions of stochastic processes introduces complexity due to the combinatorial explosion of manifold process outcomes. In contrary, fast system control loops require prompt decision making. Handling problem complexity in this setting and simultaneously providing sufficient sampling rates of well-posed control signals constitute two major challenges associated with the optimized control of microgrids with high shares of RES. This problem complexity is usually handled by the setup of a temporal control hierarchy – the problem complexity is then managed by several specialized control routines. Figure 3 presents an illustration of this principle. Control hierarchies are also considered in related areas such as ancillary services provision.

II-B Dynamic Participation of Doubly Fed Induction Generators in Multi-Control Area Load Frequency Control

Ahmadi *et al.* [27] introduced a new control strategy to consider the doubly fed induction generators (DFIG) wind generation contribution in frequency control and regulation of multi-area interconnected power system. In this approach, the output power of the wind turbine was determined based on the grid conditions. The grid frequency feedback triggers the controller which controls power electronic switches in the DFIG control system. As a result, wind generation units output was not always at its maximum possible amount but changed flexibly based on demand. In a low-wind or high-load situation, wind generation would be set at its maximum possible amount, and the remaining power would be compensated by generations in other areas. Design practice on a three-area power system showed that the proposed approach was easy to apply for a multi-area power system and could achieve good damping performance.

A multi-area power system comprises areas that are interconnected by high-voltage transmission lines or tie lines. The trend of frequency measured in each control area is an indicator of the trend of the mismatch power in the interconnection, and not in the control area alone. The load frequency control (LFC) in each control area of an interconnected (multi-area) power system should control the interchange power with the other control areas as well as its local frequency. Therefore, the described dynamic LFC model should be modified by taking into account the tie-line power signal. The power flow on the tie-line from area 1 to other area 2 is:

$$P_{\mathrm{tir},1,2} = \frac{U_1 U_2}{X_{1,2}} \sin(\delta_1 - \delta_2) \tag{1}$$

where $X_{1,2}$ is the tie-line reactance between areas 1 and 2, δ_1 and δ_2 are the power angles of equivalent machines of the areas 1 and 2 and U_1 and U_2 are the voltages at equivalent machine's terminals of the areas 1 and 2. By linearizing Equation 1:

$$\Delta P_{\mathrm{tir},1,2} = T_{1,2}(\Delta\delta_1 - \Delta\delta_2) \tag{2}$$

where $T_{1,2}$ is the synchronizing torque coefficient. For example in a three-area system, the total tie power change between area 1 and the other two areas can be expressed in the frequency domain.

II-C Robust Load Frequency Control of Nonlinear Power Networks

Trip *et al.* [28] proposed a decentralized Sub-optimal Second Order Sliding Mode control scheme for Load Frequency Control. They considered a power network partioned into control areas, where each area is modeled by an equivalent generator including second-order turbine-governor dynamics, and where the areas are non-linearly coupled through the power flows. Relying on stability considerations made on the basis of an incremental energy (storage) function, a suitable nonlinear sliding function is designed. Local asymptotic convergence is proven to the state where the frequency deviation is zero and where the (net) power flows are identical to their desired values.

II-C.1 Frequency Regulation and Power Flows

Before focusing on the controller design, they formulated the two main objectives of load frequency control (automatic generation control). The first objective is concerned with the steady state frequency deviation $\bar{\omega}$, i.e., with $\lim_{t\to\infty} \omega(t)$.

Frequency Regulation:

$$\lim_{t\to\infty} \omega(t) = \bar{\omega} = 0 \tag{3}$$

Let $(\mathcal{B}P_f^*)_i$ denote the total desired power flow exchanged by control area $i \in \mathcal{V}, P_f^*$ being an external reference signal. The second objective is to maintain the scheduled net power flows between the control areas.

Maintaining Scheduled Net Power Flows:

$$\lim_{t\to\infty} \mathcal{B}\Gamma \sin(\eta(t)) = \mathcal{B}\Gamma \sin(\bar{\eta}) = \mathcal{B}P_f^* \tag{4}$$

In case the power network does not contain cycles,This is equivalent to $\lim_{t\to\infty} \Gamma \sin(\eta(t)) = P_f^*$, such that the power flow on every line is regulated towards its desired value.

III Proposed Method

This section presents the proposed method to investigate the potency of a model predictive control (MPC) based load frequency control (LFC) scheme in a deregulated power system environment, where deregulated LFC benchmark models can be obtained via the modification of the traditional LFC modelling framework.

III-A Proposed Deregulated Load Frequency Control Model of a 2-Area System

This model presents the modification required in the traditional LFC model to incorporate the various power transactions in the deregulated environment. The formulation here is focused on a 2-area system whose single line diagram is shown in Figure 4. It is assumed, that area 1 has two GenCos and two DisCos; the same applies to area 2. $\mathrm{GenCo}_{i,k}$, represent the k^{th} GenCo in the i^{th} area, while $\mathrm{DisCo}^{i,l}$ represents the l^{th} DisCo in the i^{th} area. The 2-area deregulated LFC framework is based on the transfer function block representation. The equations presented are based on Figure 4. In the deregulated

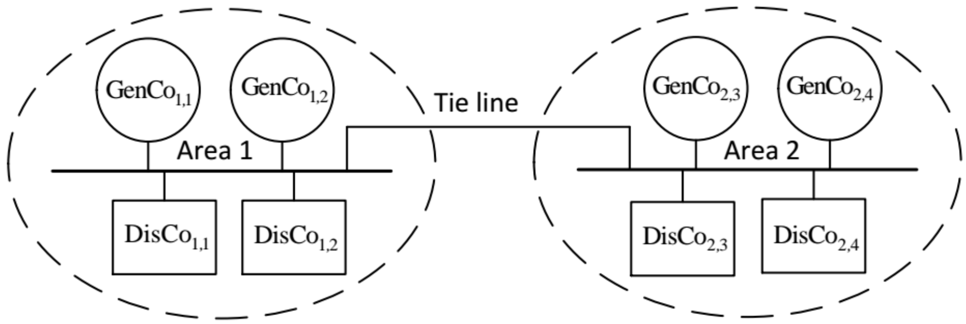

Figure 4: Single Line of a 2-Area Deregulated System

environment, the total load change in each area is:

$$\Delta P_1^D = \underbrace{\Delta P_{1,1}^L + \Delta P_{1,2}^L}_{\text{Contracted}} + \underbrace{\Delta P_1^U}_{\text{Uncontracted}} \tag{5}$$

$$\Delta P_2^D = \underbrace{\Delta P_{2,3}^L + \Delta P_{2,4}^L}_{\text{Contracted}} + \underbrace{\Delta P_2^U}_{\text{Uncontracted}} \tag{6}$$

The uncontracted load changes in each area (ΔP_1^U and ΔP_2^U) take a zero value if the total load changes in each area are supplied through bilateral LM contract only with no contract violations. The rated area capacity ratio between any two control areas linked by a tie line is $\alpha_{ij} = \dfrac{P_{r_i}}{P_{r_j}}$. In the context of the 2-area deregulated system studied here, equal area rated capacities are assumed, that is, the value of α is taken to be unity.

III-B Model for LFC

We consider the swing equation as our main state in the controller model

$$\frac{d}{dt}\Delta f(t) = -\frac{D}{2H}\Delta f(t) + \frac{1}{2H}\Delta P_{\text{mech}}(t) \tag{7}$$

Δf denotes the frequency deviation from nominal frequency, D is the load damping coefficient and H is the inertia-based supply time. ΔP_{mech} is the power balance within the grid. The model maps the overall power imbalance to an angular frequency deviation from the nominal grid frequency by taking the approximated system inertia into account. The swing equation is a means to express the lumped system inertia and its parameters are both unknown and time varying. Consequently, adaptive estimation techniques should be applied to obtain a precise model for varying conditions.

The considered underlying processes are non-linear and can be modelled using stochastic differential equations (SDEs) such as formulated:

$$dx_t = f(x_t, u_t, t, \theta)dt + \sigma(u_t, t, \theta)d\omega_t \tag{8}$$

$$y_k = h(x_k, u_k, t_k, \theta) + v_k \tag{9}$$

where t is the time variable; t_k are sampling instants; x_t is a vector of system states with the main state being the frequency deviation from nominal frequency $\Delta f; u_t$ is a vector of input variables; y_k is the single-output variable and equals the main state $\Delta f; \theta$ is a vector of parameters; f, σ and h are non-linear functions; ω_t is a standard Wiener process; and v_k is a white noise process with $v_k \in \mathcal{N}[0, S(u_k, t_k, \theta)]$.

All used system models are linearized, enabling the application of linear control theory. The power balance is obtained by using lumped system models – groups of actors sharing dominant dynamics and requirements are lumped together, resulting in a reduced-order model. The accepted loss in precision of this reduced model compared with the untreated linear system model is a design choice and has to be traded against the gained reduction in computational load in the optimization step. The linearized discrete-time system model can then be formulated as stated.

$$\frac{dx_{t|j}}{dt} = f_0 + A(x_t - x_j) + B(u_t - u_j) + G_s(d_t - d_j) + w_t \tag{10}$$

$$y_t = Cx_t + e_t \tag{11}$$

x is the system state; u is the controlled system input; and d is the uncontrolled system input (disturbance). w and e are process and measurement noise, respectively. This is a multiple-input–single- output (MISO) system if more than one unit in the MG are considered.

III-C Target-Adjusted Discrete-Time Linear Quadratic Regulator (LQR)

The feedback control law of the classical discrete-time linear quadratic regulator (DLQR) is commonly formulated as

$$u_k^* = -K\hat{x}_{k|k} \tag{12}$$

whereas the target-adjusted discrete-time linear quadratic regulator (DLQR) can be stated as

$$u_k^* = \tilde{u}_{k|k} - K(\hat{x}_{k|k}\tilde{x}_{k|k}) \tag{13}$$

K is at this moment found as a solution to the discrete-time algebraic equation. The equilibrium operating point of the system can be stated in terms of the input and state of the system $\tilde{p}$. $\tilde{p}$ can be linearly related to the filtered lumped disturbance $\tilde{d}$

$$\tilde{p}_{k|k} = \{\tilde{x}_{k|k}, \tilde{u}_{k|k}\} = K_\infty \hat{d}_{k|k} \tag{14}$$

K_∞ is a gain from a unit disturbance to one corresponding system equilibrium point. Scaling by the estimate d recovers another system equilibrium corresponding to $\hat{d}$. K_∞ can be obtained using a least-squares approximation, due to that the lumped system matrix M for the considered systems is non-symmetric in the MISO case

$$\overbrace{\begin{bmatrix} A-I & B \\ C & 0 \end{bmatrix}}^{M} \overbrace{\begin{bmatrix} K_{x,\infty} \\ K_{u,\infty} \end{bmatrix}}^{K_\infty} = \begin{bmatrix} B_d \\ 0 \end{bmatrix} \tag{15}$$

The system of equations above denoted has to be solved once for each model formulation. B_d as a result of this denotes the lumped modeled disturbance dynamics. Mismatch of B_d related to the real system dynamics leads to loss of controller performance. This loss of performance is then to be compensated for by application of appropriate robustness and adaptive control strategies.

III-C.1 Offset-Free Frequency Tracking

To drive the output $f \to \bar{f}$, where f is the goal frequency and $\bar{f} = f_{\text{nom}} + \Delta f$, the control law can be augmented to include the integrated offset

$$\varepsilon_{k+1|k} = \varepsilon_{k|k} - \hat{y}_{k|k} - \hat{y}_k \tag{16}$$

$\hat{y}_{k|k}$ is the output of the system model using the state estimate $\hat{x}_{k|k}$ and $\bar{y}_k = \Delta\ \bar{f}_k$ is the goal frequency deviation. Another way of achieving this is the adjustment of the target

$$\tilde{p}_{k|k} = \{\hat{x}_{k|k}, \hat{u}_{k|k}\} = K_\infty(\varepsilon_{k|k} + \hat{d}_{k|k}) \tag{17}$$

As generally in the context of MPC, online system identification techniques, incorporation of adaptive measures and robustness considerations should be considered to compensate for un-modeled uncertainty.

IV Result Analysis

In computing LFC signals, it should be considered that there is a limit to the rate at which generating units can change their output. Figure 5 shows the frequency deviations (top) and ACE (bottom) of each control area. As expected, they both converged to zero since the area catered for their total load changes via the bilateral LM contract and no violation of contracts.

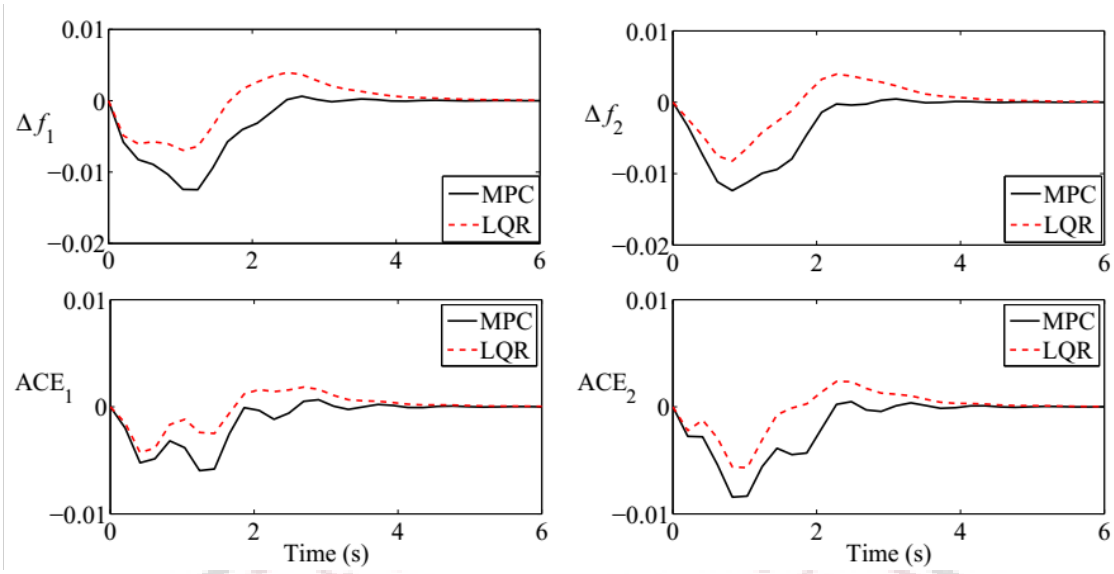

Figure 5: Frequency Deviations in Control Area

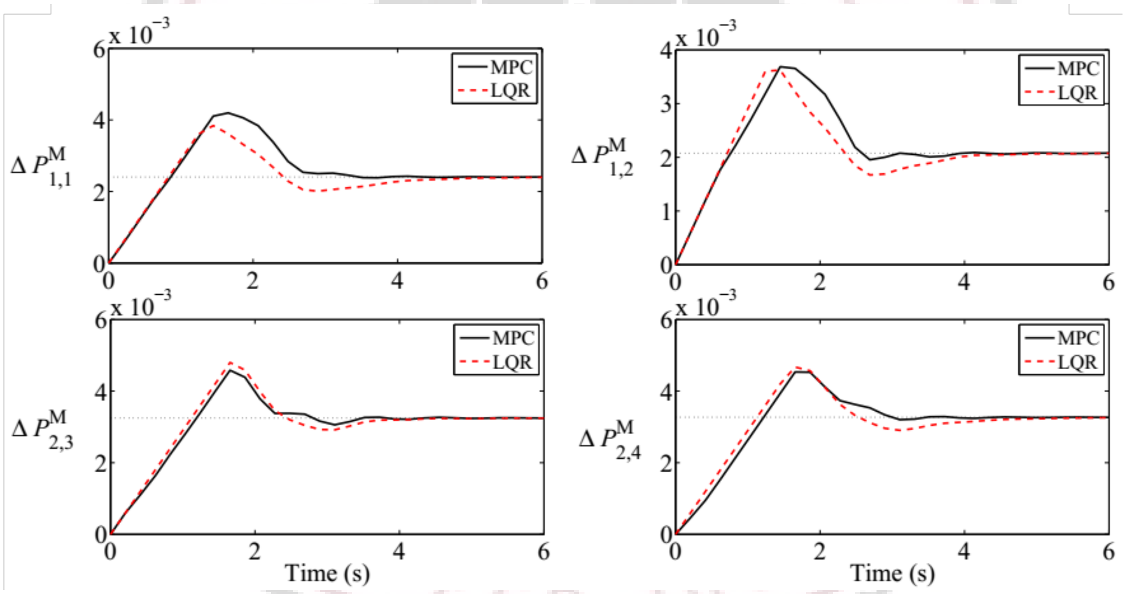

Figure 6: Frequency Deviations in Control Area

Moreover, result in Figure 5 shows the change in the power output of each area, the desired generation of each area has been calculated and represented in result. It can be seen that each area fulfilled their contractual obligation by tracking the desired incremental generation.

The control inputs converged to zero because no uncontracted load changes occurred; the area participation factors in only affected the system behavior during transients. Also, unlike in the traditional power system where the net tie line deviation is required to converge to zero. In general, there is glaring advantage of using MPC over LQR in this case as the input constraints are active and this is because the magnitudes of the contracted load changes are small; however, LQR causes some better performance and this is because of the more sustained saturation. Moreover, LQR resulted in more undershoots and overshoots and this is because it lacks systematic constraints handling. The main duty of a multi-area LFC (to eliminate active power imbalance in networks) is preserved in the deregulated environment, however with key modifications to the age-long traditional LFC framework.

Result is emphasized that a 2-area benchmark system is a good choice of multi-area system to gain insights into the key modifications required to obtain a deregulated load frequency control (LFC) model from the traditional model. It is vital to mention that the results presented in this report is simulated result and it have not be compared with the integral control LFC scheme used in the industry. This is as a result of the difficulty in obtaining a suitable integral gain that can offer a sensible response for the deregulated LFC case.

V Conclusion

The work presented in this document focused on some technical concerns inherent in load frequency control (LFC) in interconnected power systems, which have arisen because of the ongoing deregulation being experienced by electric industries around the world. The main duty of a multi-area load frequency control (LFC) (to eliminate active power imbalance in networks) is preserved in the deregulated environment, however with key modifications to the age-long traditional load frequency control (LFC) framework. The basics of such modifications, which primarily consist of accounting for bilateral load matching contracts between two areas based on the concept of area participation, can be understood when a 2-area system is considered. Moreover, this paper has demonstrated via simulation, for a 2-area deregulated system, that by explicitly incorporating traditional and modern input constraints into a load frequency control (LFC) design, a better LFC performance can be achieved, and that a predictive control technique using LQR is a better choice for LFC in that respect.

A number extensions from this paper are possible. Further research on improving the robustness and effectiveness of the proposed approach by considering hybrid generation can be extended. A large amount of fine detailed information on power system frequency control is required for further analysis. The soft computing techniques such as artificial neural network (ANN), Fuzzy systems and evolutionary algorithms can be used to develop an intelligent load frequency controller. The Performance of a Fuzzy logic controller is limited by its large number of rules and if the rules are large then computation time and requirement of memory is large. This problem can be compensated by using Polar Fuzzy logic controller.

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