Review of Automatic Generation Control in Deregulated Environment

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Abstract: This paper reviews various control methods for design of Automatic Generation Control (AGC) in the deregulated power system environment. The power system models and control techniques/structures that concern the AGC problem design and implementation issues have been addressed and analysed. Further, discussion on challenges and advantages associated with the reviewed control techniques/ structures has been presented.

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1. INTRODUCTION

World-wide, many electrical utilities and power companies changed the way they used to operate from Vertically Integrated Utility (VIU) to deregulated environment. The aim of deregulation in power systems is to encourage competition, allow open transmission access and reduce electricity cost to consumers (Bekhouche, 2002). The former VIUs which are used to regulate all the activities related to electricity in the generation, transmission, and distribution subsystems now is decomposed into separate companies (Christie & Bose, 1996, Hao et. Al., 2014). Generation Companies (GENCOs), Distribution Companies (DISCOs), Transmission Companies (TRANCOs), and an Independent System Operator (ISO) each has committed to its own tasks. For reliable operation of the power system, the ISO controls the operation of many ancillary services, one of them is frequency regulation based on the concept of Automatic Generation Control (AGC).

The automatic generation control in this new deregulated structure is designed to provide the main energy transactions such as polo-based, bilateral as well the combination of these two transactions (Tyagi and Srivastava, 2006; Kumar et. al., 1997; Donde et al, 2001). In addition, it must also fulfill the well-known objectives of AGC in a VIU. These include the regulation of the system frequency at specified nominal value, maintaining the tie-line power interchange among control areas and keeping each generating unit to its most economical value (Bevrani et al, 2005; Shayeghi, et al, 2009; Shiva and Mukherje, 2015). As it is known, any mismatch between the total generation and the total load demand may lead the nominal system frequency and scheduled power exchanges to other areas to be deviated from their nominal values, and that may cause unwanted effects (Kothari and Nagrahath, 2003).

Many studies have been conducted about AGC in a deregulated environment over last two decades. The early studies can be found in the work conducted by Chritle and Bose (1996); Kumar et. al., (1997); Bakken and Grande (1998); and Meliopoulos et al (1999)). Further, Bevrani et. al., (2005) modified the conventional AGC system (Ansarian et al, 2006) to take into account the effect of bilateral contracts on the dynamics. Tyagi and Srivastava (2006) used a state space model of multiple power system to design decentralized state feedback controller using eigenstructure assignment. The most of mentioned studies are done on thermal plants (Pandey et al 2013) which don't represent the real scenario of AGC problem in deregulated environment. As result, some recent studies have investigated the combination of multiple source generators such as thermal, hydro, nuclear, gas and renewable power plants within a single control area. For examples, Ram and Jha (2010) and Rahaman et al (2015) explored two control areas with thermal power plant in area 1 and hydro-thermal plants in area 2. In another study, the dynamic of the two control areas consisting of thermal and gas power plants have been reported in Hota and Mohanty (2016). Further, Shree and Kamaraj (2016) investigated the performance of AGC in three control areas consisting of thermal and hydro plants taking in consideration the Generation Rate Constraint (GRC) in this respect, advanced modern control theory such as soft computing control techniques, robust control, variable structure control, active disturbance rejection control and model predictive control were investigated in deregulated environment. Nowadays, interconnected power system composes of multiple power plants. This includes thermal, hydro and renewable energy power plants. However, in this study the renewable energy power plants are not considered.

This survey briefly highlights the AGC problem in deregulated power system environment. In section 2 the general model of deregulated multi-area power system is presented. Section 3 describes the AGC control techniques that are mostly investigated in the literature. Section 4 discusses the AGC control structures. A comparison between various control techniques and strategies is discussed in
2. MODELLING OF DEREGULATED POWER SYSTEM

To consider the effects of bilateral contracts between GENCOs and DISCOs in all control areas, the concept of DISCO participation matrix (DPM) is introduced. DPM is an $n \times m$ matrix where $n$ is the number of GENCOs and $m$ is the number of DISCOs in the control areas. The diagonal entries of DPM correspond to local demands; while off diagonal elements of DPM correspond to the demands of the DISCOs in one area to the GENCOs in another area. The integration of this concept in the dynamic response of AGC is well explained in the literature (Hosseini and Etemadi, 2008; Ram and Jha, 2010; Shree and Kamaraj, 2016). The general structure of DPM for large power system with $m$ DISCOs and $n$ GENCOs can be expressed as:

\[
DMP = \begin{bmatrix}
    C_{p11} & C_{p12} & \cdots & C_{p1m} \\
    C_{p21} & C_{p22} & \cdots & C_{p2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    C_{pn1} & C_{pn2} & \cdots & C_{pnm}
\end{bmatrix}
\]

where, $C_{pij}$ ($i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, m$) are the contract participation factors corresponds to the fraction of the total load power contracted by DISCO $j$ from GENCO $i$. The sum of all the entries in a column in this matrix is unity. The general AGC block diagram for the control area $i$ is shown in Figure 1 (Hassan and Bevmani, 2005), where the dashed line inputs present the new information signals and due to possible various contracts between DISCO $i$ and the other DISCOs and GENCO $j$. $V_{si}$ is the signals vector. $V_{si}$ and $V_{sj}$ are the new tie line power flows and disturbances signals respectively. The distribution of the Area Control Error among generators in each area is called ACE participation factors (apfs) (Donde et al, 2001). The new scheduled steady state power flow on tie-line is given as (Hosseini and Etemadi, 2008):

\[
P_{tie\_new} = V_{si} = P_{tie\_i} + \sum_{i=1}^{m} D_{ij} - \sum_{j=1}^{m} D_{ij}
\]

where $P_{tie\_new}$ is the new scheduled power flow on tie line, $D_{ij}$ is the demand of DISCOs in the area $j$ from GENCOs in the area $i$, and $P_{tie\_i}$ is the demand of DISCOs in the area $i$ from GENCOs in the area $j$. $P_{tie\_act}$ is the net tie line power flow from the area $i$. Hence, during transient period the tie-line power error is given as:

\[
\Delta P_{tie\_i\_error} = \Delta P_{tie\_i\_act} - \Delta P_{tie\_i\_new}
\]

The $\Delta P_{tie\_i\_error}$ is used to determine the ACE for area $i$ as:

\[
ACE_i = B_i \Delta f_i + a_{ai} \Delta P_{tie\_i\_error}
\]

where, $a_{ai}$ is an Area Control Error (ACE) participation factor. In the deregulation environment-based automatic generation control, both DPM and apfs concepts are rigorously used. The DPM matrix can be chosen based on market economic, but no approach have been identified for choosing apfs (Ram and Jha, 2010), which may lead to wrong results.

3. CONTROL TECHNIQUES

In deregulated power system (DPS), many advanced control methods have been applied to achieve ability to track the contracted/uncontracted demands, take into account the effect of bilateral contracts on the dynamics and improve the dynamic transient response of the system under competitive conditions. Here is the review of some control methods that were widely investigated in the literature:

3.1. Soft Computing Techniques in AGC

A number of researchers have investigated the control of deregulated power system using soft computing/intelligent techniques such as Newton-Raphson algorithm, Genetic Algorithms (GA), and Bacterial Foraging Optimization Algorithms (BFOA), as well as artificial intelligent control techniques. Dande et al., (2001) was one of the first researchers who used trajectory insensitivities to obtain optimal parameters of the integral control using gradient type Newton-Raphson algorithm.

Figure 1: Model of deregulated power system (Hassan and Bevmani, 2005)
Rerkpreedapong et al., (2003) used genetic algorithms and Linear Matrix Inequalities (LMI) to develop robust Proportional Integral (PI) Automatic Generation Control (AGC) against load disturbances. GA has been used for optimizing the integral control gains and frequency bias factors in a three-area power system (Demiroren and Zeynelgil 2007). AGC control based on Adaptive Artificial Neural Fuzzy Inference System (ANFIS) and Particle Swarm Optimization (PSO) has been proposed for optimal gain scheduling in deregulated power system (Hosseini and Etemadi 2008). In this study, generation rate constraint is considered in two control areas composed of steam turbines and the ANFIS is used to estimate the dead band. The simulation results demonstrated that the control system provides good dynamic response for the both control areas frequency deviations and tie-line power error. In addition, adaptive control gains can be updated in real-time according to the variations in the power demands. Despite, good performance was obtained; PSO took long time to compute the optimal gains, which is impractical for real-time applications. Bacterial foraging technique is applied to optimize simultaneously the gains of non-integer controller and speed regulation parameter \( R \) in multiple-area thermal power systems (Debbarma et al. 2013). In these studies, it is important to note that all the authors studied AGC problem without considering the combination of multiple power sources such as thermal, hydro, nuclear and renewable power sources in one control area which did not reflect the real scenario case (Hota and Mohanty 2016).

In last decade, many efforts were made to combine multiple power sources in one control area. Ram and Jha (2010) examined conventional and artificial intelligent control techniques such as fuzzy logic, neural network and neuro-fuzzy using genetic algorithms against load disturbances in hydro-thermal power system. Recent work by Shree and Kamaraj (2016) has proposed Hybrid Neuro Fuzzy approach for automatic control based on bilateral policy. The contracts were taken as set of new input signals into the new power system. The research has focused on the robustness of ANFIS control against large load changes and disturbances in presence of model uncertainties and the system nonlinearities. In this approach, three area hydro–thermal power systems with Generation Rate Constraint (GRC) under various operating conditions and different contracted scenarios are tested for the controller evaluation. Advantage of this approach over Hybrid Particle Swarm Optimization (HCPASO), Real Coded Genetic Algorithm (RCGA), and Artificial Neural Network (ANN) techniques lies on its simple structure, easy implementation and high robustness capabilities. This method requires computational power and is not efficient in industry. It needs a bigger training set to enhance the efficiency of the controller. This in turn increases the calculation time. Since in the real time the calculation is carried over the sampling period. Thus, this control technique is not useful for real-time power systems.

In another study, Rahman et al., (2015) have used Biogeography-Based Optimisation (BBO) technique to optimize simultaneously the 3DOF-PID controller gains as well as the electric governor parameters for two-area power system (thermal-hydro). In this study, Integral of Squared Error (ISE) is taken as a cost function. The physical constraints, GRC and dead band are considered in the study and the system dynamics was evaluated considering 1% step load perturbation. The results reveal that the Three Degree of Freedom Integral Derivative (3DOF-ID) controller has better performance than I, ID, and 2DOF-ID controllers in terms of settling time, peak deviation, and magnitude of oscillation. In addition, the 3DOF-ID’s parameters optimized by BBO are found to be robust against load changes and inertia constant. The weakness of this approach is that the frequency bias coefficient \( B \) and governor speed regulation parameter \( R \) are selected based on trial and error guidelines.

Later, Quasi Oppositional Harmony Search Algorithm (QOHS-PID) was proposed and applied by Shiva and Mukherje (2016) to a five area power system under deregulated environment. In this study each area consists of multiple combinations of generation units, such as reheat thermal, hydro and gas generating units. The physical constraints nonlinearities such as GRC and government dead band time delay are considered, imposed and tested on three different cases, namely, unilateral transaction, bilateral transaction, and contract violation. In addition, Integral of Squares Error (ISE) cost function was used by QOHS algorithm to optimize the PID controller parameters. The simulation results demonstrated that QOHS-PID control stabilized the frequency deviations, scheduled tie line power flow deviation profiles and regulated GENCO’s power to their nominal values in presence of the physical constraints. Although good performance was observed, the communications delays are not considered and QOHS-PID practical implementation is not yet demonstrated.

3.2. Robust control Techniques in DPS

Robust based automatic generation Control approaches also have received attention by researchers for their stability and robustness characteristics against plant uncertainties, parameters variation, and load disturbances in deregulated power system environment. Since then, there were a number of works and applications explored in the literature. In these approaches, the frequency regulation, tracking the load variations, and maintaining tie-line power exchanges with specified values in presence of physical constraints and plant uncertainties are the main objectives of these studies. The control design problems on above approaches can be classified into two main control problems: the first one is the robust control problem including \( H_\infty \) control and multi-objective control problem via mixed \( H_2/H_\infty \) control technique. The second one is the \( \mu \) synthesis and analysis theory. The following section provides a brief review of these approaches.

The early robust load frequency control problem was addressed by Feliachi (1996) where AGC problem was formulated as \( H_\infty \) control problem to guarantee the frequency regulation tracking in presence of step perturbations. However, applying this procedure yields a controller that has a higher order which may need to be minimized for real-time
and complex systems. In Addition, Bevrani et al., (2003) used $\mu$ synthesis and analysis theory to design a robust AGC and guarantee stability in presence of multiplicative uncertainty and load disturbances for four control areas. The $\mu$ synthesis approach has proven to be a useful technique for minimizing the effect of disturbances and achieving acceptable frequency regulation in presence of uncertainties and load variation. Later on, Bevrani et al (2005) proposed mixed $H_2/H_\infty$ technique to design decentralized robust AGC in deregulated environment under bilateral policy scheme. The AGC problem is formulated as multi-objective optimal control problem where several different performance and robustness objectives can be met. In this technique, $H_2$ control minimizes the linear quadratic cost of tracking error and the control input while $H_\infty$ control ensures the stability of the closed loop system in the existence of control constraints and uncertainties. Iterative linear matrix inequality method is used to solve this convex optimization problem, however, the design problem for optimal robust controllers based on H infinity techniques results in a non-convex optimization problem, which suffers from computational intractability and conservatism. (Bhatt et al., 2010).

3.3. Other control Techniques in DPS

Beside the methods above, variable structure control based on sliding mode control (VSC/SMC), Distributed Model Predictive Control (DMPC) and Decentralized Active Disturbance Rejection Control (DADRC) have been proposed for deregulated environment. Sekhar and Vaisakh (2013) presented VSC/SMC Controllers for AGC in deregulated environment to achieve high-performance and robustness of AGC. This approach combines the features of both variable structure control and sliding mode control. The results reveal that the proposed controllers are quiet insensitive to parameter variations and speed governor dead band with or without generation rate constraints.

In another study, Decentralized Active Disturbance Rejection Control (DADRC) has been designed to enhance AGC control performance in multi-area power systems under deregulated environment (Hao et al, 2014). This control The decentralized control performance is often improved by taking the amount of interactions dynamic in consideration.

Recently, distributed control systems framework has been proposed for deregulated large-size power systems (Ma et al, 2017). In this framework, the large system is decomposed to several subsystems, where each controller locally controls its own subsystem. In addition, the controllers exchange information between them via communication bus. Distributed control systems were found to be suitable for large-size systems if the proper nonlinear control has been chosen. This approach doesn’t need the complete model of the power system and disturbances. Thus, an Extended State Observer (ESO) is used for estimating unknown generalized disturbances. The approach achieves a good disturbance rejection performance and its simple structure can be easily implemented in practice. However, DADRC is associated with worse performance when anti- GRC is not optimized.

To overcome the limitations of the above control method, in 2016, Ma et al., (2016) proposed a new Distributed Model Predictive Control (DMPC) for a deregulated large-scale system. The AGC problem with contracted and uncontracted load demands was formulated as a tracking control problem of large-scale system in presence of external disturbances and constraints (GRC and load reference set-point within bounds). The main idea was to design local DMPC for each subsystem, in which controllers from different areas exchange information between themselves via communication bus. The simulation result shown that this method is effective for deregulated large-scale systems in comparison to traditional MPC and centralized MPC. However, DMPC will not be practical for real time applications for the following reasons: the control design is model based approach which needs accurate information of the plant; the closed loop stability performance is based on and dependent of constraints; the optimization step size has an impact on the online optimization time; the on-line optimization needs expensive computational power. Table I summarizes the capabilities and drawbacks of the reviewed control techniques.

4. CONTROL DESIGN STRUCTURES

During last decades, many advanced control structures and algorithms have been proposed and applied to deregulated interconnected power systems. However, few of these schemes are completely acceptable. Therefore, three control design strategies have been explored in literature, namely centralized, decentralized and distributed control systems.

In terms of control structure, centralized load frequency control is rare often to be considered for deregulated power system. For large-size systems, it is too complex and difficult to implement and tune the controllers (Tyagi and Srivastava, 2006), due to the required stability and robustness, inherent computational complexity, and communication bandwidth limitations (Li and Shi, 2013).

Decentralized control framework has been proposed to many large multivariable systems, including deregulated power system. The decentralized scheme is easy to be implemented in practice and also reduces the complexity that is associated with the centralized control scheme (Rerkpreedapong and Feliache 2002); Sedghisigarchi et al 2002). However, the dynamical performance may be degraded in case the interactions effects are not considered between adjacent subsystems, which assumes there, are no tie-line power flow exchanges, and may result in poor system performance (Hao et al, 2014). The decentralized control performance is often improved by taking the amount of interactions performance in consideration. Recently, distributed control systems framework has been proposed for deregulated large-size power systems (Ma et al, 2017). In this framework, the large system is decomposed to several subsystems, where each controller locally controls its own subsystem. In addition, the controllers exchange information between them via communication bus. Distributed control systems were found to be suitable for large-size systems if the proper nonlinear control has been chosen.
Table 1: Summary of various control methods’ capabilities and drawbacks in deregulated environment.

| Control Method               | Capabilities of the method                                                                 | Drawbacks of the method                                                                 |
|------------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Conventional linear control (P,PI,PD and PID) | Simple design and implementation.                                                           | -takes more time and gives large frequency deviation.                                                                                  |
| Newton-Raphson               | Bilateral contracts simulation, achieves optimum integral control gains and frequency bias.  | Simulation study only and not tested on real time power system.                                                                           |
| GA+ LMI                      | Robust against load disturbances, low control order.                                        | Simulation study not tested on real time power system.                                                                                  |
| ANFIS based on PSO           | -Provides good dynamic response for the both control areas frequency deviations and tie-line power error. | PSO took long time to compute the optimal gains, which is impractical for real time applications.                                      |
| ANFIS based on ANN           | Simple structure, easy implementation and high robustness capabilities.                     | Bigger training set is needed in order to enhance the efficiency of the controller which in turn increases the calculation time which impractical in real time. |
| BBO                          | -Robust against load changes and inertia constant - Very good dynamic responses terms of settling time, peak deviation and magnitude of oscillation. | The parameters $\theta$ and $R$ were selected based on trial and error guidelines.                                                         |
| QOHS-PID                     | Promising optimization method for complex multi-units power systems in presence of various nonlinearities and physical constraints. | Simulation study only, communications delays were not considered in the study.                                                            |
| $H_{\infty}$ control         | Robust against disturbances for large scale power systems                                   | yields a higher order control                                                                                                            |
| $\mu$ synthesis control      | Effective for disturbances rejection.                                                      | Has Low frequency regulation in presence of uncertainties and load variation.                                                            |
| $H_2/H_\infty$               | Has good tracking error and stability performances and robust for bilateral contracts.     | Requires static feedback synthesis and LMI for robust control design.                                                                      |
| VSC/SMC                      | Insensitive to parameter variations, nonlinearities and physical constraints as well it requires low computational cost. | Chattering effects was not considered which makes its implementation impractical.                                                         |
| DMPC                         | -Formulates the AGC problem as a tracking control Problem of large-scale system in presence of both external disturbances and constraints, bounds. | Model based approach, the closed loop stability performance is dependent of constraints and the on-line optimization needs expensive computational power. |

5. DISCUSSION

Regarding the deregulated AGC control the strengths and weaknesses of the control methods are summarized as follows: conventional control design was simple but takes more time and gives large frequency deviation (Ram and Jha 2010). “Fixed gain controllers are designed at nominal operating conditions and fail to provide best control performance over a wide range of operating conditions” (Zou et al, 2015). Both intelligent control methods and optimization algorithms are called soft computing methods (Pandey et al, 2013). Artificial intelligent control methods such as fuzzy logic control, artificial neural network, reinforcement learning and ANFIS are model independent methods, but they are time consuming, not easy to design and not efficient in the industry (Shree and Kamaraj, 2016). On the other hand, the optimization algorithms such as genetic algorithm (GA) (Demiroren and Zeynelgil, 2007), Hybrid Particle Swarm Optimization (PSO) (Bhatt et al, 2010), Bacterial Foraging (BF) algorithm (Debbarma et al, 2013), and Differential Evolution (DE) algorithm (Hota and Mohanty, 2016) have shown dynamical improvement, but are not tested to a more realistic power system model, considering time-delay, governor dead band and GRC, altogether, as imposed in real-time power system under deregulated regime. These limitations of the mentioned optimization algorithms are addressed by Shiva and Mukherje (2016) using quasi-oppositional harmony search algorithm. However, the communication delays are still not solved.

Robust control design such as $H_{\infty}$, $\mu$ synthesis and mixed $H_2/H_\infty$ schemes guaranteed closed loop robust stability from disturbances and achieved acceptable frequency regulation in presence of uncertainties and load variation. However, they were restricted to constraints uncertainties and in the most cases provided conservative solution with higher order control. On the other hand, the advanced control designs such variable structure with sliding mode control and distributed model predictive control are model based schemes which need accurate information of the plant, so they are not be practical for large size power systems.

6. CONCLUSIONS

The increasing in size and complexity in the interconnected power system makes it difficult to design a controller and analyse the performance for the entire system. Some of the above mentioned control methods could not achieve satisfactory performance since the effects of physical constraints such as GRC and load reference set-point limitation and dead band not explicitly considered in the controller design and only imposed on the systems during simulation. Therefore, to achieve better control performance, some level of communication must be established between the different subsystems and AGC problem method, has to produce distributed control of the interconnected power system.
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