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LOAD FREQUENCY CONTROL TECHNIQUES

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ABSTRACT: **In the proposed paper, we have presented the need for Load Frequency Control (LFC) of an interconnected multi-area power to minimize the transient deviations in area frequency and tie-line power interchange and to ensure their steady state errors are zeros. In this paper, the Load Frequency Control achieved by implementation of one of the following conventional controller strategies: Proportional - Integral (PI[1]) controller, Proportional - Integral- Derivative (PID[2]) controller, Fuzzy logic control (FLC[3]) is explained along with the emerging paradigm and recently introduced Active Disturbance Rejection Control (ADRC[4]) Technique. PI is a centralized controller technique which is tuned based on the trial-and-error approach whereas PID follows a decentralized discrete system controller technique and can be tuned using any soft computing technique. Fuzzy Control is a commonly used soft computing technique based on the system called fuzzy logic used for tuning the controllers. A controller is designed using any of the above method strategies and tuned using soft computing technique. ADRC is based on Extended State Observer (ESO) theory, an extension of the system model representing things which engineer doesn't include in Mathematical expression. ADRC controller can be easily deployed using any hardware-software platform.**

Keywords: **Load Frequency Control (LFC), Control Strategy (PI, PID, Fuzzy Control, ADRC), Extended State Observer (ESO), Active Disturbance Rejection Control (ADRC).**

I. INTRODUCTION

In an interconnected power system, as the power load demand varies randomly, both area frequency and tie-line power interchange also vary. The objective of the LFC in an interconnected power system is to maintain the frequency of each area within limits and to keep tie-line power flows within some pre-specified tolerances by adjusting the MW outputs of the generators so as to accommodate fluctuating load demands. A well designed and operated power system must cope with changes in the load and system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerance limits.

When subjected to any disturbance, the nominal operating point of a power system changes from its pre-specified value. As a result, the deviation occurs in the operating point such as nominal system frequency and scheduled power exchange to the other areas, which is undesirable.

The LFC issues have been tackled with by various researchers in different time through Automatic Generation Contol (AGC) regulator, excitation controller design and control performance with respect to parameter variations/uncertainties and different load characteristics. As the configuration of the modern power system is complex, the oscillation incurred due to any disturbance may spread to wide areas leading to system black out.

The control methodology of LFC is briefly explained in following sections.

The paper is organized as follows. In Section II, III, IV & V, the concept of PI Controller, PID Controller, Fuzzy Control, ADRC controller is briefly introduced followed by a list of journals that introduce their application in LFC. Concluding remarks are given in Section VI.

II. PI CONTROLLER

A PI Controller (proportional-integral controller) is a special case of the PID controller in which the derivative (D) of the error is not used. The lack of derivative action may make the system more steady in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs. Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach set-point and slower to respond to perturbations than a well-tuned PID system may be.

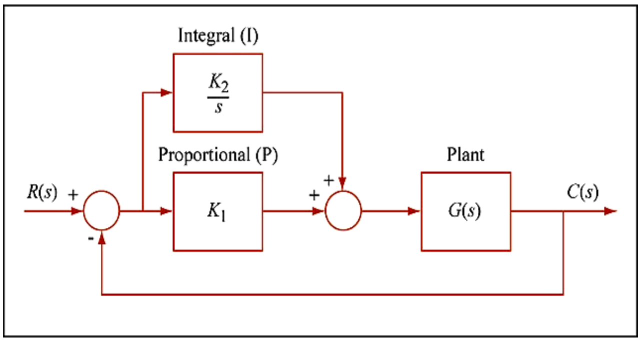

Fig.1: PI control topology

The Proportional-Integral (PI) algorithm computes and transmits a controller output (CO) signal at every sample time, T, to the final control element (e.g., valve, variable speed pump). As shown in Fig.1, PI is a error based feedback system, with R(s) as the reference signal, K_1 as proportional constant and K_2 as integral constant and C(s) representing controller output.

The computed CO (here $C_{(S)}$) from the PI algorithm is influenced by the controller tuning parameters and the controller error, e(t).

PI controllers have two tuning parameters to adjust, as shown in **Figure1**. While this makes them more challenging to tune than a P-Only controller, they are not as complex as the three-parameter PID controller.

Integral action enables PI controllers to eliminate offset, a major weakness of a P-only controller. Thus, PI controllers provide a balance of complexity and capability that makes them by far the most widely used algorithm in process control applications.

The PI algorithm is given below which can also be represented in a different form. The PI controller algorithm involves two separate constant parameters, and is accordingly sometimes called two-term control: the proportional and the integral values, denoted P and I respectively.

$$CO = CO_{bias} + K_c.\ e(t) + (K_c/T_i)\ \int e(t).\ dt \qquad (1)$$

Where:

CO = controller output signal = $C(s)$

CO_{bias} = controller bias or null value; set by bump less transfer as explained below

$e(t)$ = current controller error, defined as SP – PV

SP = set point = $R(s)$

PV = measured process variable

K_c = controller gain, a tuning parameter

T_i = reset time, a tuning parameter

The first two terms to the right of the equal sign are identical to the P-Only controller referencing to (1).

The integral mode of the controller is the last term of the equation. Its function is to integrate or continually sum the controller error, e(t), over time.

Classical control strategy of PI for two area reheat system is also addressed [1]. In [2], Initially, a PI controller using fuzzy logic for Automatic Generation Control (AGC) was designed and responses were compared with classical integral controller. The LFC problem using PI controllers in a four-area interconnected power system can be addressed [3]. Study on Multiple tab-search algorithm for fuzzy based PI load frequency controller is in [4]. Multi-Area LFC by PI and fuzzy logic controller comparison can also be seen [5]. Fuzzy PI controller LFC of interconnected Hydro Power System has been shown [6].

III. PID CONTROLLER

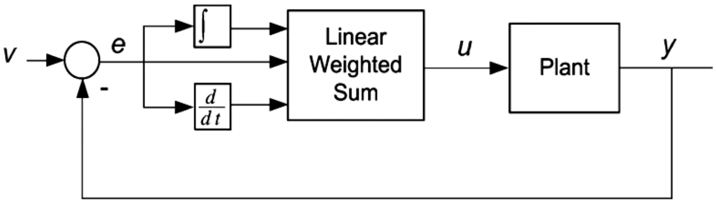

Fig.2: PID Topology

PID is a primitive and simplified implementation of the basic principle in error-based feedback control, as shown in Fig.2, where the error between the set-point v = const and plant y, i.e., $e = v - y$, as well as its differentiation (de/dt) and integration ${}_0|^t e d\tau$ are used in a linear combination to produce the control law

$$u = k_0\ {}_0|^t e d\tau + ke + k_2 de. \qquad (2)$$

This is where PID takes its name: proportional-integral-derivative. It found widespread applications in industry, even when there is little or no information available regarding plant dynamics. To help users understand this, we use the following second-order system equation:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = a_1 x_1 + a_2 x_2 + bu$$

$$y = x_1 \qquad (3)$$

Commonly found in practice, such as motion control, to illustrate why is it that a PID can be easily configured and tuned to do its job.

Let

$e = (v - y) = (v - x_1) = e_1,$

$\acute{e}_1 = (-\dot{x}_{1.}\ ) = e_2$, *and*

$\ddot{e} = -\ddot{x}_1,$

and the error dynamics can be seen as

$$\dot{e}_1 = e_2$$

$$\dot{e}_2 = a_1 e_1 + a_2 e_2 - a_1 v - bu \qquad (4)$$

Denoting $e_0 = {}_0|^t e d\tau$ then $\dot{e}_0 = e = e_1$, and (2) becomes

$$u = k_0 e_0 + k_1 e_1 + k_2 e_{2.} \qquad (5)$$

Together with (4), the error equation can be rewritten as

$$\dot{e}_0 = e_1$$

$$\dot{e}_1 = e_2$$

$$\dot{e}_2 = -bk_0 (e_0 + a_1 v/bk_0) + (a_1 - bk_1)\ e_1 + (a_2 - bk_2)\ e_2 \qquad (6)$$

which is asymptotically stable if

$$bk_0 > 0,\ (bk_1 - a_1) > 0,\ (bk_2 - a_2) > 0$$

$$(bk_1 - a_1)\ (bk_2 - a_2) > bk_0 \qquad (7)$$

That is, the design objective $e_1 = e = v - x_1 \rightarrow 0$, or $x_1 \rightarrow v$, is met if the gains k_0, k_1, *and* k_2 are selected to satisfy (6l7), for the given range of a_1, a_2, $b \neq 0$. It is rather obvious that, for most of the plants of the form of (3), a set of PID gains can be easily found, analytically when the model is given or by trial and error when it is not. Such simplicity and the ease of tuning is very well be behind the popularity of PID.

Classical control strategy of PID for two area reheat system is addressed [1]. The fractional-order-PID controller tuned by bacterial foraging technique is used for LFC in three-area power systems with deregulated environment [7], including other parameters such as order of integrator and differentiator of PID controller also tuned by BF approach. The Particle Swarm Optimization (PSO) tuned PID is mentioned [8]. Two area LFC using Genetic Algorithm (GA) tuned PID controller is available [9]. The PSO based design of the robust fuzzy logic-based-PID controller for LFC in isolated wind–diesel hybrid power system is proposed [10]. The LFC of two-area hydro–hydro power system with proportional–integral–derivative (PID) controller based on maximum peak resonance specification that is graphically supported by the Nichols chart is discussed [11]. Two-Degree-of-Freedom (TDF) Internal Model Control (IMC) method to tune decentralized PID-type controller for LFC in four area power systems with deregulated environments [12]. The TDF-IMC-PID method has been studied for LFC in conventional situation and the performance of the control system is only related to two tuning parameters [13] [14]. the design of multi-objective PID controller for LFC based on adaptive weighted particle swarm optimization in two-area power system is described [15] [16].

IV. FUZZY LOGIC CONTROL (FLC)

Fuzzy logic has been widely used in the control related problems in power system. A fuzzy control system is a control system based on fuzzy logic—a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false, respectively).

Contrary to the traditional control which is mostly based on linear mathematical model, the fuzzy logic control approach solves the problem based on experience and knowledge about the system.

Classical control strategy of fuzzy control for two area reheat system is addressed [1]. Initially designed a controller using fuzzy logic for Automatic Generation Control (AGC) and responses were compared with classical integral controller [2] will be helpful in deep understanding of Fuzzy Control.

The LFC problem using fuzzy gain scheduling of PI controllers in a four area interconnected power system with dead-bands and Generation Rate Constraints (GRC) is addressed [3]. LFC by hybrid evolution fuzzy-PI controller has been proposed [17]. Tabu-search algorithm for the automatic definition of the fuzzy rules is shown [18]. A self-adjusting, fast acting fuzzy gain scheduling scheme for conventional integral gain AGCs in a radial and ring connected three equal power system areas [19]. The study on two area interconnected thermal power system with fuzzy controller is presented [20] [21]. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) tuned fuzzy controller for AGC in three area power system has been proposed [22]. A multi-stage fuzzy PID controller in a restructured power system is also described [23]. The fuzzy logic controlled SMES as frequency stabilizer for interconnected two-area thermal power system is proposed [24]. The generation of optimal fuzzy rule based on fuzzy C-means clustering for decentralized LFC in two-area reheat thermal power system with GRC is presented [25]. (Genetic Algorithm) GA based fuzzy gain scheduling for two-area thermal power system with consideration of governor dead-band and Generation Rate Constraints (GRC) has been proposed [26].

V. ADRC

A) About ADRC

Active Disturbance Rejection Control (ADRC), a control Strategy based on Extended State Observer theory, is a robust control method that is based on extension of the system model with an additional and fictitious state variable, representing everything that the user does not include in the mathematical description of the plant. This virtual state (sum of internal and external disturbances, usually denoted as "total disturbance") is estimated online with a state observer and used in the control signal in order to decouple the system from the actual perturbation acting on the plant. This disturbance rejection feature allows user to treat the considered system with a simpler model, since the negative effects of modeling uncertainty are compensated in real time.

ADRC as originally proposed has three components: tracking differentiator, nonlinear feedback control and nonlinear extended state observer. The combination of three proves to be a powerful tool for disturbance rejection control. The key in application of ADRC is the reformulation of the control problem as that of disturbance rejection.

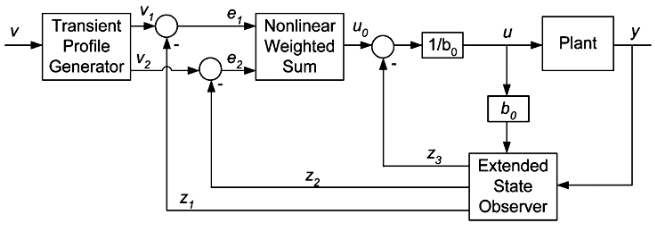

Fig.3: ADRC topology

Combining the transient profile generation, the nonlinear feedback combination and the total disturbance estimation and rejection, the ADRC takes the form as shown in Fig.3, with the corresponding control algorithm below [27].

$f_v = f\ han(v_1 - v, v_2, r_0, h)$

$v_1 = v_1 + hv_2$

$v_2 = v_2 + hfv$

$e = z_1 - y$

$f_e = f\ al(e, 0.5, h),\ fe_1 = f\ al(0.25, h)$

$z_1 = z_1 + hz_2 - \beta_{01}e$

$z_2 = z_2 + h(z_3 + b_0u) - \beta_{02}fe$

$z_3 = z_3 - \beta_{03}fe_1$

$e_1 = v_1 - z_1$; $e_2 = v_2 - z_2$

$u = f \quad han[(e_1, \quad ce_1, \quad r, \quad h_1) \quad +z_3)/b_0]$ (8)

Moreover, the observer gains are given in equation (9), leaving only four tuning parameters [27].

$$\beta_{01} = 1 \qquad \beta_{02} = 1/2h^{0.5} \qquad \beta_{03} = 2/5^2h^{1.2} \tag{9}$$

Here, *r* is the amplification coefficient that corresponds to the limit of acceleration, *c* is a damping coefficient to be adjusted in the neighborhood of unity, h_1 is the precision coefficient that determines the aggressiveness of the control loop and it is usually a multiple of the sampling period *h* by a factor of at least four, and β_0 is a rough approximation of the coefficient β in the plant within a ±50% range. Therefore, the main tuning parameter that caters the controller to a particular application is h_1, with *c* functioning as a fine-tuning adjustment

The last equation in (7) can be, of course, chosen differently as a control law. Two alternatives can be given as below.

$$u = (\beta_1 e_1 + \beta_2 e_2 - z_3) / b_0$$

$$u = (\beta_1 \, f\,al(e_1, \alpha_1, \delta) + \beta_2 \, f\,al(e_2, \alpha_2, \delta) - z_3) / b_0$$

$$0 < \alpha_1 < 1 < \alpha_2 \tag{10}$$

By using different linear or nonlinear gain combinations in the ESO and the feedback, one can easily find over 100 different controllers in the same ADRC structure. Also, the controller coefficients are not dependent on the mathematical model of the plant, thus making ADRC largely model independent. These coefficients are primarily functions of the "time scale," That is, the controller only needs to act as fast as the plant can react. In the previously given formulation, this is implicitly represented by the choice of the sampling period h.

B) ADRC Frequency Response

The frequency response of ADRC before proceeding to LFC is given below [28].

If y is the system output, u is the control signal, b is a constant and w represents external disturbances; then a general second order plant will be given as

$$\ddot{y} = f(y, \dot{y}, w, t) + bu \tag{11}$$

In the ADRC framework, the entire f (y, 'y, w, t) is assumed unknown and denoted as the total disturbance for a general second-order plant, whose problem estimation leads to unique state observer known as Extended State Observer (ESO). The ESO of augmented plant model of (10)

$$\dot{x} = Ax + Bu + Eh$$

$$y = Cx \tag{12}$$

$$\dot{z} = Az + Bu + L(x1 - z1)$$

$$\dot{y} = Cz \tag{13}$$

ADRC estates the function *f* and cancels it out, leaving very little change in bandwidth and stability margins when a_0 and a_1 vary. This is verified considering a linear time-invariant second order plant [28]:

$$\ddot{y} = -a_1\dot{y} - a_0 y + bu \tag{14}$$

Here, a_0 and a_1 are unknown. Also, $f = -(a_1 \dot{} y) - (a_0 y)$ in this particular case. (Since both the plant and the controller are linear, the robustness of the control system can be evaluated using frequency response.)

Having Transfer Function

$$G_p(s) = (b) / (s^2 + a_1 s + a_0) \tag{15}$$

The transfer function of ADRC can be derived in the form of a Two-Degree-of-Freedom (TFD) closed loop system, as shown in **Figure4**, where $G_p(s)$ represent the transfer functions of the plant, signal, control signal and output, respectively. $D_i(s)$ is input disturbance.

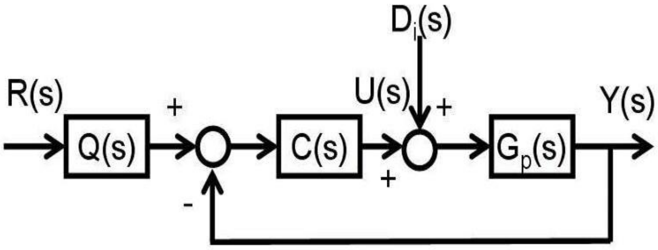

Fig.4: Transfer Function Form of ADRC

This is furthermore analyzed to obtain the transfer function from the input disturbance to the output

$$G_{Y\,D}(s) = Gp(s) / 1 + C(s)\,G(s) \tag{16}$$

From these transfer functions, the frequency analysis will proceed.

Consider a particular motion control example, where the plant represented in (14) comes with the parameters values $a_0=0$, $a_1=3.085$ and $b=206.25$,and a particular ADRC designed with $\omega_0=\omega_c=100$ rad/sec.

Then the following stability and bode plot are obtained [28].

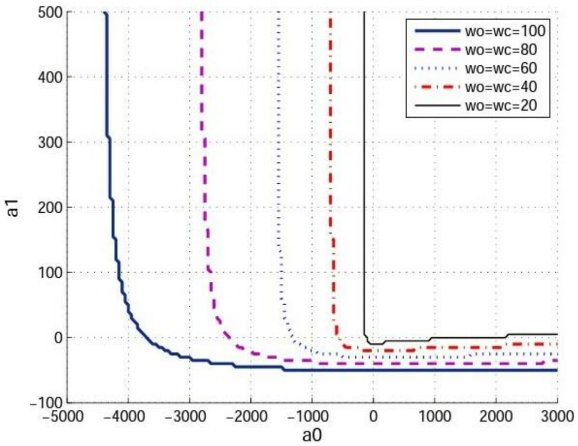

Fig.5: Stability in a_0 - a_1 plane [38]

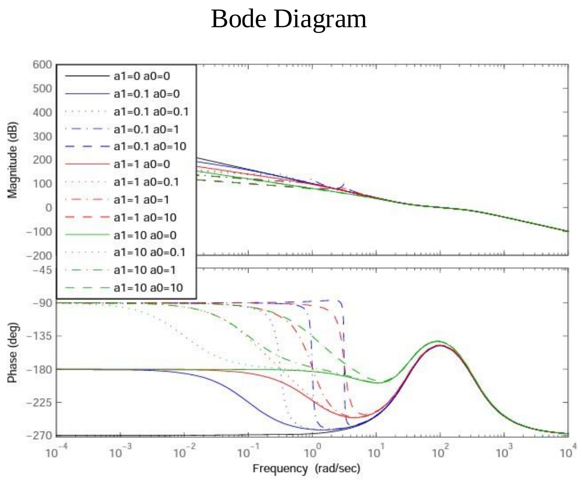

Fig.6: Loop Gain Bode plots for different a_1 and a_0

The Bode diagrams and stability margins obtained from the frequency-domain analyses further confirmed the stability, reliability, and robustness of ADRC [28].

From above, it is seen that all second-order linear systems with different values of a_0 and a_1 can be classified in one category, having two common characteristics: one is the order of the plant, and the other is the high frequency gain b [29]. One may find that these two characteristics are the essential information required for ADRC design instead of the accurate plant model.

C) ADRC for LFC

From above analysis and explanation, it is clear that the generalized disturbance containing both unknown external disturbances and the uncertainties in internal dynamics are cancelled by ADRC.

The load frequency control using ADRC technology has been proposed with detail explanation about generalized disturbances estimation, design approach, stability plots and time-domain and frequency analysis for two test system: one being a three-area three-different-unit power system including reheat, non-reheat and hydraulic unit and another being a three-area nine-unit power system consisting of only non-reheat units [30].

Control law for simplified plant [30] may be given as [29]

$$u_0 = k_1(r - z_1) - k_2 z_2 \qquad (17)$$

And its closed-loop transfer function [29] from the reference signal to the position output

$$G_d\ (s) = \omega_c^2 / (s^2 + 2\ \omega_c s + \omega_c^2) = \omega_c^2 / (s + \omega_c)^2 \qquad (18)$$

where ω_c represents the bandwidth of the controller. With the increase in ω_c, the tracking speed of the output of ADRC controlled system will increase, while the tracking error and overshoot percentage of the output will decrease [31].

The simulation results in time domain verified in the effectiveness of ADRC through successfully regulating the ACE outputs, frequency errors and tie-line power errors in the presence of external disturbances, parameter uncertainties and accidental crashing of generating units, which represent the structural or model uncertainties [30].

VI. CONCLUSION

This paper gives an account of component of ADRC as well as its structure and philosophy. Through this paper, readers are provided with an alternative- a new digital control technology arisen out of the effort to address the shortcomings of PID which are well discussed. ADRC provides a better control over LFC in linear case for a distributed generation power system. However, much work is to be done on ADRC nonlinear characteristics, stability and control so as to meet the sudden drastic change in frequency. Hence with a study and analysis of nonlinear behavior and control of ADRC, ADRC will be proven to be best effective alternative for LFC.

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