Flexible Demand Response in Smart Grid Based Automatic Generation Control

Ravindran P\textsuperscript{1}, Reeju Das K\textsuperscript{2}, Arya S Mohan\textsuperscript{3}

\textsuperscript{1}M.Tech (power system) SRM University, Chennai
\textsuperscript{1}ravindranpalanivel@gmail.com
\textsuperscript{2}reejudas@gmail.com
\textsuperscript{3}aryakalekattu@gmail.com

Abstract—In current scenario in electric power systems, customer participation of Demand Response in grid operations and management has been gaining importance in Smart Grid with the advent of information communication technology. In this paper an Automatic Generation Control (AGC) scheme that includes price based demand response scheme is proposed. The price based demand response scheme finds the optimal thermostat set point of the Thermostatically Controlled Load (TCL) for a change in price issued by Independent system operator for AGC. This paper provides a load model that includes demand response as a transfer function that provides the change in power consumed due to the price based demand response of aggregated TCLs using coupled Fokker-Planck equations. Thus the main work of this paper is the load modelling of power gain from the demand response of aggregated TCL units for AGC. Simulation results show that AGC in single area system with demand response improves system performance and leads to economic operation of the system as generators operate close to their fixed power loading.

Keywords: Automatic Generation Control Smart Grid, Price based demand response, Coupled Fokker Planck Equations.

I. INTRODUCTION

Demand response (DR) is the change in consumption by consumers in response to price signals, incentives, or directions from grid operators in the grid. Though the concept of 'Load Following Supply' existed earlier, DR is emerging as an important feature in smart grid paradigm because effective DR can be achieved only with the help of Information Communication Technology. DR broadly classified into price based and incentive based, has been extensively studied and analysed in various aspects. The focus was mainly on peak clipping, load shifting and Demand control schemes. For residential load control, Thermostatically Controlled Loads (TCL) like Heating, Ventilating and Air Conditioner (HVAC) loads are considered as they cause minimum inconvenience to the users.

Advantages of Demand Response are

1. Fewer generators would require speed governor control and thus allowing to work under fixed power loading. Thus there is more efficient power plant operation.
2. Improves system stability.

These advantages can be utilized if Demand Response can be included into system operations like Automatic Generation Control. Hence a load control scheme and model is necessary so as to include DR into AGC scheme.

The feasibility of such HVAC load control was studied in [1]. Aggregation of these loads and the impact of DR were studied in [2]. An On/OFF scheme for HVAC units was discussed in [3]. A control scheme that manipulates the thermostat set point of such loads to balance fluctuations from intermittent renewable generators was developed in [4]. A change in thermostat set point results in change in state of the unit and this has been modelled and studied in [5].

Dynamic characteristics of TCL and aggregated response of such loads had been studied and modelled using a set of ordinary and partial differential equations, called Coupled Fokker Planck Equations [6]. Load Following capability of these loads when they are under a minimum variance control law was studied in [4]. Later in [7], a transfer function that provides the aggregate response of TCL units to uniform disturbances was derived. But the limitation of the model is the assumption that the magnitude of disturbance applied to the thermostat set point is negligible when compared to the dead band zone of the thermostat set point. But with consumers aiming at minimizing the increase in amount paid by reducing the thermostat set point, this assumption will not be valid. Hence in this paper, a transfer function has been derived to obtain the change in power consumption from TCL units which undergo change in thermostat set point due to price based demand response. The transfer function derived as a part of the load model for AGC scheme.
The rest of the paper is organized as follows. Section 2 provides the load model for AGC scheme. The mathematical model for aggregated TCLs participating in the proposed demand response scheme is then discussed in Section 3. Inference arrived at, when the proposed model was applied to single area AGC simulations, is presented in Section 4 along with the simulation results. Conclusions are then drawn in Section 5.

II. LOAD MODEL FOR AUTOMATIC GENERATION CONTROL

Automatic Generation Control is based on the swing equation of the system given by,

\[
2H \frac{d\omega}{dt} = T_m - T_e
\]

Where,
- \( H \) is inertia constant (seconds)
- \( \omega \) is rotor speed
- \( T_m \) is Mechanical torque
- \( T_e \) is Electrical torque

Load can be classified as frequency independent and frequency dependent, and hence \( \Delta P_e \) is given as,

\[
\Delta P_e = (\Delta P_{L} + D \times \Delta \omega) + (\Delta P_{R} + D \times \Delta \omega_r)
\]

Where,
- \( \Delta P_{L} \) non-frequency-sensitive load change
- \( D \times \Delta \omega \) frequency-sensitive load change,
- \( D \) is load-damping constant.

With the introduction of Demand Response to AGC, the load model is to be modified as,

\[
\Delta P_e = (\Delta P_{L} + D \times \Delta \omega + \Delta P_{DR})
\]

\[
\Delta P_{DR}
\]

is the change in load due to Demand Response

A price based demand response during AGC can be achieved if customers are issued price signals in accordance with the change in frequency. When there is a decrease in frequency, which indicates a generation deficit condition, the customers are to be issued with an increase in price signal. As a result the customers initiate demand response and thus a change in demand is achieved, which is represented as \( \Delta P_{DR} \).

On further investigation, it can be understood that demand response will result in a load component that is dependent on frequency, thereby increasing the load damping value and improving the stability of the system.

Demand Response based AGC scheme for a single area, will include demand response from aggregated customers. In this paper it has been assumed that the customers participate in price based demand response by changing the thermostat set point of Thermostatically Controlled Load (Air conditioner) to an optimal value corresponding to the price issued by the system operator. As aggregated response of such thermostatically controlled loads is considered in the study, system dynamics and the probabilistic nature associated with aggregation should also be considered.

III. MODELLING OF CHANGE IN DEMAND DUE TO PRICE BASED DEMAND RESPONSE

In this section a transfer function for the response of aggregated TCLs to the change in thermostat set point is derived. The model is based on the Coupled Fokker-Plank equations (CFPE) [6] that describe the aggregated behaviour of TCLs. An exact solution for the CFPE was given in [4], so as to model the change in power demand in aggregated population of TCL due to change in thermostat set point. Aggregate power response model in a homogeneous population of TCLs was derived in [7] based on the exact solutions of CFPE. In this section the exact solution of CFPE is utilized to model the change in power consumption in aggregated TCL due to the change in thermostat set point.

Consider N homogeneous TCLs at thermostat set point 0 with dead band of \( \Delta \). Let \( P \) be the power drawn by the TCL. The dynamic characteristic of the TCL is shown in Figure 3.1. The expressions for time taken to reach temperature \( \theta_d \) from \( \theta^0 \) is the heating period and \( \theta^0 \) to \( \theta_d \) is the cooling period. The expressions for time taken to reach temperature \( \theta_n \) during cooling period \( t_c(\theta_n) \)is [7]

\[
t_c(\theta_n) = C \times \frac{R \times (\theta^0 - \theta_{amb})}{(\theta^0 - \theta_{amb})}
\]

\[
t_h(\theta_n) = \frac{E}{R \times (\theta^0 - \theta_{amb})}
\]

Where,
- \( C \) is thermal capacitance
- \( R \) is thermal resistance
- \( \theta_{amb} \) is ambient temperature

In steady state cooling time constant \( T_c \) and heating time constant \( T_h \) are defined as
The ON probability density function $f_1(\theta)$ and OFF probability density function $f_0(\theta)$ are defined as

$$f_1(\theta) = \frac{C\cdot R}{(T_c - T_s) + (F + \beta - \beta_a + \lambda)}$$

(3.5)

$$f_0(\theta) = \frac{C\cdot R}{(T_c - T_s) + \beta_a - \beta}$$

(3.6)

These are obtained by solving the CFPE equations [3.6]. Figure 3.2 shows the probability density curves given in the above equations IV.

Figure 3.2 Steady state probability densities

A. Aggregated Response of TCL Units to Price Based Demand Response

A change in thermostat set point, \(\delta\) causes a shift in the temperature band of operation \([\theta_-, \theta_+]:\). To study the response due to change in thermostat set point, four different TCL conditions namely a, b, c, d are considered on the probability density curve, as shown in Fig 3.3

Figure 3.3 Four different operating points of aggregated TCLs in the probability density curve

The power consumption waveforms for the four operating points at the initial thermostat set point and the new thermostat set point are provided in Fig 3.4. Initial waveform is shown using dotted lines and new power waveforms are shown with thick lines.

Figure 3.4 Power consumption waveforms at four operating points before and after change in thermostat set point

From Figure 3.4 a difference in power consumption can be observed. The ON time is reduced and OFF time is increased when thermostat set point increases for demand response. The difference in power consumed before and after demand response is the primary concern and thus the waveform of difference in power consumption is shown in Figure 3.5.

For operating point a, it is observed that the power gain after \(\theta_a\), occurs after cooling period which is in hours. Hence for applications like Load Frequency Control, power gain after \(\theta_a\) need not be considered. Thus the waveform relevant to LFC time frame is the power gain waveform from \(\theta_a\) to \(\theta_+.\)

Figure 3.5 Difference in power consumption waveform at four operating points after change in thermostat set point.

The Laplace transform of the relevant waveform is computed and the total power gain for aggregated TCL units
operating at point a, is calculated by integrating the transform over the distributions \( f_0 \). Integration is done over \( f_0 \) because the operating point considered lies in the off period.

Thus the total power gain from TCLs at operating point a, is

\[
P_a(s) = \int_{\theta_0}^{\theta_1} f_0(\theta_0) \cdot G_a(s) \, d\theta_0
\]

Where \( G_a(s) \) is the Laplace transform of the difference in power consumption before and after DR of loads at operating point a, given by

\[
G_a(s) = \frac{e^{-sT_H} - e^{-sT_C}}{s}
\]

and \( \tau_0 = TH - th(\theta_0) \) which can also be defined as \( \tau_0 = TH - th(\theta_0) \).

For operating point, the difference in power i.e. power gain after \( \theta_0 \), occurs after a time period equivalent to the heating period before DR, which is in hours. Thus the Laplace transform of the relevant waveform from \( \theta_0 \) to \( \theta_1 \) is computed and the total power gain is calculated by integrating over the distributions \( f_1 \).

The total power gain from TCLs at operating point b, is

\[
P_b(s) = \int_{\theta_0}^{\theta_1} f_1(\theta_0) \cdot G_b(s) \, d\theta_0
\]

Where \( G_b(s) \) is the Laplace transform of the difference in power consumption of loads at b, given by

\[
G_b(s) = \frac{e^{-sT_H} - e^{-sT_C}}{s}
\]

and \( \tau_b = TC0 - tc0(\theta_0) \).

Similar to point a, in operating point c power gain after \( \theta_0 \) occurs after cooling period. Thus the Laplace transform of the waveform from \( \theta_0 \) to \( \theta_1 \) is computed and the total power gain is calculated by integrating over the distributions \( f_0 \).

The total power gain from TCLs at operating point c, is

\[
P_c(s) = \int_{\theta_0}^{\theta_1} f_0(\theta_0) \cdot G_c(s) \, d\theta_0
\]

Where \( G_c(s) \) is the Laplace transform of the difference in power consumption of loads at c, given by

\[
G_c(s) = \frac{e^{-sT_H} - e^{-sT_C}}{s}
\]

\[
\tau_c = T_H(\theta_0) - T_C(\theta_0)
\]

Consider operating point d. The Laplace transform of the waveform from \( \theta_0 \) to \( \theta_1 \) is computed and the total power gain is calculated by integrating over the distributions \( f_1 \).

The total power gain from TCLs at operating point d, is

\[
P_d(s) = \int_{\theta_0}^{\theta_1} f_1(\theta_0) \cdot G_d(s) \, d\theta_0
\]

Where \( G_d(s) \) is the Laplace transform of the difference in power consumption of loads at d, given by

\[
G_d(s) = \frac{e^{-sT_H} - e^{-sT_C}}{s}
\]

Thus average change in power due to demand response from 'N' TCL units is given by

\[
P_{avg}(s) = P_a(s) - P_b(s) + P_c(s) - P_d(s) = \frac{\tau_0}{2T_0 + 2T_1}
\]

IV. SIMULATION OF LOAD FREQUENCY CONTROL WITH PRICE BASED DEMAND RESPONSE MODEL

The aggregated TCL demand response model is then applied to a single area AGC scheme. A single area system with 2 steam turbine units with reheat was considered Figure 4.1.

![Figure 4.1 AGC with Price based Demand Response](image_url)

In this system, the dead band nonlinearity of governor as well as the generation rate constraints was included as shown in Figure 4.2.
The system parameters are given in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia Constant, ( H )</td>
<td>5 seconds</td>
</tr>
<tr>
<td>Damping Constant, ( D )</td>
<td>( 8.33 \times 10^{-3} ) p.u. MW/Hz</td>
</tr>
<tr>
<td>Turbine time constant, ( T_t )</td>
<td>0.3</td>
</tr>
<tr>
<td>Steam turbine reheating constant, ( K_r )</td>
<td>0.5</td>
</tr>
<tr>
<td>Steam turbine reheating time constant, ( T_r )</td>
<td>10 s</td>
</tr>
<tr>
<td>Governor time constant, ( T_g )</td>
<td>0.08</td>
</tr>
<tr>
<td>Governor Droop, ( R )</td>
<td>2.4 Hz/p.u. MW</td>
</tr>
<tr>
<td>Change in Load, ( \Delta P_L )</td>
<td>0.01 p.u.</td>
</tr>
</tbody>
</table>

A single area LFC with real-time pricing scheme based on frequency deviation [8] was considered. Real time price which is proportional to the initial \( df/dt \) value [8] is assumed to be known at the system operator with the help of Phasor Measurement Units. The parameters of the single area system are provided in Appendix. System operator sends price information signals to the customers that participate in demand response. The delay in communication is assumed to be negligible. 1000 TCLs were assumed to be available for demand response.

A single area system with a step load change of 0.01 p.u. was simulated in Matlab/Simulink. The Load Frequency Control scheme with and without price based demand response are compared and the change in frequency and generation are provided in Figure 4.3.

The change in generation for 0.01 p.u. step change in load, when demand response was included in the AGC scheme is given in Figure 4.4.

The system was simulated for a load change of 0.02 p.u. The change in frequency is given in Figure 4.5.
The corresponding change in generation required when demand response was included in the scheme is given in Figure 4.6

![Figure 4.6 Change in generation for 0.02 p.u step load change](image)

Simulation for a step load change of -0.03 p.u was done and the change in frequency is shown in Figure 4.7

![Figure 4.7 Change in frequency for -0.03 p.u step load change](image)

The change in generation required in demand response based AGC is given in Figure 4.8

![Figure 4.8 Change in generation for -0.03 p.u step load change](image)

A step load change of -0.04 p.u was also simulated. The frequency deviation in this case is provided in Figure 4.9

![Figure 4.9 Change in frequency for -0.04 p.u step load change](image)

The change generation in this case is shown in Figure 4.10

![Figure 4.10 Change in generation for -0.04 p.u step load change](image)

**B. Observation and Inference**

Aggregation of TCL loads that are contracted for price based demand response is modelled to obtain the change in power consumed by these loads when a change in thermostat set point occurs. The model is then applied to Load Frequency Control scheme for a single area system. The increase in generation required when there an increase in load, can be reduced when demand response is included into LFC scheme. The results are tabulated in Table 4.2

**Table 4.2 Comparison of change in generation required, with and without Demand response**

<table>
<thead>
<tr>
<th>Step Change in Load</th>
<th>Change in Generation Without DR</th>
<th>Change in Generation With DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.01</td>
<td>0.01</td>
<td>0.00707</td>
</tr>
<tr>
<td>+0.02</td>
<td>0.02</td>
<td>0.01214</td>
</tr>
<tr>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.01731</td>
</tr>
<tr>
<td>-0.04</td>
<td>-0.04</td>
<td>-0.02731</td>
</tr>
</tbody>
</table>
V. CONCLUSION

In this paper, a demand response based AGC scheme has been proposed, which utilizes price based demand response of aggregated thermostatically controlled loads. This scheme may be used in cases where real time pricing for AGC is implemented. For the proposed AGC scheme, a transfer function was derived to model the change in demand achieved due to price based demand response from aggregated TCL units that shift their operating point with change in price signals.

With many TCL units that respond to price signals by changing the thermostat set point, a considerable change in power consumption is achieved. The advantage of the proposed demand response based AGC scheme are better performance and is economical, because at the generation level, generators are almost at fixed point operation.

VI. REFERENCES