Integration of Acceleration Feedback Control with Automatic Generation Control in Intelligent Load Frequency Control

H. Zainuddin, F. Hanafi, M. H. Hairi, A. Aman, and M.H.N. Talib

Abstract—This paper investigates the effects of knowledge-based acceleration feedback control integrated with Automatic Generation Control (AGC) to enhance the quality of frequency control of governing system. The Intelligent Acceleration Feedback Controller (IAFC) is proposed to counter the over and under frequency occurrences due to major load change in power system network. Therefore, generator tripping and load shedding operations can be reduced. Meanwhile, the integration of IAFC with AGC, a well known Load-Frequency Control (LFC) is essential to ensure the system frequency is restored to the nominal value. Computer simulations of frequency response of governing system are used to optimize the parameters of IAFC. As a result, there is substantial improvement on the LFC of governing system that employing the proposed control strategy.

Keywords—Knowledge-based Supplementary Control, Acceleration Feedback, Load Frequency Control, Automatic Generation Control.

I. INTRODUCTION

FLUCTUATIONS in frequency may affect the operation of power system plant and customer equipment, initially appearing as a malfunction and, in the extreme, causing damage [1]-[3]. Hence, generator tripping and load shedding schemes are implemented in power systems to avoid damage of the generating units and customer load units due to large disturbances. However, these schemes which activated by large frequency deviations are undesirable actions as they reduce the security and profitability of the power system operation. It is therefore important to ensure the frequency remains within the allowable frequency band. The typical variation limit set in the countries’ Electricity Grid Code is ±1% of the system frequency [4]-[7], i.e. between 49.5 Hz to 50.5 Hz for 50 Hz system.

The highly competitive market of electrical power industry has led to research on the intelligent adaptive control in improving the conventional frequency control actions by several researchers [8]-[13]. This intends to offer the utilities to have high security of supply in terms of the operation of power plants and system control and also economically dispatch the load demand. It has been recognized that knowledge-based acceleration feedback controller can reduce over and under frequency occurrences and improve substantially the quality of frequency control of steam-turbine generators [9], [10]. On the other hand, non-fixed integral gain of Automatic Generation Control (AGC) can minimize the frequency deviations and restore the nominal frequency the soonest possible, in which fixed integral gain fails to do so over a wide range of off-nominal operating conditions [12]. This paper is motivated by the desire to integrate an Intelligent Acceleration Feedback Controller (IAFC) with AGC to enhance the performance Load Frequency Control (LFC) of governing system model. The proposed system integration implements knowledge-based technique to study the feasibility and effect of LFC. Computer simulations of frequency responses for a gas turbine generator model (GAST) [14] are used to optimize all parameters of the integrated system and demonstrate its performance for major disturbances in power system. As a result, it is shown that over and under frequency occurrences can be suppressed, and frequency deviation is minimized then system frequency is restored to the nominal value as soon as possible.

II. CONTROL STRATEGY

For simulation purpose, the LFC is represented by a widely used model for representing the dynamic behavior of Gas Turbine Generator proposed in [14], GAST model (see Fig. 1). Descriptions of parameters of the model are noted in Table 1.

![Fig. 1: GAST model](image)

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TABLE I
PARAMETERS OF THE GAST MODEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Governor speed droop (pu speed / pu MW)</td>
</tr>
<tr>
<td>T₁</td>
<td>Fuel system lag time constant 1</td>
</tr>
<tr>
<td>T₂</td>
<td>Fuel system lag time constant 2</td>
</tr>
<tr>
<td>T₃</td>
<td>Load limiter time constant</td>
</tr>
<tr>
<td>L max</td>
<td>Load limit</td>
</tr>
<tr>
<td>K T</td>
<td>Temperature control loop gain</td>
</tr>
<tr>
<td>V max</td>
<td>Maximum value position</td>
</tr>
<tr>
<td>V min</td>
<td>Minimum value position</td>
</tr>
<tr>
<td>D turb</td>
<td>Turbine damping</td>
</tr>
<tr>
<td>D gen</td>
<td>Generator damping</td>
</tr>
<tr>
<td>H</td>
<td>System inertia</td>
</tr>
</tbody>
</table>

In this project, computer simulations on the GAST model are conducted without exceeding 75% of machine rating. This is due to the fact that the model does not represent gas turbine operations accurately at higher load levels when the power control is done based on the exhaust gas temperature rather than the machine speed [14].

The frequency variation, ∆f is a result of the disproportion between the mechanical and the electrical power of the generator units. A surplus of mechanical power due to load decrease causes the generator speed to increase and the frequency to rise. Meanwhile, a deficit of mechanical power due to load increase or generator outage causes the generator speed to decrease and the frequency to drop. Therefore, in this project, typical frequency limitations of ±1% of system frequency as mentioned earlier are introduced during the simulations to study the effect of the proposed control strategy in reducing the over and under frequency events.

Since acceleration/deceleration of generators is proportional to the difference between their mechanical and electrical power, large differences between mechanical and electrical power are followed by large initial acceleration/deceleration of generators. This leads to the large frequency deviations in the system. Thus, the positive or negative maximum frequency deviation, i.e. f max-f₀ and f min-f₀ is proportional to the initial acceleration, a(0) [9], [10]. If the positive initial acceleration is large, the maximum frequency deviation is also large.

Subsequently, for a large negative initial acceleration, i.e. the large deceleration, the maximum frequency deviation is negative large. Conventional controllers using the speed governors are not perceptive to acceleration. Therefore, the proposed IAFC that is sensitive to the acceleration and uses a knowledge-based control strategy can be used as an effective measure against the large frequency deviations.

The acceleration is calculated using the following expression.

\[ a(aT) = \frac{[\Delta f(nT) - \Delta f((n-1)T)]}{T} \]  

(1)

Hence, only one past data of frequency deviation, ∆f((n-1)T) is required in addition to the current measured data, ∆f(nT) to calculate the turbine acceleration and memorized control strategy is required.

The a-∆f plane shown in Fig. 3 is used in the control strategy of the IAFC. The upper-half plane represents the positive acceleration while the lower-half plane represents the negative acceleration, i.e. deceleration. The area in the right-half plane represents a frequency that is greater than the nominal value or the speed faster than the desired synchronous speed. The area in the left-half plane represents a frequency that is less than the nominal value or speed slower than the desired synchronous speed. The origin 0 is the desired equilibrium point in which all dynamic performance should reach the steady state level without neglecting the synchronous speed or frequency nominal value.

The plane is divided into eight areas. The division of the eight areas is bordered by \( a = a^+, a=a^-, a=0 \) and \( \Delta f=0 \). The required control strategies are based on the characteristics of...
is required regardless the events.

Area 8: This area is the inversion of the area 1. Thus, if the event is large under frequency, the large positive signal, \(U_{\text{max}}\) is required. However, if the event is over frequency, the small positive signal, \(U_{\text{min}}\) is required.

In addition to the above control strategies, a variable integral gain, \(K\) representing the AGC is introduced to achieve the best performance of the frequency response once the IAFC is switched OFF (deactivate). This is necessary to avoid wear and tear of the IAFC on the generating units.

III. RULE-BASED ACCELERATION FEEDBACK CONTROLLER

Now, the desired control rules for the IAFC from the eight proposed areas can be defined. Each proposed area represents a rule for the controller design for each type of disturbances, i.e. large over and under frequency events. The following rules are developed to respond to large over frequency problems, \(a(0)>a^0\).

**State A:** For \(m \geq 300\);

**Rule A1:** if \(a(0)>a^0\) and \(a(nT)>a^0\) and \(\Delta f(nT)>0\), then

\[
\begin{align*}
  m &= 0; \\
  u(nT) &= U_{\text{max}}; \\
  K(nT) &= K^0;
\end{align*}
\]

**Rule A2:** if \(a(0)>a^0\) and \(a(nT)>a^0\) and \(\Delta f(nT)<0\), then

\[
\begin{align*}
  m &= 0; \\
  u(nT) &= 0; \\
  K(nT) &= K^0;
\end{align*}
\]

**Rule A3:** if \(a(0)>a^0\) and \(a(nT)>0\) and \(a(nT)<a^+\) and \(\Delta f(nT)<0\), then

\[
\begin{align*}
  m &= m+1; \\
  u(nT) &= U_{\text{min}}; \\
  K(nT) &= K^0;
\end{align*}
\]

**Rule A4:** if \(a(0)>a^0\) and \(a(nT)>0\) and \(a(nT)<a^+\) and \(\Delta f(nT)>0\), then

\[
\begin{align*}
  m &= m+1; \\
  u(nT) &= 0; \\
  K(nT) &= K^0;
\end{align*}
\]

**Rule A5:** if \(a(0)>a^0\) and \(a(nT)>a^0\) and \(\Delta f(nT)>0\), then

\[
\begin{align*}
  m &= m+1; \\
  u(nT) &= U_{\text{min}}; \\
  K(nT) &= K^0;
\end{align*}
\]

**Rule A6:** if \(a(0)>a^0\) and \(a(nT)>a^0\) and \(\Delta f(nT)<0\), then

\[
\begin{align*}
  m &= m+1; \\
  u(nT) &= 0; \\
  K(nT) &= K^0;
\end{align*}
\]

**Rule A7:** if \(a(0)>a^0\) and \(a(nT)<a^0\) and \(\Delta f(nT)>0\), then

\[
\begin{align*}
  m &= 0; \\
  u(nT) &= 0; \\
  K(nT) &= K^0;
\end{align*}
\]
The limits of IAFC signal are defined as constraint parameters. Setting up these parameters is the most challenging task compared to other parameters for the controller. Positive values of supplementary digital control signals are used to counter negative frequency deviations and vice-versa. The optimal values for $U_{\text{max}}$ and $U_{\text{max}}$ are obtained via computer simulations by minimizing the positive and negative maximum frequency deviations correspondingly, i.e. $f_{\text{max}}-f_0$ and $f_{\text{min}}-f_0$. Whilst, the optimal values for $U_{\text{min}}$ and $U_{\text{min}}$ are gained by minimizing and smoothing the positive and negative frequency deviations correspondingly so that the frequency

The positive and negative limits of initial acceleration are defined as constraint parameters. They are determined from the knowledge that maximum and minimum frequency deviations are proportional to the initial acceleration. For 60 Hz system, a deceleration of -0.5 Hz/s corresponds to $f_{\text{max}}=59.5$ Hz [9]. Hence, for 50 Hz system, $f_{\text{max}}=50.5$ Hz will suggest $a^+=-0.5$ Hz/s and $f_{\text{min}}=49.5$ Hz will give $a^-=-0.5$ Hz/s.

The optimal value of positive and negative limits for updating acceleration sample are determined by the computer simulations and also categorized as constraint parameters. The value of $a^+$ and $a^-$ secure the minimal frequency deviations. For example, if we use $a^+=0.05$ Hz/s and $a^-=-0.05$ Hz/s for the controller which corresponds to $f_{\text{max}}=50.05$ Hz and 49.95 Hz respectively, we want the frequency response to be in that range and close to the nominal value with the help of the IAFC signal, $u$ before being restored to its nominal value via integral gain, $K$ of the AGC.

The limits of IAFC signal are defined as control parameters.
Integration of the IAFC with the AGC is meant by introducing variable integral gain, K of the AGC. The determination of variable integral gain, K value is also done from the computer simulations. Optimal value of K<sub>0</sub> is obtained before applying the IAFC on the dynamic model. Thus, it is defined as the existing integral gain value. In order to permanently reset the IAFC when the frequency has reached the steady state and returned to its nominal value after over and under frequency circumstances, the K value has to be changed from K<sub>0</sub> to K<sub>1</sub> or K<sub>2</sub> as shown in Table 4. Therefore, optimal K<sub>1</sub> and K<sub>2</sub> are determined by minimizing the frequency deviations caused by permanently switching off the IAFC, i.e. u=0. The change of K from K<sub>0</sub> to K<sub>1</sub> or K<sub>2</sub> should be synchronized with the change of u from U<sub>-min</sub> or U<sub>-min</sub> to zero in order to minimize the frequency fluctuation and deviation.

V. SIMULATION RESULTS

The performances of the proposed controller are investigated using load increase and decrease tests that signify the large under frequency and over frequency event respectively. This paper demonstrates an example of results when sudden load increased (step input from 0.4 pu to 0.6 pu) is applied to electrical power input of the GAST model. Keep in mind that the step inputs applied consider the generator loading that must not over than 75% of the machine rating as previously mentioned. Table 4 shows the parameter values that representing a 95 MVA machine [14] used in this investigation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>H</td>
<td>6.5</td>
</tr>
<tr>
<td>D&lt;sub&gt;min&lt;/sub&gt;</td>
<td>1</td>
</tr>
<tr>
<td>R</td>
<td>0.042</td>
</tr>
<tr>
<td>T&lt;sub&gt;1&lt;/sub&gt;</td>
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<tr>
<td>T&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.1</td>
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<tr>
<td>T&lt;sub&gt;3&lt;/sub&gt;</td>
<td>3</td>
</tr>
<tr>
<td>L&lt;sub&gt;max&lt;/sub&gt;</td>
<td>1</td>
</tr>
<tr>
<td>K&lt;sub&gt;T&lt;/sub&gt;</td>
<td>1</td>
</tr>
<tr>
<td>V&lt;sub&gt;max&lt;/sub&gt;</td>
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</tr>
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<td>V&lt;sub&gt;min&lt;/sub&gt;</td>
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</tr>
<tr>
<td>D&lt;sub&gt;hub&lt;/sub&gt;</td>
<td>0</td>
</tr>
</tbody>
</table>

Optimal parameters for the AGC and IAFC to function effectively based on the given event of over and under frequency are shown in Table 5. Initially, the system is simulated without IAFC. Thus, the integral gain of AGC remains constant as K<sub>0</sub>. However, as the AGC is integrated with IAFC, fixed integral gain is no longer suitable. Hence, K1 and K2 are introduced to support the integration so that the desired system response can be obtained.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a&lt;sub&gt;0&lt;/sub&gt;+</td>
<td>0.01</td>
</tr>
<tr>
<td>a&lt;sub&gt;0&lt;/sub&gt;-</td>
<td>-0.01</td>
</tr>
<tr>
<td>a&lt;sup&gt;+&lt;/sup&gt;</td>
<td>0.005</td>
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<tr>
<td>a&lt;sup&gt;-&lt;/sup&gt;</td>
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<tr>
<td>U&lt;sub&gt;+MAX&lt;/sub&gt;</td>
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<td>K&lt;sub&gt;1&lt;/sub&gt;</td>
<td>-1.15</td>
</tr>
<tr>
<td>K&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

The frequency responses after a sudden load increased with fixed and non-fixed integral gain K of AGC are illustrated in Fig. 4 and 5. It is obvious in both conditions that the IAFC able to significantly offset the large overshoot of under frequency response that occurred before using the IAFC. Thus, load shedding program can be avoided. However, the difference between both conditions is at approximately t=43s when the IAFC is switched OFF, u=0 (see Fig. 6). Result with fixed AGC, K<sub>0</sub> shows that the frequency started to decrease hugely immediately after the IAFC is switched OFF. Nevertheless, when variable AGC is integrated with the IAFC the frequency performance is improved extensively without large fluctuations. In this case, the K<sub>0</sub> is changed to K<sub>2</sub> as shown in Fig. 7.
The control strategy has obviously succeeded, in which the quality of frequency control substantially improved, and the major disturbances are suppressed, subsequently, load shedding and generator tripping operations can be prevented. In addition, the use of variable integral gain of AGC gives an opportunity for the frequency response to be restored to the nominal value smoothly without large ripple during the transient period. This condition can be achieved by determining the optimal value of integral gain once the synchronous point is reached.

VI. CONCLUSION

The control strategy has obviously succeeded, in which the quality of frequency control substantially improved, and the major disturbances are suppressed, subsequently, load shedding and generator tripping operations can be prevented. In addition, the use of variable integral gain of AGC gives an opportunity for the frequency response to be restored to the nominal value smoothly without large ripple during the transient period. This condition can be achieved by determining the optimal value of integral gain once the synchronous point is reached.

REFERENCES