Modeling and analysis of inverter air conditioners for primary frequency control considering signal delays and detection errors

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1. Background (I)

- **The large-scale blackouts are increasing.**
  - The blackout in Taiwan on Aug. 15, 2017 affected about 6.68 million customers[1].
  - The blackout in Brazil on Mar. 21, 2018 resulted in 22.5% failure of power output[2].

- **The fundamental reason is the shortage of the operating reserve.**


1. Background (Ⅱ)

Conventionally, the operating reserve is provided by traditional generation units, such as the thermal power plants or hydro turbines[3].

The development of the information and communication technology makes it easier for household appliances to provide operating reserve, which we can call smart home[4].

1. Background (Ⅲ)

Air conditioners (ACs) account for a large share in the power consumption\textsuperscript{[5]}. ACs can be regulated in a short time without much influence on the customer comfort\textsuperscript{[6]}.

**Fig. 4 Air conditioners**

- **Regular fixed speed air conditioners.**
- **Inverter air conditioners (IAC).**
  - Can be adjusted more flexibly.
  - Have little influence on the IAC life time.


2. Modeling of the inverter air conditioner (IAC)

- **The thermal model of a room**[^8]:

\[
c_A \rho_A V \frac{dT_A}{dt} = H_{gain}(t) - H_{IAC}(t)
\]  
(1)

- **Heat gains of the room:**

\[
H_{gain}(t) = (U_{O-A} A_s + c_A \rho_A V \xi) (T_O(t) - T_A(t)) + H_{dis}(t)
\]  
(2)

- **The refrigerating capacity:**

\[
H_{IAC}(t) = l_Q P_{IAC}(t) + \sigma_Q
\]  
(3)

- **The operating power of an IAC:**

\[
P_{IAC}(t) = \kappa_p f_c(t) + \mu_P
\]  
(4)


3. The control method of IACs (I)

The basic control method

- The basic control strategy of an IAC (PI controller):

\[ \Delta f_c(t) = \theta \cdot \Delta T_{dev}(t) + \eta \cdot \int \Delta T_{dev}(t) dt \]

- Temperature deviation of the indoor temperature and the set temperature:

\[ \Delta T_{dev}(t) = \Delta T_A(t) - \Delta T_{set}(t) \]

- The improved control strategy of an IAC (PI controller + P controller):

\[ \Delta f_c(t) = \theta \cdot \Delta T_{dev}(t) + \eta \cdot \int \Delta T_{dev}(t) dt + \delta \cdot \Delta f_s(t) \]  \hspace{1cm} (5)

Power system’s frequency deviation
3. The control method of IACs (Ⅱ)
The centralized detection control (CDC) of aggregated IACs

- The control strategy of an IAC:

\[
\Delta f_c(t) = \theta \cdot \Delta T_{dev}(t) + \eta \cdot \int \Delta T_{dev}(t) dt + \delta \cdot \Delta f_s(t)
\]

\[
\Delta T_{dev}(t) = \Delta T_A(t) - \Delta T_{set}(t)
\]

- More IACs will be dispatched:

\[
N_{IAC} = \begin{cases} 
0, & |\Delta f_s| \leq \Delta f_s^{\text{min}} \\
\frac{N_{IAC}^{\text{max}}}{\Delta f_s^{\text{max}} - \Delta f_s^{\text{min}}} \Delta f_s, & \Delta f_s^{\text{min}} \leq |\Delta f_s| \leq \Delta f_s^{\text{max}} \\
N_{IAC}^{\text{max}}, & |\Delta f_s| \geq \Delta f_s^{\text{max}}
\end{cases}
\]
3. The control method of IACs (Ⅲ)

The distributed detection control (DDC) of aggregated IACs

- The control strategy of an IAC:

\[
\Delta f_c(t) = \theta \cdot \Delta T_{dev}(t) + \eta \cdot \int \Delta T_{dev}(t) \, dt + \delta \cdot \Delta f_s(t)
\]

\[
\Delta T_{dev}(t) = \Delta T_A(t) - \Delta T_{set}(t)
\]

- The IACs are set different frequency thresholds to realize the same effect.
3. The control method of IAC (IV)

The comparison of the two detection control methods

<table>
<thead>
<tr>
<th></th>
<th>Centralized detection method</th>
<th>Distributed detection method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of detection devices</td>
<td>fewer</td>
<td>more</td>
</tr>
<tr>
<td>Accuracy</td>
<td>better</td>
<td>lower</td>
</tr>
<tr>
<td>Communication time</td>
<td>longer</td>
<td>shorter</td>
</tr>
</tbody>
</table>

Centralized Detection Method:
1. Customer sets the temperature $T_A$ in Room 1.
2. Room 1 sends the frequency detection $\Delta f_s$ to the control center.
3. The control center sends signals to Room 1.
4. Room 1 sets the controller.

Distributed Detection Method:
1. Customer sets the temperature $T_A$ in Room 1.
2. Room 1 sends the frequency detection $\Delta f_{sl}$ to the control center.
3. The control center sends signals to Room 1.
4. Room 1 sets the controller.

(a) Control center
- Frequency detection $\Delta f_s$
- Send signals

Centralized Method:
- Fewer detection devices
- Better accuracy
- Longer communication time

Distributed Method:
- More detection devices
- Lower accuracy
- Shorter communication time

Power Grid
- Energy
- Signal
4. Case Studies (I)

The test system

- **The initial parameters:**
  - The initial loads of the power system are 560MW.
  - The number of the aggregated IACs is 30,000.
  - The ambient temperature and the set temperature of the IAC are 33°C and 26°C, respectively.
  - The minimum and maximum thresholds of the system frequency deviation are 0.01Hz and 0.03Hz, respectively.
  - It’s assumed that the load deviation is 80MW.

- **The system:**
4. Case Studies (Ⅱ)
The simulation results - The centralized detection control

<table>
<thead>
<tr>
<th>CASE</th>
<th>( \Delta f_s^{\max} ) (Hz)</th>
<th>( \Delta P_{IAC}^{\max} ) (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>-0.270</td>
<td>-36.56</td>
</tr>
<tr>
<td>Case 2</td>
<td>-0.335</td>
<td>-44.80</td>
</tr>
<tr>
<td>Case 3</td>
<td>-0.409</td>
<td>-55.04</td>
</tr>
</tbody>
</table>
4. Case Studies (Ⅲ)
The simulation results - The distributed detection control

\begin{tabular}{ |c|c|c| } 
\hline
\textbf{CASE} & \textbf{$\Delta f_s^{\text{max}}$ (Hz)} & \textbf{$\Delta P_{IAC}^{\text{max}}$ (MW)} \\
\hline
Case 1 & -0.270 & -36.56 \\
Case 2 & -0.265 & -37.60 \\
Case 3 & -0.281 & -34.32 \\
\hline
\end{tabular}
5. Discussions and Conclusions

- The model of the inverter air conditioner (IAC) is developed in this paper.

- Two detection control methods are proposed, the centralized detection control (CDC) method and the distributed detection control (DDC) method.

- The IACs have been proved to be able to provide operating reserve for the power system.

- The communication delays in the CDC method will enlarge the system frequency deviations and even bring frequency oscillations, while the detection errors in the DDC method have less influences on the system frequency deviation.

- Therefore, as for the large-scale aggregated IACs, the DDC method may be more appropriate than the CDC method.
Thanks for your attention!