A REAL-TIME SIMULATION TOOL FOR FAULT DETECTION AND DIAGNOSIS OF HVAC SYSTEMS

YUE MA, MOHAMMED ZAHEERUDDIN
Building Civil Environmental Engineering, Concordia University, Montreal, Quebec, Canada
zaheer@bcee.concordia.ca

Abstract. In this study, a real-time simulation tool was developed for online monitoring, control and diagnosis of HVAC systems. A two-zone variable air volume terminal reheat (VAV-TRH) HVAC system is considered. The developed program can be used in offline and online environments. The offline environment allows the operators to examine optimal control strategies, and to investigate problems associated with improper size of components which could be the root cause of the fault. The online environment is useful for monitoring, control and diagnosis of HVAC systems. A set of expert rules were applied to identify the faults. Simulation results show that the developed tool is able to correctly identify the fault patterns and therefore can be used for improving operating performance of HVAC systems.

1. Introduction

As a complex electromechanical system, the heating, ventilating and air conditioning (HVAC) system experiences faults virtually everywhere. Faults in HVAC systems comprise a wide range of problems, such as poor tuning of controllers, stuck or leaky dampers and valves, broken sensors or actuators. Faults can cause increased energy consumption, worn equipment, and less comfortable conditions. In other words, faults tend to degrade the performance of HVAC systems. Accordingly, it is very important to develop fault detection and diagnosis (FDD) tools for HVAC systems.

In recent years, real-time systems have been widely applied to detect and diagnose faults in HVAC systems. Several researchers have contributed to the development of real-time FDD systems. Anderson et al. (1989) developed a quasi-real-time expert system for diagnostic analysis of an industrial HVAC system. The system consisted of a statistical analysis
preprocessor and a rule-based expert system. Peitsman and Soethout (1997) applied auto aggressive (ARX) models in real-time model-based diagnosis. The system model was used to detect faults based on performance degradation. After a fault was detected, the component models were used to locate the defective component. Dodier et al. (1998) described automated fault detection and diagnosis scheme in which Bayer’s classifier was used to predict the state of operation of a fan-powered VAV box. Han et al. (1999) presented a model-based fault detection and diagnosis tool for HVAC systems.

In this study, a real-time simulation tool will be developed for online monitoring, control and diagnosis of HVAC systems. In order to achieve this objective, a two-zone variable air volume terminal reheat (VAV-TRH) HVAC system will be utilized as a platform.

2. Two-zone VAV-TRH System

2.1. PHYSICAL MODEL

The two-zone VAV-TRH HVAC system analyzed in this study is shown in Figure 1. The major components of the system are (1) two environmental zones, (2) a supply fan, (3) a return fan, (4) a cooling and dehumidifying coil, (5) two VAV boxes with reheat coils, and (6) ductwork. In the modeled system, outdoor air (OA) enters the system and is mixed with recirculated air (RA). After being conditioned in the cooling coil and the reheat coil (if required), the mixed air is supplied to zones. In response to demand for cooling from zone thermostats, volume flow rates of supply air (SA) to Zones 1 and 2 vary by modulating the VAV dampers, which are maneuvered by the two controllers – C1 and C2. The controller C3 modulates positions of outdoor air, recirculated air, and exhaust air dampers to minimize the requirements for mechanical cooling energy. The controller C4 is used to maintain discharge air temperature at a varying set point by adjusting the chilled water valve. In addition a supervisory Energy Management and Control System (EMCS) is used to determine the set point values of zone temperatures and discharge air temperature which are then supplied to the four controllers as inputs.

2.2. DYNAMIC MODEL

2.2.1. Zone Model

A detailed zone model is too complex and is not suitable for on-line applications (Zhang and Nelson 1992, p.46). Assuming uniform temperature
and neglecting air infiltration, the model can be expressed by the following equation:

\[ k \rho_g c_p V \frac{dT_z(t)}{dt} = \dot{m}_{sa} c_p [T_{sa}(t) - T_z(t)] + q_s \]  

(1)

**Figure 1.** Schematic diagram of a two-zone VAV-TRH HVAC system.

### 2.2.2. Coil Model

The coil is the most important interface between the primary plant (e.g., chiller or boiler) and the secondary air distribution system. In this study, the coil model is described by the following equations (Clark, 1985, p.54&55):

\[ \frac{dT_{ao}}{dt} = \frac{T_{ao}}{\tau} - \frac{T_{ao} - T_{so}}{\tau} \]  

(2)
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\[
\frac{dT_{so}}{dt} = \frac{T_{woss} - T_{so}}{\tau} \tag{3}
\]

\[
\tau = \frac{C_m}{U_r A_r} \tag{4}
\]

\[
T_{aoss} = T_{ai} + \frac{\varepsilon C_{min}}{C_a} (T_{wi} - T_{ai}) \tag{5}
\]

\[
T_{woss} = T_{wi} - \frac{C_a}{C_w} (T_{aoss} - T_{ai}) \tag{6}
\]

\[
\varepsilon = 1 - \exp \left\{ \exp \left[ -\frac{Rn(NTU)}{Rn} \right] - 1 \right\} \tag{7}
\]

\[
n = (NTU)^{0.22} \tag{8}
\]

\[
R = \frac{C_{min}}{C_{max}} \tag{9}
\]

2.3. SIMULATIONS OF CONTROL STRATEGIES

For the modeled system, two control strategies were designed – an optimal control strategy and a reheat control strategy. A reheat control strategy is one in which the discharge air temperature set point is determined such that the supply airflow rate is minimized. An optimal control strategy is one where the total cost of operation is minimized while maintaining comfort conditions.

Figures 2 and 3 depict the dynamic performance of the modeled HVAC system when a reheat control strategy and an optimal control strategy are used. It is noted that temperature of Zone 2 (T22) was fluctuating, centered on the set point value when the reheat control strategy was in effect. This was because the corresponding reheat coil was activated and the hot water valve was maneuvered by a two-position controller.

A comparison of the two control strategies shows that under the same operating conditions, the optimal control strategy results in a saving of 16% input energy required by the chiller relative to the reheat control strategy by raising the discharge air temperature set point. Also, the optimal control strategy reduces the need for reheat (Wulfinghoff 1999, p. 264). Therefore, the optimal control strategy is an ideal solution to energy conservation.
3. Real-time Software Development

3.1. DEVELOPMENT ENVIRONMENT

The software is implemented in Matlab/Simulink environment. It supports linear and nonlinear systems and can be modeled in continuous time, sampled time, or a hybrid of the two. Furthermore, Matlab/Simulink provides a graphical user interface (GUI) for building models as block diagrams.

3.2. SOFTWARE REQUIREMENTS

The developed tool, which is referred to as HVAC Simulator in this study, is a simulation system using a two-zone VAV-TRH HVAC system as platform. The use-case driven approach (Jacobson et al., 1992) was used to analyze requirements of the software. Table 1 depicts a typical use case for determining optimal set points.
TABLE 2. Description of use case.

<table>
<thead>
<tr>
<th>Description</th>
<th>System determines the optimal set of control variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Detailed Description</td>
</tr>
<tr>
<td>Actors</td>
<td>HVAC operator, Weather forecast website, Load</td>
</tr>
<tr>
<td></td>
<td>predictor, Energy management and control system</td>
</tr>
<tr>
<td>Pre-Conditions</td>
<td>1. System must be loaded</td>
</tr>
<tr>
<td></td>
<td>2. Weather forecast website outputs outdoor air</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
</tr>
<tr>
<td></td>
<td>3. Load predictors outputs building loads</td>
</tr>
<tr>
<td>Flow of Events</td>
<td>1. A dialog box prompts HVAC operator to enter</td>
</tr>
<tr>
<td></td>
<td>outdoor air temperature and building loads</td>
</tr>
<tr>
<td></td>
<td>2. HVAC operator enters the required data</td>
</tr>
<tr>
<td></td>
<td>3. System determines the optimal set of control</td>
</tr>
<tr>
<td></td>
<td>variables</td>
</tr>
<tr>
<td></td>
<td>4. System displays the optimal set of control</td>
</tr>
<tr>
<td></td>
<td>variables</td>
</tr>
<tr>
<td>Basic Scenario</td>
<td>1. Step 3a: System cannot determine the optimal set of control</td>
</tr>
<tr>
<td></td>
<td>variables based on the given information</td>
</tr>
<tr>
<td></td>
<td>Step 4a: System displays the message that the optimal</td>
</tr>
<tr>
<td></td>
<td>set is not available and the reheat control strategy</td>
</tr>
<tr>
<td></td>
<td>should be used.</td>
</tr>
<tr>
<td>Alternative Scenario</td>
<td>Post-Conditions</td>
</tr>
<tr>
<td>Related Use Cases</td>
<td>None</td>
</tr>
<tr>
<td>Used Use Cases</td>
<td>None</td>
</tr>
<tr>
<td>Extending Use Cases</td>
<td>None</td>
</tr>
</tbody>
</table>

HVAC Simulator has two running modes: offline simulation and online (i.e. real-time) application. The offline environment allows the operators to test control strategies, and to investigate problems caused by incorrect sizing of HVAC components. The function can be implemented through predicting the dynamic behavior of the modeled HVAC system. Also, the user can create a real-time application to let the system run while synchronized to a real-time clock. This allows the system to control or interact with an external system. The software program has several user interface windows which facilitate running the program interactively. One such user interface is shown in Figure 4.
4. Expert FDD Rules

In general, expert rules are formulated based on the knowledge of HVAC experts. In this study, some expert rules are adapted from the literature (House et al. 2003). The expert rules are categorized according to the operation modes of the air handling unit (AHU): (1) mechanical cooling with minimum outdoor air intake (Mode#1), (2) mechanical or natural cooling with 100% outdoor air (Mode#2), and (3) natural cooling with outdoor air (Mode#3). Among these rules, those common for at least two
operation modes are referred to as common rules (Table 2) while others are specific rules. All rules are written such that a fault will be indicated if the equation defining the fault is satisfied.

<table>
<thead>
<tr>
<th>Rule #</th>
<th>Content</th>
<th>Rule #</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$T_{da} &gt; T_{ma} + \Delta T_{sf} + \varepsilon_i$</td>
<td>7</td>
<td>$T_{sa} \leq T_{da} - \varepsilon_i$</td>
</tr>
<tr>
<td>2</td>
<td>$T_{da} &gt; T_{ra} - \Delta T_{sf} + \varepsilon_i$</td>
<td>8</td>
<td>$T_{sa} = \text{const}$</td>
</tr>
<tr>
<td>3</td>
<td>$T_{da} \geq T_{dset} + \varepsilon_i$</td>
<td>9</td>
<td>$T_r \geq T_{zset} + \varepsilon_i$</td>
</tr>
<tr>
<td>4</td>
<td>$T_{da} \leq T_{dset} - \varepsilon_i$</td>
<td>10</td>
<td>$T_r \leq T_{zset} - \varepsilon_i$</td>
</tr>
<tr>
<td>5</td>
<td>$T_{da} = \text{const}$</td>
<td>11</td>
<td>$T_r = \text{const}$</td>
</tr>
<tr>
<td>6</td>
<td>$T_{ra} \geq T_{da} + \varepsilon_i$</td>
<td>12</td>
<td>$U_{wact} &gt; U_{wexp}$</td>
</tr>
</tbody>
</table>

4.1. RULES FOR MODE#1

In Mode#1, the cooling coil valve is modulated to satisfy the discharge air temperature set point value, and the mixing box dampers are set for minimum outdoor air intake.

Two rules for Mode#1 are listed as follows:

Rule 13  $T_{ra} < T_{ra} - \varepsilon_i$

Rule 14  $R_{osact} = R_{osexp}$

4.2. RULES FOR MODE#2

In Mode#2, the mixing box dampers are set for 100% outdoor air, 0% return air, and 100% exhaust air. When the outdoor air temperature is greater than the discharge air temperature set point, the cooling coil valve is modulated to satisfy the discharge air temperature set point. When the values of the above two temperatures are the same, the cooling coil valve is closed and natural cooling is utilized.
Four rules for Mode#2 are listed as follows:

Rule 15  \[ T_{oa} < T_{dset} - \Delta T_{sf} - \epsilon_i \] 

Rule 16  \[ T_{oa} > T_{ra} + \epsilon_i \] 

Rule 17  \[ T_{oa} \geq T_{ma} + \epsilon_i \] 

Rule 18  \[ T_{oa} \leq T_{ma} - \epsilon_i \] 

4.3 RULES FOR MODE#3

In Mode#3, the mixing box dampers are controlled to maintain the discharge air temperature at the set point value and no mechanical energy is required.

Two rules for Mode#3 are listed as follows:

Rule 19  \[ T_{oa} > T_{dset} - \Delta T_{sf} + \epsilon_i \] 

Rule 20  \[ T_{da} < T_{ma} + \Delta T_{sf} - \epsilon_i \] 

5. Applications

The validity and robustness of the expert rules were tested by embedding a fault in the model to simulate a faulty HVAC system and conducting real-time simulations. A sampling interval of 3-second was chosen. Only single fault cases were investigated. Results from two test cases are described.

5.1. CASE 1 – A STUCK COOLING COIL VALVE

Since the control signal to the cooling coil valve modulates to maintain the discharge air temperature at its associated set point, this fault will eventually cause the control signal to saturate at one of its limit.

Two tests were performed to simulate these two situations, where the discharge air temperature set point value was 55F (i.e., \( T_{dset} = 55F \)). Test 1 was simulated by causing the cooling coil valve to stick at \( t = 519s \) at 30% open position. In the meantime, design loads were acting on the system. As shown in Figure 5, the discharge air temperature was 64.3F (i.e., \( T_{da} = 64.3F \)), much higher than the set point value. It should also be noted that zone temperatures (\( T_{z1} = 84.5F \) and \( T_{z2} = 84.1F \)) were greater than the set point values. This was because design loads could not be satisfied even though VAV damper control signals had saturated. Test 2 was simulated by causing the cooling coil valve to stick at \( t = 2,208s \) at 70% open position. In the meantime, the system was undergoing relatively small partial loads. As shown in Figure 6, the discharge air temperature was 50.3F (i.e., \( T_{da} = 50.3F \)), much less than the set point. However, unlike Test 1, both zone
temperature set points were reached. This was because this fault could be compensated by decreasing VAV damper control signals.

From the results, it is found that zone temperatures will not necessarily be affected when the cooling coil valve is stuck. The fact that the discharge air temperature cannot be reached is the primary symptom of this fault. Accordingly, the fault – cooling coil valve stuck – can be confirmed due to satisfaction of Rules 3 and 4.

5.3. CASE 2 – A STUCK OUTDOOR AIR DAMPER

This fault belongs to economizer cycle and occurs due to failure of a linkage in the mixing box dampers, which include outdoor air damper, recirculated air damper, and exhaust air damper. It presents three different symptoms under three different AHU operation modes.

Three tests were performed to simulate the fault corresponding to the AHU operation modes. Test 1 was for Mode#1 and simulated by causing the outdoor air damper to stick at 8% open position at t = 1,266s. As shown in Figure 7, the actual ratio of outdoor air intake to supply airflow rate was 0.14 (i.e., R_{oact} = 0.14), which was less than the expected ratio (i.e., R_{oexp} = 0.18). Test 2 was for Mode#2 and simulated by causing the outdoor air damper to stick at 60% open position at t = 1,230s. As shown in Figure 8, Zone 1 temperature was 84F (i.e., T_{z1} = 84F). Test 3 was for Mode#3 and simulated by causing the outdoor air damper to stick at 30% open position at t = 1,413s. As shown in Figure 9, the discharge air temperature was 57.7F (i.e.,
$T_{\text{da}} = 57.7 \, ^\circ\text{F}$, being greater than the set point as a result of the fact that less outdoor air was drawn into the system. From the above tests, it is concluded that the fault – outdoor air damper stuck – occurred due to satisfaction of Rule 3 in Mode#1, Rule 9 in Mode#2, and Rule 14 in Mode#3.

![Graph of Ratio of Outdoor Air Intake to Supply Airflow Rate](image1)

*Figure 7. Ratio of outdoor air intake to supply airflow rate.*

![Graph of Response of Zone Temperatures](image2)

*Figure 8. Response of zone temperatures.*
Figure 9. Response of temperatures.

6. Conclusions

In this paper, a real-time simulation tool has been developed for online monitoring, control and diagnosis of HVAC systems. This program runs in two modes: offline mode and online mode. When it is running in offline mode, it facilitates HVAC operators examine control strategies, and investigate problems caused by improper sizing of HVAC components. When it is running in online mode, real-time simulations can be implemented. Non real-time simulations have shown that the optimal control strategy is advantageous to the reheat control strategy. Real-time simulations have demonstrated that the developed tool is effective in identifying the fault patterns.

Acknowledgements

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References


Nomenclature

\( C_a \) air capacitance rate (Btu/hr-F)
\( C_m \) total thermal capacitance of coil material (Btu/hr-F)
\( C_{\text{max}} \) maximum of \( C_a \) and \( C_w \) (Btu/hr-F)
\( C_{\text{min}} \) minimum of \( C_a \) and \( C_w \) (Btu/hr-F)
\( C_{pa} \) specific heat of air (Btu/lbm-F)
\( C_w \) water capacitance rate (Btu/hr-F)
\( k \) factor describing the thermal capacity of zone
\( \dot{m}_{sa} \) supply air mass flow rate (lbm/hr)
\( q_s \) instantaneous sensible load (Kw or Btu/hr)
\( R \) ratio of minimum to maximum capacitance
\( R_{\text{act}} \) actual ratio of outdoor air to supply airflow rate
\( R_{\text{exp}} \) expected ratio of outdoor air to supply airflow rate
\( T_{ai} \) entering coil air temperature (F)
\( T_{ao} \) air dynamic outlet temperature (F)
\( T_{esso} \) steady state air outlet temperature (F)
\( T_{da} \) discharge air temperature (F)
\( T_{dase} \) discharge air temperature set point (F)
\( T_{ma} \) mixed air temperature (F)
\( T_{oa} \) outdoor air temperature (F or °C)
\( T_{ra} \) return air temperature (F)
\( T_{sa} \) supply air temperature (F)
\( T_z \) zone temperature (F or °C)
\[ T_{\text{set}} \] zone temperature set point (F)

\[ T_{\text{wi}} \] inlet water temperature (F)

\[ T_{\text{wo}} \] water dynamic outlet temperature (F)

\[ T_{\text{wox}} \] steady state water outlet temperature (F)

\[ t \] time (hour)

\[ U_{\text{wact}} \] actual control signal to the cooling coil valve

\[ U_{\text{wexp}} \] expected control signal to the cooling coil valve

\[ V_z \] zone air volume (ft³)

\[ \Delta T_d \] temperature rise in ducts (°C)

\[ \Delta T_f \] temperature rise across fan (F or °C)