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Fault tolerant control for energy power systems

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ABSTRACT
In this paper, we investigate the problem of a fault tolerant control for an energy power system. The aim of our approach is to improve the availability and the reliability of the energy power system by taking into account the occurrence of faults in the design of the control algorithm. Here, we propose an observer estimating simultaneously the state and faults of the system which will be injected in the controller to compensate the faults effects.

NOMENCLATURE

\( C_{p,r} \): heat capacity of the room air,
\( C_{p,w} \): heat capacity of water in floor heating pipes,
\( C_{p,f} \): heat capacity of the floor,
\( T_r \): room air temperature,
\( T_f \): floor temperature,
\( T_w \): water temperature in floor heating pipes,
\( T_a \): ambient temperature,
\( T'_a \): ground temperature,
\( W_c \): heat pump compressor input power,
\( \phi_s \): solar radiation power,
\( (UA)_{fr} \): heat transfer coefficient between floor and room air,
\( (UA)_{wf} \): heat transfer coefficient between water and floor,
\( (UA)_{ra} \): heat transfer coefficient between room air and the ambient air,
\( Q_{fr} \): heat transmitted from the floor to the indoor air
\( Q_{wf} \): heat transmitted from the water circulating in the floor heating pipes to the floor,
\( Q_{ra} \): heat transmitted from the air in the room to the surroundings,
\( p \): fraction of incident solar radiation on floor,
\( \eta \): compressor coefficient of performance.

INTRODUCTION
Due to the global warming and climate change threatening the world, the energy consumption has to make a transition and should look elsewhere. For this reason, a great interest has been given to renewable energy and low-carbon emission energy sources during recent years [10], [12], [16], [3] and references there in.

In Europe, buildings consume about 40% of the total energy use [1], where heating is the most important energy consumer. Gas boilers combined with radiators still be the most common heating system in buildings in Europe. However, unlike gas heating or wood burners, the heat pumps systems are environmentally friendly. Driven by electricity, those systems become one of the main source of heating [9], [11], [12], [14]. A basic factor of its successful application is the availability of a cheap and dependable heat source.

In this work, we show the importance of the automation contribution in the control of the energy demand of a building. Based on a model deducted from energy balances in a building [9], we design an optimal control law in order to minimize the energy consumed. Thus, the proposed optimal control law is based on an adaptive observer which allows the reconstruction of the model variables that are not measured. This control law takes into account the estimated state of the "building-actuator" system and the effects of the environment represented by the variations in the ambient temperature.

This paper begins by giving the energy balances and the different parameters interfering in a heating buildings system. Then, we give the mathematical model of the system considered in this paper. To have an access to all the parameters of the system, we design in the fourth section a Kalman observer, in order to design a suitable controller which compensate the effects of faults and ensure the stability in the closed loop. Finally, performances and efficiency of the proposed approach are shown through an example.

ENERGY BALANCES OF A HEATING HOUSE SYSTEM
In order to get a suitable model of the energy power system, we establish the energy balances in the considered building and we assume that:

- there is one uniform air temperature,
there is no ventilation and not either an influence from the wind,
the air humidity doesn’t influence the energy balances,
the heat due to the human presence in the room, is not taken into account.

As in [9], we consider here the presence of two heat accumulating data: the room air and the floor (see figure 1(a)). Note that in this figure, the additional variables $T_a'$ and $W_c$ stand for the ground temperature and the heat pump compressor input power, respectively. These variables do not intervene in the model of the heating house).

![Figure 1: Building and heat pump floor heating systems.](image)

The energy balance in a room is given by:

$$C_{p,r} \dot{T}_r = Q_{fr} - Q_{ra} + (1 - p) \phi_s$$  \hspace{0.5cm} (1a)

$$C_{p,f} \dot{T}_f = Q_{wf} - Q_{fr} + p \phi_s$$  \hspace{0.5cm} (1b)

where $C_{p,r}, C_{p,f}$ are defined at the beginning of the paper, $Q_{ra}, Q_{fr}$ and $Q_{wf}$ are given by:

$$Q_{fr} = (UA)_{fr}(T_f - T_r)$$  \hspace{0.5cm} (2a)

$$Q_{ra} = (UA)_{ra}(T_r - T_a)$$  \hspace{0.5cm} (2b)

$$Q_{wf} = (UA)_{wf}(T_w - T_f)$$  \hspace{0.5cm} (2c)

where the product $(UA)$ represents the heat conductivity multiplying the surface area of the layer between two heat exchanging media.

The energy balance for the water in the floor heating system is expressed as follows:

$$C_{p,w} \dot{T}_w = Q_c - Q_{wf}$$  \hspace{0.5cm} (3)

where $C_{p,w}$ is the heat capacity of the water in the floor heating pipes. $Q_c$ is the amount of heat issued from the condenser to the water in the heat pump, such that:

$$Q_c = \eta W_c$$  \hspace{0.5cm} (4)

with $\eta$ and $W_c$ are defined in the first section.

Then, the theoretical model resulting from the energy balances equations and describing the heat dynamics of a house floor heating system connected to a ground source based heat pump, constitute the basis for the analysis given in this work. Here, we propose to estimate the state vector and the unknown parameter of the considered model using an adaptive observer in order to find a state feedback stabilizing the closed-loop system using an $H_{\infty}$ approach to guarantee the disturbance attenuation.

**MODELIZATION OF A HEATING HOUSE SYSTEM**

The residential heating system described before, can be modelled by the following state space linear system,

$$\dot{x} = Ax + Bu + Ed + Df$$  \hspace{0.5cm} (5a)

$$y = Cx$$  \hspace{0.5cm} (5b)

where $x = [T_r \quad T_f \quad T_w]^T$ is the state vector with $T_r$ is the room air temperature, $T_f$ is the floor temperature, $T_w$ is the water temperature in floor heating pipes. $u$ is the input vector which represent the power used by the compressor in the heat pump $W_c$. $y$ is the output vector which corresponds to the room air temperature $T_a$. The matrices $A, B, C, D$ and $E$ are known with constant values, given by:

$$A = \begin{bmatrix}
-\frac{(UA)_{fr}}{C_{p,r}} & \frac{(UA)_{fr}}{C_{p,f}} & 0 \\
\frac{(UA)_{ra}}{C_{p,r}} & \frac{(UA)_{ra}}{C_{p,f}} & 0 \\
0 & \frac{(UA)_{wf}}{C_{p,w}} & \frac{(UA)_{wf}}{C_{p,f}}
\end{bmatrix}$$

$$E = \begin{bmatrix}
\frac{(UA)_{ra}}{C_{p,r}} \\
0 \\
0
\end{bmatrix}, \quad D = \begin{bmatrix}
\frac{1}{C_{p,r}} \\
\frac{1}{C_{p,f}} \\
0
\end{bmatrix}$$
The main objective in this work is to synthesize a control law \( u = W_c \), in order to minimize the effect of the unmeasured perturbation \( f \) on the error between a setpoint reference temperature in the room, called \( T_c \) by setting \( y_c = T_c \) and the measured temperature of the room given by \( y = T_r \). This control law is described by the diagram in the figure 2 and is calculated into two steps as follows:

- **First step** The design of an observer to estimate the state vector \( x \) and the unmeasured perturbation \( f \), considered as a fault, via a Kalman filter. These estimates are called \( \hat{x} \) and \( \hat{f} \).

- **Second step** Using the observer estimates, computation of the gains \( K_x \), \( K_I \) and \( K_f \) to generate the control \( u \).

To obtain an asymptotic convergence between the setpoint \( y_c \) and the measure \( y \), an integrator is added in the control law. \( q \) and \( s \) are respectively the integration and the Laplace variable. In order to decrease the effect of the perturbation \( f \) on the control law, the estimate of this perturbation, \( \hat{f} \) is used in the control law.

\[
B = \begin{bmatrix} 0 & 0 & \eta \end{bmatrix}^T, \quad C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}
\]

Then, equations (5) and (6) are equivalent to the following augmented system,

\[
\begin{align*}
\dot{\xi} &= A\xi + Bu + Ed \\
y &= C\xi
\end{align*}
\]

where \( \xi = \begin{bmatrix} x \\ f \end{bmatrix} \), \( A = \begin{bmatrix} A & D \\ 0 & 0 \end{bmatrix} \), \( E = \begin{bmatrix} E \\ 0 \end{bmatrix} \) and \( C = \begin{bmatrix} C & 0 \end{bmatrix} \).

Before starting the design of the adaptive observer, we have to check if the system (7) is detectable (the matrices \( A, C \) are detectable.) [15], which is the case for the considered system by satisfying the following rank condition

\[
\text{rank} \begin{bmatrix} sI_3 - A & E \\ 0 & sI_1 \\ C & 0 \end{bmatrix} = 4 \quad \forall s \geq 0
\]

Notice that for most of the dynamical systems, as the heating building considered systems, the measurements are not totally accessible. To have access to all the states, the design of an observer becomes a necessity.

To estimate the states and the unknown inputs of the heating building systems modelled by equation (5), we propose the following Kalman observer:

\[
\begin{align*}
\dot{x} &= Ax + Bu + Ed + D\hat{f} + L_x(y - \hat{y}) \\
\hat{f} &= L_f(y - \hat{y}) \\
\hat{y} &= C\hat{x}
\end{align*}
\]

where \( \hat{x} \) and \( \hat{f} \) are respectively the estimates of the states vector \( x \) and the unknown input \( f \). \( L_x \) and \( L_f \) are the observer’s gain.

Using the vector \( \xi \), we rewrite the filter described by (8) as follows

\[
\begin{align*}
\dot{\hat{\xi}} &= A\hat{\xi} + Bu + Ed + L(y - \hat{y}) \\
\hat{\xi} &= C\hat{\xi} \\
\hat{\xi} &= C\hat{\xi} \\
\hat{\xi} &= C\hat{\xi}
\end{align*}
\]

where \( L = \begin{bmatrix} L_x \\ L_f \end{bmatrix} \), is obtained as follows:

\[
L = P_oC^TR^{-1}
\]

with \( P_o \) is the solution of the Riccati equation [15] described by:

\[
AP_o + P_oA^T + P_oC^TR^{-1}CP_o + Q = 0
\]

where \( R = R^T > 0 \) and \( Q = Q^T > 0 \) given by:

\[
Q = Q_0 + \mu^2BB^T
\]
is an appropriate noise intensity corresponding to the nominal Kalman filter gain, i.e for \( \mu = 0 \). \( \mu \) is a positive scalar choosing with a high value. The choice of this structure for the matrix \( Q \) is recommended to improve the robustness of the filter [5], [6].

Then, the design of the Kalman filter is based on the choice of matrices \( Q \) and \( R \), and the scalar \( \mu \).

**OBSERVER-BASED FAULT TOLERANT CONTROL**

In this section, sufficient conditions of asymptotic stability and \( H_{\infty} \) criterion of the heating systems in closed loop will be given under the action of an adaptive observer-based control. For that reason, we start by introducing the following assumption:

**Assumption 1**

\( \circ \) The pair \((A, B)\) is stabilisable.

Since only the estimates of the states \( x \) and the unknown parameter \( f \) are available for the feedback control, we propose the following fault tolerant controller (see figure (2)):

\[
\dot{x} = A\hat{x} + Bu + C_f \hat{f}
\]

where

\[
\begin{align*}
A &= \begin{bmatrix}
A - BK_x & BK_i & BK_f \\
-C & 0 & 0 \\
0 & A - L_x C & D \\
0 & 0 & -L_f C \\
\end{bmatrix} \\
B &= \begin{bmatrix}
B_k \\
0 \\
- B_k \\
0 \\
\end{bmatrix} \\
C &= \begin{bmatrix}
0 & 0 & 0 \\
0 & 1 & 0 \\
\end{bmatrix} \\
D &= \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix} \\
F &= \begin{bmatrix}
E \\
0 \\
D \\
0 \\
\end{bmatrix} \\
K &= \begin{bmatrix}
K_x \\
K_i \\
K_f \\
\end{bmatrix} \\
I &= \begin{bmatrix}
I \\
0 \\
I \\
\end{bmatrix} \\
0 &= \begin{bmatrix}
0 \\
0 \\
0 \\
\end{bmatrix} \\
\end{align*}
\]

Then, the aim is to design a control law \( u \) which minimizes the impact of the vector \( w \) on the vector \( \rho \). In other words, to find gain matrices \( K_x \), \( K_f \) and \( K_I \) such that the closed-loop system (5)-(12) is stable. So, we propose to compute the gains \( K_x \), \( K_f \) and \( K_I \) using an \( H_{\infty} \) approach. The aim of calling the latter approach is to guarantee a mapping from \( w \) to \( \rho \) with an \( L_2 \) gain attenuation less or equal to the scalar \( \gamma \), with \( \gamma > 0 \) called the level of disturbance attenuation [4], [13],[2],[7], [17], and satisfies the following criterion:

\[
sup_{w \in L_2} \frac{\|\rho\|_2}{\|w\|_2} < \gamma, \quad \|w\|_2 \neq 0
\]

Let us consider the closed loop system described by the equations (15), for which we apply the Bounded Real lemma given in the appendix, we obtain the following result:

\[
\begin{bmatrix}
P_c A + A^T P_c & P_c B \\
P_c B^T P_c & -\gamma^2 I_3 \\
C^T P_c & C^T \gamma \\
C & -I \\
\end{bmatrix} < 0
\]

The resolution of this inequality will permit to get the gains matrices which will ensure the stability and \( H_{\infty} \) performance of the closed loop.

**NUMERICAL RESULTS**

We consider the following numerical values of the different parameters used in the heating house systems:
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{p,r}$</td>
<td>810 kJ/°C</td>
</tr>
<tr>
<td>$C_{p,f}$</td>
<td>3315 kJ/°C</td>
</tr>
<tr>
<td>$C_{p,w}$</td>
<td>836 kJ/°C</td>
</tr>
<tr>
<td>$(UA)_{ra}$</td>
<td>28 kJ/°C h</td>
</tr>
<tr>
<td>$(UA)_{fr}$</td>
<td>624 kJ/°C h</td>
</tr>
<tr>
<td>$(UA)_{wf}$</td>
<td>28 kJ/°C h</td>
</tr>
<tr>
<td>$p$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\eta$</td>
<td>3</td>
</tr>
</tbody>
</table>

The resolution of the inequality (17), gives the following gains matrices:

$$L_x = \begin{bmatrix} 1.8559 \\ 1.5766 \\ 0.3287 \end{bmatrix}$$

$$L_f = 1.4142$$

$$K_x = \begin{bmatrix} 6.6951 & 26.198 & 5.1903 \end{bmatrix}$$

$$K_f = 0.5$$

$$K_f = 0.56$$

with

$$P_o = \begin{bmatrix} 0.92797 & 0.78832 & 0.16435 & 0.70711 \\ 0.78832 & 2.7024 & 0.55738 & -4.73 \\ 0.16435 & 0.55738 & 31.53 & -11.67 \\ 0.70711 & -4.73 & -11.67 & 4972.8 \end{bmatrix}$$

$$Q_0 = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R = 0.5, \ \mu = 100, \ \gamma = 526.97$$

and the Lyapunov matrix $P_c$ is given by (18) in the next page.

**CONCLUSIONS**

Based on a modelisation of energy consumption of a given building in [9, 8], we proposed an observer based control law in order to generate a control law taking into account the environment effects represented by changes in ambient temperature and by radiation from the sun. The adaptive observer makes it possible to integrate into the control law, variables which are not measured, by their estimation. In future work, we intend to take into account several sources of energy, as well as the user’s feel. This will require defining objectives to optimize in order to take into account the way energy is generated and the user’s feels.

**KEYWORDS** Observer-based control, Fault tolerant control, Energy power systems, Heating house systems, Linear systems.

**REFERENCES**


$$P = \begin{bmatrix}
1.555e + 05 & 1.5789e + 05 & 57391 & -5190.2 & -1538.5 & 7378.6 \\
1.5789e + 05 & 9.6661e + 05 & 1.3909e + 05 & -15818 & -6728.3 & 21074 \\
57391 & 1.3909e + 05 & 3.5503e + 05 & -14010 & -16565 & 46263 \\
-5190.2 & -15818 & -14010 & 1120.8 & 660.45 & -2194.6 \\
-1538.5 & -6728.3 & -16565 & 660.45 & 1.2482e + 05 & -42592 \\
7378.6 & 21074 & 46263 & -2194.6 & -42592 & 4.0076e + 05 \\
1681.6 & 10926 & 6266.6 & -791.05 & -29359 & 1402 \\
-3602.1 & -9793.8 & -13223 & 981.21 & -52875 & -2.1882e + 05 \\
1681.6 & -3602.1 & 10926 & -9793.8 & -13223 & 981.21 \\
6266.6 & -13223 & -791.05 & 981.21 & -52875 & -2.1882e + 05 \\
-29359 & -52875 & 1402 & -2.1882e + 05 & 52906 & -2.1882e + 05 \\
4.7162e + 05 & -52906 & 3.2667e + 05 & 1681.6 & -3602.1 & 10926 \\
-52906 & 3.2667e + 05 & -9793.8 & -13223 & -791.05 & 981.21
\end{bmatrix}$$