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OVERVIEW OF FAULT DETECTION AND DIAGNOSIS METHODS APPLIED TO HVAC SYSTEMS

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Abstract. *This paper presents an overview on FDD (Fault Detection and Diagnostic) applications to HVAC (Heating Ventilation and Air-Conditioning) systems. An introduction to the subject is made, followed by a presentation of the different methods considered in the development of FDD systems. A discussion about the important faults taking place in HVAC plants and, in particular the analysis of sensor errors are also considered in the paper.*

Key-Words: *Refrigeration, Fault, Failure, Detection, Fault Diagnosis.*

1. INTRODUCTION

Energy use in buildings has an enormous impact on the economy and environmental quality. Buildings may use 36 % of the total energy production in a country, and primary energy use in it accounts for 8 % of global carbon dioxide emissions. Just in the USA, improving buildings energy efficiency about 30%, corresponds to eliminating the need for 80 new nuclear power plants (US Department of Energy, 1997).

Contribution for a better energy efficiency in buildings is expected from several fields, among them, FDD studies may play an important role, by improving the performance of a BEMS (Building Energy Management System). Increasing in energy savings is estimated between 10 to 15 %, if an adequate FDD protocol is operational (Usoro et al., 1985).

However, the intensive implementation of automatic control and optimisation schemes to HVAC plants is a tendency which has allow permanent monitoring and supervision for optimum performance conditions. As a result, we verify nowadays that people involved on the plant supervision, and is no more able like in the past, to actuate efficiently when the system presents a bad-functioning. This aspect combined with the fact that the BEMS itself can not adequately neither assist in finding the cause of a fault, nor react to it, leads to inefficient usage of energy and to uncomfortable working environment.

Fault detection and diagnosis, as a research domain, has its origins in the early 1970s as consequence of the increasing availability and decreasing cost of digital hardware and software. Most of the contributions were then given preliminary from fields like electronic and control engineering, where the initial motivation was the improvement in the safety operation of critical process such as space shuttle main engine (Cianek, 1986), NASA F-8 DFBW aircraft (Deckert et al., 1977). At same time, it was also started the use of direct digital control (DDC) to HVAC systems in buildings, which has result in the first operational BEMS applications leading to significant improvements in energy efficiency, as well as the appearance of a new architectural concept - the "smart building". However, just in the US, 80 percent of the commercial buildings were built prior to 1979 and contain obsolete energy systems (US Department of Energy, 1997).

Most of the references on FDD applications to HVAC considered in this text, arise from the work developed by the Annex 25 of the International Energy Agency (Hyvarinen & Kohonen, 1993).

2. FDD CONCEPT

The meaning of the word “fault” can be defined in different ways. In this text, we consider a fault as “an accidental condition that causes a system/component to fail to perform its required function”, or, “a defect that causes a reproducible or catastrophic malfunction”. Then, when a fault occurs, a deviation from “healthy” operational performance takes place, resulting in the anomalous system behaviour.

Usually, faults are detected by observing measurable variables from the system, and comparing them to certain expected values. Once a discrepancy, which can not be associated with the physical relationships involved in the process, is observed a possible fault has been detected. Next step refers to the fault diagnosis, i.e., giving a detailed explanation about the nature of the fault, its magnitude, location and cause.

Two basic approaches are considered in order to detect faults (Isermann, 1984) : (1) state variable estimation and (2) parameter estimation (Fig. 1). While parameter estimation is intended to monitor the process directly, detecting changes in parameters with respect to the theoretical ones (for the healthy process), the state variable technique considers the process parameters as known and try to monitor the signals.

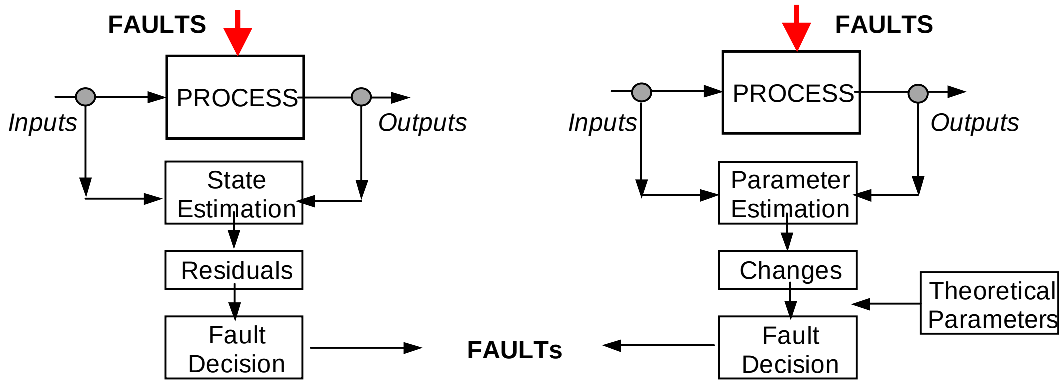

Figure 1 - Fault detection concept : state variables estimation (left) and parameters estimation (right).

The fault / no fault judgement based in the process measurable signals can be made by three main process (Rossi & Braun, 1992): (1) limit and trend checking, (2) prediction of signals and (3) analysis of signals. The first one correspond to a verification on absolute value and trend tendency with respect to previously defined threshold limits. Prediction of signals require the use of deterministic or mathematical modelling of the signals or processes. Analysis of signals refers to the taking into account of frequency variations by using methods such as auto correlation functions, spectral density or other methods of vibration analysis.

The modelling of the system healthy behaviour can be developed by means of different methods, as for example: simple-functions, physical models, black box identification, characteristic curves, etc. Each method has its specific advantages and drawbacks, depending on the point of view. Generally black box models produces a more accurate representation of system behaviour than physical models, but the lack of physical significance in the black box representation may lead to worst diagnosis capability than using a physical model.

With respect to the diagnosis of a detected fault state, the basic idea consists on the identification of the cause giving the best description for the observed discrepancies. Several techniques were proposed as convenient for the fault diagnosis, among them : knowledge-based classifiers, rule-based classifiers, statistical pattern recognition and association based classifier (Rossi & Braun, 1992).

The elementary functions and iteration of a FDD system inside a building supervision loop are shown at fig. 2 bellow. Traditionally control systems, as a part of every BEMS used in modern buildings, are dedicated to the task of maintaining the different process and components in the plant operating according to a previously defined strategy. Depending on the deviation from the desired objectives which is observed from the outputs, the control system will react changing the process inputs, in a convenient way.

In addition to the functions of the BEMS control module, fault detection and diagnosis modules are intended to the supervision of the healthy operation of the plant. In this sense, depending on the evaluation of the FDD results, a decision can be taken in order to change control strategy, stop operation or simply ask for the plant operator intervention.

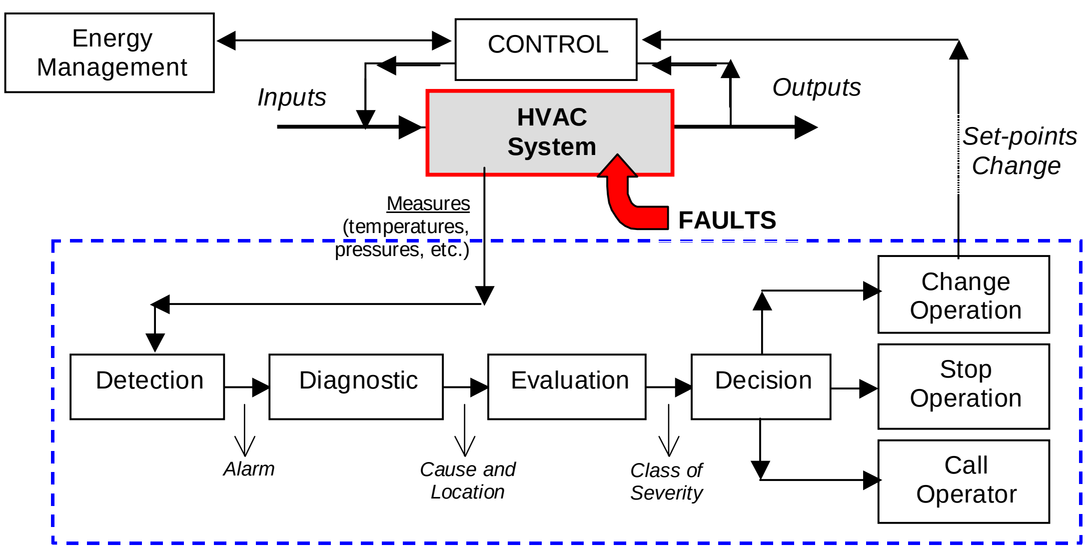

Figure 2 - Fault detection iteration within a BEMS supervision loop.

3. FDD APPROACH METHODS

Two general approaches can be considered for the functional form of a process: *physical* and *black-box* models. Physical models makes use of mathematical laws providing the functional relationships between the process driving inputs and outputs via its parameters and internal state. In a black-box model the process considered as a “box” containing unknown physical laws which can not be directly observed, but only approximated by adequate fits to experimental observations of its input/output.

3.1 Polynomials

Also called characteristic curves, there are a kind of black box commonly used to describe static input/output relationships, defined by characteristic curves, with for example a linear time invariant representation given by :

$$y(t) = a_0 x_0 + a_1 x_1 + \cdots + a_n x_n + e(t) \tag{1}$$

where the stochastic variable *e(t)*, is normally assumed to be a white noise, allowing to apply a linear regression to obtain the coefficients in equation above.

Grimmelius et al. (1995), have identified regression models from experimental data representing the healthy evolution of each variable on a chilling test bench, using them for FDD purposes. They used polynomials in order to predict the healthy operational conditions of a chiller unit, based in regression models derived from over 8000 experimental data sets, demonstrating the possibility of diagnosing faults. The diagnostic approach considered is based on the pattern recognition, which analyses by comparison with a knowledge data base the probability of occurrence of one of the pre-defined faults.

Madjidi (1994) has presented a study about the changes in energy consumption and comfort, due to the influence of faults in a VAV system, like : clogging filter, defective sensor, fouled coil and defective pump. Some components were modelled by means of polynomials fits based in their characteristic curves.

Rossi and Braun (1994) used a steady-state quadratic model, in order to detect and to diagnose faults like: refrigerant leakage, compressor valve leakage, flow restriction and condenser or evaporator fouling. Such faults were previously modelled and statistical pattern recognition was used to indicate the fault model giving the better explanation to the deviation between the plant and the model.

3.2 ARMAX models

Consists on Auto-Regressive Moving Average time-series with a general black box structure having the following form :

$$A(q)\, y(t) = \{[B(q) - 1]/F(q)\} u(t) + [C(q)/D(q)] e(t) \tag{2}$$

where *y(t)* and *u(t)* are the model scalar input and output signals respectively, *A(q), B(q),C(q)*, and *D(q)* are polynomials *P(t)* in the form :

$$P(t) = 1 + \mathrm{p}_1 q^{-1} + ... + \mathrm{p}_{\mathrm{np}} q^{-np} \tag{3}$$

with *np* indicating the order of each polynomial, and *q* the forward shift operator.

According with the polynomials used in equation (2), different model structures are defined, for example : AR(A), ARX(A and B), ARMA(A and C), ARMAX(A, B, and C), etc. The most simply simple input-output relationship is given by an ARX model, which from equs. (2) and (3) has the form :

$$y(t) + a_1 y(t-1) + ... + a_{\mathrm{na}} y(t - n_a) = b_1 u(t-1) + ... + \mathrm{b}_{\mathrm{nb}} u(t - n_b) + e(t) \tag{4}$$

which can be built from experimental inputs *u(t)* and outputs *y(t)*, by means of the identification of a parameter vector in the form :

$$\Theta = \left[a_1 .... a_{\mathrm{na}}\, ; b_1 .... \mathrm{b}_{\mathrm{nb}}\right]^T \tag{5}$$

Yoshida (1992a), has applied an ARX model in order to predict the heat load of an AHU unit linked with a thermal storage tank. Four system faults that were verified coincidentally 1) energy loss by door opening, 2) too high chilled water temperature, 3) malfunction of room temperature thermostat, and 4) malfunction of on/off control of pumps. Propositions for the detection of faults were given later (Yoshida & Iwami, 1994) with focus on the influence of a random input (temperature fluctuations inside a room) on the model response. The constant opening at the VAV unit was considered as the faulty condition, and two methods of detection were applied : summation of the residues square and auto-correlation of residues.

Vaezi-Nejad et al (1992) presented two methods using auto-regressive models. These methods were applied in order to detect two kind of faults : 1) a magnetic perturbation in an flow sensor and 2) an window left open in a room. In the first example an AR long model was used in order to predict spectral density variations in the sensor signal which was checked by means of a sequential statistic mean test (Page-Hinkley test). In the second example, the room was represented by an ARX model. Two fault detection methods were proposed to detect the open window : parameters test and residues test.

Pakanen (1992) developed an multi-input single output (MISO) ARMAX model to predict the power consumption fluctuation of a building and has considered the applicability of such model when an abrupt change of power occurs. His conclusions are the following : 1) large differences between actual and calculated results may occur without any noticeable failure in the system; 2) the fault symptoms must be known in order to develop detailed methods for detecting and locating different kinds of faults.

3.3 Artificial neural networks (ANN)

Its a relatively new technique, which consists in the development of a structure containing two or more layers of nodes (neurones), disposed in rows forming a network in direct analogy to what is thought to be the structure of the human brain.

In the network each neurone receives from other neurone (or from outside) a number of activating signals x_j , being able to produce a single output S_i sent to other neurones (or to exterior). Each activating signal is multiplied by specific weights w_{ij} for each synapse (linking connections among neurones), and summed to produce an activating potential Pi, given by :

$$P_i = \sum_{j=1}^{n} W_{ij}\; x_j \tag{6}$$

which is first compared with a threshold W_0 and then submitted to an activation function F, as for example the so-called sigmoide function bellow :

$$F(P_i, W_0) = \left[1 + e^{-(P_i, W_0)}\right]^{-1} = s_i \tag{7}$$

which then produces the neurone output signal $s_{i.}$

Increasing interest on ANNs application to FDD tasks is due to the fact that ANNs presents particular advantages (Farley & Varhol 1993) like : the ability to “learn” from past data (training process); its effectiveness when modelling complex non-linear process; can be developed quite easily by means of available neural-net software’s; can be used as an useful classification method and for prediction.

ANNs are being considered more and more as a good approach for solving different problems, as for example : measurement of wind speed and direction (Farley & Varhol, 1993), FDD in heat pumps (Stylianou & Legault, 1993), fouling, bad tuning, bad combustion, etc., at heating units (Li et al, 1994).

3.4 Fault trees

Quite similar to ANNs, fault trees consists on a sort of network which interconnects the symptoms observed in a plant with the corresponding failures.

Building a fault tree depends exclusively on the available expert knowledge associating a specific failure with different symptoms. Each symptom node in the tree is triggered from the output of the preceding node and has two possible outputs depending if the symptom is observed or not. Then there is a path through the decision tree from the starting point to the fault which is related with the set of symptoms associated with the fault.

Afgan et al. (1994) have considered the application of an expert system for FDD applied to a small refrigerating machine using a fault decision tree connecting 21 characteristic symptoms with 18 frequent failures like for instance, refrigerant leakage, defective compressor valve, etc.

3.5 Fuzzy models

As ANNs, fuzzy models are used in the case of complex system when it is difficult to obtain a good function describing the relationships between inputs and outputs. Fuzzy models are composed by sets of IF-THEN rules which can be determined from experts or from identification using experimental data. Different reference fuzzy models can be developed, allowing to associate each reference model with a possible fault.

Studies considering the application of fuzzy models for FDD in air handling units (AHU) were mainly developed by Dexter and Benouarets (1996), Maruyama (1998). Basically, fuzzy models were developed and applied in order to evaluate their feasibility to detection and diagnosis of fouling in the inside (water-side) surface of cooling coils tubes. Comparative analysis considering the performance of fuzzy, ANN and hybrid (combining fuzzy and ANN) models, when submitted to the fault described, was made concluding in essence that : generic reference models, based on expert qualitative knowledge, are useful when other methods like fuzzy an hybrid are not available; hybrid reference models can produce similar results to ANN but requires less computing effort during training.

3.6 State estimation

These are observer based models with a general mathematical structure presented as a discret form of the state of the system in time, as a function of its inputs and outputs. For the fault free case, we have :

$$\begin{cases} x(k+1) = A\,x(k) + B\,u(k) + v(k) \\ y(k) \quad = C\,x(k) \qquad\quad + w(k) \end{cases} \tag{8}$$

where x is the state vector v and w are linear transformations of the unknown disturbances, and A, B, and C are known matrices of appropriated dimensions. The observer, or Kalman filter approach (when faults actuate in the system), can be described, and combined with equ. (8), resulting on estimated state $x(t)$ and output $y(t)$ vectors. The state and output estimation errors are then given by :

$$\dot{\varepsilon}(t) = A\varepsilon(t) + Ev(\mathrm{t}) + Kf(t) - H[C\varepsilon(t) + Fv(t) + Gf(t)] \tag{9}$$

$$e(t) = C\varepsilon(t) + Fv(\mathrm{t}) + Gf(t) \tag{10}$$

therefore, vector $e(t)$ can be used as an indicator of faults because it depends only of the vector f and of the vector of unknown inputs v.

Analysis of the suitability of state estimation observer based models for FDD applications have demonstrated that such approach presents considerable drawbacks, as for example : the difficulty in solving non-linear problems, the great computational effort necessary to develop some complicated aspects, and the needs of introducing many assumptions and gross simplifications (Sprecher 1992, Stylianou 1993).

3.7 Other developments

Other methodologies like energy signatures method (Sprecher,1993; Visier, 1993), topological based modelling (Tsutsui et al. 1993), fault direction method (Hong et al 1994), and qualitative modelling approaches, simplified physical analysis (Pimenta, 1996 and 1997), were also proposed as having a potential for FDD on HVAC systems.

Moreover, methods combining different techniques such as time-frequency FFT analysis, non-stationary AR models, pattern recognition and ANN (Bardou et al, 1993), ARMAX and ARX models with both SISO and MIMO structures and Kalman filter recursive identification (Lee et al ,1994), were also investigated.

4. IMPORTANT HVAC FAULTS, ITS DETECTION AND DIAGNOSIS

In spite of the methodology adopted, one of the first steps in FDD design is the definition of the set of faults to be detected. Such faults should be selected according frequency of occurrence, repercussions on performance, available instrumentation, etc. In few words, for a given installation, the most important faults to detect are those which occur quite frequently, result in serious damages and/or significant energy consumption and can be modelled with an acceptable level of difficulty, and the instrumentation available. Moreover, it is interesting to note that a faulty condition in a plant or component can be derived from different sources, (Yoshida, 1996) such as : design, construction, control, commissioning, maintenance or users.

A convenient way to define the set of faults to detect is to develop a preliminary research in the form of questionnaire to experts (people involved in management, maintenance, etc.) in order to detect the typical faults taking place during the operation of the plant and the different symptoms which are associated. Schiel, (1991), Nakahara (1992), Yoshida (1992 b and 1996), Kelly (1991), Peitsman et al. (1992) Sagara et al. (1996), etc.

Once a list of the interesting faults to detect is defined, it is necessary to study their cause effect relationships in order to understand how the system behaviour may be affected when such faults are taking place. This is a crucial phase to attain a successful diagnostic.

Three common faults taking place in refrigeration installations are hereafter considered: measurement errors, refrigerant abnormal charge and heat exchanger fouling.

4.1 Anomalous sensors

Special attention must be paid to the possible occurrence of faults, affecting the sensors in a plant. Since the signal from sensors are used for control, monitoring and diagnosis, it follows that if a sensor fails and provide incorrect readings the system performance will be adversely affected. It might result in a incorrect control action, leading to a degradation in performance. It might result in incorrect diagnosis, leading to unnecessary repair and loss of productivity while the system is down for repairs.

Kao et al. (1983) have considered the use of a computer simulation in order to examine the effects of sensor errors on building energy consumption. Their results, for an office building where sensors of the automatic control of an AHU are affected by errors, indicates that an increase in the annual energy requirements between 30 and 50 % may occur.

A model-based approach to handle sensor failures and to provide optimum sensor allocation during diagnostic was proposed by Misra (1994).

4.2 Refrigerant abnormal charge

Abnormal refrigerant charge may occur due to a fault at the design stage (bad specification of the optimum refrigerant charge) during maintenance (inadequate correction of the refrigerant charge), or, quite often, due to occurrence of a refrigerant leakage (holes in tubing, poor connections and fittings, damage in gaskets, etc.).

Even if a premature detection of a refrigerant leak can be obtained by means of specific appropriated instruments for monitoring like IR (infrared) and CMOS (ceramic metal oxide semiconductor), the use o such hardware means an additional cost for the plant between 3000 and 7000 US$ (Sorensen, 1996).

The influence of the charge of refrigerant on the performance of refrigerating systems was studied by Farzad and O'Neal (1994) by means of a comparative study between different void fraction models, with emphasis on the estimation of system performance variables under different conditions of charge. The effects on superheating and subcooling degrees, refrigerant mass flow rate, refrigerating capacity, power consumption and COP, were modelled and compared against experimental results for charge variation between ± 20 %. The main remark is that the decreasing in both COP and refrigerating capacity is more significant when the charge is bellow its optimum value. Moreover, superheating degree is more affected by charge change than subcooling degree.

Stylianou (1996), have considered the different symptoms observed in practice when a chiller or heat pump presents a lack of refrigerant, which was defined as: low suction and discharge pressures, low compressor capacity (insufficient cooling) and high compressor discharge temperature.

4.3 Heat exchanger fouling

Fouling (also called scale) is the undesired accumulation of solids on heat transfer surfaces, resulting in the formation of a layer which represents an additional resistance to heat transfer, which reduces the heat exchanger performance.

General *causes* of fouling formation are commonly associated with one or more of the following mechanisms : precipitation fouling, particulate fouling, chemical reaction fouling, corrosion fouling, biological fouling and freezing fouling (Rohsenow et al., 1985).

As a result of the reduction in the heat exchanger performance, the main *symptom* of fouling occurrence in condensers and evaporators may be associated with the change in the outlet refrigerant temperatures, i.e., with the reduction of subcooling and superheating degree. Other symptoms of fouling action are related with the increase in the friction factor, due to the increase of the tube surface roughness, which will increase the pressure drop, reducing the flow rate and requiring more pumping power to maintain the same conditions.

Generally, designers includes some allowance factor taking into account the action of fouling during the heat exchanger operation, such that a reasonable period of operation can be maintained between shutdowns for cleaning. Therefore, in most practical applications, fouling must be considered as a normal occurrence during the exchanger life and an appropriate maintenance schedule can be previously established for cleaning at regular time intervals.

Nevertheless, fouling can become a faulty condition when its influence increases above some acceptable level, due to a bad water quality, which will anticipate the shutdown of the heat exchanger for cleaning, sooner than previewed.

5. CONCLUSIONS

Interest on FDD methods applied to HVAC systems has produced a lot of research work during the last decade. This paper presented an overview of the different methodologies considered until now, which intends to give to the reader a preliminary view on the subject. Development of FDD systems applied to actual building plants requires much more efforts in next years.

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