

AIN SHAMS UNIVERSITY  
FACULTY OF ENGINEERING  
COMPUTERS AND SYSTEMS ENGINEERING DEPARTMENT

KNOWLEDGE-BASED SYSTEM FOR FAULT DETECTION  
AND DIAGNOSIS IN INDUSTRIAL CONTROL SYSTEMS

BY

ENG. MOSTAFA MAHMOUD MAHMOUD GOMAA

This is submitted in partial fulfillment of the requirements

for the degree of

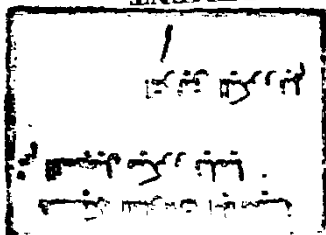
MASTER OF SCIENCE  
IN  
ELECTRICAL ENGINEERING

UNDER SUPERVISION OF

PROF. DR. M. A. SHEIRAH  
DR. MANAL M. ZAKI  
DR. HESHAM M. FARAG



1993



***TO MY PARENTS & WIFE***



## STATEMENT

This dissertation is submitted to Ain Shams University for the degree of Master of Science in Electrical Engineering.

The work included in this thesis was carried out by the author in the Department of Computer and Systems Engineering, Ain Shams University, from December 1990 to April 1993.

No part of this thesis has been submitted for a degree or qualification at any other university or institution.

Date : 24/4/1993

Signature : Mostafa Mahmoud

Name : Mostafa Mahmoud Mahmoud Gomaa

## ACKNOWLEDGEMENT

I would like to express my deep respect and gratitude to **Prof. Dr. M. A. Sheirah** for his kind supervision, guidance, and valuable remarks. Without his advice and support, it would not have been possible to complete this work. I will always be thankful to him.

Also my sincere thanks and appreciation to **Dr. Manal M. Zaki** and **Dr. Hesham M. Farag** for their unfailing support and continuous encouragement.

I would also like to thank heartily **Prof. Dr. A. M. Wahdan** and **Prof. Dr. O. Badr** for their encouragement and assistance in presenting this thesis.

## ABSTRACT

During a process control system operation, some fault may occur in some component in the overall system which may lead to dangerous results (e.g. a nuclear reactor) or loss of the operating conditions that may take a large time to be recovered. So, a fault detection and diagnosis system, which early detects, identifies, and evaluates the fault and may give advisory action to the process operator to isolate such fault before its effect increases before recovery, is needed.

A survey on the existing techniques for fault detection and diagnosis is made. A new methodology for fault detection and diagnosis (FDD) in industrial control systems is suggested and applied through the thesis where, a Knowledge-Based System for FDD is made which consists of three stages. The first stage is fault free control system modelling using a new proposed modelling methodology that is Modelling with Uncertain parameters and Incomplete Knowledge (MUPIK). The second stage is fault detection through comparing the actual control system status with its status predicted by MUPIK. The third stage is Adaptive Knowledge-Based Diagnostic System. The diagnostic system gives the operator list of the different possible faults each with a corresponding Confidence factor using inference through a rule-base for the control system. The diagnostic system presents to the operator the following facilities: explanation of the diagnosis, advisory actions, ability to add or modify the

rule base and some parameters of the system used during MUPIK, and others.

The proposed technique is formulated within the (KADS) Approach to modelling a Knowledge-Based System where a conceptual and design models are made. The suggested FDD technique was tested by being applied to computer models of a simple hypothetical control system and a complex control system of the Binary Distillation Column where the occurrence of some faults have been simulated. The suggested FDD technique was able to detect and diagnose the faults simulated to occur in both control systems.

## SYMBOLS AND ABBREVIATIONS

### Symbols:

- A : Continuous state space form coefficient matrix of the state vector.
- B : Bottom product flow rate in the distillation column in lb-mole/hr.
- C : Continuous state space form coefficient matrix of the state vector in the output equation.
- $C_p$  : Heat capacity.
- $C_v$  : Valve constant.
- D : Distillate flow rate in the distillation column in lb-mole/hr.
- E : Continuous state space form coefficient matrix of the input vector.
- e : Error signal in a control system.
- $\underline{e}$  : Measurements error vector.
- F : Feed flow to the distillation column in lb-mole/hr.
- $h_l$  : Liquid enthalpy in BTU/lb-mole.
- $\delta h_l$  : Liquid enthalpy change.
- $\underline{h_l}$  : Vector of liquid enthalpia on every tray in the distillation column
- H : Holdup in the condenser drum in lb-mole.
- $H_v$  : Vapor enthalpy in BTU/lb-mole.
- $\delta H_v$  : Vapor enthalpy change.

- $\underline{H}_v$  : Vector of vapor enthalpia on every tray in the distillation column
- $I$  : Current in mA.
- $K$  : Static gain.
- $K1$  : Minimum value of the static gain range.
- $K2$  : Maximum value of the static gain range.
- $\bar{K}$  : The nominal value of the static gain.
- $k$  : Number of the sampling period.
- $L_i$  : The liquid flow rate effluent from the tray(i) in the distillation column in lb-mole/hr.
- $\underline{L}$  : Vector of the liquid flow rates effluent from the trays.
- $N$  : The number of trays in the distillation column.
- $n$  : The number of delay samples.
- $P$  : Pressure in N/m
- $P_k$  : Percentage of the static gain uncertainty.
- $q$  : The leakage heat flow rate from the distillation column base in BTU/hr.
- $Q_i$  : Heat flow rate input to the column base. (Reboiler heat duty).
- $R$  : Reflux ratio.
- $R_r$  : Required reflux ratio.
- $R_{rfx}$  : Required reflux value.
- $r$  : A set point to a controller in percentage.
- $rfx$  : Reflux flow rate in lb-mole/hr.
- $T$  : Sampling period.
- $T_f$  : Feed flow temperature in C.
- $T_m$  : A temperature in C.
- $\underline{T}_m$  : Vector of temperature at each tray in the distillation column.

#### IV

- $u$  : A module's input.  
 $\bar{u}$  : The nominal value of (u).  
 $\hat{u}$  : Incremental value of (u).  
 $\underline{u}$  : Vector of a system inputs.  
 $V_i$  : The vapor flow rate rising up from the tray(i) in the distillation column in lb-mole/hr.  
 $\underline{V}$  : Vector of the vapor flow rates rising up from the trays.  
 $X$  : Input/output matrix that is used in process parameters estimation.  
 $X_d$  : Distillate concentration.  
 $X_i$  : The concentration of the more volatile component in liquid effluent from tray (i) in the distillation column  
 $X_f$  : The concentration of the feed flow to the distillation column.  
 $X_v$  : The vector of concentration of the more volatile component in liquid effluent from each tray  
 $\hat{X}$  : The estimated state vector.  
 $y$  : A module's output.  
 $\hat{y}$  : Incremental value of (y).  
 $\bar{y}$  : nominal value of (y).  
 $y_i$  : The concentration of the more volatile component in vapor rising up from tray (i) in the distillation column  
 $\underline{Y}_v$  : The vector of concentration of the more volatile component in vapor rising up from each tray.  
 $\tilde{y}$  : Residual output vector.

- $\tau_2$  : Time constant.  
 $\tau_d$  : Dead time.  
 $\alpha$  : Firing angle.  
 $\phi$  : Discrete state space form coefficient matrix of the state vector.  
 $\Gamma$  : Discrete state space form coefficient matrix of the input vector.  
 $\beta$  : Measurements vector used in the process parameters estimation.  
 $\underline{\theta}$  : The process parameters vector.  
 $\hat{\underline{\theta}}$  : Estimated parameters vector.  
 $\xi$  : Feedback gain matrix of the state variables.  
 $\psi$  : Total number of modules.  
 $\omega$  : Total number of rules in a module.  
 $\Sigma$  : Total number of components in a module.

### **Abbreviations:**

- CC : Concentration controller.  
 C.ct. : Conditioning circuit.  
 Cf : Confidence factor.  
 CT : Concentration transmitter.  
 DEC : Decrement.  
 DIFF : Differentiation.  
 DPT : Differential pressure transmitter.  
 FC : Flow controller.

FDD	: Fault detection and diagnosis.
Finval	: Final value a module's output aims to reach.
FT	: Flow transmitter.
GLSE	: Generalized least squares estimation method.
IQ	: Incremental quantity.
INC	: Increment.
INTEG	: Integration.
I/P	: Current to pressure converter.
JC	: Power controller.
KBS	: Knowledge-Based system.
LSE	: Least squares estimation method.
Maxval	: Maximum value a module's output aims to reach.
Minval	: Minimum value a module's output aims to reach.
MSLS	: Multi-stage least squares estimation method.
MUPIK	: Modelling with uncertain parameters and incomplete knowledge.
Op	: A module's output.
Op <sub>prev</sub>	: A module's output in the previous sampling period.
QS	: Qualitative state.
qval	: Qualitative value.
TC	: Temperature controller.
TT	: Temperature transducers.

## LIST OF FIGURES

	Page
FIG. 2.1 FDD approaches.	7
FIG. 2.2 FDD based on modelling and tracking.	17
FIG. 2.3 FDD based on Qualitative modelling.	20
FIG. 2.4 Qualitative structural description of the simple heat flow system.	23
FIG. 3.1 A first order module with dead time.	28
FIG. 3.2 Incremental step response of a first order module with a dead time.	32
FIG. 3.3 Response to a sinusoidal input.	34
FIG. 3.4 Response to underdamped input.	35
FIG. 3.5 Incremental step response of a first order module with a dead time and uncertain gain.	38
FIG. 3.6 Response to a sinusoidal input in case of uncertain gain.	40
FIG. 3.7 Response to a square input in case of uncertain gain.	41
FIG. 3.8 A module consisting of more than one component in cascade.	42
FIG. 3.9 Incremental step response of a module consisting of more than one component in cascade with uncertain gain.	43

FIG. 3.10 Incremental step response of a module consisting of a component that exhibits underdamped response.	45
FIG. 3.11 Needed information of a module for (MUPIK).	46
FIG. 3.12 Summary of (MUPIK).	48
FIG. 4.1 Decomposition of a troubleshooting task.	53
FIG. 4.2 Analysis of cooperation in KADS.	54
FIG. 4.3 An inference structure for time-dependent plan execution.	58
FIG. 4.4 An inference structure for diagnosing faults in an audio system.	58
FIG. 4.5 A task tree for the time-dependent plan execution.	59
FIG. 4.6 A task tree for systematic diagnosis.	60
FIG. 4.7 Decomposition of knowledge engineering task.	62
FIG. 4.8 A thermal system, as an example of control systems.	63
FIG. 4.9 Structure of a control system .	67
FIG. 4.10 Inference structure for fault diagnosis task in process control systems.	74
FIG. 4.11 Task tree for fault diagnosis task in process control systems.	75
FIG. 4.12 Effect of noise addition on obtaining finding in case that, $Op_{prev}$ is lower than $Minval$ .	79
FIG. 4.13 Effect of noise addition on obtaining finding in case that, $Op_{prev}$ is larger than $Maxval$ .	80
FIG. 4.14 Effect of noise addition on obtaining finding in case that, $Op_{prev}$ is lying between $Minval$ and $Maxval$ .	82
FIG. 4.15 Simple control system block diagram.	94

FIG. 4.16 System behavior during test #1 applied to the simple control system.	104
FIG. 4.17 System behavior during test #2 applied to the simple control system .	105
FIG. 4.18 System behavior during normal operation.	106
FIG. 5.1 A staged-wise distillation column structure.	109
FIG. 5.2 A packed prototype distillation column system.	112
FIG. 5.3 Feed flow rate control loop.	114
FIG. 5.4 Feed flow temperature control loop .	115
FIG. 5.5 Bottom heating power control loop.	116
FIG. 5.6 Distillate flow rate control loop.	116
FIG. 5.7 Distillation column schematic diagram.	120
FIG. 5.8 Block diagram of the distillation column.	121
FIG. 5.9 I/P converter block diagram.	124
FIG. 5.10 Reflux valve position in the column control system.	125
FIG. 5.11 Reflux valve block diagram.	127
FIG. 5.12 Conditioning circuit block diagram.	128
FIG. 5.13 Heater block diagram.	129
FIG. 6.1 Column inputs and outputs.	146
FIG. 6.2 Column block diagram, D as an output.	147
FIG. 6.3 Column block diagram, Xd as an output.	147
FIG. 6.4 The transfer functions of the distillation column.	148
FIG. 6.5 Faults and disturbances simulation <b>examples</b> .	156
FIG. 6.6 Parameters adjustment of the I/P converter plus valve module.	162
FIG. 6.7 The interaction between the KBS and the operator during test #1 applied to the simplified binary distillation column.	170