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FAULT ANALYSIS OF PROCESS SYSTEM USING MULTI BLOCK PRINCIPAL COMPONENT ANALYSIS

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Abstract

This research looks into the issues of the quality improvement based on process control instead of product control using multivariate statistical process control. A deterministic model of a Proton Exchange Membrane Fuel Cell (PEM-FC) power plant was used as a case study to represent a multi variable and multi equipment system. A three-step approach is proposed which can be classified into fault detection, fault isolation and fault diagnosis. The fault detection and the isolation utilise the multivariate analysis and the control chart methods, which uses the series multi-block principal component analysis as extended of PCA method. The Series Block Principal Component Analysis is solved using the Non linear Iteration Partial Least Squares (NIPALS) algorithm. The SB-PCA can advantageously incorporate the control chart, namely, T^2 Hotelling control chart. In the fault diagnosis step, the Normalised Variable method was successfully applied in this study with promising results. As a conclusion, the results of this study demonstrated the potentials of multivariate statistical process control in solving fault detection and diagnosis problems for multi variable and multi equipment system.

Key words: *statistical process control; principal component; fault analysis*

Abstrak

Penelitian ini mengkaji permasalahan yang berhubungan dengan perbaikan kualitas pada pengendalian proses sebagai alternatif dari kualitas produk dengan menggunakan multivariate pengendalian proses statistik. Model Proton Exchange Membrane Fuel Cell (PEM-FC) digunakan sebagai studi kasus yang menggambarkan sistem dengan bentuk multi variabel dan "multi equipment" Tiga tahap pendekatan yang diajukan pada peneltian ini yang selanjutnya diklasifikasikan dengan nama deteksi, isolasi dan diagnosa ketidak normalan dalam proses. Pendeteksi dan isolasi ketidak normalan dengan menggunakan analisis multivariate dan metoda "control chart" yaitu Series Multi block principal component analysis (SB-PCA) yang merupakan pengembangan dari metoda PCA. Penyelesaian dari SB-PCA menggunakan algoritma Non linear Iteration Partial Least Squares (NIPALS). SB-PCA ini mempunyai keunggulan dalam mengintegrasikan "control chart, yaitu T^2 Hotelling contraol chart. Pada tahap diagnosa ketidak normalan maka metoda normalisasi variabel cukup sukses untuk diaplikasikan pada sistem ini. Sebagai kesimpulan, hasil dari studi ini menunjukkan bahwa multivariate statistical process control mempunyai potensi yang cukup baik dalam menyelesaikan permasalahan dalam mendeteksi dan mendiagnosa ketidak normalan pada sistem multi variabel dan "multi equipment".

Kata kunci: *analisa ketidaknormalan;* pengendalian proses statistik; *principal component*

Introduction

Based on the ISO 9001: 2000, the quality improvement should be applied in industry, not only quality control. It means, the quality approach based on process control instead of product control. The process control prevents change from any disturbances. Therefore, it would have detected any problem (faulty condition) within the process. Conventionally, the problem (fault) in the process is detected and diagnosed by plant operators. They will employ their human senses (e.g., sight, hearing, smell and touch) to continuously check whether a process is working properly. Human errors are inevitable for routine jobs; a computer on the other hand has definite advantages over the human operator in performing routine work even though the diagnosis cannot be taken over completely by the computer. This leads to the need for appropriate allocation of tasks between man and computer, leading to an optimum use of resources. Therefore, the faulty analysis is an integral part for a successful process operation in the industry.

A process is considered to operate normally (without significant fault) if its observed variables are in the range of their desired values (Hoskins, *et. al*,

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1991). The "range" word is highlighted because the variation value appears in the measured variable. The variation occurs in all things, regardless of the product or process. It can be grouped into two types: common causes and special causes. The common causes of variation seem to be built-in to the process. In other hand, the special causes are due to acute or short term influence that are not normally a part of the process as it was designed or intended to operate. Thus, continuous analysis of the variation during plant operation is useful in monitoring the state of a system. The science of analysing data variation is known as statistics and it is a potentially powerful tool in carrying out the task of fault analysis in a process system.

A statistical method for monitoring, isolating and removing unnatural events in order to control or to improve a process is known as statistical process control (Watson, et. al, 1993). The objective of this research is to combine the statistical process control (SPC) technique and the Fault Analysis method. The SPC is emphasised on the quality of product, while Fault Detection is focused on the characteristics of equipment performance. Therefore, the Fault Analysis using SPC should maintain the product quality; on the other hand, it can reduce the sudden occurrence of disruptive equipment damage and personal accidents.

Methodology

The philosophy of this methodology is to maintain the process at its best condition. This situation is possible by keeping the variation of the process variable around the neighbourhood of the desirable condition. This variation cannot be eliminated but it can be reduced or kept in the acceptable range. If variation of the variable value departs from the acceptable range, it means the faulty condition exists in a process. This event should be detected and diagnosed to rectify the faulty condition and bring the process to the normal condition. This methodology is based on the control chart presentation as a part of the Statistical Process Control. Generally, a control chart observes only the characteristic of quality or output process. It is inadequate for large or complex system. Thus, development of the control chart to **detect and diagnose** the faulty condition in the complex system is desirable. The complex system usually consists of multi-input and multi-output variables. These variables should be manipulated in order to be applied on control chart to capture general system characteristic. In brief, two procedures should be carried out in this methodology: first, the multi-variable data reduction, this procedure obtains the simple data without loosing highly essential information. The second, the procedure makes the conclusion based on the previous procedure (multi-variable data reduction). The development of multivariate methodology only needs input, intermediate and output data of the process system, but their relations (as dependent and independent variable) are not known. For that reason, the multivariate procedure is based on the interdependency method, such as Principal Component Analysis (PCA). Multivariate results are analysed using control chart. The control chart should be displayed in a simple graph for easier interpretation if the faulty condition occurs.

Fault can be classified into two types: external fault and internal fault. The external fault is the faulty condition when the Out of Control (OC) Condition is caused by external equipment change, for example: change of input flow-rate, concentration and temperature. On the other hand, the internal fault is the faulty condition that is caused by change of equipment characteristic (equipment degradation), for example: heat transfer coefficient

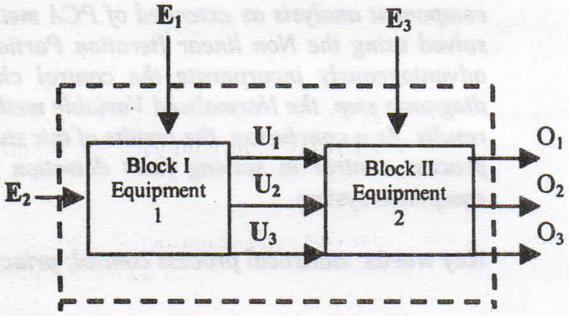


Figure 1. Input–Output connection describes External and Internal Fault relation

Figure 1 shows the distinction between the external and the internal fault. The process system, which is indicated by the dotted line, has two equipment. Based on Figure 1, input parameters of the system are denoted by E_1, E_2 and E_3. The symbol O_1, O_2 and O_3 are output of the system. The interconnection parameters between the blocks are expressed by U_1, U_2 and U_3. The faulty condition is called *external fault* if the value(s) of E_1 or E_2 or E_3 (Figure 1) change exceeds the control limits. If the value of the variance of E_1 or E_2 is over the limits, then the value of U_1 and or U_2 and or U_3 and the value of O_1 and or O_2 and or O_3 will change over the limits. It means, the *external fault* is caused in the first block. When the *external fault* occurs on second block, the value of E_3 is over the limits. Then, the value(s) of O_1 and or O_2 and or O_3 will change over the limits, but the value of U_1 and or U_2 and or U_3 do not change.

In brief, the Fault Detection and Diagnose using Multivariate Control Chart methodology can be divided into several parts of the procedure:

1. Preliminary procedure.
2. Detect faulty condition in the total system by Control Chart Multivariate procedure.
3. Isolate the Out of Control (OC) points and detect the cause of fault using Variable Contribution procedure.

Evaluation of Fault Analysis in PEM-FC plant

In this case, the PEM-FC (Proton Exchange Membrane Fuel Cell) as a multi-equipment system was used to evaluate the procedure proposed. The dynamic process system model was developed using basic mass and energy balance equations. The simulation model results ware utilized to imitate the real plant data. The simulation model was applied to perform "Fault Analysis using multi block Principal Component Analysis".

In order to test the fault analysis procedure, fifteen faulty conditions were inserted in the PEM-FC system data. The faulty type and description can be seen on Table 1.

Table 1. Fault simulation summary for PEM-FC plant

Block	FN	FT	Fault Description
I	S11	E	Conc. Of CH_4 + 0.5% from steady state
	S12	E	Conc. Of CH_4 - 0.5% from steady state
	I11	I	Heat Transfer coefficient – 0.5%
II	S21	E	Coolant flow-rate +0.5% from steady state
	S22	E	Coolant flow-rate -0.5% from steady state
	I21	I	Heat Transfer coefficient – 0.5%
III	I31	I	Heat Transfer coefficient – 0.5%
IV	S41	E	Coolant flow-rate +0.5% from steady state
	S42	E	Coolant flow-rate -0.5% from steady state
	I41	I	Heat Transfer coefficient – 0.5%
V	S51	E	Temperature Absorbent +0.5% from SS
	S52	E	Temperature Absorbent -0.5% from SS
VI	S61	E	Temperature Air +0.5% from SS
	S62	E	Temperature Air -0.5% from SS
	I61	I	Reaction frequency (catalyst) – 0.5%

Remark: FN= Fault Name; FT= Fault Type

Results of the fault analysis procedure are illustrated only one type of external fault and internal fault, respectively. According to Figures 2, the cumulative T^2 Hotelling control chart using SB-PCA can detect the faulty point precisely. The presentation of the cumulative T^2 Hotelling control chart is relatively simple compared to the 3D rectangular control chart. In addition, the cumulative T^2 Hotelling control chart correlates their values to the point observations. Thus, the faulty point can be observed directly.

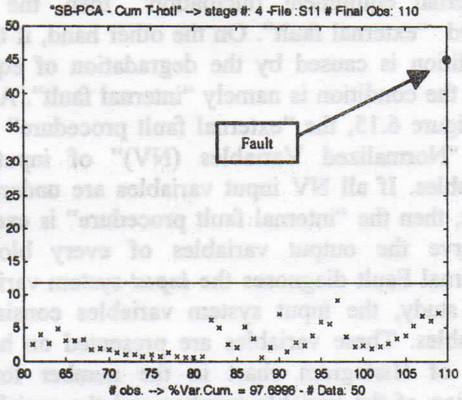


Figure 3. T^2 Hotelling control chart using SB-PCA for file S11

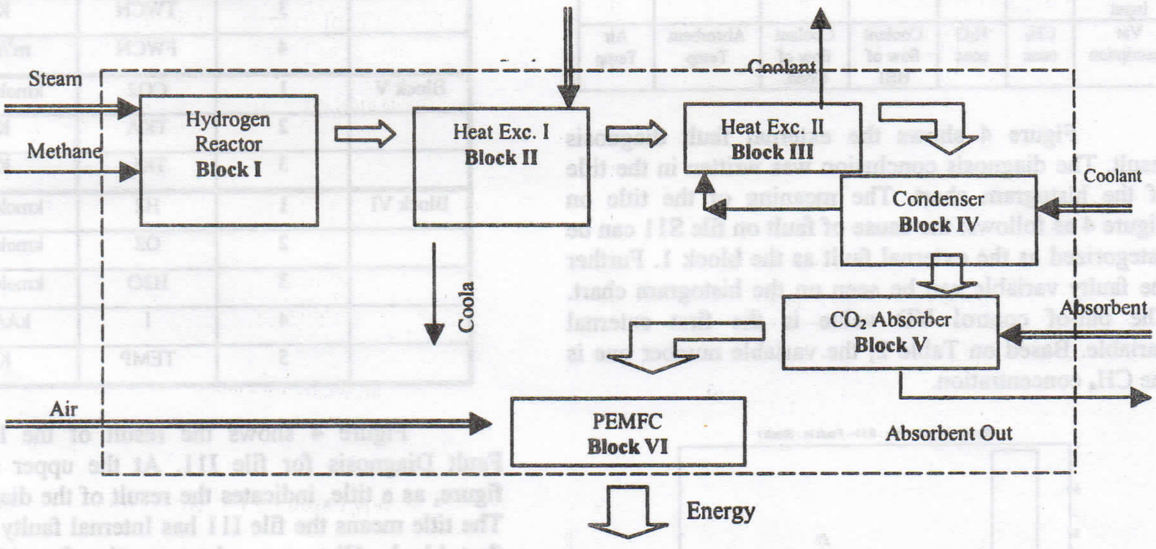


Figure 2. Flow diagram of PEM-FC plant

The procedure of the fault detection is continued by the fault diagnosis. The objective of Fault Diagnosis is to detect the cause of fault, which compose of faulty block and faulty variable. The faulty block and variable can be detected based on the information from "Fault Detection" procedure. If the fault detection procedure found the "out of control" condition, then, the fault detection procedure sign the point as ⊗ and give the faulty point to the fault diagnosis procedure. Fault diagnosis treats all faulty point based on the fault detection information. At the faulty points, the *input or output* variables are standardized at their absolute point. This manipulation is called as *Normalized Variable* at the faulty point. The Normalized Variable (NV) can be expressed as

$NV = abs(x_{fj} - x_j)/s_j$, where x_{fj} = faulty point for variable j, s_j = standard deviation for variable j. Since the NV value is standardized, the control limit, in this control chart, is *three*. When the NV value of the variable is out of control, then the variable is suspected as faulty variable. However, if the NV value of variables is inside the control limit that means the faulty point can be classified as "false alarm".

Fault Diagnosis results can be classified as "External Fault" and "Internal Fault". As mentioned in the chapter IV, if the faulty condition is caused by "external equipment fluctuation", then, the fault is called "external fault". On the other hand, if the faulty condition is caused by the degradation of equipment, thus the condition is namely "internal fault". According to Figure 6.15, the "external fault procedure" observes the "Normalized Variables (NV)" of input system variables. If all NV input variables are under control-limit, then the "internal fault procedure" is executed to observe the output variables of every block. The External Fault diagnoses the ***input*** system variables. In this study, the input system variables consist of six variables. These variables are presented on horizontal axis of Histogram chart in the number form. The relation of the variable number and the variable name can be seen in Table 2.

Table 2. Relation between Variable Number, Block Input and Variable description.

No. var	1	2	3	4	5	6
Block Input	1	1	2	4	5	6
Var description	CH_4 conc	H_2O conc	Coolant flow of HE1	Coolant flow of Cond.	Absorbent Temp	Air Temp

Figure 4 shows the external fault diagnosis result. The diagnosis conclusion was written in the title of the histogram chart. The meaning of the title on Figure 4 as follows: the cause of fault on file S11 can be categorized as the external fault as the block 1. Further the faulty variable can be seen on the histogram chart. The out-of control VD value is the first external variable. Based on Table 2, the variable number one is the CH_4 concentration.

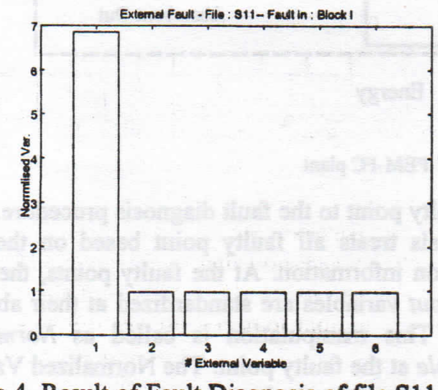


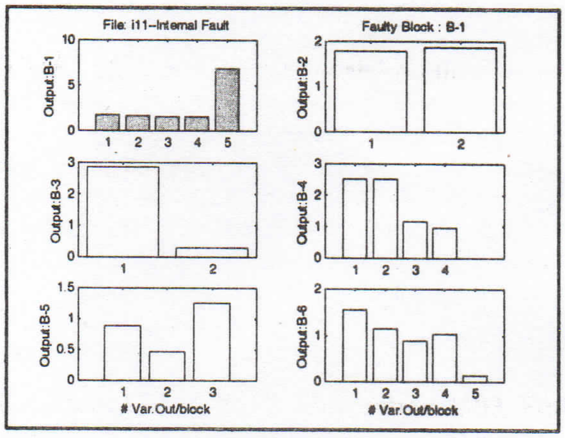
Figure 4. Result of Fault Diagnosis of file S11 (External Fault Case)

The internal fault can be executed if the external fault procedure does not detect any faulty variable. The internal fault file begins with letter *I*. The internal fault procedure analyses the output block variables. These variables are classified based on their block. At the faulty point, the normalized variables (NV) of output variables are calculated. The block is called *faulty block* since the normalized variables (NV) is more than the limit value of three. The variable name based on the variable number and their blocks are shown in Table 3.

Table 3. Relation of fault position, Variable number, Variable and Unit for the histogram control chart

Position	No. Variable	Variable	Unit
Block I	1	CH4	$kmole/m^3$
	2	H2O	$kmole/m^3$
	3	H2	$kmole/m^3$
	4	CO2	$kmole/m^3$
	5	Temp.	K
Block II	1	TKHE1	K
	2	TWHE1	K
Block III	1	TKHE2	K
	2	TWHE2	K
Block IV	1	H2O	$kmole/m^3$
	2	TKCN	K
	3	TWCN	K
	4	FWCN	m^3/sec
Block V	1	CO2	$kmole/m^3$
	2	TKA	K
	3	TKL	K
Block VI	1	H2	$kmole/m^3$
	2	O2	$kmole/m^3$
	3	H2O	$kmole/m^3$
	4	I	kA/m^3
	5	TEMP	K

Figure 4 shows the result of the Internal Fault Diagnosis for file I11. At the upper of this figure, as a title, indicates the result of the diagnosis. The title means the file I11 has Internal faulty on the first block. Histogram chart on the first block is figured using different color, which indicates the "out of control" variable on number five. Based on the Table 3, this variable is the gases output temperature from block 1. The gases output temperature from block 1 increased since the heat transfer coefficient, in block 1 being reduced.



Therefore, Fault Diagnosis, for both external and internal fault, precisely diagnoses the problematic block and variable involved. This procedure utilizes Simple Presentation, i.e. histogram chart. Indication of the *caused of fault* as the faulty variable and *fault position* as the faulty block can be obtained easily from the chart and its title.

Conclusion

This study is focused on the *multivariate control chart* to monitor process system, which must be maintained at the normal operating condition (NOC). Monitoring complex process system involves many observed variables. The method of information reduction on the observed variables onto low dimensional sub-space by using Series Multi Block Principal Component Analysis (SB-PCA). The domain of inference statistics utilizes the T^2 Hotelling control chart. The Normalized Variables (NV) method (Kourti and MacGregor, 1996) was applied in this study for the purpose of fault diagnosis. The arrangement of input and output variables to detect cause of fault is the finding of this study.

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