International Journal of Air-Conditioning and Refrigeration Vol. 16, No. 4 (2008) 137~144

# Fault Diagnosis of Variable Speed Refrigeration System Based on Current Information

Dong-Gyu Lee, Seok-Kwon Jeong†*, Li Hua*

*Samsung Electronics Co., Ltd.*

**School of Mechanical Engineering, Pukyong National University, Busan, Korea*

(Received November 10, 2008; Revision received December 2, 2008; Accepted December 22, 2008)

**Abstract**

This study deals with on-line fault detection and diagnosis(FDD) for heat exchangers of a variable speed refrigeration system(VSRS) based on current information. The current residual which is the difference between real detected current from current sensors and estimated current from no fault model was utilized to diagnose faults of the heat exchangers. Comparing to the conventional FDD of constant refrigeration system based on temperature and pressure information, the suggested FDD method shows better robustness to the VSRS which has a feedback control loop. Moreover the suggested method can be expected more precise and faster diagnosis of faults about heat exchangers. Throughout some experiments, the validity of the method was verified.

*Key words*: Fault diagnosis, Variable speed refrigeration system, Current information

## Nomenclature

$f$ : inverter reference frequency[Hz]
$I_d$ : detected current[A]
$I_e$ : estimated current[A]
$I_i$ : current of compressor(motor)[A]
$I_m$ : mean current of residual[A]
$I_r$ : residual of current [A]
$P_o$ : compressor outlet pressure[bar]
$P_i$ : compressor inlet pressure[bar]
$T_a$ : chamber temperature[℃]
$T_c$ : condensing temperature[℃]
$T_s$ : superheat[℃]
$VO$ : opening ratio of EEV[%]

## 1. Introduction

Recently variable speed refrigeration system(VSRS) driven by an inverter is popular instead of traditional constant speed refrigeration system(CSRS). The VSRS gets more complicated and it is becoming bigger for high efficiency and automation. However, this tendency leads to difficulty for identifying the cause of fault and fault position accurately when fault occurs in some part of the system. Even though a simple problem of the system may cause shut down of the whole system. Also, the simple trouble might bring a huge economic loss especially if it was not discovered quickly and treated appropriately. Moreover, faults in some part of the system cause to increase unnecessary energy consumption and eventually leads to a considerable decrease in reliability and stability of the system. Therefore, it is very important to construct an effective fault detection and diagnosis(FDD) system which enable us to find the symptom of the fault before shut down of the system and presume the cause and position of the fault in real time. Moreover, constructing an effective FDD system guarantees reliability, stability and energy saving of the VSRS.

The fault diagnosis has been done mainly on thermal load using temperature and pressure information in the CSRS. However, the VSRS basically has a feedback compensation loop on an inverter and an electronic expansion valve(EEV) controller to adjust target temperature and superheat as reference value. Fault diagnosis based on only temperature and pressure information is no longer effective in the VSRS.

†Corresponding author. Tel.: +82 51 629 6181, Fax.: +82 51 629 6174
E-mail address: skjeong@pknu.ac.kr

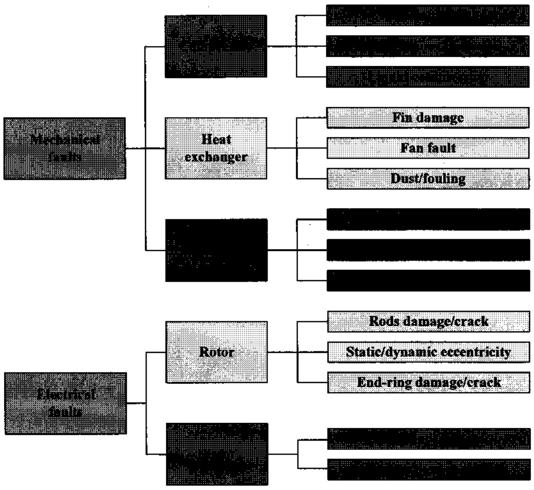



Fig. 1. Fault classification of VSRS.

Yoon et al. proposed original concept of on-line FDD for the VSRS based on current information measured from compressor driven by an induction motor with an inverter for the first time.[1] However, it did not give a detail methodology for constructing on-line FDD of the VSRS. Therefore, the purpose of this study is focused on constructing on-line FDD system for the VSRS by the current information.

Fig. 1 represents fault classification of the refrigeration system. We just restricted boundary of the FDD in this study to the mechanical fault in Fig. 1. Especially, in this study, on-line fault diagnosis using current information will be demonstrated assuming heat exchangers' fault such as decrease heat transfer surface in a condenser and a fan motor stop in an evaporator of the VSRS.

Securing reliability and quick diagnosis are very important for FDD performance. This factor will depend on sensitiveness of variables used for FDD. In this regard, the response of current according to state variation of the VSRS is very quick. Hence the current information can reflect the abnormal state of the system quickly. Therefore, we utilized the residual which is a difference of current between abnormal state and normal state. No fault model(NFM) is built to distinguish abnormal state using independent variables, compressor's rpm and opening ratio of EEV, and dependent variable, current information, for FDD. Effectiveness of this method is verified through some experiments.

## 2. FDD based on current information

Fig. 2 shows the layout of the FDD system suggested in this paper. The FDD system can be divided in major two parts: fault detection and fault diagnosis.

The fault detection part generates residual $I_r$ by comparing $I_d$ which is a result of pre-process of $I_i$ measured in real time through a compressor motor to $I_e$ which is estimated by NFM obtained under various operational conditions in steady state. The current in this study means rms(root mean square) without mentioning specially. The fault diagnosis part performs fault isolation and fault identification using the residual information.

As for the fault isolation, fault position is generally decided by pattern matching process based on data-

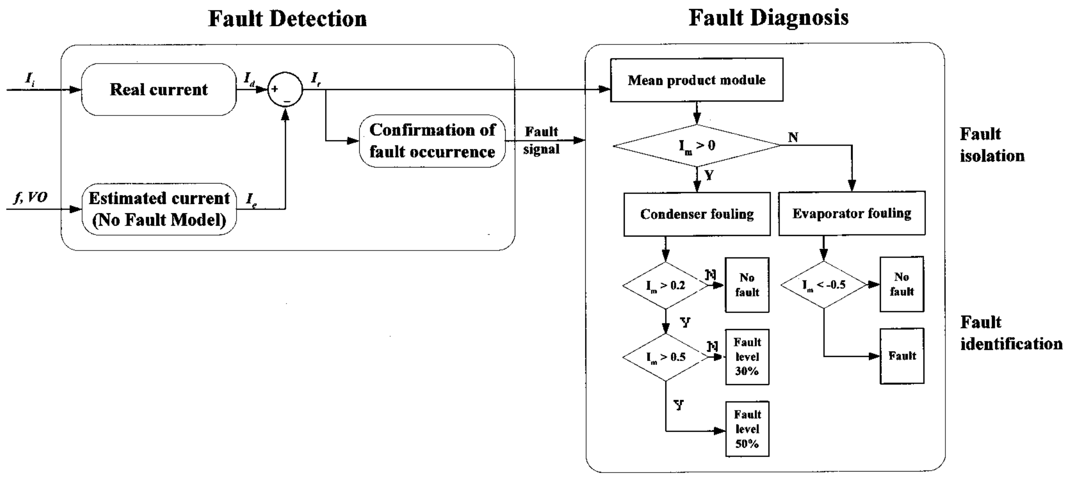



Fig. 2. Schematic diagram of the fault detection and diagnosis system.

Table 1. $I_i$ versus $f$ and $VO$.

| $f$[Hz] | $VO$ [%] | $I_i$ [A] |
|---|---|---|
| 60 | 80 | 6.70 |
| 60 | 70 | 6.62 |
| 60 | 60 | 6.58 |
| 60 | 50 | 6.44 |
| 50 | 90 | 6.86 |
| 50 | 80 | 6.75 |
| 50 | 70 | 6.72 |
| 50 | 60 | 6.57 |

base which is extracted from particular machinery's fault. However, $I_m$, average value of $I_r$ during 60 seconds in the mean product module, is utilized to determine fault position in this study. It is enough to confirm fault position by $I_m$, because we just deal with simple heat exchangers' fault.

Fault identification is also decided by the magnitude of $I_m$. As there are not criteria for classifying fault grade so far, we assumed that the fault degree was proportional to artificial fault level which we made compulsory.

Partial pollution of a condenser and a fan motor fault in an evaporator are experimentally and compulsory simulated in this study in order to verify the validity of the suggested FDD.

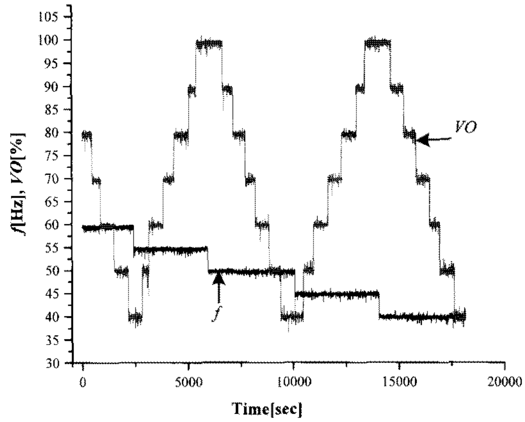
Table 1 shows a part of the experimental data for building NFM. The NFM was obtained by linear regression analysis on the experimental data. Here, the parameters $f$ and $VO$ mean frequency of compressor and opening ratio of EEV respectively. The experimental conditions were as follows: indoor(chamber) temperature was -6~12 ℃, outdoor temperature was 28~30 ℃, and humidity was 50~60%.

Fig. 3 shows the response of $I_i$ to the change of $f$ and $VO$ as an example of the experiments for linear regression analysis. Fig. 3(b) shows that the pattern of electrical current response depends more on $VO$ between two independent values.

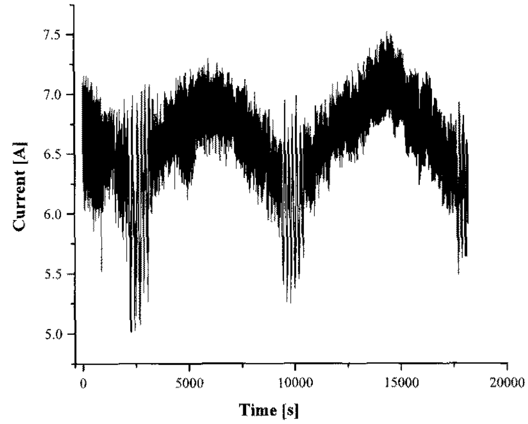
Eq. (1) is obtained by analyzing the results of experiments conducted by changing various values about $f$ and $VO$ in steady state.

$$Y = 0.683 - 0.007X_1 + 0.01X_2 \tag{1}$$

In Eq. (1), $X_1$ and $X_2$ represent $f$ and $VO$ as independent value, $Y$ represents $I_i$ as dependent value. As you can see in Fig. 3, because of bigger contribution of $VO$ than the other to $Y$,




(a) Variation of $f$ and $VO$




(b) Current response

Fig. 3. Current response versus $f$ and $VO$

the coefficient of regression of $VO$ comes out higher in the Eq. (1). It is noted here that electrical current of a compressor in VSRS can be decided by control variables, $f$ and $VO$, in non-fault state.

## 3. Experimental equipment and results

Fig. 4 shows composition of experimental equipment to verify proposed FDD in this study. Photo. 1 also shows the real experimental system. Fuzzy control logic instead of model based PID(Proportional, Integral, Derivative) was programmed inside a programmable logic controller(PLC) to keep target temperature and superheat as reference values. The control variables of the Fuzzy control were $f$ and $VO$. Therefore two input variables of the Fuzzy controller, 'e' and 'ee', were used as membership function. Here

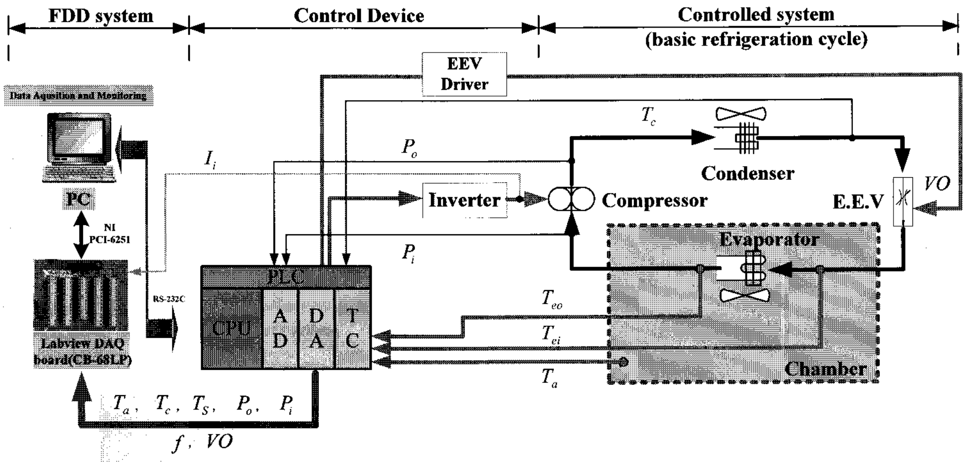
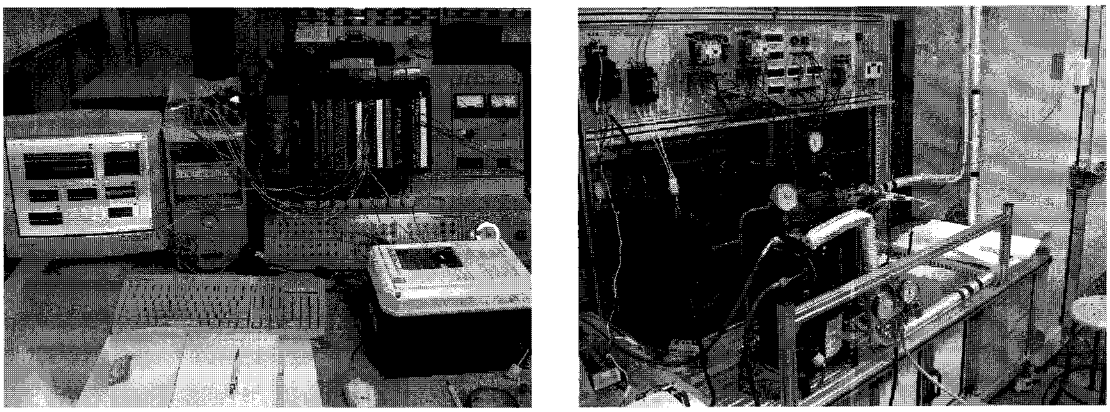



Fig. 4. Composition of experimental equipment for FDD in VSRS.



(a) Data acquisition and control system

(b) Variable speed refrigeration system

Photo. 1 Experimental system

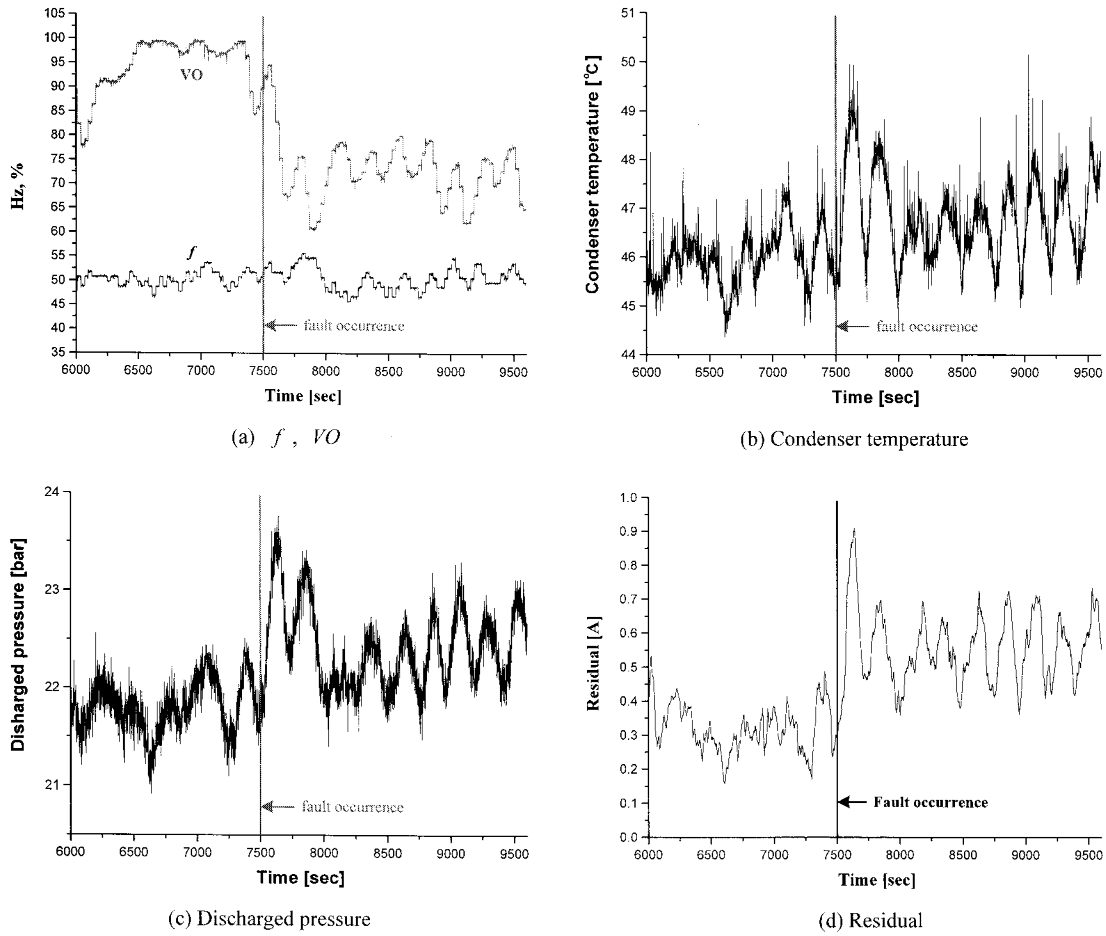
'e' means control error and 'ee' represents gradient of the 'e' during sampling period.

Inverter and EEV driver were controlled by the control logic from PLC to control rpm of a compressor and opening ratio of the EEV respectively. The inverter of V/f=constant type and stepping motor driven by pulse drive were adopted in the VSRS.

The temperatures and pressures collected by TC module of the PLC were transmitted to a data acquisition(DAQ) board through a DA converter. In addition, current was measured by a current transformer sensor from one of three-phase circuit connected to compressor's motor driven by an inverter. Real-time measured data is used for fault diagnosis in PC after being transmitted to DAQ board and going through pre-process of low pass filter(LPF) and high pass filter(HPF). However, estimated current $I_e$ is calculated by substituting $f$ and $VO$ to Eq. (1). The value of $f$ and $VO$ was obviously decided by control logic in PLC to maintain set value of temperature and superheat.

The set value of temperature in chamber, $T_a$, was set at 11℃ and the value of superheat $T_s$ to maintain maximum coefficient of performance(COP) was set at 6℃ through experiments in the test unit. Temperature of $T_a$, $T_c$, and $T_s$ were measured by using T-type thermocouple. Pressure of $P_o$ and $P_i$ were measured by using pressure sensor.

First of all, the merit of FDD using current information was examined. As for VSRS, we used feedback controller to maintain set value of chamber temperature and superheat. Feedback controller based on Fuzzy logic was designed to maintain $T_a$ and $T_s$ at a constant value under various disturbances.




(a) $f$, $VO$

(b) Condenser temperature

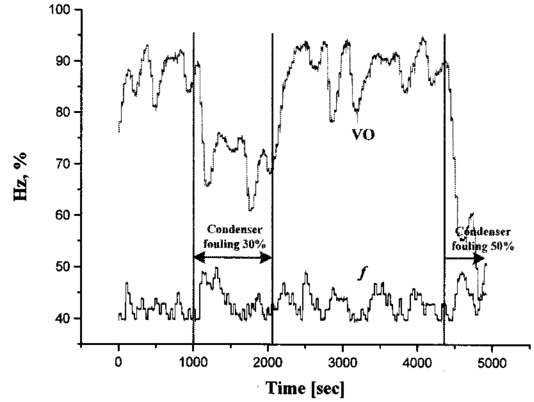
(c) Discharged pressure

(d) Residual

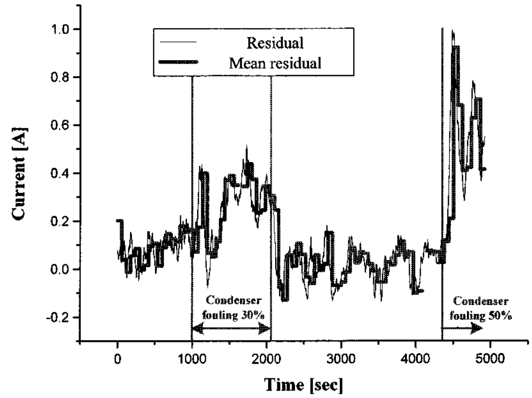
Fig. 5. Experimental results of condenser fouling

Two types of faults are supposed in this study. One is a fault of a condenser. The other is fan motor stop in an evaporator. In the case of condenser's fault, the surface of heat transfer was compulsory changed within 10~70% scope. In the case of fan motor's fault, the fan motor was stopped at arbitrary time.

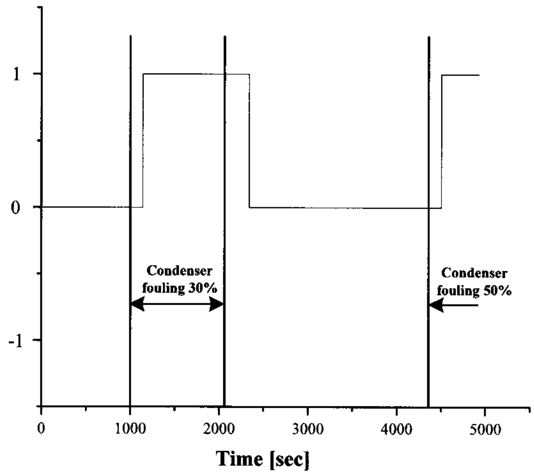
Fig. 5 shows an example of experimental results. As you can see in Fig. 5(a), feedback controller changes $f$ and $VO$ in order to maintain control variables, target chamber temperature and superheat, as reference value. After artificial fault operation, the temperature of inlet of an evaporator increases and $T_s$ declines sharply. Fig. 5(b) shows $T_c$ according to pollution of a condenser. The reason for presenting only $T_c$ is because pollution of condenser affects $T_c$ the most. $T_a$ and $T_s$ are useless as information for fault diagnosis because they are controlled constantly thorough compensation loop of feedback controller. After fault operation, $T_c$ went up because condenser's heat exchange with exterior is not enough by decreasing heat transfer surface. However, the value oscillated within a big range because of the compensation effect of feedback controller. And about 8,000 seconds later, there was no change compared to the temperature before the fault. Fig. 5(c) shows $P_o$ according to pollution of condenser. Input pressure $P_i$ was omitted because the difference between steady state value before the fault and one after the fault is too little. But $P_o$ responded sensitively to pollution of condenser transiently. After fault operation, $P_o$ rose temporarily but about 8,000 seconds later it declined like $T_c$ and maintained at similar state of steady state value before the fault. Fig. 5(d) shows $I_r$ according to pollution of condenser. The change of $I_r$ depends on the magnitude of compressor load. Compressor load is linked directly with state of refrigerant. Therefore, $I_r$ increases after fault simulation and collects constant value by compensa-



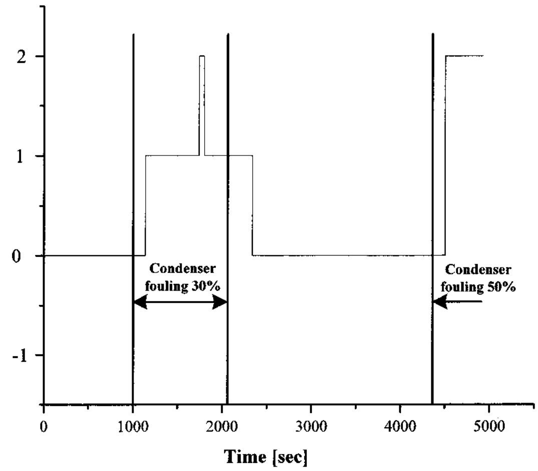

(a) $f$ , $VO$




(b) Residual




(c) Result of fault isolation




(d) Result of fault identification

Fig. 6. FDD result of condenser fouling.

Table 2. Isolation of fault location.

| Number | Fault location |
|---|---|
| 1 | Condenser fouling |
| 0 | No fault |
| -1 | Evaporator fouling |

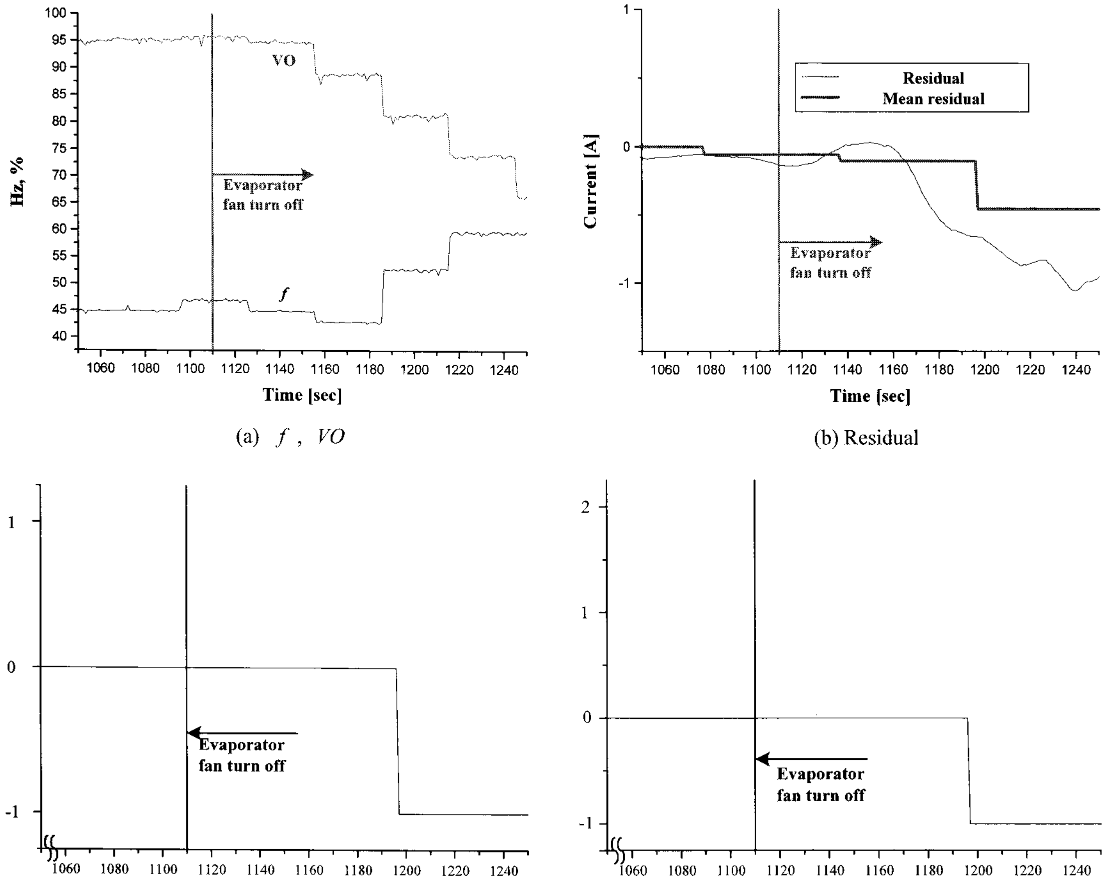
Table 2. Identification of fault level.

| Number | Fault location |
|---|---|
| 2 | Condenser fouling high |
| 1 | Condenser fouling low |
| 0 | No fault |
| -1 | Evaporator fan stop |

tion effect like temperature and pressure. However you can see that the difference between steady state value before the fault and after the fault is clear. The difference of mean value of $I_r$ is about 0.2~0.3A. Therefore, it can be trusted for fault diagnosis considering current sensor's accuracy and resolution.

Fig. 6 shows the result of VSRS corresponding to condenser fouling using current information. During 1,000~2,050 seconds and 4,400~4,900 seconds, heat transfer surface of condenser was reduced by 30% and 50% each. Fig. 6(a) shows variation of $f$ and $VO$ after fault simulation. As the fault degree goes higher, $VO$ tends to decrease radically and the decrease gets bigger. Fig. 6(b) shows $I_m$, average value of current. It can be said that as the fault degree goes higher, $I_r$ increases. Fig. 6(c) and Fig. 6(d) show the result of fault isolation and fault identification respectively. The threshold of 30% and 50% of the fault was 0.2A and 0.5A respectively.

At the end of fault isolation, fault position was identified accurately after fault simulation. Also, at




(a) $f$ , $VO$

(b) Residual

(c) Result of fault isolation

(d) Result of fault identification

Fig. 7. FDD result of evaporator.

the end of fault identification, fault degree was identified accurately after fault simulation, too. However, there is one error observed at 1,740 seconds on fault identification in Fig. 6(d), it can be easily resolved by setting up appropriate threshold. As for a result of Fig. 6, fault diagnosis system using current information for pollution of condenser in VSRS can be said to have both reliability and quick response.

Table 2 and 3 show the isolation of fault location and identification of fault level in Fig. 6 and 7 of (c), (d) respectively.

Fig. 7 shows the result of fault diagnosis on VSRS's fault in a fan motor of an evaporator using current information. Fault in the evaporator's fan motor was simulated at 1,150 seconds. Fig. 7(a) shows variation of $f$ and $VO$ after fault simulation. It can be inferred that fault in the evaporator's fan motor results a decrease in $T_s$ because of a decrease in temperature of outlet of the evaporator leads to decrease in $VO$ and increase in $T_a$ leads to a increase in $f$ . Fig. 7(b) shows $I_m$ , the average value of current per second. Concerning fault in the evaporator fan motor, $I_r$ showed a sharp decline. This implies that damage of refrigeration system can be minimized by rapid fault diagnosis providing that quicker information than temperature and pressure information is given. As for the result of Fig. 7, fault diagnosis system has enough reliability and quick speed responses about VSRS's fault in the fan motor of evaporator using current information. Fig. 7(c) and Fig. 7(d) show the result of fault isolation and fault identification respectively.

## 4. Conclusion

On-line fault diagnosis system for heat exchangers of VSRS based on current information was investigated. We showed that the FDD based on conventional temperatures and pressures are not sufficient any more in the VSRS when the system had feedback loop. The proposed system was verified through some experiments under the assumption that the pollution of the condenser and the fan motor fault in the evaporator.

From the experimental results, it was proven that the FDD based on proposed current information was more efficient for fault of the heat exchangers than the FDD based on temperatures and pressures.

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