

Studies of Monitoring and Diagnosis Systems for Substation Apparatus

Yishan Liang

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Electrical Engineering

Dr. Yilu Liu, Chair
Dr. Jason Lai
Dr. Anbo Wang

December 2005
Blacksburg, Virginia

On-line monitoring, diagnostics, dissolved gas-in-oil analysis, power transformers,
substation batteries

Copyright @ 2005 Yishan Liang

ABSTRACT

Studies of Monitoring and Diagnosis Systems for Substation Apparatus

Yishan Liang

Substation apparatus failure plays a major role in reliability of power delivery systems. Traditionally, most utilities perform regular maintenance in order to prevent equipment breakdown. Condition-based maintenance strategy monitors the condition of the equipment by measuring and analyzing key parameters and recommends optimum maintenance actions. Equipment such as transformers and standby batteries which are valuable and critical assets in substations has attracted increased attentions in recently years.

An automated monitoring and diagnosis tool for power transformers based on dissolved gas analysis, ANNEPS v4.0, was developed. The new tool extended the existing expert system and artificial neural network diagnostic engine with automated data acquisition, display, archiving, and alarm notification functions.

This thesis also studied substation batteries types and failure mode and surveyed the market of current on-line battery monitors. A practical battery monitoring system architecture was proposed. Analysis rules of measured parameters were developed. The above study and results can provide basics for further designing of a simple battery monitoring system in industry applications.

ACKNOWLEDGEMENTS

ACKNOWLEDGEMENTS

I would like to give my sincere appreciation to my advisor, Dr. Yilu Liu, who gave much guidance and assistance throughout my master research. I would like to thank my committee members, Dr. Jason Lai and Dr. Anbo Wang, for serving on my thesis committee.

I would like to thank Dr. David Lubkeman and Dr. Khoi Vu of ABB for their comments and information during the battery project. I would like to acknowledge ABB for funding part of my study.

A special thank goes to Ms. Cindy Hopkins for her help during my studies at Virginia Tech.

Specifically, I would like to thank my colleagues in our power group and my friends for their technical support and friendship.

Finally, I would like to express my deepest appreciation to my husband, Qing Tian, my parents, sister, and sister in law who showed me the endless support and love.

TABLE OF CONTENTS

TABLE OF CONTENTS

ABSTRACT	II
ACKNOWLEDGEMENTS	III
TABLE OF CONTENTS	IV
LIST OF TABLES	VI
LIST OF FIGURES	VII
CHAPTER 1 INTRODUCTION	1
1.1 BACKGROUND AND THE OBJECTIVE OF THE STUDY	1
1.2 ORGANIZATION OF THIS THESIS	3
CHAPTER 2 STUDY OF MONITORING AND DIAGNOSIS SYSTEM OF POWER TRANSFORMERS	5
2.1 ANNEPS OVERVIEW.....	5
2.1.1 Expert System Based Fault Diagnosis	7
2.1.2 Neural Network Based Fault Diagnosis.....	7
2.1.3 ANNEPS Based Fault Diagnosis	8
2.1.4 Maintenance Recommendation and Condition Assessment	9
2.1.5 Fault Location Analysis	9
2.2 IMPLEMENTATION OF AUTOMATED DIAGNOSIS SYSTEM.....	10
2.2.1 On-line Gas-in-oil Monitors Review	10
2.2.2 Proposal of an Automated System.....	11
2.2.3 Design Overview	12
2.2.3.1 <i>Software Interface Design</i>	14
2.2.3.2 <i>Automated Database Design</i>	18
2.2.3.3 <i>Alarm Notification Design</i>	23
2.3 SUMMARY	26
2.4 REFERENCES	27
CHAPTER 3 STUDY OF MONITORING SYSTEM OF SUBSTATION BATTERIES	28

TABLE OF CONTENTS

3.1 BASICS OF SUBSTATION BATTERIES	28
3.1.1 Substation Battery Types	29
3.1.2 Substation Battery Failure Mode	30
3.2 TECHNICAL CRITERIA OF BATTERY MONITORING	31
3.2.1 Measurement and Analysis Parameters	32
3.2.1.1 Temperature Analysis	34
3.2.1.2 Current Analysis	36
3.2.1.3 Voltage Analysis.....	37
3.2.1.4 Internal Ohmic Analysis	39
3.2.1.5 On-line Discharge Analysis	40
3.2.2 Determination of Battery State	41
3.2.2.1 State of Charge Determination	42
3.2.2.2 State of Health Determination	44
3.3 ARCHITECTURE OF BATTERY MONITORING SYSTEM.....	46
3.4 SUMMARY	50
3.5 GLOSSARY OF BATTERY TERMS	51
3.6 REFERENCES	52
CHAPTER 4 CONCLUSIONS.....	55
4.1 CONCLUSIONS	55
4.2 FUTURE RESEARCH.....	55
APPENDICES	57
APPENDIX A ANNEPS SOFTWARE USER'S MANUAL V4.0	57
APPENDIX B CURRENT MARKET SURVEY OF ON-LINE BATTERY MONITORING SYSTEMS.....	60
APPENDIX C C CODE OF TEMPERATURE BASED BATTERY MONITORING ANALYSIS.....	62
APPENDIX D C CODE OF IMPEDANCE BASED BATTERY MONITORING ANALYSIS.....	65
VITA.....	69

LIST OF TABLES

LIST OF TABLES

Table 1 On-line gas-in-oil monitors.....	11
Table 2 Database variable definition	16
Table 3 Description of class operations of ANNEPS v4.0	22
Table 4 Description of class mail operations.....	24
Table 5 Substation battery types.....	29
Table 6 Basic parameters for battery monitoring	33
Table 7 Additional parameters for battery monitoring	34
Table 8 Variable specification for temperature data.....	35
Table 9 Variable specification for current data.....	37
Table 10 Variable specification for voltage data	38
Table 11 Variable specification for internal ohmic data.....	40
Table 12 Variable specification for on-line discharge analysis	41

LIST OF FIGURES

LIST OF FIGURES

Figure 1 Flow chart of the ANNEPS	6
Figure 2 Basic structure of ANNEPS v4.0	13
Figure 3 Screen shot of the ANNEPS v4.0.....	15
Figure 4 Connection between databases.....	20
Figure 5 Flow chart of ANNEPS v4.0.....	22
Figure 6 Routine of email notification.....	24
Figure 7 Configuration dialog of email alarm notification.....	25
Figure 8 Backup batteries in the substation	28
Figure 9 Flowchart of temperature analysis.....	35
Figure 10 Flowchart of current analysis	37
Figure 11 Flowchart of voltage analysis.....	38
Figure 12 Flowchart of internal ohmic analysis	40
Figure 13 Flowchart of on-line discharge analysis.....	41
Figure 14 Methods of battery SOC determination.....	43
Figure 15 Architecture diagram of battery monitoring system.....	46
Figure 16 Flow chart of decision logic module	48

CHAPTER 1 INTRODUCTION

This introductory chapter describes the background of this research topic and the goals of the study. A short outline for the rest of the thesis is also provided.

1.1 Background and the Objective of the Study

In recent years, increased emphasis has been placed on power equipment reliability. In particular, facing deregulation and increasing competition, many utilities are looking for ways to generate and transmit power in more economical and reliable ways. The health of equipment constituting the substation is critical to assuring the supply of power.

Historically the maintenance of electrical power equipment has been time-based. Maintenance crews would inspect the equipment at set intervals based on its age and performance history. As can be expected, this leaves room for many catastrophic failures of improperly or untimely diagnosed equipment. The cost in disruption of business could far outweigh the savings in maintenance costs. On the other hand, too-frequent maintenance can be very costly and unnecessary. Because of the cost of scheduled and unscheduled maintenance, especially at remote sites, new approaches using on-line monitoring and analysis systems of the substation equipment may be more reliable and cost-effective.

Unlike traditional time-based maintenance (TBM), condition-based maintenance (CBM) relies on on-line monitoring parameters that indicate possible problems of the

CHAPTER I

equipment and using this to determine the condition of the equipment and then optimize maintenance strategies. The ability to continuously monitor the condition of energized equipment (on-line monitoring) enables operation and maintenance personnel to determine the operational status of equipment, to evaluate present condition of equipment, timely detection of abnormal conditions, and initiate actions preventing upcoming possible forced outages.

In recent years a range of monitoring and diagnosis devices have become available that provide continuous, real-time condition monitoring and analysis of substation equipment. The effective use of on-line monitoring and diagnosis has potential to provide significant benefits for substation owners, technical personnel, and even utility consumers.

The key benefits of on-line monitoring and diagnosis can be summarized as follows:

- Early detection and possible prevention of equipment failure, especially catastrophic failure;
- Long-term data acquisition and understanding about equipment performance;
- Automatically assessing electrical equipment condition by integrating with diagnostic algorithms; and
- Resulting in reducing maintenance time and labor, and reducing maintenance costs associated with any failure.

The essential criteria for developing an effective monitoring and diagnosis system are

CHAPTER I

evaluating its performance to detect incipient or impending failure. The user will also consider the initial purchase and maintenance cost for such a system and its ease of installation.

Transformers are the most expensive piece of equipment in the substation, and therefore, preventing transformer failures is the key to greatly reducing the cost and increasing the reliability of providing the needed electrical energy. Batteries continuously supply back up energy for the control of breaker and other auxiliary equipment. Its reliability must be of the highest order since a failure may result not only in serious damage to single equipment but to the entire system as well. In this thesis, an automated monitoring and health diagnosis system of transformers is investigated. The study of on-line battery monitoring system is also presented.

1.2 Organization of this Thesis

Chapter 1 gives basic background of substation apparatus maintenance and the benefits of monitoring and diagnosis system.

Chapter 2 explores the overview of an expert and artificial network diagnosis system for transformers. The new system with several automated functions is proposed after reviewing the current on-line transformer monitors. The design details of new interface, database interactions, and alarm notification functions are provided.

Chapter 3 presents a review of on-line monitoring system for stationary batteries, especially focused on batteries in substation applications. The review has included battery types, failure modes, monitoring parameters and implementation, and on-line monitoring

CHAPTER I

devices available on the market. The architecture of a battery monitoring system is proposed.

Finally, a summary of the results from this thesis, the future research and conclusions are provided in Chapter 4.

In the thesis, there are separate reference lists about transformers and battery studies in order to be easily searched by readers. The glossary of battery terms will be covered in Chapter 3. Appendix A provides ANNEPS v4.0 user manual. The market of available on-line battery monitoring devices is reviewed in Appendix B. Computer codes for the battery monitoring analysis appear in Appendices C and D.

CHAPTER 2 STUDY OF MONITORING AND DIAGNOSIS SYSTEM OF POWER TRANSFORMERS

2.1 ANNEPS Overview

In cases of electrical and thermal stresses inside the transformer, several gases are produced and dissolved in the oil within liquid-immersed transformer. The following gases are typically found in transformer insulating liquid under fault conditions: Nitrogen (N_2), Oxygen (O_2), Hydrogen (H_2), Carbon dioxide (CO_2), Carbon monoxide (CO), Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4), and Acetylene (C_2H_2). These gases are the indicatives of developing faults in the transformer, and their early detection will call for necessary actions to prevent costly equipment failures.

Dissolved gas-in-oil analysis (DGA), which analyzes the above gases, has proved to be a valuable and reliable diagnostic technique for the detection of incipient fault conditions and has been widely used throughout the industry as the primary diagnostic tool for transformer maintenance. The analysis techniques include the conventional ratio methods and key gas methods, and the artificial intelligent (AI) methods. AI techniques include expert system (EPS), fuzzy logic, and artificial neural network (ANN).

Since 1995, Virginia Tech working with experts in the industry have begun to study the artificial neural network approach to diagnose the transformer faults, combined it with the expert system methods, finally developed a powerful artificial neural network and expert system based diagnosis tool (ANNEPS) [2-1][2-2]. The software can not only detect the types of fault, but also provide transformer condition assessment, maintenance

CHAPTER II

recommendations and fault location function. The flow chart of the ANNEPS is shown in Figure 1 [2-3]. ANN based abnormal and EPS based abnormal detectors are first used to screen out abnormal cases for further diagnosis. Then, ANN based individual fault detector analyzes all possible fault types with different confidences. Similarly, EPS based individual fault detector also detects all possible fault types. A more accurate diagnostic result is provided by combining outputs of EPS and ANN based individual fault detectors. Finally, maintenance is recommended, insulation condition is evaluated, and fault position is located.

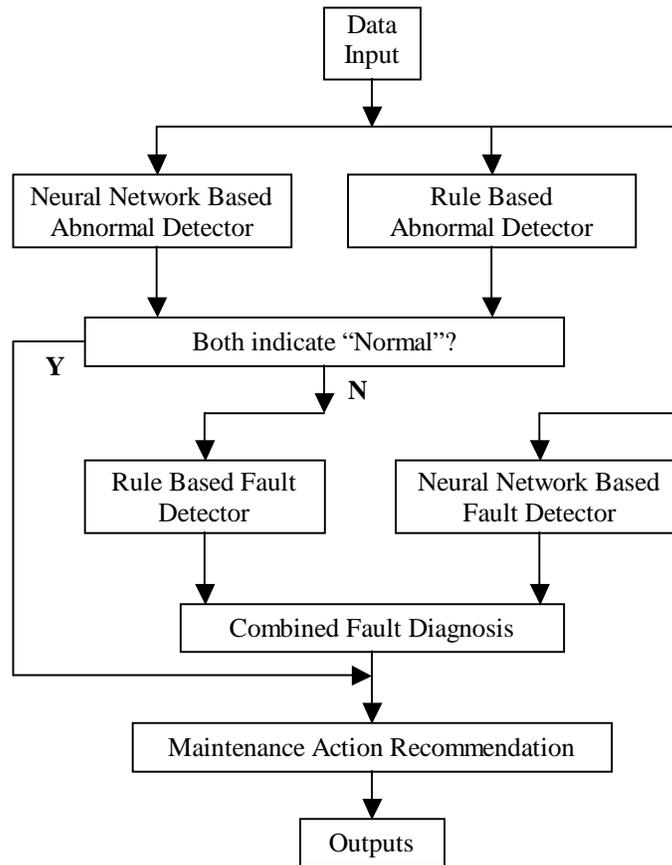


Figure 1 Flow chart of the ANNEPS

In order to easily understand the functions and advantages of ANNEPS software,

CHAPTER II

main features of this diagnosis tool will be reviewed in the following subsections, separately.

2.1.1 Expert System Based Fault Diagnosis

The expert system is a decision-making system programmed to provide fault analysis and improve the intelligent level of the condition-based monitoring for the power equipment [2-4]. A set of rules in the expert system are mostly developed from standards and human expertise. The disadvantage of expert system method is that its diagnostic rules must be manually constructed and cannot be adjusted from new data samples.

Since IEC standard 599 and its revision both have some blank zones where the “no decision” problem occurs, Wang’s study [2-3] made some modifications when he applied them as the rule basis of its expert system. By taking into consideration oil and cellulose decomposition, special fault diagnosis rules were developed. They were overheating (OH) and overheating of oil (OHO) diagnosis, ratio CO/CO₂ based diagnosis, additional cellulose degradation (CD) and overheating of cellulose (OHC) diagnosis, and normal (NR) diagnosis. These special rules were combined with modified IEC rules to form the rule database. The confidence of a fault diagnosis was fuzzily represented by a number between 0 and 1.

2.1.2 Neural Network Based Fault Diagnosis

The artificial neural network method can detect the obvious and hidden relationship between gases dissolved in oil and faults in transformers. It can also overcome some limitations of an expert system. When the training data set is adequate and accurate,

CHAPTER II

artificial neural network method performance was demonstrated to be superior to expert system method.

Compared with testing accuracies for learning vector quantization (LVQ) neural network and multivariate Gaussian (MVG) classifiers, single-output one-hidden-layer multi-layer perceptron (MLP) was the best choice and M-3M-1 type MLP is selected to be the optimal MLP topology for power transformer fault diagnosis. As mentioned in Wang's study, MLP should be trained on-line by using additional data samples if an on-line power transformer fault diagnosis system is used. Its topology must ensure that it can be trained to a preset residual error level within a reasonable time frame.

2.1.3 ANNEPS Based Fault Diagnosis

Combining outputs of expert system and artificial neural network based individual fault detectors provide a weighted final diagnostic result. When sufficient data are not available for the artificial neural network training, the rule bases of the expert system make major diagnosis decision. For example, when expert system detects the fault with high confidence for certain fault type, the combined output of ANNEPS will try to give more weight to the human expertise represented in expert system. Under other conditions the mechanism ensures that the combined output reflects the compromise of the two results.

The system tool also takes advantages of the self-learning capability of artificial neural network. Applications in real cases demonstrated that ANNEPS has shown better diagnostic performance than the ANN or EPS used individually due to its ability of

CHAPTER II

combining positive aspects of the two.

2.1.4 Maintenance Recommendation and Condition Assessment

Maintenance recommendations are also important besides the fault diagnosis. Transformer oil is normally tested annually. Five different schemes from both IEEE standard and key gas DGA method were used to set the new sampling interval. The recommended sample interval includes half a year, three months, one month, one week, and one day. The result was also modified according to transformer size, age and the location of the transformer.

Transformer condition assessment can be classified into two categories, transformer oil assessment and solid insulation assessment. For AI based oil condition assessment, interfacial tension (IFT), acid number (KOH), power factor (PF), and water (H₂O) were used to implement in ANNEPS, because these tests are relatively easier to perform. Fuzzy logic transfer functions were defined to output a set of indices for oil condition assessment. Then, an unconditional fuzzy proposition was used to combine the indices and provide an overall oil insulation condition assessment index. For solid insulation condition assessment, partial discharge (PD), degree of polymerization (DP) and furan concentration 2-furfural (FUR) were used. Similarly, an overall solid insulation condition index can be obtained.

2.1.5 Fault Location Analysis

Fault location can provide critical information for power transformer maintenance. ANNEPS uses 7x21x5 MLP network to locate the faults. The seven inputs of the network

CHAPTER II

are the gas-in-oil concentration of the seven gases. The five outputs correspond to the five fault location categories: LTC, TANK, LEADS, WNDG and OTHER.

LTC category includes load tap charger (LTC) tap board terminals, in-tank LTC components, and surrounding areas. TANK category includes the oil tank case, core laminations and assembly bolts, and so on. LEADS category includes leads between winding coils, between windings and bushings, between windings and LTC tap board, between neutral point and ground, and so on. WNDG category refers to winding problems. OTHER category refers to areas other than the previously defined ones, such as forgotten tools in the tank, static shielding, cooling system, and so on.

2.2 Implementation of Automated Diagnosis System

2.2.1 On-line Gas-in-oil Monitors Review

Laboratory-based DGA tests were typically conducted every six months or one year according to different transformer type or application. Between normal laboratory test intervals some problems could develop in very short time and are easy to be undetected. Installation of continuous gas-in-oil monitors may detect the start of incipient failure conditions, thus allowing the user to make the right maintenance plan.

Several different dissolved gas monitors or analyzers have been developed by industries. Table 1 gives a list of available on-line dissolved gas monitors on the market. The most commonly used analyzer is the Hydran series by GE-Syprotec. It detects four of the major dissolved gases present in the oil, and provides daily values and trending information. Severon makes an on-line transformer monitor which measures not only

CHAPTER II

eight critical fault gases but also the water content in the oil. Similarly, transfix on-line dissolved gas analyzer from Kelman also measures eight fault gases and water in oil and determines ratios of gases. Mitsubishi's on-line DGA analyzer monitors six gases and uses total combustible gas to analyze any faults. Transformer gas monitor from Gatron analyzes five gases and determines gas rates. Oil sampling of these on-line monitors is continuous and gas analysis interval is from 2 hours to 12 hours, which is much shorter than the interval of traditional DGA test. It should be noted that the aforementioned types of monitoring and analyzing systems are very expensive and may cost several thousand dollars or more each.

Table 1 On-line gas-in-oil monitors

Monitor Name	Company	Features
HYDRAN 201R Model i [2-5]	GE Syprotec	-analyzes and monitors four fault gases (C ₂ H ₂ , H ₂ , CO, C ₂ H ₄)
On-line Transformer Monitor [2-6]	Serveron	- measures eight critical fault gases (H ₂ , CO, CO ₂ , O ₂ , CH ₄ , C ₂ H ₂ , C ₂ H ₄ , C ₂ H ₆); - measures other parameters (i.e. moisture-in-oil)
Transfix On-line Dissolved Gas Analysis (DGA) [2-7]	Kelman	- measures eight critical fault gases (H ₂ , CO, CO ₂ , O ₂ , CH ₄ , C ₂ H ₂ , C ₂ H ₄ , C ₂ H ₆); - determine gas ratios; - measures water in oil
C-TCG-6C on-line DGA [2-8]	Mitsubishi	- monitored individual six gases (H ₂ , CO, CH ₄ , C ₂ H ₂ , C ₂ H ₄ , C ₂ H ₆); - uses total combustible gas
Transformer Gas Monitor TGM-M [2-9]	Gatron	- analyzes five fault gases (H ₂ , CO, CO ₂ , O ₂ , N ₂); - determines the gas rate ; - measures the degree of gas saturation

2.2.2 Proposal of an Automated System

ANNEPS diagnosis system has been confirmed having high performance of

CHAPTER II

diagnosing multiple faults in power transformers. However, the current version of ANNEPS can only be used as an off-line diagnosis tool. The user must create a txt type input file with specific data format each time or manually type the data following the screen guidance. The input data files and output files must also be manually saved. It is inconvenient to users when there are bulks of raw DGA data need to be analyzed. To take advantages of the on-line monitors and the off-line diagnosis tool, an additional step is needed to come up with an on-line monitoring and diagnosis system which can automatically interact with data during different steps, notify users when any fault is detected, and recommend related action.

The objective of this research work is to develop ANNEPS into such an automated monitoring and diagnosis tool to collect and analyze dissolved gas-in-oil data in power transformers to detect the fault. In the automated mode of operation, the new ANNEPS should receive DGA data from a database and then store all information into a database. The neural network and expert system engine in the ANNEPS validates data, detects the faults, and recommends appropriate action. When the diagnosis engine indicates an “abnormal” condition, a notification of the diagnosis results can be sent to transformer maintenance personnel through email. The proposed ANNEPS tool allows users to combine the measuring capability of an on-line dissolved gas in oil monitor with a comprehensive diagnosis system.

2.2.3 Design Overview

The system, called ANNEPS v4.0, expands the capability of an existing software package, ANNEPS v3.0. The extended functions included in new version are data read,

CHAPTER II

data processing, data storage, data visualization, and Alarm procedure. Figure 2 illustrates the structure of the system, which gives the basic idea of this design work. The detailed implementation of each function will be discussed as following sections in detail.

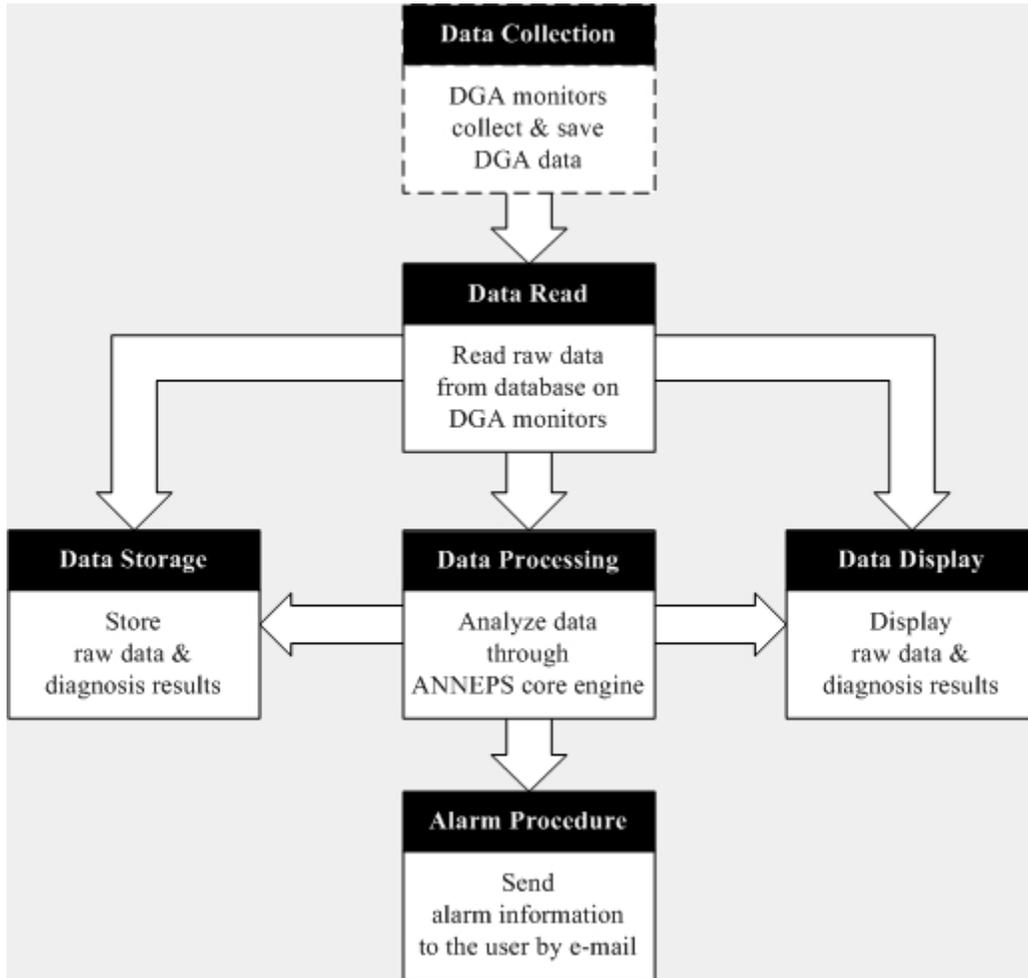


Figure 2 Basic structure of ANNEPS v4.0

Data read: Every ten minutes, sets of measuring quantities are read from the database of the on-line DGA monitor. The information is stored in a temporary Microsoft Access database on the server.

Data processing: The core step is running the analysis procedure through the

CHAPTER II

ANNEPS diagnosis engine.

Data storage: After data processing, a check is made as to whether the full day has been reached. If true, a raw data backup process is started. On the hard disk of the computer, an archive with the daily values is created. The archives can be stored in a Microsoft Access file. Thus, the recorded data can further be used by all commercially available software. Similarly, the diagnosis results will also be saved into txt type files for future work.

Data visualization: Both original raw data and analysis results can be displayed on the screen of the server with time change.

Alarm procedure: Once the diagnosis result shows that the transformer condition is abnormal, an alarm procedure is started. An alarm email message with fault information is sent to the user through Internet.

The platform of the software is Microsoft Windows 2000 or XP. The tool has been developed using Visual C++ 6.0 with Microsoft Foundation Class (MFC) library. It is a product of the Microsoft Corporation, which is an interactive Windows programming language. This is a convenient choice because many libraries exist in C++ which expedites the developmental process. It meets the desired criteria and will allow ANNEPS to be built as a powerful and fast computer program.

2.2.3.1 Software Interface Design

As this is a software tool, special attention is given to the user interface. The operator interface is graphical and mainly mouse driven via toolbars and buttons. The system

CHAPTER II

provides standard windows that can be opened for performing system setup and normal operation. The following basic window types are supported: operation primary window used for system monitoring and control; configuration window used for defining system initial setup resources.

Figure 3 provides an overview of screen display seen while using ANNEPS v4.0.

Screen shows that there are three parts on its user interface.

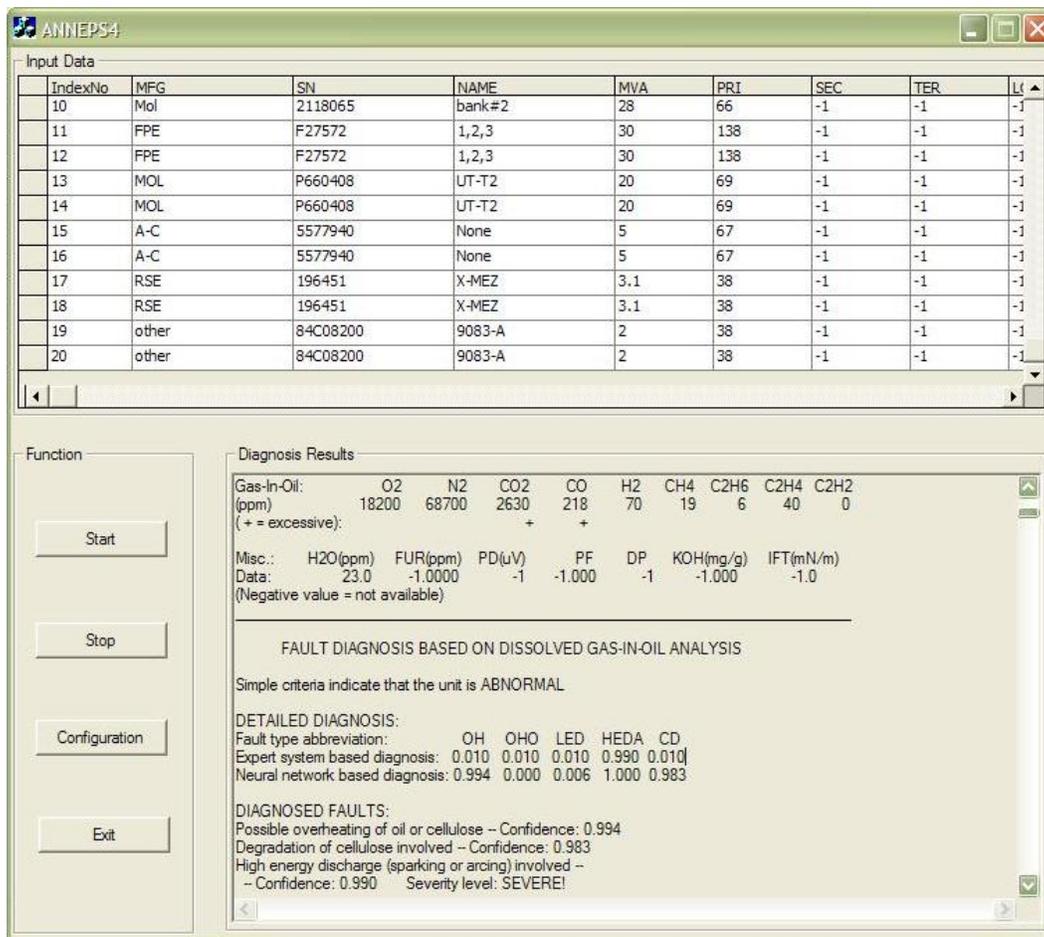


Figure 3 Screen shot of the ANNEPS v4.0

1. Function Area: Four buttons provide the basic functions.

"Start" button is responsible for starting the timer and reading the raw data.

CHAPTER II

"Stop" button is responsible for stopping the timer and cutting the connection from input database.

"Configuration" button is responsible for launching the configuration dialog to setup email notification function. The details about that will discuss in later section.

"Exit" button is responsible for stopping and exiting the software.

2. Input Data Area: Datagrid shows all the input data on the screen, which are collected from a DGA monitor. Each row includes all information related to each oil sample, and there are thirty four items as listed in Table 2. According to different oil sample data and ID number, gas-in-oil concentrations (in ppm) of H₂, CH₄, C₂H₂, C₂H₄, C₂H₆, CO, CO₂, O₂, and N₂ are from the DGA monitor. They are the key input parameters for diagnosis. Power factor (PF), furan concentration (FUR), acid number (KOH), interfacial tension number (ITF), degree of polymerization number (DP), and partial discharge value (PD) are used to analyze the insulation condition of paper and oil. Transformer information included manufacturer, serial number and name, capacity and voltage level, LTC type, age, oil volume, water content, top oil temperature, and so on, are also stored for results validation. Many factors affect the gas-in-oil development behaviors and only some of them are used for fault diagnosis at present.

Table 2 Database variable definition

Field Name	Date Type	Description
IndexNo	Number/Integer	Index
MFG	Text	Manufacturer
S/N	Text	Serial Number

CHAPTER II

NAME	Text	Name of the transformer
MVA	Number/Single	transformer Capacity (MVA)
PRI	Number/Single	Primary Voltage (kV)
SEC	Number/Single	Secondary Voltage (kV)
TER	Number/Single	Tertiary voltage (kV)
LOAD	Number/Single	Average load level (percent)
VOL	Number/Single	Volume of oil (gallon)
OPS	Number/Integer	Oil preservation system: 1-gas blanket; 2-close conservator; 3-open conservator
AGE	Number/Single	Service years
DEGS	Number/Single	Months since last degassing
LTC	Number/Integer	load tap changer 1-yes 2-no
SLTC	Number/Integer	1-separate LTC compartment 2-LTC in main tank
DATE	Date/Time	Sampling date
SID	Text	Sample's ID number
TOT	Number/Single	Top oil temperature
PF	Number/Single	Power factor (@25C)
FUR	Number/Single	Furan concentration 2-furfural (ppm)
KOH	Number/Single	Acid number (mg KOH/g)
ITF	Number/Single	Interfacial tension number (mN/m)
H2O	Number/Single	Dissolved water (ppm)
O2	Number/Single	Dissolved Oxygen (ppm)
N2	Number/Single	Dissolved Nitrogen (ppm)
CO2	Number/Single	Dissolved Carbon dioxide (ppm)
CO	Number/Single	Dissolved Carbon monoxide (ppm)
H2	Number/Single	Dissolved Hydrogen (ppm)
CH4	Number/Single	Dissolved Methane (ppm)
C2H6	Number/Single	Dissolved Ethane (ppm)
C2H4	Number/Single	Dissolved Ethylene (ppm)
C2H2	Number/Single	Dissolved Acetylene (ppm)

CHAPTER II

DP	Number/Single	Degree of polymerization number
PD	Number/Single	Partial discharge value

In order to implement the real-time display on the screen, Microsoft DataGrid Control is used into the project. The wizard provides several classes in their respective header and implementation files. In this application, CDataGrid, CPicture and CSELBookmarks classes are selected to generate. No modification is made in Datagrid and its dependent files for current use. After using the Class Wizard to bind the Datagrid control to the main dialog, Datagrid connects the data by assigning it a recordset object. When displayed in the screen, these data will be stored in background.

3. Output Data Area: Once the analysis is done, Edit Box tool displays the diagnosis results on the screen. Diagnosis outputs include diagnosed fault types (Normal (NR), Overheating regardless of oil or cellulose (OH), Overheating of oil (OHO), Low energy discharge (LED), High energy Discharge or arcing (HEDA), Cellulose degradation (CD)) and their confidences, retest interval and maintenance action recommendations, and condition evaluation. At the same time, the results are also stored into a txt type output file.

On-screen display provides apparatus monitoring and diagnostic condition for users in the field.

2.2.3.2 Automated Database Design

On-line devices usually produce enormous amounts of data, and it's not practical to manually process this information. The automated interaction among different data

CHAPTER II

sources is essential for this design work.

Applications use different data access techniques to extract data from data sources. Some of various data access technologies available are: ODBC (Open Database Connectivity), DAO (Data Access Objects), and ActiveX Data Objects (ADO). ADO is a popular choice of data access today, which can be used to access the data in multiple formats, from complex databases to simple text files through an OLE DB provider. ADO also supports a web-based application which provides greater flexibility for further development. However, before using any of the ADO methods, the ADO library, such as the ADO.dll (Msado15.dll) must be imported into the project. Generally, the windows operation system with default installation has such files. Since ANNEPS is industry application software and may run under different operation environments, all necessary files will be included in the same project folder.

There are several databases and text files used during ANNEPS v4.0 application. Their relationships are illustrated in Figure 4. DGA database (ANNEPS4 INPUT.mdb) includes the raw DGA data which is created by on-line DGA monitors. Since the DGA monitors from different vendors store data on the computer using different frame formats, we therefore decided to receive data with a simple Microsoft Access-based format. Currently, this database is repeatedly connected to simulate database connection in real conditions. Because a DGA monitor maybe places in different servers with the ANNEPS software or gives us read-only access to their database, all raw data collected should be stored separately from the original into another database for further manipulation. The temporary database (tempdb.mdb) includes the original raw data and also is a MS access file. Because of the frequency of requesting oil samples in on-line monitors will be much

CHAPTER II

higher than conventional off-line devices, the much greater amounts of data will be collected. Considering the requirement of size of access database, the software is designed to have daily database backup function. It uses the current date as the file name, for example, 20051114-INPUTBACKUP.mdb. As soon as two records of DGA information are read into the memory of the server, the core diagnosis engine of ANNEPS will analyze these data, and then provide the fault diagnosis. The detailed results will be stored into a text file, 20051114-OUTPUT.out. Similarly, its file name is the current local date.

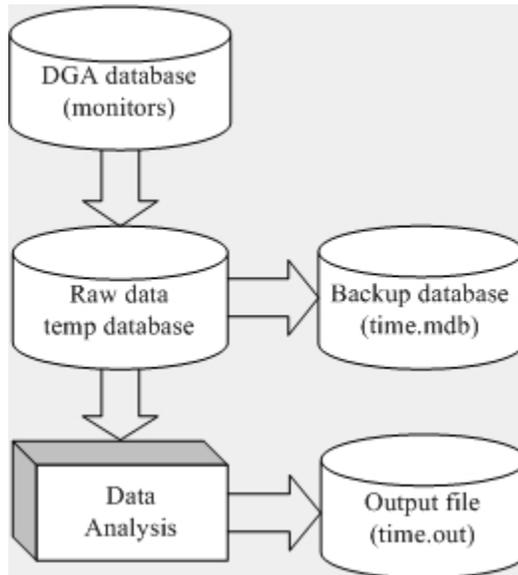


Figure 4 Connection between databases

The flow diagram in Figure 5 clearly shows the path of the software. Table 3 briefly describes the functions of some classes used in ANNEPS software. The executable file built in release type, ANNEPS4.exe is the start point of the software. Once activating the ANNEPS v4.0, the main window will be launched. First, the alarm notification needs to be configured. Otherwise, the software will fail to send out alarm messages to the remote

CHAPTER II

user if any fault is detected, and also pops up a screen message. At this point, both input and output areas are blank and there is no any information in the computer memory and databases. Start button at the function area will begin the main function, and also set a ten-minute timer which recalls the main function every ten minutes.

After creating an instance of an ADO connection and recordset object, it opens the input database and tables. The input database connection has been built. The current data in memory are display on the screen through Datagrid. Next, the temporary input database is connected and the output file is created. Since the ANNEPS diagnosis method needs to process two samples data, the tool successively reads two sets according to different times and assigns them to new and old variables respectively. At the same time, the data is also stored into temporary input database for later work. The interval between two sampling times is calculated. Based on these data, expert system and artificial network methods are used to detect if any abnormal condition exists and calculate its fault confidence. Combination function combines the results of EPS and ANN methods and obtains the more accurate conclusion of fault types. It also gives the location of the fault. After that, the tool recommends resample interval based on gas-in-oil analysis and assesses insulation quality based on miscellaneous data. All analysis results are saved into the output file and displayed on screen at the same time. If diagnosis results show that the condition of the transformer is abnormal, email-sending function is activated and sends an alarm message to the user. The connections of databases are closed. Now, one working cycle is done.

If preset backup time is reached, the temporary database changes its name to the current local date and a new empty temporary file is created. The timer will recall all

CHAPTER II

above steps every ten minutes. Finally, the user can stop the timer and exit the software.

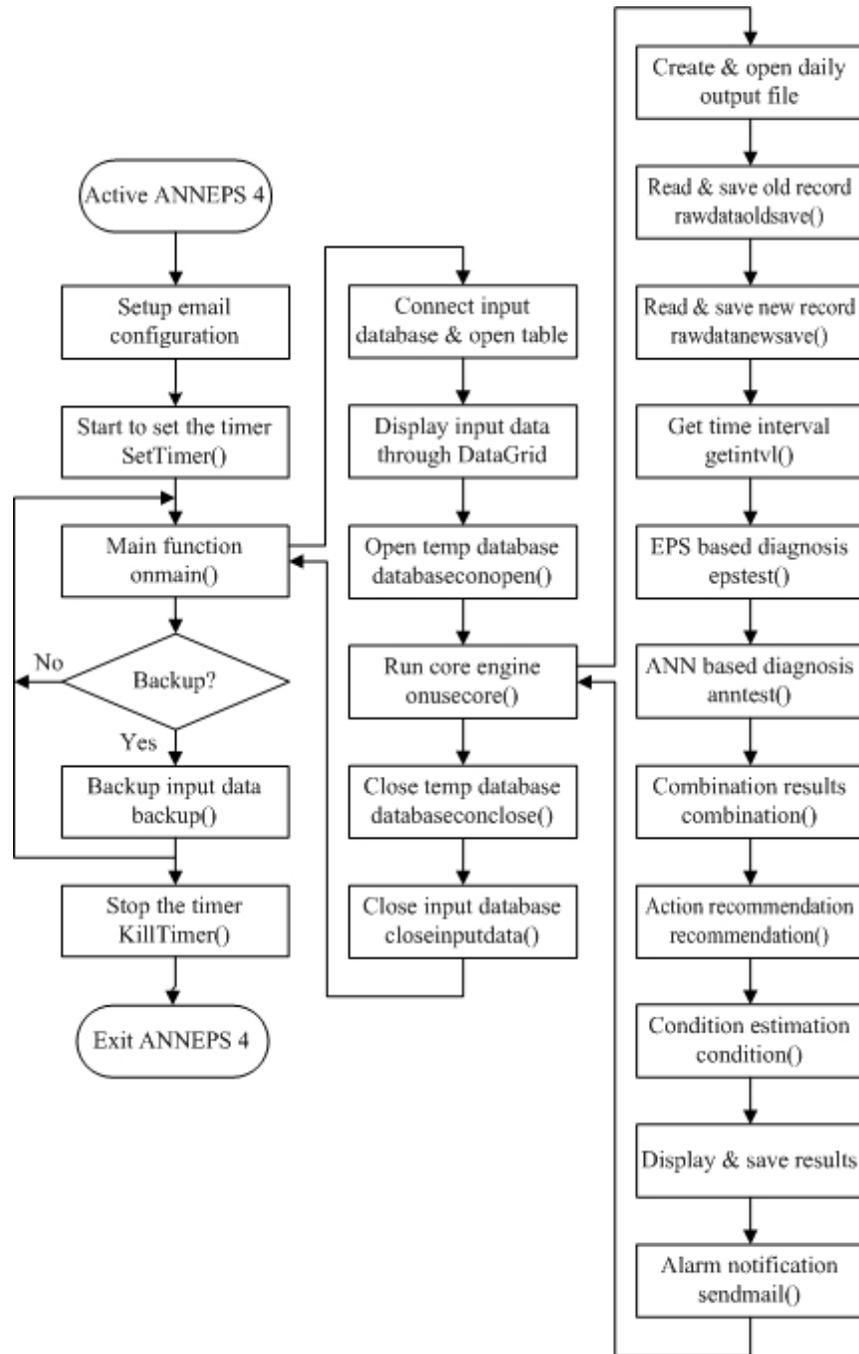


Figure 5 Flow chart of ANNEPS v4.0

Table 3 Description of class operations of ANNEPS v4.0

Operations	Description
------------	-------------

CHAPTER II

onconfigure()	Configuration dialog
onstart()	Set timer and activate main function
onmain()	Main function
onusecore()	Run diagnosis engine
getintvl()	Get time interval between two sets of oil samples
anntest(int)	Perform ANN based diagnosis
epstest()	Perform EPS based diagnosis
combination()	Combine two diagnosis results
recommendation()	Estimate the resample time
condition()	Evaluate the insulation condition of oil and paper
sendmail()	Active send email function
databaseconopen()	Open the connection with temp Access database
databaseconclose()	Close the connection with temp Access database
openinputdata()	Open the connection with input Access database
closeinputdata()	Close the connection with input Access database
rawdatanewsave()	Save new record into temp Access database
rawdataoldsave()	Save old record into temp Access database
automaticbackup()	Backup the database
backupornot()	Judge if backup needed
onstop()	Stop the timer
onexit()	Exit the ANNEPS

2.2.3.3 Alarm Notification Design

As part of monitoring, it is vital that the user can get alerted when there is a fault. The alarm processing application responds in various ways to alarms generated, such as, email, pager, cell phone, and so on. ANNEPS delivers email messages to user's e-mail box. The technique personnel can promptly know the condition of the transformer

CHAPTER II

whether he or she is on site or at the remote control room.

The alarm trigger is based on the combination result of EPS and ANN diagnosis methods. If the condition is abnormal, an alarm signal is set as true and alarm notification module enhances the functionality of alarm processing applications.

For this feature to work, the Simple Mail Transfer (SMTP) protocol is required. Several parameters need to be defined in the software code to enable it to correctly invoke the e-mail routine and consequently use the SMTP protocol to access the SMTP server. Figure 6 gives the basic idea of implementing the e-mail routine, and Table 4 lists operations of mail class.

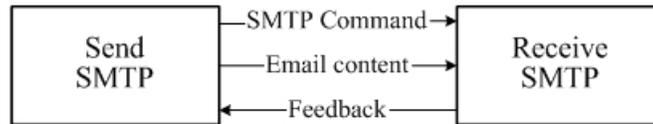


Figure 6 Routine of email notification

Table 4 Description of class mail operations

Operations	Description
sendmail()	Main function
login()	Send hello command
sendlogin()	Send data on a connected socket
back()	Test feedback function
con()	Create connect to the server
body()	Construct the email message
cut()	Close connect to the server
readtxt()	Read the context
base64()	Base64 content transfer encoding

CHAPTER II

A “Configuration” button on the graphical user interface (GUI) launches the configuration dialog box, as shown in Figure 7. The user can manually fill in the information in each edit box. These parameters are listed below:

Email Server: Input the address of SMTP server.

Account: Input the account name to log in the above server.

Password: Input the password to log in the above server.

From Email Address: This mail address is used as the sender’s address of alarm mail.

To Email Address: Input e-mail address of the user who will receive the notifications.



The image shows a "Configuration Dialog" window with a title bar containing a close button. The dialog contains five input fields, each with a label and a placeholder example: "Email Server:" with "(e.g.: smtp.domain.com)", "Account:", "Password:", "From Email Address:" with "(e.g.: sender@domain.com)", and "To Email Address:" with "(e.g.: receiver@domain.com)". At the bottom of the dialog are two buttons labeled "OK" and "Cancel".

Figure 7 Configuration dialog of email alarm notification

The message will include the transformer information, a brief description of diagnosis results, and the time of occurrence. One email sample is listed here.

Message Header

“From: sender@fromdomain.com

CHAPTER II

To: receiver@todomain.com
Sent: Monday, Nov 14, 2005 10:40 AM
Subject: ANNEPS v4.0 Fault Warning”

Message Body

“The following fault summary message is for

NAME: 9083-A; SERIAL NO: 84C08200;

DIAGNOSED FAULTS:

Possible overheating of oil or cellulose -- Confidence: 1.000

Overheating of oil involved -- Confidence: 1.000

Degradation of cellulose involved -- Confidence: 1.000

High energy discharge (sparking or arcing) involved -- Confidence: 0.990

Please go to the output file, 20051114-OUTPUT.out, for more details of the diagnosis results.

This is an automatically generated message! Please do not reply.”

2.3 Summary

An abbreviated overview of early version of ANNEPS was presented. After reviewing available on-line monitors, an automated on-line monitoring and diagnosis system for power transformers was proposed, followed by a more detailed look at the modules that make up the program.

The ANNEPS v4.0 has a friendly user interface which provides the real-time display of input data and diagnosis outputs. Different access database and text files can automatically be operated. The alarm notification function will provide the user the newest condition information of the transformer. The resulting system is developed to be an automated on-line monitoring and diagnosis system from a manually off-line analysis tool. It has much powerful diagnosis ability than any general on-line DGA monitor. The new ANNEPS system provides operators and maintenance engineers with an early

CHAPTER II

warning of the need for preventive maintenance or corrective actions.

2.4 References

- [2-1] “An Artificial Neural Network Approach to Transformer Fault Diagnosis”, Y. Zhang, X. Ding, Y. Liu, P. J. Griffin, IEEE Transactions on Power Delivery, Vol.11, No.4, Oct. 1996, Page(s):1836-1841
- [2-2] “A Combined ANN and Expert System Tool for Transformer Fault Diagnosis”, Zhenyuan Wang, Yilu Liu, P.J. Griffin, IEEE Transactions on Power Delivery, Vol.13, No.4, Oct. 1998, Page(s):1224-1229
- [2-3] “Artificial Intelligence Applications in the Diagnosis of Power Transformer Incipient Faults”, Zhenyuan Wang, Ph.D. dissertation, Aug. 2000
- [2-4] “An Expert System for Transformer Fault Diagnosis Using Dissolved Gas Analysis”, C.E. Lin, J.M. Ling, C.L. Huang, IEEE Transactions on Power Delivery, Vol.8, No.1, Jan. 1993, Page(s):231-238
- [2-5] www.gepower.com/home/index.htm
- [2-6] www.serveron.com/products/TG-tga-main.asp
- [2-7] www.kelman-usa.com/English/Products/transfix/Index.asp
- [2-8] www.meppi.com/gentran.html
- [2-9] www.gatron.de/start_e.htm

CHAPTER 3 STUDY OF MONITORING SYSTEM OF SUBSTATION BATTERIES

3.1 Basics of Substation Batteries

Each substation typically has its own backup battery power supply, as shown in Figure 8. In the event of a power failure, stationary batteries in the control house of the substation can provide back up power to support the control systems and other devices for several hours.



Figure 8 Backup batteries in the substation

As the last line of defense against total shutdown during power outages, users must be sure that their battery is sufficiently healthy to carry the intended load. Conventional battery maintenance programs consist of monthly, quarterly, and annual manual measurements of battery and cell voltages, specific gravity, fluid level, connection resistance, visual observation, and so on. These processes are costly, time-consuming, and labor-intensive. On-line battery monitoring could be a necessary and efficient way to improve the reliability and performance of the battery system. In order to design a

CHAPTER III

monitoring system for substation application, basic knowledge of battery will be discussed in the following subsections. Finally, the practical architecture of a monitoring system will be proposed.

3.1.1 Substation Battery Types

Substation batteries are required to provide high power to operate circuit breakers and other protective devices for a short period, while also providing low power for the continuous operation of lighting and control functions. There are several types of stationary batteries commonly used as backup power sources [3-1], and their benefits and drawbacks are listed in Table 5. By far, the lead-acid (LA) battery type is the most dominant use in substation applications. The flooded LA batteries were already reliable to maintain the operation of the control systems in substation. Because of their high maintenance cost, flooded battery has been gradually replaced by valve-regulated lead-acid (VRLA) battery. The following work is mainly focused on these two types of LA batteries.

Table 5 Substation battery types

Type of Battery	Benefits and Drawbacks
Vented lead-acid battery (unsealed)	Used for several decades, satisfactory service, but high cost of some battery maintenance operations
Valve-regulated lead-acid (VRLA) battery (sealed)	Alternative to vented LA battery, most commonly used, low cost, high energy density, and maintenance free
Nickel-cadmium (Ni-Cd) battery	Not extensively used in substations, high resistance ability to high temperature, but high initial cost
Other types (Ni-MH, Li-ion, and Li-polymer)	Not commonly used in substations

CHAPTER III

Newton-Evans [3-2] has conducted a survey about substation batteries among substation owners and engineers in the U.S. It indicated that most substations are using the standard 125 volt DC system. 60 cells with about 2.1 volt terminal voltage each are connected in series. The unit of 48 volt with 40 cells is the second commonly used. Smaller distribution substation is having a smaller 24 volt battery. The unit 250-volt with 60 cells is also used in some power generation station applications.

3.1.2 Substation Battery Failure Mode

An understanding of the potential failure modes of the battery employed is essential for designing a reliable monitoring system. Batteries with different cell chemistries and applications may fail in different ways. Here we outline some of the most common battery failures. They can be attributed to internal and external failure mechanisms during three steps of the battery life [3-3] [3-4] [3-5].

Battery design faults such as weak mechanical design, inadequate pressure seals and vents, the specification of poor quality materials and improperly specified tolerances can be responsible for many potential failures.

Some failures can be introduced during the manufacturing process. It is very difficult to achieve precision and repeatability using manual production methods. Poor weld and sealing quality can result in leaks and unreliable connections. Contamination of the active chemicals gives rise to unwanted chemical effects.

The personal or operating condition also influences the longevity of batteries. It includes personnel errors during operation, maintenance, and testing, and defective

CHAPTER III

procedures or set points. Some examples of the later are excessive cycling, low/high float voltage, high storage temperature, discharges without recharge, over discharge.

Because of chemical reactions, battery loses its capacity and its performance gradually deteriorates with time. This process is called normal aging which eventually results in battery failure.

These reasons outlined above could result in potential forms of battery failure such as overheating, thermal runaway, short circuits, increased internal impedance, reduced capacity, and more failures.

3.2 Technical Criteria of Battery Monitoring

The aim of battery monitoring is to get information of the condition of the battery especially under float and its ability to provide the reserve needed when a power outage occurs, not only at that moment but for a reasonable period in the future. Monitoring of a battery covers a wide range of possibilities, depending on the grade of supervision. A battery monitoring system (BMS) can occur in the simple form of manual measurements and comparison of the data (off-line monitoring), but also by expensive installations that continuously measure various parameters and automatically analyze the data (on-line monitoring) [3-6].

Some general demands on a monitoring system are:

- It has to check that each cell operates properly, such as, no abnormal voltage deviations;

CHAPTER III

- The monitoring system should indicate the state of charge and/ or the state of health of the battery;

- Abnormal operating conditions should release an alarm to maintenance personnel;

and

- It possibly provides certain operations responding to any abnormal conditions, such as cutting of discharge or charging currents.

To achieve these objectives, the BMS may follow one or more of the following technical criteria: measuring and analyzing battery electrical and non-electrical parameters; estimating state of charge (SOC) of batteries; and estimating state of health (SOH) of batteries.

3.2.1 Measurement and Analysis Parameters

Monitoring systems normally measure battery voltage, current, temperature, and so on. These collected parameters reflect the real time and trend behaviors of the battery variables. Together with their trend analysis, data can provide an indication of the battery status.

The common parameters used to implementing the battery monitoring and condition assessment algorithms are voltage, temperature and current measurements. To consider the incidences of both overall battery system and single cell failures, parameters in Table 6 are usually chosen to measure by all currently available battery monitoring systems listed in Appendix B, and systems stated in several reference papers [3-7][3-8][3-9] and books [3-6][3-10].

Table 6 Basic parameters for battery monitoring

	Parameters Measured	Technical Value
Cell Level	Individual cell DC voltages	To verify all cells are charging correctly
	Individual cell temperature	To signal thermal stress problem in cells
String/ System Level	Overall string charge and loaded voltage	To verify the charger has been set correctly and is properly operating
	String DC and AC current	Useful in VRLA batteries to detect thermal runaway conditions
	Ambient temperature	To verify the temperature environment is at or near optimum temperature for long life and maximum capacity

However, some reference papers [3-4][3-11][3-12][3-13][3-14][3-15][3-16] also recommend more parameters to be monitored such as resistance/impedance/conductance, specific gravity, and discharge, as shown in Table 7. Most available battery monitoring systems can provide the functions to measure and analyze resistance/impedance values beside the current, voltage, and temperature. The monitoring systems from Alber, Enersafe, and Lem can also store the discharge profiles [3-17][3-18][3-19]. The battery and cell management system from Serveron can measure the specific gravity of batteries [3-20]. As noted, special sensors should be used to measure these physical values. For example, a fiber-optic density sensor was developed for measuring specific gravity of the electrolyte in a lead acid battery [3-21]. Also, the battery conductance transducer from Monitron is special for only measuring the conductance of battery and very expensive [3-22].

The cost and complexity of battery monitoring systems typically increase with the

CHAPTER III

number of additional parameters measured. However, each additional parameter adds to the accuracy and diagnostic capability of the monitoring system. “IEEE Standard 1491-2005,” which has recently been published, presents more measurable parameters of batteries for battery monitoring purpose. They are voltage (float, equalizing, recharge, open-circuit, discharge, midpoint, and AC ripple voltages), current (discharge, charge, float, and AC ripple currents), temperature (cell/battery and ambient temperatures), interconnection resistance, internal ohmic values, specific gravity, electrolyte level, Coup de Fouet, discharge run-time analysis, and ground fault detection [3-23].

Table 7 Additional parameters for battery monitoring

Parameters Measured	Technical Value
Cell specific gravity	To determine the state of charge (SOC) by measuring the specific gravity of the electrolyte in the cells
Cell resistance/impedance/conductance	To verify the state of health (SOH) by identifying low capacity cells
Battery discharge profile	To determine the state of health (SOH)

3.2.1.1 Temperature Analysis

The temperature is a critical parameter for stationary batteries, especially lead-acid batteries. The effects of temperature extremes in both cell (internal) and ambient (external) conditions have a tremendous impact on battery performance and life. The increased temperature causes faster positive grid corrosion as well as other failure modes. The temperature that need be monitored includes ambient temperature, t_{amb} , and cell temperature, t_i , which i indicates the number of each cell. An alarm will be activated once the temperature difference between the maximum and the minimum cells goes beyond

CHAPTER III

the limit T_A . Most backup batteries are designed to last around 20 years at temperatures around 77 degrees Fahrenheit (25 degrees Celsius). For every 18 degrees Fahrenheit increase in temperature, the battery life is cut in half. The temperature difference between each cell and ambient and each battery temperature compared with the maximum temperature requirement also need to be checked. The flow chart in Figure 9 was tested using temperature data provided by ABB. The codes in C are listed in Appendix C.

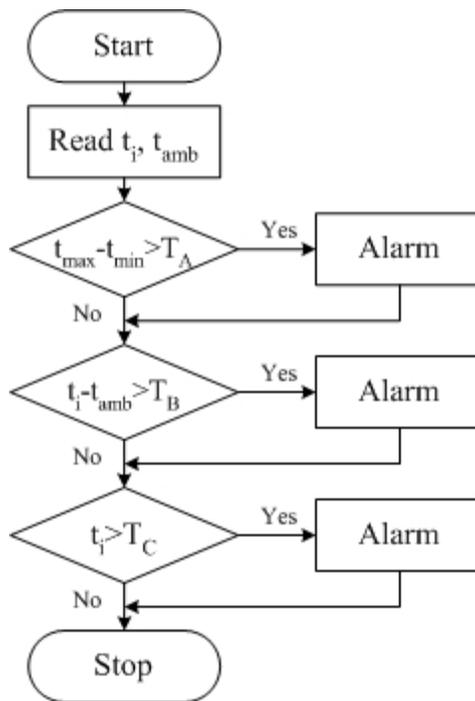


Figure 9 Flowchart of temperature analysis

Table 8 Variable specification for temperature data

Symbol	Specification
t_{amb}	Measured ambient temperature
t_i	Measured individual cell temperature
t_{max}	Maximum cell temperature
t_{min}	Minimum cell temperature

CHAPTER III

T_A	Specified differential limit between maximum and minimum cell temperatures
T_B	Specified differential limit between battery and ambient temperatures
T_C	Specified maximum cell temperature limit

3.2.1.2 Current Analysis

In standby power systems, batteries are deployed in a manner where the battery spends the majority of time operating in a “float” or standby condition. In a float condition, a small current passes through the battery that effectively replaces capacity lost due to self-discharge and maintains the battery at full capacity. If the float current increases due to some impending failure or overcharging condition, the temperature increases. The increased temperature allows more current to flow and further increases the temperature of the battery, then causing thermal runaway. Therefore, float current is an important parameter to measure, especially in VRLA-type battery systems. If the measured float current exceeds the maximum float current, it will set an alarm signal.

Ripple current is a by-product of the conversion process of converting ac into dc by the rectifier circuit of the charger [3-24]. Filters in the charger reduce the effects of ripple current. However, ripple current will increase while these circuit components degrade. As with float current, an increase in ripple current to a certain point leads to increased temperature and shortened battery life. Thus, monitoring ripple current periodically ensures proper charger operation and helps ensure a healthy battery system. If ripple current exceeds this amount, the technical personnel should receive an alarm and repair or replace the charger.

CHAPTER III

The flow chart of analyzing float and ripple currents of batteries is shown in Figure 10.

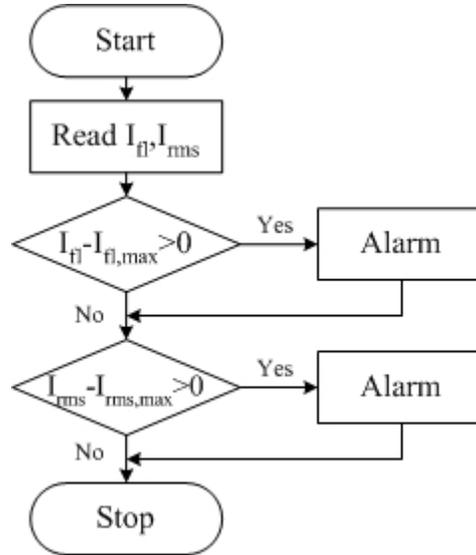


Figure 10 Flowchart of current analysis

Table 9 Variable specification for current data

Symbol	Specification
I_{fl}	Measured float current
$I_{fl,max}$	Specified maximum float current limit
I_{rms}	Measured superimposed effective ripple current *
$I_{rms,max}$	Specified maximum ripple current limit

*Note: IEC guide mentions that the effective ripple current can be calculated by the equation, $I_{rms} = \sqrt{\sum_{i=1}^k I_i^2}$, where i is an integer number; k is the number of harmonic frequencies; I_i are the AC currents.

3.2.1.3 Voltage Analysis

CHAPTER III

Float voltage can be one of easily measured parameters. While voltage readings of individual cells are usually monitored and compared with the limit, the sum of the voltages of all the batteries is also important and must equal to the output of the charger. This condition ensures that the charger is functioning properly. While an abnormal reading on a cell does indicate the condition of that cell and requires further investigation by watching the trends over time.

The flow chart of analyzing float voltages of batteries is shown in Figure 11.

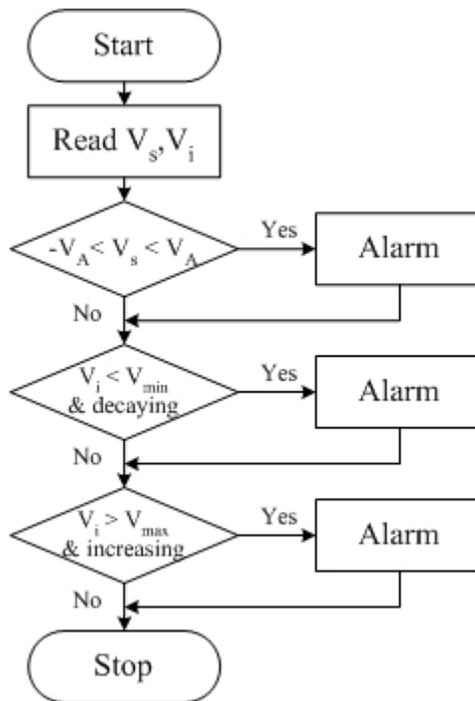


Figure 11 Flowchart of voltage analysis

Table 10 Variable specification for voltage data

Symbol	Specification
V_s	Measured battery string voltage (volts)
V_i	Measured individual cell voltage (volts)
V_A	Specified float voltage range for the battery string (percentage of volts)

CHAPTER III

V_{\min}	Specified minimum float voltage limit for the cells (volts)
V_{\max}	Specified maximum float voltage limit for the cells (volts)

3.2.1.4 Internal Ohmic Analysis

Internal battery problems can be detected by monitoring the internal ohmic value of each cell in the battery system. The internal ohmic value can be any value of resistance, conductance, or impedance derived from the relationships between changes in voltages and currents [3-23]. The flow chart in Figure 12 was tested using impedance data provided by ABB. The codes in C are listed in Appendix D. After the magnitude of each cell AC voltage and injected AC test current are measured, the impedance is calculated for each cell. The values from the initial test should be stored as the initial values. The cell average values are calculated for each string and are used to generate a battery index, Z. If Z exceeds a maximum percentage level, an alarm is set off. Also, if cell impedance goes outside preset limits compared to a percentage of the string average, it may indicate a fault.

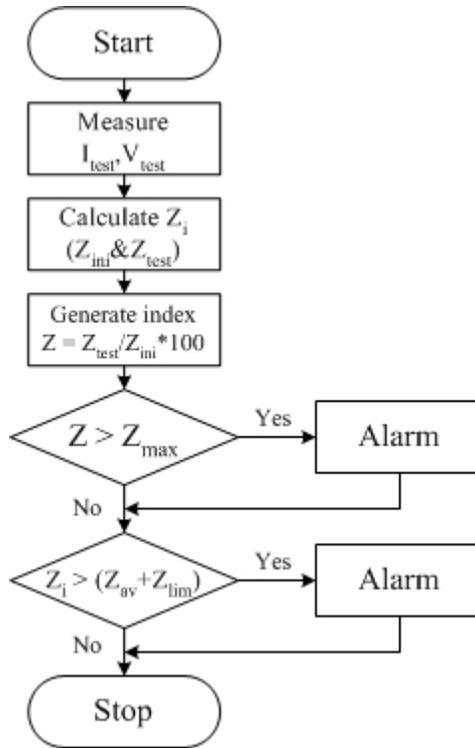


Figure 12 Flowchart of internal ohmic analysis

Table 11 Variable specification for internal ohmic data

Symbol	Specification
Z_i	Calculated Cell impedance
Z_{ini}	Average initial impedance
Z_{test}	Average test impedance
Z	Battery impedance index
Z_{max}	Specified maximum impedance limit
Z_{av}	Average impedance
Z_{lim}	Specified maximum impedance percentage level limit

3.2.1.5 On-line Discharge Analysis

On-line discharge test can assess the state of a battery. At the end of discharge, the voltage of each cell should not exceed the minimum system voltage. If any voltage falls

CHAPTER III

outside limits compared to the string average may activate an alarm. The flow chart of analyzing on-line discharge of batteries is shown in Figure 13.

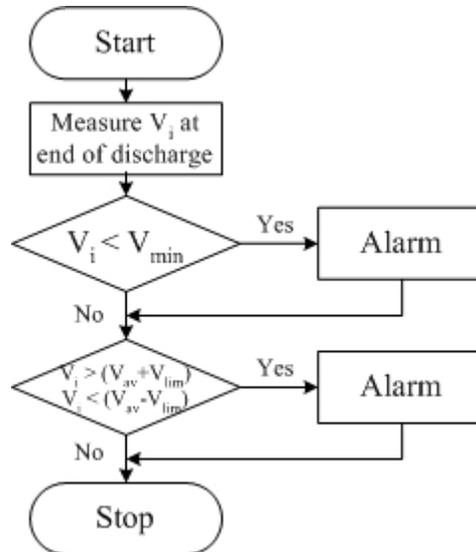


Figure 13 Flowchart of on-line discharge analysis

Table 12 Variable specification for on-line discharge analysis

Symbol	Specification
V_i	Measured individual cell discharge voltage
V_{min}	Specified minimum discharge voltage limit
V_{av}	Average cell voltage, $V_{av} = (V_1 + V_2 + \dots + V_n) / n$
V_{lim}	Specified voltage percentage level limit

The limits mentioned above should be set up follow manufacturers' guidelines or according to the requirements of the users' specific applications in order to gain the most life from a battery without increasing the risk.

3.2.2 Determination of Battery State

Battery and environmental parameters should be monitored to produce an accurate

CHAPTER III

measurement of the battery state-of-charge (SOC) and state-of-health (SOH). These SOC and SOH diagnostics will be further used to warn any impending battery failure [3-25] [3-26].

3.2.2.1 State of Charge Determination

The state of charge of a battery is its available capacity expressed as a percentage of its rated capacity. Knowing the amount of energy left in a battery compared with the energy it had when it was new gives the user an indication of how much longer a battery will continue to perform before it needs recharging. The cell capacity gradually reduces as the cell ages and it is also affected by temperature and discharge rate. These aging and environmental factors must therefore be taken into account if an accurate estimate is required. The existing techniques for the determination of battery SOC are shown in Figure 14, as given by the references [3-10] [3-27].

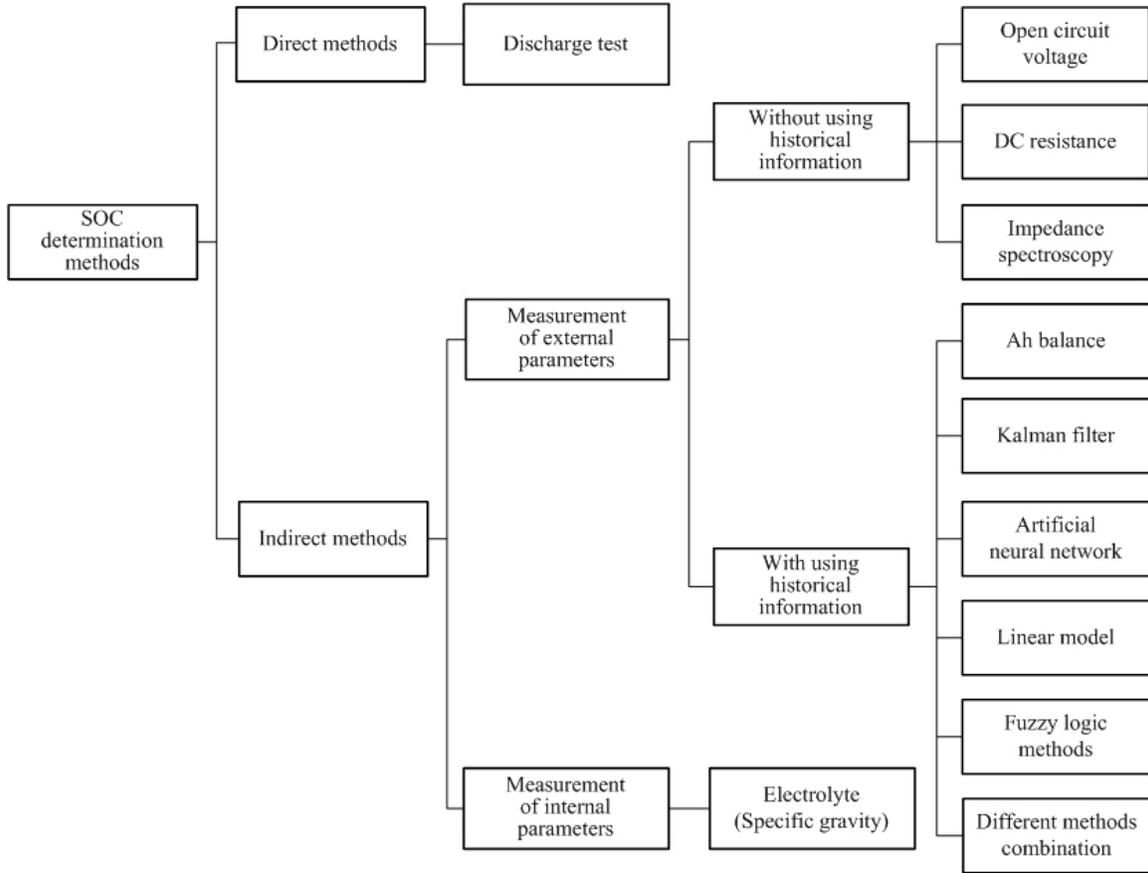


Figure 14 Methods of battery SOC determination

The direct method of determining SOC is taking a discharge test, which is also called a capacity test. It can give the information about the available charge of a battery. However, this process is time consuming and expensive, and it modifies the battery state and often drastically shortens battery’s operational life-time. Because of the need for disconnecting and reconnecting the battery, discharge test is not suitable for on-line monitoring purpose.

The indirect methods of determining SOC can be based on the measurement of internal parameters (electrolyte or active mass parameters) or external parameters (temperature, voltage, and current).

CHAPTER III

For determination by measurement of internal parameters, it is possible to measure a representative electrolyte parameter, for example, measurement of specific gravity (SG). It depends on measuring changes in the weight of the active chemicals. As the battery discharges the active electrolyte is consumed and the concentration of the sulphuric acid in water is reduced. This in turn reduced the specific gravity of the solution in direct proportion to the state of charge. The measurement is performed with a hydrometer which is impractical for continuous use. Nowadays developed electronic or fiber-optic density sensors [3-21] can be incorporated directly into the cells to give a continuous and accurate reading of the battery condition.

The measurements of external parameters are based on the relation between current and voltage, with or without taking into account the history of the battery. Essentially, the SOC is determined by integrating the current flow over time, modified to take account of the many factors which affect the performance of the cells, then subtracting the result from the known capacity of the fully charged battery.

3.2.2.2 State of Health Determination

The state of health reflects the general condition of a battery and it is used to estimate losses in rated capacity, as well as predicting impending failures. Unlike the SOC which can be determined by measuring the actual charge in the battery there is no absolute definition of the SOH. It takes into account such factors as charge acceptance, internal resistance, voltage and self-discharges [3-28].

The discharge test mentioned above can be also used to determine the state of health

CHAPTER III

of a battery. The discharge profile includes two major values: end of the discharge voltage (cut-off voltage), and voltage dip at the beginning of the discharge called Coup de Fouet (CDF). The CDF phenomena might be one of the indicators of battery state of health.

Any parameter which changes significantly with age, such as cell impedance or conductance, can be used as a basis for providing an overall indication of state of health of a battery when combined with additional information. The presently available instruments use either an AC current injection method (instruments known as impedance or conductance meters) or a momentary load test (DC measurement). The AC injection instruments apply an AC current through the battery and measure the resulting AC voltage drop across battery and current. Since the battery capacitance is huge and the reactance component defined by capacitance is extremely low, the AC voltage drop represents the practical resistance of the battery. However, AC instruments are limited and cannot be used while the battery is on-line because they are susceptible to charger ripple currents and other noise sources. The DC load test instruments subjects the battery to a momentary load current and measures the instantaneous change in battery terminal voltage. Because of the internal resistance, the voltage instantaneously drops when the load is applied and the instantaneous voltage recoveries when the load is removed. The resultant resistance is simply $R = V/I$. This type of instrument is capable of operating on-line, even in high noise environments.

As noted in reference [3-29], there exist no universally accepted criteria for utilizing measurements. Detailed criteria and associated procedures can be worked out based on specific battery data provided by and in close cooperation with the battery manufacturer.

3.3 Architecture of Battery Monitoring System

The battery monitoring system has three main building parts: multiple sensors, a battery monitoring unit (BMU), and connection and communication networks [3-7] [3-8] [3-23]. Figure 15 illustrates a conceptual representation of the primary battery monitoring system functions.

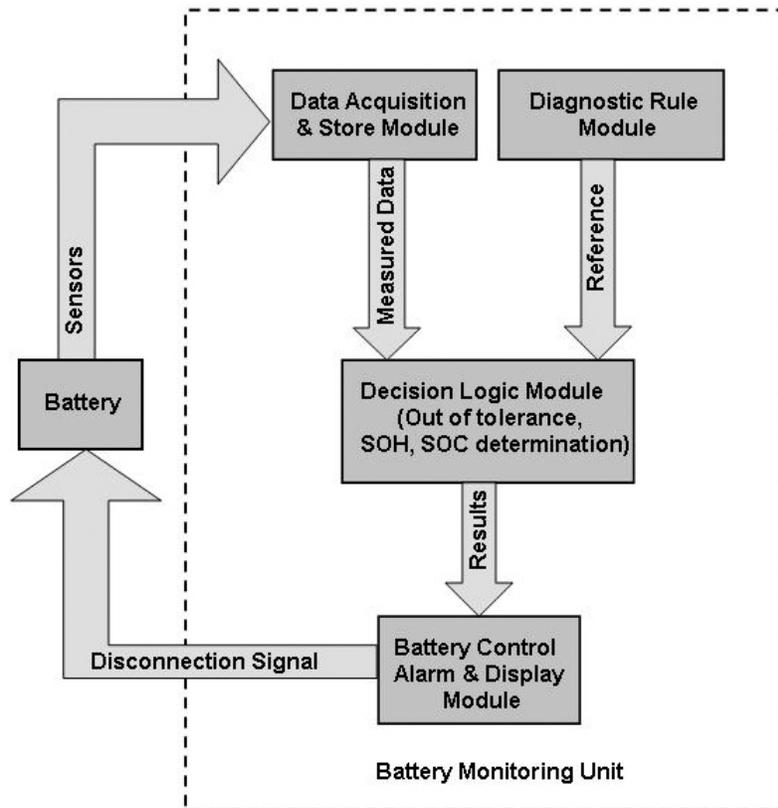


Figure 15 Architecture diagram of battery monitoring system

1. Multiple Sensors

Depending on the system configuration, multiple parameters can be measured at each cell and string. These different sensors measure voltages, currents, and temperatures listed in Table 6 and specific gravity listed in Table 7.

CHAPTER III

2. Communication Networks

The connections among batteries, sensors, and the monitoring unit may be used by fiber optic cable or other medium. Access to the BMU for setting system parameters and for downloading the battery history can be provided through common communication links, such as Fieldbus, standard RS 232 or RS485 serial bus, or Modbus.

3. Battery Monitoring Unit

The battery monitoring unit is designed to perform following operations: data acquisition data from sensors, data storing, data processing and analysis, and alarm mode of operation. It can be divided into four main functions or sub-modules. These sub-modules are not necessarily separate physical units but are shown separately here for clarity.

(a) Data Acquisition and Store Module

The data acquisition and store module can control the sensors, collect data from connected sensors in predefined time periods, and make data archives. Also, this module should have the function to check whether the sensors and connections functionally work or not.

(b) Diagnostic Rule Module

The diagnostic rule module contains a reference model with all the tolerances and limits relevant to the various parameters monitored by the data acquisition module. This module allows the user to set alert and alarm levels on all parameters into the system

CHAPTER III

which are specific to their application.

(c) Decision Logic Module

The decision logic module characterizes in a software algorithm. It compares the status of the measured or calculated battery parameters from the data acquisition module with the desired or reference result from the diagnostic rule module. Then, it estimates the status of the battery (SOC and SOH) at any instant in time in response to various external and internal conditions. The procedures of measurements and analysis for specific parameters are shown in Figure 16. The flow chats of measuring and analyzing individual parameters shown in Figures 9 to 13 are implemented in decision logic module.

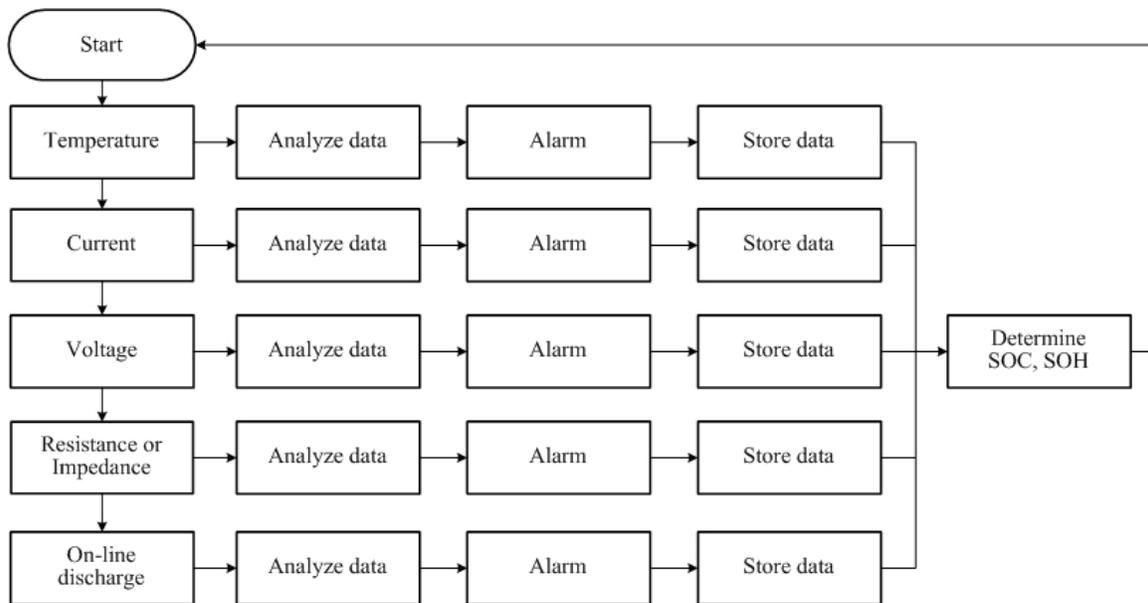


Figure 16 Flow chart of decision logic module

(d) Battery Control, Alarm, and Display Module

Battery control, alarm, and display module generates a sound or light signal on site or

CHAPTER III

sends a notice to the substation personnel once the system is in any abnormal state. Based on the latest set of measurements, the system, string and individual batteries can be categorized in one of three states, normal, alert and alarm indicated by the colors green, yellow and red respectively. Alarm conditions may take precedence over alert conditions.

- Normal state (Green): A battery is in normal state, indicated by green, if all measured parameters are inside their preset limits.

- Alert state (Yellow): A battery is in alert state, indicated by yellow, if any of the battery's measured parameters are outside their maintenance limits but are all inside their critical limits.

- Alarm state (Red): A battery is in alarm state, indicated by red, if any of the battery's measured parameters are outside their critical limits.

The module also allows the user to view the data collected from the sensors in the form of tables, reports, and diagrams. Data can be seen in different data views: system overview, string and cell summary view, cell condition view and trend view. It only displays data based upon what is stored in the battery monitoring unit database. After each database update, close and reopen the battery information to see the latest status.

- System Overview: The system overview presents summary states for the overall system, each site and each battery.

- String and Cell Summary View: The string and cell summary view show the basic status of the battery strings and cells symbolically or numerically.

CHAPTER III

- Cell Condition View: The Cell Condition View displays data in bar chart form, with each bar representing one cell. This view can be used to compare measured values between cells of a battery.

- Trend View: The Trend view shows line graphs of measured string and cell values over time. This view is used to see parameter changes over time which the user select the start and end dates and times. Both string and cell parameters can be shown in the Trend view. Cell parameters can be shown in two modes: single mode or summary mode. In single mode, all cell parameters are shown for one particular cell. In summary mode, the minimum, average and maximum parameter values are shown over all cells.

Finally, the module may provide protection function by disconnecting the battery from the load or charger.

3.4 Summary

As providing reliable back up power in any substation in case of any power outage, the conditions of battery systems are critical. Compared to traditional regular onsite maintenance methods, an on-line battery monitoring system will present the real-time performance of battery systems with reduced costs and increased reliability of the system.

The basic knowledge of stationary batteries, including battery types used in substations and typical failure mode, has been discussed. The available monitoring devices have also been surveyed. Finally, an on-line battery monitoring system is proposed. The system is to monitor and trend all battery information over time and determine the states of charge and health of battery systems. The measured parameters

CHAPTER III

include temperature, float voltages, float current, internal resistance, and on-line discharge files. This study provides basics for further design of battery monitoring system in industry applications.

3.5 Glossary of Battery Terms

Aging - Permanent loss of capacity with frequent use or the passage of time due to unwanted irreversible chemical reactions in the cell.

Active material - The material in the electrodes that takes part in the electrochemical reactions which store and deliver the electrical energy.

Battery - A number of cells arranged into a DC electrical storage system. Usually this will consist of a number of strings of cells or jars arranged in parallel.

Cell - The basic unit of a battery. An electrochemical system that converts chemical energy into electrical energy.

Cut-off voltage - The specified voltage at which the discharge of a cell is considered complete.

Coup de fouet (CDF) - A dramatic initial voltage drop when a battery is suddenly called upon to supply a heavy load. The voltage recovers after a short time once the electro-chemical discharge process stabilizes.

Depth of discharge (DOD) - The ratio of the quantity of electricity or charge removed from a cell on discharge to its rated capacity.

Discharge rate - The current at which a battery is discharged, can be expressed in ampere-hours.

Electrolyte - The medium which provides ionic conductivity between the two electrode polarities of a cell.

Float Voltage - A constant voltage applied to a battery to maintain the battery capacity.

Flooded (vented) cell - A cell in which the products of electrolysis and evaporation are allowed to escape to the atmosphere as they are generated. These batteries are also referred to as “vented.”

Internal impedance - Resistance to the flow of AC current within a cell. It takes into account the capacitive effect of the plates forming the electrodes.

Internal resistance - Resistance to the flow of DC electric current within a cell, causing a voltage drop across the cell in closed circuit proportional to the current drain from the cell. A low internal impedance is usually required for a high rate cell.

Jar/ Monobloc: American/European term for a multiple cell container.

CHAPTER III

Over-charge - Continuous charging of the battery after it reaches full charge. Generally overcharging will have a harmful influence on the performance of the battery which could lead to unsafe conditions. It should therefore be avoided.

Over-discharge - Discharging a battery below the end voltage or cut-off voltage specified for the battery.

Rated capacity - The capacity assigned to a cell by its manufacturer for a given discharge rate, at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.

Self-discharge - Capacity loss during storage due to the internal current leakage between the positive and negative plates.

Specific Gravity (SG) - The ratio of the weight of a solution compared with the weight of an equal volume of water at a specified temperature. It is used to determine the charge condition in lead acid batteries.

State of Charge (SOC) - The available capacity of a battery expressed as a percentage of its rated capacity.

State of Health (SOH) - A measurement that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery.

String - A sub division of a battery. Often a battery will consist of several strings of series connected cells or jars. These strings are arranged in parallel.

Thermal runaway - A condition in which an electrochemical cell will overheat and destroy itself through internal heat generation. This may be caused by overcharge or high current discharge and other abusive conditions.

Valve-regulated lead-acid (VRLA) cell - A cell that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds atmospheric pressure by a pre-selected amount. VRLA cells provide a means for recombination of internally generated oxygen and the suppression of hydrogen gas evolution to limit water consumption.

3.6 References

- [3-1] "Substation Battery Options: Present and Future", James A. McDowall, IEEE Power Engineering Review, November 2000
- [3-2] "Substation Battery Management and Monitoring", MARKET TRENDS DIGEST for the Computer, Communications, and Controls Industries, Vol.18, Third Quarter 2002
- [3-3] "IEEE Std 1375-1998 Guide for the Protection of Stationary Battery Systems"
- [3-4] "Battery Monitoring: Why Not Do It Right?" Alber Corp. Application Note, www.albermonitor.com/Docs2/MonRight0999.pdf

CHAPTER III

- [3-5] “Battery Failure Prediction”, Manfred R. Laidig , John W. Wurst, BTECH Inc. Whippany, New Jersey
- [3-6] “Maintenance-Free Batteries: Lead-Acid, Nickel-Cadmium, and Nickel-Hydride: A Handbook of Battery Technology,” D. Berndt, John Wiley and Sons, Inc., 2003
- [3-7] “Single Cell Battery Management Systems (BMS)”, Gotaas, E.; Nettum, A.; Telecommunications Energy Conference, 2000 INTELEC. Twenty-second International, 10-14 Sept. 2000, Page(s):695~702
- [3-8] “The Monitoring System of Valve Regulated Lead-Acid Batteries – BMS”, Romuald Kaniewski, Franciszek Kotz; National Institute of Telecommunications, Poiand
- [3-9] “Knowledge Based VRLA Battery Monitoring and Health Assessment”, Anbuky, A.H.; Pascoe, P.E.; Hunter, P.M.; Telecommunications Energy Conference, 2000 INTELEC. Twenty-second International, 10-14 Sept. 2000, Page(s):687~694
- [3-10] “Valve-Regulated Lead-Acid Batteries”, D.A.J. Rand, ELSEVIER Inc., 2004
- [3-11] “Life Management of Station Batteries through Cell Management”, Gary W. McDermott, EPRI Substation Equipment Diagnostics Conference, February, 2002
- [3-12] “Monitoring System for Lead-Acid Wet Cell Station Batteries”, J. Rasmussen; C. Feyk, Proceedings of the American Power Conference, 1994, Vol. 53-56, Page(s):1235-1240
- [3-13] “Battery Monitoring and Integrity Testing of Large Lead-Acid Storage Batteries”, Glenn Alber, Journal of Power Sources, Vol. 17, No. 1-3, Jan-April 1986, Page(s):203-206
- [3-14] “Battery State of Health Monitoring, Combining Conductance Technology with Other Measurement Parameters for Real-Time Battery Performance Analysis”, Daniel C. Cox, Regina Perez-Kite, Telecommunications Energy Conference, 2000. INTELEC. Twenty-second International, 10-14 Sept. 2000, Page(s):342-347
- [3-15] “Emerging Issues and Solutions in Battery Monitoring System Design and Application”, Wojciech Porebski, V.P. Engineering, Enersafe Inc., St. Petersburg, Florida
- [3-16] “Secondary Cells and Batteries - Monitoring of Lead Acid Stationary Batteries - User Guide”, CE/IEC/TR 62060, First edition, 2001-09
- [3-17] www.alber.com/Products.htm
- [3-18] www.enersafeinc.com/products.html
- [3-19] www.lemcellguard.com/featured-products.php
- [3-20] www.serveron.com
- [3-21] “A Fiber-optic Density Sensor for Monitoring the State-of-Charge of a Lead Acid Battery”, Hancke GP, Description IEEE Transactions on Instruments and Measurements 39(1) 247-250

CHAPTER III

- [3-22] www.midtronics.com
- [3-23] “IEEE 1491-2005 Guide for Selection and Use of Battery Monitoring Equipment in Stationary Applications”
- [3-24] C&D Technologies, “Charger Output AC Ripple Voltage and the Effect on VRLA Batteries”, www.dynastybattery.com/contact/tech_support/pdf/2131.pdf
- [3-25] “IEEE Std 450-2002 Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications”
- [3-26] “IEEE Std 1188-1996 Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications”
- [3-27] “Methods for State-of-Charge Determination and their Applications”, S. Piller, M. Perrin, Journal of Power Sources, Vol. 96, Page(s): 113-211, 2001
- [3-28] “Are Internal Cell Parameter Measurements a Substitute or Supplement to Capacity Testing”, Glenn Alber, NE Utilities Battery Conference. Albany, NY 1994
- [3-29] “New Approaches to Battery Monitoring Architecture, Design and Methodologies”, Wojciech Porebski, Enersafe Inc.
- [3-30] www.on-lineinc.com/lvira.html
- [3-31] www.multitel.com/RemoteMonitoring.asp
- [3-32] www.cellwatch.com/

CHAPTER 4 CONCLUSIONS

4.1 Conclusions

With monitoring and diagnosis system, substation owners gain real-time conditions of equipment based on parameters measured and, even more important, the ability to receive early warnings of any abnormal problems and to place efficient maintenance actions. It helps to consistently achieve demanding goals of both minimum risk and maximum performance of electric power delivery systems.

In this thesis work, the functions of ANNEPS v3.0 software have been extended. The new tool is constantly running to retrieve information from monitors or sensors, interpreting the data by using an artificial neural network and expert system diagnostic engine, achieving the raw data and analysis results, and sending notifications of problem alarms. ANNEPS v4.0 has been developed to be an automated transformer monitoring and diagnosis system.

A study of on-line monitoring system for stationary batteries in substation has been conducted including battery types, failure modes, monitoring parameters and implementation, and on-line monitoring devices available on the market. The architecture of a monitoring system has been proposed.

4.2 Future Research

In order to make the ANNEPS v4.0 system work in a real application, further

CHAPTER IV

development is necessary. The first thing is to obtain the information from the DGA monitor company such as its database format and databases connection methods. According to that information, necessary modifications will be needed. The second work is to test the topology of ANNEPS based on continuous on-line input data. Also, the system can be extended to simultaneously perform more than one transformer. As this would enlarge the amount of data considerably, major problems that would be encountered are the slow computation time of results and the sequence of accessing multiple databases.

Along with measured battery parameters available, algorithms of float voltage, float current, and on-line discharge analysis will be programmed and tested. The software design work may include databases design for storing measured parameters data and interface design for displaying real-time values and their trends.

APPENDICES

Appendix A ANNEPS Software User's Manual v4.0

BEFORE YOU BEGIN

About this guide

This User Manual provides the information that you need to setup and use ANNEPS software.

Introduction

The ANNEPS is an automated on-line transformer monitoring and fault diagnosis system using dissolved gas-in-oil analysis (DGA).

ANNEPS simply retrieves measurements from the on-line DGA monitor. It takes advantage of the inherent positive features of the artificial neural network method and the expert system method and offers more accurate diagnosis results. It also provides on-screen data and result display and alarm email notification.

New Features

The ANNEPS interface is designed to provide the user with both on-screen data and diagnostic results as well as a convenient set of buttons for operating the software.

The ANNEPS automatically retrieves and stores measurements at preset time period. It also provides daily raw data and diagnosis result backup.

Once the diagnosis engine indicates an “abnormal” condition, a notification with a brief fault description is sent to the user through e-mail.

USING ANNEPS

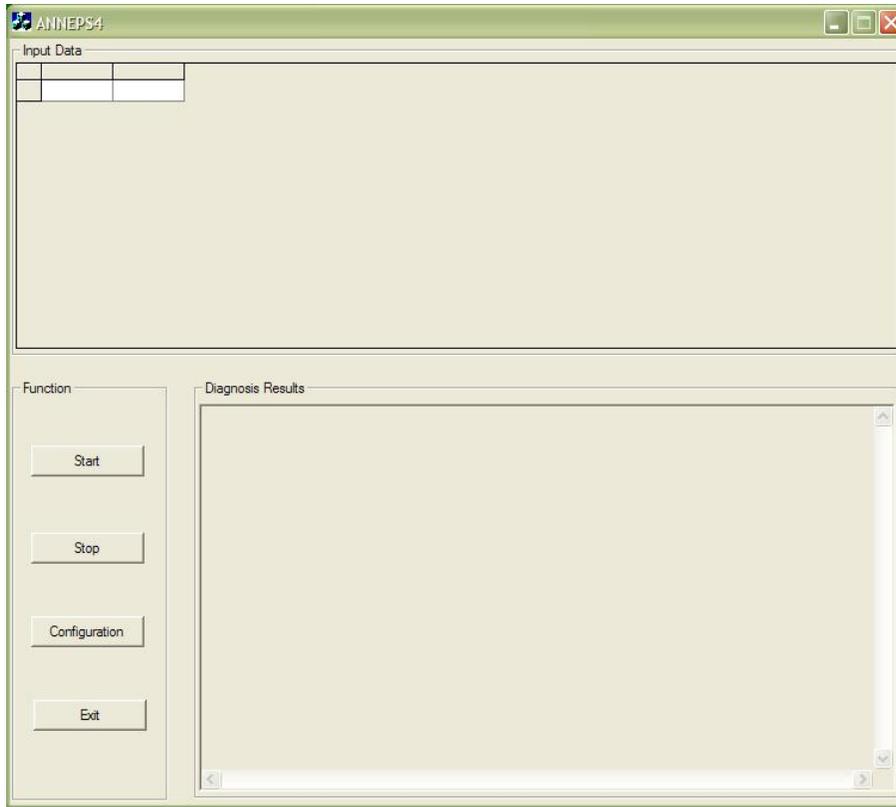
Activation

The files in “ANNEPS4.zip” are needed to run the program. They are to be in the same working directory. Upon a successful extraction of the .zip file, the program folder should contain an executable file, ANNEPS4.exe to start the software.



Click this file to launch the main window. At this point, both input and output areas are blank and there is no any information in the computer memory and databases.

APPENDICES



Initialization

First, the alarm notification needs to be configured. Otherwise, the software will fail to send out alarm messages to the remote user if any fault is detected. Press the “Configuration” button, the window to set up email information will appear.



These parameters are listed below:

Email Server: Input the address of SMTP server.

Account: Input the account name to log in the above server.

APPENDICES

Password: Input the password to log in the above server.

From Email Address: This mail address is used as the sender's address of alarm mail.

To Email Address: Input e-mail address of the user who will receive the notifications.

Enter the email server, account, password, from email address, and to email address, then press "OK."

Running

Press "Start" button at the function area to begin the main function, and also set a ten-minute timer which recalls the main function every ten minutes.

After creating an input database connection, the current data in memory are displayed on the screen through Datagrid. At the same time, the data is also stored into temporary input database, tempdb.mdb.

The diagnosis results are displayed on the screen and saved into the output file, for example, 20051114-OUTPUT.out.

The screenshot displays the ANNEPS4 software interface. The top section is titled "Input Data" and contains a table with 20 rows and 9 columns: IndexNo, MFG, SN, NAME, MVA, PRI, SEC, TER, and a final column with values -1. The bottom section is titled "Diagnosis Results" and contains a table of gas-in-oil analysis data, a "Misc." section, and a detailed diagnosis report.

IndexNo	MFG	SN	NAME	MVA	PRI	SEC	TER	
10	Mol	2118065	bank#2	28	66	-1	-1	-1
11	FPE	F27572	1,2,3	30	138	-1	-1	-1
12	FPE	F27572	1,2,3	30	138	-1	-1	-1
13	MOL	P660408	UT-T2	20	69	-1	-1	-1
14	MOL	P660408	UT-T2	20	69	-1	-1	-1
15	A-C	5577940	None	5	67	-1	-1	-1
16	A-C	5577940	None	5	67	-1	-1	-1
17	RSE	196451	X-MEZ	3.1	38	-1	-1	-1
18	RSE	196451	X-MEZ	3.1	38	-1	-1	-1
19	other	84C08200	9083-A	2	38	-1	-1	-1
20	other	84C08200	9083-A	2	38	-1	-1	-1

Gas-In-Oil:	O2	N2	CO2	CO	H2	CH4	C2H6	C2H4	C2H2
(ppm)	18200	68700	2630	218	70	19	6	40	0
(+ = excessive):			+	+					

Misc.: H2O(ppm) FUR(ppm) PD(μV) PF DP KOH(mg/g) IFT(mN/m)
Data: 23.0 -1.0000 -1 -1.000 -1 -1.000 -1.0
(Negative value = not available)

FAULT DIAGNOSIS BASED ON DISSOLVED GAS-IN-OIL ANALYSIS

Simple criteria indicate that the unit is ABNORMAL

DETAILED DIAGNOSIS:
Fault type abbreviation: OH OHO LED HEDA CD
Expert system based diagnosis: 0.010 0.010 0.010 0.990 0.010
Neural network based diagnosis: 0.994 0.000 0.006 1.000 0.983

DIAGNOSED FAULTS:
Possible overheating of oil or cellulose -- Confidence: 0.994
Degradation of cellulose involved -- Confidence: 0.983
High energy discharge (sparking or arcing) involved --
-- Confidence: 0.990 Severity level: SEVERE!

Database Backup

If preset backup time is reached, the temporary database changes its name to the current local date and a new empty temporary file is created. For example, 20051221-INPUTBACKUP.mdb.

Exit

Press "Stop" button to stop the timer and cut the connection from input database. Press "Exit" button to exit the software.

Email Sample

One email sample is listed here.

Message Header:

APPENDICES

“From: sender@fromdomain.com
To: receiver@todomain.com
Sent: Monday, Nov 14, 2005 10:40 AM
Subject: ANNEPS v4.0 Fault Warning”

Message Body:

“The following fault summary message is for
NAME: 9083-A; SERIAL NO: 84C08200;
DIAGNOSED FAULTS:
Possible overheating of oil or cellulose -- Confidence: 1.000
Overheating of oil involved -- Confidence: 1.000
Degradation of cellulose involved -- Confidence: 1.000
High energy discharge (sparking or arcing) involved -- Confidence: 0.990
Please go to the output file, 20051114-OUTPUT.out, for more details of the diagnosis
results.
This is an automatically generated message! Please do not reply.”

BUG REPORTS AND FEEDBACK

If you find any bugs in the software or have any comments or questions about it, please feel free to contact us.

Contact Information:

Dr. Yilu Liu
Office: 439 Whittemore
Mailing Address: 340 Whittemore (0111)
Virginia Tech
Blacksburg, VA 24061
Tel: (540) 231-3393
Fax: (540) 231-3362
Email: yilu@vt.edu

Copyright © 2005 PowerIT
All rights reserved

Appendix B Current Market Survey of On-line Battery Monitoring Systems

Monitor Name	Company	Features
--------------	---------	----------

APPENDICES

<p>Continuous Battery Monitor [3-17]</p>	<p>Alber</p>	<p>- Individual cell parameters measured: Individual cell voltage Individual cell resistance (a.k.a. internal resistance) Cell charging current Connection resistance Pilot cell electrolyte temperature (optional)</p> <p>- Bank parameters measured: Ambient temperature Number and depth of discharges String current String voltage</p>
<p>LifeLink™ battery monitoring [3-18]</p>	<p>ENERSAFE</p>	<p>- Parameters measured: Cell impedance Cell temperature Cell voltage System voltage System current String current Float current Total number of discharges Total energy removed Ambient temperature</p> <p>- No SOC & SOH determination function</p>
<p>MicroGuard Cost-effective Standby Battery Monitoring [3-19]</p>	<p>LEM</p>	<p>- Parameters measured: Cell voltages Cell impedances Current Temperatures Discharge profiles</p>
<p>BCM 200 Series Battery and Cell Management System [3-20]</p>	<p>Serveron</p>	<p>- Cell parameters measured: Electrolyte level Specific gravity Bypass/maintenance current DC impedance (post-to-plate, strap-to-post) Voltage (float, discharge, charge, peak load) Jar temperature Post temperature</p> <p>- Bank parameters measured: Voltage (DC and ripple) Voltage drop under load Current (float and load) Ripple current (AC peak-to-peak) Ambient temperature</p> <p>- SOC & SOH determination</p>

APPENDICES

<p>On-line Battery Monitor OMB [3-30]</p>	<p>On-line Monitoring Inc.</p>	<p>- Parameters measured: Temperature, voltage, and impedance of each cell Total voltage during float, charge and discharge Individual string voltage during float, charge and discharge Individual cell voltage during float, charge and discharge Ambient temperature Average impedance per string String current during float, charge and discharge Total bus current during float, charge and discharge Interconnect resistance</p> <p>- SOC & SOH determination</p>
<p>MIRADOR Large (Middle, Small) Site Management System [3-31]</p>	<p>Multitel</p>	<p>- list of available channel choices: Ambient temperature DC power plant Load current Battery current Battery temperature Battery midpoint voltage Individual current Individual cell voltage Battery float current</p>
<p>CELLWATCH Battery Monitoring System [3-32]</p>	<p>CellWatch</p>	<p>- Parameters measured: Individual battery voltage String voltage measurement Individual jar resistance Pilot jar temperature String current Ambient temperature</p> <p>- SOC & SOH determination</p>

Appendix C C Code of Temperature Based Battery Monitoring Analysis

```
#include <stdio.h>
#include <iostream.h>
#include <stdlib.h>

void main()
{
    float tAmb,A,B,C,tMax,tMin;
    float tCell[2000];
    int i;
    FILE * fp1_in;
    FILE * fp2_in;
    FILE * fp3_in;
    FILE * fp_out;
```

APPENDICES

```
//open Batt_Alarms2.txt
//exit if cannot create file
if (( fp_out=fopen("Batt_Alarms2.txt", "w"))==NULL)
{
    cout << "\nError!--Cannot open output file: Batt_Alarms2.txt\n\n";
    exit(0);
}

//open tAmb.txt
//exit if cannot create file
if (( fp1_in=fopen("tAmb.txt", "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: tAmb.txt\n\n";
    exit(0);
}
fscanf(fp1_in, "%f", &tAmb);
printf("tAmb===%f\n",tAmb);
fclose(fp1_in);

//open initFile.txt
//exit if cannot create file
if (( fp2_in=fopen("initFile.txt", "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: initFile.txt\n\n";
    exit(0);
}
fscanf(fp2_in, "%f%f%f\n",&A,&B,&C);
printf("A=%f,B=%f,C=%f\n",A,B,C);
fclose(fp2_in);

//write alarm to a file
fprintf(fp_out, "\nBattery Temperature Monitoring Results:\n\n");
printf("\nBattery Temperature Monitoring Results:\n\n");

//open tCells.txt
//exit if cannot create file
if (( fp3_in=fopen("tCells.txt", "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: tCells.txt\n\n";
    exit(0);
}
tMax = -9999.0;
tMin = 9999.0;

i = 0;
while (!feof(fp3_in)) //test if EOF encountered
{
    fscanf(fp3_in, "%f\n",&tCell[i]);
    printf("tCell[%d]=%f\n",i,tCell[i]);
    if (tCell[i]>tMax) tMax=tCell[i];
}
```

APPENDICES

```
    if (tCell[i]<tMin) tMin=tCell[i];

    if (tCell[i]-tAmb>B)
    {
        fprintf(fp_out,"ALARM: Temperature for the cell No. %d HAS
EXCEEDED the ambient, tCell-tAmb>B. (tCell=%f; tAmb=%f; B=%f)\n",i,tCell[i],tAmb,B);
        printf("ALARM: Temperature for the cell No. %d HAS EXCEEDED the
ambient, tCell-tAmb>B. (tCell=%f; tAmb=%f; B=%f)\n",i,tCell[i],tAmb,B);
    }
    else
    {
        fprintf(fp_out,"*****: Temperature for the cell No. %d is normal relative
to the ambient, tCell-tAmb>B. (tCell=%f; tAmb=%f; B=%f)\n",i,tCell[i],tAmb,B);
        printf("*****: Temperature for the cell No. %d is normal relative to the
ambient, tCell-tAmb>B. (tCell=%f; tAmb=%f; B=%f)\n",i,tCell[i],tAmb,B);
    }

    if (tCell[i]>C)
    {
        fprintf(fp_out,"ALARM: Temperature for the cell No. %d is TOO
HIGH, tCell>C. (tCell=%f; C=%f)\n",i,tCell[i],C);
        printf("ALARM: Temperature for the cell No. %d is TOO HIGH,
tCell>C. (tCell=%f; C=%f)\n",i,tCell[i],C);
    }
    else
    {
        fprintf(fp_out,"*****: Temperature for the cell No. %d is normal,
tCell>C. (tCell=%f; C=%f)\n",i,tCell[i],C);
        printf("*****: Temperature for the cell No. %d is normal, tCell>C.
(tCell=%f; C=%f)\n",i,tCell[i],C);
    }
    i = i + 1;
}
fclose(fp3_in);

if (tMax-tMin>A)
{
    fprintf(fp_out,"ALARM: Temperature variations within the string of cells are
TOO HIGH, tMax-tMin>A. (tMax=%f; tMin=%f; A=%f)\n",tMax,tMin,A);
    printf("ALARM: Temperature variations within the string of cells are TOO
HIGH, tMax-tMin>A. (tMax=%f; tMin=%f; A=%f)\n",tMax,tMin,A);
}
else
{
    fprintf(fp_out,"*****: Temperature variations within the string of cells are
normal, tMax-tMin<A. (tMax=%f; tMin=%f; A=%f)\n",tMax,tMin,A);
    printf("*****: Temperature variations within the string of cells are normal,
tMax-tMin<A. (tMax=%f; tMin=%f; A=%f)\n",tMax,tMin,A);
}

fclose(fp_out);
```

APPENDICES

```
}
```

Appendix D C Code of Impedance Based Battery Monitoring Analysis

```
#include <stdio.h>
#include <iostream.h>
#include <stdlib.h>
#include <string.h>

void main()
{
    char unit[80];
    char dirzcal[80],dirzInit[80],dirzMax[80],diralarmMessage[80];
    float zCalc[2000],zIndex[2000];
    float zCalcArray[100][2000]={0};
    float zAve[2000],sum[2000]={0};
    float zMax,zInit,zY;
    int numOfRecords,numOfUnits,i,j,count=0,count1[100]={0};
    FILE *fp0_in;
    FILE *fp1_in;
    FILE *fp2_in;
    FILE *fp3_in;
    FILE *fp4_in;
    FILE *fp1_out;
    FILE *fp2_out;

    //open Batt_Alarms_c.txt
    if (( fp1_out=fopen("Batt_Alarms_c.txt", "w"))==NULL)
    {
        cout << "\nError!--Cannot open output file: Batt_Alarms_c.txt\n";
        exit(0);
    }
    //open Units.txt
    //exit if cannot create file
    if (( fp0_in=fopen("Units.txt", "r"))==NULL)
    {
        cout << "\nError!--Cannot open input file: Units.txt\n";
        exit(0);
    }
    numOfUnits=0;
    while (!feof(fp0_in))
    {
        //scan units.txt
        fscanf(fp0_in,"%s\n",unit);

        //define the path of alarmMessage_c.txt
        strcpy (diralarmMessage,".");
        strcat(diralarmMessage,unit);
        strcat(diralarmMessage,"\\alarmMessage_c.txt");
    }
}
```

APPENDICES

```
printf("\nAlarm Message for %s :\n\n",unit);
//open alarmMessage_c.txt
if (( fp2_out=fopen(diralarmMessage, "w"))==NULL)
{
    cout << "\nError!--Cannot open output file: alarmMessage_c.txt\n\n";
    exit(0);
}

//define the path of zInit.txt
strcpy(dirzInit, ".\\");
strcat(dirzInit, unit);
strcat(dirzInit, "\\zInit.txt");
//open zInit.txt
if (( fp2_in=fopen(dirzInit, "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: zInit.txt\n";
    exit(0);
}
//read initial impedance
fscanf(fp2_in, "%f", &zInit);

//define the path of zMax.txt
strcpy(dirzMax, ".\\");
strcat(dirzMax, unit);
strcat(dirzMax, "\\zMax.txt");
//open zMax.txt
if (( fp3_in=fopen(dirzMax, "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: zMax.txt\n";
    exit(0);
}
//read maximum impedance limit
fscanf(fp3_in, "%f", &zMax);

//define the path of zcalculation.txt
strcpy (dirzcal, ".\\");
strcat(dirzcal, unit);
strcat(dirzcal, "\\zcalculation.txt");
//open zcalculation.txt
numOfRecords=0;
if (( fp1_in=fopen(dirzcal, "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: zCalculation.txt\n";
    exit(0);
}
//scan impedance data from zcalculation.txt
while (!feof(fp1_in))
{
    fscanf(fp1_in, "%f\n",&zCalc[numOfRecords]);
    //calculate the battery index
    zIndex[numOfRecords] = zCalc[numOfRecords]/zInit;
```

APPENDICES

```
//          printf("zIndex[%d]=%f\n",numOfRecords,zIndex[numOfRecords]);

//write alarms to alarmMessage.txt
if (zIndex[numOfRecords]<zMax)
{
    //Situation is normal
    count=0;
}
else
{
    //Send an alarm if violation is repeated
    count=count+1;
    if (count>=3)
    {
        fprintf(fp2_out,"ALARM: Starting with Record #d,
the battery's internal impedance exceeded the threshold %0.5f
(=zInit*zMax)\n",numOfRecords+1,zInit*zMax);
        printf("ALARM: Starting with Record #d, the battery's
internal impedance exceeded the threshold %0.5f
(=zInit*zMax)\n",numOfRecords+1,zInit*zMax);
    }
}
zCalcArray[numOfUnits][numOfRecords]=zCalc[numOfRecords];
//save impedance data into an array
sum[numOfRecords]=sum[numOfRecords]+zCalc[numOfRecords]; //
calculate the sum of different units for current record
OfRecords=numOfRecords+1; // count the number of records in one unit
}
// count the number of units
numOfUnits=numOfUnits+1;
}
//open zY.txt
if (( fp4_in=fopen("zY.txt", "r"))==NULL)
{
    cout << "\nError!--Cannot open input file: zY.txt\n";
    exit(0);
}
fscanf(fp4_in, "%f", &zY);
// printf("zY===%f\n",zY);

//calculate the average
for (i=0;i<=numOfRecords-1;i++)
{
    zAve[i]=sum[i]/numOfUnits;
}

printf("\nAlarm Message for the battery:\n");

//compare each unit against the group average. Alarm if necessary
for (i=0;i<=numOfRecords-1;i++)
{
```

APPENDICES

```
    for (j=0;j<=numOfUnits-1;j++)
    {
        if (zCalcArray[j][i]<(zAve[i]*(1+zY)))
        {
            //Situation is normal
            count1[j] = 0;
        }
        else
        {
            //Send an alarm if violation is repeated
            count1[j] = count1[j]+1;
            if (count1[j]>=3)
            {
                fprintf(fp1_out,"ALARM: Starting with Record #%d, Unit %d
deviated from group's average\n",i+1,j+1);
                printf("ALARM: Starting with Record #%d, Unit %d deviated
from group's average\n",i+1,j+1);
            }
        }
    }
}
//close all files
fclose(fp0_in);
fclose(fp1_in);
fclose(fp2_in);
fclose(fp3_in);
fclose(fp4_in);
fclose(fp1_out);
fclose(fp2_out);
}
```

VITA

VITA

Yishan Liang received her B.S. degree in electrical engineering from Hebei University of Technology (Tianjin, China) in 1999. She worked as an Assistant Electrical Design Engineer in Tianjin Chemical Engineering Designing Institute (Tianjin, China) from 1999 to 2001. Ms. Liang pursued her master program in the Department of Electrical and Computer Engineering at Virginia Tech from August 2004. Her research interests include transformer monitoring, diagnosis and analysis, and power system analysis.