# การเพิ่มระดับความพร้อมใช้งานแบตเตอรี่และเพิ่มประสิทธิภาพในการบำรุงรักษา โดยวิธีการวัดค่าอิมพีแดนซ์ของแบตเตอรี่: กรณีศึกษาในโรงงานผลิตไฟฟ้า

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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# IMPROVING AVAILABILITY AND MAINTENANCE BY MEASURING BATTERY IMPEDANCE: A CASE STUDY OF ELECTRIC POWER PLANT

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ชนฎ ศรีพรวัฒนา : การเพิ่มระดับความพร้อมใช้งานแบตเตอรี่และเพิ่มประสิทธิภาพในการบำรุงรักษาโดยวิธีการวัดค่าอิมพีแดนซ์ของแบตเตอรี่: กรณีศึกษาในโรงงานผลิตไฟฟ้า (IMPROVING AVAILABILITY AND MAINTENANCE BY MEASURING BATTERY IMPEDANCE : A CASE STUDY OF ELECTRIC POWER PLANT) อาจารย์ที่ปรึกษา : ผศ. ดร. จิตรา รู้กิจการพานิช 112 หน้า. ISBN 974-13-1226-1


วิทยานิพนธ์ฉบับนี้มีวัตถุประสงค์เพื่อปรับปรุงความพร้อมใช้งานและการบำรุงรักษาแบตเตอรี่ที่จ่ายกำลังไฟฟ้าให้กับอุปกรณ์ควบคุมที่เป็นส่วนสำคัญในกระบวนการผลิตไฟฟ้า อุปกรณ์ควบคุมจะหยุดทำงานทันทีหากแบตเตอรี่ไม่สามารถจ่ายกำลังไฟฟ้าในเวลาที่ต้องการจนเป็นสาเหตุทำให้กระบวนการผลิตไฟฟ้าต้องหยุดลงไปด้วย แม้ว่าจะมีการบำรุงรักษาเป็นประจำอยู่แล้ว แต่ก็เป็นวิธีการที่ไม่สามารถหาความพร้อมของแบตเตอรี่ได้ ความพร้อมสามารถหาได้โดยวิธีการทดสอบปล่อยกระแสให้กับตัวต้านทานด้วยปริมาณกระแสและระยะเวลาทดสอบตามที่กำหนดในคู่มือบำรุงรักษาของแบตเตอรี่ ซึ่งเป็นวิธีที่ยุ่งยาก ใช้เวลานานและค่าใช้จ่ายสูง อีกทั้งผลที่ได้ก็ไม่สามารถใช้ในการคาดคะเนค่าความพร้อมของแบตเตอรี่ได้

ในการดำเนินการจะศึกษาส่วนประกอบต่างๆของแบตเตอรี่ วิธีการตรวจวัดความจุ และหาความพร้อมใช้งานของแบตเตอรี่ รวมทั้งผลกระทบต่อความสามารถในการจ่ายกำลังไฟฟ้า ในการวัดระดับความพร้อมใช้งานในวิทยานิพนธ์นี้จะใช้วิธีการทดสอบอิมพีแดนซ์ของแบตเตอรี่ ซึ่งเป็นความต้านทานภายในของแบตเตอรี่ การตรวจวัดความพร้อมสามารถกระทำได้ทั้งขณะที่แบตเตอรี่ยังต่ออยู่กับระบบจ่ายไฟฟ้า วิธีการวิเคราะห์ความพร้อมของแบตเตอรี่จะนำค่าอิมพีแดนซ์ของแบตเตอรี่แต่ละตัวเปรียบเทียบกับค่าอิมพีแดนซ์เฉลี่ยในระบบเดียวกันเพื่อหาเปอร์เซ็นต์ความเบี่ยงเบนของแบตเตอรี่แต่ละตัว โดยแบตเตอรี่ตัวที่มีค่าเบี่ยงเบนมากกว่า 20% ของค่าเฉลี่ย จะถูกนำมาวางแผนบำรุงรักษาเพื่อปรับปรุงความพร้อมของแบตเตอรี่ ก่อนที่จะถูกใช้งาน ในการศึกษาจะนำผลจากวิธีการทดสอบอิมพีแดนซ์เปรียบเทียบกับผลที่ได้จากการทดสอบด้วยวิธีการปล่อยกระแสให้กับตัวต้านทาน เพื่อยืนยันความถูกต้องของวิธีการทดสอบและผลที่ได้

ในการทำวิทยานิพนธ์นี้ผลที่ได้จะนำไปใช้กับงานวางแผนการบำรุงรักษาระบบแบตเตอรี่ของโรงไฟฟ้าในการไฟฟ้าฝ่ายผลิตแห่งประเทศไทย เพื่อเพิ่มระดับความพร้อมใช้งานของแบตเตอรี่และเพิ่มประสิทธิภาพการบำรุงรักษา อีกทั้งยังช่วยลดเวลาการทดสอบและสามารถลดค่าใช้จ่ายการบำรุงรักษาลงได้ 56%


ศูนย์ระดับภูมิภาคทางวิศวกรรมระบบการผลิต
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ลายมือชื่อนิสิต..................................................
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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The Electricity Generating Authority of Thailand (EGAT) is a state-owned electric utility with the responsibility to produce and transmit electricity to private and government sectors. There is much critical equipment that can affect the generation system and can cause plants to shutdown, when the equipment can not function. Storage battery is a direct current (DC) power source that is used for backup power source for critical equipment. It is used in uninterruptible power supply (UPS), switchgear, emergency DC-motor oil pumps, computer control system, etc. In Figure 1, the battery system is connected to DC distribution bus. Charger is used for converting alternate current from the main power supply to direct current. When the main power supply fails, charger can not supply direct current to the load, and for this reason, the battery will be used instead. Therefore, the availability of batteries is importance and must be known.

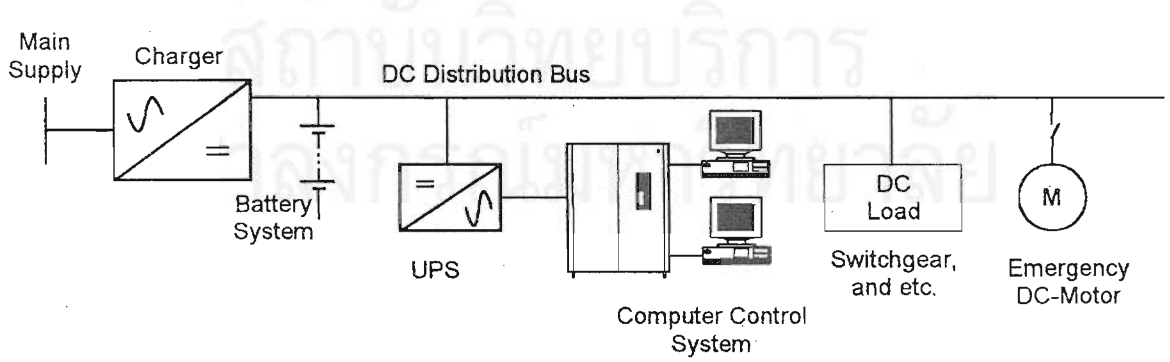



Figure 1. DC distribution circuit in the generation process

## 1.2 Statement of Problems

The conventional approach of maintenance for the batteries in EGAT is time based maintenance by monthly and yearly the inspection, and the load test every six year or during power plant major overhaul period. The activities for inspection are measurement of specific gravity, voltage for each cell, the cell-to-cell connection resistance as well as inspection of the structural integrity of the battery rack and/or cabinets.

The load testing is major overhaul work. Its purpose is to determine the capacity and availability of a battery system. The battery system comprises several battery cells which are connected in series; some system has 60 to 120 cells. The test requires a resistor bank and a method of measuring the voltage of each cell and discharge time.

The conventional approach cannot provide the status of the batteries regarding when each cell should be replaced by a new one. The approach provides only the present battery condition, therefore the maintenance staffs cannot accurately predict that when the batteries would fail.

In conclusion, the weak points of the conventional maintenance approach are:

(a) unable to predict the availability of batteries. The availability will be known when the load testing has been performed, which could be too late. So, the batteries may be called upon to perform under the unavailability condition.

(b) Costly and time consuming. Because of the complexity of the conventional approach, it requires a considerable amount of time, costs, and other resources. By this approach, the status of the availability of the batteries is difficult to know. Then the preventive maintenance planing cannot be done completely.

In order to solve the weak points as mentioned above, another testing approach that is the impedance testing is concerning in this thesis. The method has several advantages. The test can be done during the battery system on-line. It is not necessary to take the load off. This method also takes less time and costs than the conventional testing. The test data obtained from this test method is quite reliable in predicting the battery condition thus the availability of batteries can be estimated. Then the maintenance can be planned and performed in order to improve the availability of batteries.

## 1.3 Objectives

The main objectives of this thesis are:

1.3.1 To improve availability and maintenance of battery in electric power plant.

1.3.2 To reduce outage service time and cost of maintenance.

## 1.4 Scope of the Research

This research focuses on the availability of battery by measuring battery cell impedance. The results of the research will be analyzed and used to set maintenance plan.

## 1.5 Research Procedures

1.5.1 Study related literature and theory surveys for battery impedance monitoring, battery testing and maintenance method, and battery performance predictive analysis.

1.5.2 Collect historical data and consider the observational power plant and test method for collecting actual test data.

1.5.3 Measure the actual test data by impedance testing method.

1.5.4 Evaluate the test data and confirm the results of battery impedance testing and availability of battery.

1.5.5 Summarize research and suggestion.

1.5.6 Write up thesis and submit.

1.5.7 Prepare for presentation and final report.

## 1.6 Expected Benefits

1.6.1 To reduce the number of emergency shutdown of the EGAT's power plants and substations.

1.6.2 To improve the efficiency of power plant operations.

# CHAPTER 2

# THEORETICAL CONSIDERATION AND LITERATURE SURVEY

## 2.1 Introduction

This chapter presents the related theoretical considerations comprising life characteristics curve, area of maintenance and operation of battery. The literatures in this thesis relate to battery maintenance criteria, performance-testing method, impedance testing method, and methodology to determine the availability of battery.

## 2.2 Life Characteristics Curve

During the life of a device, there are three distinctive phases of failure. The first is called early failures phase (or infant failures); failure occurrence during this period can be eliminated by burn-in process. Normally, Failures occur due to the result of substandard components with gross defects and the lack of adequate controls in manufacturing process. The second phase is called useful life phase (or operating phase) which has constant failure rate, caused by randomly occurring defects and stresses. The third is called wear out phase (or deterioration phase); the failure of device in this stage increases rapidly. As device wears out, failure usually occurs with less stress and does not occur randomly in time. In general, these failures cannot be eliminated but can be reduced with proper preventive maintenance plan and component replacement. Figure 2.1 is life characteristic curve or bathtub curve showing, the pattern of failure rate in each phase, [2].

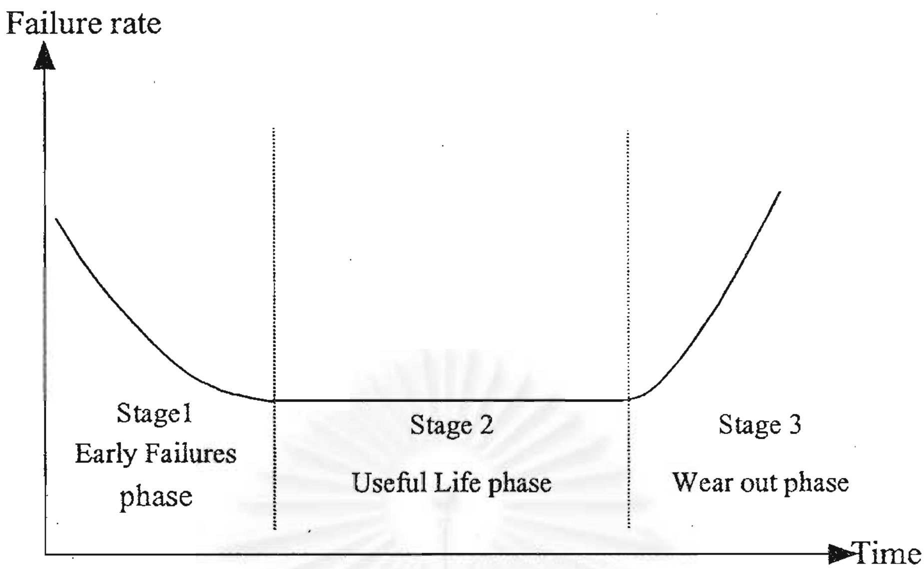



Figure 2.1 Life Characteristic Curve (Bathtub Curve)

## 2.3 Concept of Maintenance

The main objectives of maintenance are as follows (A K GOVIL)[2]:

- To extend the useful life of devices.
- To ensure the optimum availability of installed devices for service and obtain the maximum possible return on investment.
- To increase production.

Typically, maintenance system can be divided into *preventive* and *corrective* maintenance.

### 2.3.1 Preventive Maintenance

The principle of this function is to ensure that routine maintenance is properly done concurring with a planned schedule. The preventive maintenance plan will normally be created from maintenance departments' experience and suggestions from manufacturers who make the device. Preventive maintenance can either be performed during plant shut down or running. The maintenance activities include checking, adjustments, lubrication, inspection, cleaning and corrective action.

Preventive maintenance also includes replacement of parts which are reaching the end of operating life-time as recommended by manufactures, before equipment fails, even though they are still functioning. The reason is that if they suddenly fail, the production process will have to shutdown [2].

### 2.3.2 Corrective Maintenance

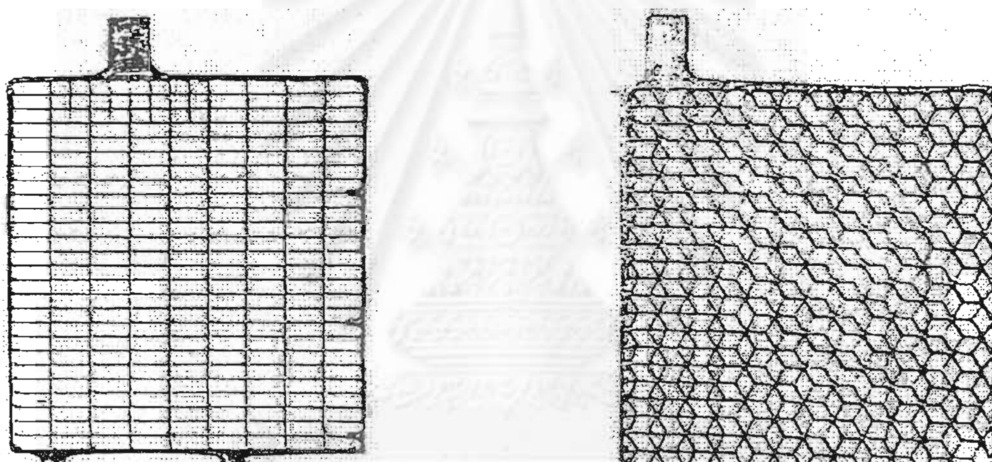
Corrective maintenance is correction when system or device is malfunction or fails to operate. Even though there is a preventive maintenance regularly. In general, corrective maintenance may need new parts or may of device which have failed or involve sets repairing the parts that do not breakdown. Corrective maintenance usually involves shut down maintenance and sometimes need to force device out of service [2].

## 2.4 Basic Structure of Lead Acid Battery

Lead-Acid battery is a device that converts chemical energy into electrical energy. In addition, battery provides back-up power to replace electricity from power main grid for a variety of critical functions. All lead batteries work on the same set of reactions and use the same active materials. The fundamental elements of lead-acid battery comprise electrodes or plate, plate grids, electrolyte, separators and etc. Each element is explained in more detail as follows (Wolfgang Fischer)[3]:

### 2.4.1 Plate Grid

The grids are the supporting framework for the active material of the plates. They also conduct the current to and from the active material plates. They are made from alloy of lead. Some alloys use a small amount of antimony to strengthen and stiffen the soft lead. Several grid mesh designs are used. The objective of these designs is to use the grid metal more efficiently, placing more metal where the current density is greater and less metal where there is less current flowing.



Negative grid type　　　　Positive grid Type

Figure 2.2 Plates Grid [3]

### 2.4.2 Positive and Negative Plates Structure

The positive and negative plates consist of grid framework. To make the plates, a material, which has a consistency of firm mud, will be pasted onto a grid. This paste is a mixture of lead oxide, sulphuric acid and water. It will be dried by a special process until the paste has hardened. Some additives, such as fibers, are often contained in the paste mix, in order to help bind the active material together.

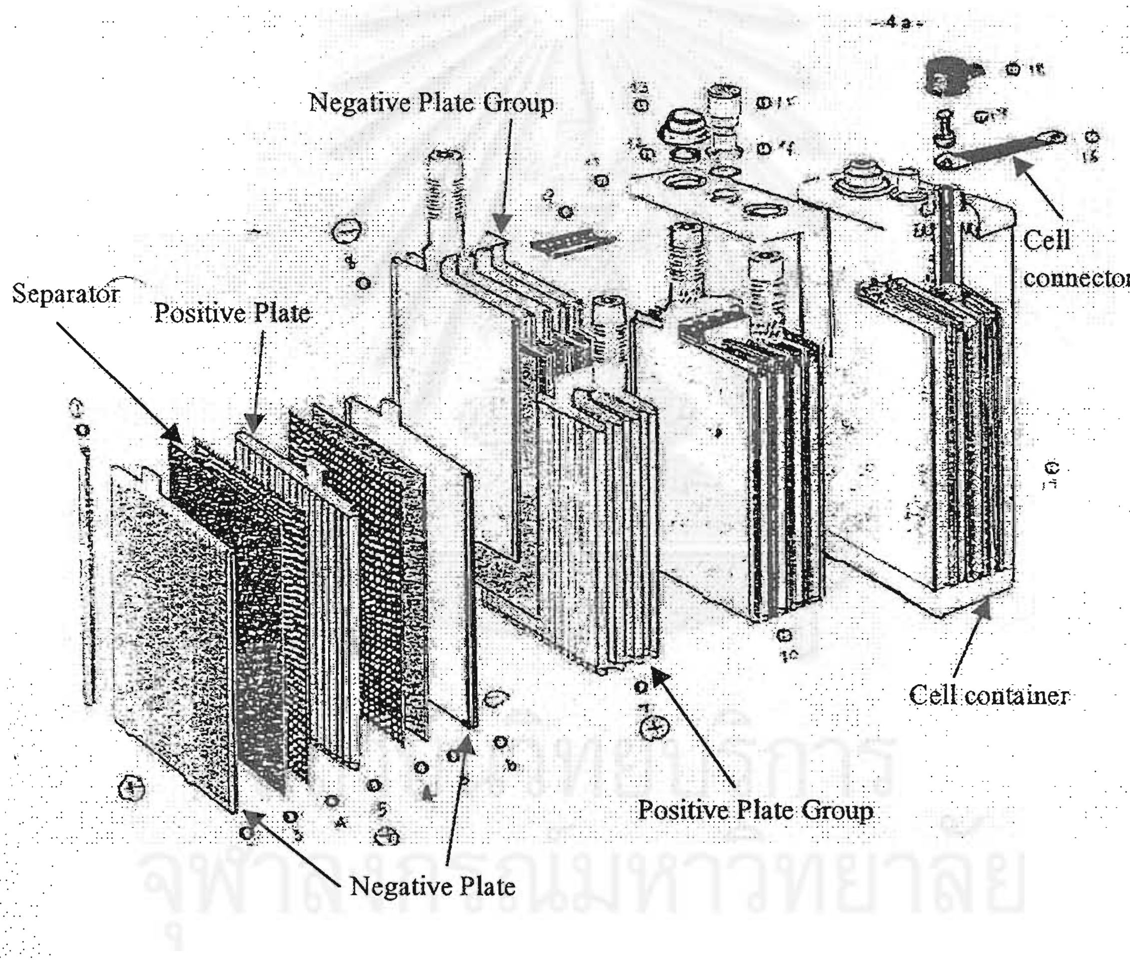



Figure 2.3 Positive and Negative Plate [3]

### 2.4.3 Separators

Separators, as shown in Figure 2.3, are thin sheets of electrically insulating porous material used as spacers between the positive and negative plates to prevent short circuits within the cells. Fine pores in the separators allow ionic current flow in the electrolyte between the positive and negative plates. Normally, the separator has vertical ribs on the face of the positive plate to provide greater acid volume next to the positives and to minimize the area of separator contact. The ribs also provide space to improve acid circulation and to permit any gas formed to rise to the surface of the electrolyte. In addition, it provides a path for sediment to settle to the bottom of the cell [3].

### 2.4.4 Plate Groups

Plate groups in Figure 2.3 in are made by joining a number of similar plates to a common terminal post by means of a plate strap. The number and size of plates in a group is a significant capacity of battery. Each plate is made with a lug at the top to which is fused to the strap. A positive group consists of a number of positive plates connected to a plate strap, and a negative group consists of negative plates connected in the same manner. The two groups joined together with separators between the positive and negative plates constitute a cell element.

### 2.4.5 Cell Container

Usually, cell container, as show in Figure 2.4, is made of plastic (e.g. polypropylene) to contain the cell elements which are assembled. The cell container is made up in one-piece with as many compartments as there are cells in the battery.

The plastic used is selected for its resistance to sulfuric acid, low permeability and impact strength. In addition, it is designed to:

1. Withstand the extremely high and low temperature.
2. Resist damage caused by mechanical shock.

The inner bottom portion of the container has supporting plates to permit the separators to extend below the bottom of active plates' surface. It helps to reduce the possibility of short circuit between positive and negative plates according to the growth of sediment, it is a part of plate material which is shed by repeated discharging and charging of battery, at the bottom.

### 2.4.6 Cell Covers, Vent Valves

The cell covers in Figure 2.4 are usually made from a plastic material similar to the cell container. It is a one-piece cover case. The cell cover is provided with holes through which the terminal posts extend, and a threaded hole for each cell. Lead bushings are molded in the cover for the two battery terminal posts. When the cover is placed on the cell, it is sealed to prevent leakage and loss of electrolyte.

The vent valves of the cover are designed to provide the proper air space above the electrolyte to permit gas to vent from the cell without forcing electrolyte from the battery. The cover also provides the hole into which is screwed the vent valve. This hole is used for testing the strength of electrolyte and adding water.


(Source: From VARTA co.,Manual of Lead-acid Batteries for Stationary Installation)

Figure 2.4 Cell Container, Cover and Vent Valve

### 2.4.7 Cell Connectors

The output voltage of battery is equal to the sum of number of cells in series connection. In order to increase output current of battery, the cells are connected in parallel. The cell connectors are placed over the terminal posts, and are welded to them. These connectors are short in order to provide lower resistance paths through the battery [3].

### 2.4.8 Electrolyte

In lead-acid battery, electrolyte is a mixture of sulphuric acid ($H_2SO_4$) and water. The specific gravity, quantity, purity, and temperature of the electrolyte within the cell affect the operation of the battery. The specific gravity of electrolyte is the weight of the sulphuric acid-water mixture compared to the weight of water with equal volume. Pure water has a specific gravity of 1.0. The rated capacity of the battery cell is determined by selection of the specific gravity. Normally, the specific gravity of the new battery from manufacturer is 1.265-1.285. With full discharge, the specific gravity will decrease down to 1.130. If discharge is frequently below this point, battery life will be shorted [3].

## 2.5 Battery Operation Concepts

As mention above, Lead acid battery is composed of positive and negative plates or electrodes and an electrolyte. The electrodes connect to several pairs of negative and positive plates enclosed in one another to form a plate pack. The positive plate in the charged state is lead dioxide ($PbO_2$) and the negative plate is pure lead (Pb), while the influential active ingredient of electrolyte is sulphuric acid ($H_2SO_2$). Usually, sulphuric acid will mix with water by ratio of 30-35% sulfuric acid and 65-70% water solution. This solution causes a chemical reaction that produces electrons [3].

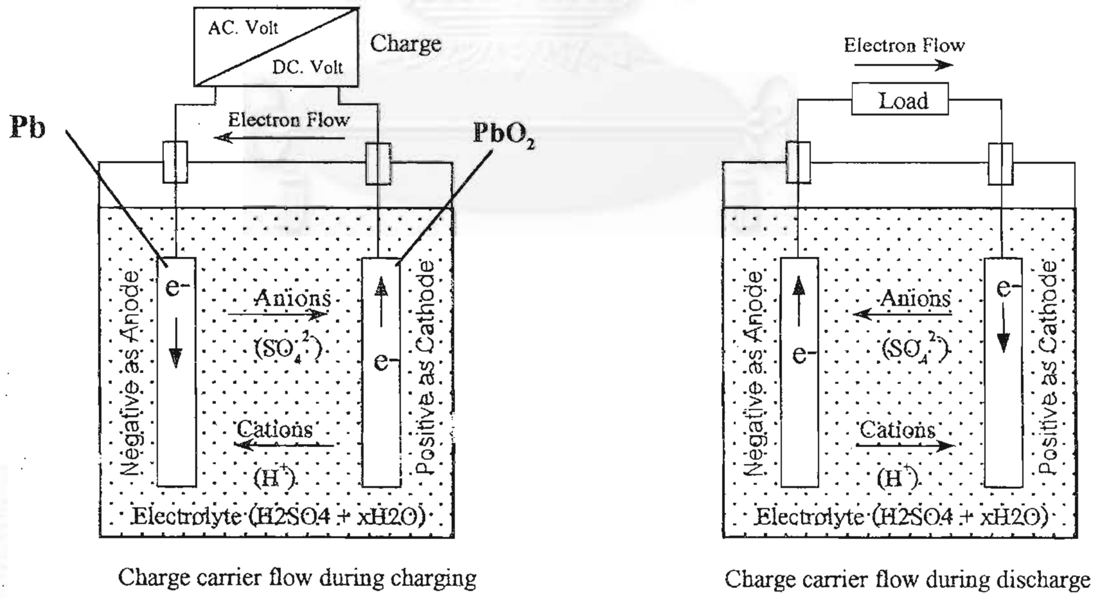



Figure 2.5 Basic Operations of Lead-Acid Battery

### 2.5.1 The Chemical Reactions

The chemical reactions of the electrodes (active materials) that are immersed into sulphuric acid can be showed by the following equation [3].

(1) During Charging, Lead sulphate ($PbSO_4$) of negative electrode will be reduced, while the $PbO_2$ in the positive electrode is oxidized. The reactions are:

*Negative Electrode :*

$$PbSO_4 + 2e^{-1} \longrightarrow Pb + SO_4^{-2} \tag{2.1}$$

*Positive Electrode :*

$$PbSO_2 + 2H_2O \longrightarrow PbO_2 + SO_4^{-1} + 4H^{+1} + 2e^{-1} \tag{2.2}$$

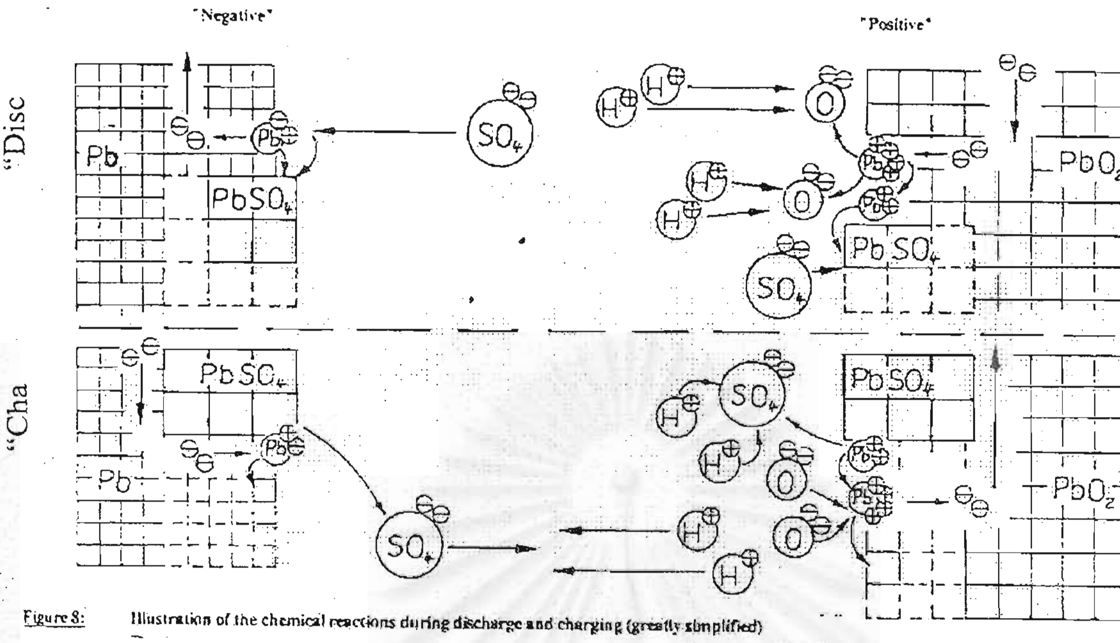
(2) During Discharge, when the battery is used as a voltage supply, electrons flow from the lead (Pb) to lead dioxide ($PbO_2$). The lead of negative electrode and lead dioxide of the positive electrode are reverted to lead sulphate ($PbSO_4$). The sulphuric acid plays a role of sulphate ions. The acid will be consumed and diluted in this process, the solution can be indicated by water. The sulphuric acid density declines. The reaction can be shown as follows:

*Negative Electrode:*

$$Pb + SO_4^{-2} \longrightarrow PbSO_4 + 2e^{-1} \tag{2.3}$$

*Positive Electrode:*

$$PbO_2 + 4H^{+1} + 2e^{-1} + SO_4^{-2} \longrightarrow PbSO_4 + 2H_2O \tag{2.4}$$




(Source: Wolfgang Fischer, 1994:p9a)

Figure 2.6 Illustration of the Chemical reactions during discharging and discharging

The combination of sulphate and hydrogen ions will produce sulphuric acid.

$$4H^{+1} + SO_4^{-2} \longrightarrow 2H_2SO_4 \qquad (2.5)$$

Total chemical reactions of charge and discharge can be represented as follows:

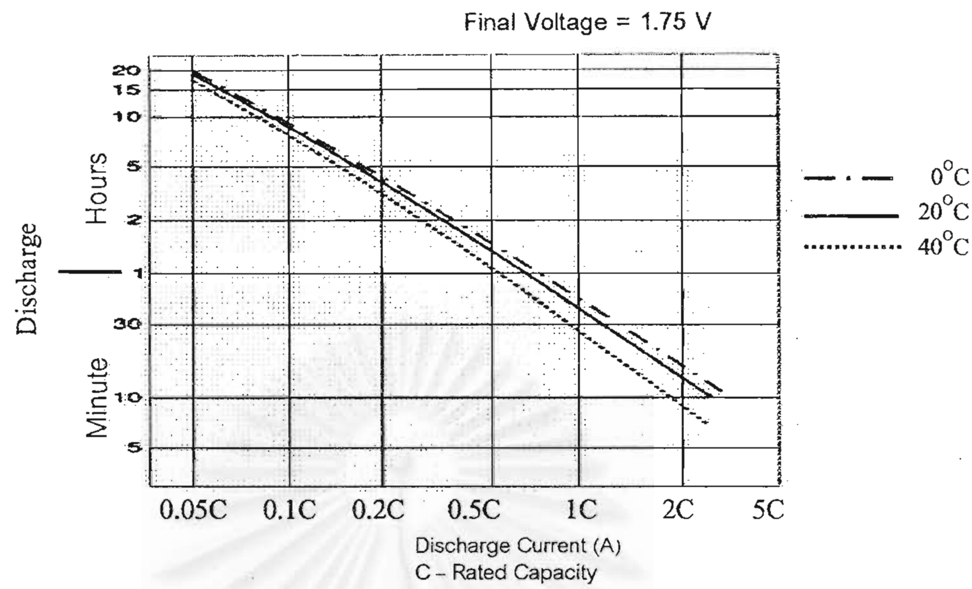
$$Pb + PbO_2 + 2H_2SO_4 \underset{charging}{\overset{disch\,arg\,e}{\rightleftarrows}} 2PbSO_2 + 2H_2O \qquad (2.6)$$

### 2.5.2 Battery Cell Voltage

The voltage of a battery cell can be determined by the materials used in it. The reduction and oxidation reactions will produce a fixed voltage. The sum of the two reaction potentials is the output voltage of the cell. During discharge, at the positive electrode has a potential of 1.685 volts, while the negative electrode has a potential of 0.356 volts. Therefore, the overall voltage of lead-acid cell is 2.04 volts which is known as the standard electrode potential [3]. The typical commercial cell voltage is about 2.15-2.21 volts. Cell voltage level depends on a number of factors, for instance the acid concentration can effect the voltage of a lead-acid cell.

### 2.5.3 Battery Capacity

The capacity of battery is measured in Ampere-Hours (Ah) - amperes supplied by the battery times the amount of time current can be drawn. This rating indicates how the battery may be used at a given rate before it becomes completely discharged. Usually, the rate of batteries in power plant are 200 to 1,350 ampere-hours, it depends on the amount of load. The Uninterruptible Power Supply (UPS) system is a critical load of the battery. UPS system will convert direct current (DC) from batteries to alternative current (AC) source. It is used for many important control equipment that need continuous power supply such as computer control systems, power plant control equipment, etc.; this equipment can cause plant shutdown when its power supply loses.




(Source: Technical Information Lead-Acid Batteries, Francis Deutshe, Italian)

Figure 2.7 Relation of Discharge capacity and Time

Figure 2.7 show a typical characteristic of 1 Ah of battery. The graph shows discharge time that will be reduced when discharge current increases. Discharge current is on the horizontal scale and the discharge time is on the vertical scale; the product of these values is the battery capacity. Normally, for battery capacity testing, in practice, the 0.1C (10% of battery rated Ah) load is selected for 10 hours discharge testing.

## 2.6 Battery Discharging and Charging

### 2.6.1 Battery Discharging

As battery discharge continues, the amount of lead sulphate ($PbSO_4$) on the negative and positive plates increases and coats the surface of active materials. When the sulphate coating become thick enough, it is difficult for the electrolyte to effectively reach the plates. The chemical reaction is retarded and the output of the cell voltage and capacity will be reduced. Usually, the cell is not allowed to be discharged beyond 50% of rated capacity because it is difficult to remove the thick coating of lead sulphate in charging state. In normal operation, lead sulphate is moved out both the positive and negative plates when cell is being charged. The sulphuric acid is again formed. In this process, the water content of the electrolyte is decreased and the density of the electrolyte is increased [3].

IEEE standard 450-1995 [1], recommends procedure for battery discharge test or load test in order to determine batteries capacity. Load testing is performed by discharge constant current to a controllable resistor bank until the terminal voltage is decreased to a specific value or at the given time; the test is then stopped. The healthy cell is the cell that has the remaining voltage equal to or over the specific value.

<u>Load testing procedure</u>

- Charge the batteries in full state
- Check all battery connections and resistance reading; cleaning and fixing are performed prior to the test if there are corrosion at the connection
- Record electrolyte temperature of 10% of the battery system to found an average temperature
- Remove all loads from batteries or transfer to other battery system
- Disconnect the battery charger
- Connect the controllable resistor bank to the battery
- Start the timing and continue to maintain the selected discharge rate
- Read and record the individual cell voltage at specified intervals and at the completion of the test.

During testing, the following items should be observed so as to avoid battery to be damaged.

- Observe the battery for cell connector heating.
- If early in the test, if there is a rapid voltage drop for any cell, the test for that weak cell will be stopped and disconnected from the system and bypassed with a jumper of adequate conductor rated current. The test is then continued in order to determine the capacity of the remaining cells. The downtime shall not be included in the test discharge period. The test for weak cell is stopped to prevent deep discharge. Deep discharge has great impact on battery performance and life. If that cell discharges until the capacity is lower than 50% of rated capacity, it may not be recover back to an acceptable state.

Trojan [14], battery maker, recommends that in order to perform load testing the following items should be concerned:

- Do not fully discharge batteries; this will damage the battery.
- Do not leave batteries deeply discharged for any length of time.
- Lead-acid batteries need not be fully discharged before recharging, because it does not develop a memory.
- Shallow discharge will result in a longer battery life; 50% or less are recommended

### 2.6.2 Battery Equalizing Charge

Equalizing charge is an overcharge performed on batteries after they have been discharged or charged for a long time in floating mode. It is performed to ensure that the conversion of the active material in all cells is completely accomplished. Equalizing charge or equalization is also often used to remove moveable that causes of short circuits of positive and negative plates. Usually, it should be done periodically, such as once a month. It is also performed when the electrolyte has low or wide ranging specific gravities, in general about ± 0.015 of the design value [1] [3]. The other consideration for under taking equalization is when an individual cell deviates from average value about ± 0.04 V [1]. Some manufacturers recommend that batteries should be equalized from once a month to three per year.

Equalizing charge voltage for lead acid battery is typically 108 to 110 % of cell voltage and charging time depending on manufacturer's recommendation. The time used for equalization is a continuous 35 to 70-hour period [1].

Trojan [14] recommends step of equalizing charge when low or wide ranging specific gravities are detected. The changes of specific gravity can come from:

- Incompletely reverse the build up of negative chemical effects like stratification, a condition where acid concentration is greater at the bottom of the battery than at the top.
- Sulphation, sulfate crystals might have build up on the plates; it can reduce the overall capacity of battery.

Step of equalizing charge

- Remove all loads from batteries.
- Connect battery charger.
- Set charger for equalizing voltage.

- Start charging batteries.
- Batteries will begin gassing and bubbling vigorously; sulfate crystals are removed in this state.
- Take specific gravity readings every hour.
- Equalization is complete when specific gravity values no longer rise during the gassing stage.

## 2.7 Battery Maintenance

There are three main types of maintenance for lead acid battery system as follow a (IEEE450, 1995):

### 2.7.1 Routine Maintenance

The maintenance sections of power plants regularly perform routine maintenance once a month. Maintenance activities will usually conform to maintenance manuals of manufacture. These activities include:

- measuring specific gravity of the pilot cells,
- measuring voltage for each cell,
- checking electrolyte level, and
- inspecting corrosion of battery connection.

### 2.7.2 Yearly Inspection

Performed at least once a year. The yearly inspection includes all activities of monthly inspection, with addition work on reading the temperature of each cell, measuring the specific gravity of each cell, cleaning cell connection and measuring resistance, inspecting structural integrity of battery rack and/or cabinet, and performing equalization.

### 2.7.3 Major Overhaul

The major overhaul is usually performed every six years. Maintenance activities for overhaul include all activities in yearly inspection and capacity determination. The capacity of batteries will be determined at this time by load testing method, as mention in 2.6.1.

In general, the amount of discharge current depends on the capacity of battery, ampere-hours, and the chosen rate of discharge, as shown in Figure 2.9. Discharge rate is the percentage of capacity or rated current of battery to be delivered to the load bank. It can be less or more than 100% of battery rated capacity. The load test connection diagram can be shown as Figure 2.8.

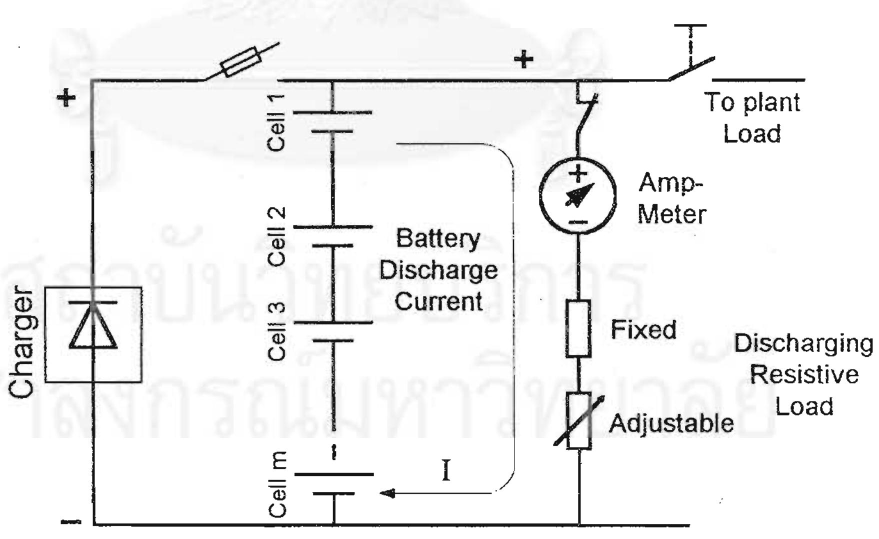
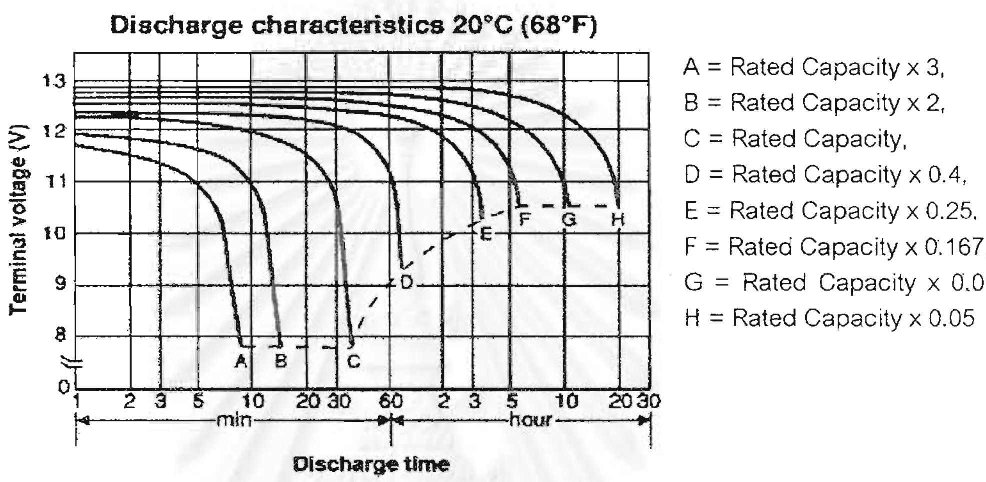



Figure 2.8 Simplified load discharging connection diagram

The following graph illustrates discharge characteristics for battery at different discharge rates. The curves show different discharge time and final voltage at each rate of discharging. Higher discharge rate will has less discharge time than lower discharge rate.




(Source: Technical Information Lead-Acid Batteries, Francis Deutshe, Italiano)

Figure 2.9 Discharge characteristics with different discharge rate

In Figure 2.9, discharge curves A, B and C are the results taken from discharge in rated 3,2 and 1 times of capacity rate respectively. They show duration of time that battery is discharged to specific voltage within a short time. Usually, 10 to 20% of rated current or capacity is often used for battery capacity testing.

### 2.7.4 Battery Capacity Calculation

After load testing the remaining capacity of batteries can be determined by one of the two approach as shown by the following:

*(1)* *by current and time:*

$$Capcity = i_d \, x \, t_d \qquad \text{(Amp-hour)} \qquad (2.10)$$

where $i_d$ is the discharge current (Ampere)

$t_d$ is the duration time at the specified final voltage (Hour)

*(2)* *by the ratio of time:*

$$Percent\ capacity = \frac{t_a}{t_s} x\,100 \qquad (2.11)$$

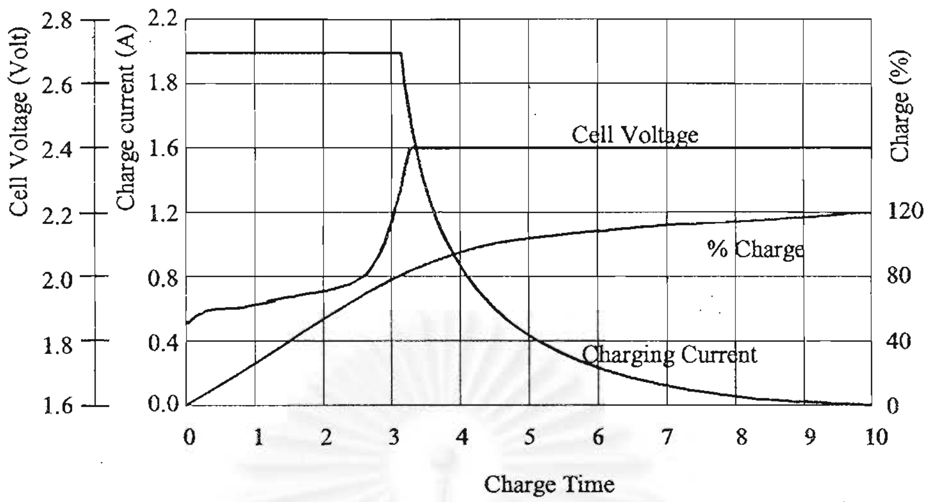
where $t_a$ is the actual time that the cell takes to reach the specific voltage level

$t_s$ is the standard discharge time ( in accordance with manufacturing specification)

## 2.8 Battery Charging Methods

A lead acid battery is charged by passing direct current through the battery in a direction opposite to that of the discharge current. When lead acid battery has been charged, electric current is supplied to perform the discharge reversal electro-chemical process. The battery can be charged as long as it is not overcharged, overheated, or allowed to form excessive gas. Figure 2.10 shows the characteristic of battery during charge.

The new battery needs to be charged prior to be in service. It can be charged with higher current, but the current must be reduced near full charge in order to avoid overcharging. Either the constant voltage or constant current method can be adopted to charge battery.

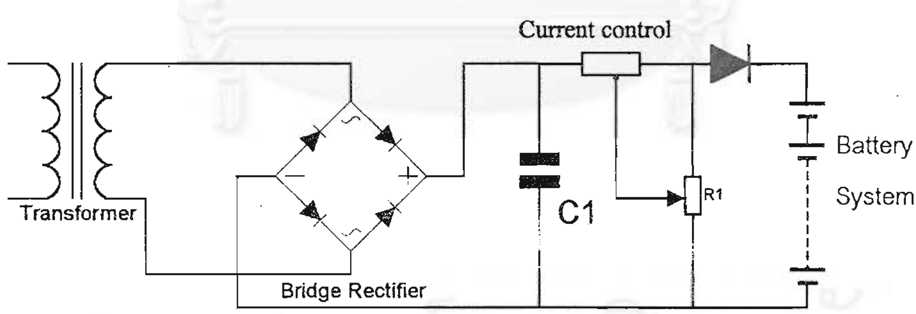



(Source: Technical Information Lead-Acid Batteries, Francis Deutshe, Italiano)

Figure 2.10 Battery charging characteristics

### 2.8.1 The Constant-Current Charging Method

In this method, direct current is kept constant at selected levels but voltage will be varied during the charging process. Unless the charging time is extended to long periods with low currents.

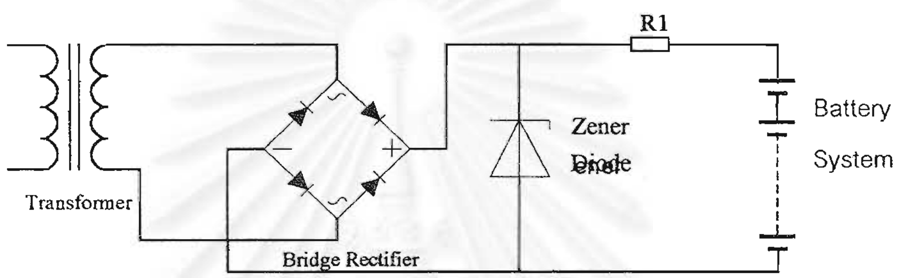



(Source: from Technical Information Lead-Acid Batteries, Francis Deutshe, Italiano)

Figure 2.11 Constant Current charging circuit

### 2.8.2 The Constant-Voltage Charging Method

This method will be kept constant voltage at selected levels and vary current. While charging, the current at the beginning is high and then automatically decreases when the battery is closely reaching fully charge state. This method requires less time when compared with other method. In normal operation, constant voltage charging is used to maintain battery voltage during standby or float charging mode.




(Source: from Technical Information Lead-Acid Batteries, Francis Deutshe, Italiano)

Figure 2.12 Constant voltage charging circuit

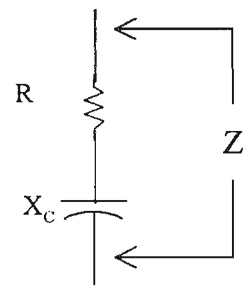
## 2.9 Impedance Calculation

The impedance value is calculated from the measured signals based on Ohm's Law that can be expressed as the ratio of voltage and current, as follows:

$$Z = \frac{V}{I} \tag{2.12}$$

Where $Z$ is impedance (ohm), $V$ is voltage (volt), $I$ is current (ampere). Both voltage and current are measured in AC (alternating current) quantity, therefore, impedance is an AC resistance that is comprised of two vectors, resistive and capacitive reactance. The relation of impedance (Z), resistance (R), and capacitive reactance ($X_C$) can be shown in the following figures and formulars:

(1) in series circuit

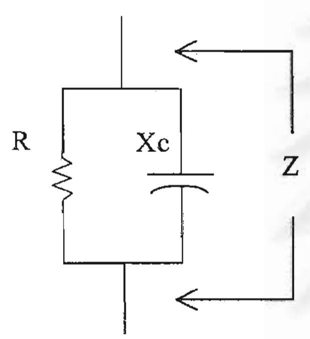



$$Z = R + jX_C$$

$$Z^2 = R^2 + X_C^2 \qquad \text{or}$$

$$Z = \sqrt{R^2 + X_C^2} \qquad (2.13)$$

(2) in parallel circuit




$$Z = R \; // \; jX_C \qquad \text{or}$$

$$Z = \frac{R * X_C}{\sqrt{R^2 + X_C^2}} \qquad (2.14)$$

## 2.10 Battery Cell Impedance Model

The overall conductance path through a cell includes the metallic and ohmic path, which are involved electrochemically, as shown in Figure 2.13 [7].

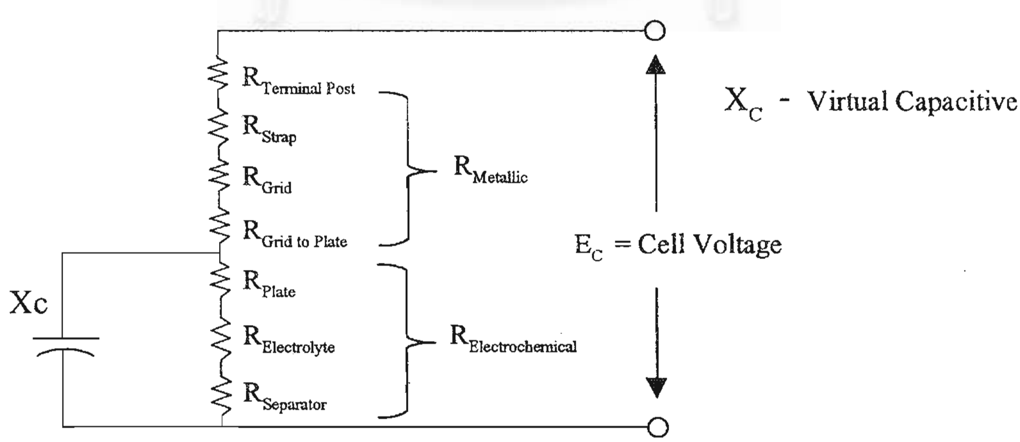



Figure 2.13 Simplified Model of a Lead-Acid Cell

The ohmic path of metallic composes of resistance of the terminal posts, strap, grid structure, and grid to plate connection. The second path is electromechanical which compose of plates, electrolyte, and separators. The result of all the negative and positive parallel plates with a dielectric between them generates a capacitor. This capacitor value is about 1.3 to 1.7 farad per 100 ampere-hours of capacity rating, depending on the design of battery.

The capacitive reactance ($X_C$) on the simplified model divides current from $R_E$ (electrochemical part of the path), therefore, $X_C$ has direct influential on the impedance in this path. The electrochemical path includes the plate and the electrolyte in which energy is stored. The increase of internal impedance causes sulphation on the plates, which leads to decrease of current being generated. Obviously, the impedance of the internal circuit path is the factor that influences the capacity of battery, and therefore it needs to be measured accurately.

# CHAPTER 3

# METHODOLOGY

Availability of equipment in the process of electric power generation is very important. There is need to verify equipment availability in order to assure that this equipment is available over time. Preventive and routine maintenance are the activities purpose to maintain the equipment to continue functioning as its design. They include planned and unplanned maintenance. However, some equipment, such as battery, needs more intensive preventive and routine maintenance programs than other equipment, in order to reliably function when called upon to prevent production process failure. To improve availability and maintenance of battery, impedance measurement has been adopted to assess the current and future trend of capacity and health of battery. In this thesis, lead acid battery is used for studying. The step of study could be shown as follows:

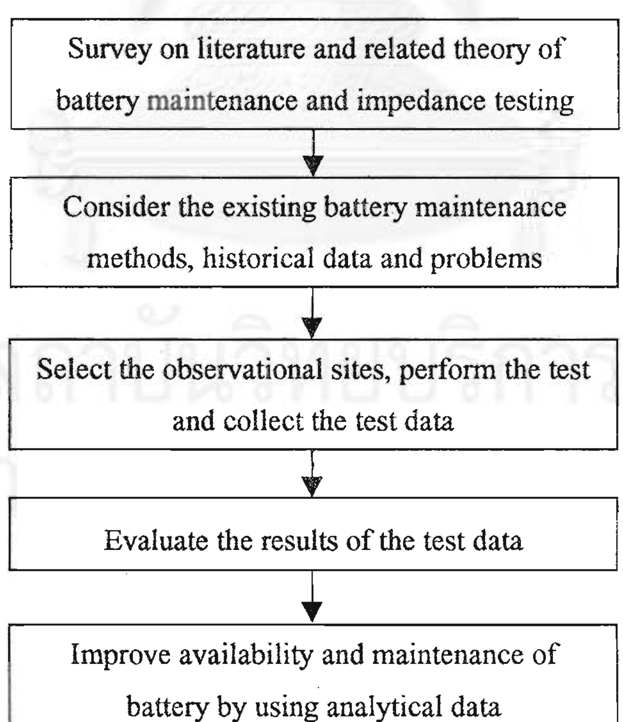



Figure 3 The steps of thesis study

## 3.1 Survey on Literatures and Related Theory of Battery Maintenance and Impedance Testing

There are literatures and related theory that are particular helpful to use as a theoretical framework for thesis study. Some standards such as IEEE include the standard operation and maintenance inspection, replacement criteria and installation on battery system. The theory of battery introduces the design of battery, material used in positive and negative plates, electrochemical resistance and impedance, conversion of chemical and electrical energy and factors affecting battery life. The technical papers on impedance concept and testing give detail of battery impedance model, the changing of impedance, impedance and capacity relationship, impedance test method and the result verification and analysis. Test equipment, procedures and results of analysis can also be found in those papers.

## 3.2 Consider the Existing Battery Maintenance Method, Historical Data and Problems

The existing battery maintenance method has been set by recommendation of manufacturers who make battery. The recommendations of manufacturers are almost similar procedures; they are only different in the specific design values. The maintenance procedures, mostly conforming to manufacturers' recommendation, are performed to ensure that the battery operate at design conditions. The maintenance consists of volt per cell and specific gravity readings and load testing. Although the maintenance is performed regularly, there are many batteries that still suffer damage before design life and fail to function when needed. Frequently, these problems come from improper or inadequate maintenance and lack of effective maintenance method.

## 3.3 Select the Observational Sites, Perform the Test and Collect the Test Data

This study will introduce the additional battery maintenance method in order to improve the existing maintenance and availability of battery. The additional method is battery impedance measuring or impedance testing which can be used to determine the internal characteristics of batter cell for tracking the health and available capacity.

### 3.3.1 Observation Sites Selection

The impedance test data will be collected from three sites. The criteria for selecting those three sites are different year in service, and rated capacity of the battery system. In addition, they are due to be tested load discharge. The results of battery impedance measuring will be compared with the results of load testing in order to verify the accuracy of the tests. The sites that are selected name South Bangkok power plant unit 4 (SBP-4), Nakhonayok substation (NYS), and Chulabhorn hydro plant unit 2 (CBP-2).

The battery system of SBP-4 was installed since October 5, 2000. The rate capacity of battery system is 600 ampere-hour. The system consists of 116 cells, voltage of each cell is 2.2 volt.

The battery system of NYS was installed since July 17, 1991. The rate capacity of battery system is 200 ampere-hour. The system consists of 60 cells, voltage of each cell is 2.2 volt.

The battery system of CBP-2 was installed since May 23, 1989. The rate capacity of battery system is 175 ampere-hour. The system consists of 51 cells, voltage of each cell is 2.2 volt.

Besides the impedance testing, the specific gravity and volt per cell are also measured for reference and analysis. Load testing will be performed under manufacture's recommendation criteria.

### 3.3.2 Test Data Collection

In order to measure battery impedance and collect test data for analyzing. The parameters that must be measured and controlled during impedance test are ambient temperature and state of battery charge. For load testing, constant current discharge and deep discharge are concerned during test.

The increasing temperature will cause internal battery resistance and impedance decrease due to the sulphuric acid is less viscous, more detail in section 4.3.1 of Chapter 4. In order to determine the individual change of cell impedance from previous measuring, so, the ambient temperature nearly battery case must be recorded. However, the method of impedance comparisons between cells in a same system can be accepted without concern to temperature effects, because all cells in the system are at the same temperature.

During discharge state there is change the active materials on the battery plates from $PbO_2$ to the more resistive $PbSO_4$. Therefore, battery impedance in this time is not constant. Prior to measure battery impedance, all cells must be at float charging state.

In order to determine the availability of battery by measuring impedance, the collected data include individual cell impedance, connection resistance, cell voltage, and ambient temperature. The following Table is used for planning data collection.

- Battery information

The battery information consists of:

| | | |
|---|---|---|
| Manufacturer: | Type/Model: | |
| Number of cell: | Capacity: | Ah. |
| Voltage per cell: | Float voltage: | volt |
| Year in service: | Equalizing voltage: | volt |

Table 3.1 Battery information

The battery information in each site can be used to assist in analyzing problems of battery, such as battery plates sulphation or deterioration may be come from battery age or improper of charging voltage.

- Battery cell impedance measuring

| Site name: | | | | sheet no. 1/ |
|---|---|---|---|---|
| Ambient temperature: | | | | |
| Date/Time | Cell no. | Cell Voltage (volt) | Cell Impedance (mohm) | Connection Resistance (mohm) |
| | 1 | | | |
| | 2 | | | |
| | 3 | | | |
| | 4 | | | |
| | . | | | |
| | . | | | |
| | . | | | |
| | N | | | |

Table 3.2 Impedance measuring data collected form

The measured data of battery cell will be performed during battery on-line. The cell connection resistance is used for determining the corrosion of terminal post and connector. If cell impedance is same as previous measurement while the connection resistance increases, it will affect the cell impedance measurement.

Voltage of each cell is also important. If cell voltage is too high or low from specific value, it can affect battery performance. Excessive float charging causes internal heat which will in turn create pressure build up; loss of electrolyte comes from this cause. Under float charging voltage causes internal self discharge; sulphation is become by this cause.

- Battery load testing data collection

| Cell # | Voltage of each cell at each hour | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | Nth |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| N | | | | | | | | | | |

Table 3.3 Battery load testing data collected form

During load test performing, the purposes of data collection are to record voltage of each cell throughout the test, and detect weak cells that decrease voltage faster than other cells and early reach the specific value before given time. The test will be stopped when the weak cells are detected in order to prevent deep discharge.

## 3.4 Evaluate Results Of the Test Data



### 3.4.1 Impedance measurement and load test performing

All battery cell impedance will be measured by battery impedance testing equipment is called EBITE and BITE model, detailed discussion in Chapter 4. The results of the tests will be evaluated by the criteria that is introduced in the research and instruction manual of the impedance test equipment. The evaluation will be done on computer spreadsheet program with results shown in graphical diagram. Impedance of each cell will be compared with the system impedance average in order to determine the percent deviation of each cell. This criterion is used to determine the questionable or near-failing cells that have percent impedance deviation higher than the acceptable value, 20% of system average, which may have remaining capacity level lower than acceptable value, 80% of rated capacity; AVO international operation manual for BITE and EBITE [13].

After impedance measuring, load testing will be performed to determine the remaining capacity of each cell. Battery system will be isolated from DC distribution bus and charger, and then connect the controllable resistor load bank to the battery system terminal. Every hour or specific interval, cell voltages and time are measured until the test is finish. Usually, the cell that has high internal impedance, the terminal voltage will decrease faster than other cells in the same system.

The result of impedance measuring will be compared with the result of load testing. For cell that has impedance higher than 20% of the average and conforms to the result load testing; fast decrease of terminal voltage and reach the specific value before design time, will be taken to analyse the problems of that cell.

### 3.4.2 Criteria of Analysis and Correction

In the battery backup system, causes of failure are numerous and varied. Manfred R. Laidig and John W. Wurst [10] summarizes some of the causes of early battery failure as follows:

- Jar case cracks
- Specific gravity changes

- Electrolyte level/Dryout
- Excessive temperature
- High cycling rates/load test/battery discharge
- Defective post seals
- Strap corrosion
- Plate sulphation
- Plate deterioration/separator problems
- Post/connection hardware problems

Manfred R. Laidig and John W. Wurst [10] also recommend that for high impedance cell, over 20% of average, should be done as follows:

- Check, clean and retorque connections when corrosion is detected.
- Check cell voltage at float charging voltage; if it is lower than other cell about 0.04 volts, IEEE [1], or 2.19 volts, normally the specific gravity will be low. It requires equalizing charge. If the cell impedance is still over 20% of average, this cell is needed to consider replacing.
- Inspect the cell for corroding internal plate interconnections, plate sulphation, excessive shedding of active material accumulating at the bottom of the cell. These conditions usually cause an increased cell resistance and impedance.

## 3.5 Improve Availability of Battery by Impedance Measuring Data

The results of impedance testing will be used to plan for replacing the cells that have impedance higher than 20% of the system average and can not be repaired or improved to satisfactory state. It is very useful if the near-failing cells are detected and repaired or replaced earlier before they fail during in service.

In addition, load testing can be placed on an extended schedule, if the result of impedance measuring found that all cells in the system have impedance deviation lower than 20% of the average and narrow range deviation of specific gravity. Usually, the specific gravity should be deviated from design value less than 0.015, IEEE standard 450-1995 [1]. By this approach, the battery system is not necessary to outage or takes the load off.

# CHAPTER 4

## THE MAINTENANCE APPROACH USING THE IMPEDANCE TESTING

The impedance testing method is set up in EGAT's Electrical Maintenance Division in order to determine and improve the availability of battery. Availability of battery is defined as a probability that it will operate satisfactory under operating conditions [2]. In this study, impedance testing will be performed in the EGAT's plants and sub-stations. Load testing is also performed. The result of impedance testing will be verified by the result of load testing.

## 4.1 Battery Impedance Concept

### 4.1.1 Battery Life Cycle Curve

The condition of battery cell does change over the useful life. In addition, the internal characteristics of each cell are different. The impedance testing is performed in order to predict the change and deviation of the battery cell. The following graph shows the impedance life cycle versus age of a battery, Pete E. Langan [11].

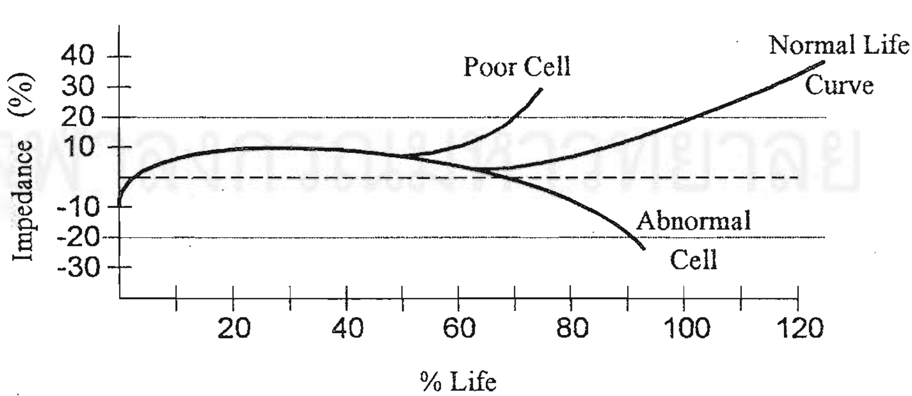



Figure 4.1 Typical impedance life cycle curve for a battery

In Figure 4.1, the normal life curve stands for normal operation of battery over its useful life. The percent deviation of cell impedance will increase over 20% of its initial value when the battery reaches the end of life. The poor cell indicates the profile of premature deterioration of cell, and the abnormal line is the shorted cell. The impedance life cycle curve can assist maintenance staff to predict the life of battery.

The changes of internal resistance of battery may come from plate's corrosion, internal weld breakdown, and poor contact between conductance materials. So, there is direct correlation between internal impedance and life of a battery.

### 4.1.2 Cell Impedance and capacity

The batteries in the same system should have slightly different in their impedance. However, any cell can fail by several reasons; the main ones are as follows:



- Installation damage arising from such factors as improperly torqued connections (damaging case or seal), reverse polarity, poor crimp joint, neglect of non-oxidizing grease from joints, or corrosion due to acid spill.
- For new batteries, it may fail due to reversed plates, plate separation, seal separation, or cracked cases.
- Improper float charging: The internal heat will in turn create pressure build up; this condition leads to gradual water loss and finally capacity loss.

The relationship of impedance and capacity is reverse; it can be shown as follows.

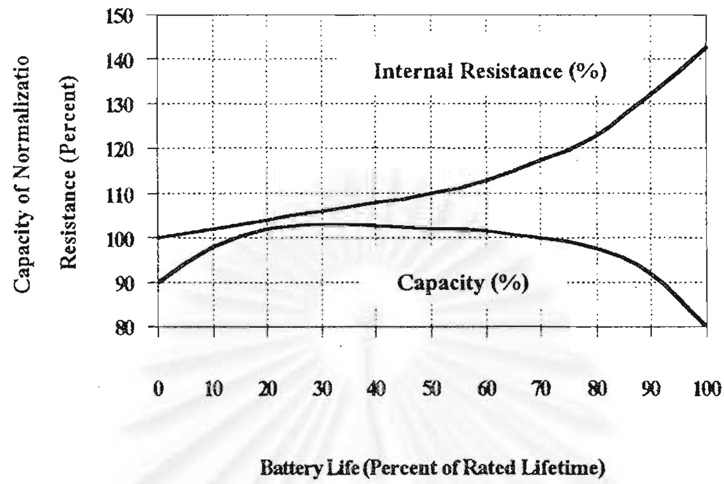



Figure 4.3 The relationship of battery Internal impedance and its capacity

In Figure 4.3, when the battery internal resistance (impedance) is increasing, it can be used as an indicator that there are some problems in battery cell, and the capacity is decreasing [11]. The sulphation is a cause of resistance and impedance increasing, as mentioned in the impedance model on section 2.10 and Figure 2.13 of Chapter 2.

## 4.2 Influence Factors On Cell Impedance

In normal operation, batteries are standby and charged in floating mode; the charging voltage of charger will be set higher than battery about 5-7% in order to maintain the battery voltage and compensate self-discharge. The battery internal impedance are most affected by the state of charge and temperature. Detailed discussions on factors influencing cell impedance are as follows.

### 4.2.1 Temperature Effects on Cell Impedance

Results from some the studies of Wolfgang Fischer [3] show that when cell temperature increases the impedance will decrease due to the activity of the electrolyte increases; higher temperature, the sulphuric acid becomes less viscous.

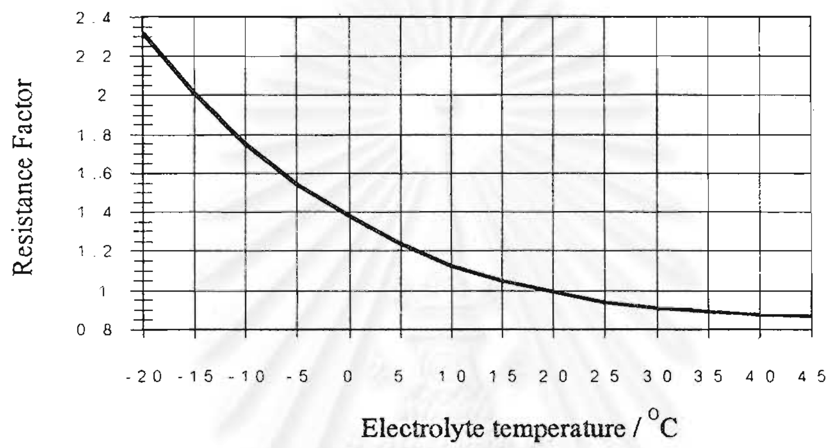



Figure 4.4 Internal resistance of lead acid battery depending on electrolyte

Changes in internal resistance also have effects on cell impedance, as mentioned in chapter 2. The the internal resistance in Figure 4.4, deceases when the electrolyte temperature increases. The correlation shows similarities for different battery types but precise characteristics are determined by battery design and are specific for each model.

However, the higher electrolyte temperature also affect battery serviceable life. Usually, the battery manufacturers guarantee performance and life where the temperature remains within a small range around a design temperature, e.g. 20$^{O}$C. A rise in temperature accelerates the corrosion processes which is constantly at work, while the lower temperature inhibit them. The following rule of thumb applies [3]:

*"A 10 degree rise in the mean annual temperature over the reference temperature double the rate of corrosion and consequently halves the serviceable life".*

The example of serviceable life of HOPPECKE GroE cells is 15 to 18 years at 20$^{o}$C. Serviceable life reduces when annual temperatures rise:

| Annual mean Temperature $^{o}$C | Approx. serviceable life (years) |
|---|---|
| 25 | 12 –12.5 |
| 30 | 8 – 8.5 |
| 35 | 6 – 6.5 |
| 40 | 4 – 4.5 |

Table 4.1 The correlation of temperature and service life

The example of correlation of impedance and temperature can be found in a study conducted by Manfred R. Laidig and John W. Wurst [10]; the results are shown in Figure 4.5. They were tested in the thermal chamber with stabilization control.

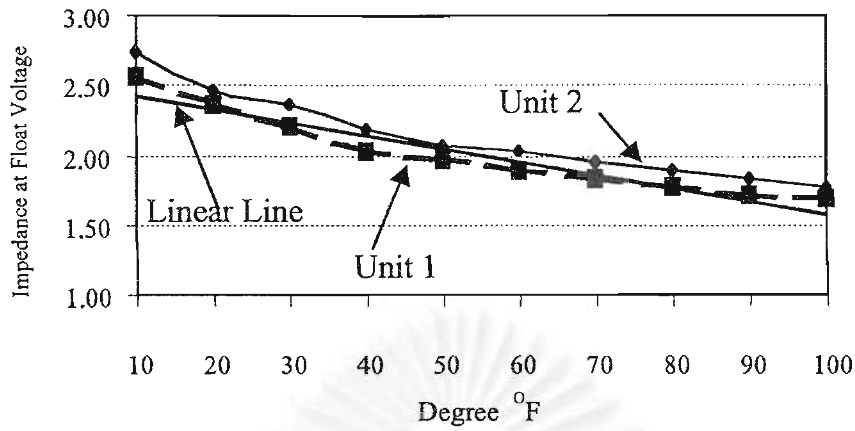



Figure 4.5 Effect of Temperature on Impedance

Thus, during measuring cell impedance, the electrolyte temperatures should be recorded for correcting the result of reading.

### 4.2.2 Charging Effects on Cell Impedance

The electrochemical resistance is comprised the plates, separators, and electrolyte. It changes during the battery is discharged and recharged cycle. In discharge cycle, the electrochemical resistance was changed, increasing resistance, due to the two reasons, as follows:

(1) The drop of specific gravity, decreasing the conductivity.

(2) The changes of the active material on the plates from $PbO_2$ to the more resistive $PbSO_4$ and the resistance cells are increase.

In state of charging, a lead acid battery is driven to convert $PbSO_4$ to into Pb and $PbO_2$ respectively and the concentrated sulphuric acid is formed again. During charging the cells voltage are steep rises until there is less and less $PbSO_4$ to be converted, the current flowing through the cell causes separation of water (electrolysis), besides the gassing. Thus, during charging, the conversion process will effect to a disproportionate change in cell voltage and impedance. Research [3] [10], shows that all impedance cells should be settled at float charge prior to testing.

## 4.3 Battery Impedance Measurement Concept

To measure battery impedance, the AC current signal is injected across the battery system terminals. Voltage and current of each cell will be measured. The impedance measurement method is shown in Figure 4.6.

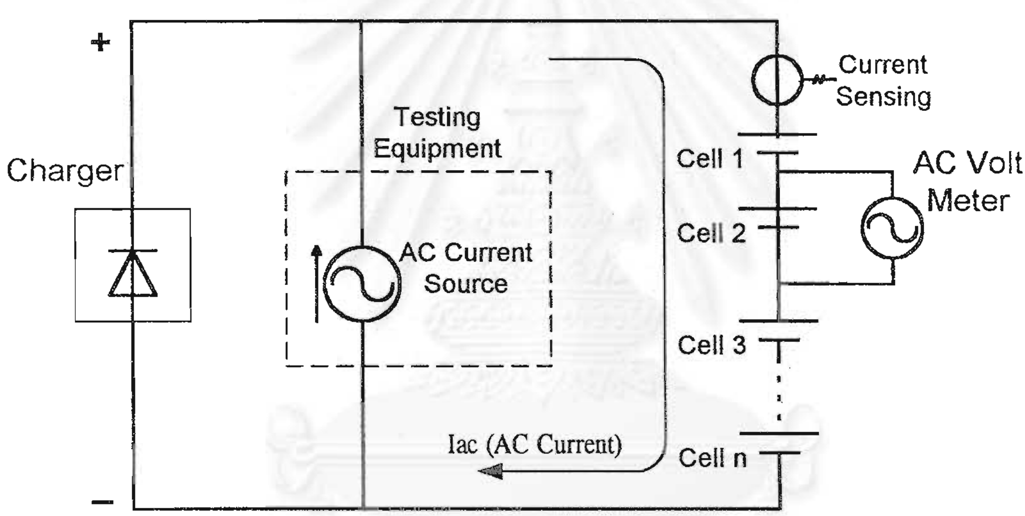



Figure 4.6 Impedance measurement concepts

The results of measurement can be used to calculate the individual impedance of each cell. The impedance measuring unit model “EBITE” and “BITE”, which are made by AVO international’s Biddle division, are used in this study.

### 4.3.1 Transmitter Unit (EBITE)

Transmitter provides the AC current to the cells under test and can store test data from the receiver and printout the results after test. The output current is automatically injection into the battery cell range from 7.8 to 9.4 A at 50 to 60 Hz, depending on the rated of battery. The transmitter can direct connect across the positive and negative terminal of battery system.

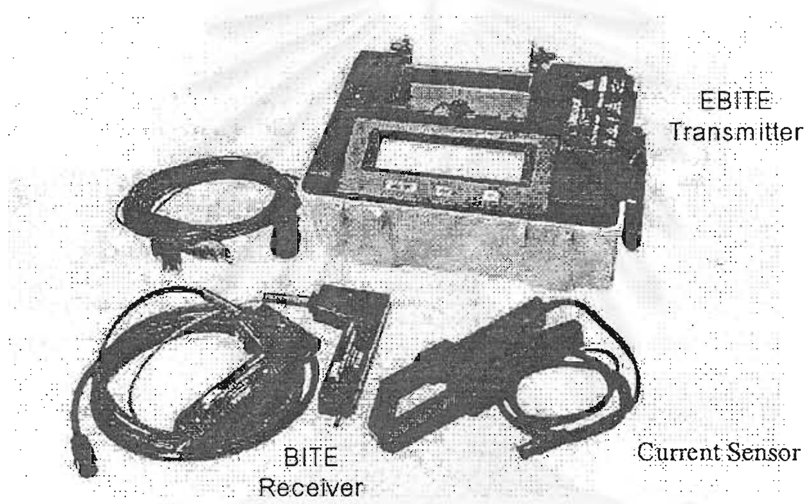



Figure 4.7 Battery Impedance Test Equipment

### 4.3.2 Receiver unit (BITE)

The receiver, in Figure 4.6, is used to measure cell voltage and current, and calculate the cell impedance. It incorporates the potential leads, camp-on sensor, and the data storage. During test, the camp-on sensor is connected to the receiver and clamped around cell connection within the loop. It needs only one person to perform the overall test. Each cell is required test time about 10 seconds per reading. It quickly and precisely measures internal impedance and cell voltage without taking the battery system off line.

### 4.3.3 The Step of Impedance Measuring

The following steps are carried out in order to measure battery impedance.

1. Clean the terminal post and connector, if corrosion is detected.
2. Check battery charger, it must be operated in full float charge state.
3. Connect the test current source leads from transmitter (EBITE) across the battery system terminal and connect clamp-on current sensor lead to the receiver (BITE) and the test clamp around cell connection within the loop.
4. Power on the impedance test equipment and verify state of operations, it will show the selected menu for operation.
5. Turn on the test current by "return to test" menu, the test ac current will enter the battery system.
6. Measure cell impedance (Zb); touch the potential probes of the receiver to the positive (+) and negative (-) of each battery cell terminal and then pulling the trigger on the receiver to load the data into the memory.
7. Measure cell connection impedance (Rs); touch the potential probes to the negative (-) terminal of the #1 cell and the positive (+) terminal of the #2 cell and then pulling the trigger on the receiver to load the data into the memory.
8. Repeat from step 7 to 8 until all cells are completely measured.
9. Download measured data from the receiver to the transmitter for display the test data and print the result of percent impedance deviation of each cell from the entire system average value.

Figure 4.8 and 4.9 show the typical measurement diagram, and Figure 4.10, 4.11 and 4.13 show impedance measurement at site.

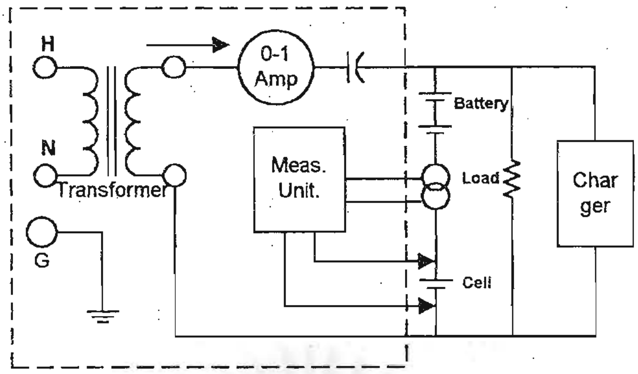



Figure 4.8 Typical diagram of Impedance measurement

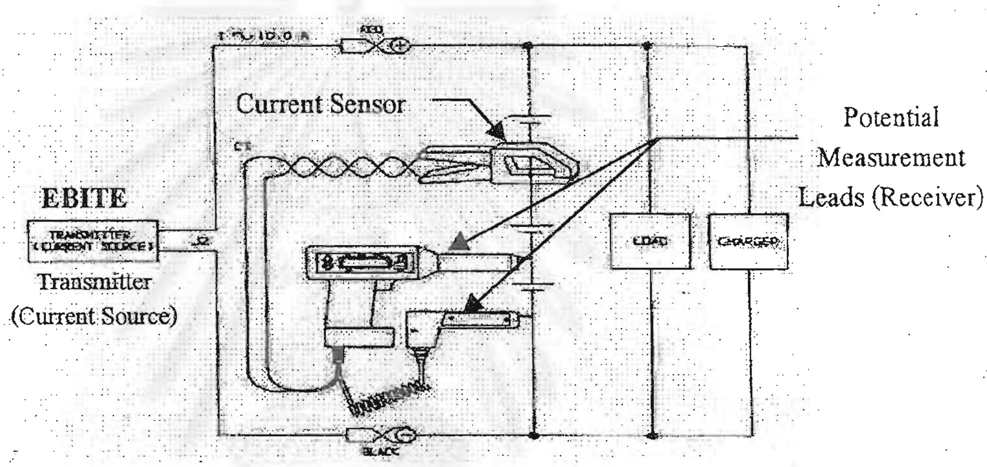



Figure 4.9 Typical of Receiver measurement diagram

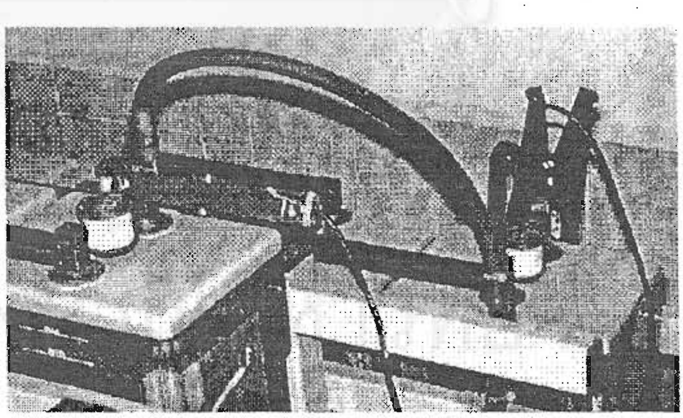


Figure 4.10 The clamp-on current sensor is placed on the cell connection for reading ac test current, Chulabhorn hydro plant

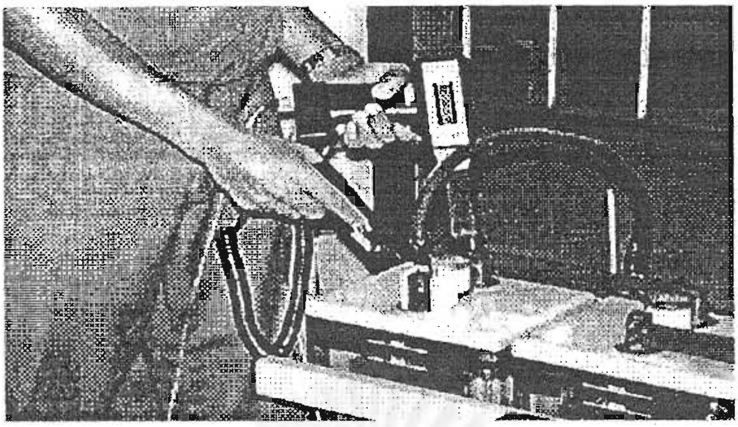


Figure 4.11 The receiver unit during measured impedance on battery cell at Chulabhorn hydro plant

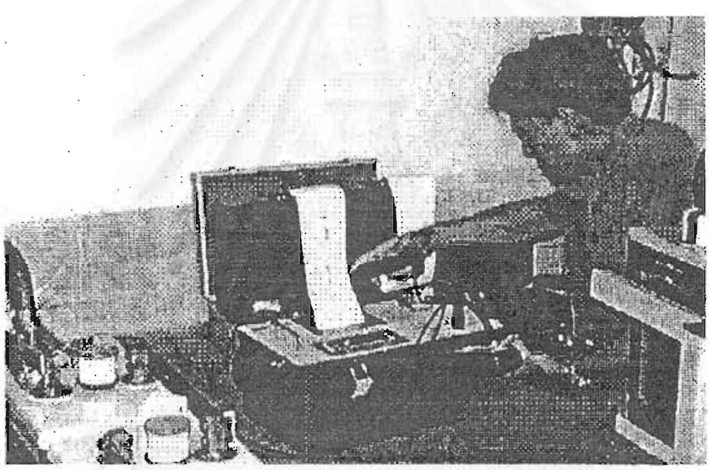


Figure 4.12 The report printout after measurement

### 4.3.4 Report Printout from Transmitter

The output data of the receiver are numerical numbers form and can also be download to EBITE transmitter for printing the result of measurement. The printouts are in form of collated impedance statistics for all cells in the battery system and normalized to the average impedance value for the battery system. The report includes a calculation of the system deviations, as well as a collation of all strap values.

Sample Battery Analysis Report

Notes:..................................................................................

Date...../...../.....

Ambient temp ............................... Pilot Temp. ...................

ACR ....................................A AC 1 .....................A

User ID:..................................................................................

| Cell | Notes | Zb. mΩ | Rs. MΩ | Volts DC | Time |
|---|---|---|---|---|---|
| 001 | ........... | 2.46 | 0.356 | 6.18 | 10:56 |
| 002 | ........... | 2.34 | 0.359 | 6.23 | 10:57 |
| 003 | ........... | 2.65 | 0.341 | 6.23 | 10:57 |
| 004 | ........... | 2.47 | 0.355 | 6.18 | 10:58 |
| 005 | ........... | 2.34 | 0.337 | 6.23 | 10:58 |
| 006 | ........... | 2.65 | 0.347 | 6.23 | 10:58 |

Cell Impedance Summary

| Minimum | Average | Maximum |
|---|---|---|
| 2.34 | 2.48 | 2.65 |

Percent Deviation from Average

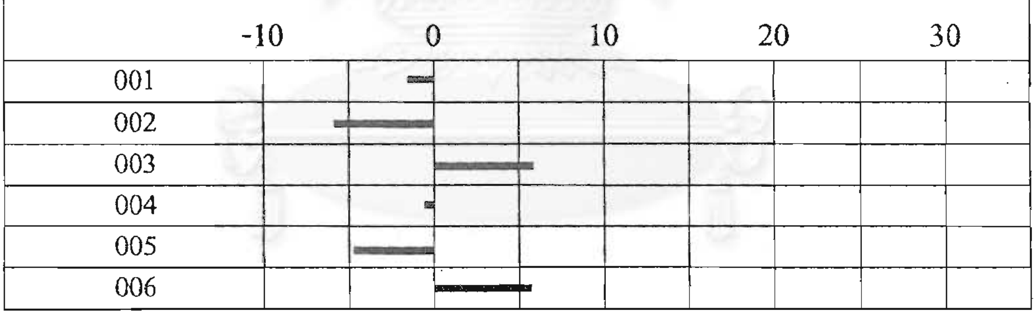



Figure 4.13 The report form of impedance testing report



In Figure 4.13, the graph shows the percent deviation of impedance of each cell from the system average. It is easy to determine the cells that have impedance higher than the specified value.

## 4.4 Criteria of Impedance Testing Analysis

There are two methods of impedance testing analysis; short and long-term time frames [9] [10].

### 4.4.1 Deviation of Impedance from Average Analysis (Short - Term)

The measured impedance data of each cell will be compared with the average impedance readings for the entire battery system. The individual cell that has percent impedance deviation more than ± 20% of the system impedance average, questionable cell, usually indicates a problem with that cell. Charles M. Gabriel (1993) [6] recommends that the large deviation impedance cell can be verified the result of impedance testing by an individual cell load testing. The questionable cell will be taken off from the system and investigated the problems, while the healthy cells can be continuously serviced. The impedance testing is performed during battery on-line.

### 4.4.2 Predictive Analysis (Long - Term)

The impedance of each cell will be periodically recorded and compared to the previous measurements in order to determine the rising of cell impedance against cell life, as shown in Figure 4.1. Gary J. Markle (1992)[8] suggests that the impedance of questionable cell should be recorded by every three months when the impedance higher than 15% of initial value [8]. The changes of cell impedance, rising direction, can imply that the cell capacity is reducing and also be warning to determine the developing problems.

Base line impedance values are the significant data that will be used for compare with the measured value. These data should be provided by manufacturer, in fact, most manufacturers are not provide its. However, the baseline data can be obtained by measurement it within three months of commissioning [9]. Prior to measure the baseline data the batteries should be equalizing charge about 72 hour and after that the batteries must be rest for about three days for the float voltage to stabilize [1]. The following example is the history record of impedance in cell #9 from October 27, 1994 to April 20, 1995; performed by Gary J. Markle [8].

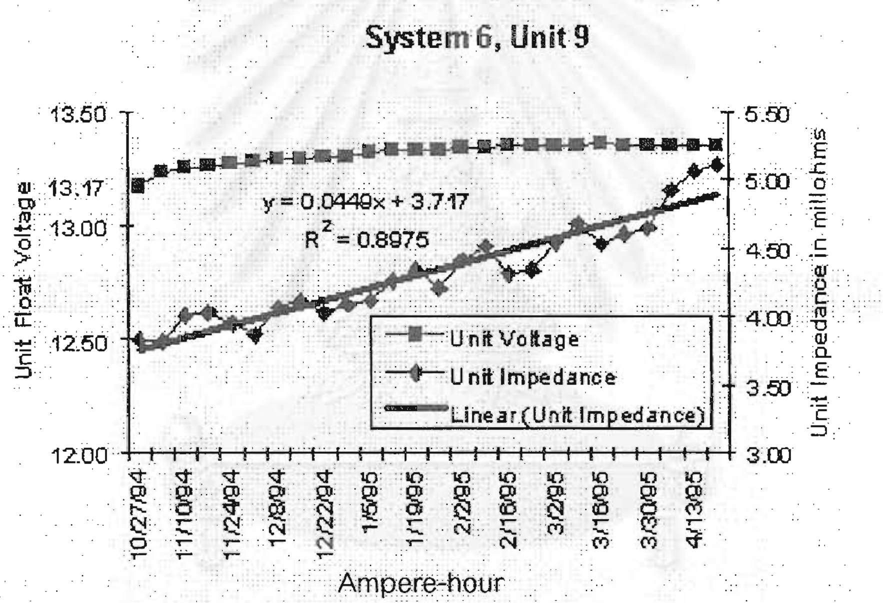



Figure 4.15 Example of impedance record periodically in questionable cell

In Figure 4.15, the problem in cell #9 is cell dryout, it can be shown the rise of cell impedance that can be warning for repairing or replacing, before it fails to provide power to load [8]. It can also be applied to predict the battery performance and capacity in order to improve the availability of battery before it fails in service.

### 4.4.3 Comparison with Load Testing Methods

Load testing method is a battery capacity determination, which is impractical for frequent performing, because it needs to be taken load off and battery outage. However, it can be used for verification the result impedance testing . Either individual cell or all batteries in the system can be performed load testing. In Figure 4.16, shows the relation of cell impedance and capacity [10].

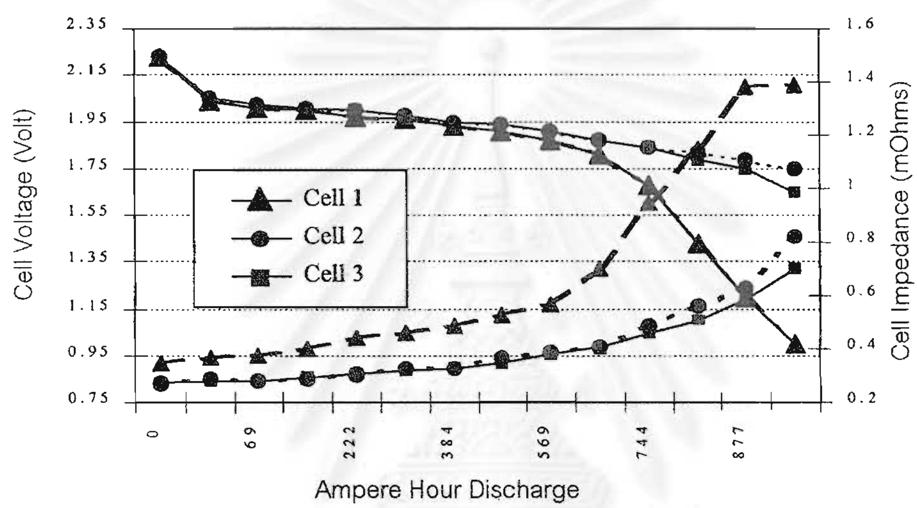



Figure 4.16 Load discharge testing and impedance changing in poor cell

In Figure 4.16, Cell#1 is a weak cell, the voltage decreases faster than the other cell during discharge current to load, while its impedance fast increases. As a result, it shows that the capacity of cell#1 is very low. The rising impedance of healthy cells is gradually increase while the voltages are gradually decrease. This result can also confirm that battery capacity and impedance are directly correlation.

In this thesis, the deviation of impedance from the average will only be used for study, because there are not base line values of existing batteries in service and the criteria of predictive analysis needs accumulated measured data that might be taken more one or two years for some sites.

# CHAPTER 5

# IMPLEMENTATION

## 5.1 Introduction

The study of battery impedance testing on EGAT plants and substations were performed during batteries normal operation. The tests were performed on three sites. After impedance measuring, load testing will be performed in order to verify the correction of impedance measuring result. Test data are shown in numeric numbers and graphical diagram which comprise individual cell impedance data and percent deviation of each cell from the system average. The result of impedance measuring provides the significant information of battery health and sign for near-fail cell that need to be repaired or replaced the new one. The impedance measuring and load testing will be done as the following.

*(1) Impedance Measuring and Analysis*

The impedance measuring will be performed during batteries are on-line and float charging operation. The step of impedance measuring consists of:

- Perform the test performed during batteries are on-line and float charging operation.
- Measure impedance of all cells in the same system; measurement method as mentioned in section 4.3.3.
- Convert all measured cell impedance value to percent deviation by compare with the entire system average.

The cells that have percent deviation higher than 20% of the average value are the unacceptable cells that have their remaining capacity lower than 80%, which is the level required for qualified battery systems in power generating stations [1][9][11].

The unacceptable cells will be corrected by investigating the cause of problems. As mentioned in 3.3, the causes of battery are numerous, Trojan [14] recommends that equalizing charge should be performed when sulphation on battery plates and low specific gravity are detected. The equalizing charge can be used to remove plate sulphation and improve the specific gravity.

However, when this cell has returned to normal voltage and has stabilized for some hours, measure its impedance and compare with other cells. If it is still out of range, over 20% of average, the study of Manfred R. Laidig and John W. Wurst [10] indicates that this cell should be considered for replacing

Furthermore, the corrosion on cell connection and high resistance of terminal post should be removed by cleaning; in order to avoid the terminal meltdown due to over heat when battery has supplied power to load. Corrosion is also a cause of cell under charge voltage due to voltage drop, leading to internal discharge, low specific gravity and plate sulphation.

*(2) Load Testing Verification*

In this study, in order to confirm impedance testing can be in place of other approach, load testing will be performed thereafter. Load testing will be performed by take the load off and the battery system out of service. The amount of current to be used for discharging depends on the rated capacity of battery which is specified by manufacturer. The result of load testing will be composed with result of impedance measuring cell by cell. For the weak cell, its impedance will higher than 20% of the average and its voltage will a more rapid decline, comparing with other cell, during load testing [10]

Load testing requires heavy and large power resister and a long length of time for testing. In this study, rate of current to be discharged is 10% rated capacity of batter. Usually, the rate of discharge is not higher than 10% of rated capacity because it is difficult to carry the load to some battery locations and it may be a cause of deep discharge for weak cell.

## 5.2 Performing the test on selected sites

The following test data were performed on three sites; South Bangkok power plant unit 4, Chulabhorn hydro power plant unit 2 and Nakhonayok Substation. The reasons for selecting these sites are the different year of in service and rated capacity, and they are due to be tested load discharge.

The test will be performed by two method; impedance measuring and load testing method.

### 5.2.1 Test result of South Bangkok power plant unit 4

The batteries of this site are just installed. The test was performed on Dec 26, 2000. The impedance testing was performed during batteries were operated in float charging state. Thereafter, load testing was performed by 10% rated capacity or about 61A The reference data sheet in page 111 shows discharge current and time. The discharging time decreases When discharge current increase.

Battery information

| | |
|---|---|
| Manufacturer : HOPPECKE | Model / Type 60PzV600 |
| Number of cell : 116 | Capacity: 600 Ah. |
| Volt/Cell : 2.2 | Float charge: 258 V. |
| Year in service: 2000 | Equalize charge: 278.4 V. |

Table 5.1 The battery information of South Bangkok plant unit 4

The float and equalize charge voltage values are specified by manufacturer.

- ***Impedance test performing***

The test result in Table 5.2 comes from the impedance testing method, which is measured by impedance test equipment model BITE and EBITE. The data in the table consists of test date and time, voltage of each cell, impedance of each cell (Zb) in milli-Ohms (mOhms), and connection resistance of each cell (Rs) in milli-Ohms. The time used for testing of 116 cells is about 36 minutes.

From Table 5.2, there are three interesting of impedance values, they are:

| | | |
|---|---|---|
| Average impedance value of entire system | : 0.486 | mOhms |
| Maximum impedance value | : 0.538 | mOhms |
| Minimum impedance value | : 0.446 | mOhms |

The absolute values in table 5.2 and 5.3 are no significant for availability determination [9] [13]. They must be converted to percent deviation from the entire system average value. The impedance of each cell will be compared with the average impedance of the entire battery system. The following calculation is method of percent deviation determination. The Impedance of maximum and minimum are 0.538 and 0.446 mOhms respectively. So, the percent deviation of each cell from the system average is

Min. Impedance:

$$Z_b\% = \frac{\textit{Cell impedance} - \textit{Average}}{\textit{Average}} * 100\% \quad (5.1)$$

$$Z_b\% = \frac{0.446 - 0.486}{0.486} * 100\%$$

$$Zb_{min}\% = -8.23\ \% \quad (5.2)$$

Max.Impedance:

$$Z_b\% = \frac{0.538 - 0.486}{0.486} * 100\% \quad (5.3)$$

$$Zb_{max}\% = 10.7\ \% \quad (5.4)$$

*Average is the value of summation of cells impedance in the system divide by number of those cells.

The percent deviation of cells that have minimum and maximum impedance are –8.23% and 10.7% respectively. The maximum of percent deviation in this system is lower than 20% of the average value.

The percent deviation of all cells are shown in Table 5.4 and 5.5.

Impedance testing data of South Bangkok power plant unit 4 page 1/2

| Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm | Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs mOhm |
|---|---|---|---|---|---|---|---|---|---|
| 12/26/00 10:19:15 | 1 | 2.223 | 0.467 | 0.047 | 12/26/00 10:31:56 | 31 | 2.221 | 0.489 | 0.042 |
| 12/26/00 10:19:29 | 2 | 2.243 | 0.467 | 0.046 | 12/26/00 10:32:12 | 32 | 2.233 | 0.501 | 0.042 |
| 12/26/00 10:19:47 | 3 | 2.233 | 0.461 | 0.04 | 12/26/00 10:32:23 | 33 | 2.243 | 0.485 | 0.042 |
| 12/26/00 10:20:00 | 4 | 2.233 | 0.485 | 0.044 | 12/26/00 10:32:52 | 34 | 2.228 | 0.47 | 0.04 |
| 12/26/00 10:20:18 | 5 | 2.248 | 0.463 | 0.044 | 12/26/00 10:33:15 | 35 | 2.248 | 0.47 | 0.045 |
| 12/26/00 10:20:54 | 6 | 2.231 | 0.477 | 0.044 | 12/26/00 10:33:26 | 36 | 2.24 | 0.482 | 0.041 |
| 12/26/00 10:21:20 | 7 | 2.243 | 0.495 | 0.046 | 12/26/00 10:33:47 | 37 | 2.233 | 0.477 | 0.043 |
| 12/26/00 10:25:56 | 8 | 2.233 | 0.487 | 0.044 | 12/26/00 10:33:58 | 38 | 2.214 | 0.475 | 0.042 |
| 12/26/00 10:26:13 | 9 | 2.245 | 0.498 | 0.043 | 12/26/00 10:34:11 | 39 | 2.238 | 0.485 | 0.042 |
| 12/26/00 10:26:34 | 10 | 2.258 | 0.477 | 0.046 | 12/26/00 10:34:22 | 40 | 2.228 | 0.481 | 0.042 |
| 12/26/00 10:26:51 | 11 | 2.233 | 0.485 | 0.042 | 12/26/00 10:34:33 | 41 | 2.206 | 0.451 | 0.042 |
| 12/26/00 10:27:02 | 12 | 2.238 | 0.481 | 0.047 | 12/26/00 10:35:06 | 42 | 2.245 | 0.478 | 0.04 |
| 12/26/00 10:27:13 | 13 | 2.233 | 0.471 | 0.042 | 12/26/00 10:35:21 | 43 | 2.226 | 0.461 | 0.095 |
| 12/26/00 10:27:28 | 14 | 2.233 | 0.481 | 0.043 | 12/26/00 10:35:34 | 44 | 2.223 | 0.459 | 0.042 |
| 12/26/00 10:27:41 | 15 | 2.228 | 0.475 | 0.133 | 12/26/00 10:36:09 | 45 | 2.243 | 0.49 | 0.044 |
| 12/26/00 10:27:53 | 16 | 2.221 | 0.474 | 0.043 | 12/26/00 10:36:21 | 46 | 2.226 | 0.506 | 0.042 |
| 12/26/00 10:28:10 | 17 | 2.248 | 0.465 | 0.046 | 12/26/00 10:36:33 | 47 | 2.228 | 0.486 | 0.042 |
| 12/26/00 10:28:20 | 18 | 2.265 | 0.498 | 0.326 | 12/26/00 10:36:49 | 48 | 2.214 | 0.473 | 0.044 |
| 12/26/00 10:28:34 | 19 | 2.228 | 0.485 | 0.046 | 12/26/00 10:37:26 | 49 | 2.233 | 0.498 | 0.04 |
| 12/26/00 10:28:44 | 20 | 2.262 | 0.479 | 0.044 | 12/26/00 10:37:38 | 50 | 2.233 | 0.475 | 0.042 |
| 12/26/00 10:28:57 | 21 | 2.24 | 0.504 | 0.043 | 12/26/00 10:37:52 | 51 | 2.218 | 0.478 | 0.042 |
| 12/26/00 10:29:08 | 22 | 2.262 | 0.49 | 0.047 | 12/26/00 10:38:05 | 52 | 2.218 | 0.489 | 0.044 |
| 12/26/00 10:29:21 | 23 | 2.238 | 0.478 | 0.043 | 12/26/00 10:38:21 | 53 | 2.243 | 0.461 | 0.042 |
| 12/26/00 10:30:07 | 24 | 2.211 | 0.477 | 0.042 | 12/26/00 10:38:32 | 54 | 2.223 | 0.483 | 0.04 |
| 12/26/00 10:30:28 | 25 | 2.221 | 0.482 | 0.15 | 12/26/00 10:38:43 | 55 | 2.218 | 0.459 | 0.044 |
| 12/26/00 10:30:43 | 26 | 2.218 | 0.49 | 0.042 | 12/26/00 10:38:54 | 56 | 2.209 | 0.49 | 0.043 |
| 12/26/00 10:30:56 | 27 | 2.216 | 0.538 | 0.046 | 12/26/00 10:39:07 | 57 | 2.211 | 0.487 | 0.044 |
| 12/26/00 10:31:11 | 28 | 2.223 | 0.524 | 0.043 | 12/26/00 10:40:53 | 58 | 2.209 | 0.464 | 0.329 |
| 12/26/00 10:31:25 | 29 | 2.214 | 0.495 | 0.325 | 12/26/00 10:41:06 | 59 | 2.226 | 0.475 | 0.047 |
| 12/26/00 10:31:44 | 30 | 2.223 | 0.482 | 0.042 | 12/26/00 10:41:22 | 60 | 2.223 | 0.485 | 0.05 |

Table 5.2 Battery measurement data of South Bangkok unit 4 (1/2)

Impedance testing data of South Bangkok power plant unit 4 page 2/2

| Date · Time | Cell No. | V/Cell | Zb mOhm | Rs mOhm | Date / Time | Cell No. | V/Cell | Zb mOhm | Rs mOhm |
|---|---|---|---|---|---|---|---|---|---|
| 12/26/00 10:41:49 | 61 | 2.218 | 0.491 | 0.048 | 12/26/00 10:49:44 | 91 | 2.228 | 0.495 | 0.048 |
| 12/26/00 10:42:07 | 62 | 2.228 | 0.485 | 0.052 | 12/26/00 10:49:58 | 92 | 2.218 | 0.52 | 0.05 |
| 12/26/00 10:42:20 | 63 | 2.204 | 0.498 | 0.051 | 12/26/00 10:50:12 | 93 | 2.231 | 0.485 | 0.079 |
| 12/26/00 10:42:39 | 64 | 2.214 | 0.507 | 0.048 | 12/26/00 10:50:51 | 94 | 2.236 | 0.512 | 0.086 |
| 12/26/00 10:42:54 | 65 | 2.238 | 0.505 | 0.052 | 12/26/00 10:51:05 | 95 | 2.245 | 0.495 | 0.044 |
| 12/26/00 10:43:22 | 66 | 2.228 | 0.506 | 0.05 | 12/26/00 10:51:22 | 96 | 2.248 | 0.512 | 0.048 |
| 12/26/00 10:43:50 | 67 | 2.226 | 0.532 | 0.064 | 12/26/00 10:51:33 | 97 | 2.223 | 0.493 | 0.048 |
| 12/26/00 10:44:03 | 68 | 2.214 | 0.479 | 0.165 | 12/26/00 10:51:50 | 98 | 2.27 | 0.507 | 0.048 |
| 12/26/00 10:44:21 | 69 | 2.223 | 0.51 | 0.052 | 12/26/00 10:52:02 | 99 | 2.233 | 0.49 | 0.047 |
| 12/26/00 10:44:35 | 70 | 2.228 | 0.489 | 0.046 | 12/26/00 10:52:14 | 100 | 2.214 | 0.477 | 0.048 |
| 12/26/00 10:44:48 | 71 | 2.218 | 0.495 | 0.05 | 12/26/00 10:52:28 | 101 | 2.214 | 0.454 | 0.107 |
| 12/26/00 10:45:00 | 72 | 2.218 | 0.465 | 0.047 | 12/26/00 10:52:40 | 102 | 2.228 | 0.474 | 0.052 |
| 12/26/00 10:45:12 | 73 | 2.214 | 0.467 | 0.154 | 12/26/00 10:52:52 | 103 | 2.214 | 0.486 | 0.047 |
| 12/26/00 10:45:27 | 74 | 2.204 | 0.479 | 0.051 | 12/26/00 10:53:08 | 104 | 2.211 | 0.446 | 0.05 |
| 12/26/00 10:45:40 | 75 | 2.214 | 0.486 | 0.049 | 12/26/00 10:53:21 | 105 | 2.233 | 0.487 | 0.05 |
| 12/26/00 10:45:57 | 76 | 2.248 | 0.494 | 0.05 | 12/26/00 10:53:48 | 106 | 2.236 | 0.477 | 0.05 |
| 12/26/00 10:46:08 | 77 | 2.231 | 0.513 | 0.051 | 12/26/00 10:53:58 | 107 | 2.236 | 0.49 | 0.05 |
| 12/26/00 10:46:28 | 78 | 2.238 | 0.498 | 0.05 | 12/26/00 10:54:11 | 108 | 2.228 | 0.483 | 0.05 |
| 12/26/00 10:46:49 | 79 | 2.262 | 0.521 | 0.05 | 12/26/00 10:54:22 | 109 | 2.243 | 0.474 | 0.048 |
| 12/26/00 10:47:02 | 80 | 2.231 | 0.487 | 0.047 | 12/26/00 10:54:33 | 110 | 2.243 | 0.487 | 0.051 |
| 12/26/00 10:47:13 | 81 | 2.243 | 0.52 | 0.052 | 12/26/00 10:54:44 | 111 | 2.24 | 0.47 | 0.05 |
| 12/26/00 10:47:26 | 82 | 2.258 | 0.482 | 0.05 | 12/26/00 10:54:56 | 112 | 2.238 | 0.461 | 0.05 |
| 12/26/00 10:47:40 | 83 | 2.238 | 0.479 | 0.05 | 12/26/00 10:55:07 | 113 | 2.236 | 0.485 | 0.052 |
| 12/26/00 10:47:54 | 84 | 2.236 | 0.499 | 0.05 | 12/26/00 10:55:18 | 114 | 2.228 | 0.475 | 0.058 |
| 12/26/00 10:48:09 | 85 | 2.233 | 0.519 | 0.06 | 12/26/00 10:55:34 | 115 | 2.214 | 0.463 | 0.044 |
| 12/26/00 10:48:39 | 86 | 2.211 | 0.517 | 0.093 | 12/26/00 10:55:46 | 116 | 2.236 | 0.465 | 0.048 |
| 12/26/00 10:48:55 | 87 | 2.211 | 0.49 | 0.324 | | | | | |
| 12/26/00 10:49:10 | 88 | 2.218 | 0.482 | 0.049 | | | | | |
| 12/26/00 10:49:22 | 89 | 2.253 | 0.485 | 0.048 | | | | | |
| 12/26/00 10:49:33 | 90 | 2.236 | 0.501 | 0.052 | | | | | |

Table 5.3 Battery measurement data of South Bangkok unit 4 (2/2)

Impedance testing data of South Bangkok power plant unit 4 ( Percent Deviation) page 1/2

| Date / Time | Cell No. | Zb m. Ohm | %Dev | | Date / Time | Cell No. | Zb m. Ohm | %Dev | |
|---|---|---|---|---|---|---|---|---|---|
| 12/26/00 10:19:15 | 1 | 0.467 | -3.91% | | 12/26/00 10:31:56 | 31 | 0.489 | 0.62% | |
| 12/26/00 10:19:29 | 2 | 0.467 | -3.91% | | 12/26/00 10:32:12 | 32 | 0.501 | 3.09% | |
| 12/26/00 10:19:47 | 3 | 0.461 | -5.14% | | 12/26/00 10:32:23 | 33 | 0.485 | -0.21% | |
| 12/26/00 10:20:00 | 4 | 0.485 | -0.21% | | 12/26/00 10:32:52 | 34 | 0.47 | -3.29% | |
| 12/26/00 10:20:18 | 5 | 0.463 | -4.73% | | 12/26/00 10:33:15 | 35 | 0.47 | -3.29% | |
| 12/26/00 10:20:54 | 6 | 0.477 | -1.85% | | 12/26/00 10:33:26 | 36 | 0.482 | -0.82% | |
| 12/26/00 10:21:20 | 7 | 0.495 | 1.85% | | 12/26/00 10:33:47 | 37 | 0.477 | -1.85% | |
| 12/26/00 10:25:56 | 8 | 0.487 | 0.21% | | 12/26/00 10:33:58 | 38 | 0.475 | -2.26% | |
| 12/26/00 10:26:13 | 9 | 0.498 | 2.47% | | 12/26/00 10:34:11 | 39 | 0.485 | -0.21% | |
| 12/26/00 10:26:34 | 10 | 0.477 | -1.85% | | 12/26/00 10:34:22 | 40 | 0.481 | -1.03% | |
| 12/26/00 10:26:51 | 11 | 0.485 | -0.21% | | 12/26/00 10:34:33 | 41 | 0.451 | -7.20% | |
| 12/26/00 10:27:02 | 12 | 0.481 | -1.03% | | 12/26/00 10:35:06 | 42 | 0.478 | -1.65% | |
| 12/26/00 10:27:13 | 13 | 0.471 | -3.09% | | 12/26/00 10:35:21 | 43 | 0.461 | -5.14% | |
| 12/26/00 10:27:28 | 14 | 0.481 | -1.03% | | 12/26/00 10:35:34 | 44 | 0.459 | -5.56% | |
| 12/26/00 10:27:41 | 15 | 0.475 | -2.26% | | 12/26/00 10:36:09 | 45 | 0.49 | 0.82% | |
| 12/26/00 10:27:53 | 16 | 0.474 | -2.47% | | 12/26/00 10:36:21 | 46 | 0.506 | 4.12% | |
| 12/26/00 10:28:10 | 17 | 0.465 | -4.32% | | 12/26/00 10:36:33 | 47 | 0.486 | 0.00% | |
| 12/26/00 10:28:20 | 18 | 0.498 | 2.47% | | 12/26/00 10:36:49 | 48 | 0.473 | -2.67% | |
| 12/26/00 10:28:34 | 19 | 0.485 | -0.21% | | 12/26/00 10:37:26 | 49 | 0.498 | 2.47% | |
| 12/26/00 10:28:44 | 20 | 0.479 | -1.44% | | 12/26/00 10:37:38 | 50 | 0.475 | -2.26% | |
| 12/26/00 10:28:57 | 21 | 0.504 | 3.70% | | 12/26/00 10:37:52 | 51 | 0.478 | -1.65% | |
| 12/26/00 10:29:08 | 22 | 0.49 | 0.82% | | 12/26/00 10:38:05 | 52 | 0.489 | 0.62% | |
| 12/26/00 10:29:21 | 23 | 0.478 | -1.65% | | 12/26/00 10:38:21 | 53 | 0.461 | -5.14% | |
| 12/26/00 10:30:07 | 24 | 0.477 | -1.85% | | 12/26/00 10:38:32 | 54 | 0.483 | -0.62% | |
| 12/26/00 10:30:28 | 25 | 0.482 | -0.82% | | 12/26/00 10:38:43 | 55 | 0.459 | -5.56% | |
| 12/26/00 10:30:43 | 26 | 0.49 | 0.82% | | 12/26/00 10:38:54 | 56 | 0.49 | 0.82% | |
| 12/26/00 10:30:56 | 27 | 0.538 | 10.70% | | 12/26/00 10:39:07 | 57 | 0.487 | 0.21% | |
| 12/26/00 10:31:11 | 28 | 0.524 | 7.82% | | 12/26/00 10:40:53 | 58 | 0.464 | -4.53% | |
| 12/26/00 10:31:25 | 29 | 0.495 | 1.85% | | 12/26/00 10:41:06 | 59 | 0.475 | -2.26% | |
| 12/26/00 10:31:44 | 30 | 0.482 | -0.82% | | 12/26/00 10:41:22 | 60 | 0.485 | -0.21% | |

Table 5.4 Impedance percent deviation calculation of South Bangkok (1/2)

Impedance testing data of South Bangkok power plant unit 4 ( Percent Deviation) page 2/2

| Date / Time | Cell No. | Zb m. Ohm | %Dev. | | Date / Time | Cell No. | Zb m. Ohm | %Dev | |
|---|---|---|---|---|---|---|---|---|---|
| 12/26/00 10:41:49 | 61 | 0.491 | 1.03% | | 12/26/00 10:49:44 | 91 | 0.495 | 1.85% | |
| 12/26/00 10:42:07 | 62 | 0.485 | -0.21% | | 12/26/00 10:49:58 | 92 | 0.52 | 7.00% | |
| 12/26/00 10:42:20 | 63 | 0.498 | 2.47% | | 12/26/00 10:50:12 | 93 | 0.485 | -0.21% | |
| 12/26/00 10:42:39 | 64 | 0.507 | 4.32% | | 12/26/00 10:50:51 | 94 | 0.512 | 5.35% | |
| 12/26/00 10:42:54 | 65 | 0.505 | 3.91% | | 12/26/00 10:51:05 | 95 | 0.495 | 1.85% | |
| 12/26/00 10:43:22 | 66 | 0.506 | 4.12% | | 12/26/00 10:51:22 | 96 | 0.512 | 5.35% | |
| 12/26/00 10:43:50 | 67 | 0.532 | 9.47% | | 12/26/00 10:51:33 | 97 | 0.493 | 1.44% | |
| 12/26/00 10:44:03 | 68 | 0.479 | -1.44% | | 12/26/00 10:51:50 | 98 | 0.507 | 4.32% | |
| 12/26/00 10:44:21 | 69 | 0.51 | 4.94% | | 12/26/00 10:52:02 | 99 | 0.49 | 0.82% | |
| 12/26/00 10:44:35 | 70 | 0.489 | 0.62% | | 12/26/00 10:52:14 | 100 | 0.477 | -1.85% | |
| 12/26/00 10:44:48 | 71 | 0.495 | 1.85% | | 12/26/00 10:52:28 | 101 | 0.454 | -6.58% | |
| 12/26/00 10:45:00 | 72 | 0.465 | -4.32% | | 12/26/00 10:52:40 | 102 | 0.474 | -2.47% | |
| 12/26/00 10:45:12 | 73 | 0.467 | -3.91% | | 12/26/00 10:52:52 | 103 | 0.486 | 0.00% | |
| 12/26/00 10:45:27 | 74 | 0.479 | -1.44% | | 12/26/00 10:53:08 | 104 | 0.446 | -8.23% | |
| 12/26/00 10:45:40 | 75 | 0.486 | 0.00% | | 12/26/00 10:53:21 | 105 | 0.487 | 0.21% | |
| 12/26/00 10:45:57 | 76 | 0.494 | 1.65% | | 12/26/00 10:53:48 | 106 | 0.477 | -1.85% | |
| 12/26/00 10:46:08 | 77 | 0.513 | 5.56% | | 12/26/00 10:53:58 | 107 | 0.49 | 0.82% | |
| 12/26/00 10:46:28 | 78 | 0.498 | 2.47% | | 12/26/00 10:54:11 | 108 | 0.483 | -0.62% | |
| 12/26/00 10:46:49 | 79 | 0.521 | 7.20% | | 12/26/00 10:54:22 | 109 | 0.474 | -2.47% | |
| 12/26/00 10:47:02 | 80 | 0.487 | 0.21% | | 12/26/00 10:54:33 | 110 | 0.487 | 0.21% | |
| 12/26/00 10:47:13 | 81 | 0.52 | 7.00% | | 12/26/00 10:54:44 | 111 | 0.47 | -3.29% | |
| 12/26/00 10:47:26 | 82 | 0.482 | -0.82% | | 12/26/00 10:54:56 | 112 | 0.461 | -5.14% | |
| 12/26/00 10:47:40 | 83 | 0.479 | -1.44% | | 12/26/00 10:55:07 | 113 | 0.485 | -0.21% | |
| 12/26/00 10:47:54 | 84 | 0.499 | 2.67% | | 12/26/00 10:55:18 | 114 | 0.475 | -2.26% | |
| 12/26/00 10:48:09 | 85 | 0.519 | 6.79% | | 12/26/00 10:55:34 | 115 | 0.463 | -4.73% | |
| 12/26/00 10:48:39 | 86 | 0.517 | 6.38% | | 12/26/00 10:55:46 | 116 | 0.465 | -4.32% | |
| 12/26/00 10:48:55 | 87 | 0.49 | 0.82% | | | | | | |
| 12/26/00 10:49:10 | 88 | 0.482 | -0.82% | | | | | | |
| 12/26/00 10:49:22 | 89 | 0.485 | -0.21% | | | | | | |
| 12/26/00 10:49:33 | 90 | 0.501 | 3.09% | | | | | | |

Table 5.5 Impedance percent deviation calculation of South Bangkok (2/2)

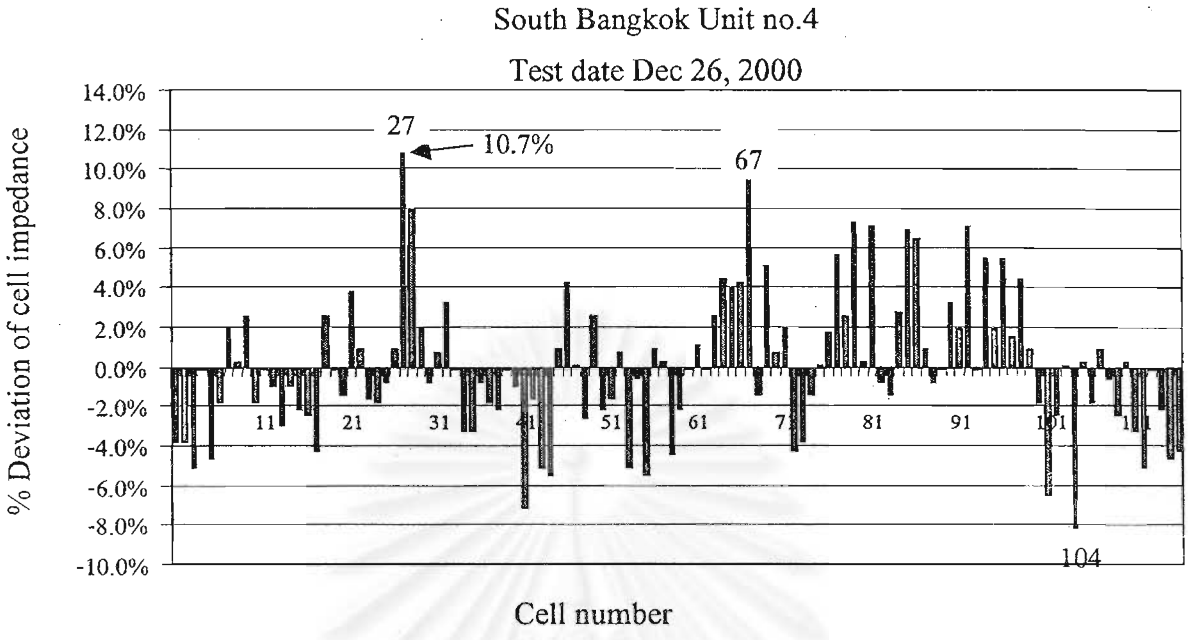



Figure 5.1 Impedance deviation of each cell Impedance from the average

The percent deviation of all cells in Table 5.4 and 5.5 can be shown as Figure 5.1. Cell #27 is the highest impedance cell, 0.538 mOhms, while the impedance average of the system is 0.486 mOhms. By calculation in percent deviation, cell #27 is 10.70% of the average. Cell #104 is the lowest impedance cell, 0.446 mOhms, and its deviation is –8.23% of the average. The deviation of all cells in this system are lower than 20% of the average. Therefore, the remaining capacity of all cells in this battery system can be accepted. In order to verify this conclusion the load testing will be performed thereafter.

- ***Load Test Performing***

After impedance testing, load testing was performed in order to determine the capacity of the battery system. All batteries in the system will be discharged by 61 amperes (about 10% of rated current). The result of both tests will be taken to compare with each other. The condition of load testing are:

- All battery cells will be taken off from the DC distribution bus.
- The resistive load will be connected across the battery system terminal.
- Voltage of each cell will be recorded with time.
- At 10th hour the voltage of each cell should be equal or higher than 1.83 volt. This condition is specified by the manufacturer, and it is accepted by IEEE standard 450-1995.

The results of load testing of all cells are shown in Table 5.7, 5.8 and 5.9. The following test data are the result of load testing of cells that have highest, average, and lowest impedance. They are cell #27, #75 and #104 respectively.

| Cell # | Load testing data | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1'st | 2'nd | 4'th | 6'th | 8'th | 9'th | 10'th |
| 27 | 2.216 | 2.000 | 1.981 | 1.955 | 1.923 | 1.899 | 1.878 |
| 75 | 2.214 | 2.005 | 1.985 | 1.960 | 1.929 | 1.904 | 1.882 |
| 104 | 2.211 | 2.005 | 1.983 | 1.957 | 1.926 | 1.904 | 1.883 |

Table 5.6 The result of load testing on the highest, average and lowest impedance cell

From the manufacture's recommendation the final-voltage at hour 10th should be 1.83 volts or over [13]. The result of load test show that all three cells, which have percent deviation 10.7%, 0%, -8.23% respectively, have the final-voltage higher than 1.83 volts and percent deviation less than 20% of the average. Therefore, the remaining capacity of all cells are higher than the level of requirement. The graph of load testing can be plotted in cell voltage versus discharge time axis as follows:

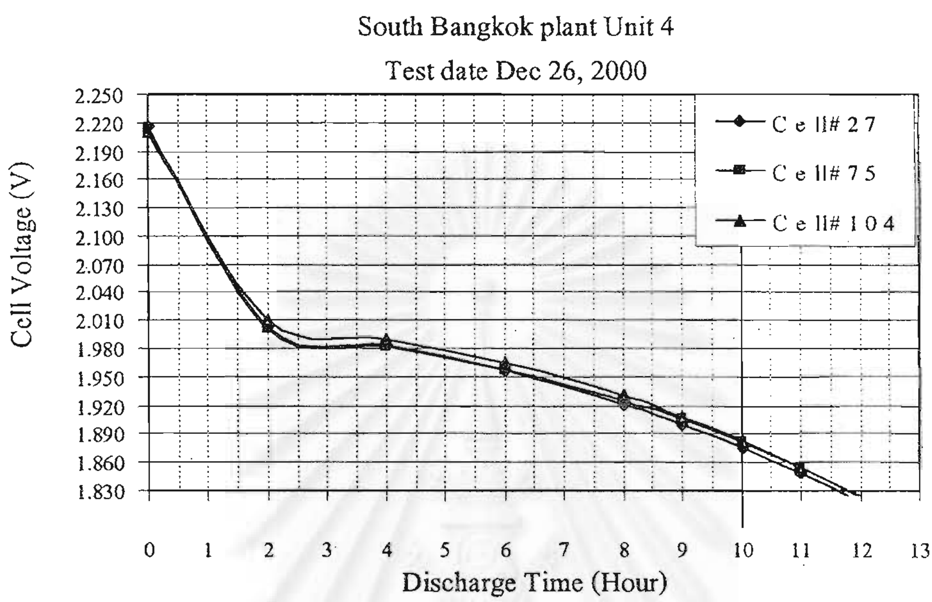



Figure 5.2 Load testing on the highest, average, and lowest impedance cell

Load Testing data of South Bangkok power plant unit4 Page 1/3

| Cell No. | Voltage of each cell at specific Hour | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0th | 2nd | 4th | 6th | 8th | 9th | 10th | 11th | 12th |
| 1 | 2.273 | 2.002 | 1.983 | 1.958 | 1.925 | 1.906 | 1.884 | 1.859 | 1.832 |
| 2 | 2.273 | 1.999 | 1.979 | 1.955 | 1.924 | 1.905 | 1.885 | 1.861 | 1.835 |
| 3 | 2.273 | 2.009 | 1.989 | 1.963 | 1.929 | 1.910 | 1.889 | 1.865 | 1.840 |
| 4 | 2.273 | 2.001 | 1.981 | 1.957 | 1.926 | 1.907 | 1.885 | 1.860 | 1.831 |
| 5 | 2.233 | 2.011 | 1.991 | 1.965 | 1.932 | 1.912 | 1.890 | 1.864 | 1.836 |
| 6 | 2.231 | 2.004 | 1.984 | 1.959 | 1.926 | 1.905 | 1.882 | 1.855 | 1.824 |
| 7 | 2.214 | 2.002 | 1.983 | 1.956 | 1.921 | 1.900 | 1.877 | 1.851 | 1.822 |
| 8 | 2.233 | 1.999 | 1.979 | 1.955 | 1.924 | 1.905 | 1.883 | 1.858 | 1.829 |
| 9 | 2.245 | 2.007 | 1.987 | 1.960 | 1.925 | 1.903 | 1.878 | 1.850 | 1.818 |
| 10 | 2.258 | 2.009 | 1.987 | 1.961 | 1.929 | 1.909 | 1.886 | 1.860 | 1.831 |
| 11 | 2.233 | 2.002 | 1.983 | 1.957 | 1.924 | 1.903 | 1.880 | 1.853 | 1.823 |
| 12 | 2.238 | 1.998 | 1.979 | 1.955 | 1.924 | 1.906 | 1.885 | 1.862 | 1.835 |
| 13 | 2.233 | 2.005 | 1.986 | 1.960 | 1.925 | 1.904 | 1.881 | 1.854 | 1.825 |
| 14 | 2.233 | 2.008 | 1.987 | 1.961 | 1.927 | 1.906 | 1.881 | 1.852 | 1.820 |
| 15 | 2.228 | 1.998 | 1.980 | 1.956 | 1.924 | 1.905 | 1.883 | 1.859 | 1.831 |
| 16 | 2.221 | 2.009 | 1.989 | 1.963 | 1.930 | 1.910 | 1.887 | 1.860 | 1.831 |
| 17 | 2.211 | 2.013 | 1.992 | 1.966 | 1.933 | 1.913 | 1.890 | 1.865 | 1.837 |
| 18 | 2.265 | 1.996 | 1.976 | 1.952 | 1.922 | 1.903 | 1.881 | 1.856 | 1.827 |
| 19 | 2.265 | 1.996 | 1.976 | 1.952 | 1.922 | 1.903 | 1.881 | 1.856 | 1.827 |
| 20 | 2.262 | 2.011 | 1.988 | 1.962 | 1.929 | 1.910 | 1.888 | 1.863 | 1.834 |
| 21 | 2.240 | 2.007 | 1.988 | 1.961 | 1.926 | 1.905 | 1.880 | 1.852 | 1.821 |
| 22 | 2.262 | 2.006 | 1.986 | 1.960 | 1.927 | 1.907 | 1.884 | 1.857 | 1.826 |
| 23 | 2.238 | 1.999 | 1.980 | 1.956 | 1.923 | 1.904 | 1.882 | 1.858 | 1.830 |
| 24 | 2.211 | 2.002 | 1.981 | 1.956 | 1.923 | 1.904 | 1.881 | 1.855 | 1.826 |
| 25 | 2.221 | 2.003 | 1.984 | 1.959 | 1.926 | 1.906 | 1.883 | 1.857 | 1.828 |
| 26 | 2.218 | 1.995 | 1.973 | 1.950 | 1.921 | 1.903 | 1.882 | 1.857 | 1.828 |
| 27 | 2.216 | 2.003 | 1.984 | 1.957 | 1.922 | 1.901 | 1.876 | 1.848 | 1.817 |
| 28 | 2.223 | 1.994 | 1.975 | 1.951 | 1.919 | 1.900 | 1.877 | 1.851 | 1.822 |
| 29 | 2.214 | 2.002 | 1.983 | 1.956 | 1.921 | 1.900 | 1.877 | 1.851 | 1.822 |
| 30 | 2.223 | 2.008 | 1.987 | 1.960 | 1.925 | 1.903 | 1.878 | 1.849 | 1.816 |
| 31 | 2.221 | 2.003 | 1.983 | 1.958 | 1.924 | 1.904 | 1.880 | 1.854 | 1.824 |
| 32 | 2.233 | 2.001 | 1.981 | 1.955 | 1.923 | 1.903 | 1.881 | 1.856 | 1.828 |
| 33 | 2.265 | 1.996 | 1.976 | 1.952 | 1.922 | 1.903 | 1.881 | 1.856 | 1.827 |
| 34 | 2.228 | 2.003 | 1.983 | 1.958 | 1.926 | 1.906 | 1.884 | 1.859 | 1.830 |
| 35 | 2.248 | 2.003 | 1.983 | 1.957 | 1.924 | 1.904 | 1.881 | 1.855 | 1.826 |
| 36 | 2.240 | 1.998 | 1.973 | 1.953 | 1.929 | 1.913 | 1.892 | 1.865 | 1.831 |
| 37 | 2.248 | 2.008 | 1.987 | 1.961 | 1.929 | 1.909 | 1.887 | 1.862 | 1.833 |
| 38 | 2.273 | 1.999 | 1.979 | 1.955 | 1.924 | 1.905 | 1.885 | 1.861 | 1.835 |
| 39 | 2.228 | 2.005 | 1.983 | 1.958 | 1.925 | 1.906 | 1.883 | 1.857 | 1.827 |
| 40 | 2.228 | 2.005 | 1.983 | 1.958 | 1.925 | 1.906 | 1.883 | 1.857 | 1.827 |

Table 5.7 The result of load testing at South Bangkok power plant unit 4 (1/3)

Load Testing data of South Bangkok power plant unit4 Page 2/3

| Cell No. | Voltage of each cell at specific Hour | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0th | 2nd | 4th | 6th | 8th | 9th | 10th | 11th | 12th |
| 41 | 2.245 | 2.005 | 1.986 | 1.961 | 1.930 | 1.911 | 1.889 | 1.864 | 1.836 |
| 42 | 2.248 | 2.008 | 1.987 | 1.961 | 1.929 | 1.909 | 1.887 | 1.862 | 1.833 |
| 43 | 2.211 | 2.013 | 1.992 | 1.966 | 1.933 | 1.913 | 1.890 | 1.865 | 1.837 |
| 44 | 2.223 | 2.007 | 1.987 | 1.962 | 1.930 | 1.911 | 1.890 | 1.866 | 1.840 |
| 45 | 2.243 | 2.002 | 1.982 | 1.956 | 1.924 | 1.904 | 1.881 | 1.855 | 1.826 |
| 46 | 2.226 | 2.012 | 1.990 | 1.963 | 1.929 | 1.908 | 1.884 | 1.857 | 1.825 |
| 47 | 2.228 | 2.010 | 1.989 | 1.964 | 1.931 | 1.910 | 1.887 | 1.860 | 1.830 |
| 48 | 2.233 | 2.011 | 1.991 | 1.965 | 1.932 | 1.912 | 1.890 | 1.864 | 1.836 |
| 49 | 2.233 | 2.008 | 1.988 | 1.962 | 1.927 | 1.906 | 1.882 | 1.856 | 1.826 |
| 50 | 2.233 | 2.003 | 1.983 | 1.959 | 1.927 | 1.907 | 1.885 | 1.860 | 1.831 |
| 51 | 2.218 | 2.006 | 1.987 | 1.961 | 1.928 | 1.907 | 1.884 | 1.857 | 1.827 |
| 52 | 2.228 | 2.004 | 1.984 | 1.958 | 1.924 | 1.904 | 1.880 | 1.854 | 1.824 |
| 53 | 2.243 | 2.009 | 1.987 | 1.963 | 1.933 | 1.914 | 1.891 | 1.865 | 1.833 |
| 54 | 2.223 | 2.009 | 1.988 | 1.963 | 1.931 | 1.911 | 1.889 | 1.863 | 1.834 |
| 55 | 2.218 | 2.009 | 1.989 | 1.964 | 1.931 | 1.910 | 1.887 | 1.860 | 1.830 |
| 56 | 2.213 | 2.009 | 1.987 | 1.961 | 1.929 | 1.909 | 1.886 | 1.860 | 1.830 |
| 57 | 2.233 | 1.999 | 1.979 | 1.955 | 1.924 | 1.905 | 1.883 | 1.858 | 1.829 |
| 58 | 2.245 | 2.005 | 1.986 | 1.961 | 1.930 | 1.911 | 1.889 | 1.864 | 1.836 |
| 59 | 2.226 | 2.015 | 1.994 | 1.967 | 1.932 | 1.911 | 1.887 | 1.860 | 1.830 |
| 60 | 2.233 | 2.008 | 1.988 | 1.962 | 1.927 | 1.906 | 1.882 | 1.856 | 1.826 |
| 61 | 2.218 | 1.997 | 1.977 | 1.953 | 1.922 | 1.903 | 1.881 | 1.856 | 1.827 |
| 62 | 2.248 | 2.003 | 1.983 | 1.957 | 1.924 | 1.904 | 1.881 | 1.855 | 1.826 |
| 63 | 2.233 | 2.008 | 1.988 | 1.962 | 1.927 | 1.906 | 1.882 | 1.856 | 1.826 |
| 64 | 2.214 | 2.006 | 1.983 | 1.957 | 1.925 | 1.905 | 1.882 | 1.855 | 1.824 |
| 65 | 2.238 | 2.011 | 1.990 | 1.964 | 1.930 | 1.910 | 1.886 | 1.859 | 1.828 |
| 66 | 2.231 | 2.006 | 1.985 | 1.960 | 1.927 | 1.907 | 1.884 | 1.857 | 1.826 |
| 67 | 2.214 | 2.011 | 1.989 | 1.963 | 1.929 | 1.907 | 1.882 | 1.853 | 1.819 |
| 68 | 2.214 | 2.001 | 1.980 | 1.956 | 1.924 | 1.905 | 1.883 | 1.857 | 1.828 |
| 69 | 2.223 | 2.005 | 1.984 | 1.958 | 1.923 | 1.902 | 1.877 | 1.847 | 1.814 |
| 70 | 2.228 | 2.000 | 1.980 | 1.956 | 1.925 | 1.905 | 1.884 | 1.858 | 1.830 |
| 71 | 2.222 | 2.008 | 1.988 | 1.962 | 1.927 | 1.906 | 1.881 | 1.853 | 1.821 |
| 72 | 2.273 | 1.999 | 1.979 | 1.955 | 1.924 | 1.905 | 1.885 | 1.861 | 1.835 |
| 73 | 2.245 | 2.005 | 1.986 | 1.961 | 1.930 | 1.911 | 1.889 | 1.864 | 1.836 |
| 74 | 2.204 | 1.998 | 1.978 | 1.954 | 1.923 | 1.904 | 1.882 | 1.857 | 1.828 |
| 75 | 2.214 | 2.002 | 1.982 | 1.957 | 1.925 | 1.905 | 1.882 | 1.855 | 1.824 |
| 76 | 2.214 | 2.001 | 1.980 | 1.956 | 1.924 | 1.905 | 1.883 | 1.857 | 1.828 |
| 77 | 2.238 | 2.004 | 1.985 | 1.959 | 1.926 | 1.905 | 1.882 | 1.855 | 1.825 |
| 78 | 2.238 | 2.002 | 1.981 | 1.955 | 1.923 | 1.903 | 1.881 | 1.855 | 1.826 |
| 79 | 2.228 | 2.007 | 1.986 | 1.960 | 1.924 | 1.903 | 1.878 | 1.850 | 1.818 |
| 80 | 2.231 | 2.004 | 1.983 | 1.957 | 1.925 | 1.905 | 1.883 | 1.857 | 1.828 |

Table 5.8 The result of load testing at South Bangkok power plant unit 4 (2/3)

Load Testing data of South Bangkok power plant unit4 Page 3/3

| Cell No. | Voltage of each cell at specific Hour | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0st | 2nd | 4th | 6th | 8th | 9th | 10th | 11th | 12th |
| 81 | 2.248 | 2.004 | 1.984 | 1.957 | 1.922 | 1.900 | 1.875 | 1.847 | 1.815 |
| 82 | 2.258 | 2.006 | 1.984 | 1.958 | 1.924 | 1.902 | 1.877 | 1.848 | 1.814 |
| 83 | 2.238 | 2.004 | 1.985 | 1.959 | 1.926 | 1.905 | 1.882 | 1.855 | 1.825 |
| 84 | 2.236 | 2.002 | 1.983 | 1.956 | 1.920 | 1.898 | 1.875 | 1.848 | 1.820 |
| 85 | 2.233 | 2.002 | 1.983 | 1.957 | 1.924 | 1.903 | 1.880 | 1.853 | 1.823 |
| 86 | 2.214 | 2.000 | 1.982 | 1.957 | 1.923 | 1.902 | 1.879 | 1.853 | 1.825 |
| 87 | 2.211 | 2.004 | 1.985 | 1.961 | 1.928 | 1.908 | 1.885 | 1.859 | 1.829 |
| 88 | 2.218 | 2.008 | 1.987 | 1.961 | 1.929 | 1.909 | 1.887 | 1.861 | 1.832 |
| 89 | 2.265 | 1.996 | 1.976 | 1.952 | 1.922 | 1.903 | 1.881 | 1.856 | 1.827 |
| 90 | 2.236 | 2.003 | 1.981 | 1.957 | 1.925 | 1.905 | 1.883 | 1.857 | 1.827 |
| 91 | 2.228 | 2.004 | 1.984 | 1.958 | 1.924 | 1.904 | 1.880 | 1.854 | 1.824 |
| 92 | 2.228 | 2.007 | 1.986 | 1.960 | 1.924 | 1.903 | 1.878 | 1.850 | 1.818 |
| 93 | 2.231 | 2.003 | 1.982 | 1.957 | 1.925 | 1.906 | 1.884 | 1.858 | 1.829 |
| 94 | 2.228 | 2.005 | 1.983 | 1.958 | 1.925 | 1.906 | 1.883 | 1.857 | 1.827 |
| 95 | 2.228 | 2.004 | 1.984 | 1.958 | 1.924 | 1.904 | 1.880 | 1.854 | 1.824 |
| 96 | 2.265 | 1.996 | 1.976 | 1.952 | 1.922 | 1.903 | 1.881 | 1.856 | 1.827 |
| 97 | 2.223 | 1.999 | 1.980 | 1.955 | 1.923 | 1.903 | 1.881 | 1.855 | 1.826 |
| 98 | 2.238 | 2.003 | 1.983 | 1.957 | 1.925 | 1.905 | 1.882 | 1.856 | 1.827 |
| 99 | 2.222 | 2.008 | 1.988 | 1.962 | 1.927 | 1.906 | 1.881 | 1.853 | 1.821 |
| 100 | 2.243 | 2.006 | 1.985 | 1.960 | 1.929 | 1.910 | 1.888 | 1.862 | 1.832 |
| 101 | 2.214 | 2.009 | 1.990 | 1.965 | 1.932 | 1.913 | 1.891 | 1.866 | 1.838 |
| 102 | 2.228 | 2.010 | 1.989 | 1.963 | 1.930 | 1.909 | 1.886 | 1.859 | 1.827 |
| 103 | 2.214 | 2.013 | 1.992 | 1.965 | 1.930 | 1.909 | 1.885 | 1.858 | 1.828 |
| 104 | 2.214 | 2.009 | 1.990 | 1.965 | 1.932 | 1.913 | 1.891 | 1.866 | 1.838 |
| 105 | 2.233 | 2.011 | 1.991 | 1.965 | 1.932 | 1.912 | 1.890 | 1.864 | 1.836 |
| 106 | 2.236 | 2.005 | 1.983 | 1.957 | 1.923 | 1.901 | 1.876 | 1.847 | 1.813 |
| 107 | 2.236 | 1.995 | 1.975 | 1.950 | 1.918 | 1.898 | 1.875 | 1.848 | 1.817 |
| 108 | 2.228 | 2.007 | 1.985 | 1.959 | 1.924 | 1.903 | 1.878 | 1.849 | 1.815 |
| 109 | 2.262 | 2.011 | 1.988 | 1.962 | 1.929 | 1.910 | 1.888 | 1.863 | 1.834 |
| 110 | 2.243 | 2.002 | 1.982 | 1.956 | 1.924 | 1.904 | 1.881 | 1.855 | 1.826 |
| 111 | 2.228 | 2.007 | 1.986 | 1.960 | 1.924 | 1.903 | 1.878 | 1.850 | 1.818 |
| 112 | 2.245 | 2.005 | 1.986 | 1.961 | 1.930 | 1.911 | 1.889 | 1.864 | 1.836 |
| 113 | 2.236 | 2.003 | 1.984 | 1.958 | 1.925 | 1.904 | 1.881 | 1.854 | 1.824 |
| 114 | 2.233 | 2.008 | 1.987 | 1.961 | 1.927 | 1.906 | 1.881 | 1.852 | 1.820 |
| 115 | 2.233 | 2.011 | 1.991 | 1.965 | 1.932 | 1.912 | 1.890 | 1.864 | 1.836 |
| 116 | 2.273 | 1.999 | 1.979 | 1.955 | 1.924 | 1.905 | 1.885 | 1.861 | 1.835 |

Table 5.9 The result of load testing at South Bangkok power plant unit 4 (3/3)

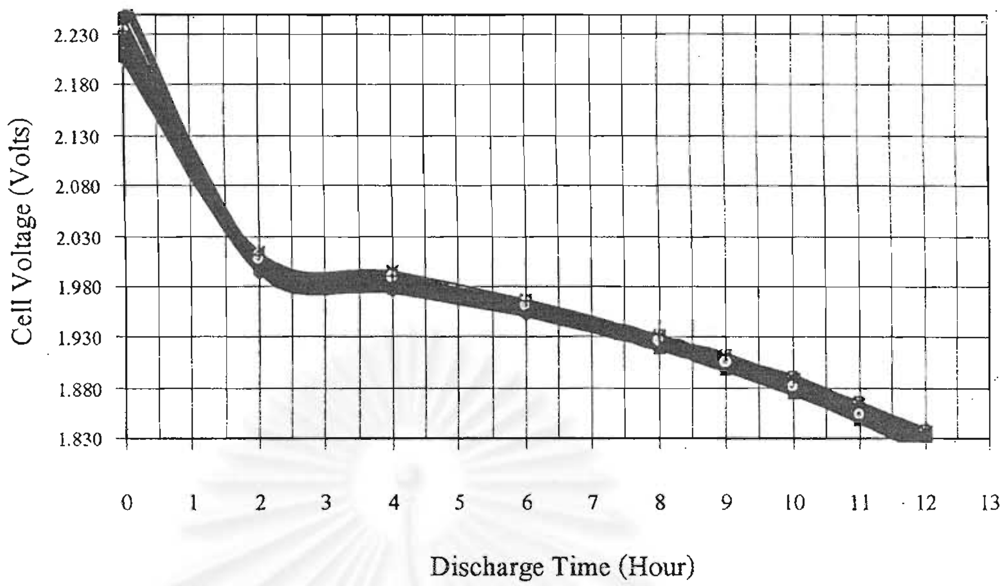



Figure 5.3 Load testing of 116 cells

Figure 5.3 shows the result of load testing of 116 cells. All of them have the final voltage at hour 10th higher 1.83 volt. The manufacturer guarantees capacity of the cells that meet this condition will have the remaining capacity equal or higher than 100% of rated capacity.

- ***Capacity Calculation***

The capacity of battery can be determined by calculation from the ratio of actual discharge time to rated discharge time, as mentioned in section 2.7.4. From Figure 5.2, the discharge time has been extended until the voltage of cell reduced to 1.83 volt. The discharge time will be recorded. This discharge time will be divided by the rated discharge time, which is specified by manufacturer; for this test is 10 hours. The battery capacity will be calculated in percentage by multiply with 100.

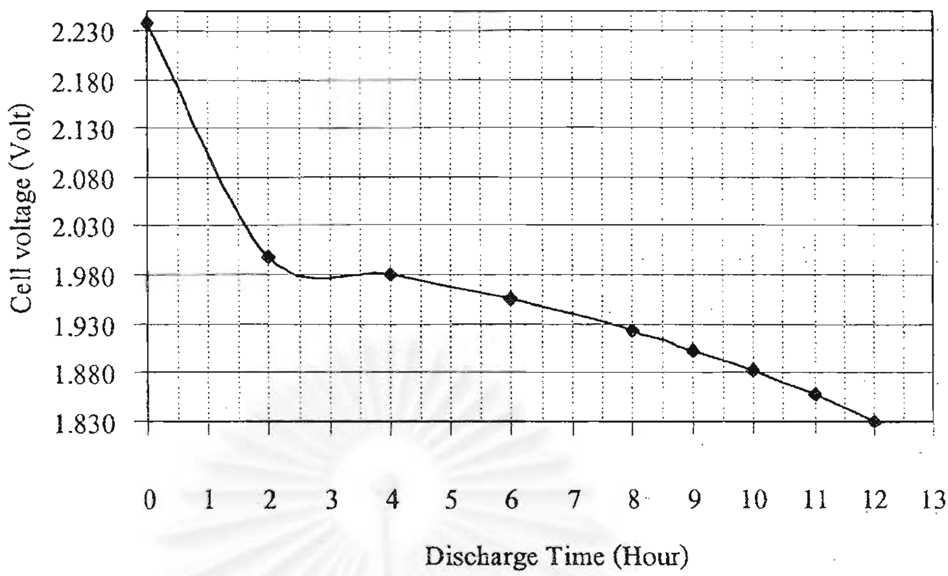



Figure 5.4 Discharge time at specified final-voltage

In Figure 5.4 the discharge time at specified final-voltage, 1.83 volt, of this cell is 12.0 hours. Therefore, the capacity of this cell is 120% of rated capacity. Table 5.8 contain all battery capacity and its impedance.

Cell impedance and capacity data of South Bangkok power plant unit4

| Cell No. | impedance | Capacity | Cell No. | impedance | Capacity | Cell No. | impedance | Capacity |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.467 | 120.3% | 40 | 0.481 | 119.0% | 79 | 0.521 | 116.3% |
| 2 | 0.467 | 121.3% | 41 | 0.451 | 122.0% | 80 | 0.487 | 119.3% |
| 3 | 0.461 | 122.1% | 42 | 0.478 | 121.1% | 81 | 0.52 | 115.4% |
| 4 | 0.485 | 120.0% | 43 | 0.461 | 122.2% | 82 | 0.482 | 115.5% |
| 5 | 0.463 | 121.9% | 44 | 0.459 | 122.6% | 83 | 0.479 | 118.5% |
| 6 | 0.477 | 117.8% | 45 | 0.49 | 118.7% | 84 | 0.499 | 116.6% |
| 7 | 0.495 | 117.5% | 46 | 0.506 | 118.6% | 85 | 0.519 | 117.9% |
| 8 | 0.487 | 119.2% | 47 | 0.486 | 119.8% | 86 | 0.517 | 118.4% |
| 9 | 0.498 | 115.9% | 48 | 0.473 | 121.6% | 87 | 0.49 | 119.7% |
| 10 | 0.477 | 119.7% | 49 | 0.498 | 118.8% | 88 | 0.482 | 120.6% |
| 11 | 0.485 | 118.3% | 50 | 0.475 | 120.4% | 89 | 0.485 | 118.9% |
| 12 | 0.481 | 117.0% | 51 | 0.478 | 119.1% | 90 | 0.501 | 119.1% |
| 13 | 0.471 | 120.5% | 52 | 0.489 | 118.1% | 91 | 0.495 | 118.1% |
| 14 | 0.481 | 120.3% | 53 | 0.461 | 121.0% | 92 | 0.52 | 111.6% |
| 15 | 0.475 | 121.4% | 54 | 0.483 | 121.4% | 93 | 0.485 | 119.8% |
| 16 | 0.474 | 118.9% | 55 | 0.459 | 120.1% | 94 | 0.512 | 119.0% |
| 17 | 0.465 | 122.1% | 56 | 0.49 | 119.8% | 95 | 0.495 | 118.0% |
| 18 | 0.498 | 118.9% | 57 | 0.487 | 119.2% | 96 | 0.512 | 118.9% |
| 19 | 0.485 | 118.9% | 58 | 0.464 | 122.0% | 97 | 0.493 | 118.7% |
| 20 | 0.479 | 121.4% | 59 | 0.475 | 119.9% | 98 | 0.507 | 119.0% |
| 21 | 0.504 | 117.3% | 60 | 0.485 | 118.8% | 99 | 0.49 | 117.2% |
| 22 | 0.49 | 118.8% | 61 | 0.491 | 119.1% | 100 | 0.477 | 120.8% |
| 23 | 0.478 | 120.1% | 62 | 0.485 | 118.6% | 101 | 0.454 | 122.6% |
| 24 | 0.477 | 118.7% | 63 | 0.498 | 118.8% | 102 | 0.474 | 119.2% |
| 25 | 0.482 | 119.3% | 64 | 0.507 | 118.3% | 103 | 0.486 | 117.3% |
| 26 | 0.49 | 119.4% | 65 | 0.505 | 119.4% | 104 | 0.446 | 122.6% |
| 27 | 0.538 | 115.7% | 66 | 0.506 | 118.6% | 105 | 0.487 | 117.3% |
| 28 | 0.524 | 117.3% | 67 | 0.532 | 116.8% | 106 | 0.477 | 118.6% |
| 29 | 0.495 | 117.4% | 68 | 0.479 | 119.3% | 107 | 0.49 | 116.1% |
| 30 | 0.482 | 115.9% | 69 | 0.51 | 115.4% | 108 | 0.483 | 118.5% |
| 31 | 0.489 | 118.0% | 70 | 0.489 | 119.9% | 109 | 0.474 | 121.4% |
| 32 | 0.501 | 119.2% | 71 | 0.495 | 117.2% | 110 | 0.487 | 118.7% |
| 33 | 0.485 | 118.9% | 72 | 0.465 | 121.3% | 111 | 0.47 | 118.3% |
| 34 | 0.47 | 120.1% | 73 | 0.467 | 122.0% | 112 | 0.461 | 121.8% |
| 35 | 0.47 | 118.6% | 74 | 0.479 | 119.4% | 113 | 0.485 | 118.2% |
| 36 | 0.482 | 120.3% | 75 | 0.486 | 118.3% | 114 | 0.475 | 120.3% |
| 37 | 0.477 | 121.1% | 76 | 0.494 | 119.3% | 115 | 0.463 | 121.7% |
| 38 | 0.475 | 121.3% | 77 | 0.513 | 118.5% | 116 | 0.465 | 121.2% |
| 39 | 0.485 | 119.0% | 78 | 0.498 | 118.6% | | | |

Table 5.10 Listof cell impedance and capacity of South Bangkok plant unit4

- ***Test result conclusion***

The results of both testing methods show the correlation between impedance testing and load testing method as follows:

- The battery cells that have impedance deviation lower than 20% of the system average will also have their capacity equal or over the level of requirement; such as the cell that has highest impedance deviation, 10.7% of the average, its capacity is 115.7%.
- The correlation between cell impedance and its capacity show that the high impedances will have low capacities and low impedances will have high capacities.

The result of both impedance measuring and load testing show that all battery cells are not need to improve their capacity, due to they meet the level of requirement.

Accordingly, the battery system of South Bangkok power plant unit 4 is new installed system, therefore the result of impedance measuring can be used as base line value fore comparing with the next measuring.

### 5.2.2 Test result of Nakhonayok substation

Test data are taken during battery system on-line. The batteries life of this site are about 10 years in service. The test was performed on September 18, 2000. The test condition are performed in two ways, first is impedance measuring and second is load testing by 10% of capacity.

Battery information

| | |
|---|---|
| Manufacturer : OLDHAM Hawker | Mode/Type : E8-5674 |
| Number of cell : 60 | Capacity : 200 Ah. |
| Volt/Cell : 2.0 | Float charge : 133.8 V. |
| Year of in service: 1991 | Equalize charge : 144 V. |

Table 5.11 The battery information of Nakhonayok substation

From Table 5.12, there are three interesting of impedance value, they are:

| | | |
|---|---|---|
| Average impedance value of entire system | : 1.118 | mOhms |
| Maximum impedance value | : 1.96 | mOhms |
| Minimum impedance value | : 0.99 | mOhms |

The calculation of percent deviation is same as above. The percent deviations of each cell from the average are shown as Table 5.12.

The test condition and procedure will conform to the section 5.1.

Impedance testing data of Nakhonayok Substation page 1/1

| Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm | Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm |
|---|---|---|---|---|---|---|---|---|---|
| 09/18/00 14:02 | 1 | 2.272 | 1.05 | 0.044 | 09/18/00 14:08 | 31 | 2.272 | 1.06 | 0.045 |
| 09/18/00 14:02 | 2 | 2.277 | 1.03 | 0.046 | 09/18/00 14:08 | 32 | 2.199 | 1.89 | 0.055 |
| 09/18/00 14:02 | 3 | 2.272 | 1.05 | 0.063 | 09/18/00 14:08 | 33 | 2.199 | 1.8 | 0.04 |
| 09/18/00 14:02 | 4 | 2.275 | 1.06 | 0.058 | 09/18/00 14:08 | 34 | 2.267 | 1.02 | 0.048 |
| 09/18/00 14:03 | 5 | 2.214 | 1.49 | 0.057 | 09/18/00 14:09 | 35 | 2.265 | 1.01 | 0.042 |
| 09/18/00 14:03 | 6 | 2.194 | 1.96 | 0.06 | 09/18/00 14:09 | 36 | 2.267 | 1.01 | 0.052 |
| 09/18/00 14:03 | 7 | 2.27 | 1.04 | 0.05 | 09/18/00 14:09 | 37 | 2.265 | 1.05 | 0.04 |
| 09/18/00 14:03 | 8 | 2.275 | 1.04 | 0.052 | 09/18/00 14:09 | 38 | 2.275 | 1.05 | 0.051 |
| 09/18/00 14:03 | 9 | 2.27 | 1.02 | 0.046 | 09/18/00 14:09 | 39 | 2.262 | 1.03 | 0.049 |
| 09/18/00 14:03 | 10 | 2.275 | 1.03 | 0.053 | 09/18/00 14:10 | 40 | 2.192 | 1.87 | 0.052 |
| 09/18/00 14:04 | 11 | 2.226 | 1.3 | 0.05 | 09/18/00 14:10 | 41 | 2.27 | 1.01 | 0.043 |
| 09/18/00 14:04 | 12 | 2.277 | 1.05 | 0.06 | 09/18/00 14:10 | 42 | 2.267 | 1.05 | 0.055 |
| 09/18/00 14:04 | 13 | 2.277 | 1.06 | 0.046 | 09/18/00 14:10 | 43 | 2.27 | 1.04 | 0.049 |
| 09/18/00 14:04 | 14 | 2.28 | 1.05 | 0.053 | 09/18/00 14:10 | 44 | 2.272 | 1.1 | 0.055 |
| 09/18/00 14:04 | 15 | 2.277 | 1.02 | 0.282 | 09/18/00 14:11 | 45 | 2.28 | 1.05 | 0.247 |
| 09/18/00 14:05 | 16 | 2.275 | 1.02 | 0.046 | 09/18/00 14:11 | 46 | 2.284 | 1.02 | 0.042 |
| 09/18/00 14:05 | 17 | 2.27 | 1.07 | 0.064 | 09/18/00 14:11 | 47 | 2.223 | 1.48 | 0.049 |
| 09/18/00 14:05 | 18 | 2.272 | 1.05 | 0.05 | 09/18/00 14:12 | 48 | 2.27 | 1.02 | 0.045 |
| 09/18/00 14:05 | 19 | 2.236 | 1.21 | 0.057 | 09/18/00 14:12 | 49 | 2.248 | 1.06 | 0.046 |
| 09/18/00 14:05 | 20 | 2.248 | 1.03 | 0.052 | 09/18/00 14:12 | 50 | 2.262 | 1.03 | 0.04 |
| 09/18/00 14:06 | 21 | 2.272 | 1.03 | 0.05 | 09/18/00 14:12 | 51 | 2.265 | 0.99 | 0.046 |
| 09/18/00 14:06 | 22 | 2.253 | 1.06 | 0.05 | 09/18/00 14:12 | 52 | 2.26 | 1.05 | 0.042 |
| 09/18/00 14:06 | 23 | 2.253 | 1.02 | 0.049 | 09/18/00 14:12 | 53 | 2.272 | 1.01 | 0.044 |
| 09/18/00 14:06 | 24 | 2.27 | 1.01 | 0.051 | 09/18/00 14:13 | 54 | 2.272 | 1.04 | 0.041 |
| 09/18/00 14:06 | 25 | 2.275 | 1.07 | 0.048 | 09/18/00 14:13 | 55 | 2.28 | 1.05 | 0.049 |
| 09/18/00 14:06 | 26 | 2.272 | 1.02 | 0.047 | 09/18/00 14:13 | 56 | 2.28 | 1.07 | 0.04 |
| 09/18/00 14:07 | 27 | 2.248 | 1.03 | 0.051 | 09/18/00 14:13 | 57 | 2.28 | 1.06 | 0.049 |
| 09/18/00 14:07 | 28 | 2.272 | 1.02 | 0.049 | 09/18/00 14:13 | 58 | 2.28 | 1.06 | 0.043 |
| 09/18/00 14:07 | 29 | 2.179 | 0.994 | 0.052 | 09/18/00 14:13 | 59 | 2.28 | 1.05 | 0.043 |
| 09/18/00 14:08 | 30 | 2.272 | 1.08 | 0.258 | 09/18/00 14:14 | 60 | 2.28 | 1.07 | 0.043 |

Table 5.12 Battery measurement data of Nakhonayok Substation

Impedance testing data of Nakhonayok Substation (Percent Deviation) page 1/1

| Date / Time | Cell No. | Zb m. Ohm | %Dev | | Date / Time | Cell No. | Zb m. Ohm | %Dev | |
|---|---|---|---|---|---|---|---|---|---|
| 09/18/00 14:02 | 1 | 1.05 | -6.06% | | 09/18/00 14:08 | 31 | 1.06 | -5.17% | |
| 09/18/00 14:02 | 2 | 1.03 | -7.85% | | 09/18/00 14:08 | 32 | 1.89 | 69.09% | |
| 09/18/00 14:02 | 3 | 1.05 | -6.06% | | 09/18/00 14:08 | 33 | 1.8 | 61.04% | |
| 09/18/00 14:02 | 4 | 1.06 | -5.17% | | 09/18/00 14:08 | 34 | 1.02 | -8.74% | |
| 09/18/00 14:03 | 5 | 1.49 | 33.31% | | 09/18/00 14:09 | 35 | 1.01 | -9.64% | |
| 09/18/00 14:03 | 6 | 1.96 | 75.35% | | 09/18/00 14:09 | 36 | 1.01 | -9.64% | |
| 09/18/00 14:03 | 7 | 1.04 | -6.95% | | 09/18/00 14:09 | 37 | 1.05 | -6.06% | |
| 09/18/00 14:03 | 8 | 1.04 | -6.95% | | 09/18/00 14:09 | 38 | 1.05 | -6.06% | |
| 09/18/00 14:03 | 9 | 1.02 | -8.74% | | 09/18/00 14:09 | 39 | 1.03 | -7.85% | |
| 09/18/00 14:03 | 10 | 1.03 | -7.85% | | 09/18/00 14:10 | 40 | 1.87 | 67.30% | |
| 09/18/00 14:04 | 11 | 1.3 | 16.31% | | 09/18/00 14:10 | 41 | 1.01 | -9.64% | |
| 09/18/00 14:04 | 12 | 1.05 | -6.06% | | 09/18/00 14:10 | 42 | 1.05 | -6.06% | |
| 09/18/00 14:04 | 13 | 1.06 | -5.17% | | 09/18/00 14:10 | 43 | 1.04 | -6.95% | |
| 09/18/00 14:04 | 14 | 1.05 | -6.06% | | 09/18/00 14:10 | 44 | 1.1 | -1.59% | |
| 09/18/00 14:04 | 15 | 1.02 | -8.74% | | 09/18/00 14:11 | 45 | 1.05 | -6.06% | |
| 09/18/00 14:05 | 16 | 1.02 | -8.74% | | 09/18/00 14:11 | 46 | 1.02 | -8.74% | |
| 09/18/00 14:05 | 17 | 1.07 | -4.27% | | 09/18/00 14:11 | 47 | 1.48 | 32.41% | |
| 09/18/00 14:05 | 18 | 1.05 | -6.06% | | 09/18/00 14:12 | 48 | 1.02 | -8.74% | |
| 09/18/00 14:05 | 19 | 1.21 | 8.25% | | 09/18/00 14:12 | 49 | 1.06 | -5.17% | |
| 09/18/00 14:05 | 20 | 1.03 | -7.85% | | 09/18/00 14:12 | 50 | 1.03 | -7.85% | |
| 09/18/00 14:06 | 21 | 1.03 | -7.85% | | 09/18/00 14:12 | 51 | 0.99 | -11.43% | |
| 09/18/00 14:06 | 22 | 1.06 | -5.17% | | 09/18/00 14:12 | 52 | 1.05 | -6.06% | |
| 09/18/00 14:06 | 23 | 1.02 | -8.74% | | 09/18/00 14:12 | 53 | 1.01 | -9.64% | |
| 09/18/00 14:06 | 24 | 1.01 | -9.64% | | 09/18/00 14:13 | 54 | 1.04 | -6.95% | |
| 09/18/00 14:06 | 25 | 1.07 | -4.27% | | 09/18/00 14:13 | 55 | 1.05 | -6.06% | |
| 09/18/00 14:06 | 26 | 1.02 | -8.74% | | 09/18/00 14:13 | 56 | 1.07 | -4.27% | |
| 09/18/00 14:07 | 27 | 1.03 | -7.85% | | 09/18/00 14:13 | 57 | 1.06 | -5.17% | |
| 09/18/00 14:07 | 28 | 1.02 | -8.74% | | 09/18/00 14:13 | 58 | 1.06 | -5.17% | |
| 09/18/00 14:07 | 29 | 0.994 | -11.07% | | 09/18/00 14:13 | 59 | 1.05 | -6.06% | |
| 09/18/00 14:08 | 30 | 1.08 | -3.38% | | 09/18/00 14:14 | 60 | 1.07 | -4.27% | |

Table 5.13 Percent deviation calculation of Nakhonayok substation

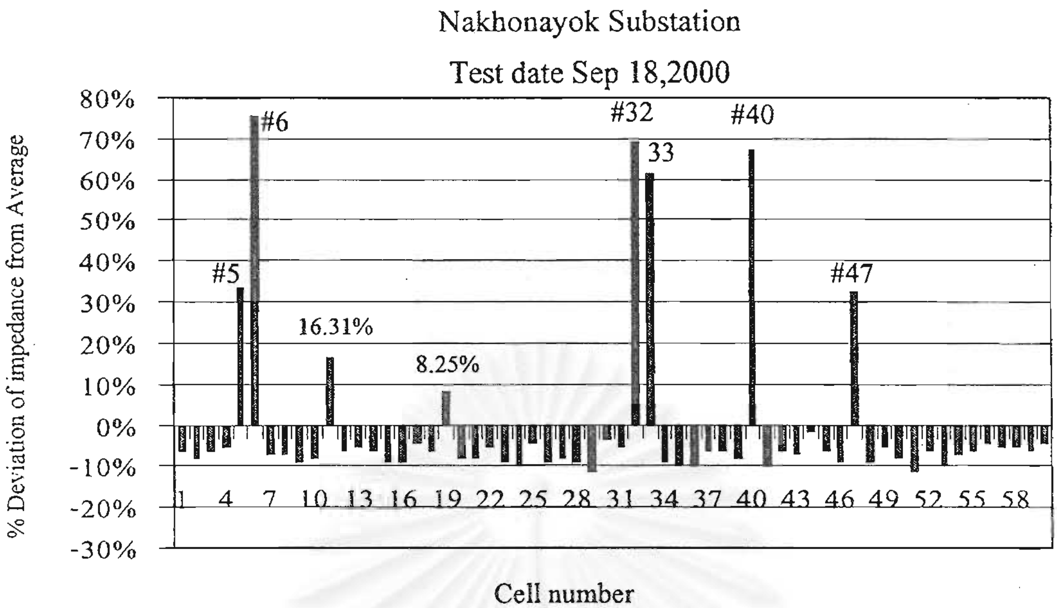



Figure 5.5 Percent Deviation of cell Impedance from the average

From Figure 5.5, there are six cells that have very high percent deviation of impedance from average; they are over 30% of the average. It can be expected that the capacity of those cells should be lower than 80% or level of requirement.

The system average value is included the six out-of-range cells that can distort to calculate the actual average value of the system. In order to determine an actual average value of the battery system, those cells that have impedance higher than 20% should be left out. As a result of calculation, the new average value of system impedance has changed from 1.118 to 1.048 mOhms. The new percent deviation calculation is shown as Table 5.14. The new percent deviation of each cell can be shown as Figure 5.6.

Impedance testing data of Nakhonayok Substation (Percent deviation recalculation) page 1/1

| Date / Time | Cell No. | Zb m. Ohm | %Dev | | Date / Time | Cell No. | Zb m. Ohm | %Dev | |
|---|---|---|---|---|---|---|---|---|---|
| 09/18/00 14:02 | 1 | 1.05 | 0.22% | | 09/18/00 14:08 | 31 | 1.06 | 1.18% | |
| 09/18/00 14:02 | 2 | 1.03 | -1.69% | | 09/18/00 14:08 | 32 | 1.89 | 80.40% | |
| 09/18/00 14:02 | 3 | 1.05 | 0.22% | | 09/18/00 14:08 | 33 | 1.8 | 71.81% | |
| 09/18/00 14:02 | 4 | 1.06 | 1.18% | | 09/18/00 14:08 | 34 | 1.02 | -2.64% | |
| 09/18/00 14:03 | 5 | 1.49 | 42.22% | | 09/18/00 14:09 | 35 | 1.01 | -3.60% | |
| 09/18/00 14:03 | 6 | 1.96 | 87.08% | | 09/18/00 14:09 | 36 | 1.01 | -3.60% | |
| 09/18/00 14:03 | 7 | 1.04 | -0.73% | | 09/18/00 14:09 | 37 | 1.05 | 0.22% | |
| 09/18/00 14:03 | 8 | 1.04 | -0.73% | | 09/18/00 14:09 | 38 | 1.05 | 0.22% | |
| 09/18/00 14:03 | 9 | 1.02 | -2.64% | | 09/18/00 14:09 | 39 | 1.03 | -1.69% | |
| 09/18/00 14:03 | 10 | 1.03 | -1.69% | | 09/18/00 14:10 | 40 | 1.87 | 78.49% | |
| 09/18/00 14:04 | 11 | 1.3 | 24.09% | | 09/18/00 14:10 | 41 | 1.01 | -3.60% | |
| 09/18/00 14:04 | 12 | 1.05 | 0.22% | | 09/18/00 14:10 | 42 | 1.05 | 0.22% | |
| 09/18/00 14:04 | 13 | 1.06 | 1.18% | | 09/18/00 14:10 | 43 | 1.04 | -0.73% | |
| 09/18/00 14:04 | 14 | 1.05 | 0.22% | | 09/18/00 14:10 | 44 | 1.1 | 5.00% | |
| 09/18/00 14:04 | 15 | 1.02 | -2.64% | | 09/18/00 14:11 | 45 | 1.05 | 0.22% | |
| 09/18/00 14:05 | 16 | 1.02 | -2.64% | | 09/18/00 14:11 | 46 | 1.02 | -2.64% | |
| 09/18/00 14:05 | 17 | 1.07 | 2.13% | | 09/18/00 14:11 | 47 | 1.48 | 41.27% | |
| 09/18/00 14:05 | 18 | 1.05 | 0.22% | | 09/18/00 14:12 | 48 | 1.02 | -2.64% | |
| 09/18/00 14:05 | 19 | 1.21 | 15.49% | | 09/18/00 14:12 | 49 | 1.06 | 1.18% | |
| 09/18/00 14:05 | 20 | 1.03 | -1.69% | | 09/18/00 14:12 | 50 | 1.03 | -1.69% | |
| 09/18/00 14:06 | 21 | 1.03 | -1.69% | | 09/18/00 14:12 | 51 | 0.99 | -5.50% | |
| 09/18/00 14:06 | 22 | 1.06 | 1.18% | | 09/18/00 14:12 | 52 | 1.05 | 0.22% | |
| 09/18/00 14:06 | 23 | 1.02 | -2.64% | | 09/18/00 14:12 | 53 | 1.01 | -3.60% | |
| 09/18/00 14:06 | 24 | 1.01 | -3.60% | | 09/18/00 14:13 | 54 | 1.04 | -0.73% | |
| 09/18/00 14:06 | 25 | 1.07 | 2.13% | | 09/18/00 14:13 | 55 | 1.05 | 0.22% | |
| 09/18/00 14:06 | 26 | 1.02 | -2.64% | | 09/18/00 14:13 | 56 | 1.07 | 2.13% | |
| 09/18/00 14:07 | 27 | 1.03 | -1.69% | | 09/18/00 14:13 | 57 | 1.06 | 1.18% | |
| 09/18/00 14:07 | 28 | 1.02 | -2.64% | | 09/18/00 14:13 | 58 | 1.06 | 1.18% | |
| 09/18/00 14:07 | 29 | 0.994 | -5.12% | | 09/18/00 14:13 | 59 | 1.05 | 0.22% | |
| 09/18/00 14:08 | 30 | 1.08 | 3.09% | | 09/18/00 14:14 | 60 | 1.07 | 2.13% | |

Table 5.14 Percent deviation calculation of Nakhonayok substation

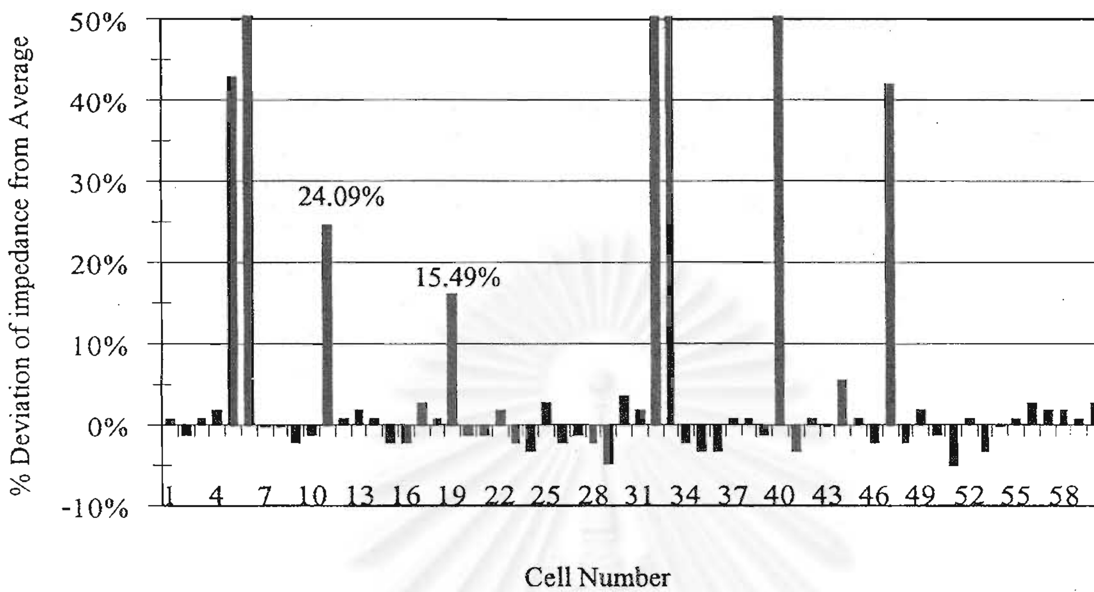



Figure 5.6 Percent deviation of cell impedance from average excludes six cells that have impedance over than 30%

After recalculation, the percent deviation of Cell #11 has increased from 16.31% to 24.09% which is higher than maximum limit of 20%. Therefore, cell #11 is also needed to investigate and correct the problems. Cell #19 has increased percent deviation from 8.25% to 15.49%, it is warning that there are some problems on the cell, which may be from manufacture's fabrication quality, lack of proper maintenance, sulphation or initial installation of battery.

In order to verify the results of the impedance testing, load testing was performed on the battery system by discharging rate 10% of capacity with 10 hours. It starts from 9.30 a.m. to 7.30 p.m. continuously. Those cells in the system are recorded decay voltages of each cell in every hour for determining their health and capacity. The result of load testing are shown in Table 5.15 and 5.16.

Load Testing data of Nakhonayok substation

Page 1/2

| Cell # | Voltage of each cell at specific Hour | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0th | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th |
| 1 | 2.27 | 2.055 | 2.046 | 2.031 | 2.017 | 2.002 | 1.987 | 1.971 | 1.957 | 1.944 | 1.929 |
| 2 | 2.275 | 2.054 | 2.043 | 2.027 | 2.017 | 1.998 | 1.983 | 1.968 | 1.954 | 1.940 | 1.925 |
| 3 | 2.267 | 2.054 | 2.044 | 2.030 | 2.015 | 2.001 | 1.985 | 1.970 | 1.954 | 1.943 | 1.929 |
| 4 | 2.275 | 2.054 | 2.045 | 2.030 | 2.018 | 2.001 | 1.986 | 1.972 | 1.958 | 1.944 | 1.930 |
| 5 | 2.204 | 1.961 | 1.934 | 1.901 | 1.870 | 1.825 | 1.718 | 0.298 | BY PASS | BY PASS | BY PASS |
| 6 | 2.172 | 0.461 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 7 | 2.27 | 2.061 | 2.050 | 2.036 | 2.021 | 2.005 | 1.990 | 1.974 | 1.960 | 1.945 | 1.932 |
| 8 | 2.275 | 2.060 | 2.049 | 2.034 | 2.021 | 2.003 | 1.988 | 1.974 | 1.959 | 1.945 | 1.931 |
| 9 | 2.272 | 2.059 | 2.049 | 2.035 | 2.021 | 2.006 | 1.990 | 1.975 | 1.960 | 1.946 | 1.932 |
| 10 | 2.275 | 2.062 | 2.051 | 2.035 | 2.024 | 2.006 | 1.991 | 1.976 | 1.962 | 1.948 | 1.935 |
| 11 | 2.218 | 2.005 | 1.988 | 1.966 | 1.946 | 1.925 | 1.902 | 1.877 | 1.845 | 1.784 | 0.683 |
| 12 | 2.277 | 2.057 | 2.046 | 2.030 | 2.018 | 2.001 | 1.986 | 1.971 | 1.954 | 1.942 | 1.927 |
| 13 | 2.277 | 2.053 | 2.042 | 2.027 | 2.013 | 1.998 | 1.982 | 1.967 | 1.952 | 1.938 | 1.924 |
| 14 | 2.277 | 2.055 | 2.044 | 2.027 | 2.016 | 1.998 | 1.983 | 1.968 | 1.953 | 1.940 | 1.925 |
| 15 | 2.275 | 2.053 | 2.043 | 2.029 | 2.014 | 1.999 | 1.984 | 1.968 | 1.955 | 1.941 | 1.927 |
| 16 | 2.27 | 2.059 | 2.048 | 2.034 | 2.021 | 2.004 | 1.988 | 1.974 | 1.960 | 1.946 | 1.933 |
| 17 | 2.27 | 2.052 | 2.041 | 2.026 | 2.013 | 1.997 | 1.982 | 1.967 | 1.952 | 1.938 | 1.923 |
| 18 | 2.272 | 2.060 | 2.049 | 2.034 | 2.021 | 2.003 | 1.988 | 1.973 | 1.960 | 1.945 | 1.932 |
| 19 | 2.226 | 2.020 | 2.004 | 1.984 | 1.967 | 1.948 | 1.929 | 1.910 | 1.887 | 1.860 | 1.822 |
| 20 | 2.262 | 2.059 | 2.048 | 2.034 | 2.021 | 2.003 | 1.988 | 1.973 | 1.959 | 1.945 | 1.931 |
| 21 | 2.27 | 2.058 | 2.047 | 2.033 | 2.019 | 2.004 | 1.988 | 1.974 | 1.590 | 1.945 | 1.932 |
| 22 | 2.258 | 2.057 | 2.046 | 2.031 | 2.019 | 2.001 | 1.987 | 1.971 | 1.958 | 1.943 | 1.930 |
| 23 | 2.253 | 2.051 | 2.041 | 2.025 | 2.012 | 1.997 | 1.981 | 1.967 | 1.954 | 1.939 | 1.925 |
| 24 | 2.272 | 2.054 | 2.044 | 2.031 | 2.017 | 2.002 | 1.987 | 1.972 | 1.958 | 1.944 | 1.929 |
| 25 | 2.272 | 2.060 | 2.050 | 2.035 | 2.024 | 2.007 | 1.992 | 1.977 | 1.963 | 1.949 | 1.935 |
| 26 | 2.275 | 2.061 | 2.050 | 2.037 | 2.024 | 2.008 | 1.992 | 1.977 | 1.962 | 1.947 | 1.932 |
| 27 | 2.26 | 2.066 | 2.056 | 2.040 | 2.028 | 2.011 | 1.995 | 1.980 | 1.965 | 1.951 | 1.936 |
| 28 | 2.272 | 2.055 | 2.045 | 2.032 | 2.018 | 2.002 | 1.987 | 1.973 | 1.958 | 1.944 | 1.928 |
| 29 | 2.262 | 2.048 | 2.038 | 2.023 | 2.011 | 1.995 | 1.980 | 1.965 | 1.951 | 1.936 | 1.922 |
| 30 | 2.272 | 2.058 | 2.047 | 2.032 | 2.018 | 2.002 | 1.987 | 1.972 | 1.958 | 1.944 | 1.930 |

Table 5.15 The result of load testing at Nakhonayok substation (1/2)

Load Testing data of Nakhonayok substation Page 2/2

| Cell No. | Voltage of each cell at specific Hour | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0th | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th |
| 31 | 2.275 | 2.042 | 2.031 | 2.015 | 2.003 | 1.987 | 1.972 | 1.956 | 1.943 | 1.928 | 1.911 |
| 32 | 2.182 | 1.882 | 1.774 | 0.303 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 33 | 2.189 | 1.926 | 1.883 | 1.812 | 1.407 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 34 | 2.265 | 2.053 | 2.044 | 2.030 | 2.016 | 2.001 | 1.986 | 1.971 | 1.954 | 1.941 | 1.926 |
| 35 | 2.265 | 2.060 | 2.049 | 2.035 | 2.023 | 2.004 | 1.991 | 1.976 | 1.963 | 1.949 | 1.935 |
| 36 | 2.27 | 2.058 | 2.048 | 2.034 | 2.020 | 2.005 | 1.990 | 1.976 | 1.961 | 1.947 | 1.930 |
| 37 | 2.267 | 2.055 | 2.044 | 2.029 | 2.017 | 1.999 | 1.985 | 1.970 | 1.956 | 1.942 | 1.927 |
| 38 | 2.277 | 2.058 | 2.048 | 2.034 | 2.020 | 2.005 | 1.990 | 1.976 | 1.961 | 1.947 | 1.935 |
| 39 | 2.26 | 2.056 | 2.046 | 2.030 | 2.018 | 2.001 | 1.987 | 1.972 | 1.960 | 1.945 | 1.932 |
| 40 | 2.179 | 1.050 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 41 | 2.272 | 2.061 | 2.050 | 2.035 | 2.022 | 2.005 | 1.992 | 1.977 | 1.964 | 1.949 | 1.935 |
| 42 | 2.27 | 2.059 | 2.049 | 2.034 | 2.020 | 2.004 | 1.988 | 1.975 | 1.959 | 1.945 | 1.932 |
| 43 | 2.27 | 2.056 | 2.045 | 2.030 | 2.017 | 2.000 | 1.986 | 1.970 | 1.956 | 1.941 | 1.927 |
| 44 | 2.275 | 2.059 | 2.049 | 2.034 | 2.020 | 2.003 | 1.988 | 1.973 | 1.957 | 1.943 | 1.928 |
| 45 | 2.272 | 2.063 | 2.052 | 2.037 | 2.024 | 2.007 | 1.993 | 1.977 | 1.963 | 1.949 | 1.935 |
| 46 | 2.275 | 2.058 | 2.048 | 2.035 | 2.021 | 2.005 | 1.990 | 1.974 | 1.959 | 1.945 | 1.929 |
| 47 | 2.209 | 1.975 | 1.951 | 1.919 | 1.890 | 1.852 | 1.792 | 0.545 | BY PASS | BY PASS | BY PASS |
| 48 | 2.267 | 2.058 | 2.047 | 2.033 | 2.020 | 2.003 | 1.988 | 1.974 | 1.960 | 1.946 | 1.932 |
| 49 | 2.253 | 2.045 | 2.033 | 2.017 | 2.003 | 1.987 | 1.971 | 1.954 | 1.939 | 1.923 | 1.904 |
| 50 | 2.277 | 2.055 | 2.045 | 2.031 | 2.017 | 2.001 | 1.985 | 1.971 | 1.956 | 1.942 | 1.928 |
| 51 | 2.267 | 2.059 | 2.049 | 2.034 | 2.021 | 2.004 | 1.990 | 1.975 | 1.962 | 1.948 | 1.935 |
| 52 | 2.27 | 2.058 | 2.048 | 2.033 | 2.020 | 2.004 | 1.989 | 1.974 | 1.590 | 1.945 | 1.931 |
| 53 | 2.272 | 2.059 | 2.048 | 2.034 | 2.020 | 2.004 | 1.989 | 1.974 | 1.961 | 1.947 | 1.934 |
| 54 | 2.27 | 2.052 | 2.041 | 2.028 | 2.015 | 1.998 | 1.984 | 1.969 | 1.954 | 1.941 | 1.927 |
| 55 | 2.287 | 2.051 | 2.042 | 2.027 | 2.016 | 2.001 | 1.988 | 1.975 | 1.963 | 1.948 | 1.935 |
| 56 | 2.287 | 2.048 | 2.039 | 2.027 | 2.014 | 1.999 | 1.986 | 1.974 | 1.960 | 1.945 | 1.931 |
| 57 | 2.287 | 2.059 | 2.051 | 2.037 | 2.025 | 2.011 | 1.957 | 1.985 | 1.972 | 1.957 | 1.943 |
| 58 | 2.287 | 2.053 | 2.045 | 2.033 | 2.020 | 2.006 | 1.993 | 1.980 | 1.966 | 1.952 | 1.937 |
| 59 | 2.287 | 2.046 | 2.037 | 2.023 | 2.011 | 1.997 | 1.985 | 1.972 | 1.959 | 1.945 | 1.930 |
| 60 | 2.284 | 2.047 | 2.039 | 2.027 | 2.015 | 2.001 | 1.988 | 1.975 | 1.963 | 1.948 | 1.933 |

Table 5.16 The result of load testing at Nakhonayok substation

Table 5.17 shows the results of the load testing on the weak cells and some of healthy cells. The by-pass in early hour of some cells means that those cells were terminated of load testing, because those cells are fast decrease of the terminal voltage. They might be damaged due to deep discharging if it were tested continuously. They were taken out from the system and bypassed by jumper to the next cell.

| Cell# | Voltage of each cell at specific Hour | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0th | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th |
| 5 | 2.204 | 1.961 | 1.934 | 1.901 | 1.870 | 1.825 | 1.718 | 0.298 | BY PASS | BY PASS | BY PASS |
| 6 | 2.172 | 0.461 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 11 | 2.218 | 2.005 | 1.988 | 1.966 | 1.946 | 1.925 | 1.902 | 1.877 | 1.845 | 1.784 | 0.683 |
| 32 | 2.182 | 1.882 | 1.774 | 0.303 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 33 | 2.189 | 1.926 | 1.883 | 1.812 | 1.407 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 40 | 2.179 | 1.050 | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS | BY PASS |
| 47 | 2.209 | 1.975 | 1.951 | 1.919 | 1.890 | 1.852 | 1.792 | 0.545 | BY PASS | BY PASS | BY PASS |
| 19 | 2.226 | 2.020 | 2.004 | 1.984 | 1.967 | 1.948 | 1.929 | 1.910 | 1.887 | 1.860 | 1.822 |
| 49 | 2.253 | 2.045 | 2.033 | 2.017 | 2.003 | 1.987 | 1.971 | 1.954 | 1.939 | 1.923 | 1.904 |

Table 5.17 Test results of load testing on the healthy and weak cells

The result of load testing on Table 5.17 and impedance testing on Figure 5.8 both tests are given similar meaning. The cells that have percent deviation higher than 20% of the average will have poor capacity. Figure 5.7 shows the result of load testing of poor and healthy cells. The final-voltage target of the cell for this test is 1.8 volts [13].

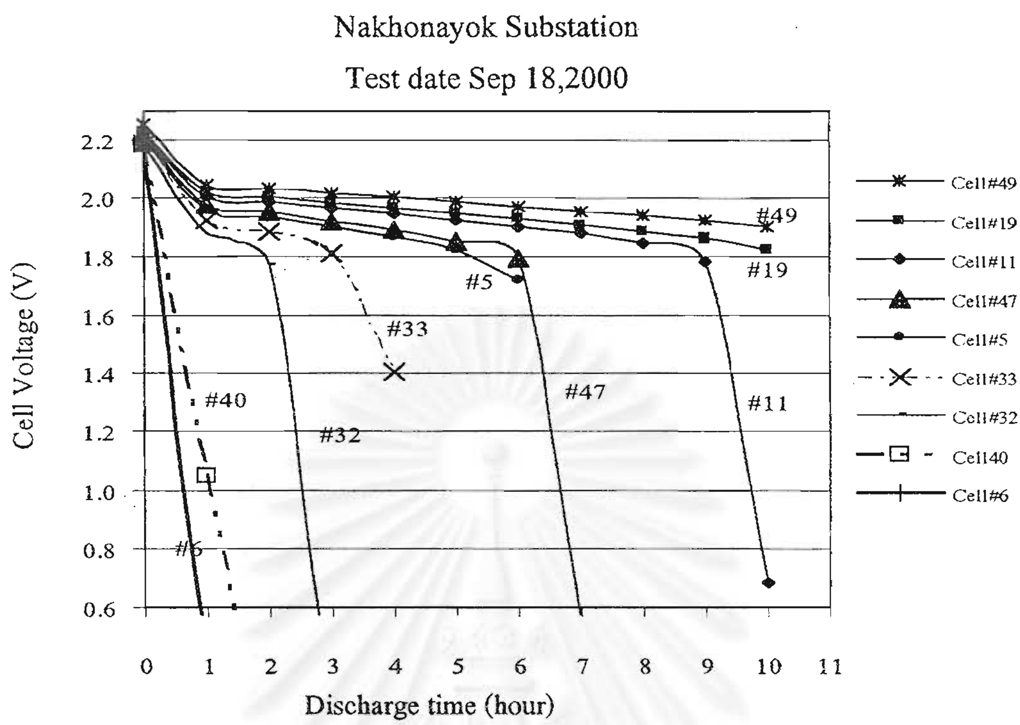



Figure 5.7 Load testing on healthy and questionable cells

Those seven cells, which have percent impedance deviation higher than 20% of the average, are fast decrease of terminal voltage to the specified value, 1.8 volts, before the specific time, 10 hours. Therefore, from the IEEE standard 450-1995, the remaining capacity of those cells are lower than 80% of capacity and level of requirement. This test also gives the significant correlation between an increase in cell impedance and a decrease in battery capacity.

### 5.2.3 Problem Evaluation and Correction of Nakhonayok Substation's battery system

After impedance measuring and load testing, the battery's problems on weak cells have been investigated. Manfred R. Laidig and John W. Wurst [10] have been summarized causes of battery capacity reductions, they are usually come from:

- plate deterioration
- plate sulphation
- specific gravity too low or cell voltage at float charge lower than 0.04 volt.
- defective post seals.

The problems of those weak cells are determined after investigation, they come form:

- plate sulphation; it can be seen by visual inspection
- voltage of each cell is lower than 0.04 volts at float charge, therefore specific gravity is also below; the normal voltage at float charge of this system is 2.23 volts. The measured voltage of each cell at float charge can be shown as follows:

| Cell# | 5 | 6 | 11 | 32 | 33 | 40 | 47 |
|---|---|---|---|---|---|---|---|
| Volt/cell | 2.204 | 2.172 | 2.218 | 2.182 | 2.189 | 2.179 | 2.209 |
| Volt-Deviation | -0.026 | -0.058 | -0.012 | -0.048 | -0.041 | -0.051 | -0.021 |

Cell #5, #11, and #47 slightly deviate from specified value, but the others deviate higher than 0.04 volt.

- there are less corrosion at the terminal posts.

In order to correct the above problems, the manufacturer and IEEE standard 450-1995 recommend that the battery should be equalizing charge until the voltage of each cell or the specific gravity values no longer rise during equalization.

The equalizing charge for the seven weak cells were performed by isolate them from the system. The equalizing voltage is 144 volts, it is specified by the manufacturer's recommendation. After perform equalizing charge until voltage of each cell and specific gravity no longer change, the results of voltage of each cell are:

| Cell# | 5 | 6 | 11 | 32 | 33 | 40 | 47 |
|---|---|---|---|---|---|---|---|
| Volt/cell | 2.214 | 2.194 | 2.226 | 2.199 | 2.199 | 2.192 | 2.223 |
| Volt-Deviation | -0.016 | -0.036 | -0.004 | -0.031 | -0.031 | -0.038 | -0.007 |

The results are better than before equalization. The terminal posts and connections have been cleaned in order to protect the corrosion. The impedance measuring was performed again, the result are shown as Table 5.18.

From Table 5.18, the three interesting of impedance value are:

| | | |
|---|---|---|
| Average impedance value of entire system | : 0.962 | mOhms |
| Maximum impedance value | : 1.05 | mOhms |
| Minimum impedance value | : 0.89 | mOhms |

The percent deviations of each cell from the average are shown as Table 5.19.

Impedance testing data of Nakhonayok Substation (After improving) page 1/1

| Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm | Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm |
|---|---|---|---|---|---|---|---|---|---|
| 11/30/00 12:59 | 1 | 2.272 | 0.976 | 0.044 | 11/30/00 13:07 | 31 | 2.272 | 1.01 | 0.045 |
| 11/30/00 12:59 | 2 | 2.277 | 0.953 | 0.046 | 11/30/00 13:08 | 32 | 2.199 | 0.966 | 0.055 |
| 11/30/00 13:00 | 3 | 2.272 | 0.984 | 0.063 | 11/30/00 13:08 | 33 | 2.199 | 0.997 | 0.04 |
| 11/30/00 13:00 | 4 | 2.275 | 0.982 | 0.058 | 11/30/00 13:08 | 34 | 2.267 | 0.943 | 0.048 |
| 11/30/00 13:00 | 5 | 2.214 | 0.939 | 0.057 | 11/30/00 13:08 | 35 | 2.265 | 0.93 | 0.042 |
| 11/30/00 13:00 | 6 | 2.194 | 1.03 | 0.06 | 11/30/00 13:09 | 36 | 2.267 | 0.936 | 0.052 |
| 11/30/00 13:01 | 7 | 2.27 | 0.953 | 0.05 | 11/30/00 13:09 | 37 | 2.265 | 0.965 | 0.04 |
| 11/30/00 13:01 | 8 | 2.275 | 0.959 | 0.052 | 11/30/00 13:09 | 38 | 2.275 | 0.969 | 0.051 |
| 11/30/00 13:01 | 9 | 2.27 | 0.938 | 0.046 | 11/30/00 13:09 | 39 | 2.262 | 0.931 | 0.049 |
| 11/30/00 13:01 | 10 | 2.275 | 0.955 | 0.053 | 11/30/00 13:10 | 40 | 2.192 | 1.02 | 0.052 |
| 11/30/00 13:02 | 11 | 2.226 | 0.942 | 0.05 | 11/30/00 13:10 | 41 | 2.27 | 0.927 | 0.043 |
| 11/30/00 13:02 | 12 | 2.277 | 0.967 | 0.06 | 11/30/00 13:10 | 42 | 2.267 | 0.968 | 0.055 |
| 11/30/00 13:02 | 13 | 2.277 | 0.978 | 0.046 | 11/30/00 13:10 | 43 | 2.27 | 0.961 | 0.049 |
| 11/30/00 13:02 | 14 | 2.28 | 0.97 | 0.053 | 11/30/00 13:11 | 44 | 2.272 | 1 | 0.055 |
| 11/30/00 13:03 | 15 | 2.277 | 0.949 | 0.282 | 11/30/00 13:11 | 45 | 2.28 | 0.96 | 0.247 |
| 11/30/00 13:03 | 16 | 2.275 | 0.937 | 0.046 | 11/30/00 13:11 | 46 | 2.284 | 0.954 | 0.042 |
| 11/30/00 13:03 | 17 | 2.27 | 1 | 0.064 | 11/30/00 13:11 | 47 | 2.223 | 0.948 | 0.049 |
| 11/30/00 13:03 | 18 | 2.272 | 0.976 | 0.05 | 11/30/00 13:12 | 48 | 2.27 | 0.954 | 0.045 |
| 11/30/00 13:04 | 19 | 2.236 | 0.923 | 0.057 | 11/30/00 13:12 | 49 | 2.248 | 0.933 | 0.046 |
| 11/30/00 13:04 | 20 | 2.248 | 0.926 | 0.052 | 11/30/00 13:12 | 50 | 2.262 | 0.955 | 0.04 |
| 11/30/00 13:04 | 21 | 2.272 | 0.953 | 0.05 | 11/30/00 13:12 | 51 | 2.265 | 0.931 | 0.046 |
| 11/30/00 13:05 | 22 | 2.253 | 0.997 | 0.05 | 11/30/00 13:13 | 52 | 2.26 | 0.977 | 0.042 |
| 11/30/00 13:05 | 23 | 2.253 | 0.916 | 0.049 | 11/30/00 13:13 | 53 | 2.272 | 0.949 | 0.044 |
| 11/30/00 13:05 | 24 | 2.27 | 0.933 | 0.051 | 11/30/00 13:13 | 54 | 2.272 | 0.967 | 0.041 |
| 11/30/00 13:05 | 25 | 2.275 | 0.974 | 0.048 | 11/30/00 13:13 | 55 | 2.28 | 0.972 | 0.049 |
| 11/30/00 13:06 | 26 | 2.272 | 0.928 | 0.047 | 11/30/00 13:14 | 56 | 2.28 | 0.995 | 0.04 |
| 11/30/00 13:06 | 27 | 2.248 | 0.919 | 0.051 | 11/30/00 13:14 | 57 | 2.28 | 0.992 | 0.049 |
| 11/30/00 13:06 | 28 | 2.272 | 0.949 | 0.049 | 11/30/00 13:14 | 58 | 2.28 | 0.992 | 0.043 |
| 11/30/00 13:06 | 29 | 2.179 | 0.89 | 0.052 | 11/30/00 13:15 | 59 | 2.28 | 0.982 | 0.043 |
| 11/30/00 13:07 | 30 | 2.272 | 1.05 | 0.258 | 11/30/00 14:15 | 60 | 2.28 | 0.992 | 0.043 |

Table 5.18 The measurement data of Nakhonayok (after improve)

Impedance testing data of Nakhonayok Substation (Percent deviation After improving) 1/1

| Date / Time | Cell No. | Zb m. Ohm | %Dev | Date / Time | Cell No. | Zb m. Ohm | %Dev |
|---|---|---|---|---|---|---|---|
| 11/30/00 12:59 | 1 | 0.976 | 1.45% | 11/30/00 13:07 | 31 | 1.01 | 4.99% |
| 11/30/00 12:59 | 2 | 0.953 | -0.94% | 11/30/00 13:08 | 32 | 0.966 | 0.41% |
| 11/30/00 13:00 | 3 | 0.984 | 2.28% | 11/30/00 13:08 | 33 | 0.997 | 3.63% |
| 11/30/00 13:00 | 4 | 0.982 | 2.08% | 11/30/00 13:08 | 34 | 0.943 | -1.98% |
| 11/30/00 13:00 | 5 | 0.939 | -2.39% | 11/30/00 13:08 | 35 | 0.93 | -3.33% |
| 11/30/00 13:00 | 6 | 1.03 | 7.06% | 11/30/00 13:09 | 36 | 0.936 | -2.71% |
| 11/30/00 13:01 | 7 | 0.953 | -0.94% | 11/30/00 13:09 | 37 | 0.965 | 0.31% |
| 11/30/00 13:01 | 8 | 0.959 | -0.32% | 11/30/00 13:09 | 38 | 0.969 | 0.72% |
| 11/30/00 13:01 | 9 | 0.938 | -2.50% | 11/30/00 13:09 | 39 | 0.931 | -3.23% |
| 11/30/00 13:01 | 10 | 0.955 | -0.73% | 11/30/00 13:10 | 40 | 1.02 | 6.03% |
| 11/30/00 13:02 | 11 | 0.942 | -2.08% | 11/30/00 13:10 | 41 | 0.927 | -3.64% |
| 11/30/00 13:02 | 12 | 0.967 | 0.52% | 11/30/00 13:10 | 42 | 0.968 | 0.62% |
| 11/30/00 13:02 | 13 | 0.978 | 1.66% | 11/30/00 13:10 | 43 | 0.961 | -0.11% |
| 11/30/00 13:02 | 14 | 0.97 | 0.83% | 11/30/00 13:11 | 44 | 1 | 3.95% |
| 11/30/00 13:03 | 15 | 0.949 | -1.35% | 11/30/00 13:11 | 45 | 0.96 | -0.21% |
| 11/30/00 13:03 | 16 | 0.937 | -2.60% | 11/30/00 13:11 | 46 | 0.954 | -0.84% |
| 11/30/00 13:03 | 17 | 1 | 3.95% | 11/30/00 13:11 | 47 | 0.948 | -1.46% |
| 11/30/00 13:03 | 18 | 0.976 | 1.45% | 11/30/00 13:12 | 48 | 0.954 | -0.84% |
| 11/30/00 13:04 | 19 | 0.923 | -4.06% | 11/30/00 13:12 | 49 | 0.933 | -3.02% |
| 11/30/00 13:04 | 20 | 0.926 | -3.75% | 11/30/00 13:12 | 50 | 0.955 | -0.73% |
| 11/30/00 13:04 | 21 | 0.953 | -0.94% | 11/30/00 13:12 | 51 | 0.931 | -3.23% |
| 11/30/00 13:05 | 22 | 0.997 | 3.63% | 11/30/00 13:13 | 52 | 0.977 | 1.56% |
| 11/30/00 13:05 | 23 | 0.916 | -4.79% | 11/30/00 13:13 | 53 | 0.949 | -1.35% |
| 11/30/00 13:05 | 24 | 0.933 | -3.02% | 11/30/00 13:13 | 54 | 0.967 | 0.52% |
| 11/30/00 13:05 | 25 | 0.974 | 1.24% | 11/30/00 13:13 | 55 | 0.972 | 1.04% |
| 11/30/00 13:06 | 26 | 0.928 | -3.54% | 11/30/00 13:14 | 56 | 0.995 | 3.43% |
| 11/30/00 13:06 | 27 | 0.919 | -4.47% | 11/30/00 13:14 | 57 | 0.992 | 3.11% |
| 11/30/00 13:06 | 28 | 0.949 | -1.35% | 11/30/00 13:14 | 58 | 0.992 | 3.11% |
| 11/30/00 13:06 | 29 | 0.89 | -7.49% | 11/30/00 13:15 | 59 | 0.982 | 2.08% |
| 11/30/00 13:07 | 30 | 1.05 | 9.14% | 11/30/00 14:15 | 60 | 0.992 | 3.11% |

Table 5.19 Percent deviation calculation of Nakhonayok substation (after improving)

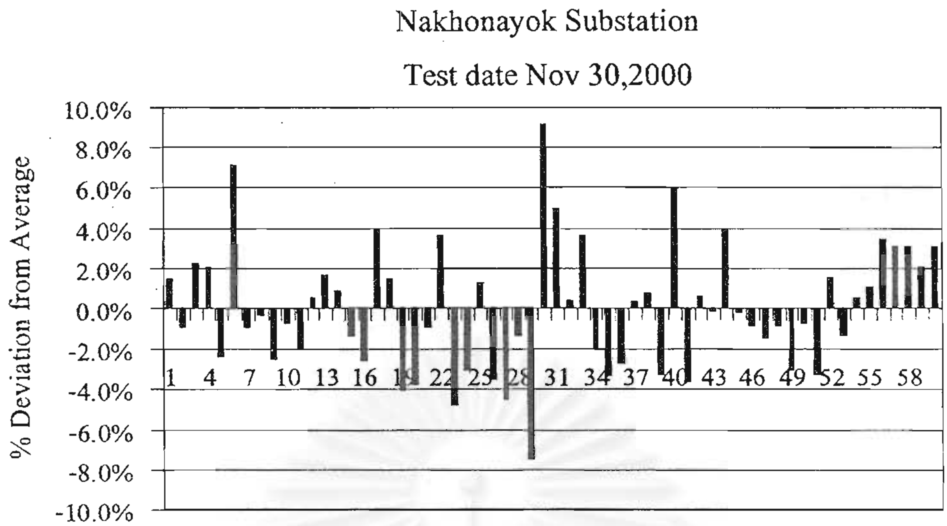



Figure 5.8 Percent deviation of cell impedance after equalization

Figure 5.8 indicates the cells that have been improved their health. All of them have percent deviation lower than 20% of average. therefore, the capacity of the battery system should be over the level of requirement. Table 5.18 shows the values of improving.

| Cell # | % Deviation of impedance from Average | |
|---|---|---|
| | Before equalization | After equalization |
| 5 | 33.31% | -2.39% |
| 6 | 75.35% | 7.06% |
| 11 | 16.31% | -2.08% |
| 32 | 69.09% | 0.41% |
| 33 | 61.04% | 3.63% |
| 40 | 67.30% | 6.03% |
| 47 | 32.41% | -1.46% |

Table 5.20 The improving of percent deviation from average after equalization

### 5.2.4 Test result of Chulabhorn Hydro Power plant unit 2

Test data are taken during battery on-line. The test condition is only impedance testing. The batteries of this site are about 12 years in service. The test was performed on March 15, 2001.

Battery information

| | |
|---|---|
| Manufacturer : FIAMM | Model/Type: SGL 15 |
| Number of cell : 51 | Capacity : 175 Ah. |
| Volt/Cell : 2.2 | Float charge : 112.5 V. |
| Year of in service: 1989 | Equalize charge : 118.5 V. |

Table 5.21 The battery information of Chulabhorn hydro plant unit 2

The test condition and procedure will conform to the procedure in section 5.1.

From Table 5.22, the results of measurement and calculation are:

| | | |
|---|---|---|
| Average impedance value of entire system | : 0.473 | mOhms |
| Maximum impedance value | : 0.545 | mOhms |
| Minimum impedance value | : 0.447 | mOhms |

The percent deviations of each cell from the average are shown as Table 5.23.

Impedance testing data of Chulabhorn Hydro Power Plant unit2 1/1

| Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm | Date / Time | Cell No. | V/Cell | Zb m. Ohm | Rs m.Ohm |
|---|---|---|---|---|---|---|---|---|---|
| 03/15/01 9:31 | 1 | 2.194 | 0.475 | 0.077 | 03/15/01 9:39 | 31 | 2.233 | 0.466 | 0.062 |
| 03/15/01 9:31 | 2 | 2.209 | 0.490 | 0.076 | 03/15/01 9:39 | 32 | 2.152 | 0.455 | 0.071 |
| 03/15/01 9:31 | 3 | 2.150 | 0.447 | 0.066 | 03/15/01 9:40 | 33 | 2.179 | 0.456 | 0.059 |
| 03/15/01 9:32 | 4 | 2.209 | 0.492 | 0.073 | 03/15/01 9:40 | 34 | 2.162 | 0.459 | 0.067 |
| 03/15/01 9:32 | 5 | 2.170 | 0.476 | 0.062 | 03/15/01 9:40 | 35 | 2.196 | 0.467 | 0.059 |
| 03/15/01 9:33 | 6 | 2.238 | 0.459 | 0.069 | 03/15/01 9:40 | 36 | 2.192 | 0.478 | 0.062 |
| 03/15/01 9:33 | 7 | 2.201 | 0.452 | 0.055 | 03/15/01 9:41 | 37 | 2.284 | 0.481 | 0.055 |
| 03/15/01 9:33 | 8 | 2.201 | 0.468 | 0.070 | 03/15/01 9:41 | 38 | 2.280 | 0.467 | 0.064 |
| 03/15/01 9:33 | 9 | 2.245 | 0.470 | 0.056 | 03/15/01 9:41 | 39 | 2.216 | 0.492 | 0.901 |
| 03/15/01 9:34 | 10 | 2.233 | 0.465 | 0.064 | 03/15/01 9:41 | 40 | 2.270 | 0.490 | 0.059 |
| 03/15/01 9:34 | 11 | 2.194 | 0.461 | 0.052 | 03/15/01 9:41 | 41 | 2.280 | 0.474 | 0.055 |
| 03/15/01 9:34 | 12 | 2.199 | 0.468 | 0.063 | 03/15/01 9:42 | 42 | 2.211 | 0.474 | 0.062 |
| 03/15/01 9:34 | 13 | 2.182 | 0.490 | 0.792 | 03/15/01 9:42 | 43 | 2.228 | 0.481 | 0.052 |
| 03/15/01 9:34 | 14 | 2.267 | 0.506 | 0.066 | 03/15/01 9:42 | 44 | 2.218 | 0.462 | 0.065 |
| 03/15/01 9:35 | 15 | 2.275 | 0.545 | 0.125 | 03/15/01 9:42 | 45 | 2.148 | 0.465 | 0.062 |
| 03/15/01 9:35 | 16 | 2.265 | 0.486 | 0.063 | 03/15/01 9:43 | 46 | 2.196 | 0.470 | 0.068 |
| 03/15/01 9:35 | 17 | 2.262 | 0.512 | 0.071 | 03/15/01 9:43 | 47 | 2.167 | 0.457 | 0.064 |
| 03/15/01 9:36 | 18 | 2.174 | 0.475 | 0.064 | 03/15/01 9:43 | 48 | 2.233 | 0.468 | 0.069 |
| 03/15/01 9:36 | 19 | 2.072 | 0.478 | 0.055 | 03/15/01 9:43 | 49 | 2.130 | 0.451 | 0.058 |
| 03/15/01 9:36 | 20 | 2.157 | 0.465 | 0.063 | 03/15/01 9:43 | 50 | 2.194 | 0.489 | 0.070 |
| 03/15/01 9:36 | 21 | 2.177 | 0.456 | 0.056 | 03/15/01 9:44 | 51 | 2.238 | 0.481 | 0.009 |
| 03/15/01 9:36 | 22 | 2.177 | 0.459 | 0.064 | | | | | |
| 03/15/01 9:37 | 23 | 2.165 | 0.479 | 0.058 | | | | | |
| 03/15/01 9:37 | 24 | 2.221 | 0.459 | 0.066 | | | | | |
| 03/15/01 9:37 | 25 | 2.170 | 0.467 | 0.062 | | | | | |
| 03/15/01 9:38 | 26 | 2.214 | 0.467 | 0.481 | | | | | |
| 03/15/01 9:38 | 27 | 2.204 | 0.472 | 0.068 | | | | | |
| 03/15/01 9:38 | 28 | 2.270 | 0.464 | 0.075 | | | | | |
| 03/15/01 9:38 | 29 | 2.140 | 0.451 | 0.063 | | | | | |
| 03/15/01 9:38 | 30 | 2.150 | 0.470 | 0.075 | | | | | |

Table 5.22 The impedance measurement data of Chulabhorn hydro plant

Impedance testing data of Chulabhorn Hydro Power Plant unit 2 – Percent Deviation 1/1

| Date / Time | Cell No. | Zb m. Ohm | %Dev | | Date / Time | Cell No. | Zb m. Ohm | %Dev | |
|---|---|---|---|---|---|---|---|---|---|
| 03/15/01 9:31 | 1 | 0.475 | 0.49% | | 03/15/01 9:39 | 31 | 0.466 | -1.41% | |
| 03/15/01 9:31 | 2 | 0.490 | 3.66% | | 03/15/01 9:39 | 32 | 0.455 | -3.74% | |
| 03/15/01 9:31 | 3 | 0.447 | -5.43% | | 03/15/01 9:40 | 33 | 0.456 | -3.53% | |
| 03/15/01 9:32 | 4 | 0.492 | 4.09% | | 03/15/01 9:40 | 34 | 0.459 | -2.90% | |
| 03/15/01 9:32 | 5 | 0.476 | 0.70% | | 03/15/01 9:40 | 35 | 0.467 | -1.20% | |
| 03/15/01 9:33 | 6 | 0.459 | -2.90% | | 03/15/01 9:40 | 36 | 0.478 | 1.12% | |
| 03/15/01 9:33 | 7 | 0.452 | -4.38% | | 03/15/01 9:41 | 37 | 0.481 | 1.76% | |
| 03/15/01 9:33 | 8 | 0.468 | -0.99% | | 03/15/01 9:41 | 38 | 0.467 | -1.20% | |
| 03/15/01 9:33 | 9 | 0.470 | -0.57% | | 03/15/01 9:41 | 39 | 0.492 | 4.09% | |
| 03/15/01 9:34 | 10 | 0.465 | -1.63% | | 03/15/01 9:41 | 40 | 0.490 | 3.66% | |
| 03/15/01 9:34 | 11 | 0.461 | -2.47% | | 03/15/01 9:41 | 41 | 0.474 | 0.28% | |
| 03/15/01 9:34 | 12 | 0.468 | -0.99% | | 03/15/01 9:42 | 42 | 0.474 | 0.28% | |
| 03/15/01 9:34 | 13 | 0.490 | 3.66% | | 03/15/01 9:42 | 43 | 0.481 | 1.76% | |
| 03/15/01 9:34 | 14 | 0.506 | 7.05% | | 03/15/01 9:42 | 44 | 0.462 | -2.26% | |
| 03/15/01 9:35 | 15 | 0.545 | 15.30% | | 03/15/01 9:42 | 45 | 0.465 | -1.63% | |
| 03/15/01 9:35 | 16 | 0.486 | 2.82% | | 03/15/01 9:43 | 46 | 0.470 | -0.57% | |
| 03/15/01 9:35 | 17 | 0.512 | 8.32% | | 03/15/01 9:43 | 47 | 0.457 | -3.32% | |
| 03/15/01 9:36 | 18 | 0.475 | 0.49% | | 03/15/01 9:43 | 48 | 0.468 | -0.99% | |
| 03/15/01 9:36 | 19 | 0.478 | 1.12% | | 03/15/01 9:43 | 49 | 0.451 | -4.59% | |
| 03/15/01 9:36 | 20 | 0.465 | -1.63% | | 03/15/01 9:43 | 50 | 0.489 | 3.45% | |
| 03/15/01 9:36 | 21 | 0.456 | -3.53% | | 03/15/01 9:44 | 51 | 0.481 | 1.76% | |
| 03/15/01 9:36 | 22 | 0.459 | -2.90% | | | | | | |
| 03/15/01 9:37 | 23 | 0.479 | 1.34% | | | | | | |
| 03/15/01 9:37 | 24 | 0.459 | -2.90% | | | | | | |
| 03/15/01 9:37 | 25 | 0.467 | -1.20% | | | | | | |
| 03/15/01 9:38 | 26 | 0.467 | -1.20% | | | | | | |
| 03/15/01 9:38 | 27 | 0.472 | -0.15% | | | | | | |
| 03/15/01 9:38 | 28 | 0.464 | -1.84% | | | | | | |
| 03/15/01 9:38 | 29 | 0.451 | -4.59% | | | | | | |
| 03/15/01 9:38 | 30 | 0.470 | -0.57% | | | | | | |

Table 5.23 Percent deviation calculation of Chulabhorn hydro plant

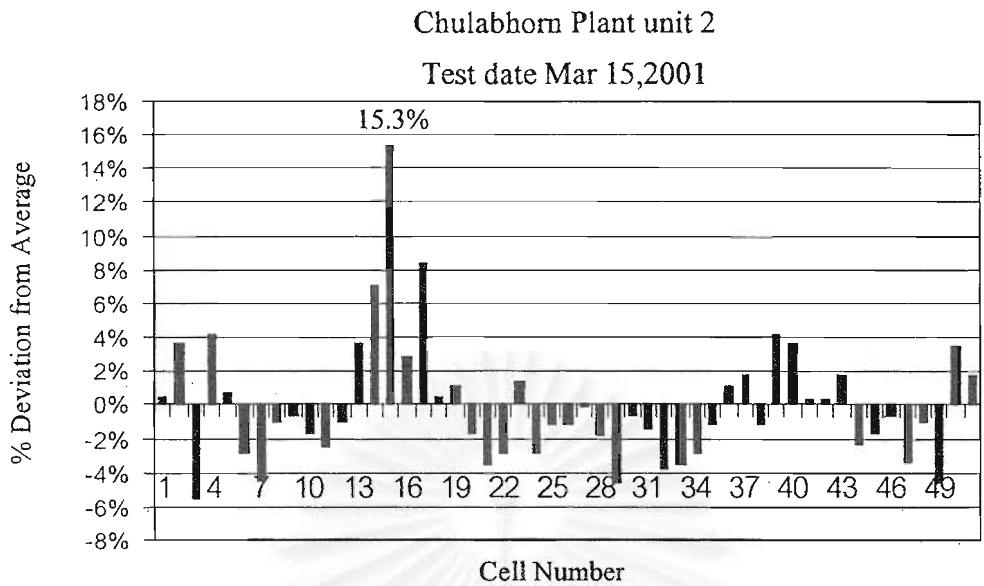



Figure 5.9 Percent Deviation of cell Impedance from system average

Figure 5.9 shows the percent deviation from the average value. The maximum of percent deviation is 15.3% that is inside of 20%. It is, therefore, sure that all the cells are healthy and the remaining capacity is higher than 80% of capacity, Charles M. Gabriel (1993), and the test experience on South Bangkok power plant unit 4 and Nakhonayok.

Cell #15 has been investigated its operating condition and visual inspection on the plate. The result of investigations are:

- cell voltage at float voltage is 2.275 volts, which is nearly other cells.
- Specific gravity is 1.195, which is lower than 0.01 of the 1.205. Normally, it can deviate from specified value about 0.015.
- There are two points of sulphation on the plate that can be determined by visual inspection.

After impedance measuring and inspection, the equalizing charge was performed on the battery system in order to improve the specific gravity and eliminate sulphation on the cell plates. The equalizing charge was performed by charge voltage at 118.5 volts with 8 hours; this was specified by the manufacturer. The voltage and specific gravity of cell #15 has been measured again. The results after equalization are:

- Cell voltage is reduced to 2.262 volts, which is slightly changed.
- The specific gravity is 1.200, which is better than the previous measuring.

The impedance measuring has been performed again. The results of measuring are shown in Table 5.23. The change of maximum, average, and minimum impedance values can be shown as follows:

| | | Before equalization | After equalization |
|---|---|---|---|
| Average value | (mohms) | : 0.473 | : 0.472 |
| Maximum value | (mohms) | : 0.545 | : 0.534 |
| Minimum value | (mohms) | : 0.447 | : 0.445 |

The percent deviation on cell #15 deceased from 15.3% to 13.11% while the average value of string impedance was small change from 0.473 to 0.472 mOhms. The percent deviations of battery system after equalization are shown as Table 5.11. The comparison of percent deviation values both before and after equalization is shown as Figure 5.10.

Impedance Testing data of Chulabhorn Hydro Plant unit 2 – Percent Deviation after Equalization 1/1

| Date / Time | Cell No. | Zb m. Ohm | %Dev | | Date / Time | Cell No. | Zb m. Ohm | %Dev | |
|---|---|---|---|---|---|---|---|---|---|
| 03/15/01 9:31 | 1 | 0.474 | 0.40% | | 03/15/01 9:39 | 31 | 0.466 | -1.29% | |
| 03/15/01 9:31 | 2 | 0.492 | 4.21% | | 03/15/01 9:39 | 32 | 0.460 | -2.56% | |
| 03/15/01 9:31 | 3 | 0.445 | -5.74% | | 03/15/01 9:40 | 33 | 0.457 | -3.20% | |
| 03/15/01 9:32 | 4 | 0.497 | 5.27% | | 03/15/01 9:40 | 34 | 0.457 | -3.20% | |
| 03/15/01 9:32 | 5 | 0.479 | 1.46% | | 03/15/01 9:40 | 35 | 0.469 | -0.66% | |
| 03/15/01 9:33 | 6 | 0.465 | -1.50% | | 03/15/01 9:40 | 36 | 0.468 | -0.87% | |
| 03/15/01 9:33 | 7 | 0.450 | -4.68% | | 03/15/01 9:41 | 37 | 0.478 | 1.25% | |
| 03/15/01 9:33 | 8 | 0.473 | 0.19% | | 03/15/01 9:41 | 38 | 0.466 | -1.29% | |
| 03/15/01 9:33 | 9 | 0.468 | -0.87% | | 03/15/01 9:41 | 39 | 0.495 | 4.85% | |
| 03/15/01 9:34 | 10 | 0.460 | -2.56% | | 03/15/01 9:41 | 40 | 0.467 | -1.02% | |
| 03/15/01 9:34 | 11 | 0.460 | -2.56% | | 03/15/01 9:41 | 41 | 0.474 | 0.40% | |
| 03/15/01 9:34 | 12 | 0.465 | -1.50% | | 03/15/01 9:42 | 42 | 0.476 | 0.83% | |
| 03/15/01 9:34 | 13 | 0.486 | 2.94% | | 03/15/01 9:42 | 43 | 0.474 | 0.40% | |
| 03/15/01 9:34 | 14 | 0.506 | 7.18% | | 03/15/01 9:42 | 44 | 0.46 | -2.56% | |
| 03/15/01 9:35 | 15 | 0.534 | 13.11% | | 03/15/01 9:42 | 45 | 0.461 | -2.35% | |
| 03/15/01 9:35 | 16 | 0.478 | 1.25% | | 03/15/01 9:43 | 46 | 0.473 | 0.19% | |
| 03/15/01 9:35 | 17 | 0.510 | 8.03% | | 03/15/01 9:43 | 47 | 0.457 | -3.20% | |
| 03/15/01 9:36 | 18 | 0.474 | 0.40% | | 03/15/01 9:43 | 48 | 0.46 | -2.56% | |
| 03/15/01 9:36 | 19 | 0.476 | 0.83% | | 03/15/01 9:43 | 49 | 0.458 | -2.99% | |
| 03/15/01 9:36 | 20 | 0.468 | -0.87% | | 03/15/01 9:43 | 50 | 0.486 | 2.94% | |
| 03/15/01 9:36 | 21 | 0.458 | -2.99% | | 03/15/01 9:44 | 51 | 0.484 | 2.52% | |
| 03/15/01 9:36 | 22 | 0.465 | -1.50% | | | | | | |
| 03/15/01 9:37 | 23 | 0.482 | 2.10% | | | | | | |
| 03/15/01 9:37 | 24 | 0.455 | -3.62% | | | | | | |
| 03/15/01 9:37 | 25 | 0.462 | -2.14% | | | | | | |
| 03/15/01 9:38 | 26 | 0.471 | -0.23% | | | | | | |
| 03/15/01 9:38 | 27 | 0.474 | 0.40% | | | | | | |
| 03/15/01 9:38 | 28 | 0.460 | -2.56% | | | | | | |
| 03/15/01 9:38 | 29 | 0.466 | -1.29% | | | | | | |
| 03/15/01 9:38 | 30 | 0.478 | 1.25% | | | | | | |

Table 5.24 Percent deviation calculation of Chulabhorn hydro plant (after equalization)

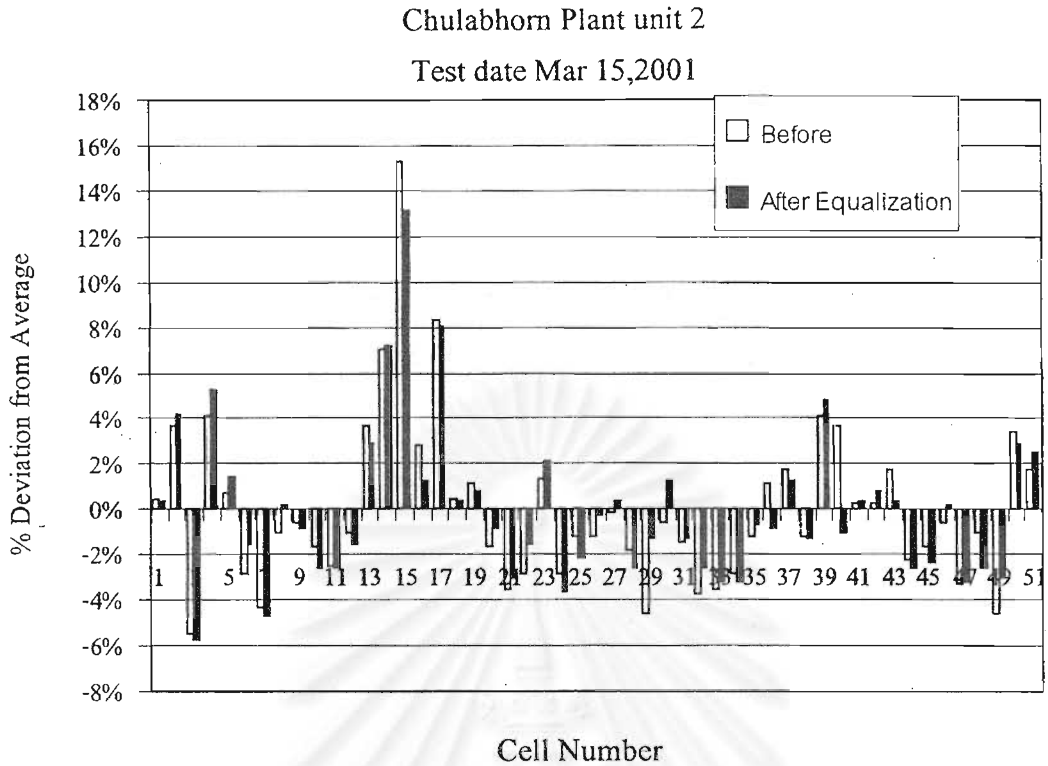



Figure 5.10 The percent deviation of battery system before and after equalization performing, Chulabhorn hydro plant

The results of this impedance testing can help the maintenance decision to extend load testing schedule to the next period of maintenance due to the result of test indicates that all cells in the system are healthy and battery plates are less sulphation.

## 5.3 Conclusion of the Test

The test results of the three sites show the different outcomes. The result of impedance testing method for those three sites can be indicated the capacity and state of health of battery, although it cannot be indicated direct proportional between impedance and capacity value. However, the percent deviations of each cell can assist the maintenance people to investigate the problems in order to improve the battery capacity. The examples from the study are:

- In case of Nakhonayok substation when the weak cells have been detected by the percent deviation higher than 20% of average, the weak cells should be investigated the causes of problems that are affected to battery capacity, such as changing of specific gravity, cell voltage or plate sulphation. The causes of problems can be determined from inspection, the instruction manual of the manufacturer, researches, and standards such as IEEEs.
- In case of Chulabhorn hydro plant the all cell impedances in the system are lower than 20% of average, but there is one cell that has percent impedance deviation, 15.3%, higher than other cells. This cell has been investigated the operating condition and inspection, such as voltage and specific gravity of cell measuring and visual inspection sulphation on the cell plate. The battery cell that has percent deviation higher than other cells will be corrected and improved its capacity before it cannot be recovered.

The results of impedance testing implementation in this study can be concluded as follows:

### 5.3.1 The availability of battery improving

The impedance testing method can be used to improve the availability of battery system by detection the percent deviation of cell impedance from the system average. Before it fails in service, the maintenance section can correct the detected problems. In the case study of Nakhonayok substation if the main supply fails then the battery will in service with unavailable capacity. So, the control equipment such as line switching and computer control will be shut down, which may cause of electricity distribution problem in that area.

In the case of Chulabhorn hydro plant, impedance testing can also improve the capacity of the cell that has percent impedance deviation higher than other cells and sulphation on the plates. The result of cell impedance improving, the capacity of battery can also be improved. The load testing can be extended by the result of battery impedance testing and improving.

The existing or conventional maintenance is performed by time based and time consuming, especially load testing. Therefore, the impedance testing can be used for additional maintenance in order to increase the capability of maintenance.

### 5.3.2 The maintenance planning program

When impedance testing had performed, the people from the maintenance section found that the problems of this battery system are voltage of cells low and plates sulphation. The maintenance section can plans to correct the problems and send the planning schedule to operator prepares the battery for improving. So, the availability of battery can be improved the before it fails to supply load.

The other case, when the percent deviation of impedance higher than 15% and the cell voltage and specific gravity of battery also change, the equalization program may be frequently performed in order to improve the capacity. The program will then be set to normal when the impedance and cell voltage are improved. The equalization can be performed once or twice a month when sulphation is increasing. The impedance testing can also be used to plan for replacing when the impedance is nearly 20% and battery's useful life is nearly design life.

### 5.3.3 Reduce Outage Time and Cost Reduction

The load testing requires to take the plant's load off and a high power resistor bank, which is complexity and expensive, to perform the test. The test also needs a long duration time for test and for battery outage. In addition, load testing for high capacity rate needs high power resistor and heavy for test, so, the manpower also increases. In case of South Bangkok power plant the amount of discharge current is 60 amperes and 258 volts, therefore resistor bank takes the power from battery system about 15,480 watts. In practice, the rate of resistor bank will higher than battery capacity.

The total time for load test is about 14 hours. It includes time for takeout the battery from the dc distribution bus and charger and connect it back about 2 hours, prepare and connect the resistor bank to the battery system and disconnect about 2 hours, during discharge about 10 hours. The time for impedance testing is about 2 hours, it includes time for set up the transmitter and receiver about 0.5 hour, measuring of voltage of each cell about 0.5 hour, and transferring data from receiver to transmitter and analysis about 1 hour.

Load testing includes cost of resistor bank, test equipment, labor, and overtime. The following list can be shown the cost of both methods.

Cost of load testing

- labor cost (operating hour per month 154 hours)
    - Foreman 1 person; salary 23,000 baht, Therefore cost per hour = 23,000/154 = 162 baht/hour.
    - Skilled labor 2 person; salary 12,500 baht/person, Therefore cost per hour = 12,500/154 = 81 baht/hour.

- time for testing is 14 hours; 7 for working hour and 7 for overtime. Rate of overtime is 1.5 of working hour.

- Total operating cost of load testing = (162+81x2)x(7+7x1.5) = 5,670 baht.

Cost of impedance testing

- labor cost; 1 foreman.
- Time for testing is 2 hours
- Total operating cost of impedance testing = 162x2 = 324 baht.
- Cost of test equipment for impedance test is 250,000 baht; the average of life time 5 years. The number of use in one year about 20% of 115 battery system in EGAT's = 115x0.2 = 23 times/year. So, cost of impedance testing equipment is 250,000/(23 x 5) times-years = 2,174 baht/times.
- Total cost of impedance testing = 324+2,174 = 2,498 baht.

Comparison between load testing and impedance testing cost

- Load testing cost – impedance testing cost = 5,670 – 2,498 = 3,172 baht.; Impedance testing cost is about 2,498/5,670 x 100 = 44%. Therefore it can be reduced maintenance cost 56%.
- Cost reduction in one year = 3,172 baht x 23 times in one year = 72,956 baht.
- Return on investment = 250,000/72,956 = 3.4 years.

Production cost and losses

The purposes of impedance testing are to determine battery capacity during battery on-line and reduce the maintenance outage time of battery. If the weak cells can be detected by impedance testing and corrected before they are in service, it can be reduced plant shut down due to batteries failure. The penalty for sudden plant shutdown or plant trip from the power system is about 600,000 baht; for 300,000 Kilo-watts as South Bangkok power plant. The start up cost includes fuel oil and power consumption are about 80,000 baht. Loss of opportunity for selling is 1,000,000 baht per day or 42,000 baht per hours. (source: monthly report on January 2001 of the power plant)

### 5.3.4 The Correlation between cell impedance and capacity

Battery cell impedance and its capacity can be used for determination of the correlation between impedance testing and load testing method. In Figure 5.11 is the plot of cell impedance and capacity by using data in Table 5.10. The trend line on Figure 5.11 shows how cell impedance and capacity can be related in the battery system. The statistical significance of the correlation is the coefficient of determination, $R^2$ or r-squared value. The value of $R^2$ is 0.5293; $R^2$ is determined by:

- plot all cell impedance and capacity on the Microsoft Excel and then select xy (scatter) chart type.
- Select Add-trendline function and Linear-regression type
- Select option and then select equation on chart and R-squared value on chart; the equation and R2 value will be shown as Figure 5.11

The coefficient of correlation (r) is 0.7275. By the coefficient value, the cell impedance can not be used for representative of the actual battery capacity. However, the result of impedance testing and load testing show that high impedances have low capacities and low impedances have high capacities.

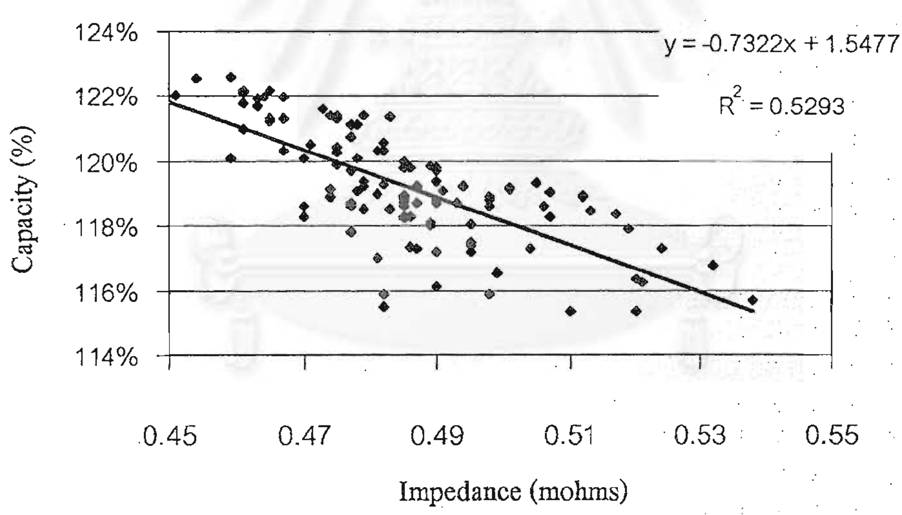



Figure 5.11 The correlation between cell impedance and capacity

# CHAPTER 6

# CONCLUSION AND RECOMMENDATION

## 6.1 Conclusions

This thesis is aimed at improving availability and maintenance for stationary battery of the power plant in order to reduce the maintenance outage time and cost. The conventional maintenance is performed by manufacture's recommendation, which are time-based or breakdown maintenance. The conventional approach cannot provide the information that correlates to the battery capacity or availability. The study commences by considering the battery structure, maintenance procedures, battery capacity assessment and battery capacity determined by impedance testing method.

The study is performed at EGAT's plant and substation. There are three sites for performing impedance testing in this study. Each site has different rated capacity, number of cell in the system, year of in service, and it is due to be tested load testing. Impedance testing will be performed during battery on-line. The result of the test will be compared with the result of load testing in order to confirm the accuracy of impedance testing. Weak cells can be detected by impedance measuring when they have impedance deviation higher than 20% of the system impedance average. The manufacturer who makes the impedance testing equipment and the researchers who have experience in this testing specifies this percent reference value.

The results of impedance testing at South Bangkok power plant unit 4 and Nakhonayok substation offer the significant information of the correlation between battery impedance and its capacity. The impedance of a cell increases as the capacity of that cell decrease. The impedance testing at South Bangkok power plant unit 4 shows that when cells impedance lower than 20% of the system average value, the capacity of battery will higher than 80% of rated capacity. The 80% of rated battery capacity level required for qualified battery system in power generating plant; IEEE standard 450-1995 specifies it. If battery capacity is equal or below 80%, it shows that the battery rate of deterioration is increasing.

The case of Nakornayok substation is another good example. The battery system was routinely maintained by volt per cell and specific gravity measurement over the five years, without record of equalization frequency. The operators could not know that the standby capacity was available or not until load testing was performed. There are seven cells that have impedance deviation higher than 20% of the system average. The result of load testing shows that these cells have remaining capacity lower than 80% of rated capacity. The results of battery investigation are specific gravity and cell voltages of the battery are too low, and there are sulphation on the battery plates. The result of this test can assist the maintenance staff to solve the problems and improve the capacity and health of the batteries before they cannot be recovered. Equalizing charge is a method used to improve specific gravity and battery capacity; this method is recommended by the manufacturer. However, the equalizing charge cannot be performed frequently because it can cause of battery plates deterioration due to over charging. After performing, the capacity and specific gravity has improved in the acceptable level.

Corrective maintenance can be conducted before scheduled period when the problems are detected by the result of impedance testing analysis, such as the case of Chulabhorn hydro power plant that one cell has impedance 15.3% higher than the average level. After performing equalization, cell impedance has reduced to 13.11% above the average level.

Although load testing method is a direct capacity assessment tool, and is recommends by most manufactures, but it can not be performed during battery on-line. In addition, load testing can cause an impact on life cycle of battery due to sulphation during test. Load testing method is costly and impractical. It requires battery outage and a long duration time to take during test.

The advantages of impedance testing applied on preventive maintenance are:

1. Non-destructive testing method during determines internal characteristics of batteries, because it does not need to discharge battery.
2. Less costly in terms of time, testing equipment and resources; it needs shorter shortly test and setup time when compared with load testing which takes a long time to measure cell voltage.
3. Availability improvement can be performed prior to supply loads.
4. Systematic data collection and analysis for determining and tracking health and performance of batteries by using the percentage deviation from the base-line value and from the string average value.

Maintenance cost for battery testing composes of two types; direct and indirect cost. The direct cost is the cost of battery capacity determination. The impedance testing approach can be reduced this cost by using time for testing and workforce less than load testing approach, although the cost of impedance testing equipment is added. In this study, the operating cost can be reduced 56% from load testing. The indirect cost comes from repairing or replacing when failures of battery are occurred, such as the weak cells of Nakhonayok substation, although their capacity have been improved but the cell voltages are still lower than other cells. Therefore, they are needed to be improved until their capacity are return to near design state. This improving cost is increased due to the period of inspection is reduced from one month to two weeks. If the weak cells are detected and corrected before they fail in service, the sudden plant shut down due to battery failure can be avoided. Because of the penalty for unavailable of power plant capacity 300,000 kilo-watts is about 600,000 baht for one times of sudden outage.

## 6.2 Recommendations

The conventional maintenance on battery comprises terminal posts clean, connection retorque, specific gravity readings, electrolyte level checks and water replenishing. They are usually recommended by manufacture to maintain the battery operation in the designed condition and ensure that it will generate power continuously. Therefore, the maintenance staffs should periodically perform on this manufacture's recommendation. Even though the impedance testing is to be implemented.

The result from this study can be applied to other sites and battery types as VRLA (Valve Regulated Lead Acid) battery, which is maintenance-free battery without need to replenish with water and gel-filled electrolyte.

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# APPENDIX

Battery Analysis Report

Notes:______________________________

09/18/00

Ambient Temp. ° Pilot Temp. °

AC_R: A AC_I: A

Multiplier: 1

User ID:______________________________

| Cell | Notes | Zb mΩ | Rs mΩ | Volt DC | Time |
|---|---|---|---|---|---|
| 001 | ........ | 1.05 | 0.050 | 2.270 | 14:02 |
| 002 | ........ | 1.03 | 0.045 | 2.275 | 14:02 |
| 003 | ........ | 1.05 | 0.056 | 2.267 | 14:02 |
| 004 | ........ | 1.06 | 0.053 | 2.275 | 14:02 |
| 005 | ........ | 1.49 | 0.054 | 2.204 | 14:03 |
| 006 | ........ | 1.96 | 0.054 | 2.172 | 14:03 |
| 007 | ........ | 1.04 | 0.051 | 2.270 | 14:03 |
| 008 | ........ | 1.04 | 0.050 | 2.275 | 14:03 |
| 009 | ........ | 1.02 | 0.045 | 2.272 | 14:03 |
| 010 | ........ | 1.03 | 0.050 | 2.275 | 14:03 |
| 011 | ........ | 1.30 | 0.050 | 2.218 | 14:04 |
| 012 | ........ | 1.05 | 0.059 | 2.277 | 14:04 |
| 013 | ........ | 1.06 | 0.045 | 2.277 | 14:04 |
| 014 | ........ | 1.05 | 0.056 | 2.277 | 14:04 |
| 015 | ........ | 1.02 | 0.229 | 2.275 | 14:04 |
| 016 | ........ | 1.02 | 0.044 | 2.270 | 14:05 |
| 017 | ........ | 1.07 | 0.054 | 2.270 | 14:05 |
| 018 | ........ | 1.05 | 0.042 | 2.272 | 14:05 |
| 019 | ........ | 1.21 | 0.060 | 2.226 | 14:05 |
| 020 | ........ | 1.03 | 0.050 | 2.262 | 14:05 |
| 021 | ........ | 1.03 | 0.048 | 2.270 | 14:06 |
| 022 | ........ | 1.06 | 0.050 | 2.258 | 14:06 |
| 023 | ........ | 1.02 | 0.047 | 2.253 | 14:06 |
| 024 | ........ | 1.01 | 0.047 | 2.272 | 14:06 |
| 025 | ........ | 1.07 | 0.050 | 2.272 | 14:06 |
| 026 | ........ | 1.02 | 0.042 | 2.275 | 14:06 |
| 027 | ........ | 1.03 | 0.053 | 2.260 | 14:07 |
| 028 | ........ | 1.02 | 0.047 | 2.272 | 14:07 |
| 029 | ........ | 0.994 | 0.049 | 2.262 | 14:07 |
| 030 | ........ | 1.08 | 0.267 | 2.272 | 14:08 |
| 031 | ........ | 1.06 | 0.046 | 2.275 | 14:08 |
| 032 | ........ | 1.89 | 0.055 | 2.182 | 14:08 |
| 033 | ........ | 1.80 | 0.045 | 2.189 | 14:08 |
| 034 | ........ | 1.02 | 0.045 | 2.265 | 14:08 |
| 035 | ........ | 1.01 | 0.039 | 2.265 | 14:09 |
| 036 | ........ | 1.01 | 0.047 | 2.270 | 14:09 |
| 037 | ........ | 1.05 | 0.039 | 2.267 | 14:09 |
| 038 | ........ | 1.05 | 0.044 | 2.277 | 14:09 |
| 039 | ........ | 1.03 | 0.045 | 2.260 | 14:09 |
| 040 | ........ | 1.87 | 0.048 | 2.179 | 14:10 |
| 041 | ........ | 1.01 | 0.057 | 2.272 | 14:10 |
| 042 | ........ | 1.05 | 0.050 | 2.270 | 14:10 |
| 043 | ........ | 1.04 | 0.047 | 2.270 | 14:10 |
| 044 | ........ | 1.10 | 0.052 | 2.275 | 14:10 |
| 045 | ........ | 1.05 | 0.265 | 2.272 | 14:11 |
| 046 | ........ | 1.02 | 0.050 | 2.275 | 14:11 |
| 047 | ........ | 1.48 | 0.045 | 2.209 | 14:11 |
| 048 | ........ | 1.02 | 0.053 | 2.267 | 14:12 |
| 049 | ........ | 1.06 | 0.044 | 2.253 | 14:12 |
| 050 | ........ | 1.03 | 0.044 | 2.277 | 14:12 |
| 051 | ........ | 0.990 | 0.045 | 2.267 | 14:12 |
| 052 | ........ | 1.05 | 0.045 | 2.270 | 14:12 |
| 053 | ........ | 1.01 | 0.042 | 2.272 | 14:12 |
| 054 | ........ | 1.04 | 0.046 | 2.270 | 14:13 |
| 055 | ........ | 1.05 | 0.046 | 2.287 | 14:13 |
| 056 | ........ | 1.07 | 0.042 | 2.287 | 14:13 |
| 057 | ........ | 1.06 | 0.045 | 2.287 | 14:13 |
| 058 | ........ | 1.06 | 0.043 | 2.287 | 14:13 |
| 059 | ........ | 1.05 | 0.039 | 2.287 | 14:13 |
| 060 | ........ | 1.07 | 0.040 | 2.284 | 14:14 |

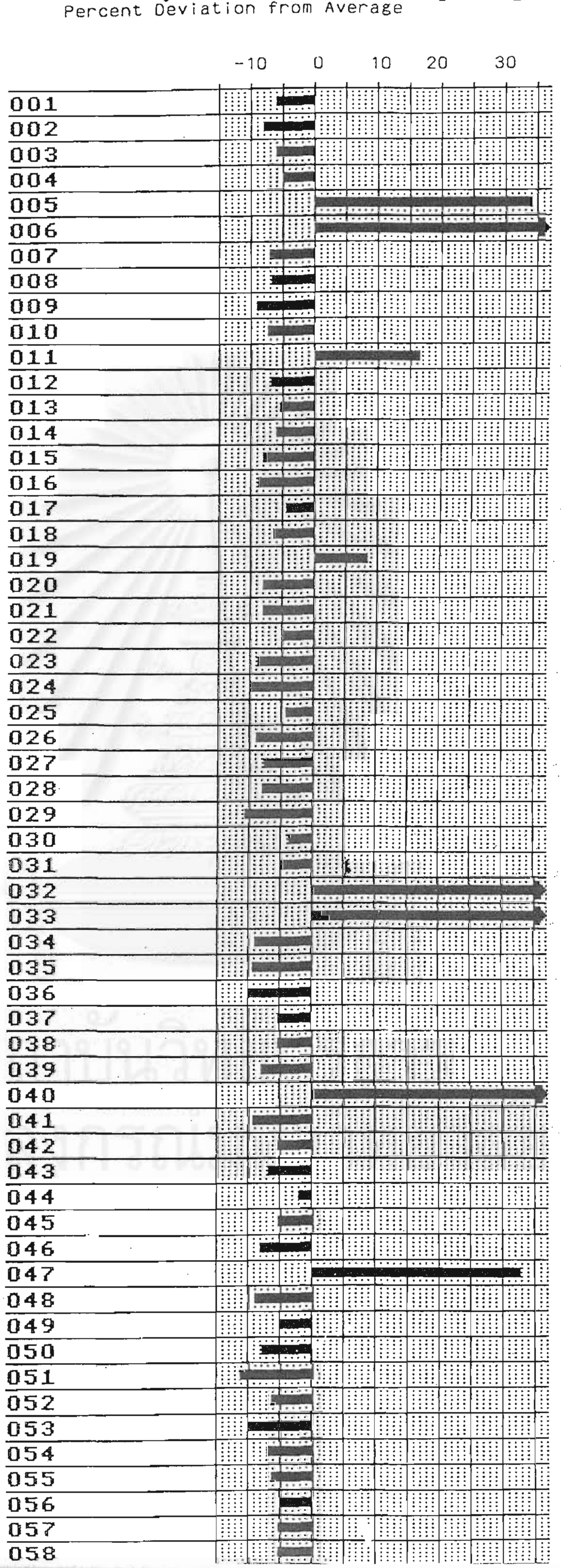
Cell Impedance Summary

| Minimum | Average | Maximum |
|---|---|---|
| 0.99 | 1.12 | 1.96 |

NY-Sub



## Nakornayok Substation (before improving)



## ข้อมูลการทดสอบ Battery ด้วยเครื่องทดสอบ Impedance

สถานีไฟฟ้าแรงสูง นครนายก

Battery 125 Vdc (60 Cell 2V/Cell) OLDHAM Hawker Siddeley Type. E8-5674 200 Ahr.

Battery Analysis Report

otes:

11/30/00

mbient Temp. 28 C° Pilot Temp.

AC_R: A AC_I: 8.00 A

Multiplier: 1

ser ID: NY - SUB

| ell | Notes | ① Zb mΩ | ② Rs mΩ | ③ Volt DC | ④ Time |
|---|---|---|---|---|---|
| 01 | ........ | 0.976 | 0.044 | 2.272 | 12:59 |
| 02 | ........ | 0.953 | 0.046 | 2.277 | 12:59 |
| 03 | ........ | 0.984 | 0.063 | 2.272 | 13:00 |
| 04 | ........ | 0.982 | 0.058 | 2.275 | 13:00 |
| 05 | ........ | 0.939 | 0.057 | 2.214 | 13:00 |
| 06 | ........ | 1.03 | 0.060 | 2.194 | 13:00 |
| 07 | ........ | 0.953 | 0.050 | 2.270 | 13:01 |
| 08 | ........ | 0.959 | 0.052 | 2.275 | 13:01 |
| 09 | ........ | 0.938 | 0.046 | 2.270 | 13:01 |
| 10 | ........ | 0.955 | 0.053 | 2.275 | 13:01 |
| 11 | ........ | 0.942 | 0.050 | 2.226 | 13:02 |
| 12 | ........ | 0.967 | 0.060 | 2.277 | 13:02 |
| 13 | ........ | 0.978 | 0.046 | 2.277 | 13:02 |
| 14 | ........ | 0.970 | 0.053 | 2.280 | 13:02 |
| 15 | ........ | 0.949 | 0.282 | 2.277 | 13:03 |
| 16 | ........ | 0.937 | 0.046 | 2.275 | 13:03 |
| 17 | ........ | 1.00 | 0.064 | 2.270 | 13:03 |
| 18 | ........ | 0.976 | 0.050 | 2.272 | 13:03 |
| 19 | ........ | 0.923 | 0.057 | 2.236 | 13:04 |
| 20 | ........ | 0.926 | 0.052 | 2.248 | 13:04 |
| 21 | ........ | 0.953 | 0.050 | 2.272 | 13:04 |
| 22 | ........ | 0.997 | 0.050 | 2.253 | 13:05 |
| 23 | ........ | 0.916 | 0.049 | 2.253 | 13:05 |
| 24 | ........ | 0.933 | 0.051 | 2.270 | 13:05 |
| 25 | ........ | 0.974 | 0.048 | 2.275 | 13:0 |
| 26 | ........ | 0.928 | 0.047 | 2.272 | 13:0 |
| 27 | ........ | 0.919 | 0.051 | 2.248 | 13:0 |
| 28 | ........ | 0.949 | 0.049 | 2.272 | 13:0 |
| 29 | ........ | 0.890 | 0.052 | 2.179 | 13:0 |
| 30 | ........ | 1.05 | 0.258 | 2.272 | 13:0 |
| 31 | ........ | 1.01 | 0.045 | 2.272 | 13:0 |
| 32 | ........ | 0.966 | 0.055 | 2.199 | 13:0 |
| 33 | ........ | 0.997 | 0.040 | 2.199 | 13:0 |
| 34 | ........ | 0.943 | 0.048 | 2.267 | 13:0 |
| 35 | ........ | 0.930 | 0.042 | 2.265 | 13:0 |
| 36 | ........ | 0.936 | 0.052 | 2.267 | 13:0 |
| 37 | ........ | 0.965 | 0.040 | 2.265 | 13:0 |
| 38 | ........ | 0.969 | 0.051 | 2.275 | 13:0 |
| 39 | ........ | 0.931 | 0.049 | 2.262 | 13:0 |
| 40 | ........ | 1.02 | 0.052 | 2.192 | 13:1 |
| 41 | ........ | 0.927 | 0.043 | 2.270 | 13:1 |
| 42 | ........ | 0.968 | 0.055 | 2.267 | 13:1 |
| 43 | ........ | 0.961 | 0.049 | 2.270 | 13:1 |
| 44 | ........ | 1.00 | 0.055 | 2.272 | 13:11 |
| 45 | ........ | 0.960 | 0.247 | 2.280 | 13:11 |
| 46 | ........ | 0.954 | 0.042 | 2.284 | 13:11 |
| 47 | ........ | 0.948 | 0.049 | 2.223 | 13:11 |
| 48 | ........ | 0.954 | 0.045 | 2.270 | 13:12 |
| 49 | ........ | 0.933 | 0.046 | 2.248 | 13:12 |
| 50 | ........ | 0.955 | 0.040 | 2.262 | 13:12 |
| 51 | ........ | 0.931 | 0.046 | 2.265 | 13:12 |
| 52 | ........ | 0.977 | 0.042 | 2.260 | 13:13 |
| 53 | ........ | 0.949 | 0.044 | 2.272 | 13:13 |
| 54 | ........ | 0.967 | 0.041 | 2.272 | 13:13 |
| 55 | ........ | 0.972 | 0.049 | 2.280 | 13:13 |
| 56 | ........ | 0.995 | 0.040 | 2.280 | 13:14 |
| 57 | ........ | 0.992 | 0.049 | 2.280 | 13:14 |
| 58 | ........ | 0.992 | 0.043 | 2.280 | 13:14 |
| 59 | ........ | 0.982 | 0.043 | 2.280 | 13:15 |
| 60 | ........ | 0.992 | 0.043 | 2.280 | 13:15 |

Cell Impedance Summary

| Minimum | Average | Maximum |
|---|---|---|
| 0.89 | 0.96 | 1.05 |

Design data: **Reference Data for Load Discharge Test** see page 6

| Cut-off voltage: $U_s$ | Model | DIN designation | Available current in Amps in relation to discharge time 10′ | 15′ | 30′ | 1 h | 2 h | 3 h | 4 h | 5 h | 8 h | 10 h | 20 h | 100 h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1.77 V/cell** (e.g. at $C_5$) | 6/ 600 | 6 OPzV 600 | 425 | 412 | 353 | 277 | 195 | 151 | 127 | 107 | 74 | 63 | | |
| | 8/ 800 | 8 OPzV 800 | 685 | 651 | 551 | 407 | 271 | 208 | 175 | 143 | 98 | 84 | | |
| | 10/1000 | 10 OPzV 1000 | 821 | 772 | 643 | 489 | 334 | 258 | 218 | 179 | 124 | 104 | | |
| | 12/1200 | 12 OPzV 1200 | 881 | 840 | 721 | 563 | 394 | 307 | 255 | 214 | 146 | 123 | | |
| | 12/1500 | 12 OPzV 1500 | 940 | 928 | 814 | 657 | 477 | 377 | 321 | 268 | 183 | 156 | | |
| | 16/2000 | 16 OPzV 2000 | 1253 | 1237 | 1085 | 876 | 636 | 502 | 428 | 357 | 244 | 208 | | |
| | 20/2500 | 20 OPzV 2500 | 1566 | 1546 | 1356 | 1095 | 795 | 628 | 535 | 446 | 305 | 260 | | |
| | 24/3000 | 24 OPzV 3000 | 1879 | 1855 | 1627 | 1314 | 954 | 753 | 642 | 535 | 366 | 312 | | |
| **1.80 V/cell** (e.g. at $C_{10}$) | 4/ 200 | 4 OPzV 200 | 224 | 199 | 153 | 108 | 71 | 54 | 45 | 37 | 25 | 22 | 12 | 2.8 |
| | 5/ 250 | 5 OPzV 250 | 258 | 233 | 183 | 132 | 88 | 67 | 56 | 46 | 32 | 27 | 15 | 3.5 |
| | 6/ 300 | 6 OPzV 300 | 286 | 261 | 210 | 154 | 104 | 80 | 68 | 56 | 39 | 33 | 18 | 4.2 |
| | 5/ 350 | 5 OPzV 350 | 300 | 275 | 221 | 164 | 111 | 85 | 72 | 59 | 41 | 35 | 19 | 4.5 |
| | 6/ 420 | 6 OPzV 420 | 326 | 303 | 250 | 189 | 131 | 101 | 86 | 71 | 50 | 42 | 23 | 5.3 |
| | 7/ 490 | 7 OPzV 490 | 339 | 326 | 274 | 212 | 150 | 117 | 99 | 82 | 58 | 49 | 27 | 6.2 |
| | 6/ 600 | 6 OPzV 600 | 373 | 378 | 320 | 255 | 185 | 147 | 126 | 105 | 73 | 62 | 35 | 8.0 |
| | 8/ 800 | 8 OPzV 800 | 595 | 590 | 500 | 380 | 261 | 202 | 170 | 141 | 96 | 83 | 46 | 10.6 |
| | 10/1000 | 10 OPzV 1000 | 705 | 700 | 586 | 453 | 319 | 249 | 212 | 176 | 122 | 102 | 58 | 13.2 |
| | 12/1200 | 12 OPzV 1200 | 769 | 765 | 655 | 518 | 374 | 295 | 252 | 210 | 144 | 120 | 68 | 15.8 |
| | 12/1500 | 12 OPzV 1500 | 813 | 813 | 737 | 601 | 447 | 359 | 309 | 259 | 180 | 153 | 86 | 19.8 |
| | 16/2000 | 16 OPzV 2000 | 1084 | 1084 | 982 | 801 | 596 | 478 | 412 | 345 | 240 | 204 | 114 | 26.0 |
| | 20/2500 | 20 OPzV 2500 | 1355 | 1355 | 1228 | 1002 | 745 | 598 | 515 | 432 | 300 | 255 | 143 | 33.0 |
| | 24/3000 | 24 OPzV 3000 | 1626 | 1626 | 1473 | 1202 | 894 | 717 | 618 | 518 | 360 | 306 | 171 | 39.0 |
| **1.83 V/cell** (e.g. at $C_{100}$) | 4/ 200 | 4 OPzV 200 | 200 | 180 | 140 | 101 | 68 | 52 | 44 | 36 | 25 | 21 | 12 | 2.7 |
| | 5/ 250 | 5 OPzV 250 | 230 | 209 | 166 | 122 | 83 | 64 | 54 | 45 | 31 | 27 | 15 | 3.4 |
| | 6/ 300 | 6 OPzV 300 | 253 | 234 | 190 | 142 | 94 | 76 | 65 | 54 | 38 | 32 | 18 | 4.1 |
| | 5/ 350 | 5 OPzV 350 | 263 | 246 | 200 | 151 | 104 | 81 | 69 | 58 | 41 | 34 | 19 | 4.4 |
| | 6/ 420 | 6 OPzV 420 | 282 | 271 | 225 | 173 | 122 | 96 | 82 | 69 | 49 | 41 | 23 | 5.3 |
| | 7/ 490 | 7 OPzV 490 | 289 | 289 | 246 | 193 | 139 | 110 | 94 | 79 | 57 | 48 | 27 | 6.2 |
| | 6/ 600 | 6 OPzV 600 | 316 | 316 | 286 | 231 | 171 | 137 | 118 | 100 | 74 | 61 | 34 | 7.9 |
| | 8/ 800 | 8 OPzV 800 | 514 | 514 | 447 | 348 | 245 | 192 | 164 | 137 | 94 | 82 | 45 | 10.5 |
| | 10/1000 | 10 OPzV 1000 | 619 | 619 | 526 | 413 | 297 | 236 | 202 | 169 | 120 | 100 | 57 | 13.2 |
| | 12/1200 | 12 OPzV 1200 | 657 | 657 | 587 | 469 | 345 | 277 | 239 | 201 | 142 | 118 | 68 | 15.6 |
| | 12/1500 | 12 OPzV 1500 | 695 | 695 | 658 | 541 | 409 | 333 | 289 | 246 | 179 | 151 | 86 | 19.8 |
| | 16/2000 | 16 OPzV 2000 | 926 | 926 | 877 | 721 | 545 | 444 | 385 | 328 | 238 | 201 | 113 | 26.0 |
| | 20/2500 | 20 OPzV 2500 | 1158 | 1158 | 1096 | 900 | 682 | 555 | 482 | 410 | 298 | 252 | 142 | 33.0 |
| | 24/3000 | 24 OPzV 3000 | 1389 | 1389 | 1315 | 1080 | 818 | 666 | 578 | 492 | 357 | 302 | 170 | 39.0 |
| **1.87 V/cell** | 4/ 200 | 4 OPzV 200 | 165 | 151 | 120 | 88 | 61 | 47 | 40 | 34 | 24 | 20 | 12 | 2.7 |
| | 5/ 250 | 5 OPzV 250 | 182 | 176 | 142 | 107 | 74 | 58 | 50 | 42 | 30 | 25 | 15 | 3.4 |
| | 6/ 300 | 6 OPzV 300 | 195 | 195 | 161 | 123 | 87 | 69 | 59 | 50 | 36 | 30 | 17 | 4.1 |
| | 5/ 350 | 5 OPzV 350 | 204 | 204 | 170 | 130 | 92 | 73 | 63 | 53 | 40 | 32 | 18 | 4.3 |
| | 6/ 420 | 6 OPzV 420 | 215 | 215 | 190 | 149 | 107 | 86 | 74 | 62 | 46 | 38 | 22 | 5.2 |
| | 7/ 490 | 7 OPzV 490 | 224 | 224 | 207 | 165 | 121 | 97 | 84 | 72 | 52 | 44 | 26 | 6.1 |
| | 6/ 600 | 6 OPzV 600 | 244 | 244 | 240 | 195 | 147 | 120 | 104 | 89 | 66 | 56 | 33 | 7.8 |
| | 8/ 800 | 8 OPzV 800 | 397 | 397 | 375 | 299 | 215 | 171 | 148 | 125 | 91 | 77 | 44 | 10.4 |
| | 10/1000 | 10 OPzV 1000 | 478 | 478 | 443 | 352 | 258 | 208 | 180 | 153 | 110 | 95 | 55 | 13.0 |
| | 12/1200 | 12 OPzV 1200 | 507 | 507 | 491 | 398 | 298 | 242 | 211 | 180 | 133 | 112 | 66 | 15.5 |
| | 12/1500 | 12 OPzV 1500 | 537 | 537 | 537 | 456 | 350 | 288 | 252 | 217 | 160 | 138 | 82 | 19.5 |
| | 16/2000 | 16 OPzV 2000 | 716 | 716 | 716 | 608 | 466 | 384 | 336 | 289 | 213 | 184 | 109 | 26.0 |
| | 20/2500 | 20 OPzV 2500 | 895 | 895 | 895 | 760 | 583 | 480 | 420 | 362 | 266 | 230 | 136 | 32.0 |
| | 24/3000 | 24 OPzV 3000 | 1074 | 1074 | 1074 | 912 | 699 | 576 | 504 | 434 | 319 | 276 | 163 | 39.0 |
| **1.90 V/cell** | 4/ 200 | 4 OPzV 200 | 128 | 128 | 103 | 77 | 53 | 42 | 36 | 30 | 21 | 18 | 10 | 2.4 |
| | 5/ 250 | 5 OPzV 250 | 142 | 142 | 122 | 93 | 64 | 51 | 44 | 37 | 26 | 22 | 13 | 3.0 |
| | 6/ 300 | 6 OPzV 300 | 152 | 152 | 137 | 106 | 76 | 60 | 51 | 43 | 31 | 26 | 15 | 3.6 |
| | 5/ 350 | 5 OPzV 350 | 159 | 159 | 145 | 112 | 80 | 64 | 55 | 46 | 32 | 28 | 16 | 3.8 |
| | 6/ 420 | 6 OPzV 420 | 168 | 168 | 158 | 128 | 93 | 75 | 64 | 54 | 40 | 34 | 20 | 4.6 |
| | 7/ 490 | 7 OPzV 490 | 174 | 174 | 167 | 141 | 104 | 84 | 73 | 62 | 44 | 39 | 23 | 5.4 |
| | 6/ 600 | 6 OPzV 600 | 190 | 190 | 188 | 166 | 126 | 103 | 90 | 77 | 57 | 49 | 28 | 6.9 |
| | 8/ 800 | 8 OPzV 800 | 309 | 309 | 300 | 257 | 186 | 149 | 129 | 112 | 80 | 67 | 39 | 9.2 |
| | 10/1000 | 10 OPzV 1000 | 372 | 372 | 358 | 302 | 223 | 180 | 156 | 133 | 98 | 83 | 48 | 11.5 |
| | 12/1200 | 12 OPzV 1200 | 395 | 392 | 388 | 340 | 256 | 209 | 182 | 156 | 115 | 98 | 55 | 13.8 |
| | 12/1500 | 12 OPzV 1500 | 418 | 418 | 418 | 386 | 300 | 247 | 217 | 188 | 147 | 119 | 71 | 17.2 |
| | 16/2000 | 16 OPzV 2000 | 557 | 557 | 557 | 514 | 400 | 329 | 289 | 250 | 186 | 158 | 94 | 23.0 |
| | 20/2500 | 20 OPzV 2500 | 696 | 696 | 696 | 643 | 500 | 412 | 362 | 312 | 232 | 198 | 118 | 28.0 |
| | 24/3000 | 24 OPzV 3000 | 835 | 835 | 835 | 771 | 600 | 494 | 434 | 374 | 278 | 237 | 141 | 34.0 |

# BIOGRAPHY

Mr. Chanod Sripornwattana was born on July 13, 1958 in Bangkok, Thailand. He graduated from King Mongkut's Institute of Technology, North Bangkok with a Bachelor's Degree in Electrical Engineering, since 1983. He has continued his graduate study in Engineering Management at the Regional Centre for Manufacturing Systems Engineering at Chulalongkorn University in 1998.

He worked for Electrical Maintenance Division of Electricity Generating Authority of Thailand (EGAT) since 1983 in a maintenance engineer position. Now he is the manager of Turbine and Generator Control System Section, Control System and Instrumentation Department, Maintenance Business Unit of EGAT.