

**An-Najah National University
Faculty of Graduate Studies**

Modeling and Simulation of Lead-Acid Storage Batteries within Photovoltaic Power Systems

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**This thesis is submitted in Partial Fulfillment of the Requirements
for the Degree of Master in Clean Energy and Energy
Conservation Strategy Engineering, Faculty of Graduate Studies,
at An-Najah National University, Nablus, Palestine**

2012

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This Thesis was defended successfully on 22/11/2012 and approved by:

Defense Committee Members

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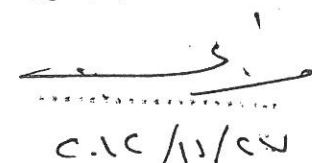
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C.A.C / 11/12

Dedication

I would like to dedicate my thesis work to

My father, mother, brothers and sisters.....

All friends and colleagues...

Everyone who works in this field.....

Acknowledgment

I would like to thank my family for constant love and support that have always given me.

Thanks go also to all my friends and fellow graduate Students.

My thanks and appreciations go to the staff of Clean Energy and Conservation Strategy Engineering Master Program at An-Najah National University

Finally, and most importantly, my furthestmost appreciation goes to my supervisor, Prof. Dr. Marwan Mahmoud for his exceptional guidance and insightful comments and observations throughout the duration of this project.

Ola

الإقرار

أنا الموقعة أدناه، مقدمة الرسالة التي تحمل العنوان:

Modeling and Simulation of Lead-Acid Storage Batteries within Photovoltaic Power Systems

نمذجة ومحاكاة بطاريات الرصاص - الحامض ضمن أنظمة الخلايا الشمسية

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Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name:

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Date:

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List of Abbreviations

Ah	Ampere hour
Wh	Watt hour
C	Capacity
AhC	Ampere hour capacity
WhC	Watt hour capacity
SOC	State of charge
DOD	Depth of discharge
V_{oc}	Open circuit voltage
η_{Ah}	Ampere hour efficiency
η_{Wh}	Watt hour efficiency
SLI	Starting, Lighting and Ignition
VRLA	Valve - Regulation Lead Acid

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**Modeling and Simulation of Lead-Acid Storage Batteries within
Photovoltaic Power Systems**

By

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Supervisor

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Abstract

Storage batteries are indispensable in all standalone solar electric systems (PV power systems). Their efficiency and life time affects significantly the overall PV system performance and economics. Batteries specified especially for use in PV systems have to be distinguished with standing of a very deep discharge rate and high cycling stability. The most proper types of storage batteries (rechargeable batteries) are discussed, and the most important characteristics of lead acid batteries necessary for evaluation of their performance are presented and discussed in this thesis. Selecting the optimum conditions of lead acid battery to obtain the maximum efficiency and maximum ampere hour and watt hour capacities by implemented measurements on a lead acid battery are presented in this thesis. The internal resistance of the battery is a reliable key for determination of its state of charge. The value of this resistance increases almost linearly with increasing of the stored energy. At the same time the specific gravity of the electrolyte decreases linearly with the degradation of ampere hour capacity. The experiments have shown that the battery internal temperature doesn't change significantly from the ambient temperature during charge and discharge process. The implemented experimental tests have proved that a regular battery cell will be not more rechargeable if it is fully discharged. This issue requires using always a controllable battery

charger within the PV power systems to protect the storage batteries against deep discharge and extremely over charge. Such equipment will extend the life time of the battery and consequently improve the economic feasibility and reliability of the PV power systems. In addition the tests have shown that the watt hour efficiency of a battery is considerably less than the ampere hour efficiency, which advises to depend more on the watt hour efficiency when designing storage battery systems to secure higher reliability.

Moreover, depending on an earlier developed algorithm for determination of the ampere hour capacity of a battery cell, a new similar algorithm based on specific gravity and cell voltage have been developed which enables also the determination of the ampere hour capacity from the implemented tests on the new battery. This algorithm enables the correct settings of the limits of charge - discharge hysteresis of the battery charger in order to avoid extremely deep discharge and over charge of the battery.

Moreover, this thesis presents a construction of an equivalent circuit for lead acid battery using MATLAB program, defines all the components that the circuits consist of and defines the components equations and the parameters with their constants that the equivalent circuit depends on. The final simulation results related to this circuit are also presented. A simulation of the battery on the MATLAB has shown that a realization of an equivalent circuit for a battery cell is possible. With respect to battery characteristic functions, it was found that simulation and practical testing results are almost similar.

Chapter One
Introduction
and Literature Review

Chapter One

Introduction and Literature Review

1.1 Introduction

Renewable energy sources, such as wind energy and photovoltaic (PV) energy, are widely used as stand-alone power systems supplying different electrical loads in rural and remote areas. These sources are of intermittent nature and, therefore, the stand alone power systems should include storage battery banks. The storage battery banks improve the reliability of these systems because the excess energy is stored in the battery bank, and this energy is delivered to the load when the solar or wind energy is not available or not sufficient.

With respect to reliability and cost of standalone PV power systems, storage batteries represent main and important components. Even a battery block represents only 8% of the initial cost of a new PV system; it represents 23% of the total system cost when considering the replacement of batteries during the total life time of the system (20 years) [1]. Storage batteries provide the PV system with advantages such as ability of providing energy during night time and sunless periods, ability to meet momentary peak power demands and stabilizing the system voltage.

The first chapter includes introduction and literature review.

Chapter two is established to illustrate the most important characteristics of storage battery types.

Chapter three represents the general lead acid battery characteristics, types and chemistry. Charging and discharging conditions are discussed. In addition, it discusses the battery maintenance, safety and operating features.

Chapter four discusses the nickel cadmium battery and iron electrode battery regarding its types, characteristics, chemistry, charging and discharging performance.

Chapter five presents experiments with comprehensive measurements that were used to determine the ampere hour capacity, watt hour capacity, depth of discharge and efficiency of lead acid battery. Selecting the optimum conditions of lead acid battery to obtain the maximum efficiency and maximum ampere hour and watt hour capacities in charging and discharging process and a mathematical algorithm of lead acid battery was developed for determining the battery ampere hour capacity (C_{Ah}) and watt hour capacity (C_{Wh}).

Development of an equivalent electrical circuit for a lead acid battery cell using MATLAB program with the results of this model and their comparison with the results obtained from the measurements are presented in chapter six.

1.2 Literature Review

A useful and systematic dynamic model of a battery energy storage system (BES) is developed for a large-scale power system stability study.

The model takes into account converter equivalent circuits, battery characteristics and internal losses. Both charging mode and discharging mode are presented. The model is expressed in equivalent transfer function blocks, and it can be easily used in dynamic stability analysis of a power system. To examine the dynamic behavior of the model, applications to the damping of turbo generator torsional oscillations are performed. Active and reactive power modulation by the BES can be controlled according to system requirements. Eigen value analysis and dynamic simulations are performed to demonstrate the damping effect of the BES. A dynamic model of a BES was presented. The model was expressed in the frequency domain and can be easily applied in the stability application of a power system. The control scheme let the BES have the ability of active power and reactive power modulation according to system requirement. In the dynamic period, the BES can be thought of as a current sink in the charging mode or a current source in the discharging mode. To examine the dynamic behavior of the model, the investigation into the damping of torsional oscillations was performed. The BES with an auxiliary lead-lag controller was proposed to enhance the torsional modes damping of the turbo generator. Eigen values were analyzed and dynamic simulations were shown that the torsional oscillations could be effectively suppressed. The dynamic performance of the power system was greatly improved. There have been some commercial applications of the BES in Germany, South Africa and the USA. However, since there was more and more desire for better load management and electric power quality, the BES would receive more

attention in the future. The investigations of the BES fall into two categories: modified lead-acid battery and advanced battery researches; and BES control and operation technology researches. The establishment of the BES dynamic model can provide a basis for the control method development and the observation of responses and behavior of batteries [2].

Some of the issues and aspects associated with the use of lead-acid batteries for energy storage in small PV systems were represented. Battery performance depends on the PV system design and operation and the type of battery technology employed. New and emerging energy storage technologies such as the vanadium redox battery and high-speed flywheel are considered as possible alternative energy storage systems in PV applications. Lead-acid battery is the technology of choice for most PV applications. However, there are performance limitations which result in excessive replacement costs, work-place Occupational Health and Safety (OS& H) issues and operational maintenance overheads for many end-users. The technical shortcoming of the lead acid battery continues to fuel research and developmental activity for comparative, low cost, alternatives. Two recent developments - the VRB and the high-speed flywheel - have progressed sufficiently to be now considered as possible alternatives to the ubiquitous lead-acid battery in many PV applications [3].

A model of a lead-acid battery with the Advanced Vehicle Simulator (ADVISOR) package was developed. The integrated model was used to simulate the performance of a series-hybrid vehicle through 12 successive

FUDS cycles. Successful completion of the vehicle simulations demonstrates the feasibility of using a fundamentally based battery model. The additional information available from such a model is illustrated by the ability of the model to predict a change in the local utilization of the negative electrode as a result of cycling. A fundamentally based lead-acid battery model has been developed and integrated into the vehicle simulation package ADVISOR. A key issue related to model integration was the need to converge the model in response to rapidly changing power requests that may exceed the capability of the batteries. Another important issue was the need for parameters suitable for simulation of both charge and discharge. The integrated model was used successfully to simulate the performance of a series-hybrid vehicle through 12 successive FUDS cycles, corresponding to a total distance of approximately 80 miles. The simulations included the power output from the battery pack, the state-of-charge, and power output from the generator as a function of time. These simulations demonstrate the feasibility of using a fundamentally based battery model for the simulation of hybrid vehicle performance [4].

Charge algorithms were developed to improve the life cycle of Valve Regulated Lead-Acid (VRLA) batteries to 1000 deep discharges for electric vehicle applications. Hypotheses that VRLA batteries could reach end-of-life prematurely with the "normal" constant voltage charge because of insufficient recharge at the negative plate and the "oxygen cycle" or recombination reactions interfering with recharge of the negative plate. Zero delta voltage (ZDV) and current interrupt charging algorithms were

developed and strategies that improved the cycle life of VRLA modules from 150-200 deep discharge cycles to 300-350 deep discharge cycles. Implementing a current interrupt charged algorithm on a 24-module battery pack that resulted in 700 deep discharge cycles. No correlation between operating temperature and failure were found when batteries stayed below the manufacturer's recommended temperature limit of 60°C. However, warmer modules appear to have longer lives, and so applying a ZDV technique similar to the one used for NiCd batteries, the cycle life of the Optima VRLA must be increased by a factor of 2. As VRLA batteries age, increasingly higher finishing currents are drawn because of the oxygen cycle; the charge/termination algorithm must be adjustable to respond to this. A fixed, monotonic algorithm will result in overcharge early in life and undercharge later in life, and so applying the multi-step constant current / current interrupt (CC/CI) charge algorithm without battery management results in excellent pack cycle lifetime for the Optima product. Insufficient recharge of 12V modules in a large pack appears to be amplified relative to single-module cycling. Weight losses are very low, on the order of 100-150 grams, suggesting that "dry-out" is not a failure mode. The small differences between initial and final open circuit voltages (V_{OC}) and impedances indicate that negative-plate sulfation is not severe [5].

Models of electrochemical batteries suitable for the use of the electrical engineer, in particular for the analysis of electrical systems with batteries were studied. The problem of simulating electrochemical batteries by means of equivalent electric circuits is defined in a general way; then

special attention is devoted to the problem of modeling of Lead–Acid batteries. For this kind of batteries general model structure is defined from which specific models can be inferred, having different degrees of complexity and simulation quality. In particular, the implementation of the third-order model, that shows a good compromise between complexity and precision, is developed in detail. The behavior of the proposed models is compared with results obtained with extensive lab tests on different types of lead–acid batteries. And so the complex, nonlinear behavior of electrochemical batteries can be conveniently modeled using equivalent electric networks. Although these networks contain elements that are nonlinear and dependent on battery state-of-charge and electrolyte temperature, they are very useful for the electric engineer, since they allow them to think in terms of electric quantities, instead of internal battery electrochemical reactions. The third-order model proposed has accuracy satisfactory for the majority of uses; for particular situations more sophisticated models can be derived from the general model structure which was proposed. The proposed model can be used for several purposes; the more important fields of application are: computer simulation of battery behavior under different operating conditions (possibly containing both charge and discharge processes); management of on-line systems containing electrochemical batteries: state-of-charge estimation, battery monitoring and diagnostics; estimate of residual range of electric vehicles. The use of the proposed models, in particularly, the third order formulation, is complicated by the fact that the proposed equations contain

several parameters that have to be identified. This identification can, however, be simplified a lot since some of the parameters can be taken as constant for all the batteries built with the same technology [6].

The problem of lead acid battery state-of-charge (SOC) estimation for (hybrid) electric vehicles was discussed. The problem is to accurately estimate the remaining battery capacity for both driver notification and automated energy management. Simple solution methods, presentation of a new solution method, and experimental analysis of the performance of that method were given. A new algorithm was given and its application was demonstrated on experiment data. The experimental involves battery discharge only. As additional data sets become available, future research will also address battery recharge. The results indicated that the method is very promising. The advantages of the new algorithm are: (1) it accurately estimates SOC without undesirable increases in SOC when the load current changes, (2) it provides estimates of the battery internal parameters. These estimated parameters yield robustness across aging and different batteries [7].

A Radial Basis Function based learning system method has been proposed for estimation of State of Charge (SOC) of Lead Acid Battery. Coulomb metric method is used for SOC estimation with correction factor computed by Radial Basis Function Method. Radial basis function based technique is used for learning battery performance variation with time and other parameters. A new approach has been described to estimate the SOC

of lead acid battery using Radial basis function based learning method. The proposed method considers battery non linearity due to discharge rate, with temperature and corrects itself for aging and other variations of the battery characteristics to estimate SOC. Experimental results suggest that the proposed method gave excellent prediction of SOC assuming that the initial charging state of battery is known and is able to learn performance variation. The proposed algorithm can further be extended to include factors such as incomplete charging and interrupted discharging [8].

The various estimation methods for the SOC of the lead acid battery have been proposed. However, not any method can accurately predict the residual capacity. A new estimation method of the SOC on the lead acid battery is proposed. This method is based on the terminal voltage and the internal resistance of the battery. This proposed equation can decrease the estimation error for the little SOC region. Experiments of discharging the lead acid battery were made and compared the former method with the proposed new method. A new estimated equation was proposed, in which the square root about the internal resistance and the terminal voltage are used and the SOC can be estimated more precisely by the proposed equation especially when the SOC is very small [9].

Two electrical models of a lead-acid battery, a short-term discharge model and a long term integrated model, were used to investigate the system performance of a battery-supported dynamic voltage restorer (DVR). The short-term model provides a simple but effective description

when the DVR compensates voltage sags over a short period. The integrated model can predict accurately the terminal voltage, state of charge, battery capacity and gassing current. It gives a good description of the battery response during both discharge and charge. Parameters of both models can be determined easily from measured battery output voltages obtained from load-step tests. Both models were successfully implemented in EMTDC/PSCAD and interfaced with the digital model. They gave a very close agreement between extensive experimental data and simulation results. Application issues such as current harmonics and micro cycles during charge/discharge are discussed with respect to their impact on loss of capacity and reduced lifetime of the lead-acid battery. A short-term discharge model and long-term integrated models are presented to investigate the system performance of a dynamic voltage restorer (DVR). The short-term model is based on the Thevenin battery model and provides a simple but effective representation when the DVR experiences voltage sags for a short period. The integrated model, which is based on Giglioli's fourth-order dynamic-battery model, can predict accurately the terminal voltage, state of charge, battery capacity, and gassing current. It gives an excellent description of the battery response during both discharge and charge. Parameters in both models can easily be extrapolated from measured battery output voltages obtained from a set of load responses. Both models were successfully implemented in EMTDC/ PSCAD and interfaced with the digital model. They gave close agreement between extensive experimental data and simulation results. Application issues such

as harmonic ripple and micro cycle charge/discharge remain a cause for concern because of their potential negative impacts on loss of capacity and reduced life time of the lead-acid battery. The proposed electrical battery models can not only be used in the DVR system, but can also be applied to other battery energy storage systems [10].

The most important characteristics of lead acid batteries necessary for evaluation of their performance were discussed. Moreover, an experimental procedure is illustrated for developing a mathematical algorithm for determining the ampere hour capacity of batteries operating in PV systems. This algorithm enables to determine the state -of-charge of a battery by measuring its voltage and electrolyte-specific gravity at a definite temperature. This enables correct settings of the limits of the charge - discharge hysteresis of the battery charger to avoid extremely deep discharge and over charge of the battery. The derived algorithm, which has been verified by data acquisition capacity measurements, is applicable also to large battery storage systems. Lead - acid storage batteries are usually used in small and large PV power systems operating in stand-alone mode. Selection of battery type and capacity are important factors to realize an efficient PV system. Battery types marketed for use in automobile are economically not appropriate for utilization in PV systems because their life time is relatively very short since they cannot stand deep discharge and high cycling rate. Battery voltage in function of electrolyte temperature, depth of discharge and specific gravity as well as the battery capacity in function of discharge current, have to be given special consideration when

evaluating or designing storage batteries for PV power systems. Battery voltage and specific gravity together is the key for determining the ampere - hour capacity of a battery and the stored energy in it. Measuring them at the same time and substituting their values in the developed algorithm leads to determine the capacity of the battery Ah. The algorithm enables to know the energy storage within a PV power system and to perform accordingly in setting the battery charger control limits correctly, which consequently elongate the life time of the battery and enhance the overall PV system performance and economics [1].

A new estimation method of the SOC on the lead acid battery is proposed. Using an electric circuit model of the battery, it is shown how the open circuit voltage (which is directly related to the SOC) can be estimated based on the terminal voltage and current measurements provided there is sufficient variation in the battery current. A modified Thevenin equivalent circuit model given was used to represent the lead-acid battery. Treatment of nonlinear time varying model to a linear time varying model is done with an unknown constant parameter. Conditions were found on the battery current that ensure the observability Gramian of the system is full rank so that the initial state of the system can be found using the inverse of the system Gramian [11].

In a bid to perform model-based diagnostics on the electrical network of an automobile, experimental work and analysis was conducted to model an automotive lead-acid battery over the domain in which one is expected to operate. First, a thorough literature review discusses previous

attempts at modeling, as well as state and parameter estimation. Also, the literature on the aging and failure modes of batteries is presented. Next, the model selected is described, consisting of a locally linear time-invariant system approximation of a globally nonlinear time-variant battery. To obtain the best parameters which enable this approximation, a series of experiments was performed on a battery, the methodologies of which are detailed. Finally, the details of parameter extraction are also presented, along with their results. The work here presents a common battery modeling methodology and the results of its application to modeling automotive lead-acid batteries over the range of environmental conditions that it is expected to operate in. The two major portions of the work, and the biggest contributions, were the experimental methods (excitation currents used) and parameter estimation. Both of these have appeared previously, and were applied successfully to the specific task of automotive battery modeling. This picture was incomplete of the full process of modeling and fault-diagnosis of these batteries. The modeling was done separately from fault diagnosis; the fault modes were investigated and presented as a literature review, but no batteries were aged to validate or quantify these highly variable processes. The modeling also cannot be considered complete as it was based only on one battery. A number of improvements could be made to the experimental methodology and analysis techniques presented in this work [12].

In stand-alone photovoltaic (PV) systems, charge controllers prevent excessive battery overcharge by interrupting or limiting the current flow

from the PV array to the battery when the battery becomes fully charged. Charge regulation is most often accomplished by limiting the battery voltage to a predetermined value or cut-off voltage, higher than the gassing voltage. These regulation voltages are dependent on the temperature and battery charge current. An adequate selection of overcharge cut-off voltage for each battery type and operating conditions would maintain the highest battery state of charge without causing significant overcharge and thus improving battery performance and reliability. To perform this, a sample of nine different lead-acid batteries typically, used in stand-alone PV systems including vented and sealed batteries with 2V cells and mono block configurations have been selected. Simple mathematical expressions were fit to charge characteristic voltages: the gassing voltage (V_g) and the end-of-charge voltage (V_{fc}) as function of charge current and temperature for the tested batteries. With these expressions, we have calculated (V_g) and (V_{fc}) at different current rates. An analysis of the different values obtained is presented here focusing on the implication in control strategies of batteries in standalone PV systems. The Experimental values of both gassing voltage (V_g) and end-of-charge voltage (V_{fc}) at different operating conditions of nine different lead-acid batteries typically used in stand-alone photovoltaic systems have been obtained. The experimental values of (V_g) and (V_{fc}) have been fitted with a good degree of accuracy to simple mathematical expressions that include the influence of charge current rate and temperature. From the regression analysis, it can be observed that the temperature coefficient α does not remain constant during all the charge

process. In all cases (except one battery), the temperature coefficient for the gassing voltage is clearly lower than the temperature coefficient for the end-of-charge voltage. It indicates that the temperature effect on battery voltage is more important as the battery SOC increases. The values of temperature coefficients we have obtained are lower than typical values ranging from -4 to -6 mV/°C recommended by other authors current rate also has influence on charge voltages. In the case of V_g no large, differences have been found among different technologies tested: at the same current rate the maxima differences of (V_g) values have varied from 0.08Vat C100 to 0.12Vat C5. In the case of (V_{fc}), large differences have been found among the batteries with an influence of the battery type obtaining high, intermediate and low values corresponding to sealed, vented 2V cells and vented mono block batteries. In consequence, it is observed that voltage interval ($V_{fc} - V_g$) tends to be narrower for slower current rates, being influenced by the battery type: sealed batteries present high values, vented 2V cells intermediate values and vented mono block low values. The dependence of (V_g) and (V_{fc}) with both current rate, temperature and battery type, especially in the case of overcharge cut-off voltage, should be taken into account in the concept of operational strategy of charge regulators for stand-alone PV systems [13].

A simple, fast, and effective equivalent circuit model structure for lead-acid batteries was implemented to facilitate the battery model part of the system model. Tools and processes for estimating the battery parameters from laboratory data were implemented. After estimating

parameters from laboratory data, the parameterized battery model was used for electrical system simulation. The battery model was capable of providing accurate simulation results and very fast simulation speed. A lead-acid battery model was developed, along with tools to parameterize the model from laboratory data. Construction of an equivalent circuit model has been described. A semi-automated process was used to estimate parameters for the battery model from laboratory data. The completed battery model simulated at approximately 10,000 times real-time. The accuracy of the simulated battery model voltage was within 3.2% in comparison to vehicle drive cycle measurements [14].

The storage of energy in batteries is a cause of the failure and loss of reliability in PV systems. The two general lead acid battery models and their agreement with experimental data were reviewed. In order to validate these models, the behavior of different battery cycling currents has been simulated. The results obtained have been compared to real data. The CIEMAT model presents a good performance compared to Monegon's model. An experimental study was presented for a different type of batteries. The two models used for comparison with experimental data are general and can be applied for wide range of lead acid batteries. The Monegon model was analyzed and found that the equation of charge and discharge does not reproduce the experimental curves. Probably, the value of parameters was fitted for to another type of battery and different operational conditions. The term included in Monegon model for the overcharge does not reproduce these effects and values of RMSE indicate

the deviation. The CIEMAT model presents a good performance to represent dynamic and complex battery operation. This is, in contrast to Monegon's model; which presents significant limitations with respect to charging process. In this way, other results could be evaluated considering parameter variations effects in the life of battery. The aging model describing life time of a battery is useful for an economic analysis [15].

The principle of the lead-acid battery was presented. A simple, fast, and effective equivalent circuit model structure for lead-acid batteries was implemented. The identification of the parameters of the proposed lead-acid battery model is treated. This battery model is validated by simulation using the Matlab/Simulink Software. Several lead-acid battery models are conceived, for example, the mathematical model and the parallel branch model. But the third order model is the simplest one to identify. All parameters of this model can be identified by laboratory tests or taken from the manufacturer's data. The third order model of the lead-acid has been validated by simulation on the software MATLAB/Simulink [16].

An improved and easy-to-use battery dynamic model was presented. The charge and the discharge dynamics of the battery model are validated experimentally with four battery types. An interesting feature of this model is the simplicity to extract the dynamic model parameters from batteries datasheets. Only three points on the manufacturer's discharge curve in steady state are required to obtain the parameters, and the battery model is included in the Sim Power Systems simulation software and used in a

detailed simulation of an electric vehicle based on a hybrid fuel cell-battery power source. The model could accurately represent the dynamic behavior of the battery. The new Sim Power Systems battery model allows for an adequate representation of a battery's real behavior based on only three points on the battery manufacturer's discharge curve. It has been demonstrated that even if the points are extracted from a constant-current discharge curve, the dynamic behavior obtained in simulation is close to the experimental behavior, and the integration of the new battery model in a multi-domain simulation of an EV based on a fuel cell enables to design and adequately adjust the energy management system as well as the battery's management system. The obtained results are coherent with reality and the vehicle's total energy consumption concords with the public information available on the Honda FCX Clarity [17].

The battery system modeling and user studies, are thus essential for battery system design and optimization. The investigation detailed was presented on battery system modeling and user study for emerging PHEVs. The proposed modeling solution can accurately characterize battery system run-time charge-cycle efficiency, and long-term cycle life. In particular, it models battery system capacity variation and fading due to fabrication and run-time aging effects. An embedded monitoring system is designed and deployed in a number of HEVs and PHEVs, which can monitor users' driving behavior and battery usage at real time. The user can employ the proposed modeling and monitoring solutions to investigate battery system run-time usage, characterize user driving behavior, and study the impact of

user driving patterns on battery system run-time charge-cycle efficiency, capacity variation and reliability, and life-cycle economy, and these is the first step in battery system design and optimization for emerging green-energy CPS transportation applications. User-centric driving pattern and battery system energy usage analysis are critical for PHEV manufacturers, drivers and potential consumers. A large-scale battery system model had been developed for PHEVs, which supports short-term energy usage profile analysis, long-term thermal distribution and lifetime estimation, based on heterogeneous real-world user driving behavior. A real time user driving data acquisition system and conducted a user study on six participants with diverse driving patterns was developed. Detailed evaluation results have shown that our battery system model can accurately estimate real-world battery system energy usage; user driving behavior affects battery system usage significantly on both short term and long term. Generally, steadier and smoother driving behaviors are better for electric-drive vehicle lifetime and cost saving [18].

Chapter Two

Rechargeable Battery

Chapter Two

Rechargeable battery

2.1 Rechargeable Battery Cells

As electrical and electronic devices become increasingly essential parts of modern society, we are ever more dependent on our sources of electrical power. Batteries are one of the few practical methods of storing electrical energy. As such, they are vital components in electrical and electronic devices ranging from portable electrical shavers to satellites in space. Recent advances in battery technology, both in new battery types and in improvements to existing batteries, have fueled a surge in battery applications. As battery applications become more diverse and more critical to system operation, it is especially important that system designers and users understand the fundamentals of battery function [19].

A rechargeable battery or storage battery is a group of one or more electrochemical cells. They are known as secondary cells because their electrochemical reactions are electrically reversible. Rechargeable batteries come in many different shapes and sizes, ranging anything from a button cell to megawatt systems connected to stabilize an electrical distribution network. Several different combinations of chemicals are commonly used, including: lead–acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion) [20].

2.2 Battery History

Batteries of one form or another have existed for nearly 200 years. From the beginning, researchers have been attempting to improve the

energy density and make battery packaging more convenient for the user. This development work continues today because market opportunities expand immensely with each significant improvement in battery performance [21].

2.2.1 Early works

Most historians date the invention of batteries to about 1800 when experiments by Alessandro Volta resulted in the generation of electrical current from chemical reactions between dissimilar metals. The original voltaic pile used zinc and silver disks and a separator consisting of a porous non conducting material saturated with sea water. When stacked as sketched in figure (2.1), a voltage could be measured across each silver and zinc disk. Experiments with different combinations of metals and electrolytes continued over the next 60 years. Even though large and bulky, variations of the voltaic pile provided the only practical source of electricity in the early 19th century.

Johann Ritter first demonstrated a rechargeable battery couple in 1802, but rechargeable batteries remained a laboratory curiosity until the development, much later in the century, of practical generators to recharge them [21].

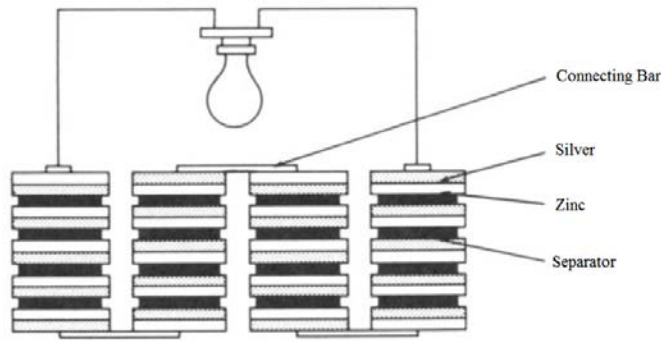


Figure (2.1): Voltaic pile [21].

2.2.2 Development of Lead Acid batteries

In 1859, Gaston Planté developed a spirally wound lead-acid battery system. His cell used two thin lead plates separated by rubber sheets. He rolled the combination up and immersed it in a dilute sulfuric acid solution. Initial capacity was extremely limited since the positive plate had little active material available for reaction. As repetitive cycling resulted in an increased conversion of the lead in the positive plate to lead dioxide, the capacity increased materially. This formation process remains a significant aspect of lead-acid battery manufacture today.

About 1881, Faure and others developed batteries using a paste of lead oxides for the positive-plate active materials. This allowed much quicker formation and better plate efficiency than the solid Planté plate. This improvement in battery technology occurred just as central-station electrical generation was becoming practical. One result of these two events was development of a diversity of commercial uses for lead acid batteries including such applications as central stations, telephone exchanges, and train and residential lighting.

The next major influence on lead-acid battery development was the Charles Kettering's invention in 1912 of the first practical self-starter for automobiles. General Motors subsequent adoption of battery-started cars provided the key for massive growth in use of lead-acid batteries. The use of lead-acid batteries in automotive starting, lighting, and ignition (SLI) service remains their largest market. Although the rudiments of the flooded lead-acid battery were in place in the 1880's, there has been a continuing stream of improvements in the materials of construction and the manufacturing processes. Today, flooded lead-acid batteries exist in a variety of configurations tailored to the requirements of specific applications.

The improved manufacturing quality control had eliminated the present day batteries that made concerns over reliability and performance that prevailed as recently as twenty years ago. Even recognizing the improvements in flooded batteries, they still contain liquid sulfuric acid with attendant safety, handling, and transportation concerns. Investigators have attempted a variety of approaches to immobilize the electrolyte in lead-acid batteries. The first effective result was the gelled electrolyte battery developed in Germany in the 1960's. This used silica gel in the electrolyte to greatly increase its viscosity. The result was a battery that substantially reduced concerns about leakage and spillage.

Working from a different approach, Gates Energy Products developed and was awarded a basic patent (U.S. Patent 3,862,861) on a

sealed-lead battery. Using only minimal amounts of electrolyte and recombining evolved oxygen, the Gates sealed lead battery provided major improvements in both performance and ease of use over both flooded and gelled-electrolyte batteries [21].

2.2.3 Development of Nickel–Cadmium

Development of practical rechargeable batteries using alkaline electrolytes lagged about 50 years behind lead-acid technology. About 1900, Edison began experimenting with a nickel storage battery with the goal of developing a practical electric automobile.

In 1910 Edison demonstrated a commercial battery that used a nickel positive electrode, an iron negative electrode, and a potassium hydroxide electrolyte. Because of its ruggedness and high life cycle with repeated deep discharges, the Edison battery found commercial success in a variety of applications in the U.S. As nickel-cadmium batteries have become more cost competitive, nickel-iron batteries have lost most of their markets. At about the same time as Edison's work in the U.S., Waldmar Jungner was working with first the nickel-iron and then the nickel-cadmium couple in Sweden. The result of his efforts was the pocket-plate nickel-cadmium battery which found widespread application in Europe, especially in larger sizes for stationary applications.

During World War II, the Germans developed the sintered-plate nickel-cadmium battery offering exceptionally high energy densities when

compared with other rechargeable batteries. The sintered-plate, vented or flooded nickel-cadmium battery has found primary use in those applications such as aircraft engine starting where high performance will command a price premium.

In the 1950's, European experimenters developed a revolutionary form of nickel cadmium battery that recombined gases evolved on overcharge instead of venting them. This closed cycle allowed them to develop a sealed cell with excellent performance characteristics. Because of its cleanliness and high energy density, the sealed nickel-cadmium cell continues to find broad application in electronics and consumer products [21].

2.2.4 Recent developments

Interest in new and improved batteries remains strong today. The demand for versatile, clean, high-power energy sources grows as electronics becomes an increasingly essential part of both consumer and industrial products. To date, the results of the battery industry's development efforts have been most evident in the dramatic improvements in existing battery types. However, three new battery types, using different materials and technology, are beginning to find application.

Batteries using lithium metal offer the combination of high voltage and high energy density, although at a premium price. Lithium batteries are finding increasing application in situations that require the battery to supply a low drain rate for a long period.

A long cycle life combined with a high energy density has been the goal of the nickel-hydrogen development program which has focused on spacecraft applications. Here the complex design and attendant high cost are less important than high performance. Nickel-hydrogen cells are now viable competitors to nickel-cadmium cells in this very specialized market.

Finally, the system which is currently exhibiting the greatest application in commercial products is a hybrid of the nickel-hydrogen and nickel-cadmium technologies called the nickel-metal hydride system. Here absorption of hydrogen within a metal alloy's structure provides the energy source which powers the cell [21].

2.3 Types and Characteristics of Secondary Batteries

The important characteristics of secondary or rechargeable batteries are that the charge and discharge the transformation of electric energy to chemical energy and back again to electric energy should precede nearly reversibly, should be energy efficient, and should have minimal physical changes that can limit cycle life. Chemical action, which may cause deterioration of the cell's components, loss of life, or loss of energy, should be absent, and the cell should possess the usual characteristics desired of a battery such as high specific energy, low resistance, and good performance over a wide temperature range. These requirements limit the number of materials that can be employed successfully in a rechargeable battery system [19].

2.3.1 Lead-Acid batteries

The lead-acid battery system has many of these characteristics. The charge-discharge process is essentially reversible, the system does not suffer from deleterious chemical action, and while its energy density and specific energy are low, the lead-acid battery performs reliably over a wide temperature range. A key factor for its popularity and dominant position is its low cost with good performance and cycle-life.

The automotive Starting, Lighting and Ignition (SLI) battery is by far the most popular and the one in widest use. Most significant of the advances in SLI battery design are the use of lighter-weight plastic containers, the improvement in shelf life, the “dry-charge” process, and the “maintenance- free” design. The latter, using calcium-lead or low-antimony grids, has greatly reduced water loss during charging (minimizing the need to add water) and has reduced the self-discharge rate so that batteries can be shipped or stored in a wet, charged state for relatively long periods.

The lead-acid industrial storage batteries are generally larger than the SLI batteries, with a stronger, higher-quality construction. Applications of the industrial batteries fall in several categories. The motive power traction types are used in materials-handling trucks, tractors, mining vehicles, and, to a limited extent, golf carts and personnel carriers, although the majority in use are automotive-type batteries. A second category is diesel locomotive engine starting and the rapid-transit batteries, replacing the nickel-iron battery in the latter application.

Significant advances are the use of lighter-weight plastic containers in place of the hard-rubber containers, better seals, and changes in the tubular positive-plate designs. Another category is stationary service: telecommunications systems, electric utilities for operating power distribution controls, emergency and standby power systems, uninterruptible power systems (UPS), and in railroads, signaling and car power systems.

The industrial batteries use three different types of positive plates: tubular and pasted flat plates for motive power, diesel engine cranking, and stationary applications, and Plante' designs, forming the active materials from pure lead, mainly in the stationary batteries. The flat-plate batteries use either lead-antimony or lead-calcium grid alloys. A relatively recent development for the telephone industry has been the "round cell", designed for trouble-free long-life service. This battery uses plates, conical in shape with pure lead grids, which are stacked one above the other in a cylindrical cell container, rather than the normal prismatic structure with flat, parallel plates.

An important development in lead-acid battery technology is the Valve-Regulated Lead- Acid battery (VRLA). These batteries operate on the principle of oxygen recombination, using a "starved" or immobilized electrolyte. The oxygen generated at the positive electrode during charge can, in these battery designs, diffuse to the negative electrode, where it can react, in the presence of sulfuric acid, with the freshly formed lead. The

VRLA design reduces gas emission by over 95% as the generation of hydrogen is also suppressed. Oxygen recombination is facilitated by the use of a pressure-relief valve, which is closed during normal operation. When pressure builds up, the valve opens at a predetermined value, venting the gases. The valve reseals before the cell pressure decreases to atmospheric pressure. The VRLA battery is now used in about 70% of the telecommunication batteries and in about 80% of the uninterrupted power source (UPS) applications.

Lead-acid batteries are also used in other types of applications, such as in submarine service, reserve power in marine applications, and in areas where engine-generators cannot be used, such as indoors and in mining equipment. New applications, to take advantage of the cost effectiveness of this battery, include load leveling for utilities and solar photovoltaic systems. These applications will require improvements in the energy and power density of the lead-acid battery [19].

2.3.2 Alkaline secondary batteries

Most of the other conventional types of secondary batteries use an aqueous alkaline solution (KOH or NaOH) as the electrolyte. Electrode materials are less reactive with alkaline electrolytes than with acid electrolytes. Furthermore, the charge-discharge mechanism in the alkaline electrolyte involves only the transport of oxygen or hydroxy ions from one electrode to the other; hence the composition or concentration of the electrolyte does not change during charge and discharge.

Nickel-Cadmium batteries: The nickel-cadmium secondary battery is the most popular alkaline secondary battery and is available in several cell designs and in a wide range of sizes. The original cell design used the pocket-plate construction. The vented pocket-type cells are very rugged and can withstand both electrical and mechanical abuse. They have very long lives and require little maintenance beyond occasional topping with water. This type of battery is used in heavy-duty industrial applications, such as materials-handling trucks, mining vehicles, railway signaling, emergency or standby power, and diesel engine starting. The sintered-plate construction is a more recent development, having higher energy density. It gives better performance than the pocket-plate type at high discharge rates and low temperatures but is more expensive. It is used in applications, such as aircraft engine starting and communications and electronics equipment, where the lighter weight and superior performance are required. Higher energy and power densities can be obtained by using nickel foam, nickel fiber, or plastic-bonded (pressed-plate) electrodes. The sealed cell is a third design. It uses an oxygen-recombination feature similar to the one used in electrolyte lead acid batteries to prevent the buildup of pressure caused by gassing during charge. Electrolyte cells are available in prismatic, button, and cylindrical configurations and are used in consumer and small industrial applications.

Nickel-Iron batteries: It was used in materials-handling trucks, mining and underground vehicles, railroad and rapid-transit cars, and in stationary applications. The main advantages of the nickel-iron battery,

with major cell components of nickel-plated steel, are extremely rugged construction, long life, and durability. Its limitations, namely, low specific energy, poor charge retention, and poor low-temperature performance, and its high cost of manufacture compared with the lead-acid battery led to a decline in usage.

Silver Oxide batteries: The silver-zinc (zinc / silver oxide) battery is noted for its high density, low internal resistance desirable for high-rate discharge, and a flat second discharge plateau. This battery system is useful in applications where high energy density is a prime requisite, such as electronic news gathering equipment, submarine and training target propulsion, and other military and space uses. It is not employed for general storage battery applications because its cost is high, its cycle life and activated life are limited, and its performance at low temperatures falls off more markedly than with other secondary battery systems. The silver-cadmium (cadmium/ silver oxide) battery has significantly a longer life cycle and better low-temperature performance than the silver-zinc battery but is inferior in these characteristics compared with the nickel-cadmium battery. Its energy density, too, is between that of the nickel-cadmium and the silver-zinc batteries. The battery is also very expensive, as it uses two of the most costly electrode materials. As a result, the silver-cadmium battery was never developed commercially but is used in special applications, such as nonmagnetic batteries and space applications. Other silver battery systems, such as silver-hydrogen and silver-metal hydride

couples, have been the subject of development activity but have not reached commercial viability.

Nickel-Zinc batteries: The nickel-zinc (zinc /nickel oxide) battery has characteristics midway between those of the nickel-cadmium and the silver-zinc battery systems. Its energy density is about twice that of the nickel-cadmium battery, but the life cycle, previously, has been limited due to the tendency of the zinc electrode toward shape change which reduces capacity and dendrite formations, which cause internal short-circuiting. Recent development work has extended the life cycle of nickel-zinc batteries through the use of additives in the negative electrode in conjunction with the use of a reduced concentration of KOH to repress zinc solubility in the electrolyte. Both of these modifications have extended the life cycle of this system so that it is being now marketed for use in electric bicycles, scooters and trolling motors.

Hydrogen Electrode batteries: Another secondary battery system uses hydrogen for the active negative material (with a fuel-cell-type electrode) and a conventional positive electrode, such as nickel oxide. These batteries are being used exclusively for the aerospace programs which require long cycle life at low depth of discharge. The high cost of these batteries is a disadvantage which limits their application.

The advantage of this battery is that its specific energy and energy density are significantly higher than that of the nickel-cadmium battery. The sealed nickel-metal hydride batteries, manufactured in small prismatic

and cylindrical cells, are being used for portable electronic applications and are being employed for other applications including hybrid electric vehicles. Larger sizes are finding use in electric vehicles.

Zinc/Manganese Dioxide batteries: Its major advantage is a higher capacity than the conventional secondary batteries and a lower initial cost, but its life cycle and capability rate are limited [19].

2.4 Why we Need Batteries Getting Unplugged: Portable Energy and Long-Term Energy Storage.

We use electrical energy to power most of the devices, equipment, appliances, gadgets, and tools we use every day. This means we have two basic needs with respect to electrical energy: generation and storage.

The electricity in the distribution grid is generated by converting heat and kinetic energy into electrical energy.

Using the electricity that is distributed through the electrical grid requires stationary outlets connected to the electrical grid distribution system. This limits the use of devices and equipment to locations that are served by the electrical distribution grid. It also limits their portability to the length of the power cords that convey the electricity from the grid to the device or equipment.

In cases where connecting to the electric distribution grid through wall outlets is inconvenient, such as with devices that are intended to be mobile and not tied down by an electrical cord or not feasible because the

location of the equipment is far from the electrical grid, other means of providing electrical energy become necessary. This is where batteries come into play.

There are two basic reasons to store energy: (1) the energy generated needs to be available for use at a later time, or (2) you want to carry energy with you. Examples of the former include storing energy generated by the wind or sun for use when the wind is not blowing or the sun is not shining. Examples of the latter are portable applications, like cell phones, pacemakers, and electric vehicles [19].

2.5 The Many Uses of Batteries

Secondary or rechargeable batteries are widely used in many applications. The most familiar are starting, lighting, and ignition (SLI) automotive applications; industrial truck materials handling equipment; and emergency and standby power. Small, secondary batteries are also used in increasing numbers to power portable devices such as tools, toys, lighting, and photographic, radio, cell phones, laptop computers, MP3 players, cameras, and calculators and more significantly, consumer electronic devices (computers, camcorders, cellular phones). More recently, secondary batteries have received renewed interest as a power source for electric and hybrid electric vehicles [19].

We can't list every single application that uses batteries. The numbers of applications and battery types are just too large. What follows

is a brief survey of some of the applications, especially those that require some specialized batteries:

- Portable consumer devices (mobile power for an unplugged society, power tools) such as laptop computers, electronic games, battery-operated toys, and flashlights.
- Medical devices: life-sustaining and life-enhancing medical devices, including pacemakers, defibrillators, hearing aids, pain management devices, and drug pumps.
- Electric vehicles, including hybrids vehicles. Rechargeable batteries are used for automobile starters, portable consumer devices, light vehicles (such as motorized wheelchairs, golf carts, electric bicycles, and electric forklifts), tools and uninterruptible power supplies.
- Large-scale energy storage.
- Space Satellites require battery power when they enter the Earth shadow and their solar panels do not function.
- Military batteries: Like space batteries, military batteries need to be designed with long life and high reliability in mind. They could also experience a wide range of environmental conditions [22].

The lead-acid battery is designed in many configurations, as listed in table (2.1), from small sealed cells to large cells.

Table (2.1): Major characteristics and applications of secondary batteries [19].

System	Characteristics	Applications
Lead-Acid (H_2SO_4):		
Automotive	Popular, low-cost secondary battery, moderate specific-energy, high-rate, and low-temperature performance; maintenance-free designs	Automotive SLI, golf carts, lawn mowers, tractors, aircraft, marine
Traction (motive power)	Designed for deep 6–9 h discharge, cycling service	Industrial trucks, materials handling, electric and hybrid electric vehicles, special types for submarine power
Stationary	Designed for standby float service, long life, VRLA designs	Emergency power, utilities, telephone, UPS, load leveling, energy storage, emergency lighting
Portable	Sealed, maintenance-free, low cost, good float capability, moderate cycle life	Portable tools, small appliances and devices, TV and portable electronic equipment
Nickel-Cadmium (NiCd):		
Industrial and fiber nickel cadmium (FNC)	Good high-rate, low-temperature capability, flat voltage, excellent cycle life	Aircraft batteries, industrial and emergency power applications, communication equipment
Portable	Sealed, maintenance-free, good high-rate low-temperature performance, excellent cycle life	Railroad equipment, consumer electronics, portable tools, pagers, appliances, and photographic equipment, standby power, memory backup
Nickel-metal hydride (NiMH)	Sealed, maintenance-free, higher capacity than nickel-cadmium batteries	Consumer electronics and other portable applications; electric and hybrid electric vehicles
Nickel-iron (NiFe)	Durable, rugged construction, long life, low specific energy	Materials handling, stationary applications, railroad cars

System	Characteristics	Applications
Nickel-zinc (NiZn)	High specific energy, extended cycle life and rate capability	Bicycles, scooters, trolling motors
Silver-zinc (AgZn)	Highest specific energy, very good high rate capability, low cycle life, high cost	Lightweight portable electronic and other equipment; training targets, drones, submarines, other military equipment, launch vehicles and space probes
Silver-cadmium (Ag-Cd)	High specific energy, good charge retention, moderate cycle life, high cost	Portable equipment requiring a lightweight, high-capacity battery; space satellites
Nickel-hydrogen (Ni-H ₂)	Long cycle life under shallow discharge, long life	Primarily for aerospace applications such as LEO and GEO satellites

2.6 Battery Performance

The battery chemistry is often the focus of performance discussions, and certainly the electrode materials play a dominant role in determining the battery performance characteristics. Yet, there is more to it than the reactivity of the electrode materials in the battery. The rate at which energy is released is modulated by practical factors associated with the battery design and selection of other materials used in the battery construction, including the type and amount of electrolyte [22].

2.6.1 Potential or voltage

The electrochemical potential, or voltage (in volts, or V), is the amount of work or energy (in joules, or J) that can be done by a unit of electrical charge (in coulombs) [22].

2.6.2 Current

The electric current is a flow of electric charge through a medium. This charge is typically carried by moving electrons in a conductor such as wire. The SI unit for measuring the rate of flow of electric charge is the ampere, which is charge flowing through some surface at the rate of one coulomb per second. The electric current is measured using an ammeter [22].

2.6.3 Resistance

Electrons or currents traveling through a material experience a resistance against their movement. The current, that a potential, or voltage, is capable of producing is limited by the resistance in the circuit according to Ohm's law. According to Ohm's law, the voltage difference between the two points is directly proportional to the current between those two points in a conducting medium and inversely proportional to the resistance of the conductor:

$$v = i * R \quad (2.1)$$

Where, i is the current (A), v is the voltage difference (V), and R is the resistance (ohms). The unit of resistance is the ohm. The unit may be written as ohm or Ω . A manufactured electrical component with a known resistance is a resistor [22].

2.6.4 Capacity

The quantity of electricity delivered by a battery is its capacity and measured in units of ampere-hours or amp-hours (Ah). It quantifies how long a battery will last in hours at some discharge current in amps. This is an easy calculation to make when a battery is discharged at a constant current. The discharge current in amperes (A) is multiplied by discharge time in hours (h) to give capacity in ampere-hours:

$$\text{Capacity (Ah)} = \text{current (A)} \times \text{time (h)} \quad (2.2)$$

A battery that lasted 10 h when discharged with a constant current of 0.25 A delivered a capacity of 2.5 Ah. Alternatively, if you know the capacity of the battery and you want to know how long it will last, and then divide the capacity in Ah by the discharge current in A. For example: A battery rated at 1.5 Ah when discharged at a constant current of 0.3 A is expected to provide 5 hours of use ($1.5 \text{ Ah} / 0.3 \text{ A} = 5 \text{ h}$).

Many applications do not drain batteries using a constant current, though. How the battery is discharged will affect how long it lasts and the discharge voltage figure (2.2). The current is probably not constant throughout discharge for batteries discharged through a resistance or using a power load, so simply multiplying current by time will yield a wrong answer.

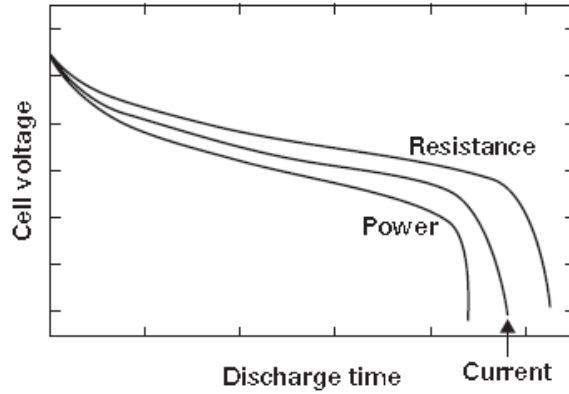


Figure (2.2): How different discharge loads affect battery discharge voltage [22].

The capacity is calculated by integrating the current produced by a battery over the discharge time [22].

2.6.5 Power

The electrical energy is the amount of work done to move coulombs of charge through volts potential difference. The electrical power is the how much energy is delivered per period of time. It can be calculated by multiplying the potential or voltage by the current:

$$P = i \times v \quad [w] \quad (2.3)$$

Where P is the power with units in watts (W), i is the current in (A) and v is the potential or voltage in (V). Other ways to write an equation for electrical power can be done by substituting E from Ohm's law [22]:

$$P = i^2 \times R \quad \text{or} \quad = \frac{V^2}{R} \quad (2.4)$$

2.6.6 Energy

The energy delivered by a battery is measured in units of watt-hours (Wh). It quantifies how long a battery will last in hours at some discharge

power load in watts. Just as it is for calculating capacity with the constant current case just described, the energy delivered by a battery is easy to calculate when it is discharged with a constant power load. The power in watts (W) is multiplied by discharge time in hours (h) to give energy in watt-hours:

$$\text{Energy (Wh)} = \text{power (W)} \times \text{time (h)} \quad (2.5)$$

Again, if the power load is not constant throughout discharge, the energy is determined using the following equation [22]:

$$\text{Energy (Wh)} = \int_0^t P \, dt \quad (2.6)$$

2.7 General Battery Concepts

This section describes some common terms and definitions that are often used in describing batteries or in defining battery applications [21].

2.7.1 Batteries cells

In casual usage, a battery is anything that supplies electrical power through chemical reactions. However, when discussing battery design it is important to understand the distinction between batteries and cells. Cells are the basic electrochemical building blocks. Batteries consist of one or more cells.

Table (2.2): Cell voltage for different battery types

Battery type	Cell voltage
Lead-acid	2
Nickel-cadmium	1.3
Iron Electrode	1.2

A battery can be a single cell provided with terminations and insulation and considered ready for use. More often, a battery is an assembly of several cells connected in series or parallel and with electrical output terminals. In many batteries, such as those used in automobiles, all inter cell connections are made internally. The number of cells within the battery may not even be apparent from the finished package [21].

2.7.2 Cell and battery voltage

The voltage performance characteristics of a battery scale directly with the number of cells in the battery. This means that the voltage obtained on discharge or the voltage required on charge is usually just the appropriate single cell voltage multiplied by the number of cells in the battery. If a 2V electrolyte -lead cell requires a charge voltage of 2.4 V, a 6V (3 cells) battery requires a charge voltage of $3 \times 2.4 \text{ V}$ or 7.2 V, a 12 V (6 cells) battery will require 14.4 V, etc. In discussions of battery output and charging, voltages are often presented on a per cell basis. These normalized values can then be converted to the appropriate voltages for a specific battery by multiplying by the number of cells in the battery [21].

2.7.3 Cell and battery capacity

While the voltage of a cell is determined by its chemistry, cell capacity is infinitely variable. The capacity of a cell is essentially the

number of electrons that can be obtained from it. Since current is the number of electrons per unit time, cell capacity is the integration of current supplied by the cell over time. Cell capacity is normally measured in ampere-hours.

The capacity of a cell is generally determined by the quantity of active materials included in it. Individual cells range in capacity from fractions of an ampere-hour to many thousands of ampere-hours. Cell capacity is usually directly related to cell volume, i.e. bigger cells usually mean higher capacities.

Balancing the amounts of positive active material, negative active material, and electrolyte in a cell is one of the cell designer's tools. Adjusting the relative quantities of these three items allows the cell to be tailored for a specific application [21].

2.7.4 Connecting cells to form a battery: series or parallel

Every cell has a positive and a negative terminal. The terminals may be specific sites such as the positive and negative tabs on the electrolyte - lead cell or may be more general locations such as the positive cover and negative can on the electrolyte nickel-cadmium cell. In connecting multiple cells into batteries, there are two options: the positive from one cell may be linked to the negative of the succeeding cell (series connection) or the cell positive terminals may be linked together and the negative terminals may be linked together (parallel connection).

Series connection means that the voltages of the connected cells are added while the capacity remains constant. So the battery voltage becomes the cell voltage multiplied by the number of cells and the battery capacity is the capacity of the individual cell. Thus, to obtain a nominal 12 volt DC output, a battery might consist of 10 nickel cadmium cells in series or 6 electrolyte lead cells. Series strings are the most common means of connecting cells.

Batteries employing parallel connections are used when a higher capacity than that provided by the individual cell is needed. When possible, it is ordinarily less costly and more reliable to use a cell with a higher capacity than it is to connect multiple cells in parallel. However, situations do arise where larger cells are either unavailable or unsuitable, so a battery consisting of parallel strings of cells is used. In such cases, the battery voltage is that of the individual cell while the battery capacity is the individual cell capacity multiplied by the number of cells in the battery. Parallel connection of nickel-cadmium cells requires special charging considerations [21].

2.7.5 Cell components

The cell, the basic unit of the battery, has four main components as sketched in figure (2.3). These are:

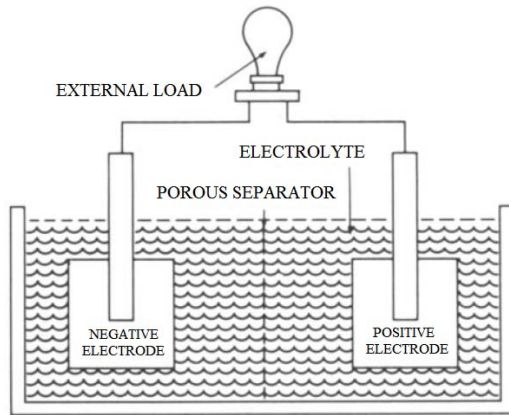


Figure (2.3): Cell essentials [21].

The negative electrode (the anode during discharge reactions) supplies electrons to the external circuit when oxidized during discharge. For the nickel-cadmium battery, the active material for the negative electrode is metallic cadmium, while metallic lead fills the same function for lead batteries.

The positive electrode (the cathode during discharge reactions) accepts the electrons from the external circuit when reduced during discharge. The active materials for the positive electrode are nickel oxyhydroxide (NiOOH) and lead dioxide (PbO_2) for the nickel-cadmium and electrolyte lead batteries respectively. Because of their typical shapes, the electrodes are commonly referred to as the positive or negative plates. Both terms, electrode and plate, normally encompass the active material and any substrate used for support and for current collection.

The electrolyte completes the circuit internally by furnishing the ions for conductance between the positive and negative electrodes. The electrolyte can be either an alkaline solution which supplies negative ions

(OH^-) or an acidic solution which provides positive ions (H^+) to conduct current. Charge flows from positive to negative electrode in two manners. In an alkaline electrolyte, negative ions are created at the positive electrode and absorbed at the negative. In an acidic electrolyte, positive ions are created at the negative electrode and absorbed at the positive one. In either case, the effective flow of the current is the same. The nickel-cadmium couple uses an alkaline electrolyte a dilute mixture of potassium hydroxide (KOH) and water. The lead battery uses an acidic electrolyte a dilute mixture of sulfuric acid (H_2SO_4) and water. In lead batteries, the sulfuric acid is consumed as the cell discharges. Thus, the acid concentration is a measure of the state of charge of the cell. This concentration (or specific gravity) variation is the operating principle behind the hydrometers used to indicate state of charge for flooded lead-acid batteries. The electrolyte in nickel cadmium batteries acts only to convey ions; it does not participate in the reaction. As a result, monitoring the state of charge through electrolyte concentration changes is not possible for nickel batteries.

A separator is normally used to electrically isolate the positive and negative electrodes. If the two electrodes make direct electrical contact, they form an internal short-circuit, discharging the battery and rendering it useless. Strictly speaking, the separator is not necessary since physical isolation can provide electrical isolation. However, all commercial batteries use a separator to allow closer electrode to space without creating internal shorts. The type of separator used varies by cell type. Electrolyte nickel-cadmium cells use a porous plastic separator while advanced versions of

the electrolyte lead cell use a porous glass-fiber separator. In these examples, both nickel cadmium and electrolyte lead, the separator also absorbs electrolyte, limiting the amount of free electrolyte found in the cell and keeping the electrolyte next to the electrode.

These components are then housed in a cell jar or can. Depending on the type of battery, a variety of other components may be used to package the cell, to support the various components, or to provide for easy electrical connection. But only the four components listed above are essential to cell function [21].

2.8 Voltage and Discharge Profiles

The discharge curves of the conventional secondary battery systems, at the C/5 rate, are compared in figure (2.4). The lead-acid battery has the highest cell voltage of the aqueous systems. The average voltage of the alkaline systems ranges from about 1.65 V for the nickel zinc system to about 1.1 V. At the C/5 discharge rate at 20°C there is relatively little difference in the shape of the discharge curve for the various designs of a given system. However, at higher discharge rates and at lower temperatures, these differences could be significant, depending mainly on the internal resistance of the cell. Most of the conventional rechargeable battery systems have a flat discharge profile, except for the silver oxide systems, which show the double plateau due to the two-stage discharge of the silver oxide electrode, and the rechargeable zinc /manganese dioxide battery. The discharge curve of a lithium ion battery, the carbon/lithiated

cobalt oxide system, is shown for comparison. The cell voltages of the lithium ion batteries are higher than those of the conventional aqueous cells because of the characteristics of these systems. The discharge profile of the lithium ion batteries is usually not as flat due to the lower conductivity of the non-aqueous electrolytes that must be used and to the thermodynamics of intercalation electrode reactions. The average discharge voltage for a lithium ion cell is 3.6 V, which allows one unit to replace three Nicad or NiMH cells in a battery configuration [19].

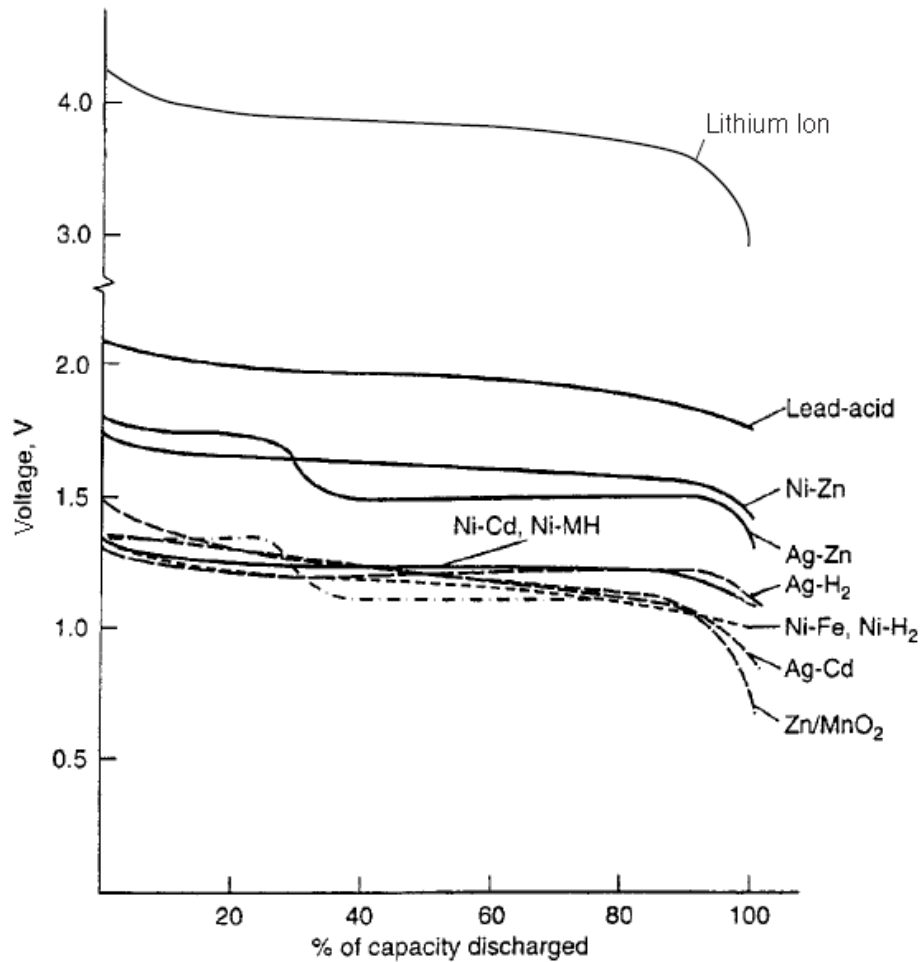


Figure (2.4): Discharge profiles of conventional secondary battery systems and rechargeable lithium ion battery at approximately $C/5$ discharge rates [19].

2.9 Effect of Discharge Rate on Performance

The effects of the discharge rate on the performance of these secondary battery systems are compared again in figure (2.5). This figure shows that hours of service each battery type (unitized to 1-kg battery weight) will deliver at various power (discharge current * midpoint voltage) levels. The higher slope is indicative of superior retention of capacity with increasing discharge load. The specific energy can be calculated by the following equation [19].

Specific Energy = specific power \times hours of service or

$$Wh / kg = W / kg \times h = \frac{A \times V \times h}{kg} \quad (2.7)$$

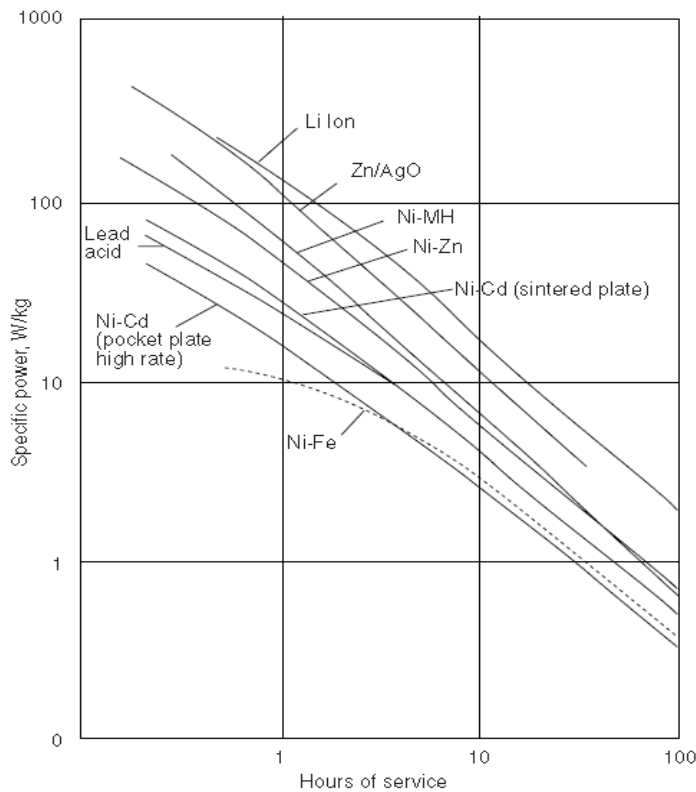


Figure (2.5): Comparison of performance of secondary battery systems at 20°C [19].

2.10 Effect of Temperature

The performance of the various secondary batteries over a wide temperature range is shown in figure (2.6) on a gravimetric basis. In this figure, the specific energy for each battery system is plotted from -40 to 60°C at about the $C/5$ discharge rate. The lithium ion system has the highest energy density at -20°C . The sintered-plate nickel-cadmium and nickel-metal hydride batteries show higher percentage retention. In general the low-temperature performance of the alkaline batteries is better than the performance of the lead-acid batteries, again with the exception of the nickel-iron system. The lead-acid system shows better characteristics at the higher temperatures. These data are necessarily generalized for the purposes of comparison and present each system under favorable discharge conditions. The performance is strongly influenced by the specific discharge conditions [19].

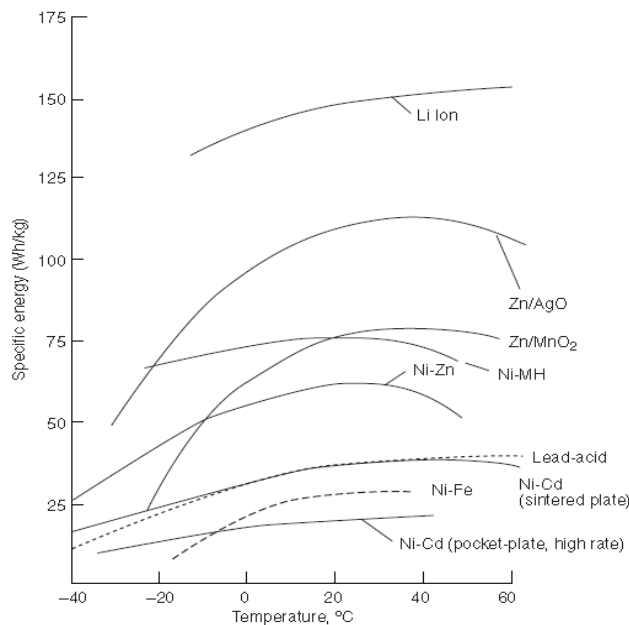


Figure (2.6): Effect of temperature on specific energy of secondary battery systems at approximately $C/5$ discharge rates [19].

2.11 Charge Retention (Self-Discharge)

The charge retention of most of the conventional secondary batteries is poor. Normally, secondary batteries are recharged on a periodic basis or maintained on “float” charge if they are to be in a state of readiness. Most alkaline secondary batteries, especially the nickel oxide batteries, can be stored for long periods of time even in a discharged state without permanent damage and can be recharged when required for use. The lead-acid batteries, however, cannot be stored in a discharged state because sulfation of the plates, which is detrimental to battery performance, will occur. Figure (2.7) shows the charge retention properties of several different secondary battery systems. These data are also generalized for the purpose of comparison. There are wide variations of performance depending on design and many other factors, with the variability increasing with increasing storage temperature. Typically, the rate of loss of capacity decreases with increasing storage time. The silver secondary batteries, the Zn/MnO₂ rechargeable battery, and lithium-ion systems have the best charge retention characteristics of the secondary battery systems with typical lithium ion batteries; self-discharge is typically 2% per month at ambient temperature. Low-rate silver cells may lose as little as 10 to 20% per year, but the loss with high-rate cells with large surface areas could be 5 to 10 times higher. The vented pocket- and sintered plate nickel-cadmium batteries and the nickel-zinc systems are next; the sealed cells and the nickel-iron batteries have the poorest charge retention properties of the alkaline systems.

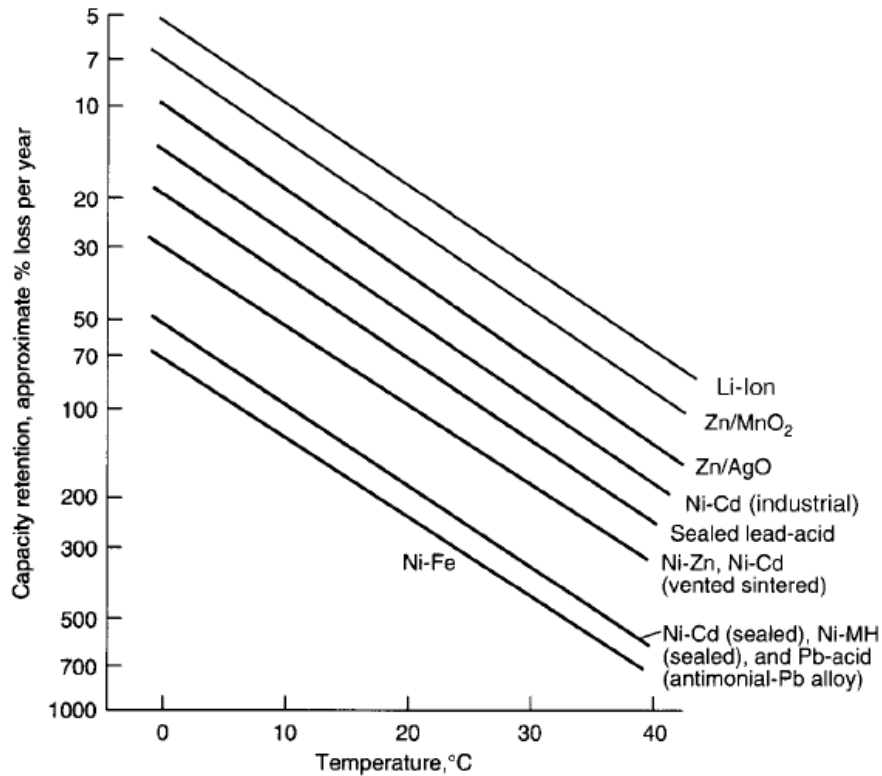


Figure (2.7): Capacity retention of secondary battery systems [19].

The charge retention of the lead-acid batteries is dependent on the design, electrolyte concentration, and formulation of the grid alloy as well as other factors. The charge retention of the standard automotive SLI batteries using the standard antimonial-lead grid is poor and these batteries have little capacity remaining after six-month' storage at room temperature. The low antimonial-lead designs and the maintenance-free batteries have much better charge retention with losses on the order of 20 to 40% per year [19].

2.12 Life

The depth of discharge (DOD), for example, as illustrated in figure (2.7) and the charging regime strongly influences the battery's life. Of the

conventional secondary systems, the nickel-iron and the vented pocket-type nickel cadmium batteries are best with regard to life cycle and total lifetime. The nickel-hydrogen battery, developed mainly for aerospace applications, has demonstrated very long life cycle under shallow depth of discharge. The lead-acid batteries do not match the performance of the best alkaline batteries. The pasted cells have the shortest life of the lead-acid cells; the best life cycle is obtained with the tubular design, and the Plante' design has the best lifetime.

One of the disadvantages of using zinc, lithium, and other metals with high negative standard potentials in rechargeable batteries is the difficulty of successful recharging and obtaining good cycle and calendar lives. The nickel-zinc battery has recently been improved to provide extended life cycle as seen in figure (2.8). The lithium-ion system, however, has also been shown to have a good life cycle [19].

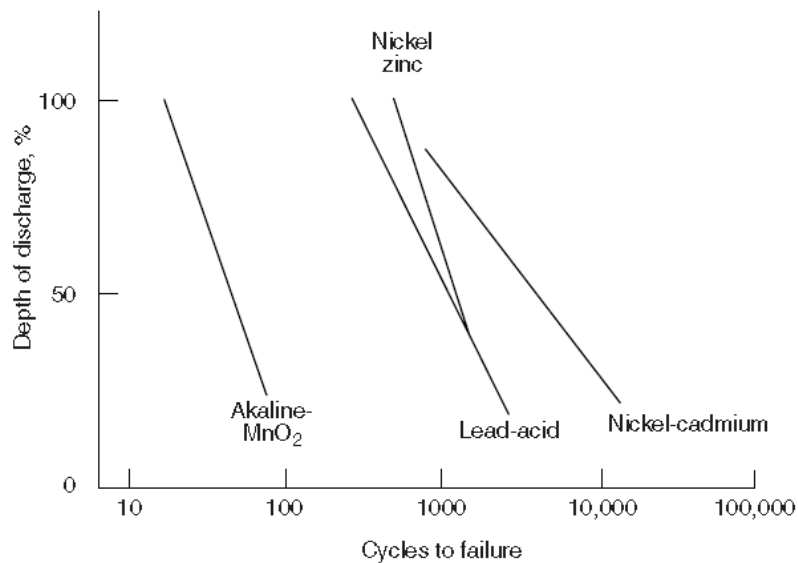


Figure (2.8): Effect of depth of discharge on cycle life of secondary battery systems [19].

2.13 Charge Characteristics

The typical charge curves of the various secondary aqueous-systems at normal constant current charge rates are shown in figure (2.9). Most of the batteries can be charged under constant-current conditions, which is usually the preferred method of charging, although, in practice, constant-voltage or modified constant-voltage methods are used. Some of the sealed batteries, however, may not be charged by constant-voltage methods because of the possibility of thermal runaway. Generally, the vented nickel-cadmium battery has the most favorable charge properties and can be charged by a number of methods and in a short time.

These batteries can be charged over a wide temperature range and can be overcharged to some degree without damage. Nickel-iron batteries, sealed nickel-cadmium batteries, and sealed nickel /metal hydride batteries have good charge characteristics, but the temperature range is narrower for these systems. The nickel /metal hydride battery is more sensitive to overcharge, and charge control to prevent overheating is advisable. The lead-acid battery also has good charge characteristics, but care must be considered to prevent excessive overcharging.

The zinc /manganese dioxide and zinc / silver oxide batteries are most sensitive with regard to charging; overcharging is very detrimental to battery life. Figure (2.10) shows typical constant current–constant voltage charging characteristics of an 18650 lithium ion battery.

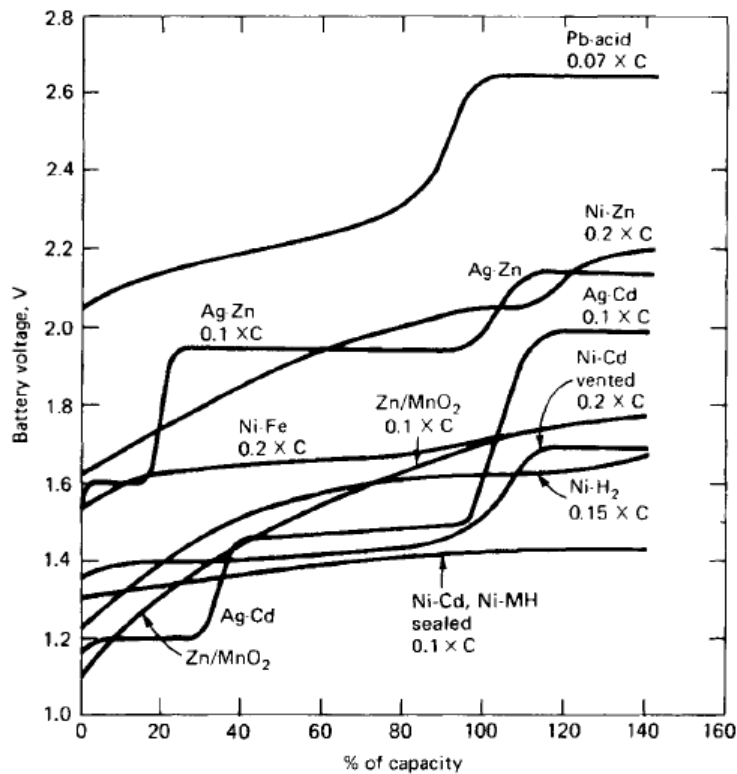


Figure (2.9): Typical charge characteristics of secondary battery systems, constant-current charge at 20°C [19].

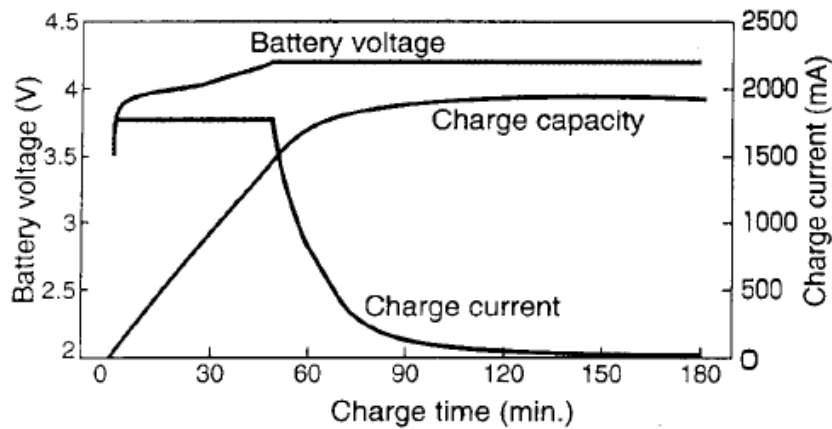


Figure (2.10): Charging characteristics of a typical cylindrical 18650 lithium ion battery at 20°C. Battery is charged at constant current of 1.8 Amps (nominal C rate) to 4.2 Volts followed by a taper charge at this voltage for a total time of 2 hours [19].

Many manufacturers are now recommending “fast” charge methods to meet consumer and application demand for recharging in less than 2 to 3

h. These methods require control to cut off the charge before an excessive rise in gassing, pressure, or temperature occurs. These could cause venting or a more serious safety hazard, or they could result in a deleterious effect on the battery's performance or life. Pulse charging is also being employed with some systems to provide higher charge rates.

In general, control techniques are useful for recharging most secondary batteries. They can be employed in several ways: to prevent overcharging, to facilitate "fast" charging, to sense when a potentially deleterious or unsafe condition may arise and cut off the charge or reduce the charging rate to safe levels. Similarly, discharge controls are also being used to maintain cell balance and to prevent over discharge.

Another approach is the "smart" battery. These batteries incorporate features. Like:

1. To control the charge so that the battery can be charged optimally and safely.
2. For fuel gauging to indicate the remaining charge left in the battery.
3. Safety devices to alert the user to unsafe or undesirable operation or to cut off the battery from the circuit when these occur [19].

2.14 Cost

The cost of a secondary battery may be evaluated on several bases, depending on the mode of operation. The initial cost is one of the bases for

consideration. Other factors are the number of charge-discharge cycles that are available, or the number delivered in an application, during a battery's lifetime, or the cost determined on a dollar-per-cycle or dollar-per total-kilowatt-hour basis. The cost of charging, maintenance, and associated equipment may also have to be considered in this evaluation. In an emergency standby service or SLI-type application, the important factors may be the calendar life of the battery (rather than as cycle life) and the cost is evaluated on a dollar-per-operating-year basis [19].

2.15 General Information for Selection of Batteries for Photovoltaic Systems

At night and during continuing overcast days, the energy stored in the battery subsystem can be depleted. When the battery voltage drops below a predetermined value, the auxiliary DC power supply cuts in to carry the load and recharges the battery.

In the simplest stand-alone system, the only components which may appear to be needed are the solar module, the battery and the DC load. The battery is sized to accept the highest power output from the solar panel without overcharge damage.

In most cases, however, insulations are not that predictable, and the array output varies over such a wide range that charge regulators are needed and recommended to control charging current. A low voltage disconnect is also recommended to protect the battery from deep discharge.

The battery stores excessive energy generated by the solar array during bright days of high insulations and discharges this stored energy back into the load at night or on overcast days. For a continuous power output capability, the battery is a very essential component. Batteries can be selected to give a higher peak output than the solar array to provide:

- High peak energy for starting motors or engines.
- For opening and closing circuit breakers.
- For steady power output for long periods of time.

In addition, the battery can repeat these functions through many charge / discharge cycles within a wide temperature range during its long life. Correct battery selection and sizing are most important to the success of the solar photovoltaic system [23].

2.16 Key Elements in Battery Selection

Selection of the proper battery for a solar photovoltaic system requires a complete analysis of the battery discharge requirements. The kilowatt-hours of energy stored in the battery will depend upon the load requirements, the number of days of storage, the insulations patterns in the geographical area of the installation and the solar array output.

Factors in sizing the battery are operating temperature variations, environmental temperature extremes and weekly / daily use age, the voltage regulator design, and the efficiency of the inverter.

The energy required to charge a battery will be the sum of the previous discharge energy output and the energy expended as work and excessive heat during the recharge. Longer charge times and lower charge currents tend to increase charge efficiency.

In lead-acid batteries, turn around energy efficiency can approach 85 percent. Shorter charge times and higher charge currents will sacrifice energy efficiency and battery life. Charge time and power available from the solar array must, therefore, be considered in selecting the battery type and size.

The analysis of the application requirements must include as a minimum the review of the following performance parameters:

- The minimum and maximum operating voltage of electronic equipment, battery and components of the load: i.e., the voltage window.
- The power cycle including all sequences of charge and discharge.
- The power output profile of the photovoltaic panel predicted at the site under the prevailing insulations patterns.
- Seasonal and environmental variations.
- Availability and frequency of maintenance.

A corresponding study of the photovoltaic panel output must establish the sequential pattern of power output and duration expected on site for the full period of the system operation for not less than one year.

Seasonal (and yearly) variations may show, as in figure (2.11), that excessive power may be expected during high insulations months but that, in some months, the power required by the anticipated load can exceed power available from the solar panel. Unbalance of power requirements of this kind must be corrected by increasing the panel size, by power conservation in the load, or by use of an auxiliary power source. From the analysis above considerations must establish:

- The size of the photovoltaic panel/array required to provide the energy for the load and for recharging the battery subsystem.
- The recharging time and power available.
- The size of the battery required for energy storage, i.e., number of cells in series and parallel, the individual cell capacity, the subsystem storage energy in kilowatt-hours and capacity in ampere-hours.

Battery cell type, plate and separator designs must then be selected in consultation with the sales engineers representing the battery supplier. Cell design must match the highest charge and discharge rates and the extremes in operating temperature predicted for the battery under conditions at each site. The battery supplier must provide operating voltage data to assure the system designer that the required capacities are delivered within the specified acceptable voltage range, over the expected range of environmental conditions.

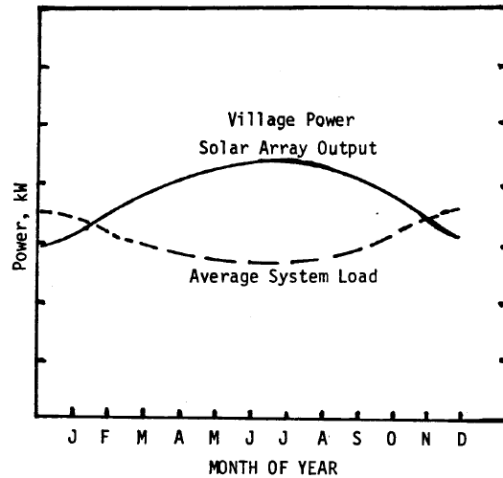


Figure (2.11): Solar array system load power requirement [23].

For each load period in the duty cycle, the battery supplier can select from the product line cells with the most desirable number of plates, plate thickness, active material density, plate grid design, specific gravity and separator system to control the cell and battery performance.

The battery maintenance must also be considered. Visiting remote installations for the purpose of the system or battery maintenance can require a substantial transportation and labor cost. Maintenance-free or reduced maintenance batteries are attractive in these applications if other performance attributes are also demonstrated. Replacement of water loss from overcharge electrolysis of battery electrolyte is the major task of maintenance in vented batteries, both lead-acid and nickel-cadmium. Other tasks keep inter cell and inter-row battery connections tight and the battery clean and dry. Maintenance can be scheduled from knowledge of the overcharge in the duty cycle and the number of cycles per week.

The battery operating life in the solar PV system is a function of the operating temperature, the duty cycle, the depth of discharge, the charge

control and the cell design. Significantly, the higher average operating temperature decreases life and the number of available charge-discharge cycles decreases with increasing depth of discharge.

In general, longer-life batteries have a higher initial cost. Replacing a battery, especially a very large array of cells, can be a substantial element in storage battery costs. Economic studies should be made to reflect the sum of initial battery price, installation costs, operating and maintenance costs, and the cost of replacement. The overall price of a long-life battery may be less than the price of two shorter-life batteries when all factors are considered. The battery manufacturer or supplier can provide an estimate of the operating life of each battery type on the market when the operating time-temperature and duty cycles are well known [23].

Chapter Three

Lead Acid Battery

Chapter Three

Lead Acid Battery

3.1 General Characteristics of Electrolyte Lead Acid Battery

The lead-acid battery has been a successful article of commerce for over a century. Its production and use continue to grow because of new applications for battery power in energy storage, emergency power, and electric and hybrid vehicles (including off-road vehicles) and because of the increased number of vehicles for which it provides the energy for engine starting, vehicle lighting, and engine ignition (SLI). This battery system is also used extensively in telephone systems, power tools, communication devices, emergency lighting systems, and as the power source for mining and material-handling equipment. The wide use of the lead-acid battery in many designs, sizes, and system voltages is accounted for by the low price and the ease of manufacture on a local geographic basis of this battery system. The lead-acid battery is almost always the least expensive storage battery for any application, while still providing good performance and life characteristics.

The overall advantages and disadvantages of the lead-acid battery, compared with other systems, are listed in table (3.1).

Table (3.1): Major advantages and disadvantages of lead-acid batteries [19].

Advantages	Disadvantages
<ol style="list-style-type: none"> 1. Popular low-cost secondary battery—capable of manufacture on a local basis, worldwide, from low to high rates of production 2. Available in large quantities and in a variety of sizes and designs—manufactured in sizes from smaller than 1 Ah to several thousand Ampere-hours 3. Good high-rate performance —suitable for engine starting 4. Moderately good low- and high-temperature performance Electrically efficient—turnaround efficiency of over 70%, comparing discharge energy out with charge energy in 6. High cell voltage—open-circuit voltage of >2.0 V is the highest of all aqueous electrolyte battery systems 7. Good float service 8. Easy state-of-charge indication 9. Good charge retention for intermittent charge applications (if grids are made with high overvoltage alloys) 10. Available in maintenance-free designs 11. Low cost compared with other secondary batteries 12. Cell components are easily recycled 	<ol style="list-style-type: none"> 1. Relatively low cycle life (50–500 cycles) 2. Limited energy density—typically 30–40 Wh/kg 3. Long-term storage in a discharged condition can lead to irreversible polarization of electrodes (sulfation) 4. Difficult to manufacture in very small sizes (in mAh size) Hydrogen evolution in some designs can be an explosion hazard (flame arrestors are installed to prevent this hazard) 6. Stibene and arsine evolution in designs with antimony and arsenic in grid alloys can be a health hazard 7. Thermal runaway in improperly designed batteries or charging equipment 8. Positive post blister corrosion with some designs

The lead-acid battery is manufactured in a variety of sizes and designs, ranging from less than 1 to over 10,000 Ah. Table 3.2 lists many of the various types of lead-acid batteries that are available [19].

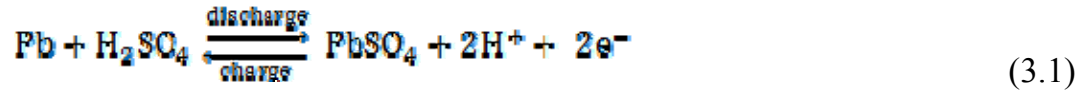
Table (3.2): Types and characteristics of lead-acid batteries [19].

Type	Construction	Typical applications
SLI (starting, lighting, ignition)	Flat-pasted plates (option: maintenance-free construction)	Automotive, marine, aircraft, diesel engines in vehicles and for stationary power
Traction	Flat-pasted plates; tubular and gauntlet plates	Industrial trucks (material handling)
Vehicular propulsion	Flat-pasted plates; tubular and gauntlet plates; also composite construction	Electric vehicles, golf carts, hybrid vehicles, mine cars, personnel carriers
Submarine	Tubular plates; flat-pasted plates	Submarines
Stationary (including energy storage types such as charge retention, solar photovoltaic)	Plante'; Manchester; tubular and gauntlet plates; flat-pasted plates; circular conical plates	Standby emergency power: telephone exchange, uninterruptible power systems (UPS), load leveling, signaling
Portable	Flat-pasted plates (gelled electrolyte, electrolyte absorbed in separator); spirally wound electrodes; tubular plates	Consumer and instrument applications: portable tools, appliances, lighting, emergency lighting, radio, TV, alarm systems

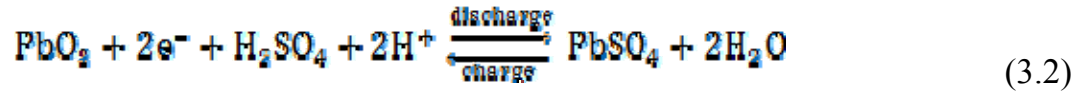
3.2 Lead Acid Chemistry

Lead (Pb), lead oxide (PbO_2), and sulfuric acid (H_2SO_4) are the negative electrode, positive electrode, and electrolyte of lead acid batteries, respectively. The negative electrode discharge reaction involves the oxidation of Pb metal to Pb ion in the +2 oxidation state (abbreviated Pb(II) or Pb^{+2}).

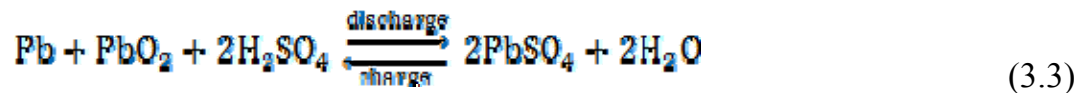
The Pb(II) so formed precipitates as PbSO_4 at the negative electrode by combining with sulfate ions from the electrolyte solution:



The positive electrode proceeds by the reduction of PbO_2 with Pb in the +4 oxidation state, Pb(IV) or Pb^{+4} , to Pb(II), which precipitates as PbSO_4 at the positive electrode:



The overall battery reaction



The discharge products of both the positive and negative electrodes are the same: PbSO_4 . The charging reactions are just the reverse. PbSO_4 is reduced to form Pb at the negative electrode and PbSO_4 is oxidized to PbO_2 at the positive electrode.

The potential for each Pb/ PbO_2 cell is nominally about 2.0 V. They are generally charged to less than 2.4 V per cell to minimize gas formation. The plates are connected in series within the battery case to boost the voltage. Common battery voltages are 6 V (three cells) and 12 V (six cells), but batteries with higher or lower voltages can be found. A higher-voltage battery can be made by connecting carefully matched, multiple batteries in series.

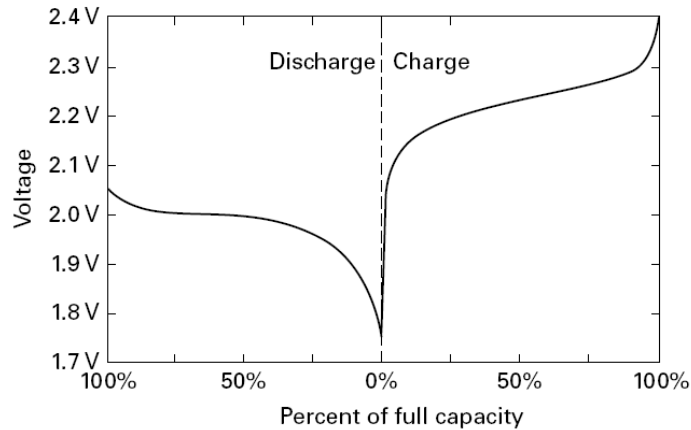


Figure (3.1): Discharge and charge voltage for a lead acid battery [22].

A 12 V battery is usually charged to no more than 14.4 V, or about 2.4 V per cell. This voltage is a trade-off between charging the battery more completely with minimizing the overcharge reactions. Minimum discharge voltages can range from 1.8 V down to about 1.2 V per cell, depending on the battery type and the application requirements. Discharge and charge voltage characteristics are shown in figure (3.1).

The change in the H_2SO_4 level during discharge is an important design consideration when specifying a starting concentration volume of electrolyte. The density of the electrolyte changes with the concentration of H_2SO_4 presents another way to monitor the state of charge of a battery, the specific gravity of the electrolyte [22].

An overview of lead acid battery attributes is given in table (3.3).

Table (3.3): Over view of lead acid battery attributes [22].

Attribute	Description
Negative active material	Lead (Pb) plates Negative electrode reaction (discharge left to right, charge right to left): $\text{Pb} \rightleftharpoons \text{Pb}^{2+} + 2\text{e}^-$
Positive active material	Lead dioxide (PbO_2) Positive electrode reaction (discharge left to right, charge right to left): $\text{PbO}_2 + 4\text{H}^+ + 2\text{e}^- \rightleftharpoons \text{Pb}^{2+} + 2\text{H}_2\text{O}$
Electrolyte	30% to 40% sulfuric acid (H_2SO_4) in water. May include SiO_2 as a gelling agent in VRLA batteries
Battery reactions (discharge left to right, charge right to left)	$\text{Pb} + \text{PbO}_2 + 2\text{H}_2\text{SO}_4 \rightleftharpoons 2\text{PbSO}_4 + 2\text{H}_2\text{O}$
Nominal cell voltage	2.0 V
Discharge voltage profile	Flat to sloped, depending on battery type and discharge load
Energy density	10 to 44 Wh kg^{-1} and 50 to 111 Wh dm^{-3}
Self-discharge	4% to 8% per month (traction) 15% to 30% per month (SLI) 2% to 3% per month (maintenance free)
Commonly available types	Prismatic 6 V, 12 V Cylindrical 2 V

3.3 Open-Circuit Voltage Characteristics

The open-circuit voltage for a battery system is a function of temperature and electrolyte concentration as expressed in the Nernst equation for the lead-acid cell.

$$E = 2.047 + \frac{RT}{F} \ln \left(\frac{\alpha_{\text{H}_2\text{SO}_4}}{\alpha_{\text{H}_2\text{O}}} \right) \quad (3.4)$$

Where,

E: cell voltage.

R: gas constant.

T: absolute temperature.

F: constant known as the Faraday (96,487 coulombs).

α : activity of relevant species.

Since the concentration of the electrolyte varies, the relative activities of H_2SO_4 and H_2O in the Nernst equation change. A graph of the open-circuit voltage versus electrolyte concentration at 25°C is given in figure (3.2). The plot is fairly linear above (1.10) specific gravity, but shows strong deviations at lower concentrations [19].

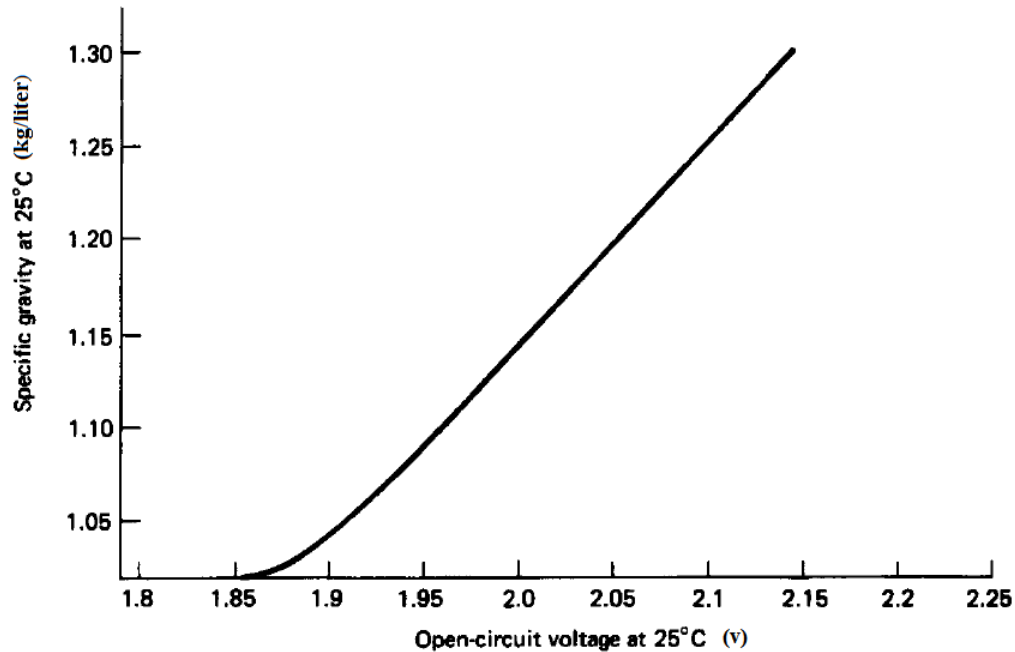
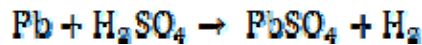
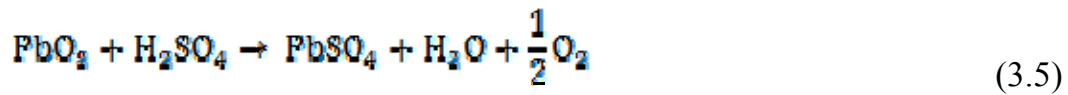


Figure (3.2): Open-circuit voltage of lead-acid cell as a function of electrolyte specific gravity [19].

3.4 Self-Discharge

Self-discharge means gradual loss of charge in the positive and/or negative electrode, when the battery is idle at the open circuit. One reason can be the gradual reduction of the oxidation state in the positive electrode [24].

The rate of self-discharge depends on several factors. Lead and lead dioxide are thermodynamically unstable in sulfuric acid solutions, and on open circuit, they react with the electrolyte. Oxygen is evolved at the positive electrode and hydrogen at the negative, at a rate dependent on temperature and acid concentration as follows:



For most positives, the formation of PbSO_4 by self-discharge is slow, typically much less than 0.5%/day at 25°C. The self-discharge of the negative is generally more rapid, especially if the cell is contaminated with various catalytic metallic ions.

Self-discharge is temperature-dependent, as shown in figure (3.3). The graph shows the fall in specific gravity per day of a new fully charged battery with 6% antimonial lead grids. Self-discharge can thus be minimized by storing batteries at temperatures between 5 and 15°C.

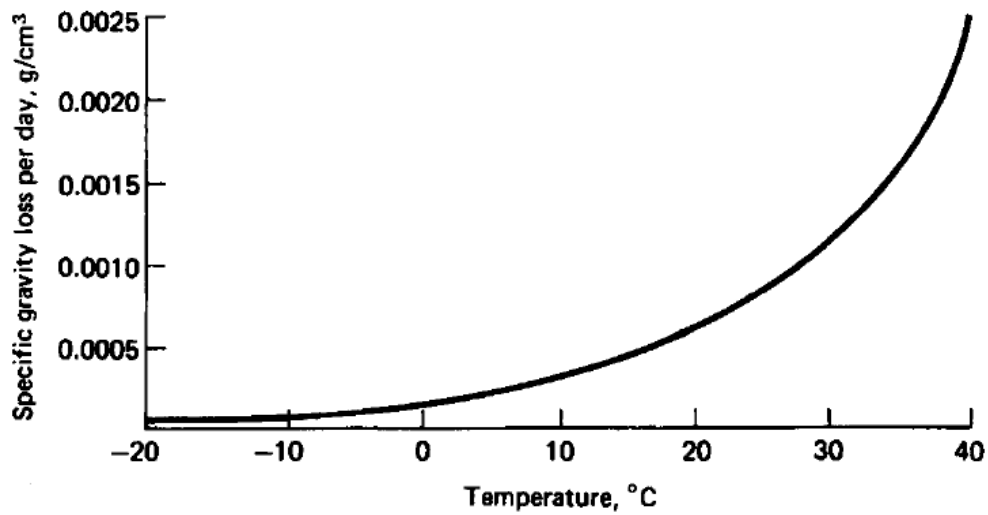


Figure (3.3): Loss of specific gravity per day with temperature of a new, fully charged lead-acid battery with 6% antimonial lead grids [19].

3.5 Discharge Characteristics

A significant design advantage of electrolyte cells and batteries is their versatility in discharge performance. One product design provides superior performance in applications ranging from starting engines to providing memory backup for computer equipment. Thus, battery users may use the same battery to handle widely varying product load scenarios [21].

3.5.1 Discharge types

There are three general classes of discharges for which electrolyte-lead batteries are typically applied. Each one of them has its own design considerations and each serves substantially different forms of applications. The differentiating parameter is the rate of discharge whether it is high, medium, or low. Some considerations regarding each category will be presented below [21].

3.5.1.1 High-rate discharges

Typically high-rate discharges are described as anything above 4A. The primary application of interest here is starting engines where the discharge rate requirement may be quite high (over 10A). The discharges normally last only a few seconds each although there may be several pulses in a train. Certain appliance applications may also have discharge rates that approach the lower end of the high-rate category [21].

3.5.1.2 Medium-rate discharges

Stepping down from the high-rate applications, there is a family of applications clustered around the 1A rate. Among the products that often need a battery, that is good for a half hour to about two hours, are many portable appliances, backup power for alarm and emergency lighting, and uninterruptible power supplies. In many respects, these are the easiest discharges for the battery to handle, neither too high nor too low [21].

3.5.1.3 Low-rate discharges

Low-rate applications are those with a discharge rate below 0.2A, i.e. applications that require the battery to last more than about five hours. This may be anything from an instrument that is required to operate for an eight-hour shift to microprocessor memory holdup that must provide current for a week or more. These discharges may remove essentially all the capacity and thereby place great strain on a battery [21].

3.6 Measures of Discharge Performance

The discharge parameters of concern are cell (or battery) voltage and capacity (the integral of current multiplied by time). The values of these two discharge parameters are functions of a number of application-related factors. The general shape of the discharge curve, voltage as a function of capacity (or time if the current is uniform), is shown in figure (3.4). The discharge voltage of the electrolyte-lead battery typically remains relatively constant until most of its capacity is discharged. It then drops off rather sharply. The area of relatively constant voltage is called the voltage plateau. The flatness and the length of this plateau, relative to the length of the discharge, are major features of this electrolyte -lead cells and batteries. The point at which the voltage leaves the plateau and begins to decline rapidly is often identified as the knee of the curve.

The discharge curve, when scaled by considering the effects of all the application variables, provides a complete description of the output of a battery. Differences in design, internal construction, and conditions of actual use of the battery affect one or both of these performance characteristics (voltage or capacity) [21].

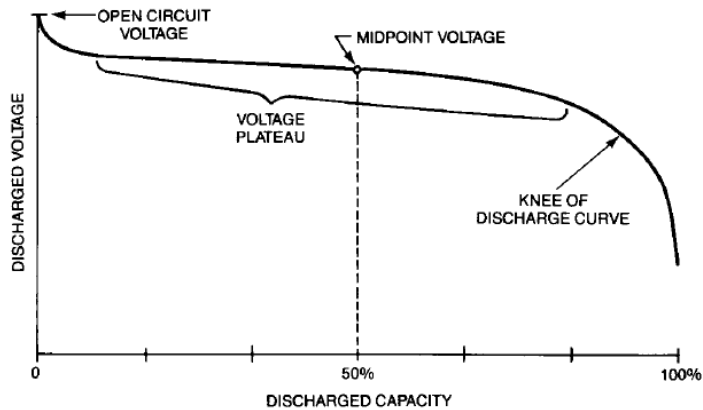


Figure (3.4): Nominal discharge performances for electrolyte – lead cells [21].

3.7 Battery Voltage – General Overview

In most battery applications, the discharge current is approximately constant and the parameter of concern is the behavior of the battery voltage with time. Constant power and constant-resistance discharges are also important, but are usually well modeled by a constant-current discharge.

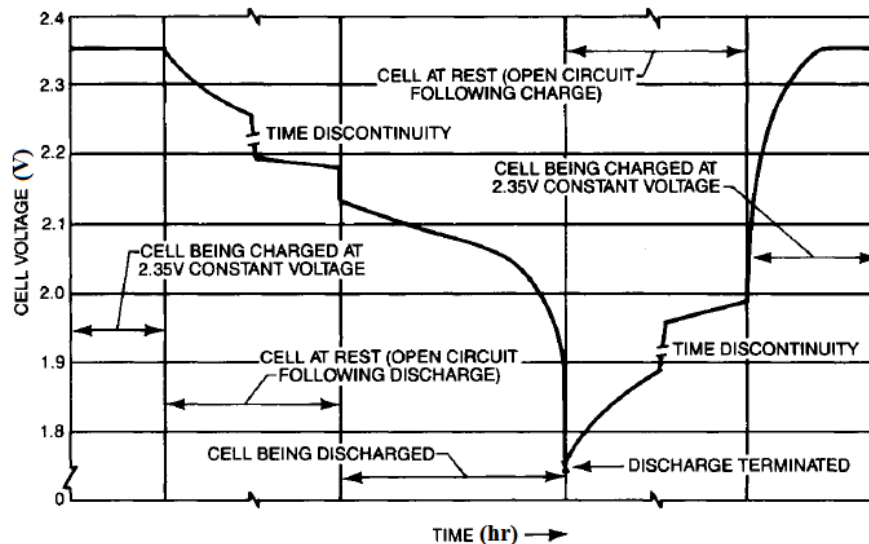


Figure (3.5): Cell voltages before, during and after a nominal discharge [21].

The various stages of a typical battery duty cycle, including charge, discharge, and rest, are illustrated in figure (3.5).

No matter what type of charger is used, it will hold the battery at some artificially high voltage during the charge process. When the battery is fully charged and removed from the charger, the battery voltage will drop to its full-charge open-circuit value. This value will decay only very slightly as the battery self-discharges.

When the battery is placed on discharge, the voltage will normally drop immediately from its open-circuit value to its on-load value. The loaded battery voltage will remain on a plateau, declining only slightly, for most of the battery's useful discharge. When the voltage hits the knee of the curve, the fall to zero volts is extremely rapid. The discharge is normally terminated at this point.

After discharge, if the battery is left at rest in an open circuit condition, the voltage will gradually recover to a level near 2.0 volts depending on the degree of discharge [21].

3.7.1 Mid-point Voltage

A common way of evaluating the discharge characteristics of a cell is to use midpoint voltages. Mid-point voltage, by definition, is the voltage of the cell when it has delivered 50 per cent of its capacity at the given discharge rate. In other words, it is the half-way point for any given discharge rate. The voltage characteristic for many electrolyte-lead batteries is shown in figure (3.6) is such that the mid-point voltage is also the approximate average voltage for the plateau of the discharge curve.

This makes it a convenient point to estimate average performance in terms of voltage delivery to the load [21].

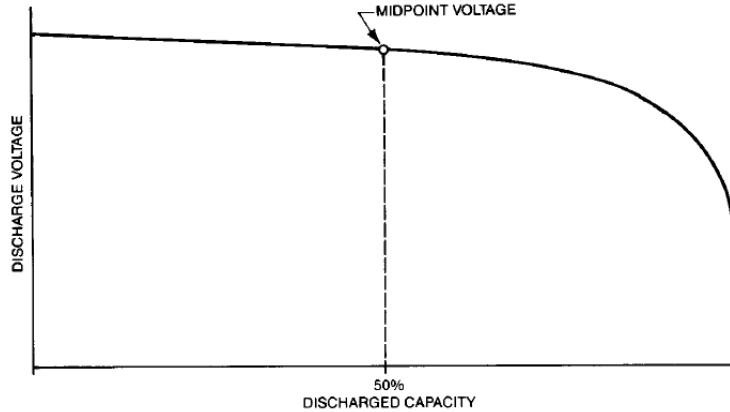


Figure (3.6): Illustration of mid-point voltage [21].

3.7.2 Battery discharge voltage as a function of discharge rate

The effects of increased discharge rate on the battery voltage are manifested in three ways: depression of the voltage plateau, an increase in the slope of the plateau, and shortening of the length of the plateau.

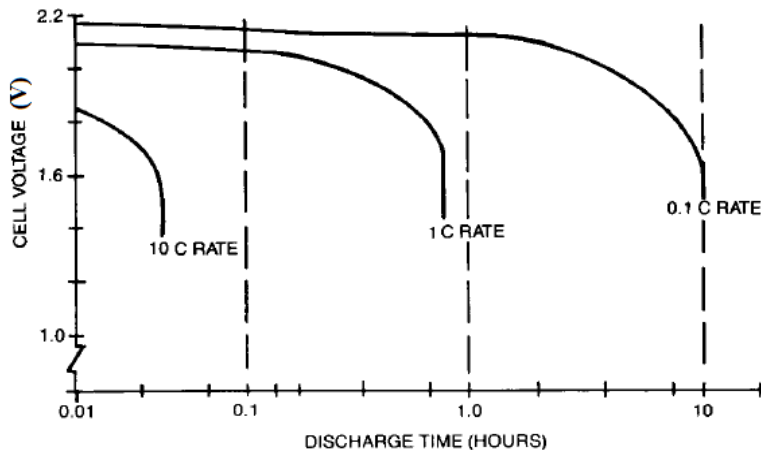


Figure (3.7): Cell discharge voltage versus time [21].

Figure (3.7) shows a family of discharge curves for three different discharge rates as a function of time. As can be seen from those plots, low

to medium-rate discharges behave similarly. Although there is some voltage depression with the increase in rate, the primary effect is shortening the discharge time. However, the high-rate (10A) discharge behaves quite differently [21].

3.8 Charging and Charging Equipment

3.8.1 General considerations

In the charging process, DC electric power is used to reform the active chemicals of the battery system to their high-energy, charged state. In the case of the lead-acid battery, this involves, the conversion of lead sulfate in the positive electrodes to lead oxide (PbO_2), the conversion of lead sulfate of the negative electrode to metallic lead (sponge lead), and the restoration of the electrolyte from a low-concentration sulfuric acid solution to the higher concentration of approximately 1.21 to 1.30 specific gravity. Since a change of phase from solid to solution is involved with the sulfate ion, charging lead-acid batteries has special diffusion considerations and is temperature-sensitive. During charge and discharge the solid materials which go into solution as ions are re precipitated as a different solid compound. This also causes a redistribution of the active material. The rearrangement will tend to make the active material contain a crystal structure with fewer defects, which results in less chemical and electrochemical activity. Therefore the lead-acid battery is not as reversible physically as it is chemically. This physical degradation can be minimized

by proper charging, and often batteries discarded as dead can be restored with a long, slow recharge (3 to 4 days at 2 to 3 A for SLI batteries).

A lead-acid battery can generally be charged at any rate that does not produce excessive gassing, overcharging, or high temperatures. The battery can absorb a very high current during the early part of the charge, but there is a limit to the safe current as the battery becomes charged. This is shown in Figure (3.8), which is a graphic representation of the Ampere-hour rule

$$I = A e^{-t} \quad (3.6)$$

Where I is the charging current, A is the number of Ampere-hours previously discharged from the battery, and t equals time. Because there is considerable latitude, there are a number of charging regimes, and the selection of the appropriate method depends on a number of considerations, such as the type and design of the battery, service conditions, time available for charging, number of cells or batteries to be charged and charging facilities [19].

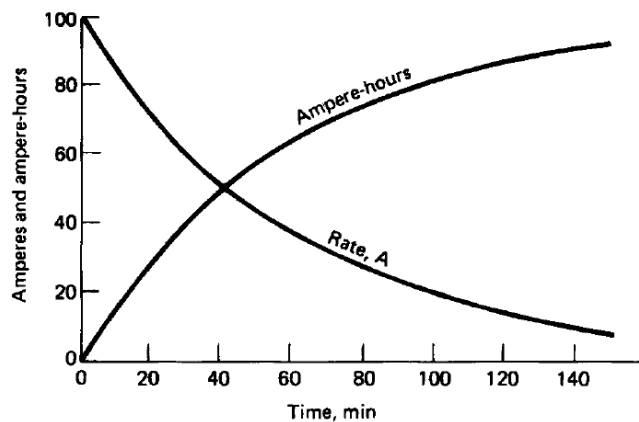


Figure (3.8): Graphic illustration of ampere-hour law [19].

3.8.2 Methods of charging lead-acid batteries

Proper recharging is important to obtain optimum life from any lead-acid battery under any conditions of use. Some of the rules for proper charging are given below and they are applicable to all types of lead-acid batteries.

1. The charge current at the start of recharge can be any value that does not produce an average cell voltage in the battery string greater than the gassing voltage (about 2.4 V per cell).
2. During the recharge and until 100% of the previous discharge capacity has been returned, the current should be controlled to maintain a voltage lower than the gassing voltage. To minimize charge time, this voltage can be just below the gassing voltage.
3. When 100% of the discharged capacity has been returned under this voltage control, the charge rate will have normally decayed to the charge “finishing” rate. The charge should be finished at a constant current no higher than this rate, normally 5 A per 100 Ah of rated capacity (referred to as the 20-h rate) [19].

A number of methods for charging lead-acid batteries have evolved to meet these conditions. These charging methods are commonly known as:

1. Constant-current, one-current rate.
2. Constant-current, multiple decreasing-current steps.

3. Modified constant current.
4. Constant potential.
5. Modified constant potential with constant initial current.
6. Modified constant potential with a constant finish rate.
7. Modified constant potential with a constant start and finish rate.
8. Taper charge.
9. Pulse charging.
10. Trickle charging.
11. Float charging.
12. Rapid charging.

3.8.2.1 Constant-current charging

Constant-current recharging, at one or more current rates, is not widely used for lead-acid batteries. This is because of the need for current adjustment unless the charging current is kept at a low level throughout the charge (Ampere-hour rule), which will result in long charge times of 12 h or longer. Typical charger and battery characteristics for the constant-current charge, for single and two-step charging are shown in figure (3.9). Constant-current charging is used for some small lead-acid batteries. Constant-current charging is also used at times in the laboratory because of

the convenience of calculating Ampere-hour input and because constant-current charging can be done with simple, inexpensive equipment. Constant-current charging at half the 20-h rate can be used in the field to decrease the sulfating in batteries which have been over discharged or undercharged. This treatment, however, may diminish the battery life and should be only used with the advice of the battery manufacturer [19].

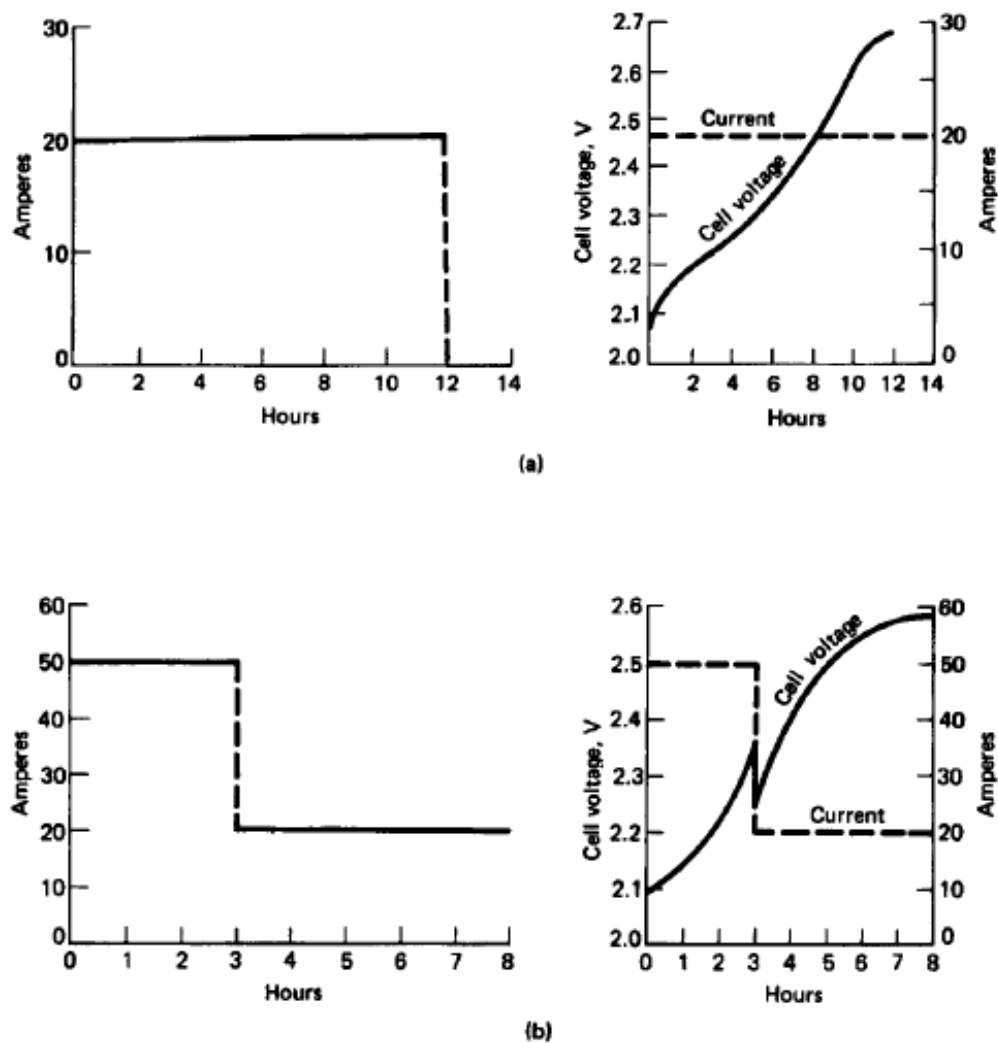


Figure (3.9): Typical charger and battery characteristics for constant-current charging of lead-acid batteries. (a) Single-step constant-current charging. (b) Two-step constant-current charging [19].

3.8.2.2 Constant-potential charging

The characteristics of constant-potential and modified constant-potential charging are illustrated in figure (3.10). In normal industrial applications, modified constant-potential charging methods are used (methods 5, 7, and 8). Modified constant potential charging (method 5) is used for on-the-road vehicles and utility, telephone, and uninterruptible power system applications where the charging circuit is tied to the battery. In this case, the charging circuit has a current limit, and this value is maintained until a predetermined voltage is reached. Then, the voltage is maintained constant until the battery is called on to discharge. Decisions must be made regarding the current limit and the constant - voltage value. This is influenced by the time interval when the battery is at the constant voltage and in a 100% state of charge. For this “float”-type operation with the battery always on charge, a low charge current is desirable to minimize overcharge, grid corrosion associated with overcharge, water loss by electrolysis of the electrolyte, and maintenance to replace this water. Achieving a full recharge with a low constant potential requires the proper selection of the starting current, which is based on the manufacturer’s specifications.

The modified constant-potential charge, with constant start and finish rates, is common for deep-cycling batteries which are typically discharged at the 6-h rate to a depth of 80%; the recharge is normally completed in an 8-h period. The charger is set for the constant potential of 2.39 V per cell (the gassing voltage), and the starting current is limited to

16 to 20 A per 100 Ah of the rated 6-h Ampere-hour capacity by means of a series resistor in the charger circuit. This initial current is maintained constant until the average cell voltage in the battery reaches 2.39 V. The current decays at constant voltage to the finishing rate of 4.5 to 5 A per 100 Ah, which is then maintained to the end of the charge. Total charge time is controlled by a timer. The time of charge is selected to ensure a recharge input capacity of a predetermined percent of the Ampere-hour output of the previous discharge, normally 110 to 120%, or 10 to 20% overcharge. The 8-h charging time can be reduced by increasing the initial current limit rate [19].

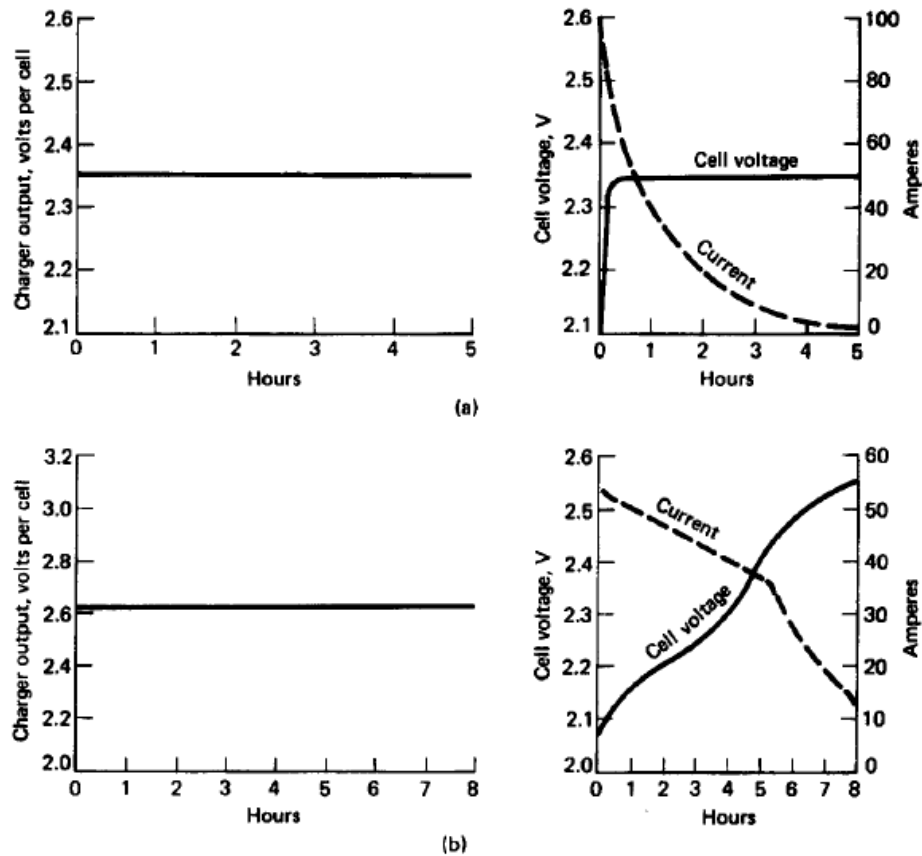


Figure (3.10): Typical charger and battery characteristics for constant-potential charging of lead-acid batteries. (a) Constant-potential charging. (b) Modified constant-potential charging [19].

3.8.2.3 Taper charging

Taper charging is a variation of the modified constant-potential method, using less sophisticated controls to reduce equipment cost. The characteristics of taper charging are illustrated in figure (3.11). The initial rate is limited, but the taper of voltage and current is such that the 2.39 V per cell at 25°C is exceeded prior to the 100% return of the discharge ampere-hours. This method does result in gassing at the critical point of recharge, and the cell temperature is increased. The degree of gassing and temperature rise is a variable depending on the charger design, and the battery life can be degraded from excessive battery temperature and overcharge gassing.

The end of the charge is often controlled by a fixed voltage rather than a fixed current. Therefore when a new battery has a high counter-EMF, this final charge rate is low and the battery often does not receive sufficient charge within the time period allotted to maintain the optimum charge state. During the latter part of life when the counter-EMF is low, the charging rate is higher than the normal finishing rate, and so the battery receives excessive charge, which degrades life. Thus the taper charge does degrade the battery life, which must be justified by the use of less expensive equipment.

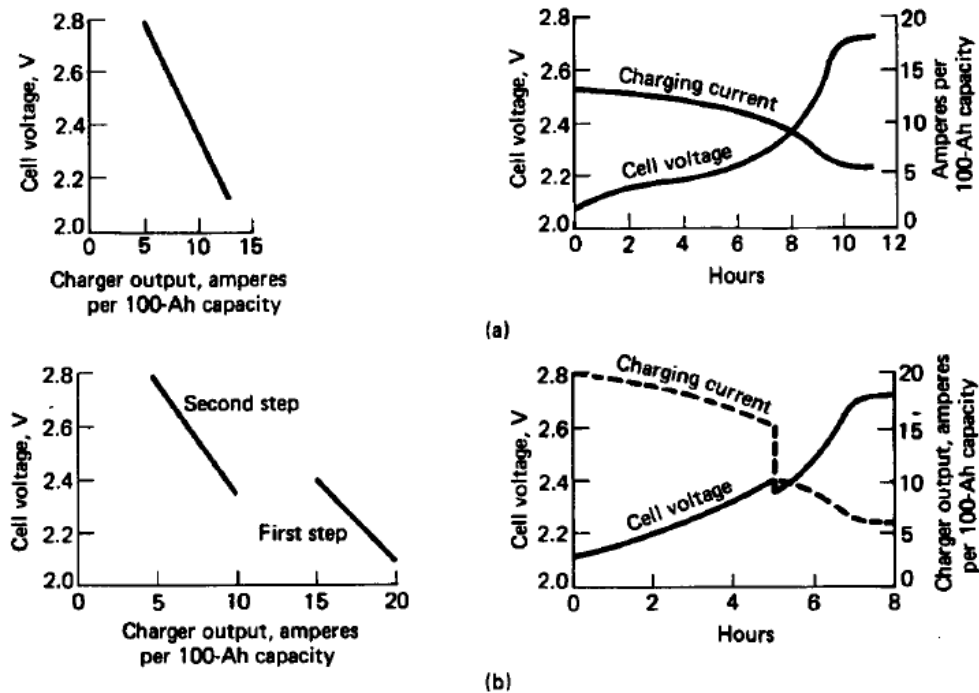


Figure (3.11): Typical charger and battery characteristics for taper charging of lead-acid batteries. (a) Single-step taper charge. (b) Two-step taper charge [19].

For photovoltaic battery systems and other systems designed for optimum life, charging control and regulation circuits should produce a pattern of voltage and current equivalent to the best industrial circuits. Modified constant-potential charging methods with constant initial current (methods 5 and 7) are preferred. Optimum control to maximize the life and energy output from the battery is best achieved when the depth of discharge and the time for recharge are predetermined and repetitive, a condition which is not always realized in solar photovoltaic applications [19].

3.8.2.4 Pulse charging

Pulse charging is also used for traction applications, particularly in Europe. In this case, the charger is periodically isolated from the battery

terminals and the open circuit voltage of the battery is automatically measured (an impedance-free measurement of the battery voltage). If the open-circuit voltage is above a preset value, depending on a reference temperature, the charger does not deliver energy. When the open-circuit voltage decays below that limit, the charger delivers a DC pulse for a fixed time period. When the battery state of charge is very low, the charging current is connected almost 100% of the time because the open-circuit voltage is below the present level or rapidly decays to it. The duration of the open-circuit and the charge pulses are chosen so that when the battery is fully charged, the time for the open-circuit voltage to decay is exactly the same as the pulse duration. When the charger controls sense this condition, the charger is automatically switched over to the finish rate current and short charging pulses are delivered periodically to the battery to maintain it at full charge. In many industrial applications high-voltage batteries may be used and the difficulty can be encountered in keeping the cells in a balanced condition. This is particularly true when the cells have long periods of standby use with different rates of self-decay. In these applications the batteries are completely discharged and recharged periodically (usually semiannually) in what is called an equalizing charge, which brings the whole string of cells back to the complete charge state. On completion of this process, the liquid levels in the cells must be checked and water added to depleted cells as required. With the newer types of maintenance-free cells, which are semi sealed, such equalizing charges and differential watering of the cells may not be possible, and special

precautions are taken in the charger design to keep the cells at an even state of charge [19].

3.8.2.5 Trickle charging

A trickle charge is a continuous constant-current charge at a low (about $C/100$) rate, which is used to maintain the battery in a fully charged condition, recharging it for losses due to self-discharge as well as to restore the energy discharged during intermittent use of the battery. This method is typically used for SLI and similar type batteries when the battery is removed from the vehicle or its regular source of charging energy for charging [19].

3.8.2.6 Float charging

Float charging is a low-rate constant-potential charge which is also used to maintain the battery in a fully charged condition. This method is used mainly for stationary batteries which can be charged from a DC bus. The float voltage for a non-antimonial grid battery containing 1.210 specific gravity electrolytes and have an open-circuit voltage of 2.059 V per cell is 2.17 to 2.25 V per cell [19].

3.8.2.7 Rapid charging

In many applications, it is desirable to be able to rapidly recharge the battery within an hour or less. As is the case under any charging condition, it is important to control the charge to maintain the morphology of the electrode, to prevent a rise in the temperature, particularly to a point where

deleterious side reactions (corrosion, conversion to non-conducting oxides, high solubility of materials, decomposition) take place, and to limit overcharge and gassing. As these conditions are more prone to occur during high-rate charging, charge control under these conditions is critical.

The availability of small, low-cost but sophisticated semiconductor chips has made effective methods of controlling the charging voltage-current-profile feasible. These devices can be used to terminate the charge, limit the charge current, or switch between charge regimes when potentially damaging conditions arise during the charge.

A number of different techniques have been developed for effective rapid recharge. In one method, referred to as “reflex” charging, a brief discharge pulse of a fraction of a second, is incorporated into the charging regime. This technique has been found to be effective in preventing an excessive rise in temperature during rapid (15-min) high-rate recharging [19].

3.9 Maximum Battery Subsystem Voltage

Selection of the battery voltage at top-of-charge and the number of cells in a series string is critical to successful operation and maximum life.

The photovoltaic system has a voltage window, a voltage range from the lowest to the highest limits acceptable to meet operating requirements. The number of cells in series in the battery subsystem times the average cell discharge end voltage must be greater than the lower voltage window limit.

Where this number of cells in series is used to set the upper voltage limit in the window, the calculation may show the upper voltage limit is not sufficiently high to charge the battery in the allotted time. A compromise must then be made [23].

3.10 Selection of Charge Current

Selection of charge currents for the initial high rate and final low rate charge periods is complicated by the following restraints:

- Completing the charge in the required time.
- Remaining within the voltage limits.
- Charging at rates which restore discharge capacity without excessive temperature rise.

Initial charge currents allowed range up to 20-25 A per 100 Ah at the rated 5-h capacity. Final or finishing constant charge current ranges from 3-5 A per 100 Ah at the rated 5-h capacity. During the last hours of charge at the finishing rate, cell charge voltage increases with increasing finishing rate. Finishing rate of 5 A per 100 Ah is end-of charge.

Voltage for newly produced cells can vary from 2.5 to 2.90 volts at 25°C depending upon the cell design and composition of the grids and the active materials. As battery life progresses the end-of-charge voltage for pure lead and lead-calcium cells remains essentially constant. For lead-antimony cells the end-of-charge voltage decays progressively during their cycle life to values as low as 2.4 volts after 2000 deep cycles.

The effect of initial charge rate and charging voltage on charge time is shown in table (3.7) for the case of a modified constant potential charge where the end-of-charge current is governed by the preset potential.

Summarizing, to decrease charge time while maintaining a consistent state-of-charge, the following procedures should be used:

- Increase the initial charge current up to a maximum value of 25 A/100 Ah rated 5-h cell capacity.
- Use the highest setting of constant potential during the initial charge current period without exceeding the temperature compensated cell gassing voltage.
- Use three step charge with final finishing current controlled at 5A/100 Ah at the 5-hr rated cell capacity.
- Allow time for a prolonged equalization charge at some regular interval of accumulated discharge capacity [23].

3.11 Effect of Specific Gravity of Electrolyte and their Operating Temperature

Another design consideration is the specific gravity of the electrolyte. Discharge capacity in any single cycle increases with an increase in specific gravity. The amount of increase will depend upon the discharge rate, the active material density and the ratio of active material to acid electrolyte.

When specific gravity is increased, the charge stand life and life cycle will be decreased. Estimates of this loss can be made by the battery manufacturer for the particular battery under consideration.

The specific gravity increases during recharge and decreases during discharge. At low operating temperatures, the specific gravity can become so low that its freezing temperature is reached and thus terminating the discharge prematurely and interfering with the subsequent charge [23].

3.12 Watering Cells

During normal operation, water is lost from a battery as the result of evaporation and electrolysis into hydrogen and oxygen which escape into the atmosphere. Evaporation is a relatively small part of the loss except in very hot, dry climates. With a fully charged battery, electrolysis consumes water at a rate of 0.336 cubic capacities (cc) per Ah overcharge. A 500 Ah cell overcharged 10 percent can thus lose 16.8 cc, or about 0.3% of its water, each cycle.

Since replacing water can be a major maintenance cost, water loss can be reduced by controlling the amount of overcharge and by using hydrogen and oxygen recombining devices in each cell where possible.

Addition of water is best accomplished after recharge and before an equalization charge.

Add water to reach the high acid level line at top-of-charge. Gassing during charge will stir the water into the acid uniformly. Do not add water

in a very cold weather when it may freeze before mixing. The water added must be distilled water, dematerialized water, or local water which has been approved for use in batteries.

Automatic water Labor costs further more. Overfilling must be avoided as the resultant overflow of acid electrolyte will cause tray corrosion, ground paths, and loss of cell capacity.

A final check of specific gravity should be made after water is added to assure correct acid concentration at the top-of-charge. A helpful approximation given in the literature [23] is given in the equation (3.8):

$$\text{Specific Gravity} = \text{Open Circuit Voltage of the Cell} - 0.845 \quad (3.8)$$

Where, the open circuit voltage is for only one elementary lead acid cell (i.e. 1.75V – 2.4V) and the obtained specific gravity in kg per liter.

This permits electrical monitoring of specific gravity on an occasional basis [23].

3.13 Maintenance Safety and Operational Features

It is common for industrial lead-acid batteries to function for periods of 10 years or longer. Proper maintenance can ensure this extended useful life. Five basic rules of proper maintenance are:

1. Match the charger to the battery charging requirements.
2. Avoid over discharging the battery.

3. Maintain the electrolyte at the proper level (add water as required).
4. Keep the battery clean.
5. Avoid overheating the battery.

In addition to these basic rules, as the battery is made of individual cells connected in series, the cells must be properly balanced periodically. The following points are related to operation and maintenance of batteries.

- a. Charging practice:** Poor charging practice is responsible for short battery life more than any other cause. Fortunately, the inherent physical and chemical characteristics of lead-acid batteries make control of charging quite simple. If the battery is supplied with DC energy at the proper charging voltage, the battery will draw only the amount of the current that it can accept efficiently, and this current will reduce as the battery approaches full charge. Several types of devices can be used to ensure that the charge will terminate at the proper time. The specific gravity of the electrolyte should also be checked periodically for those batteries that have a removable vent and adjusted to the specified value.
- b. Over discharge:** Over discharging the battery should be avoided. The capacity of large batteries, such as those used in industrial trucks, is generally rated in Ampere-hours at the 6-h discharge rate to a final voltage of 1.75 V per cell. These batteries can usually deliver more than rated capacity, but this should be done only in an emergency and not on a regular basis. Discharging cells below the specified voltage

reduces the electrolyte to a low concentration, which has a deleterious effect on the pore structure of the battery.

- c. **Electrolyte level:** During normal operation, water is lost from a battery as the result of evaporation and electrolysis into hydrogen and oxygen, which escape into the atmosphere. Evaporation is a relatively small part of the loss, except in very hot, dry climates. With a fully charged battery, electrolysis consumes water at a rate of 0.336 cm^3 per Ampere-hour overcharge. A 500-Ah cell overcharged 10% can thus lose 16.8 cm^3 , or about 0.3% of its water each cycle. It is important that the electrolyte does maintained at the proper level in the battery. The electrolyte not only serves as the conductor of electricity but also is a major factor in the transfer of heat from the plates. If the electrolyte is below the plate level, then an area of the plate is not electrochemically active; this causes a concentration of heat in other parts of the cell. Periodic checking of water consumption can also serve as a rough check on charging efficiency and may warn when adjustment of the charger is required.
- d. **Cleanliness:** Keeping the battery clean will minimize corrosion of cell post connectors and steel trays and avoid expensive repairs. Batteries commonly pick up dry dirt, which can be readily blown off or brushed away. This dirt should be removed before moisture makes it a conductor of stray currents. One problem is that the top of the battery can become wet with electrolyte any time a cell is overfilled. The acid in this electrolyte does not evaporate and should be neutralized by

washing the battery with a solution of baking soda and hot water, approximately 1 kg of baking soda to 4 L of water. After the application of such a solution, the area should be rinsed thoroughly with water.

- e. **High temperature overheating:** One of the most detrimental conditions for a battery is high temperature, particularly above 55°C, because the rates of corrosion, solubility of metal components, and self-discharge increase with increasing temperature. High operating temperature during cycle service requires a higher charge input to restore discharge capacity and local action (self-discharge) losses. More of the charge input is consumed by the electrolysis reaction because of the reduction in the gassing voltage at the higher temperature. While a 10% overcharge per cycle maintains the state of charge at 25 to 35°C, 35 to 40% overcharge may be required to maintain the state of charge at the higher (60 to 70°C) operating temperatures. On float service, float currents increase at higher temperatures, resulting in reduced life. Eleven days float at 75°C is equivalent in life to 365 days at 25°C. Batteries intended for high-temperature applications should use a lower initial specific gravity electrolyte than those intended for use at normal temperatures. Other design features, such as the use of more expander in the negative plate, are also important to improve operation at high temperatures.
- f. **Cell balancing:** During cycling, a high-voltage battery having many cells in a series string can become unbalanced, with certain cells

limiting charge and discharge. Limiting cells receive more overcharge than other cells in the string, have greater water consumption, and thus require more maintenance. The equalization charge has the function of balancing cells in the string at the top of charge. In an equalization charge, the normal recharge is extended for 3 to 6 h at the finishing rate of 5 A per 100 Ah, 5-h rated capacity, allowing the battery voltage to rise uncontrolled. The equalization charge should be continued until cell voltages and specific gravities rise to a constant, acceptable value. Frequency of equalization charge is normally a function of the accumulative discharge output and will be specified by the manufacturer for each battery design and application [19].

Chapter Four

Nickel – Cadmium Battery

Chapter Four

Nickel – Cadmium Batteries

The vented pocket-plate battery is the oldest and most mature of the various designs of nickel-cadmium batteries available. It is a very reliable, sturdy, long-life battery, which can be operated effectively at relatively high discharge rates and over a wide temperature range. It has very good charge retention properties, and it can be stored for long periods of time in any condition without deterioration. The pocket-plate battery can stand both severe mechanical abuse and electrical maltreatment such as overcharging, reversal, and short circuiting. Little maintenance is needed on this battery. The cost is lower than for any other kind of alkaline storage battery; still, it is higher than that of a lead-acid battery on a per Watt hour basis. The major advantages and disadvantages of this type of battery are listed in Table (4.1).

The pocket plate battery is manufactured in a wide capacity range, 5 to more than 1200 Ah, and it is used in a number of applications. Most of these are of an industrial nature, such as railroad service, switchgear operation, telecommunications, uninterruptible power supply, and emergency lighting. The pocket plate battery was also used in military and space applications.

The pocket plate batteries are available in three plate thicknesses to suit the variety of applications. The high-rate designs use thin plates for maximum exposed plate surface per volume of active material. They are used for the highest-rate discharge. The low-rate designs use thick plates to

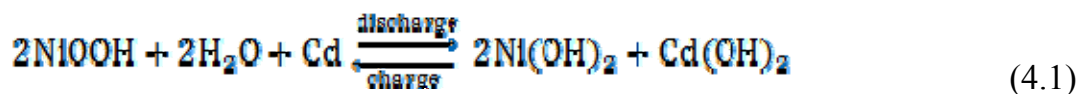
obtain maximum volume of active material per exposed plate surface. These types are used for long-term discharge. The medium-rate designs use plates of middle thickness and are suited for applications between, or combinations of, high-rate and long term discharge [19].

Table (4.1): Major advantages and disadvantages of industrial and aerospace nickel- cadmium batteries [19].

Advantages	Disadvantages
1. Long cycle life. 2. Rugged; can withstand electrical and physical abuse. 3. Reliable; no sudden death contains cadmium. 4. Good charge retention. 5. Excellent long-term storage. 6. Low maintenance.	1. Low energy density. 2. Higher cost than lead-acid batteries. 3. Contains cadmium.

4.1 Chemistry

The basic electrochemistry is the same for the vented pocket plate, sintered plate, fiber and plastic-bonded plate types as well as for other variations of the nickel-cadmium system. The reactions of charge and discharge can be illustrated by the following simplified equation:



On discharge, trivalent nickel oxy-hydroxide is reduced to divalent nickel hydroxide with consumption of water. Metallic cadmium is oxidized to form cadmium hydroxide. On charge, the opposite reactions take place. The electromotive force (EMF) is 1.29 V [19].

The electrodes are assembled in their discharged state Ni(OH)_2 and Cd(OH)_2 for the positive and negative electrodes, respectively. NiCd

batteries are sometimes categorized by the form of the current collector used pocket, sintered, fiber, or foam. The pocket plate design comes from Jungner. The active electrode materials are packed in channels formed from perforated steel.

Sintered nickel electrodes were subsequently developed to increase the contact area with the active electrode materials and, so, increase their power output. Fiber electrodes are a mat of sintered nickel plated fibers. Nickel metal foams have a very high porosity, about 90 percent open area. Sintered plate porosities are in the 80 percent to 85 percent range. Greater porosity means more active material can be loaded into the current collector electrodes thereby increasing energy density.

The negative electrode is made of cadmium hydroxide Cd(OH)_2 , up to 25 percent iron and small quantities of Ni and graphite. Cobalt oxide is added to the positive electrode material, Ni(OH)_2 which forms an electrically conductive coating of cobalt oxy hydroxide, Co(O)OH , on the surface of the Ni(OH)_2 particles during cell conditioning.

NiCd electrolytes are aqueous solutions of 20 percent to 32 percent potassium hydroxide (KOH) with up to 2 percent lithium hydroxide (LiOH). Button cell sizes are also available. Typical voltage behaviors during discharge and charge are shown in figure (4.1). An overview of NiCd characteristics is given in table (4.2).

Oxygen (O_2) is formed at the positive electrode, though, by oxidizing water in the electrolyte solution:



The O_2 so formed can diffuse to the negative electrode where it reacts with Cd to form:



Naturally, the charging current cannot exceed the rate of O_2 reduction or pressure will build within the cell [22].

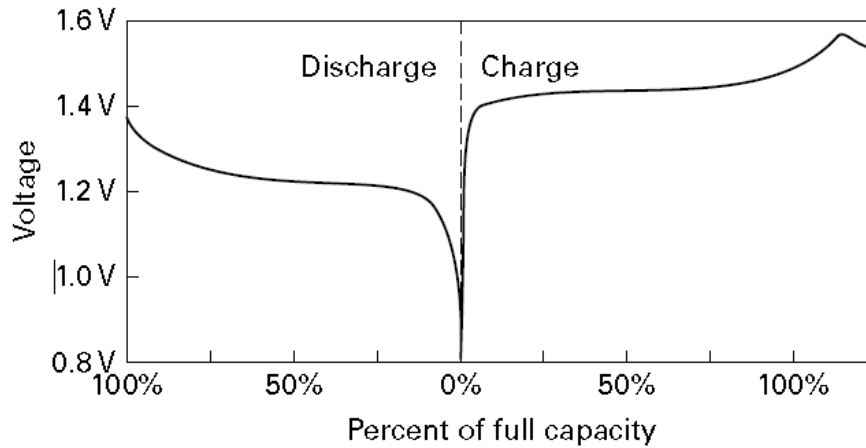


Figure (4.1): Voltage behavior for a nickel cadmium cell during discharge and charge [22].

Table (4.2): Overview of nickel-cadmium cell attributes [22].

Attribute	Description
Negative active material	Cadmium (Cd). Contains iron, Ni, and graphite. Negative electrode reaction (discharge left to right, charge right to left): $\text{Cd} + 2 \text{OH}^- \rightleftharpoons \text{Cd(OH)}_2 + 2 \text{e}^-$
Positive active material	Nickel oxy hydroxide (Ni(O)OH). Contains CoO and graphite Positive electrode reaction (discharge left to right, charge right to left): $\text{Ni(O)OH} + \text{H}_2\text{O} + \text{e}^- \rightleftharpoons \text{Ni(OH)}_2 + \text{OH}^-$
Electrolyte	20 % to 32% potassium hydroxide (KOH) and up to 2% lithium hydroxide (LiOH) in water
Battery reactions (discharge left to right, charge right to left)	$\text{Cd} + 2 \text{Ni(O)OH} + 2 \text{H}_2\text{O} \rightleftharpoons \text{Cd(OH)}_2 + 2 \text{Ni(OH)}_2$
Nominal cell voltage	1.30 V
Discharge voltage profile	Flat
Self-discharge	5% to 20% per month
Energy density	18 to 75 Wh kg^{-1} and 30 to 220 Wh dm^{-3}
Commonly available types	Cylindrical cells in a variety of sizes from AAA to D, as well as fractional sizes Button cells Prismatic, including 9V

4.2 Performance Characteristics

4.2.1 Discharge properties

The discharge parameters of concern are cell (or battery) voltage and capacity (the integral of current multiplied by time). The values of these two discharge parameters are functions of a number of application-related factors. The general shape of the discharge curve, voltage as a function of capacity (or time if the current is uniform), is shown in Figure (4.2). The

discharge voltage of the electrolyte nickel-cadmium cell typically remains relatively constant until most of its capacity is discharged. It then drops off rather sharply. The area of relatively constant voltage is called the voltage plateau. The flatness and the length of this plateau relative to the length of the discharge are major features of electrolyte nickel-cadmium cells and batteries [21].

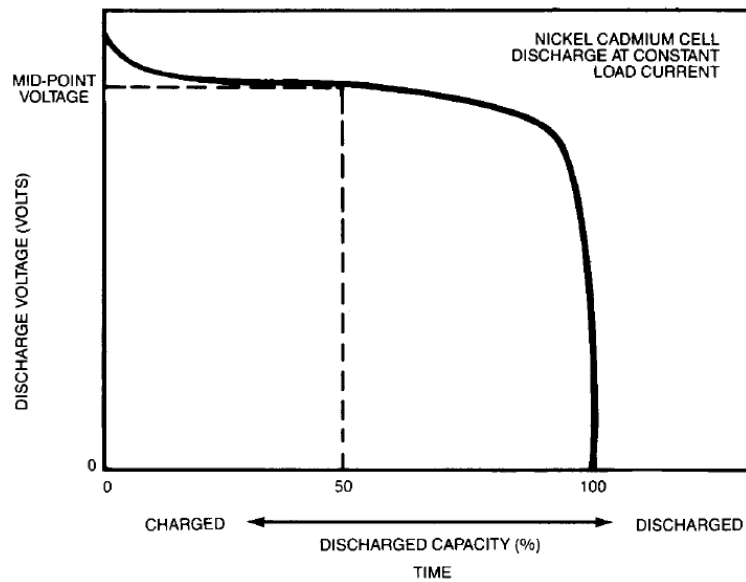


Figure (4.2): Nickel-cadmium cell discharge curve constant current [21].

The nominal voltage of a nickel-cadmium battery is 1.3 V. Although discharge rate and temperature are of importance for the discharge characteristics of all electrochemical systems, these parameters have a much smaller effect on the nickel-cadmium battery than on, for instance, the lead-acid battery. Thus pocket plate nickel-cadmium batteries can be effectively discharged at high discharge rates without losing much of the rated capacity. They can also be operated over a wide temperature range.

Typical discharge curves at room temperature for pocket plate and plastic-bonded plate batteries at various constant discharge rates are shown in figure (4.3). Even at a discharge current as high as 5C (where C is the numerical value of the capacity in Ah), a high-rate pocket plate battery can deliver 60% of the rated capacity and a plastic-bonded battery as much as 80%.

Pocket-plate nickel-cadmium batteries can be used at temperatures down to (-20°C) with the standard electrolyte. Cells filled with a more concentrated electrolyte can be used down to (-50°C). Figure (4.3) shows the effect of temperature on the relative performance of a nickel-cadmium medium-rate battery with standard electrolyte.

Batteries can also be used at elevated temperatures. Although occasional operation at very high temperatures is not detrimental, 45 to 50°C is generally considered as the maximum permissible temperature for extended periods of operation.

Occasional over discharge or reversal of nickel-cadmium batteries is not detrimental, nor is complete freezing of the cells. After warming up, they will function normally again [19].

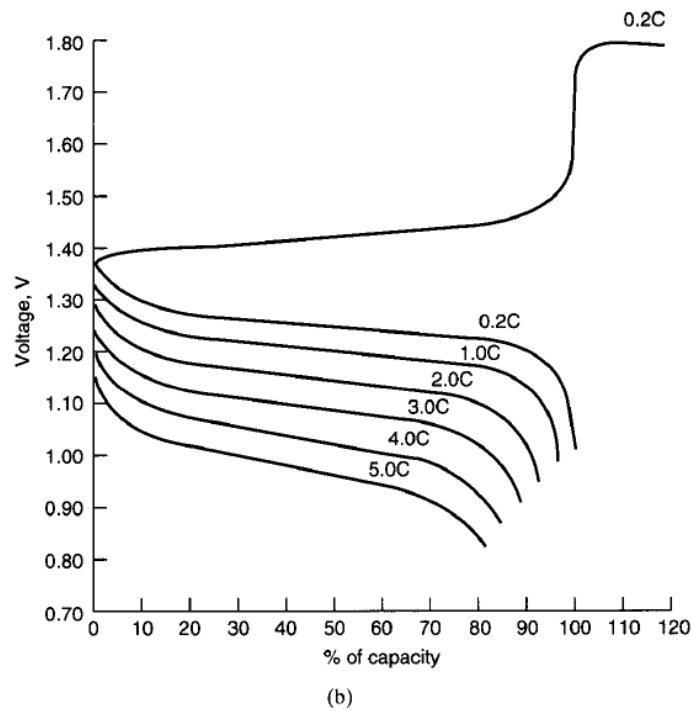
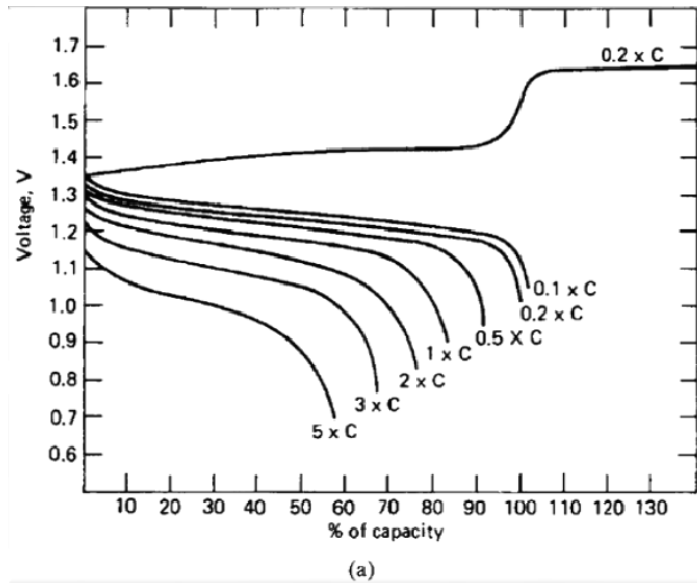


Figure (4.3): Charge and discharge characteristics of nickel-cadmium batteries at 25°C. (a) Pocket plate battery, high rate. (b) Plastic-bonded plate battery, high rate [19].

4.2.2 Internal resistance

Nickel-cadmium batteries generally have a low internal resistance. Typical DC resistance values are 0.4, 1, and 2 mΩ, respectively, for a

charged 100-Ah high, medium, and low rate pocket plate single-cell battery. The internal resistance is largely inversely proportional to the battery size in a given series. Decreasing temperature and decreasing state of charge of a battery will result in an increase of the internal resistance. The internal resistance of fiber-plate batteries is 0.3 m Ω for a high-rate design and 0.9 m Ω for a low-rate design. Plastic-bonded plate batteries have an internal resistance as low as 0.15 m Ω [19].

4.2.3 Charge retention

Charge retention characteristics of vented pocket-plate batteries at 25°C are shown in figure (4.4). Charge retention is temperature-dependent, the capacity loss at 45°C being about three times higher than at 25°C. There is virtually no self-discharge at temperatures lower than -20°C. Charge retention for fiber and plastic-bonded plate batteries has similar characteristics; their charge retention corresponds to that shown in figure (4.4) for high-rate batteries.

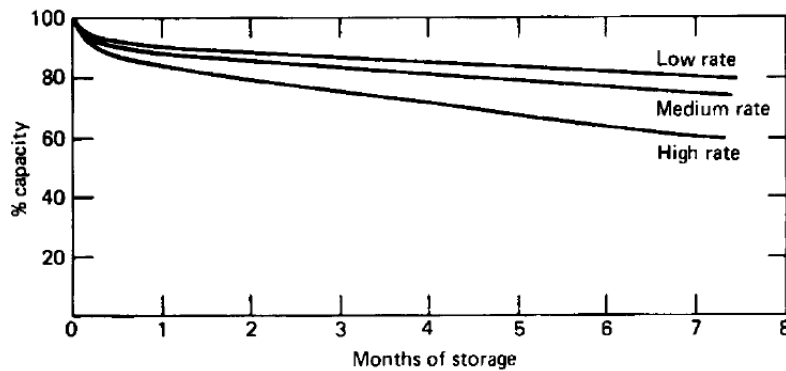


Figure (4.4): Charge retention of pocket plate batteries at 25°C. [19].

4.2.4 Life

The life of a battery can be given either as the number of charge and discharge cycles that can be delivered or as the total lifetime in years. Under normal conditions a nickel-cadmium battery can reach more than 2000 cycles. The total lifetime may vary between 8 and 25 years or more, depending on the design and application and on the operating conditions. The batteries for diesel engine cranking normally last about 15 years, the batteries for train lighting have normal lives of 10 to 15 years, and the stationary standby batteries have lives of 15 to 25 years [19].

4.3.1 Charging characteristics

Nickel-cadmium cells may be charged by constant current, constant potential or combinations of these methods. Higher charge rates can be tolerated by NiCd cells than by lead-acid cells designed for the same discharge rate, and rates of 25 A per 100 Ah of the 5-hour rated capacity are commonly used without harmful effects. One method for cycle application is to recharge at a constant current of 20 A per 100 Ah to an input 20-40 percent greater than the previous discharge output. During a typical constant current charge at 20 A per 100 Ah, cell voltage rises from near 1.40 volts to the gassing voltage (1.45 volts per cell at 25°C) and then very quickly to 1.68 volts, remaining near this voltage during overcharge see figure (4.5) [23].

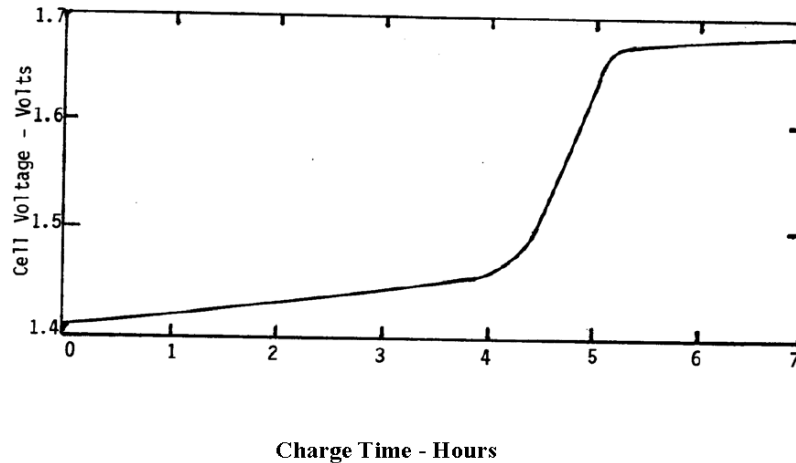


Figure (4.5): Constant current charge of pocket plate nickel – cadmium cell at 20A/100Ah, 25°C [23].

4.3.2 Charging efficiency

When a nickel-cadmium battery is charging, not all of the energy input is converting the active material to a usable (dischargeable) form. Charge energy also goes to converting active material into an unusable form, generating gas, or is lost in parasitic side reactions. The term charge acceptance, which characterizes charging efficiency, is the ratio of the dischargeable capacity obtained to the charge input.

The top curve of figure (4.6) shows the dischargeable capacity (charge output) as a function of the charge input for an electrolyte cell starting from a completely discharged state. The ideal cell, with no charge acceptance losses, would be 100 per cent efficient: all the charge delivered to the cell could be retrieved on discharge. But nickel-cadmium cells typically accept charge at different levels of efficiency depending upon the state of charge of the cell, as shown by the bottom curve of figure (4.6). Four successive types of charging behavior - Zones 1, 2, 3 and 4 in figure

(4.6) describe this performance. Each zone reflects a distinct set of chemical mechanisms responsible for loss of charge input energy.

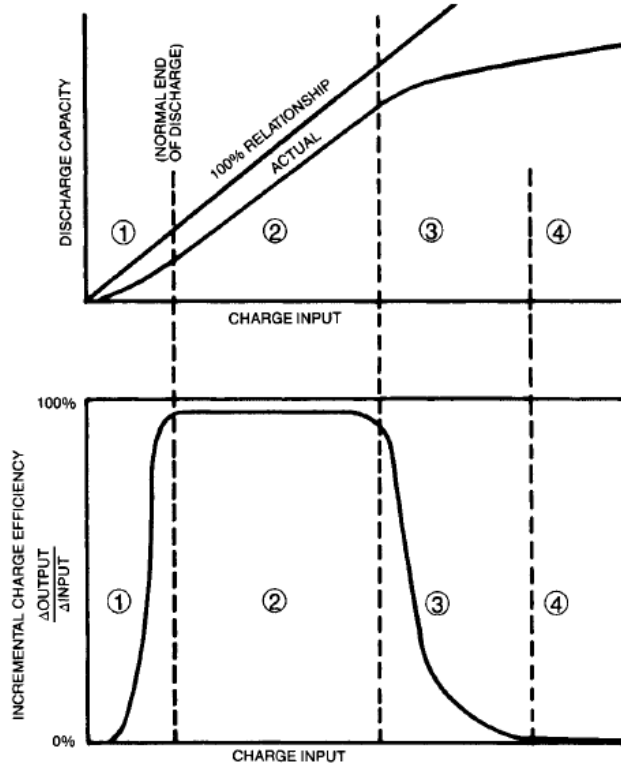


Figure (4.6): Charge acceptance of an electrolyte Cell at 0.1 C and 23°C [21].

In Zone 1 a significant portion of the charge input converts some of the active material mass into a non-usable form, i.e. into charged material which is not readily accessible during medium or high-rate discharges, particularly in the first few cycles. In Zone 2, the charging efficiency is only slightly less than 100 percent; small amounts of internal gassing and parasitic side reactions are all that prevent the charge from being totally efficient. Zone 3 is a transition region. As the cell approaches full charge, the current input shifts from charging positive active material to generating oxygen gas. In the overcharge region, Zone 4, all of the current coming in

to the cell goes to generating gas. In this zone the charging efficiency is practically zero.

The boundaries between Zones 2, 3, and 4 are indistinct and quite variable depending upon cell temperature, cell construction, and charge rate. The level of charge acceptance in Zones 1, 2, and 3 is also influenced by the cell temperature and charge rate [21].

4.3.3 Overcharge

Overcharge is the normal continued application of charging current to a battery after the battery has reached its maximum state of charge. It impacts the steady-state values of pressure, temperature, and voltage. As discussed earlier, continued charging of fully charged cells causes the oxygen pressure to stabilize at an elevated level within the cells. The magnitude of the pressure increase depends primarily on the overcharge rate. Along with this rise of pressure comes an increase in the cell temperature. Pressure, temperature, and voltage ultimately reach equilibrium in overcharge. Since cells are designed to reliably handle continuous overcharge at their cell specification rate, it is not an adverse condition. Overcharge is simply a term commonly used to describe the normal continuation of charge after the cell is fully charged.

Standard-charge cells may overcharge at rates up to 0.1 capacity. Quick-charge cells, designed to withstand higher overcharge rates for an extended time, normally charge at rates up to 0.33C. Fast-charge cells, those that may charge at 1C to 4C rates, require special charger systems

that automatically end high-rate charging. No matter which type of cell is involved, overcharge at rates above the cell specification rate may result in excessive temperatures and venting, and is therefore abusive to electrolyte nickel-cadmium cells.

The electrode design of fast-charge and quick-charge cells speeds recombination of oxygen at the negative electrode decreasing the pressure in the cell at any given rate. However, fast-charge rates still generate oxygen too rapidly to continue into overcharge without venting. Therefore, the charge rate must be reduced when the cell approaches full charge [21].

4.4 Iron Electrode Batteries

Today, the nickel-iron battery is the most common rechargeable system using iron electrodes. Iron-silver batteries have been tested in special electronic applications, and iron / air batteries have shown promise as motive power systems. The characteristics of the iron battery systems are summarized in tables (4.3) and (4.4).

As designed by Edison, the nickel-iron battery was and is almost indestructible. It has a very rugged physical structure and can withstand electrical abuse such as overcharge, over discharge, discharged stand for extended periods, and short-circuiting. The battery is best applied where high life cycle at repeated deep discharges is required (such as traction applications) and as a standby power source with a 10- to 20-year life. Its limitations are low power density, poor low-temperature performance, poor

charge retention, and gas evolution on stand. The cost of the nickel-iron battery lies between the lower-cost lead-acid and the higher-cost nickel-cadmium battery in most applications, with the exception of limited use applications in electric vehicles and mobile industrial equipment.

Most recently, iron electrodes have been considered and tested as cathodes too. Based upon high valence state iron, Fe (VI), these cathodes have shown promise in experimental cells when coupled with zinc or metal hydride anodes for secondary batteries [19].

Table (4.3): Iron electrode battery systems [19].

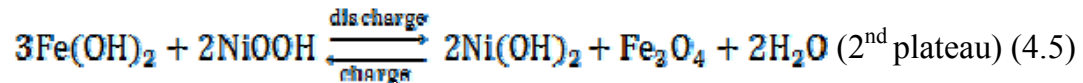
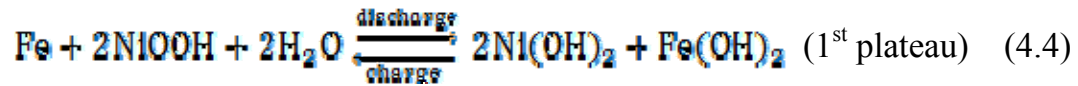
System	Uses	Advantages	Disadvantages
Iron / nickel oxide (tubular)	Material handling vehicles, underground mining vehicles, miners' lamps, railway cars and signal systems, emergency lighting	Physically almost indestructible, not damaged by discharged stand, long life, cycling or stand, withstands electrical abuse: overcharge, over discharged, short-circuiting	High self-discharge, hydrogen evolution on charge and discharge, low power density, lower energy density than competitive systems, Poor low temperature performance, damaged by high temperatures, higher cost than lead-acid, low cell voltage
Iron / air	Motive power	Good energy density, uses readily available materials, low self-discharge	Low efficiency, hydrogen evolution on charge, poor low-temperature performance, low cell voltage
Iron / silver oxide	Electronics	High energy density, high cycle life	High cost, hydrogen evolution on charge

Table (4.4): System characteristics [19].

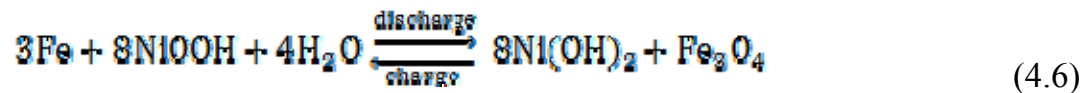
System	Nominal voltage (V)		Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Cycle Life 100% DOD
	Open-circuit	Dis-charge				
Iron / nickel oxide Tubular	1.4	1.2	30	60	25	4000
Developmental	1.4	1.2	55	110	110	>1200
Iron air	1.2	0.75	80		60	1000
Iron / silver oxide	1.48	1.1	105	160	-	>300

4.4.1 Chemistry of Nickel – Iron batteries

The active materials of the nickel-iron battery are metallic iron for the negative electrode, nickel oxide for the positive, and a potassium hydroxide solution with lithium hydroxide for the electrolyte. The nickel-iron battery is unique in many respects. The overall electrode reactions result in the transfer of oxygen from one electrode to the other. The exact details of the reaction can be very complex and include many species of transitory existence. The electrolyte apparently plays no part in the overall reaction, as noted in the following reactions:



The overall reaction is

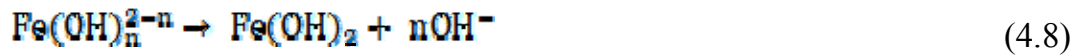


The electrolyte remains essentially invariant during charge and discharge. It is not possible to use the specific gravity of the electrolyte to determine the state of charge as for the lead acid battery. However, the individual electrode reactions do involve an intimate reaction with the electrolyte.

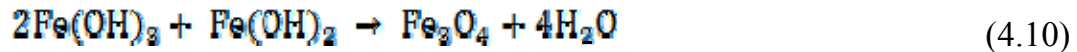
A typical charge-discharge curve of an iron electrode is shown in figure (4.7). The two plateaus on charge correspond to the formation of the stable +2 and +3 valent states of the iron reaction products. The reaction of the iron electrode can be written as



And



Then



Iron dissolved initially as the +2 species in alkaline media. The divalent iron complexes with the electrolyte to form the $\text{Fe}(\text{OH})_n^{2-n}$ complex of low solubility. The tendency to supersaturate plays an important role in the operation of the electrode and accounts for many important aspects of the electrode performance characteristics. Continued

charge forms the +3 valent iron which, in turn, interacts with +2 valent iron to form Fe_3O_4 [19].

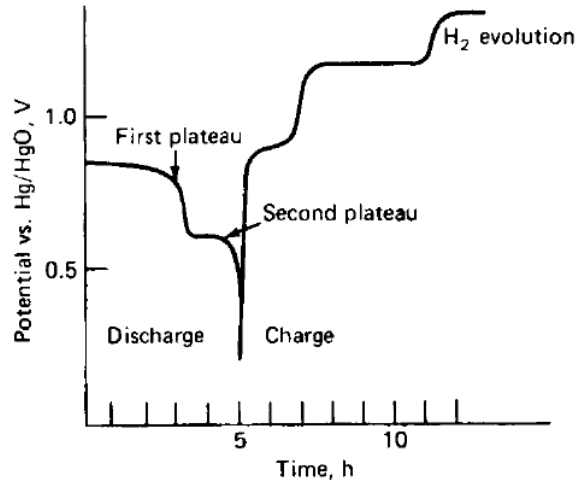


Figure (4.7): Discharge-charge curve of an iron electrode [19].

4.4.2 Performance characteristics of Nickel-Iron battery

Voltage: A typical discharge-charge curve of a commercial iron/nickel oxide battery is shown in figure (4.8). The battery's open-circuit voltage is 1.4 V; its nominal voltage is 1.2 V. On charge, at rates most commonly used, the maximum voltage is 1.7 to 1.8V.

Capacity: The capacity of the nickel-iron battery is limited by the capacity of the positive electrode and, hence, is determined by the length and number of positive tubes in each plate. The diameter of the tubes generally is held constant by each manufacturer. The 5-h discharge rate is commonly used as the reference for rating its capacity.

The conventional nickel-iron battery has moderate power and energy density and is designed primarily for moderate to low discharge rates. It is

not recommended for high-rate applications such as engine starting. The high internal resistance of the battery lowers the terminal voltage significantly when high rates are required. The relationship between capacity and rate of discharge is shown in figure (4.9).

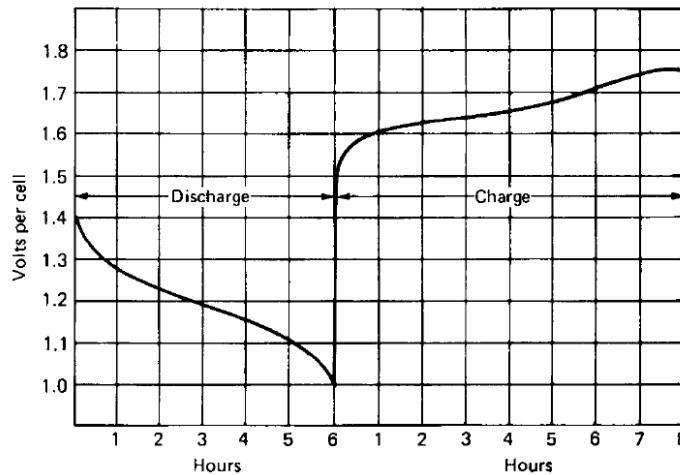


Figure (4.8): Typical voltage characteristics during constant-rate discharge and recharge [19].

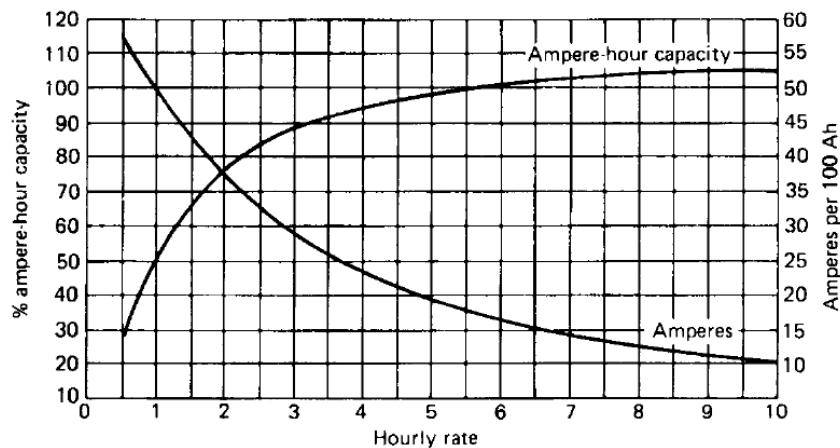


Figure (4.9): Curves of capacity, discharge rate at 25°C; end voltage 1.0 V per cell [19].

If a battery is discharged at a high rate and then at a lower rate, the sum of the capacities delivered at the high and low rates nearly equals the

capacity that would have been obtained at the single discharge rate. This is illustrated in figure (4.10) [19].

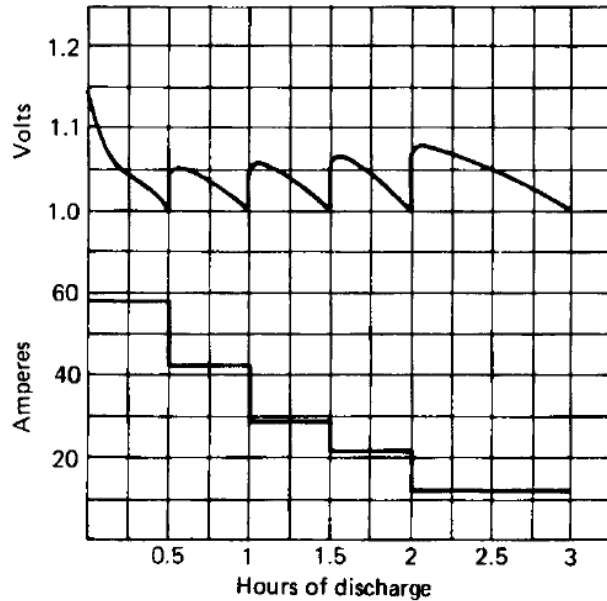


Figure (4.10): Effect of decreasing rate on battery voltage of nickel-iron cell [19].

4.4.3 Discharge characteristics

The nickel-iron battery may be discharged at any current rate it will deliver, but the discharge should not be continued beyond the point where the battery nears exhaustion. It is best adapted to low or moderate rates of discharge (1- to 8-h rate). Figure (4.11) shows the discharge curves at different rates of discharge at 25°C [19].

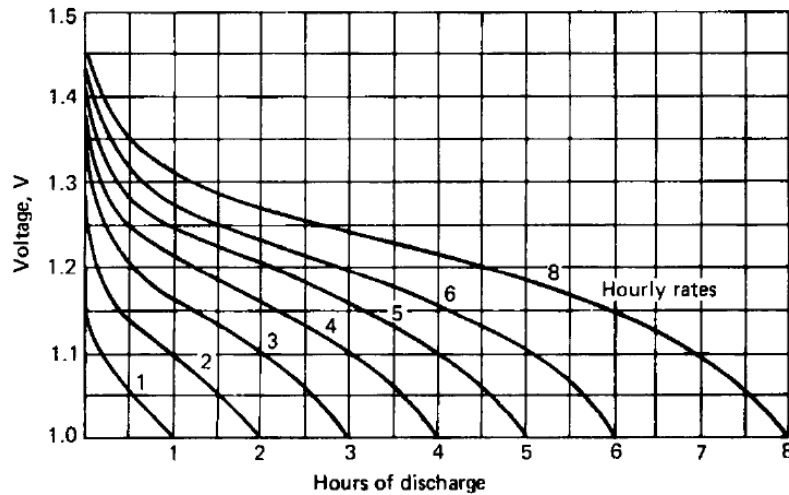


Figure (4.11): Time-voltage discharge curves of nickel-iron battery; end voltage 1.0 V per cell [19].

4.4.4 Self-discharge

The self-discharge rate, charge retention, or stand characteristic of the nickel-iron battery is poor. At 25°C a cell will lose 15% of its capacity in the first 10 days and 20 to 40% in a month. At lower temperatures, the self-discharge rate is lower. For example, at 0°C the losses are less than one-half of those experienced at 25°C [19].

4.4.5 Internal resistance

To a rough approximation, the internal resistance R_i can be estimated for tubular Ni-Fe from the equation

$$R_i \times C = 0.4 \quad (4.11)$$

Where,

R_i : internal resistance (Ω).

C: battery capacity (Ah).

For example, $R_i = 0.004 \, \Omega$ for a 100-Ah battery, the value of R_i remains constant through the first half of the discharge, and then increases about 50% during the latter half of the discharge [19].

4.4.6 Life

The main advantages of the tubular-type nickel-iron battery are its extremely long life and rugged construction. Battery life varies with the type of service but ranges from 8 years for heavy duty to 25 years or more for standby or float service. With moderate care, 2000 cycles can be expected; with good care, for example, by limiting temperatures to below 35°C, cycle life of 3000 to 4000 cycles has been achieved.

The battery is less damaged by repeated deep discharge than any other battery system. In practice, an operator will drive a battery-operated vehicle until it stalls, at which point the battery voltage is a fraction of a volt per cell (some cells may be in reverse). This has a minimal effect on the nickel-iron battery in comparison with other systems [19].

4.4.7 Charging

Charging of the batteries can be accomplished by a variety of schemes. As long as the charging current does not produce excessive gassing (spray out of the vent cap), or temperature rise (above 45°C), any current can be used. Excessive gassing will require more frequent addition of water. If the cell voltage is limited to 1.7 V, these conditions should not

be a consideration. Typical charging curves are given in Figure (4.12). The Ampere hour input should return 25 to 40% excess of the previous discharge to ensure complete charging. The suggested charge rate is normally between 15 and 20 A per 100 Ah of battery capacity. This rate would return the capacity in the 6- to 8-h time frame. The effect of temperature on charging is shown in figure (4.13).

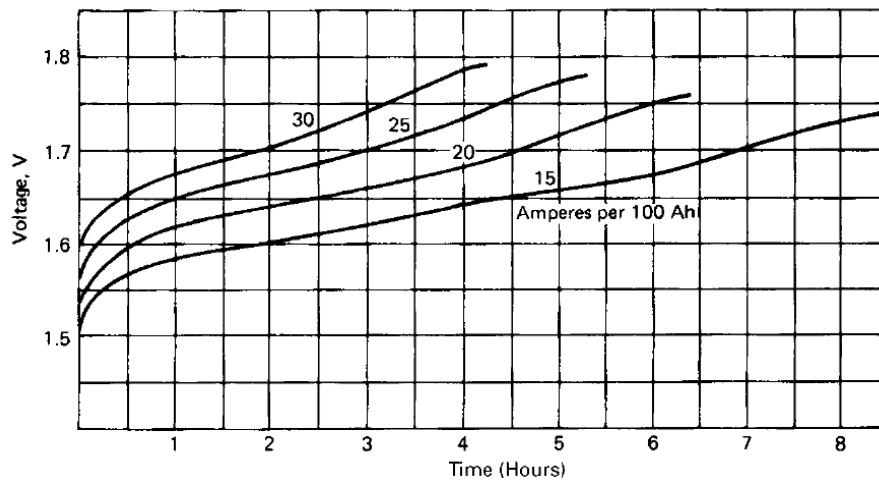


Figure (4.12): Typical charging voltage for nickel-iron battery at various rates [19].

Constant current and modified constant potential (taper), shown in figure (4.13), are common recharging techniques. The charging circuit should contain a current-limiting device to avoid thermal runaway on charge. Recharging each night after use (cycle charging) is the normal procedure. The batteries can be trickle-charged to maintain them at full capacity for emergency use. A trickle charge rate of 0.004 to 0.006 A/Ah of battery capacity overcomes the internal self-discharge and maintains the battery at full charge. Following an emergency discharge, a separate recharge is needed. For applications such as railroad signals, charging at a

continuous average current may be the most economic method. Here a modest drain is required when no trains are passing but quite a heavy drain when a train passes, yet the total Ampere-hours over a period of 24 h remains fairly constant. For this situation, a constant current equal to that required to maintain the battery can be used [19].

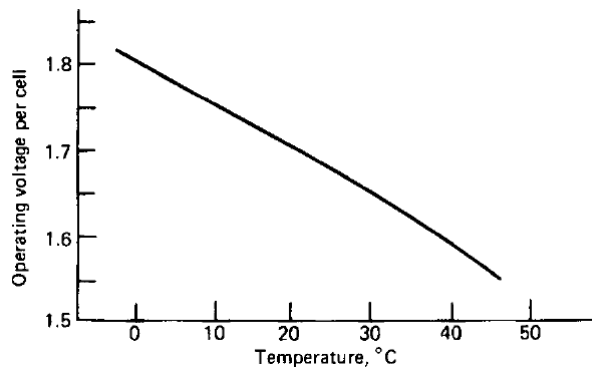


Figure (4.13): Voltage variation with temperature [19].

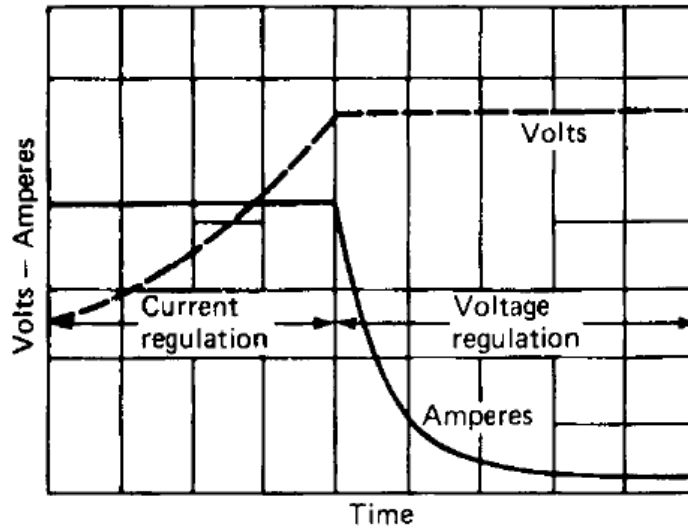


Figure (4.14): Effects of “regulators” with voltage and current regulation [19].

Chapter Five

Lead Acid Battery Characteristics

Chapter Five

Lead Acid Battery Characteristics

5.1 The Discharge Process under 8.4A Current Load

Discharge process (the function of removing current from a cell or battery) was done by a simple circuit, which consists of lamps with different power. Each one was connected with battery via a digital ampere meter, to measure the current delivered from battery. A digital volt meter was used to measure the battery voltage. A hydrometer was used to measure the electrolyte density and a thermo meter was used to measure the electrolyte and the ambient temperatures. The loads at which the battery was discharged were of the currents (8.4A, 6.2A, 4.25A and 2.2A). For each load we construct a table of many parameters as it is shown in tables (5.1), (5.2), (5.3), (5.4) and (5.5).

Hydrometer (Nicholson): Is an instrument used to measure the specific gravity (or relative density) of liquids; that is, the ratio of the density of the liquid to the density of water. A hydrometer is usually made of glass and consists of a cylindrical stem and a bulb weighted with mercury or lead shot to make it float upright. The liquid to be tested is poured into a tall container, often a graduated cylinder, and the hydrometer is gently lowered into the liquid until it floats freely. The point at which the surface of the liquid touches the stem of the hydrometer is noted. Hydrometers usually contain a scale inside the stem, so that the specific gravity can be read directly. A variety of scales exists, and is used depending on the context [25].

In this chapter some curves will show the relations between several parameters such as specific gravity (ρ), open circuit voltage (V_{OC}), battery voltage (V_b), battery current (I_b), ampere hour (Ah), watt hour (Wh), ampere hour capacity (AhC), watt hour capacity (WhC), depth of discharged (DOD) and state of charged (SOC). The curves from (5.1) to (5.11) illustrate the different reactions at a battery discharge current amounting to 2.2A.

Table (5.1): (12V/60Ah) lead acid battery behavior under (8.4A) discharge current.

No	Time (hr)	Battery voltage (V)	Current (A)	Battery resistance $\Omega(t)$	Lamp resistance $\Omega(t)$ - (load)	ρ (g/liter)	Battery voltage from equation (5.1)	Ah	AhC	State of charge (%)	DOD (%)	Wh	WhC	Battery temperature (°C)	Ambient temperature (°C)	Open circuit voltage (v)
0	0	13	8.4	0.027	1.55	1240	12.42	0	60	100	0	0	780	21	23	13.23
1	0.5	12.45	8.3	0.024	1.50	1227	12.35	4.2	55.8	93.00	7.00	54.60	725.40	21	23	12.65
2	1	12.38	8.2	0.024	1.51	1214	12.28	4.15	51.65	86.08	13.92	51.66	673.74	21	23	12.58
3	1.5	12.31	8.1	0.025	1.52	1201	12.21	4.1	47.55	79.25	20.75	50.75	622.99	21	23	12.51
4	2	12.23	8	0.025	1.53	1188	12.13	4.05	43.5	72.50	27.50	49.84	573.15	21	23	12.43
5	2.5	12.16	7.9	0.025	1.54	1175	12.06	4	39.5	65.83	34.17	48.94	524.21	21	23	12.36
6	3	12.09	7.8	0.026	1.55	1162	11.99	3.95	35.55	59.25	40.75	48.04	476.17	21	23	12.29
7	3.5	12.02	7.7	0.026	1.56	1149	11.92	3.9	31.65	52.75	47.25	47.16	429.01	21	23	12.22
8	4	11.95	7.6	0.026	1.57	1136	11.85	3.85	27.8	46.33	53.67	46.28	382.74	21	23	12.15
9	4.5	11.88	7.5	0.027	1.58	1123	11.78	3.8	24	40.00	60.00	45.40	337.33	21	23	12.08
								$\Sigma Ah = 36$				$\Sigma Wh = 442.6$				

Table (5.2): (12V/60Ah) lead acid battery behavior under (6.2A) discharge current.

No	Time (hr)	Battery resistance $\Omega(t)$	Lamp resistance $\Omega(t)$ - (load)	Battery voltage (V)	Battery voltage from equation (5.1)	Current (A)	ρ (g/liter)	Ah	AhC	State of charge (%)	DOD (%)	Wh	WhC	Open circuit voltage (v)
0	0	0.0371	2.10	13	12.42	6.2	1240	0	60	100	0	0	780	13.23
1	0.5	0.0324	2.02	12.47	12.37	6.17	1230	3.10	56.90	94.83	5.17	40.30	739.70	12.67
2	1	0.0326	2.02	12.41	12.31	6.14	1221	3.09	53.82	89.69	10.31	38.46	701.24	12.61
3	1.5	0.0327	2.02	12.36	12.26	6.11	1211	3.07	50.75	84.58	15.43	38.11	663.13	12.56
4	2	0.0329	2.02	12.31	12.21	6.08	1201	3.06	47.69	79.48	20.52	37.76	625.37	12.51
5	2.5	0.0331	2.03	12.25	12.15	6.05	1191	3.04	44.65	74.42	25.58	37.41	587.96	12.45
6	3	0.0332	2.03	12.20	12.10	6.02	1182	3.03	41.63	69.38	30.63	37.06	550.90	12.40
7	3.5	0.0334	2.03	12.14	12.04	5.99	1172	3.01	38.62	64.36	35.64	36.72	514.18	12.34
8	4	0.0336	2.03	12.09	11.99	5.96	1162	3.00	35.62	59.37	40.63	36.37	477.81	12.29
9	4.5	0.0337	2.03	12.04	11.94	5.93	1152	2.98	32.64	54.40	45.60	36.03	441.78	12.24
10	5	0.0339	2.03	11.98	11.88	5.9	1143	2.97	29.68	49.46	50.54	35.69	406.08	12.18
11	5.5	0.0341	2.03	11.93	11.83	5.87	1133	2.95	26.73	44.54	55.46	35.35	370.73	12.13
12	6	0.0342	2.03	11.88	11.78	5.84	1123	2.94	23.79	39.65	60.35	35.02	335.72	12.08
								Σ Ah = 36.21				Σ Wh = 444.28		

Table (5.3): (12V/60Ah) lead acid battery behavior under (4.25A) discharge current.

No	Time (hr)	Battery voltage (V)	Current (A)	Battery resistance $\Omega(t)$	Lamp resistance $\Omega(t)$ - (load)	ρ (g/liter)	Battery voltage from equation (5.1)	Ah	AhC	State of charge (%)	DOD (%)	Wh	WhC	Open circuit voltage (v)
0	0	13	4.25	0.054	3.06	1240	12.42	0	60	100	0	0	780	13.23
1	1	12.45	4.20	0.048	2.96	1227	12.35	4.25	55.75	92.92	7.083	52.91	727.09	12.65
2	2	12.38	4.15	0.048	2.98	1214	12.28	4.2	51.55	85.92	14.08	51.99	675.11	12.58
3	3	12.31	4.10	0.049	3.00	1201	12.21	4.15	47.4	79.00	21	51.07	624.04	12.51
4	4	12.23	4.05	0.049	3.02	1188	12.13	4.1	43.3	72.17	27.83	50.16	573.88	12.43
5	5	12.16	4.00	0.050	3.04	1175	12.06	4.05	39.25	65.42	34.58	49.26	524.62	12.36
6	6	12.09	3.95	0.051	3.06	1162	11.99	4	35.25	58.75	41.25	48.37	476.25	12.29
7	7	12.02	3.90	0.051	3.08	1149	11.92	3.95	31.3	52.17	47.83	47.48	428.77	12.22
8	8	11.95	3.85	0.052	3.10	1136	11.85	3.9	27.4	45.67	54.33	46.60	382.18	12.15
9	9	11.88	3.80	0.053	3.13	1123	11.78	3.85	23.55	39.25	60.75	45.73	336.45	12.08
								$\Sigma Ah = 36.45$				$\Sigma Wh = 443.55$		

Table (5.4): (12V/60Ah) lead acid battery behavior under (2.2A) discharge current.

No	Time (hr)	Battery voltage (V)	Current (A)	Battery resistance $\Omega(t)$	Lamp resistance $\Omega(t)$ - (load)	ρ (g/liter)	Battery voltage from equation (5.1)	Ah	AhC	Sate of charge (%)	DOD (%)	Wh	WhC	Open circuit voltage (v)
0	0	13	2.2	0.105	5.909	1240	12.42	0	60	100	0	0	780	13.23
1	1	12.48	2.18	0.108	5.727	1234	12.38	2.2	57.8	96.33	3.67	27.47	752.53	12.72
2	2	12.45	2.16	0.109	5.763	1227	12.35	2.18	55.62	92.70	7.30	27.14	725.39	12.68
3	3	12.41	2.14	0.110	5.801	1221	12.31	2.16	53.46	89.10	10.90	26.81	698.58	12.65
4	4	12.38	2.12	0.111	5.838	1214	12.28	2.14	51.32	85.53	14.47	26.49	672.09	12.61
5	5	12.34	2.1	0.112	5.877	1208	12.24	2.12	49.2	82.00	18.00	26.16	645.93	12.58
6	6	12.31	2.08	0.113	5.916	1201	12.21	2.1	47.1	78.50	21.50	25.84	620.09	12.54
7	7	12.27	2.06	0.114	5.956	1195	12.17	2.08	45.02	75.03	24.97	25.52	594.57	12.51
8	8	12.23	2.04	0.116	5.997	1188	12.13	2.06	42.96	71.60	28.40	25.20	569.36	12.47
9	9	12.20	2.02	0.117	6.039	1182	12.10	2.04	40.92	68.20	31.80	24.89	544.48	12.43
10	10	12.16	2	0.118	6.081	1175	12.06	2.02	38.9	64.83	35.17	24.57	519.91	12.40
11	11	12.13	1.98	0.119	6.125	1169	12.03	2	36.9	61.50	38.50	24.25	495.65	12.36
12	12	12.09	1.96	0.120	6.169	1162	11.99	1.98	34.92	58.20	41.80	23.94	471.71	12.33
13	13	12.06	1.94	0.122	6.214	1156	11.96	1.96	32.96	54.93	45.07	23.63	448.09	12.29
14	14	12.02	1.92	0.123	6.260	1149	11.92	1.94	31.02	51.70	48.30	23.32	424.77	12.26
15	15	11.98	1.9	0.124	6.307	1143	11.88	1.92	29.1	48.50	51.50	23.01	401.76	12.22
16	16	11.95	1.88	0.125	6.355	1136	11.85	1.9	27.2	45.33	54.67	22.70	379.06	12.18
17	17	11.91	1.86	0.127	6.405	1130	11.81	1.88	25.32	42.20	57.80	22.40	356.66	12.15
18	18	11.88	1.84	0.128	6.455	1123	11.78	1.86	23.46	39.10	60.90	22.09	334.57	12.11
								$\Sigma Ah = 36.54$				$\Sigma Wh = 445.43$		

5.1.1 Voltage, specific gravity and state of charge

Lead acid cell nominal voltage is 2V, and the lower and upper limits of charging and discharging open circuit voltage are 1.75 and 2.4V at 25°C cell temperature, which is equivalent to 10.5 and 14.4V respectively. As it is shown in figure (5.1.A) for (12V/60Ah) lead acid battery, figure (5.1.B) shows the variation of the current as a function of time. Also we can determine the relationship between current and voltage as it is shown in figure (5.2). Figure (5.3.A) show the specific gravity as a function of time and figure (5.3.B) show the voltage behavior as a function of specific gravity.

Lead - acid battery voltage could be calculated from equation (5.1) [1].

$$V_n = [1.85V + 0.917V(\rho_n - 1)] \times 6 \quad (5.1)$$

Where:

V_n : nominal cell voltage in volt.

ρ_n : electrolyte specific gravity in nominal voltage (gr/liter).

From the previous tables, we see that the under load voltage values are greater than the values from the formula (5.1). Also the open circuit voltage (V_{OC}) values are greater than the under load voltage. Figure (5.4.A) shows V_{OC} as a function of discharged time. Also figure (5.4.B) shows the relation sheep between V_{OC} and specific gravity.

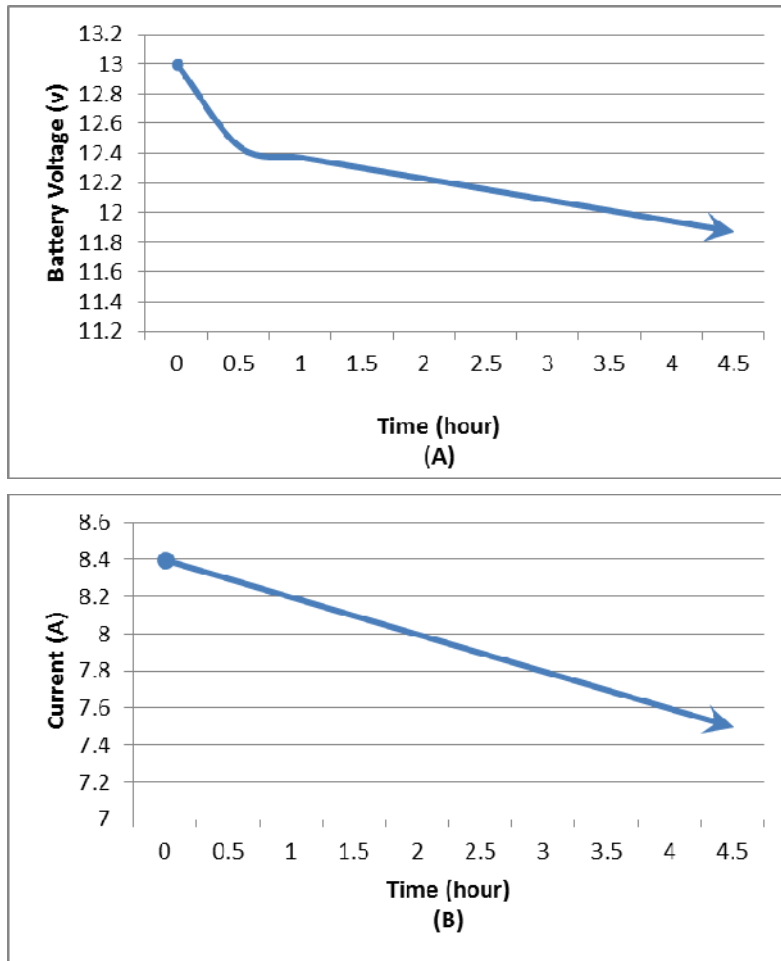


Figure (5.1): Discharge process of the lead acid battery under load

A: Variation of discharge voltage as a function of time.

B: Variation of discharge current as a function of time.

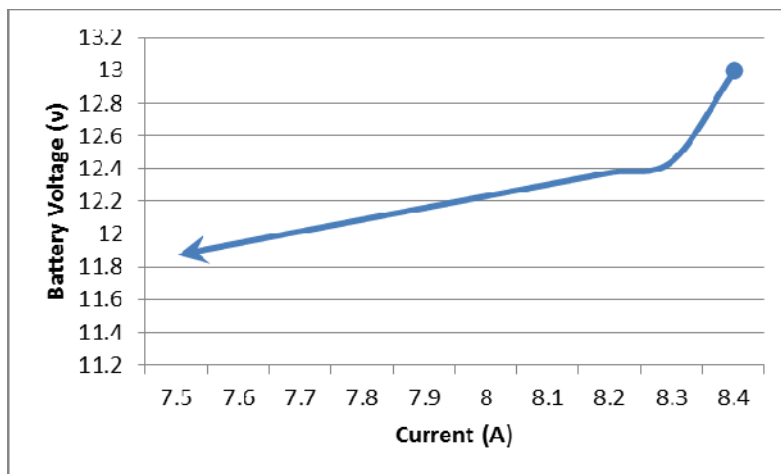


Figure (5.2): Discharge processes of the battery within 4.5 hours, the beginning point of the curve at fully charged battery and the ending point of curve at 40% charged battery.

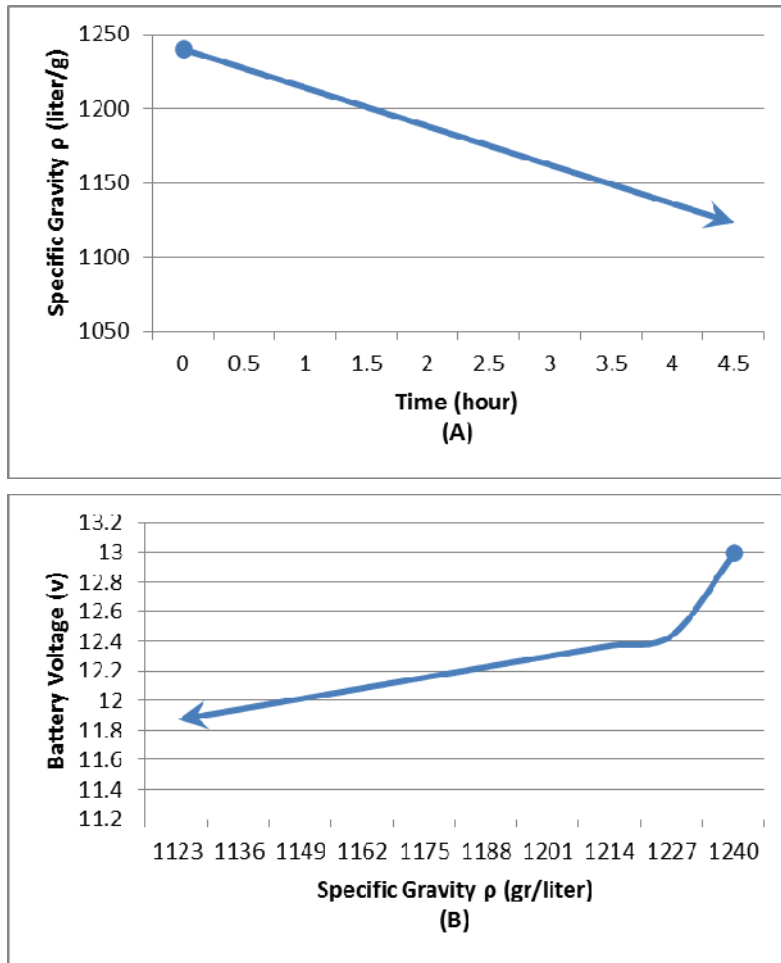
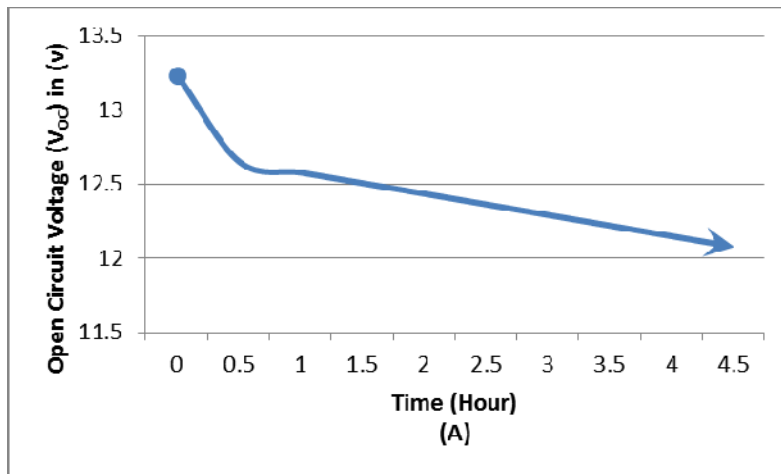


Figure (5.3): Battery discharge process within a 4.5 hours.

A: Specific gravity of the battery solution as a function of time.

B: Battery voltage as a function of specific gravity.



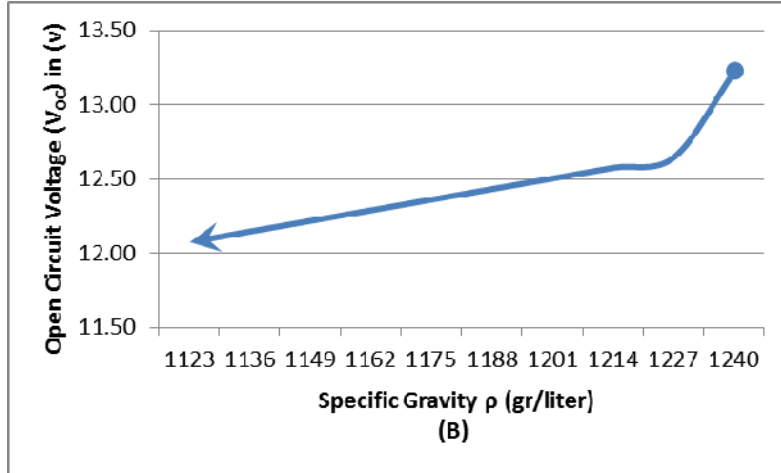


Figure (5.4): Discharge process of the battery.

A: Open circuit voltage behavior during discharge.

B: Open circuit voltage as a function of specific gravity.

5.1.2 The battery internal resistance

The internal resistance of a battery, which creates a voltage, drops in proportion to current is illustrated in figure (5.5). The battery resistance value can be calculated from equation (5.2) or (5.3) [24].

$$R_B = \frac{V_{OC} - V}{I} \quad (5.2)$$

Or

$$R_B = \left(\frac{V_{OC}}{I} \right) - R_L \quad (5.3)$$

Where,

- R_B : internal resistance of the battery.
- V_{OC} : open circuit voltage.
- V : battery voltage under load.
- R_L : total resistance of the load.
- I : the current supplied by the battery.

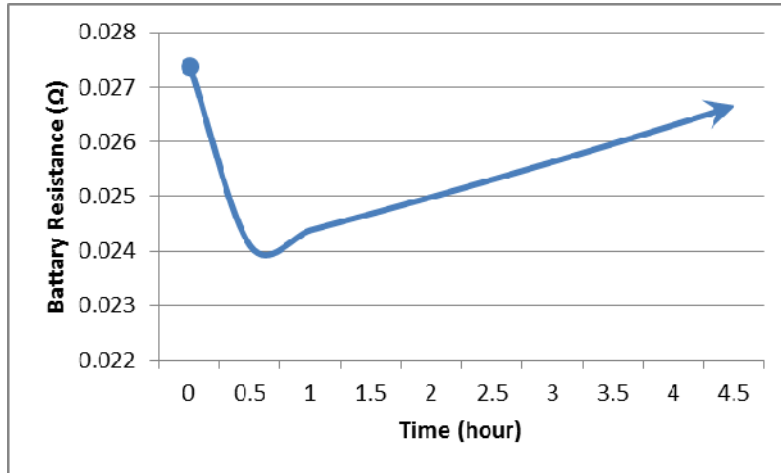


Figure (5.5): The variation of the internal battery resistance as a function of time during discharge.

5.1.3 Storage capacity and efficiency

The energy storage of a battery is expressed by its ampere hour capacity (Ah) or its watt hour capacity (Wh). Ah is the value used to define the capacity of the battery. It is current in ampere, multiplied by the time in hours, during which the current flows from the battery as shown in figure (5.6). For example, a 12V battery rated at 60Ah over 20 hours can deliver 3A per hour for 20 hours (C_{20}). The ampere hour capacity (AhC) is the time integral of the product of discharge current from fully charge (DOD = zero) to (DOD= 60%). Figure (5.7.A) show the decrease of AhC with time of discharge and figure (5.7.B) shows the relationship between AhC and discharge current for typical 60Ah/12V lead acid battery. Figure (5.7.C) shows the relation between AhC and voltage. ($12 \times 60\text{Ah}$) is equivalent to ($720\text{Wh} = 0.72\text{kWh}$) of energy which is known as watt hour capacity. Figure (5.8.A) and (5.8.B) describe the relation between Wh and time of discharge and Wh as a function of voltage. The watt – hour capacity (WhC) or energy

capacity is the time integral of the product of discharge current and voltage from fully charge (DOD = zero) to (DOD= 60%). Figure (5.9.A) shows the WhC behavior as a function of time and figure (5.9.B) shows the relationship between WhC and voltage. The ampere hour efficiency of a battery (η_{Ah}) is the ratio of the number of ampere hours delivered during discharge to that needed to return to its original condition, see equation (5.4). (η_{Wh}) is the ratio of the number of watt hours delivered (energy delivered) during discharge to that needed to return to its original condition, see equation (5.5).

$$\text{Ampere - hour efficiency} = \frac{\text{discharged ampere-hours} \times 100\%}{\text{charging ampere-hours}} \quad (5.4)$$

$$\eta_{Ah} (12V/60Ah) = \frac{(36 \times 100\%)}{44.4} = 81.1\%$$

$$\text{Watt - hour efficiency} = \frac{\text{discharged watt-hours} \times 100\%}{\text{charging watt-hours}} \quad (5.5)$$

$$\eta_{Wh} (12V/60Ah) = \frac{(443 \times 100\%)}{693} = 64\%$$

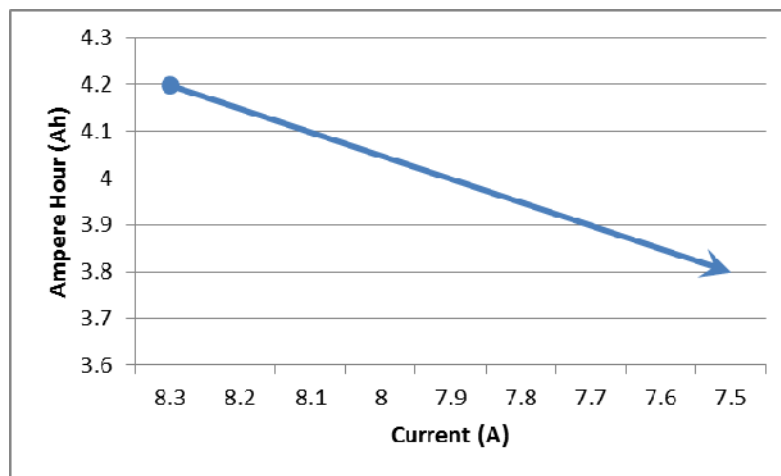


Figure (5.6): Ampere hour within 4.5 hour during discharge process.

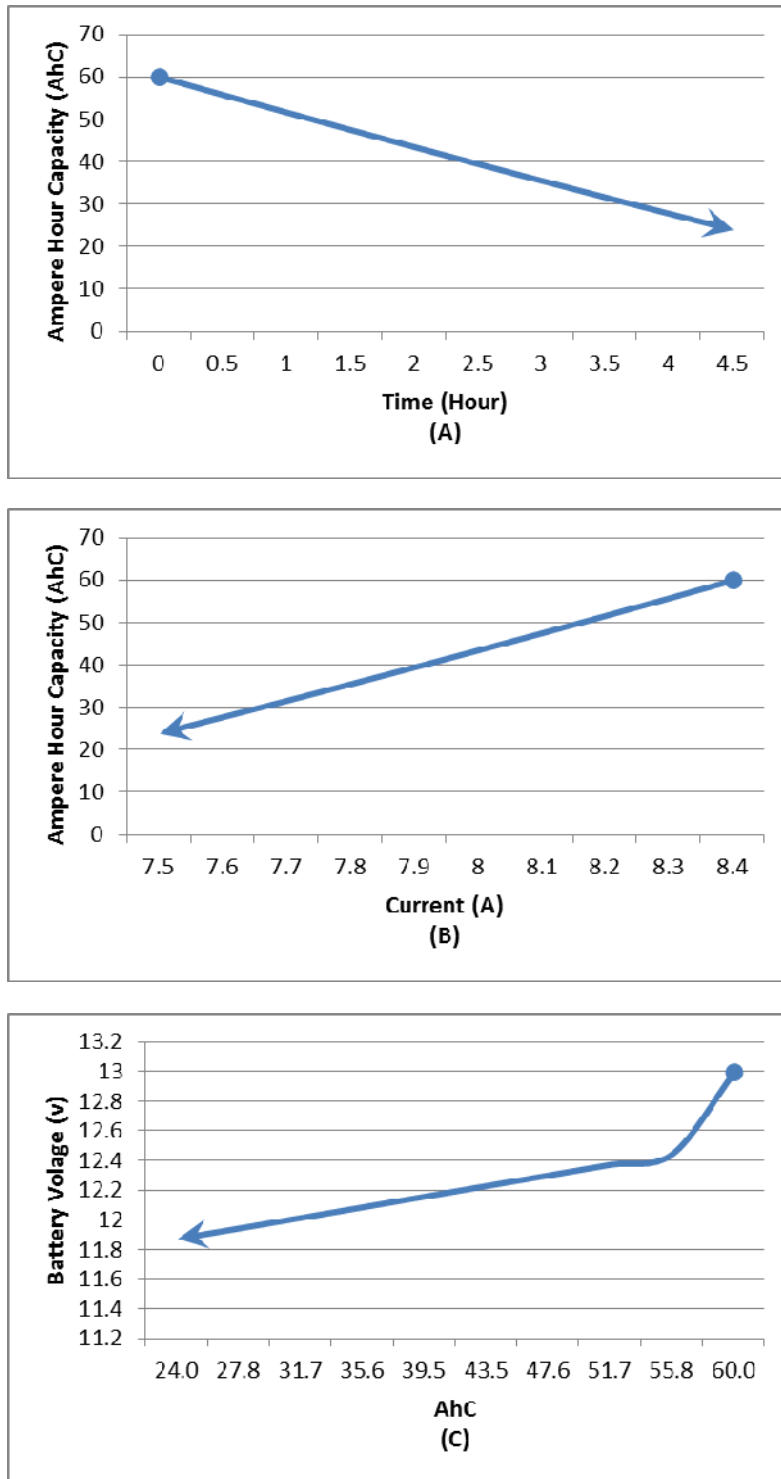


Figure (5.7): Battery ampere hour capacity under discharged process.

A: Battery ampere hour capacity under discharged time.

B: Ampere hour capacity as a function of discharge current.

C: Voltage behavior under the changed of the ampere hour capacity.

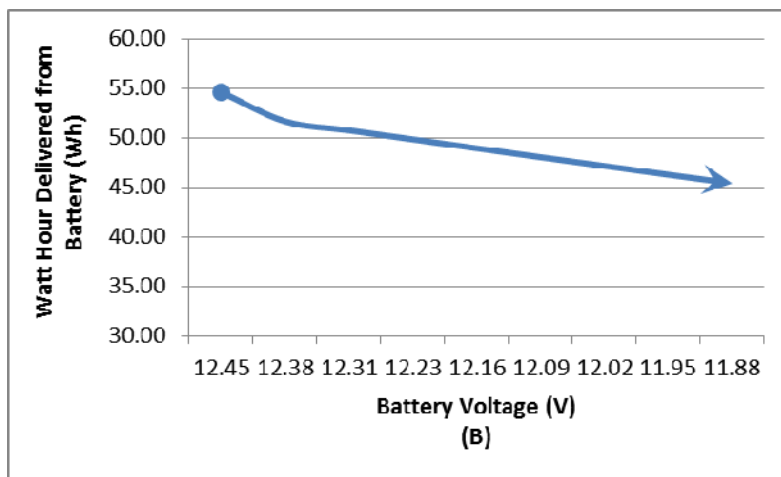
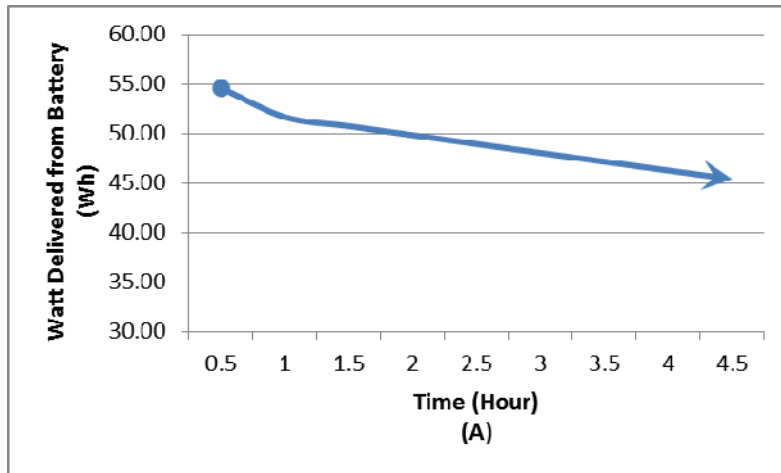
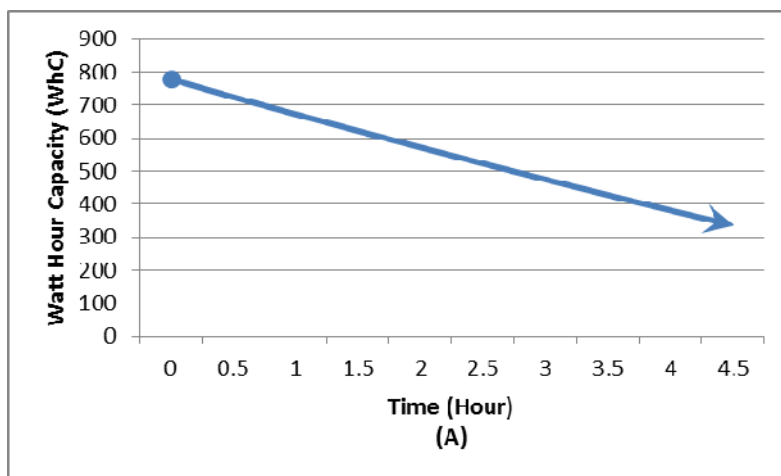


Figure (5.8): Discharge process of the battery.

A: Watt hour during discharge.

B: Relation between watt hours delivered from battery and the voltage.



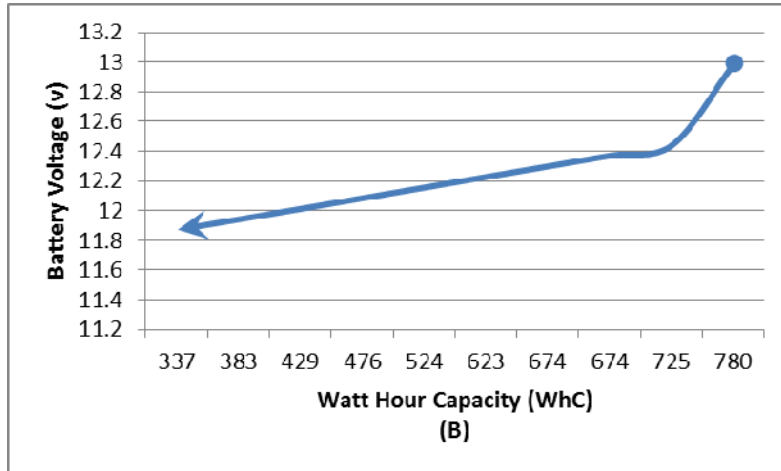


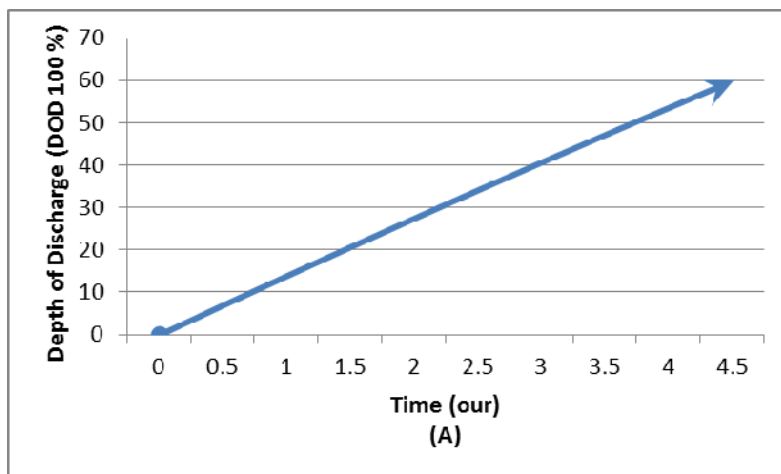
Figure (5.9): Discharge process of the battery.

A: Watt hour capacity as a function of time.

B: Relation between watt hour capacity and battery voltage.

5.1.4 Depth of discharge (DOD)

The Depth of Discharge (DOD) is a measure of how deeply a battery is discharged. When a battery is 100% full, then the DOD is 0%. Conversely, when a battery is 100% empty, the DOD is 100% [1]. Figure (5.10.A) shows how DOD increases with time of discharge while the figures (5.10.B) and (5.10.C) describe the relationship between DOD with voltage and specific gravity.



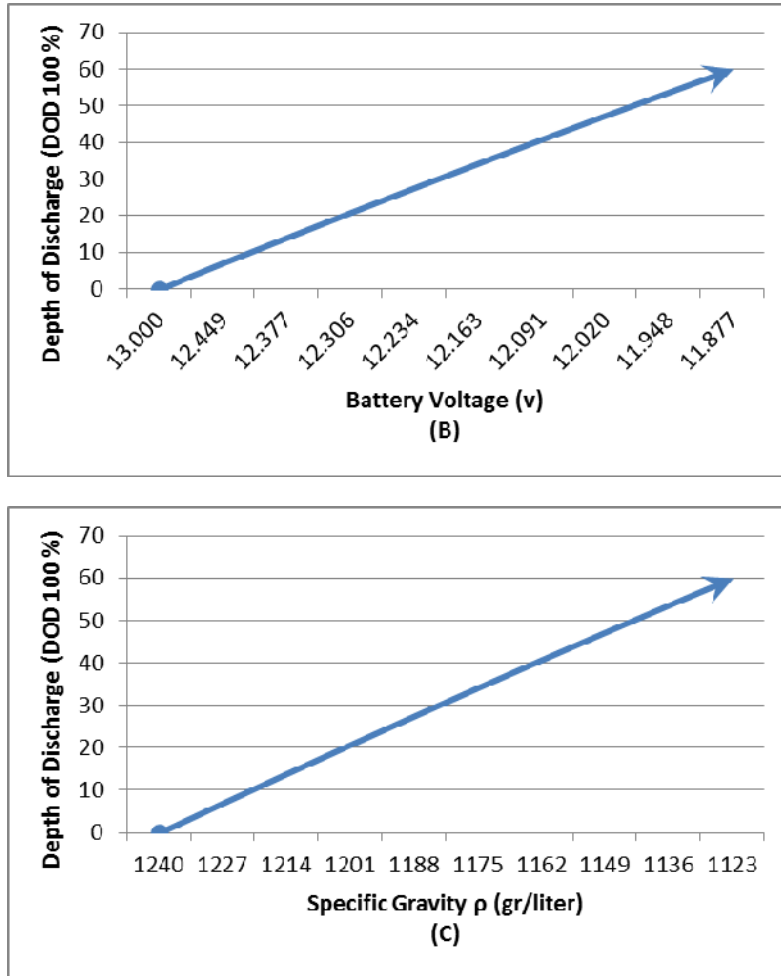


Figure (5.10): Discharge process of the battery.

A: DOD is a function of time.

B: DOD is a function of voltage.

C: DOD is a function of specific gravity.

Considering the curve in figure (5.11), we see that the temperature of battery doesn't differ during discharge.

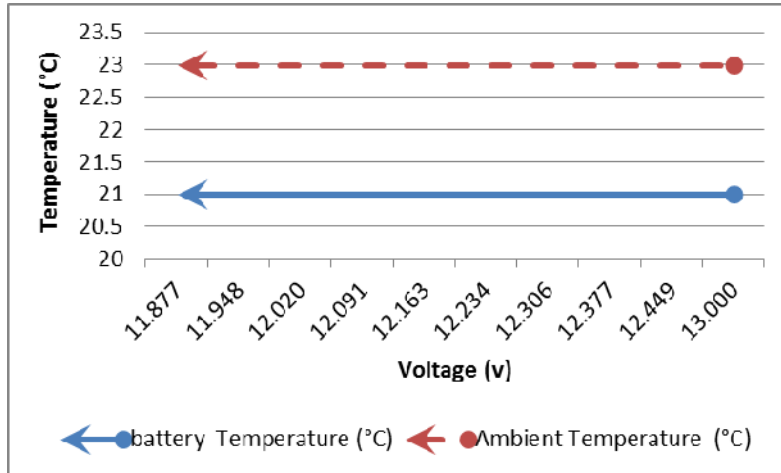


Figure (5.11): Battery temperature during battery discharge process.

Figure (5.12) shows the time needed to discharge the battery under different loads, as the current increases, the time of the discharge decreases and the battery becomes empty or reaches to (DOD = 60%) quickly and the same is true for SOC which reaches (40%) quickly for the higher current, see figure (5.13).

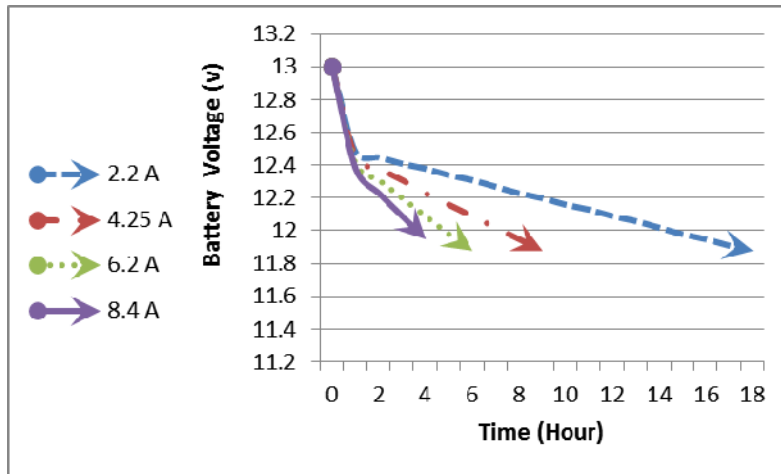


Figure (5.12): The relationship between under load voltage and time of discharge for different load currents.

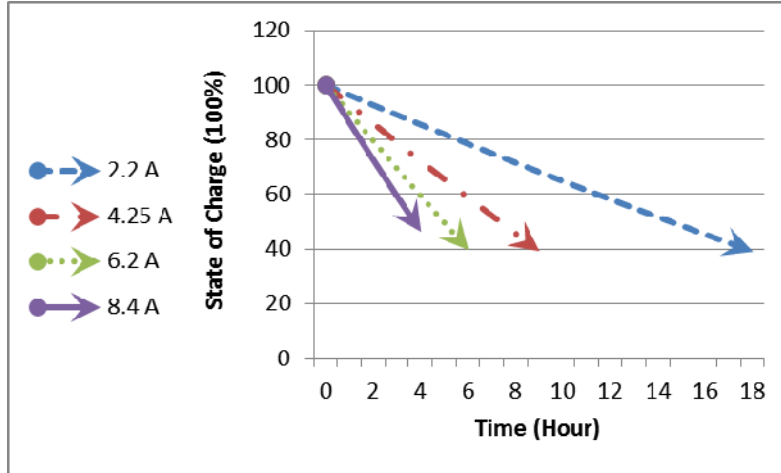


Figure (5.13): The relationship between SOC and time of discharge for different load currents.

5.1.5 Battery completed discharged under 8.4A current load

In table (5.5), the battery was discharged at 8.4A current until it reached DOD=100% or SOC=0%. It means the battery becomes completely empty and so the electrolyte was converted to water. There, upon the battery was damaged and could never be charged again. Table (5.5) shows that the electrolyte specific gravity became 1032 gr/liter which is very closed to water density which is (1000 gr/liter). At this condition, the battery voltage dropped to 9.43V while the open circuit voltage of the battery dropped to 9.63V. Therefore, the battery should never be discharged under 10.8V.

Figure (5.14) and (5.15) show the battery behavior under the mentioned damaging discharge. In this time (SOC = 0%), (DOD = 100%), (AhC = 0) and (V_{OC} = 9.63V) and the time of discharged equal (8 hr) to discharged battery under (8.4A) loads.

Table (5.5): (12V/60Ah) lead acid battery completed discharged behavior under (8.4A) current.

No	Time (hr)	Battery voltage (V)	Current (A)	Battery resistance $\Omega(t)$	Lamp resistance $\Omega(t)$ - load	ρ (g/liter)	Battery voltage from equation (5.1)	Ah	AhC	State of charge %	DOD %	Wh	WhC	Battery temperature (°C)	Ambient temperature (°C)	Open circuit voltage (v)
0	0	13	8.4	0.027	1.55	1240	12.42	0	60	100	0	0	780	21	23	13.23
1	0.5	12.45	8.3	0.024	1.50	1227	12.35	4.2	55.8	93.00	7.00	54.60	725.40	21	23	12.65
2	1	12.38	8.2	0.024	1.51	1214	12.28	4.15	51.65	86.08	13.92	51.66	673.74	21	23	12.58
3	1.5	12.31	8.1	0.025	1.52	1201	12.21	4.1	47.55	79.25	20.75	50.75	622.99	21	23	12.51
4	2	12.23	8	0.025	1.53	1188	12.13	4.05	43.5	72.50	27.50	49.84	573.15	21	23	12.43
5	2.5	12.16	7.9	0.025	1.54	1175	12.06	4	39.5	65.83	34.17	48.94	524.21	21	23	12.36
6	3	12.09	7.8	0.026	1.55	1162	11.99	3.95	35.55	59.25	40.75	48.04	476.17	21	23	12.29
7	3.5	12.02	7.7	0.026	1.56	1149	11.92	3.9	31.65	52.75	47.25	47.16	429.01	21	23	12.22
8	4	11.95	7.6	0.026	1.57	1136	11.85	3.85	27.8	46.33	53.67	46.28	382.74	21	23	12.15
9	4.5	11.88	7.5	0.027	1.58	1123	11.78	3.8	24	40.00	60.00	45.40	337.33	21	23	12.08
10	5	11.53	7.3	0.027	1.58	1110	11.43	3.75	20.25	33.75	66.25	44.54	292.80	21	23	11.73
11	5.5	11.18	7.1	0.028	1.57	1097	11.08	3.65	16.6	27.67	72.33	42.07	250.72	21	23	11.38
12	6	10.83	6.9	0.029	1.57	1084	10.73	3.55	13.05	21.75	78.25	39.68	211.05	21	23	11.03
13	6.5	10.48	6.7	0.030	1.56	1071	10.38	3.45	9.6	16.00	84.00	37.35	173.69	21	23	10.68
14	7	10.13	6.4	0.031	1.58	1058	10.03	3.35	6.25	10.42	89.58	35.10	138.60	21	23	10.33
15	7.5	9.78	6.1	0.033	1.60	1045	9.68	3.2	3.05	5.08	94.92	32.41	106.19	21	23	9.98
16	8	9.43	5.8	0.034	1.63	1032	9.33	3.05	0	0.00	100.00	29.82	76.37	21	23	9.63

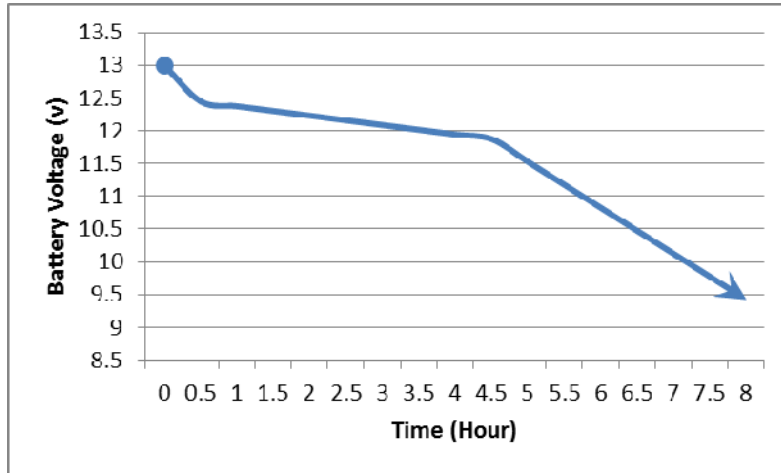


Figure (5.14): The variation of battery voltage in a function of time until it was completely discharged.

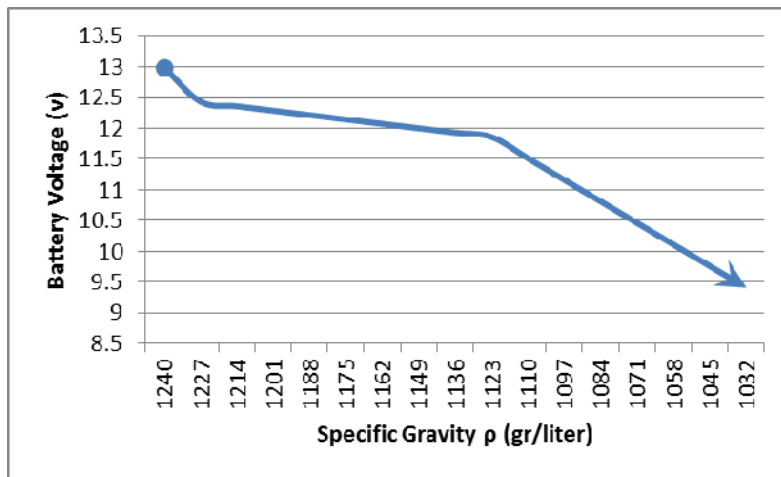


Figure (5.15): Battery voltage in a function of specific gravity until totally discharged (DOD = 100%).

5.2 Battery Charging Process

The constant voltage (constant potential) charge method applies a constant voltage to the battery which is greater than the battery voltage as it shown in figure (5.16.A). Then a current will flow through the battery in the reverse direction to when it is supplying current, and then the battery will be charge as shown in figure (5.16.B) and the charge current will

decrease automatically according to the state of charging in table (5.6). The specific gravity will increase as it is shown in figure (5.16.C).

The energy delivered from a source to charge the battery decreases with time of charge, while the current decreases and the specific gravity increases as shown in figures (5.17.A), (5.17.B) and (5.17.C). This corresponds to growth of the ampere hour capacity (AhC) when time of charge increases. The current delivered from source to battery decreases and the specific gravity increases as it is shown in figures (5.18.A), (5.18.B) and (5.18.C). The watt hour's capacity (WhC) varies as AhC as illustration in figures (5.19.A), (5.19.B) and (5.19.C).

Table (5.6): (12V/60Ah) lead acid battery behavior during constant voltage charged process

No	Time (hr)	Under load source voltage (v)	Battery voltage (v) –connected with source-	Current (A)	ρ (g/liter)	Ah	AhC	SOC	DOD	Wh	WhC	Open circuit voltage (v)
1	0	16	14.4	7	1120	0	24	40	60	0	337	12.56
2	1	15.92	14.4	6	1126	7	30.4	50.67	49.33	112.00	409.55	12.59
3	2	15.84	14.4	5	1132	6	35.8	59.67	40.33	95.52	469.67	12.62
4	3	15.76	14.4	4	1137	5	40.2	67.00	33.00	79.20	517.30	12.66
5	4	15.68	14.4	3.67	1143	4	43.6	72.67	27.33	63.04	560.86	12.69
6	5	15.60	14.4	3.34	1149	3.67	46.67	77.78	22.22	57.55	600.35	12.72
7	6	15.52	14.4	3.01	1155	3.34	49.41	82.35	17.65	52.10	636.73	12.75
8	7	15.44	14.4	2.68	1161	3.01	51.82	86.37	13.63	46.72	668.99	12.78
9	8	15.36	14.4	2.35	1166	2.68	53.9	89.83	10.17	41.38	697.11	12.82
10	9	15.28	14.4	2.02	1172	2.35	55.65	92.75	7.25	36.10	721.06	12.85
11	10	15.20	14.4	1.69	1178	2.02	57.07	95.12	4.88	30.87	740.82	12.88
12	11	15.12	14.4	1.36	1184	1.69	58.16	96.93	3.07	25.69	756.38	12.91
13	12	15.04	14.4	1.03	1190	1.36	58.92	98.20	1.80	20.56	767.71	12.94
14	13	14.96	14.4	0.7	1195	1.03	59.35	98.92	1.08	15.49	774.80	12.98
15	14	14.88	14.4	0.37	1201	0.7	59.45	99.08	0.92	10.47	777.61	13.01
16	15	14.80	14.4	0.05	1207	0.37	59.82	99.70	0.30	5.51	778.26	13.04
17	16	14.72	14.4	0.042	1213	0.05	59.87	99.78	0.22	0.74	778.81	13.07
18	17	14.69	14.4	0.034	1219	0.042	59.912	99.85	0.15	0.62	779.26	13.10
19	18	14.66	14.4	0.026	1224	0.034	59.946	99.91	0.09	0.50	779.60	13.13
20	19	14.63	14.4	0.018	1230	0.026	59.972	99.95	0.05	0.38	779.83	13.17
21	20	14.60	14.4	0.01	1236	0.018	59.99	99.98	0.02	0.26	779.97	13.20
22	21	14.57	14.4	0.002	1242	0.01	60	100.0	0.00	0.15	779.99	13.23
						$\Sigma \text{ Ah} = 44.4$				$\Sigma \text{ Wh} = 694.83$		
						$\eta_{\text{Ah}} = 0.811$				$\eta_{\text{Wh}} = 0.64$		

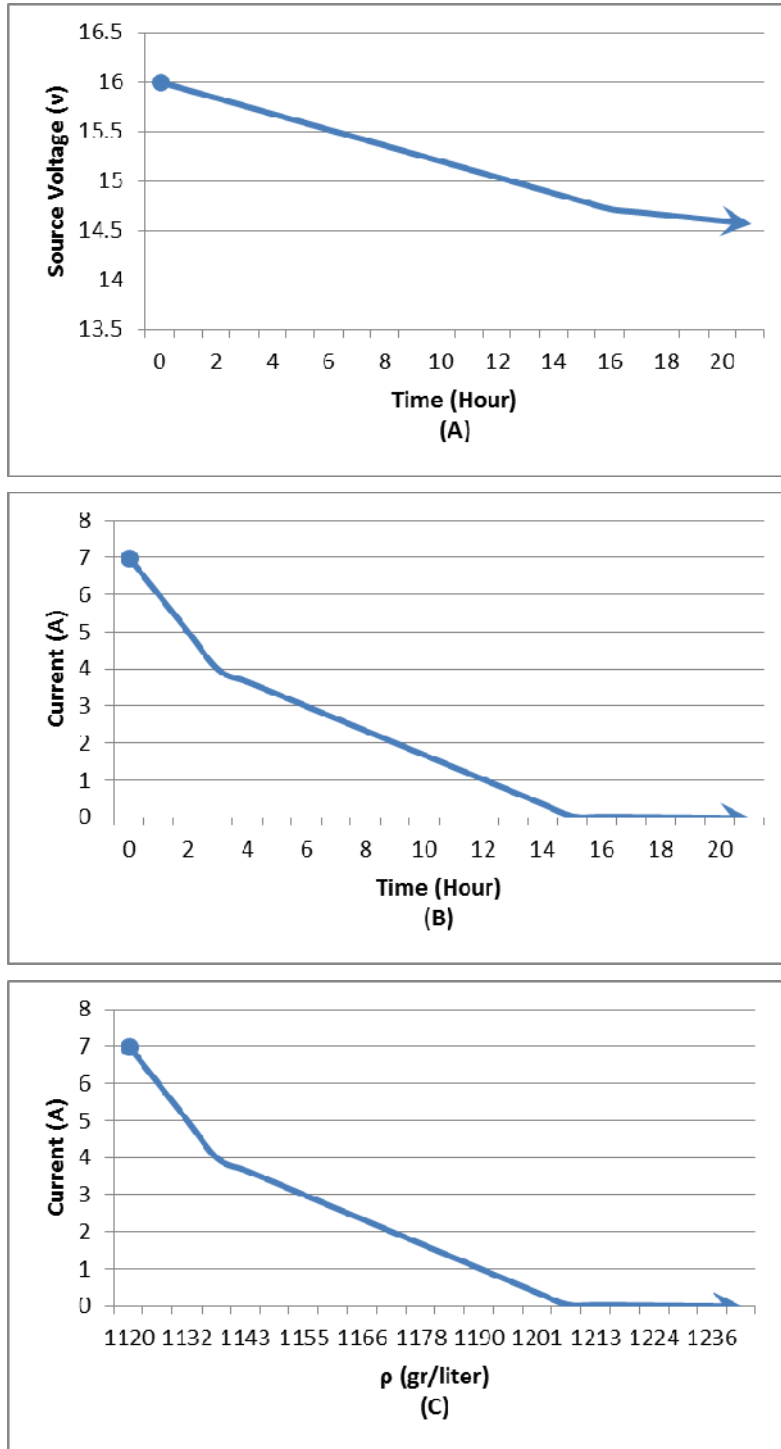


Figure (5.16): Constant voltage charge process of lead acid battery.

A: The decrease of the source voltage under charging process.

B: The current under charging within time.

C: The characteristics of electrolyte specific gravity as a function of charging current.

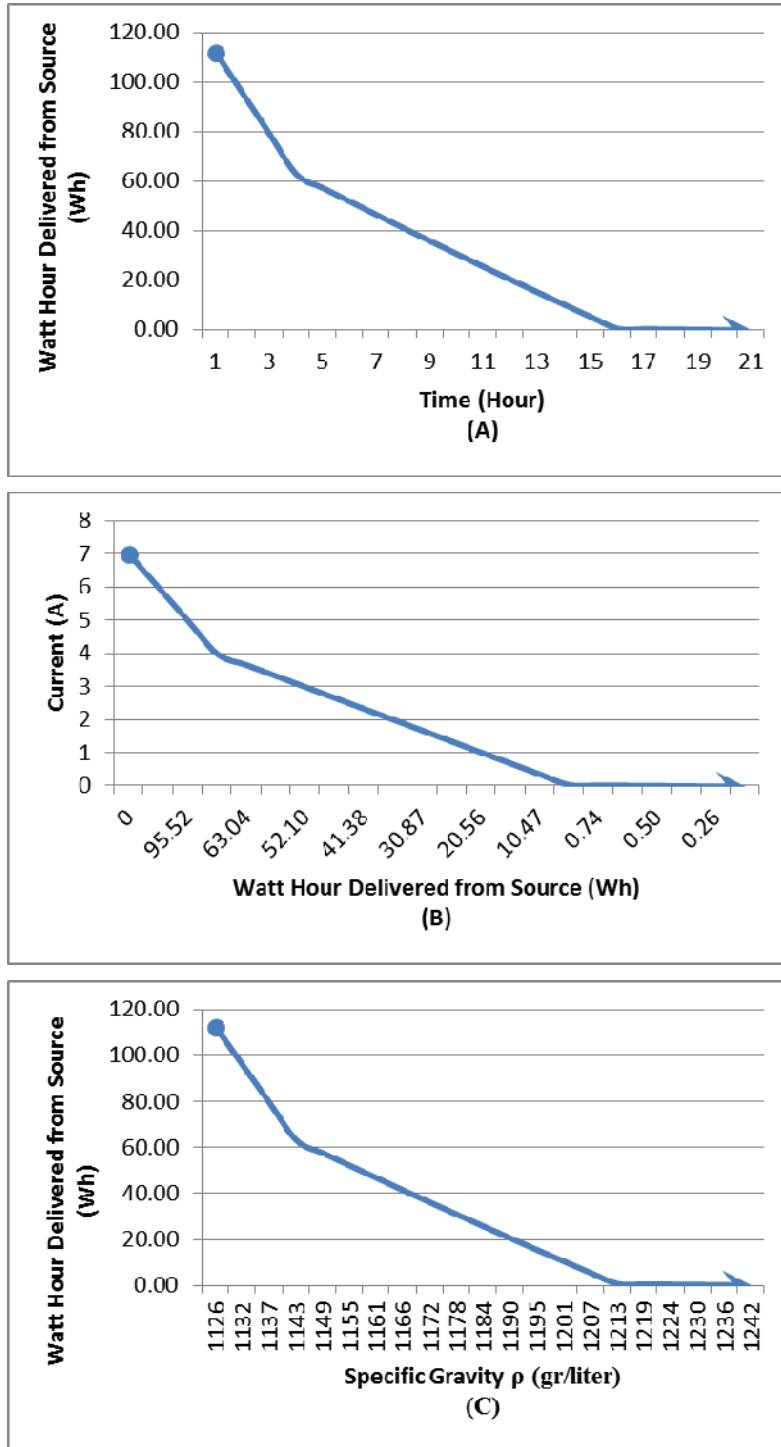


Figure (5.17): Constant voltage charge process of lead acid battery.

A: The decrease of watt hour delivered from the source within time.

B: Watt hour delivered from the source as a function of current.

C: Electrolyte specific gravity as a function of watt hour.

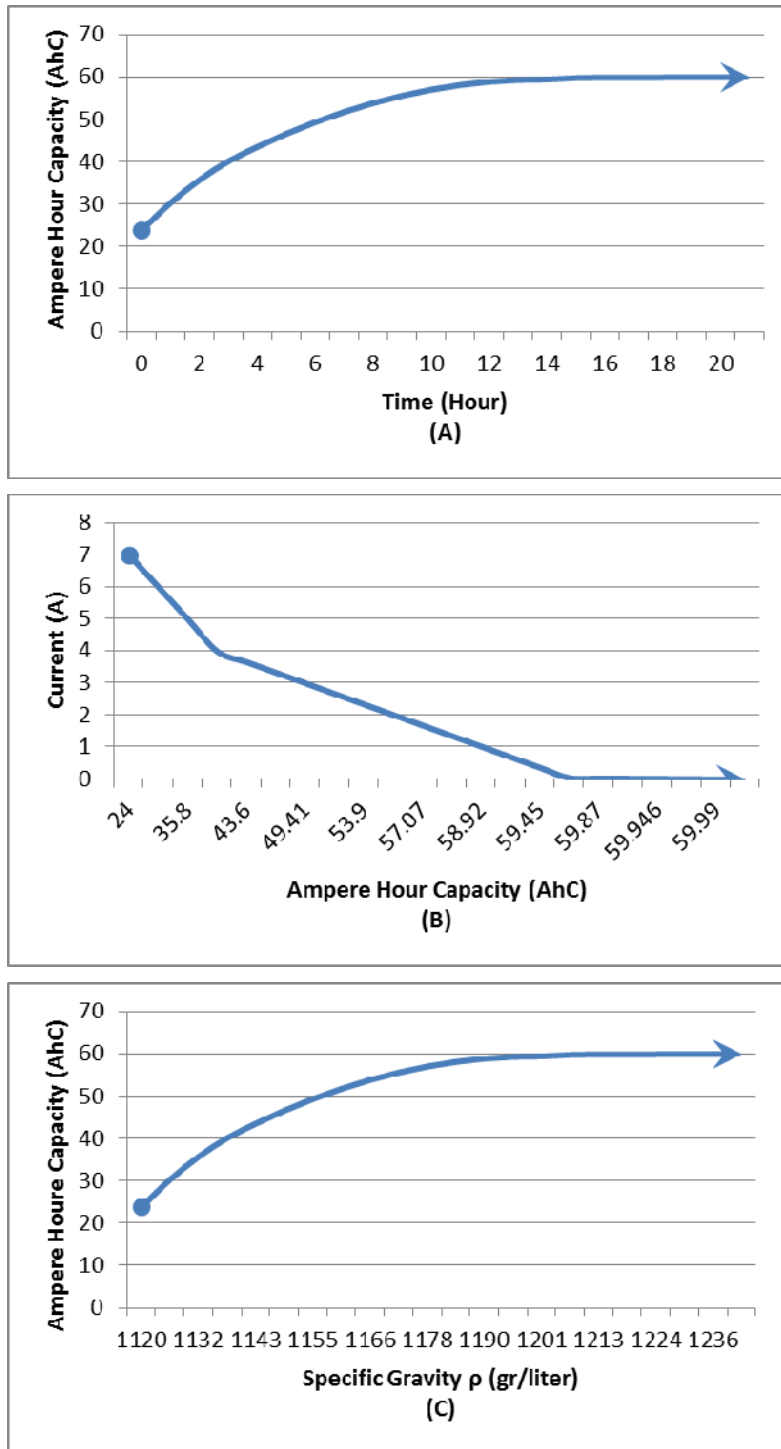


Figure (5.18): Constant potential charge process of lead acid battery.

A: Ampere hour capacity during 21 hour.

B: Ampere hour capacity as a function of current.

C: The relation between ampere hour capacity and electrolyte specific gravity.

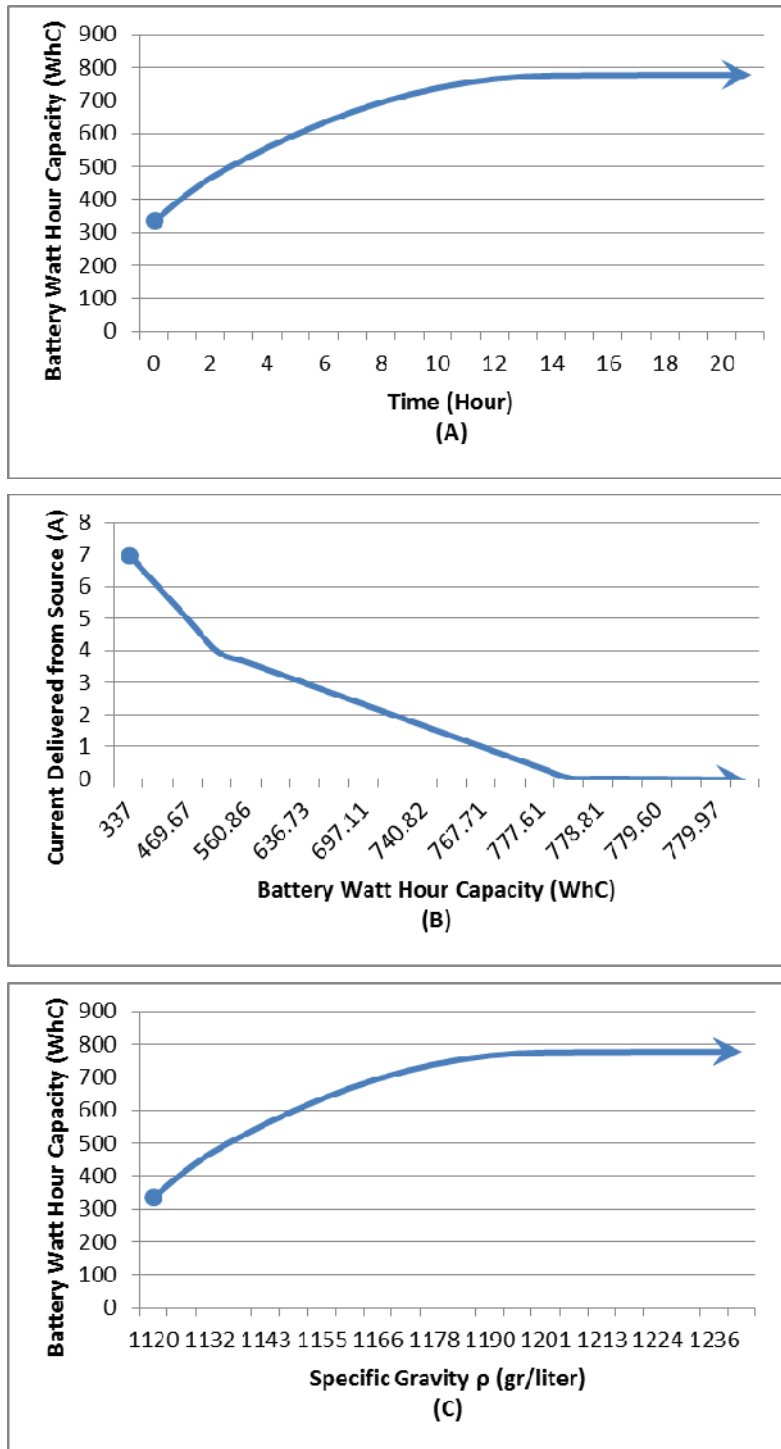


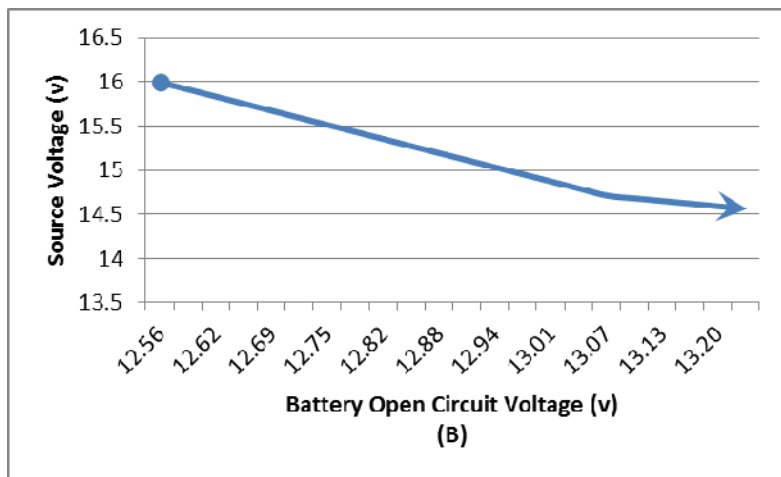
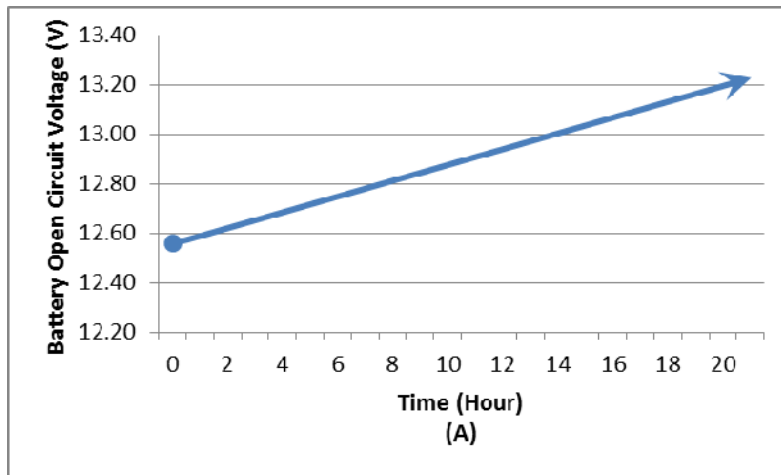
Figure (5.19): Constant voltage charge process of lead acid battery.

A: Watt hour capacity as a function of time.

B: Watt hour capacity as a function of charging current.

C: Electrolyte specific gravity as a function of watt hour capacity during battery charging.

The status of battery charging can be determined through the open circuit voltage as it is shown in figure (5.20.A). Figure (5.20.B) shows that the voltage source value decreases as the battery open circuit voltage increases. Figures (5.20.C) and (5.20.D) illustrate the variation of charging current in a function of open circuit voltage and open circuit voltage in a function of specific gravity respectively.



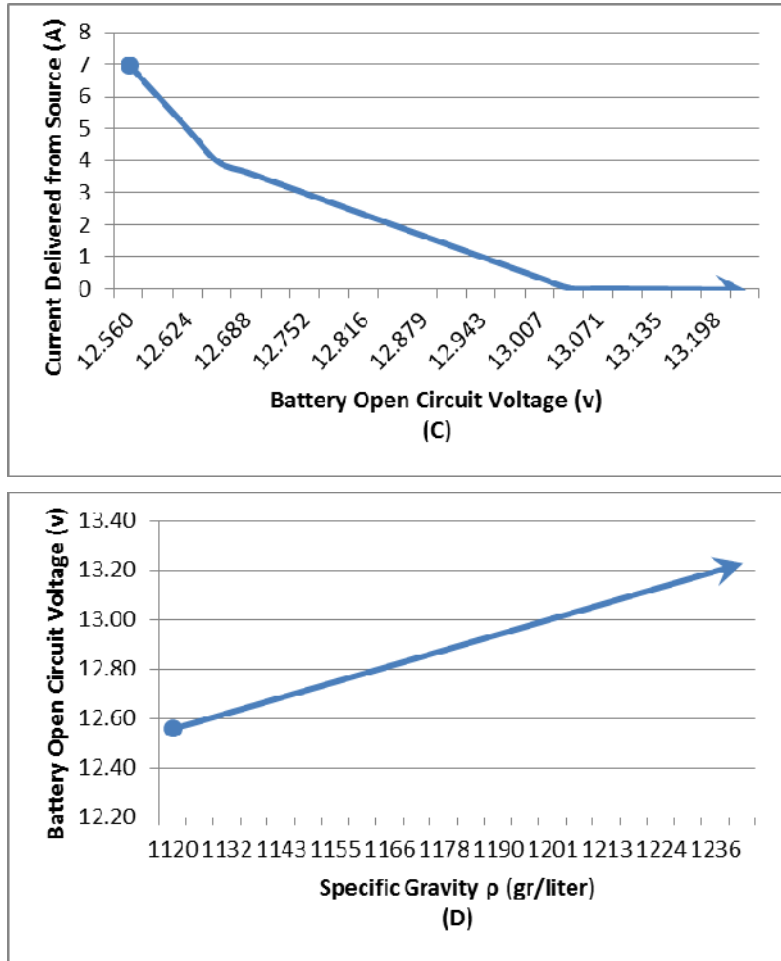


Figure (5.20): Constant voltage charge process of lead acid battery.

A: Open circuit voltage as a function of time.

B: The relation between open circuit voltage and voltage delivered from source.

C: The relation between open circuit voltage and current delivered from source.

D: Open circuit voltage as a function of solution specific gravity.

We noticed from table (5.1) that the specific gravity at (DOD = 60%) equal 1123 and after few days it becomes 1120 as it is shown in table (5.6) before the process of charge. This means that the battery loses the capacity slowly when it is not used or stored, this is known by self-discharged. At 21°C the self of discharge rate for lead acid battery approximately from 15% to 30% per month for (SLI) and 4% to 8% per month for (VRLA) [22].

5.3 Developing an Algorithm for Determining the Battery – Ah Capacity

At quasi constant acid temperature, the ampere - hour capacity of a battery (C) can be represented as a linear function of voltage and acid concentration according to equation (5.6) [1].

$$C = a V + b \rho + c \quad (5.6)$$

Applying the least square method on the measured V and ρ values illustrated in Table (5.8) we obtain equation (5.7):

$$E = \sum [C - (a V + b \rho + c)]^2 \quad (5.7)$$

Where a, b, c are constants and E is the error. For a minimum error, E will be differentiated according to a, b and c and set to zero:

$$\frac{dE}{da} = 0 \quad (5.8)$$

$$= 2 \sum \{ C - (aV + b\rho + c) \} \{-V\}$$

$$a \sum V^2 + b \sum V \rho + c \sum V = \sum C V \quad (5.9)$$

$$\frac{dE}{db} = 0 \quad (5.10)$$

$$= 2 \sum \{ C - (aV + b\rho + c) \} \{-\rho\}$$

$$a \sum V\rho + b \sum \rho^2 + c \sum \rho = \sum C \rho \quad (5.11)$$

$$\frac{dE}{dc} = 0 \quad (5.12)$$

$$= 2 \sum \{ C - (aV + b\rho + c) \} \{-1\}$$

$$a \sum V + b \sum \rho + c = \sum C \quad (5.13)$$

Table (5.7) shows the values of calculations of V^2 , $V\rho$, VC , ρ^2 and ρC and their summations from Table (5.8). Substituting the corresponding values in equations (5.9), (5.11) and (5.13), we obtain the following three equations with three unknown constants:

Table (5.7): Variables value needed to solve the equations.

Variable	Value
$\sum V$	231.8
$\sum V^2$	2828
$\sum V\rho$	274
$\sum VC$	9595
$\sum \rho^2$	26.55
$\sum \rho C$	932.85
$\sum \rho$	22.45
$\sum C$	783.2

$$2828 a + 274 b + 231.8 c = 9595 \quad (5.14)$$

$$274 a + 26.55 b + 22.45 c = 932.85 \quad (5.15)$$

$$231.8 a + 22.45 b + 19 c = 783.2 \quad (5.16)$$

Solving these equations, we obtain the values for a, b and c :

$$a = 27.46, \quad b = 164.7, \quad c = -488.4.$$

Substituting these values in equation (5.6), we obtain equation (5.17) which represents the ampere - hour capacity of the battery as a function of the voltage and acid concentration:

$$C = 27.46 V + 164.7 \rho - 488.4 \quad (5.17)$$

Substituting V and ρ values from Table (5.8) in equation (5.17), we obtain the calculated values for the ampere hour capacity presented in

column (4) of Table (5.8). Comparing these values with the measured capacity - values in column (3), one finds that the corresponding values are very close which verifies the correctness of the applied procedure.

Note that for each one of the tables (5.1), (5.2), (5.3) and (5.4) in this chapter, we can do the same thing. It means we can calculate the variable values as in table (5.7) and constructs equations as equation (5.14), (5.15) and (5.16) and after solving them; we will have the same algorithm in equation (5.17). The evaluation results are presented in tables (5.9), (5.10) and (5.11).

Table (5.8): Measured and calculated parameters of a lead acid battery rated at 12V / 60 Ah at 2.2A load current discharged.

Time (hr)	Voltage (V)	ρ (g/liter)	AhC (measured)	AhC (calculated)
0	12.52	1240	60	59.63
1	12.48	1234	57.8	57.59
2	12.45	1227	55.62	55.54
3	12.41	1221	53.46	53.48
4	12.38	1214	51.32	51.43
5	12.34	1208	49.2	49.38
6	12.31	1201	47.1	47.32
7	12.27	1195	45.02	45.27
8	12.23	1188	42.96	43.22
9	12.20	1182	40.92	41.17
10	12.16	1175	38.9	39.11
11	12.13	1169	36.9	37.06
12	12.09	1162	34.92	35.01
13	12.06	1156	32.96	32.96
14	12.02	1149	31.02	30.90
15	11.98	1143	29.1	28.85
16	11.95	1136	27.2	26.80
17	11.91	1130	25.32	24.75
18	11.88	1123	23.46	22.69

Table (5.9): Measured and calculated parameters of a lead acid battery rated at 12V / 60 Ah at 4.25A load current discharged.

Time (hr)	Voltage (V)	ρ (g/liter)	AhC (measured)	AhC (calculated)
0	12.52	1240	60	59.62
1	12.45	1227	55.75	55.53
2	12.38	1214	51.55	51.43
3	12.31	1201	47.4	47.32
4	12.23	1188	43.3	43.22
5	12.16	1175	39.25	39.11
6	12.09	1162	35.25	35.01
7	12.02	1149	31.3	30.90
8	11.95	1136	27.4	26.79
9	11.88	1123	23.55	22.69

Table (5.10): Measured and calculated parameters of a lead acid battery rated at 12V / 60 Ah at 6.2A load current discharged.

Time (hours)	Voltage (V)	ρ (g/liter)	AhC (measured)	AhC (calculated)
0	12.52	1240	60	59.63
0.5	12.47	1230	56.90	56.56
1	12.41	1221	53.82	53.48
1.5	12.36	1211	50.75	50.4
2	12.31	1201	47.69	47.32
2.5	12.25	1191	44.65	44.25
3	12.20	1182	41.63	41.17
3.5	12.14	1172	38.62	38.09
4	12.09	1162	35.62	35.01
4.5	12.04	1152	32.64	31.93
5	11.98	1143	29.68	28.85
5.5	11.93	1133	26.73	25.77
6	11.88	1123	23.79	22.69

Table (5.11): Measured and calculated parameters of a lead acid battery rated at 12V / 60 Ah at 8.4A load current discharged.

Time (hours)	Voltage (V)	ρ (g/liter)	AhC (measured)	AhC (calculated)
0	12.52	1240	60	59.62
0.5	12.45	1227	55.8	55.53
1	12.38	1214	51.65	51.43
1.5	12.31	1201	47.55	47.32
2	12.23	1188	43.5	43.21
2.5	12.16	1175	39.5	39.11
3	12.09	1162	35.55	35.01
3.5	12.02	1149	31.65	30.90
4	11.95	1136	27.8	26.79
4.5	11.88	1123	24	22.69

5.4 Conclusion

There are two methods for determining the state of charge for lead acid battery:

- Terminal voltage – the open circuit voltage (no current following) of a fully charged cell depends on its type but will be 2.1V to 2.3V equivalent to battery voltage of 12.6V to 13.8V for 12V battery and 11.9 at (DOD = 60%).
- Specific gravity – electrolyte specific gravity could be measure to know. In the normal conditions the specific gravity will vary from 1.12 for a fully discharge to 1.24 kg/liter for a fully charge.

The depth of discharge (DOD) is the obverse of state of charge (SOC), battery voltage decreases almost linearly with depth of discharge. Due to internal resistance and the fact that the charging voltage is greater

than the discharge voltage, the energy returned by the battery upon discharge will be less than the energy used for recharging. Typically, a lead-acid battery will be (80 to 90) % efficient when considering ampere-hours and for our experiment ($\eta_{Ah} = 81.1\%$). The watt-hour efficiency is typically 75% for such lead-acid battery and for our experiment ($\eta_{Wh} = 64\%$).

5.5 Vents and Valves

Vent plugs are required with a number of battery systems because of secondary reactions that generate gases which must escape. Vents, as used for some rechargeable batteries, are simple openings that allow gas flow in both directions, i.e. out of the battery but also vice versa. The openings in such vent plugs are small to minimize water loss by diffusion of the water vapor. In modern batteries, such vents are mostly equipped with porous disks that prevent ignition sparks or flames from entering the cell and hinder the escape of electrolyte fumes from the cell.

Valves allow only the escape of gas and are required in valve regulated lead acid batteries for the escape of hydrogen, but are also used in most other sealed batteries to prevent damage of the cell in the case of a too high internal pressure when the battery is abused, e.g. overcharged at a too high current rate or reversed [24].

5.6 Recombination Device

A recombination device including a gas-tight enclosure connected to receive the discharge gases from a rechargeable storage battery. Catalytic

material for the recombination of hydrogen and oxygen to form water is supported within the enclosure. The enclosure is sealed from the atmosphere by a liquid seal including two vertical chambers interconnected with an inverted U-shaped overflow tube. The first chamber is connected at its upper portion to the enclosure and the second chamber communicates at its upper portion with the atmosphere. If the pressure within the enclosure differs as overpressure or vacuum by more than the liquid level, the liquid is forced into one of the two chambers and the overpressure is vented or the vacuum is relieved. The recombination device also includes means for returning recombined liquid to the battery and for absorbing metal hydrides [26].

Chapter Six

Lead Acid Battery Equivalent Circuit Model

Chapter Six

Lead Acid Battery Equivalent Circuit Model

6.1 Introduction

Modeling and simulation are important for electrical system capacity determination and optimum component selection. The battery model is a very important part of an electrical system simulation, and the battery model needs to be high-fidelity to achieve meaningful simulation results. Electrical system modeling and simulation have been proposed to reduce the amount of physical testing necessary for component selection [14]. A simple, fast, and effective equivalent circuit model structure for lead-acid batteries was implemented to facilitate the battery model part of the system model.

6.2 Battery Model

This simulation implements a model of a lead-acid battery cell using the MATLAB program. In this simulation, initially the battery is discharged at a constant current of 10A. The battery is then recharged at a constant 10A back to the initial state of charge. A simple thermal model is used to model the battery temperature. It is assumed that cooling is primarily via convection, and that heating is primarily from the battery internal resistance. A standard 12V lead-acid battery can be modeled by connecting six copies of the 2V battery cell block in series.

6.2.1 Battery model structure

A physical system lead-acid battery model was created. The battery model was designed to accept inputs for current and ambient temperature, as shown in Figure (6.1). The outputs were voltage, SOC and electrolyte temperature.

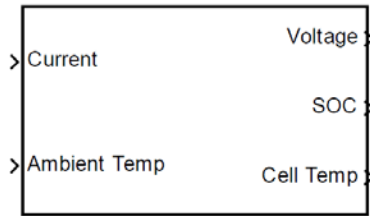


Figure (6.1): Battery model [14].

A diagram of the overall battery model structure is shown in Figure (6.2), which contains three major parts: an equivalent circuit model, thermal model, and a charge and capacity model.

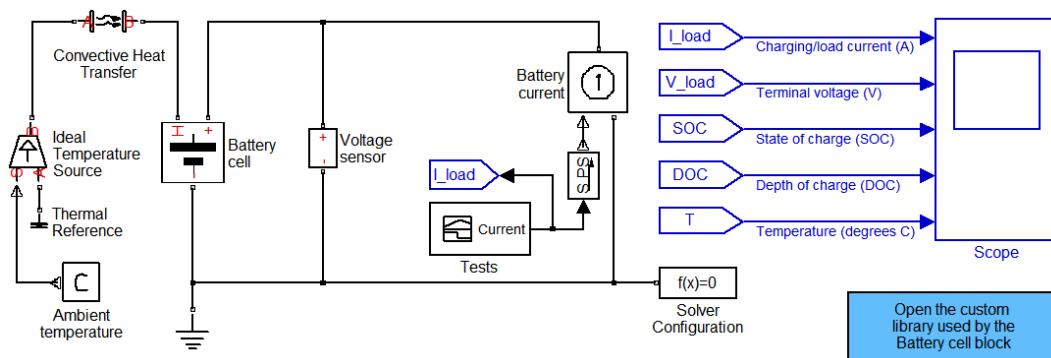


Figure (6.2): Overall lead acid battery model structure.

The major part of battery model structure:

1. Equivalent circuit model

The equivalent circuit depends on the battery current and several nonlinear circuit elements. A simple nonlinear equivalent circuit is shown

in figure (6.3). The structure of the battery circuit equations is shown in figure (6.4.A). Figure (6.4.B) shows the components inside the battery cell block represented in figure (6.4.A). The structure did not model the internal chemistry of the lead-acid battery directly; the equivalent circuit empirically approximates the behavior seen at the battery terminals. The structure consists of two main parts: a main branch which approximates the battery dynamics under most conditions, and a parasitic branch which accounts for the battery behavior at the end of a charge.

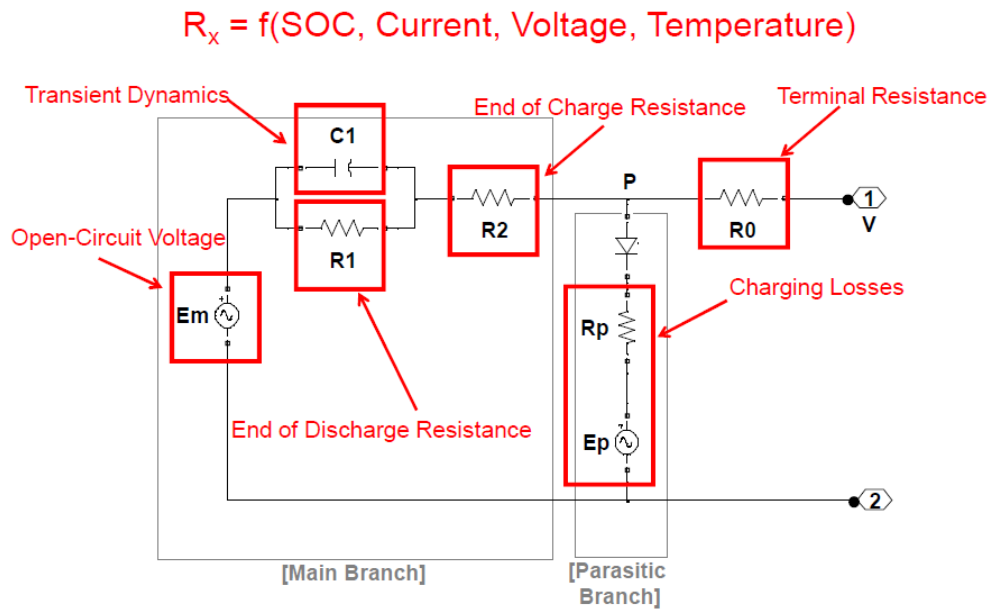


Figure (6.3): Equivalent circuit [14].

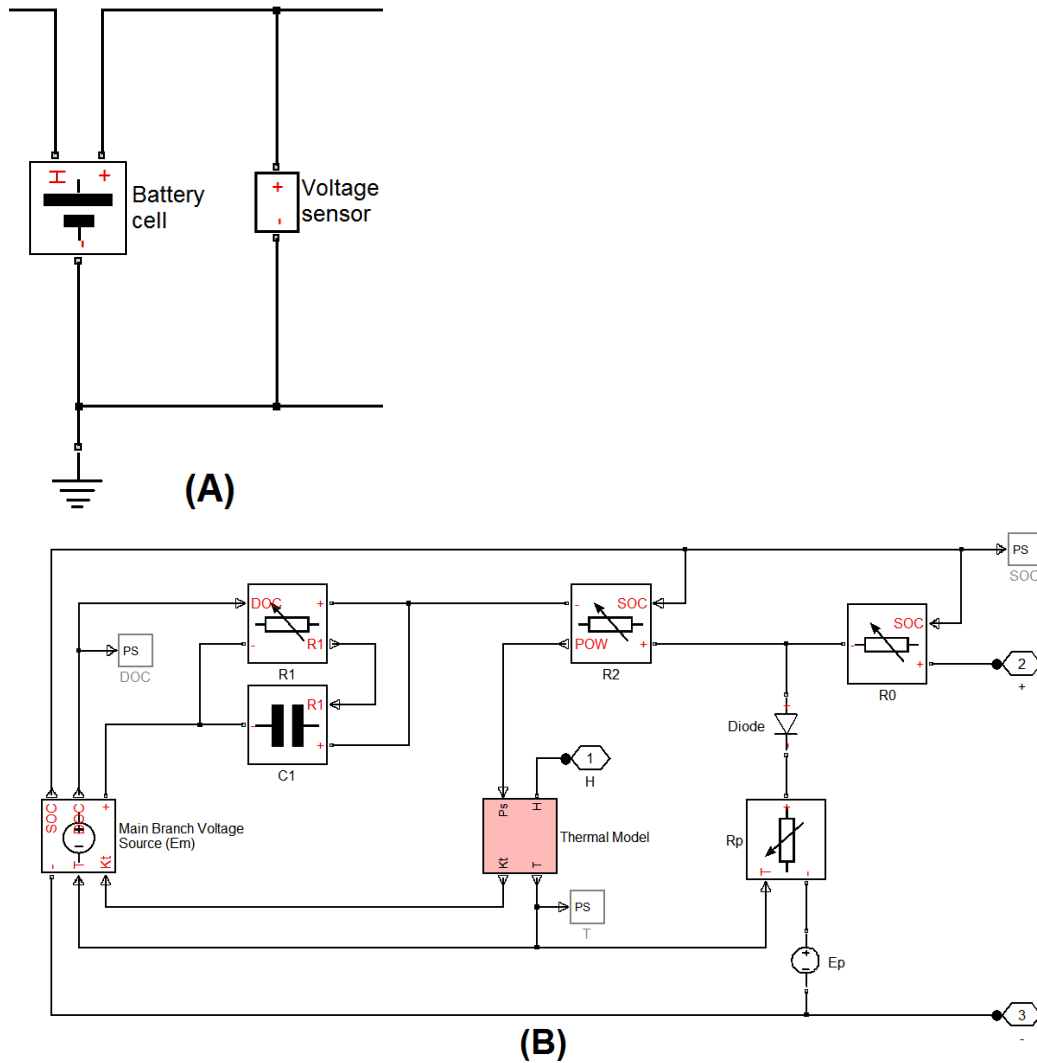


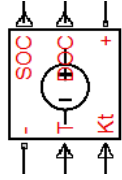
Figure (6.4): Equivalent circuit in MATLAB

The battery equivalent circuit represents one cell of the battery. The output voltage was multiplied by six, the number of series cells, to model a 12 volt automotive battery. Figure (6.3) shows the electrical circuit diagram containing elements that were used to create the battery circuit equations.

Each equivalent circuit element was based on nonlinear equations. The nonlinear equations included parameters and states. The parameters of the equations are depending on empirically determined constants. The

states included electrolyte temperature, stored charge, and circuit node voltages and currents. The equations were as follows:

Main branch voltage



This block implements the main branch voltage source.

Equation (6.1) approximates the internal electro-motive force (emf), or open-circuit voltage of one cell [14,16]. The computation was performed inside the “main branch voltage source (Em)” block in Figure (6.4.B). The emf value was assumed to be constant when the battery was fully charged. The emf varied with temperature and state of charge (SOC).

$$E_m = E_{m0} - K_E (273 + \theta)(1 - SOC) \quad (6.1)$$

Where,

E_m : the open-circuit voltage (EMF) in volts.

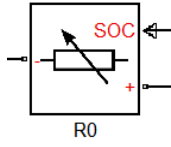
E_{m0} : the open-circuit voltage at full charge in volts.

K_E : a constant = 0.580×10^{-3} in volts / °C.

θ : electrolyte temperature in °C.

SOC: battery state of charge.

Terminal resistance



This block implements the terminal resistance R_0 .

Equation (6.2) approximates a resistance seen at the battery terminals, and it was calculated inside the “terminal resistance R_0 ” block in figure (6.4.B) [14,16]. The resistance was assumed to be constant at all temperatures, and varies with the state of charge.

$$R_0 = R_{00} [1 + A_0 (1 - SOC)] \quad (6.2)$$

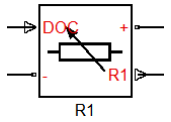
Where,

R_0 : a resistance in ohms.

R_{00} : the value of R_0 at (SOC=1) in ohms.

A_0 : a constant = -0.30.

Main branch resistance 1



This block implements the main branch resistance R_1 .

Equation (6.3) approximates a resistance in the main branch of the battery. The computation was performed inside the “main branch resistance R_1 ” block in figure (6.4.B) [14,16]. The resistance varies with depth of charge, a measure of the battery’s charge adjusted for the discharge current.

The resistance increased exponentially as the battery became exhausted during a discharge.

$$R_1 = -R_{10} \ln(DOC) \quad (6.3)$$

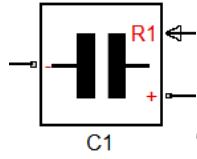
Where,

R_1 : a main branch resistance in ohms.

R_{10} : a constant = 0.7mΩ.

DOC: battery depth of charge.

Main branch capacitance 1



This block implements the main branch capacitance C1.

Equation (6.4) approximates a capacitance (or time delay) in the main branch [14]. The computation was performed inside the “main branch capacitance C1” block in figure (6.4.B). The time constant modeled a voltage delay when battery current changed.

$$C_1 = \tau_1 / R_1 \quad (6.4)$$

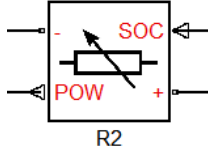
Where,

C_1 : a main branch capacitance in farads.

τ_1 : a main branch time constant in seconds.

R_1 : a main branch resistance in ohms.

Main branch resistance 2



This block implements the main branch resistance R2.

Equation (6.5) approximates a main branch resistance. The computation was performed inside the “main branch resistance R2” block in Figure (6.4.B) [14,16]. The resistance increased exponentially as the battery state of charge increased. The resistance also varied with the current flowing through the main branch. The resistance primarily affected the battery during charging. The resistance became relatively insignificant for discharge currents.

$$R_2 = R_{20} \frac{\exp[A_{21}(1-SOC)]}{1 + \exp(A_{22} I_m / I^*)} \quad (6.5)$$

Where,

R_2 : a main branch resistance in ohms.

R_{20} : a constant = 15 mΩ.

A_{21} : a constant = -8.

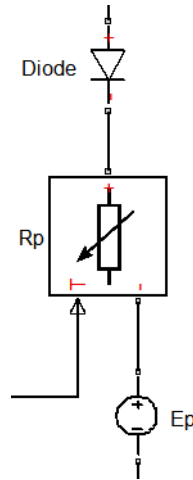
A_{22} : a constant = -8.45.

SOC: battery state of charge.

I_m : the main branch current in amperes.

I*: the nominal battery current in amperes.

Parasitic branch current



This block implements the Parasitic Branch which consists of three components (diode, Parasitic Branch resistance R_p and DC voltage source).

Diode: If the voltage across the diode is bigger than the Forward voltage V_f , then the diode behaves like a linear resistor with low on resistance R_p plus a series voltage source. If the voltage across the diode is less than the forward voltage, then the diode behaves like a linear resistor with low off conductance G_p off.

Parasitic branch resistance R_p : This block implements the parasitic branch resistance.

DC voltage source: The ideal voltage source maintains a constant voltage across its output terminals, independent of the current flowing through the source. The output voltage is defined by the constant voltage parameter, and can be any real value.

Equation (6.6) approximates the parasitic loss current which occurred when the battery is being charged [14,16]. The computation is performed inside the “Parasitic Branch Current” block in Figure (6.4.B). The current depends on the electrolyte temperature and the voltage at the parasitic branch. The current is very small under most conditions, except during charge at high SOC. Note that while the constant G_{p0} is measured in units of seconds, the magnitude of G_{p0} is very small, in the order of 10^{-12} seconds.

$$I_p = V_{PN} G_{p0} \exp\left(\frac{V_{PN}/(\tau_p s + 1)}{V_{P0}}\right) + A_p \left(1 - \frac{\theta}{\theta_f}\right) \quad (6.6)$$

Where,

I_p : the current loss in the parasitic branch.

V_{PN} : the voltage at the parasitic branch.

G_{p0} : a constant = 2pS.

τ_p : a parasitic branch time constant in seconds.

V_{P0} : a constant = 0.1 V.

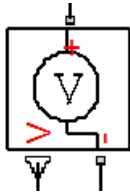
A_p : a constant = 2.

θ : electrolyte temperature in °C.

θ_f : electrolyte freezing temperature in °C.

Voltage sensor:

This block represents an ideal voltage sensor.



This block inside contains the ideal voltage sensor that is, a device that converts voltage measured between any electrical connections into a physical signal proportional to the voltage. Connections + and - are conserving electrical ports through which the sensor is connected to the circuit. Connection of V is a physical signal port that outputs voltage value.

2. Thermal model (ambient and electrolyte temperatures)

The “**ambient temperature**” block in Figure (6.5) tracked ambient temperature, which is consists of four components.

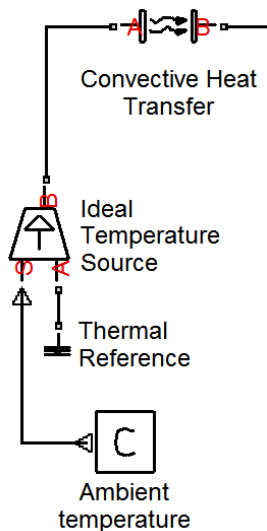


Figure (6.5): Thermal model – ambient temperature.

PS constant (ambient temperature): The PS Constant block generates a physical signal of a constant value. You specify the value of the signal as the constant parameter. You can specify both positive and negative values, the value in the model equals 25+273.

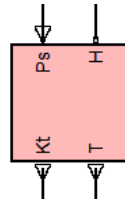
Thermal reference: The Thermal Reference block represents a thermal reference point, that is, a point with an absolute zero temperature, with respect to which all the temperatures in the system are determined.

Ideal temperature source: The ideal temperature source block represents an ideal source of thermal energy that is powerful enough to maintain specified temperature at its outlet regardless of the heat flow consumed by the system. Connections A and B are thermal conserving ports corresponding to the source inlet and outlet, respectively. Port S is a physical signal port, through which the control signal that drives the source is applied. You can use the entire variety of Simulink signal sources to generate the desired heat flow variation profile. The temperature differential across the source is directly proportional to the signal at the control port S. The block positive direction is from port A to port B. This means that the temperature differential is determined as $T_B - T_A$, where T_B and T_A are the temperatures at source ports.

Convective heat transfer: The Convective Heat Transfer block represents a heat transfer by convection between two bodies by means of fluid motion. Connections A and B are thermal conserving ports associated with the

points between which the heat transfer by convection takes place. The block positive direction is from port A to port B.

The “**Electrolyte temperature**” block tracked the battery’s electrolyte temperature.



This block implements the thermal model – electrolyte temperature. Inside this block, there is a circuit which consists of some components as it is shown in figure (6.6).

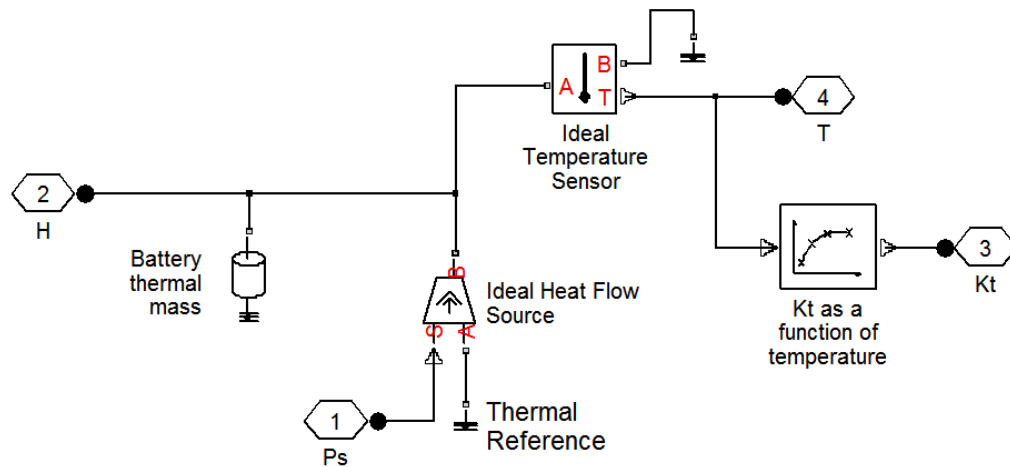


Figure (6.6): Thermal model – electrolyte temperature circuit.

Thermal reference: The block represents a thermal reference point, that is, a point with a zero or constant temperature, with respect to which all the temperatures in the system are determined.

Ideal heat flow source: The block represents an ideal source of thermal energy that is powerful enough to maintain specified heat flow at its outlet regardless of the temperature difference across the source. Block

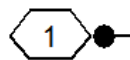
connections A and B correspond to the thermal inlet and outlet conserving ports, respectively, and connection S represents a physical signal port. The heat flow through the source is directly proportional to the control signal. The block positive direction is from port A to port B.

Battery thermal mass: The block represents a thermal mass, which is the ability of a material or combination of materials to store internal energy. The property is characterized by the mass of the material and its specific heat. The block has one thermal conserving port. The block positive direction is from its port towards the block. This means that the heat flow is positive if it flows into the block.

Ideal temperature sensor: The block represents an ideal temperature sensor, that is, a device that determines the temperature differential measured between two points without drawing any heat. The temperature differential, T , is returned at the physical signal port T. Connections A and B are conserving thermal ports. The sensor is oriented from A to B and the measured temperature is determined as $T = T_A - T_B$.

PS lookup (table - 1D) (Kt as a function of temperature): The block represents an ideal converter whose input-output relationship is specified by the lookup table. Both the input and the output are physical signals.

Connection port



Create Physical Modeling connector port for subsystem.

Equation (6.7) was modeled to estimate the change in electrolyte temperature, due to internal resistive losses and due to ambient temperature [14]. The thermal model consists of a first order differential equation, with parameters for thermal resistance and capacitance.

$$\theta(t) = \theta_{init} + \int_0^t \frac{\left(P_s - \frac{(\theta - \theta_a)^2}{R_\theta}\right)}{C_\theta} d\tau \quad (6.7)$$

Where,

θ : the battery's temperature in °C.

θ_a : the ambient temperature in °C.

θ_{init} : the battery's initial temperature in °C, assumed to be equal to the surrounding ambient temperature.

P_s : the I^2R power loss of R_0 and R_2 in Watts.

R_θ : the thermal resistance in °C / Watts.

C_θ : the thermal capacitance in Joules / °C.

τ : an integration time variable.

t : the simulation time in seconds.

3. A charge and capacity model

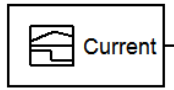
The “Charge and capacity” block in Figure (6.7) tracked the battery's capacity, state of charge, and depth of charge.

A charge and capacity model contains of some blocks which are:

A block diagram of a 'PS S' block. It is a square box with 'PS' in blue and 'S' in red. A feedback arrow points from the output back to the input. The input is a signal source symbol.

This block converts the unit less Simulink input signal to a Physical Signal. The unit expression in 'Input signal unit' parameter is associated with the unit less Simulink input signal and determines the unit assigned to the Physical Signal.

Signal builder



This block creates and generates interchangeable groups of signals whose waveforms are piecewise linear.

Goto



This block sends signals to or from blocks that have the specified tag. If tag visibility is 'scoped', then a Goto Tag Visibility block must be used to define the visibility of the tag. The block icon displays the selected tag name (local tags are enclosed in brackets, [], and scoped tag names are enclosed in braces, {}).

Capacity measured the maximum amount of charge that the battery could hold. State of charge (SOC) measured the ratio of the battery's available charge to its full capacity. Depth-of-charge (DOC) measured the fraction of the battery's charge to usable capacity, because usable capacity decreased with increasing discharge current. The equations that tracked capacity, (SOC), and (DOC) were as follows:

Extracted charge

Equation (6.8) tracked the amount of charge extracted from the battery [14]. The charge extracted from the battery was a simple integration of the current flowing into or out of the main branch. The initial value of extracted charge was necessary for simulation purposes.

$$Q_a(t) = Q_{a_init} + \int_0^t -I_m(\tau) d\tau \quad (6.8)$$

Where,

Q_a : the extracted charge in Amp-seconds.

Q_{a_init} : the initial extracted charge in Amp-seconds.

I_m : the main branch current in Amps.

τ : an integration time variable.

t : the simulation time in seconds.

Total capacity

Equation (6.9) approximated the capacity of the battery based on discharge current and electrolyte temperature [14,16]. However, the capacity dependence on current was only for discharge. During charge, the discharge current was set equal to zero in equation (6.8) for the purposes of calculating total capacity. Automotive batteries were tested throughout a large ambient temperature range. Lab data across the entire tested current range showed that battery capacity began to diminish at temperatures above approximately 60°C. The look-up table (LUT) variable K_t in Equation (6.9) was used to empirically model the temperature dependence of battery capacity.

$$C(I, \theta) = \frac{K_c C_0 K_t}{1 + (K_c - 1)(I/I_0)^\delta}, K_t = \text{LUT}(\theta) \quad (6.9)$$

Where,

K_q : a constant = 1.18.

C_0^* : the no-load capacity at 0°C in Amp-seconds.

K_t : a temperature dependent look-up table.

θ : electrolyte temperature in °C.

I : the discharge current in amperes.

I^* : the nominal battery current in amperes.

δ : a constant = 1.4.

State of charge and depth of charge

Equation (6.10) calculated the SOC and DOC as a fraction of available charge to the battery's total capacity [14,16]. State of charge measured the fraction of charge remaining in the battery. Depth of charge measured the fraction of usable charge remaining, given the average discharge current. Larger discharge currents caused the battery's charge to expire more prematurely, thus DOC was always less than or equal to SOC.

$$SOC = 1 - \frac{Q_f}{C(\theta, \theta)} , \quad DOC = 1 - \frac{Q_f}{C(I_{avg}, \theta)} \quad (6.10)$$

Where,

SOC: battery state of charge.

DOC: battery depth of charge.

Q_g : the battery's charge in Amp-seconds.

C : the battery's capacity in Amp-seconds.

θ : electrolyte temperature in °C.

I_{avg} : the mean discharge current in amperes.

Estimate of average current

The average battery current was estimated as follows in equation (6.11) [14,16].

$$I_{avg} = \frac{I_m}{(\tau_1 s + 1)} \quad (6.11)$$

Where,

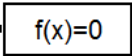
I_{avg} : the mean discharge current in amperes.

I_m : the main branch current in amperes.

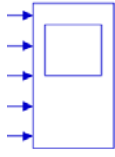
τ_1 : a main branch time constant in seconds.

Other component excites in the overall lead acid battery model structure in figure (6.2):

Solver configuration

 This block represent Physical Networks environment and solver configuration.

Scope (oscilloscope)



This block display signals generated during simulation.

6.3 Battery Simulink

The battery capacity was very difficult to estimate correctly. One reason for the difficulty was battery variability. Another reason for the difficulty was that ensuring the battery was fully charged before discharge testing was not easy. Fully charging the battery was more of an issue at higher temperatures where charging losses are significant, and thus, achieving a full charge becomes difficult. The charging difficulties at higher temperatures should be taken into consideration during the lab testing process. The batteries should be as completely charged as possible before discharge tests begin. To simplify, the battery modeling in charging and discharging state, the initial values of the SOC and DOC are equal to 20% and the final values of the SOC and DOC are equal to 80% [14,16].

The first experiment done on the battery was discharged under 5A current load and then charged under 5A constant current as it is shown in figure (6.8). And the result of this case appeared in figure (6.9) where the cell terminal voltage at the first point of discharged process is equal to 2.15V (i.e. the battery terminal voltage = 12.9V), SOC = 80%, DOC = 80% and when the load placed, the cell voltage, SOC and DOC start decreasing until they reached 2.04V (i.e. the battery terminal voltage = 12.24V), 45%,

40% (respectively), and when the battery became charged all parameter increased until cell terminal voltage reached to 2.25V (i.e. the battery terminal voltage = 13.5V) and both SOC and DOC reached to 85%.

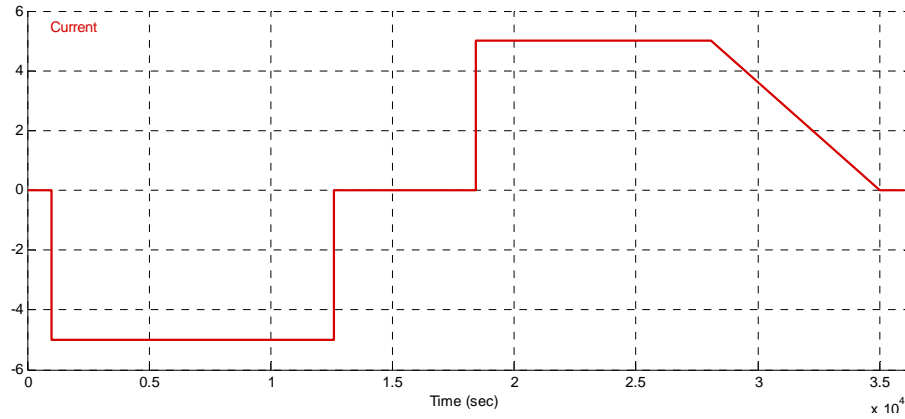


Figure (6.8): Battery current at 5A discharged and 5A charged.

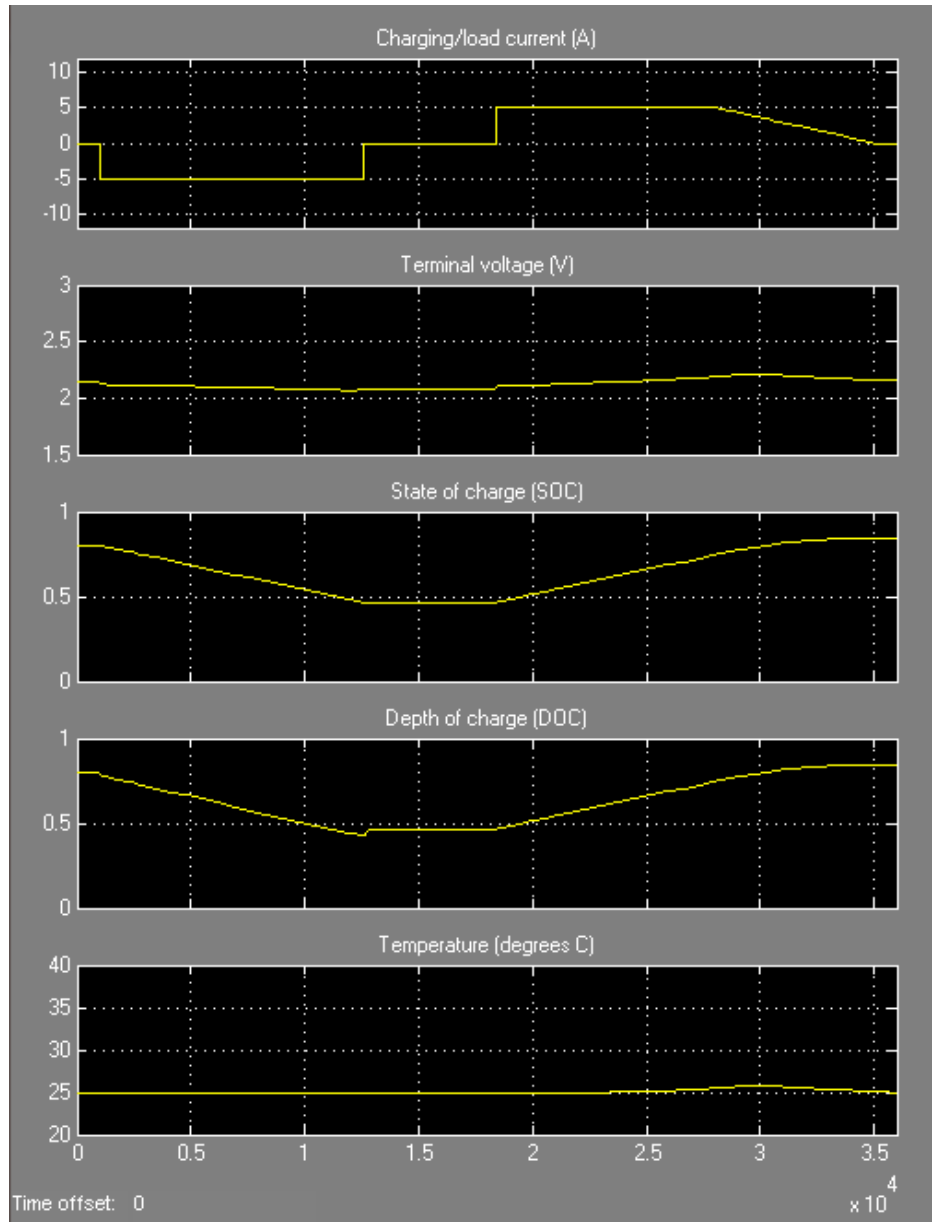


Figure (6.9): Battery discharged and charged at 5A current.

The second experiment done on the battery was discharged under 10A current load and then charged under 10A constant current as it is shown in figure (6.10). And the result of this case appeared in figure (6.11) where the cell terminal voltage at the first point of discharged process equal to 2.15V (i.e. the battery terminal voltage = 12.9V), SOC = 80%, DOC =

80% and when the load placed, the cell voltage, SOC and DOC becomes decreased until it reached 1.95V (i.e. the battery terminal voltage = 11.7V), 12%, zero% (respectively), and when the battery become charged all parameter increased until cell terminal voltage reached to 2.25V (i.e. the battery terminal voltage = 13.5V) and both SOC and DOC reached to 85%.

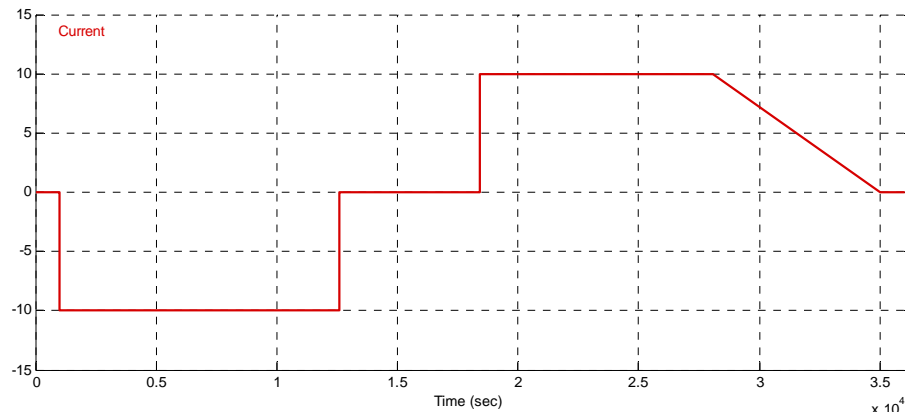


Figure (6.10): Battery current at 10A discharged and 10A charged.

About the electrolyte temperature, they are not changed under discharge process and a few change under the end of charge process as it is shown in both (6.9) and (6.11) figures.

Note that the results from MATLAB Simulink are close to the result we had obtained from the real measurements discussed in chapter 5.

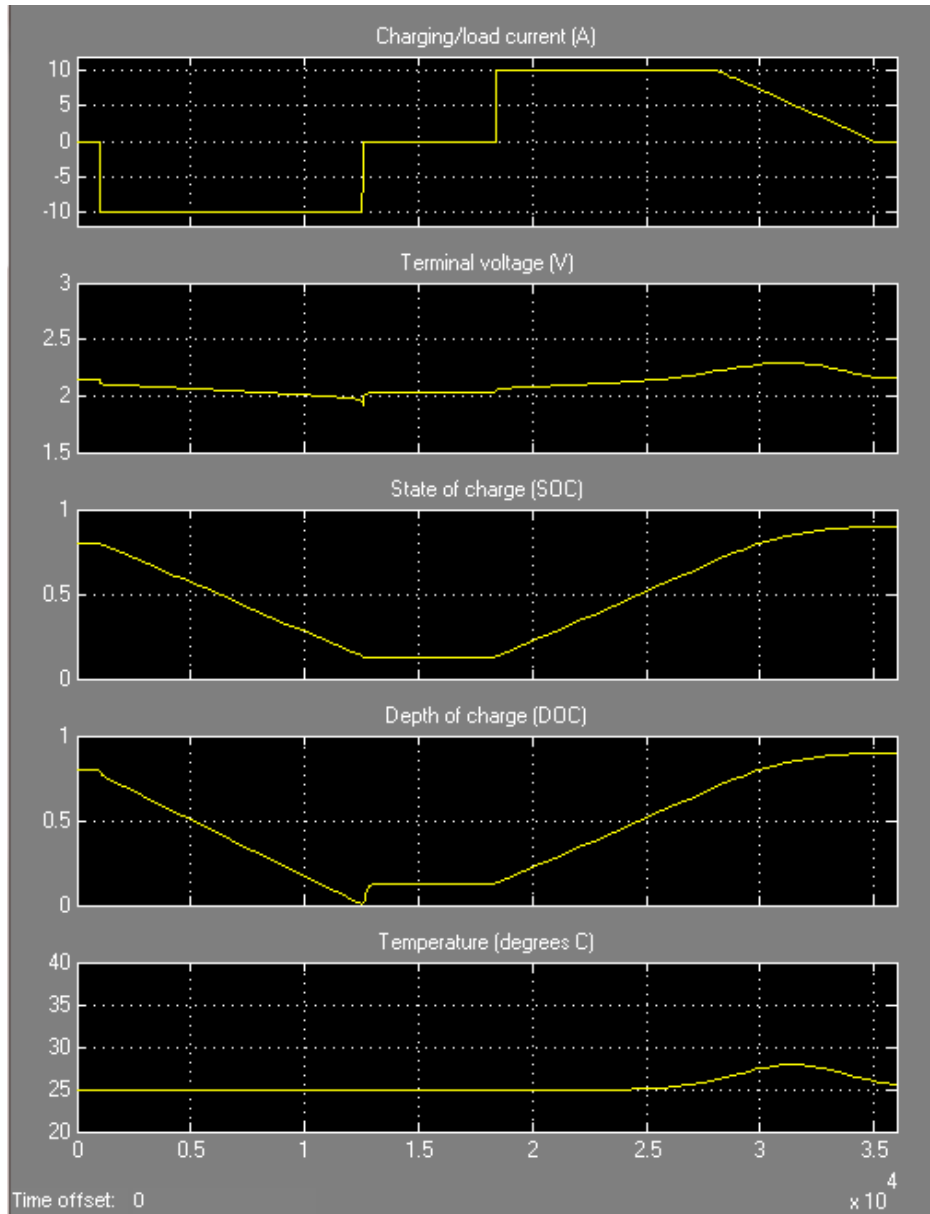


Figure (6.11): Battery discharged and charged at 10A current.

Chapter Seven

Conclusions and Recommendations

Chapter seven

Conclusions and Recommendations

7.1 Conclusions

Lead - acid storage batteries are usually used in small and large PV power systems operating in stand-alone mode. Selection of battery type and capacity are important factors to realize an efficient PV system. Battery voltage in function of electrolyte temperature, depth of discharge and specific gravity as well as the battery capacity in function of discharge current have to be given special consideration when evaluating or designing storage batteries for PV power systems.

Battery voltage and specific gravity together are the key for determining the ampere - hour capacity of a battery and the stored energy in it. Measuring them at the same time and substituting their values in the developed algorithm, result the capacity of the battery in Ah. This algorithm enables knowing the energy storage within a PV power system and to perform accordingly in setting the battery charger control limits correctly, which consequently elongate the life time of the battery and enhance the overall PV system performance and economics.

The work here presents a common battery modeling, Simulink and the results of its application to modeling lead-acid batteries over the range of conditions that it is expected to operate in.

7.2 Recommendations

Based on the studies and investigations carried out in this thesis, the following recommendations can be made:

1. Batteries within PV power systems should always be connected to charge controllers to protect them against deep discharge and extremely over charge which shorten the battery life time.
2. Long – term field testing of a storage battery block built within a PV power system where battery voltage, current (in/out), temperature and specific gravity are continuously measured via a computer supported data acquisition system would be very helpful for development of a more accurate electrical equivalent circuit and a mathematical model for determining the state of charge and capacity along the annual seasonal with different solar radiation intensity.
3. Equipment for measuring the electrolyte specific gravity with automation recording possibility is seldom or not found. More efforts should be given for developing such equipment. Such equipment will facilitate the determination of battery ampere – hour capacity at any time and its variation according to load and solar input power.

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كلية الدراسات العليا

نمذجة ومحاكاة بطاريات الرصاص - الحامض ضمن أنظمة الخلايا الشمسية

إعداد

علا صبحي وحيد القاسم

إشراف

أ. د. مروان محمود

قدمت هذه الأطروحة استكمالاً لمتطلبات نيل درجة الماجستير في هندسة الطاقة النظيفة
وإستراتيجية الترشيد بكلية الدراسات العليا في جامعة النجاح الوطنية, نابلس - فلسطين

2012م

ب

نمذجة ومحاكاة بطاريات الرصاص - الحامض ضمن أنظمة الخلايا الشمسية

اعداد

علا صبحي وحيد القاسم

اشراف

أ. د. مروان محمود

الملخص

حيث أن الطاقة المتجددة أصبحت أكثر انتشارا، وبما انه لا غنى عن بطاريات الخزن في الانظمة المستقلة المولدة للطاقة الكهربائية وخاصة انظمة الخلايا الشمسية وبما ان البطاريات تؤثر بشكل كبير في عمر هذه الانظمة وكفاءتها وثمنها، ازدادت الحاجة لمعرفة المزيد من المعلومات عن بطاريات الخزن.

هذا البحث قائم على دراسة الانواع المختلفة من بطاريات الخزن وخصائصها، والتركيز على بطاريات الرصاص - الحامض، كما ان هذا البحث يقوم على إجراء التجارب والقياسات العملية على عدة بطاريات لتطوير خوارزمية رياضية لتحديد قدرة البطارية (أمبير. ساعة) التي تعمل في أنظمة الخلايا الشمسية، هذه الخوارزمية تتيح لنا معرفة حالة البطارية من خلال معرفة جهدها او كثافة السائل الموجود بداخلها. وهذا يبين لنا انسب الظروف التي يجب ان تعمل بها البطارية لاطالة عمرها ومنعها من الوصول الى حالة من التفريغ اعلى من 60% والتي تتسبب في تلفها.

يعرض هذا البحث بناء دائرة مكافئة لبطارية الرصاص - الحامض باستخدام برنامج الماتلاب سيمو لينك، وتحديد كافة العناصر والمعادلات التي تتألف منها الدائرة ومن ثم يعرض النتائج النهائية المتعلقة بهذا الدائرة.