



UNIVERSITI PUTRA MALAYSIA

**DEVELOPMENT OF SMART LEAD-ACID BATTERY CHARGER FOR
ELECTRIC VEHICLE APPLICATION**

MUTASIM IBRAHIM NOUR

FK 1999 25



**DEVELOPMENT OF SMART LEAD-ACID BATTERY CHARGER FOR
ELECTRIC VEHICLE APPLICATION**

MUTASIM IBRAHIM NOUR

**MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA**

June 1999



**DEVELOPMENT OF SMART LEAD-ACID BATTERY CHARGER FOR
ELECTRIC VEHICLE APPLICATION**

By

MUTASIM IBRAHIM NOUR

**Thesis Submitted in Fulfilment of the Requirements for the Degree of Master of
Science in the Faculty of Engineering
Universiti Putra Malaysia**

June 1999



The author dedicates this work to the memory of his father, Ibrahim Hafez Nour, who passed away while it was still in progress.



AKNOWLEDGEMENTS

I wish to express my sincere appreciation to Dr Ishak Aris, Chairman of my supervisory committee, for his keen interest, guidance, encouragement, and support throughout the study.

I wish also to express my grateful thanks to Dr Norman Maruin for his nice help to get source of finance to complete my study. Gratitude is also extended to Dr. Samsul Bahari Mohd Noor for his meaningful supervision.

I would like to take this opportunity to show my appreciation to my parents, and all of my friends for their support and belief in me. I wish to represent this work as a gift to my family back home in Palestine.



TABLE OF CONTENTS

| | Page |
|---|-------------|
| ACKNOWLEDGEMENTS | iii |
| LIST OF TABLES | vii |
| LIST OF FIGURES | viii |
| LIST OF ABBREVIATIONS | xi |
| ABSTRACT | xv |
| ABSTRAK | xvii |
| CHAPTER | |
| I INTRODUCTION | 1 |
| II LITERATURE REVIEW | 5 |
| Rechargeable Batteries..... | 5 |
| Charge and Discharge..... | 6 |
| Functioning of Lead-acid Batteries..... | 7 |
| Battery Charger Classification..... | 10 |
| Lead-acid Battery Charger..... | 11 |
| Three Mode Charger..... | 11 |
| Two Mode Charger..... | 13 |
| One Mode Charger..... | 14 |
| Charging Techniques..... | 14 |
| Constant Voltage Charging..... | 14 |
| Pulsed Charging..... | 14 |
| Stepped Charging..... | 15 |
| Battery Voltage Equalisation..... | 17 |
| Typical Battery Charger Block Diagram..... | 18 |
| Input Rectifier..... | 19 |
| Single-phase Full-wave Rectifier..... | 19 |
| Three-phase Full-wave Rectifier..... | 20 |
| Power Factor..... | 23 |
| Power Factor Correction..... | 26 |
| Input Filter..... | 27 |
| High Power Factor Pre-regulator..... | 27 |
| Principle of the High Power Factor Pre-regulator..... | 28 |
| Control Circuit of the Pre-regulator..... | 30 |
| Switching DC-to-DC Converter..... | 30 |
| Step-down (Buck) Converter..... | 31 |



| | | |
|------------|--|-----------|
| | Step-up (Boost) Converter..... | 32 |
| | Control Circuits for Switching DC-to-DC Converter..... | 38 |
| | Conclusion..... | 35 |
| III | MATERIALS AND METHODS..... | 37 |
| | Introduction..... | 37 |
| | Design of the Power Processor | 37 |
| | Design of the AC-to-DC Converter | 38 |
| | Selecting the Rectifier Diode | 41 |
| | Selecting DC Link Smoothing Capacitor..... | 42 |
| | DC-to-DC Step-down Converter..... | 43 |
| | Buck Converter Design..... | 46 |
| | Selection the Operating Frequency | 48 |
| | Power Switch Selection..... | 48 |
| | Selecting the Power Diodes | 50 |
| | Choosing the Choke Inductor | 52 |
| | Output Capacitor..... | 52 |
| | Snubber Protection Circuit..... | 53 |
| | Output Protection Fuse..... | 54 |
| | Power Losses..... | 54 |
| | Selecting the Heat Sinks..... | 57 |
| | Battery Management Unit..... | 59 |
| | Introduction..... | 59 |
| | Controller Block Diagram..... | 60 |
| | Setting the Charging Current..... | 61 |
| | Sensing and Setting the Charging Voltage..... | 62 |
| | Current Sense Techniques..... | 64 |
| | Setting the Operating Frequency..... | 66 |
| | IGBT Gate Drive..... | 66 |
| | Current and Voltage Loop Compensation..... | 69 |
| | Design of the Compensated Error Amplifier..... | 71 |
| | Indication of the Battery State of Charge..... | 75 |
| | Layout Considerations..... | 75 |
| | Tests..... | 76 |
| IV | RESULTS AND DISCUSSION..... | 79 |
| | Experimental Results..... | 79 |
| | Charge Characteristics..... | 79 |
| | Charger Efficiency..... | 87 |
| | Pspice Simulation Results..... | 90 |
| | Discussion..... | 95 |

| | | |
|----------|---|------------|
| V | CONCLUSION AND RECOMMENDATIONS FOR FUTURE STUDY..... | 96 |
| | REFERENCES..... | 98 |
| | APPENDIX | |
| | A: Experimental Data..... | 102 |
| | B: Pspice Battery Charger Schematic Diagram..... | 104 |
| | C: Component Data Sheets..... | 105 |
| | VITA..... | 136 |



LIST OF TABLES

| Table | | Page |
|--------------|--|-------------|
| 1 | Battery Charger Input Parameters..... | 47 |
| 2 | Experimental Output Data for 30A, 12V Battery Charging Voltage and Charging Current vs. Time..... | 102 |
| 3 | Experimental Output Data for 30A, 48V Battery Charging Voltage and Charging Current vs. Time..... | 103 |



LIST OF FIGURES

| Figure | | Page |
|--------|--|------|
| 1 | Charging Process Flowchart..... | 3 |
| 2 | Changes in a Lead-acid Battery during Charging and Discharging..... | 8 |
| 3 | Typical Over Charge Characteristics at Different Charge Rates..... | 9 |
| 4 | Four-State Charging Algorithm..... | 16 |
| 5 | Typical Battery Charger Block Diagram..... | 18 |
| 6 | Full-Wave Bridge Rectifier. (a) Circuit Diagram, (b) Waveforms..... | 19 |
| 7 | Three-phase Six-pulse Full-bridge Rectifier. (a) Circuit Diagram, (b) Voltage Waveform..... | 22 |
| 8 | Line Voltage and Line Current in a Three-phase Rectifier..... | 26 |
| 9 | High Power Factor Pre-regulator..... | 28 |
| 10 | Full-wave Bridge Rectifier..... | 29 |
| 11 | Step-down Buck Converter. (a) Circuit Diagram, (b) Current and Voltage Waveforms..... | 31 |
| 12 | Step-up Boost Converter. (a) Circuit Diagram, (b) Current and Voltage Waveforms..... | 32 |
| 13 | Block Diagram of DC-to-DC Converter Switching Control Circuit..... | 34 |
| 14 | Timing Pulse Generator for DC-to-DC Converter. (a) Timing Waveform Generator, (b) PWM Output Waveform..... | 36 |
| 15 | Three-phase, Six-pulse, Full-Wave Bridge Rectifier Circuit..... | 39 |
| 16 | Voltage and Current Waveforms of Three-phase, Six-pulse, Full-wave Rectifier Circuit..... | 40 |



| | | |
|----|--|----|
| 17 | DC-to-DC Step-down Converter. (a) Practical Circuit Diagram, (b) Current and Voltage Waveforms..... | 45 |
| 18 | (a) IGBT Equivalent Circuit. (b) IGBT Symbol..... | 50 |
| 19 | (a) Power Diode Symbol. (b) I-V Diode Characteristics, (c) Diode Current during Turn Off Time..... | 51 |
| 20 | IGBT Voltage and Current Switching Waveforms..... | 56 |
| 21 | The Equivalent Electrical Analogue of Heat Transfer..... | 58 |
| 22 | Circuit of the Controller Interfaced with Current and Voltage Sensing Resistors..... | 63 |
| 23 | Circuit Diagram of the IGBT Gate Drive..... | 67 |
| 24 | Average Current and Voltage Feedback Control Circuit..... | 70 |
| 25 | Compensated Error Amplifier. (a) Circuit Diagram, (b) Gain and Phase Plot..... | 72 |
| 26 | Complete Battery Charge Circuit Diagram..... | 78 |
| 27 | 30Ah, 12V, Sealed Lead-acid Battery Charging Characteristics. (a) Charging Voltage, (b) Charging Current..... | 81 |
| 28 | 30Ah, 48V, Sealed Lead-acid Battery Charging Characteristics. (a) Charging Voltage, (b) Charging Current..... | 82 |
| 29 | Charger Waveforms for 48V Battery. (1) IGBT Switch Output Voltage, (2) Controller Output..... | 84 |
| 30 | Charger Waveforms for 48V Battery at 6A Maximum Charging Current. (1) IGBT Switch Output Voltage, (2) Inductor Current..... | 84 |
| 31 | Charger Waveforms for 12V Battery at 6A Maximum Charging Current. (1) IGBT Switch Output Voltage, (2) Inductor Current..... | 85 |
| 32 | Charger Waveforms for 48V Battery at 15A Maximum Charging Current during Bulk Charge Mode. (1) IGBT Switch Output Voltage, (2) Inductor Current..... | 85 |



| | | |
|----|---|-----|
| 33 | Charger Waveforms for 48V Battery at 15A Maximum Charging Current in Over Charge Mode. (1) IGBT Switch Output Voltage, (2) Inductor Current..... | 86 |
| 34 | Charger Waveforms for 48V Battery at 15A Maximum Charging Current during Float Charge Mode. (1) IGBT Switch Output Voltage, (2) Inductor Current..... | 86 |
| 35 | Efficiency vs. Output Voltage in charging 30Ah, 12V, Battery at 6A Charging Current from a Single-phase Supply | 88 |
| 36 | Efficiency vs. Output Voltage in charging 30Ah, 48V, Battery at 6A Charging Current from a Single-phase Supply..... | 89 |
| 37 | Efficiency vs. Output Voltage, for 30Ah, 48V, Battery at 15A Charging Current from a Three-phase Supply..... | 89 |
| 38 | Output Voltage and Current Waveforms for 48V Battery at 15A Maximum Charging Current in Trickle Charge Mode (Simulation with Pspice)..... | 91 |
| 39 | Output Voltage and Current Waveforms for 48V Battery at 15A Maximum Charging Current in Bulk Charge Mode (Simulation with Pspice)..... | 91 |
| 40 | Output Voltage and Current Waveforms for 48V Battery at 15A Maximum Charging Current in Over Voltage Mode (Simulation with Pspice)..... | 92 |
| 41 | Output Voltage and Current Waveforms for 48V Battery at 15A Maximum Charging Current in float Voltage Mode (Simulation with Pspice)..... | 92 |
| 42 | Experimental Circuit with Single-phase Input | 93 |
| 43 | Experimental Circuit with Three-phase Input | 93 |
| 44 | Experimental Circuit, with Three-phase Input | 94 |
| 45 | Pspice Schematic Diagram for the Battery Charger..... | 104 |



LIST OF ABBREVIATIONS

| | |
|--------------|--|
| ω | Radian frequency (rad/s) |
| Δi_L | Rate of Change in the inductor current (A) |
| AC | Alternating current (A) |
| Ah | Ampere hour |
| a_n | Even coefficients of Fourier series |
| BJT | Bipolar junction transistor |
| C | Capacitor (Farad) or Charge rate |
| C_B | Bootstrap capacitor (Farad) |
| CS | Current sense amplifier |
| C_S | Snubber capacitor (Farad) |
| CSO | Current sense amplifier output |
| D | Diode symbol, or duty ratio |
| D_B | Bootstrap diode |
| DC | Direct current |
| ϕ | Displacement angle |
| ESR | Equivalent series resistance (Ohm) |
| EV | Electric vehicle |
| F | Frequency (Hertz) |
| F_L | Line frequency (Hertz) |
| F_S | Switching Frequency (Hertz) |
| G | Gate |



| | |
|----------------------|---|
| I_{bulk} | Bulk charge current (A) |
| IC | Integrated Circuit |
| I_D | Diode current (A) |
| I_d | Output current of bridge rectifier (A) |
| IGBT | Insulated gate bipolar transistor |
| I_L | Inductor current (A) |
| I_O | Output current |
| I_{oct} | Over charge current (A) |
| I_{QBS} | Quiescent VBS Supply current (A) |
| I_{trickle} | Trickle charge current (A) |
| $I_{\text{Out Max}}$ | Maximum output current (A) |
| J | Junction, or energy density (Joule) |
| KCL | Kirchhoff current law |
| KVL | Kirchhoff voltage law |
| L | Inductance (Henry) |
| L_S | Source inductance (Henry) |
| MOSFET | Metal oxide silicon field effect transistor |
| P_A | Total average power loss (Watt) |
| Pb | Lead |
| PbSO_4 | Lead sulphate |
| P_C | Conduction power loss (Watt) |
| P_{diss} | Power dissipation (Watt) |
| PF | Power factor |

| | |
|-----------------|--|
| PIV | Peak inverse voltage (Volt) |
| P_s | Switching power loss (Watt) |
| PWM | Pulse width modulation |
| Q | The charge (Coulomb) or transistor symbol |
| r_c | Equivalent series resistance of the output capacitor (Ohm) |
| r_L | Equivalent series resistance of the choke inductor (Ohm) |
| R_b | Battery internal resistance (Ohm) |
| R_{CS} | Current sense resistor (Ohm) |
| R_{CS} | Thermal resistance from case to sink ($^{\circ}C/W$) |
| R_G | Gate resistor (Ohm) |
| $R_{G1,2}$ | Trickle and bulk charge current set resistors (Ohm) |
| R_{JC} | Thermal resistance from junction to case ($^{\circ}C/W$) |
| rms | Root mean squared |
| $R_{OVC1,2}$ | Overcharge current set resistors (Ohm) |
| R_S | Snubber resistor (Ohm) |
| R_{SA} | Thermal resistance from sink to ambient ($^{\circ}C/W$) |
| R_{set} | Frequency set resistor (Ohm) |
| $R_{VS1,2,3,4}$ | Voltage sense resistors (Ohm) |
| T | Time interval (Second) |
| T_A | Ambient temperature ($^{\circ}C$) |
| T_J | Junction temperature ($^{\circ}C$) |
| T_{JA} | Junction to ambient temperature ($^{\circ}C$) |
| t_{rr} | Reverse recovery time (Second) |

| | |
|----------------|--|
| V_b | Battery voltage (Volt) |
| VCO | Voltage controlled oscillator |
| V_{cutoff} | Deep discharge cutoff voltage (Volt) |
| V_d | Output voltage of bridge rectifier (Volt) |
| V_f | Forward voltage drop across the diode (Volt) |
| V_{float} | Float charge voltage (Volt) |
| V_i | Input voltage (Volt) |
| V_{L-L} | Line-to-line voltage (Volt) |
| V_m | Maximum voltage (Volt) |
| $V_{m,L-L}$ | Maximum line-to-line voltage (Volt) |
| V_O | Output voltage (Volt) |
| V_{oc} | Over charge voltage (Volt) |
| $V_{rms,L-L}$ | rms line-to-line voltage (Volt) |
| V_S | Source voltage (Volt) |
| $V_{Out. Max}$ | Maximum output voltage (Volt) |

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in
fulfilment of the requirements for the degree of Master of Science.

**DEVELOPMENT OF A SMART LEAD-ACID BATTERY CHARGER FOR
ELECTRIC VEHICLE APPLICATION**

By

MUTASIM IBRAHIM NOUR

June 1999

Chairman: Ishak Aris, Ph.D.

Faculty: Engineering

The battery charger is a critical part in an electric vehicle (EV) because it charges the battery, which is the weakest part of it. An unduly long charging time limits the use of the EV. Currently, it takes a long time to charge a battery of limited capacity, making EVs rather impractical to use.

The objective of this thesis is to design, simulate, construct and test a smart charger for fast charging a battery. The charger consists of two units - the power processing unit and the battery management unit. The power processor is based on a step-down DC-to-DC converter topology. The battery management unit uses first a current control (constant current mode) and then voltage control (constant voltage mode) to charge the battery.



The smart control mechanism is based on current and voltage sensing combined with sequenced average current and voltage control to charge the battery as fast as possible and to maximise its charge.

The charger was tested successfully on single-phase and three-phase voltage supplies at different output voltages and currents. The charger developed was able to charge a 30 Ah lead-acid battery in two hours as opposed to six hours using a conventional charger.

The research showed that it was possible to develop a battery charger which can charge a battery to its limits quickly without gassing and overheating. It is likely that the battery life will be extended without the detrimental effects experienced.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains.

**PEMBANGUNAN PENGECAS PLUMBUM-ASID BATERI CERDIK
UNTUK APLIKASI KENDERAAN ELEKTRIK**

Oleh

MUTASIM IBRAHIM NOUR

Jun 1999

Pengerusi: Ishak Aris, Ph.D.

Fakulti: Kejuruteraan

Pengecas bateri adalah bahagian yang kritikal pada kenderaan elektrik berfungsi mengecas bateri yang merupakan bahagian paling lemah pada kenderaan elektrik. Ketidaksihuan masa pengecasan yang panjang menghadkan penggunaan kenderaan elektrik.. Pada masa ini, mengecas bateri mengambil masa yang panjang dengan kapasiti terhad, mengakibatkan kenderaan elektrik tidak praktikal digunakan.

Tesis ini bertujuan merekabentuk, mensimulasi, membina dan menguji pengecas cerdas untuk pengecasan bateri dengan cepat. Pengecas terdiri daripada dua unit - unit pemprosesan kuasa dan unit pengurusan bateri. Kuasa pemproses berdasarkan kepada topologi penukar langkah-turun arus terus-ke-arus terus (DC-to-DC). Unit pengurusan bateri menggunakan kawalan arus (mod arus tetap) dan kawalan voltan (mode voltan tetap) untuk mengecas bateri.



Mekanisma kawalan cerdik berdasarkan pada arus dan pengesanan voltan, berserta dengan purata arus berjujukan dan kawalan voltan untuk mengecas bateri secepat mungkin dan untuk memaksimumkan cas.

Pengecas telah diuji dengan jayanya pada fasa-tunggal dan fasa-tiga bekalan voltan pada arus dan voltan keluaran berbeza. Pengecas yang dibangunkan berkebolehan mengecas 30 Ah bateri plumbum-asid dalam dua (2) jam dibandingkan enam (6) jam menggunakan pengecas biasa.

Kajian telah menunjukkan kebolehan membangunkan pengecas bateri, yang boleh mengecas bateri dengan had yang cepat tanpa gas dan kelebihan haba. Ini membolehkan masa hayat bateri ditambah tanpa mendatangkan kesan-kesan keburukan.

CHAPTER I

INTRODUCTION

The battery is the weakest link in an electric vehicle (EV) and much is being done to improve its performance. The important requirements for an EV battery are high power and energy densities, low cost, long life and high charging efficiency. However, its performance depends not only on its design but also on the way it is used, including how it is charged. Thus, the battery charger is important to ensure its optimum performance and long life. The two most important considerations in charging are the time required and the life conferred the battery.

The most common battery used in EVs today is still the lead-acid battery. It has remained the *prima donna* of electric storage devices because of its combination of long standby time and high cycle-life with a decent storage capacity to boot. To charge it, the charger has to accomplish two tasks:

Firstly, to restore the charge, often as quickly as possible. Secondly, to maintain the charge by minimising its self-discharge. To do both tasks well requires accurate sensing of the battery voltage and temperature. The way the battery is charged will greatly affect its performance.



The lead-acid battery is commonly used in EVs because of the greater limitations of other batteries. Manufacturers are therefore challenged to produce a cell of high capacity and long life, which can be quickly and efficiently recharged. Satisfying the contradicting requirements for quick charging and long battery life is difficult, *inter alia* requiring that the charging process be improved. To maximize the use of the battery, it must be charged quickly, but for long life, slowly.

The objective of this research is to design a smart battery charger, supplied from a three-phase or single-phase diode bridge rectifier that can charge a lead-acid battery quickly. An IGBT transistor is used as the main switch in a DC-to-DC converter circuit topology. A combination of average current mode control and voltage mode control is used to control the charging. There are three modes of charging: trickle charge, constant (bulk) current charge and constant voltage charge.

The charging process is shown Figure 1 and explained below.

When a battery is below the cut-off voltage (80% of its nominal voltage), the charger supplies a low current in trickle mode. This slowly raises the voltage to the cut-off level, at which the charger changes to bulk charging. However, if initially, the battery is already above the cut-off voltage, the trickle charge is skipped and the charger starts off with bulk charging. If one or more cells of the battery is damaged, the voltage will remain below the cut-off voltage, and the charging will always remain in trickle mode.

In bulk charge, a constant current is used. This is the maximum allowed to quickly restore most (80% - 90%) of the battery capacity. This charge is terminated at the over charge threshold voltage and the charger goes into a constant voltage mode, under which the full charge of the battery is restored.

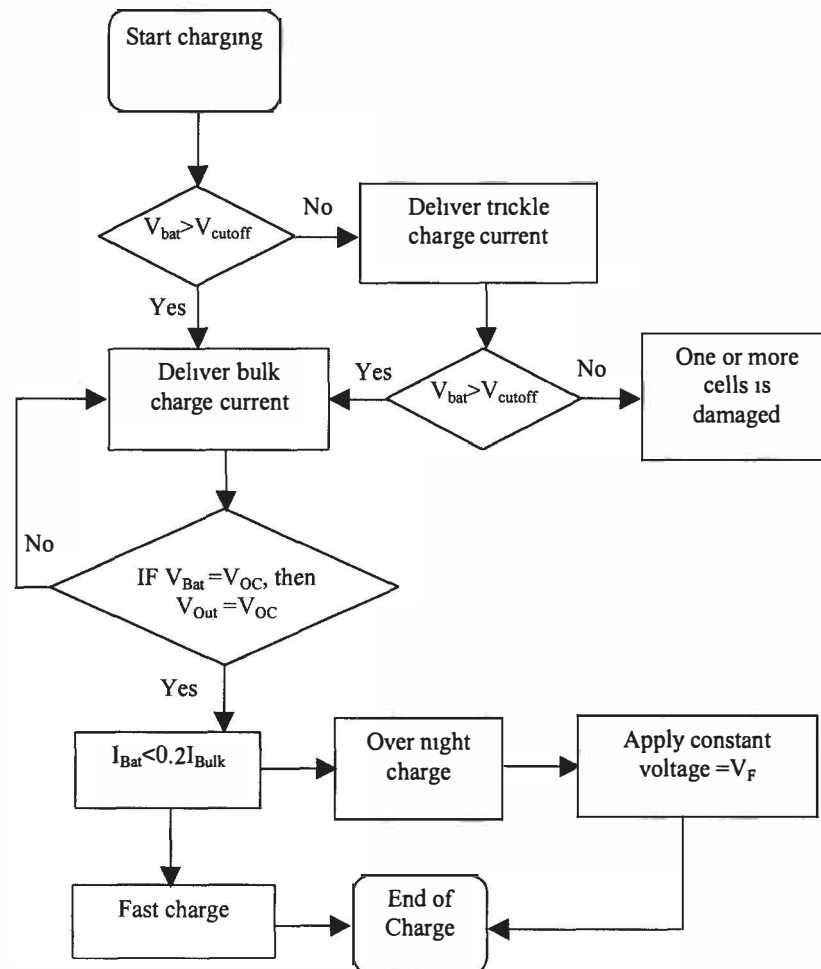


Figure 1: Charging Process Flowchart

In this mode, the voltage applied is fixed at the overcharge voltage V_{OC} . Initially, the charging current will equal the bulk current, but tapers off as the battery becomes more fully charged. Once the current taken by the battery falls to

20% of the bulk current, the battery is >95% charged - effectively “full” for fast charging. If the charger is left on, a constant float voltage, V_F , is applied until the battery is 100% full and then to maintain the capacity from self-discharge.

This dissertation is organised thus:

Chapter 2 reviews the literature on batteries and chargers. Charging techniques for the lead-acid battery are discussed, and the main parts of the battery charger are illustrated.

In Chapter 3, the design of the charger is explained, including the techniques used, the power processor unit and the battery management control unit.

Chapter 4 discusses the performance of the charger. Conclusions about the work and recommendations for future work are given in Chapter 5.

CHAPTER II

LITERATURE REVIEW

Rechargeable Batteries

The battery, a transformer of chemical energy into electrical energy and *vice versa*, is the most critical component in an EV as its performance (energy and power densities, charging time, life and cost) lags practical requirements (Seung, 1995). In a lead-acid battery, two electrodes are immersed in an electrolyte solution that allows electrons to travel between them (Rechargeable Batteries Applications Handbook, 1992). For a clear discussion on the battery, some of the terms used have first to be defined/explained.

State of Charge – The voltage, internal resistance and amount of sulphate on the plates indicate a battery's state of charge.

Gassing – When a battery is charged beyond full charge, the surplus electricity electrolyses water, producing hydrogen at the cathode and oxygen at the anode (Brant, 1994).

Ampere-Hour (Ah) – A measure of the electric charge, computed as:

$$\text{Current (in amperes)} \times \text{Time (in hours)}.$$

Capacity – The amount of electricity that a battery can store.