UNIVERSITI PUTRA MALAYSIA

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FK 1999 25

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June 1999

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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.

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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)
$I_{Out\ Max}$	Maximum output current (A)
J	Junction, or energy density (Joule)
KCL	Kirchhoff current low
KVL	Kirchhoff voltage low
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	Pule 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 (°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 (°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 (°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 (°C)
T_J	Junction temperature (°C)
T_{JA}	Junction to ambient temperature (°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 lint-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.**

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Pengecas bateri adalah bahagian yang kritikal pada kenderaan elektrik berfungsi mengecas bateri yang merupakan bahagian paling lemah pada kenderaan elektrik. Ketidaksesuian 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 bertujuaan merekabentuk, mensimulasi, membina dan menguji pengecas cerdik 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 sepantas mungkin dan untuk memaksimakan 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.

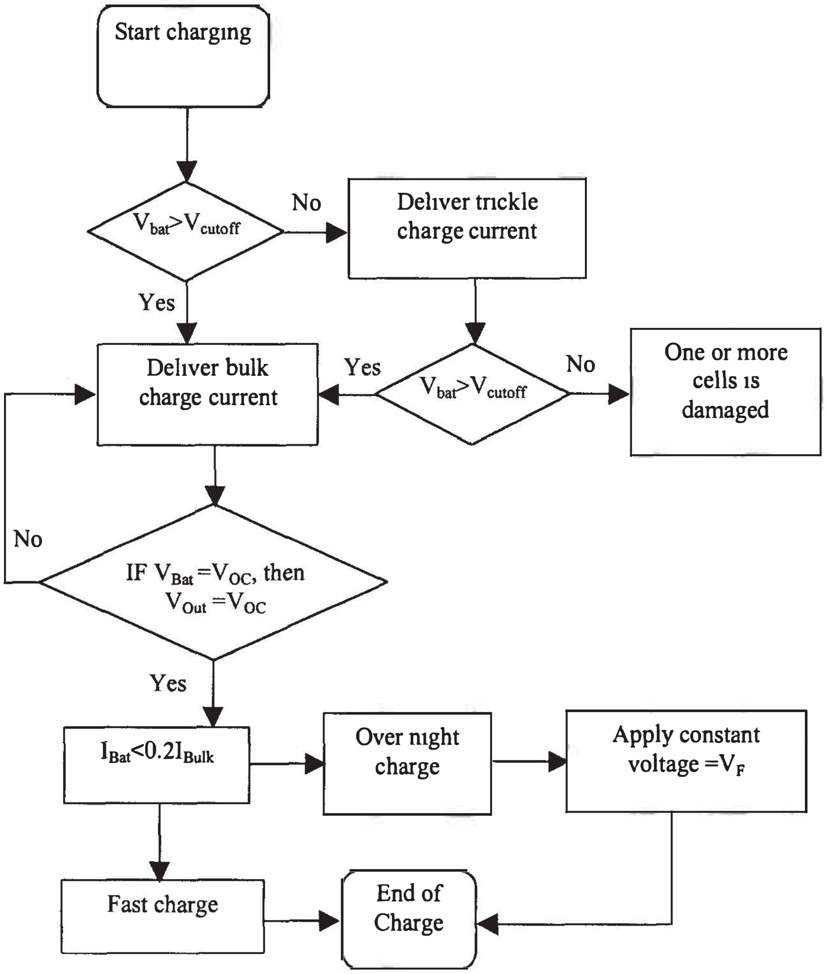

Figure 1: Charging Process Flowchart

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:

Current (in amperes) X Time (in hours).

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