UNIVERSITI PUTRA MALAYSIA

THREE-LEVEL UNIVERSAL ELECTRIC VEHICLE CHARGER BASED ON VOLTAGE-ORIENTED CONTROL AND SINUSOIDAL PULSE-WIDTH MODULATION

ALI SAADON MTAIR AL-OGAILI

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By

ALI SAADON MTAIR AL-OGAILI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2017

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DEDICATION

I would like to dedicate this thesis to my father and my mother for their endless love, support, and encouragement. Thank you both for giving me the strength to reach for the stars and chase my dreams. My uncle, Abduljabbar, My brother, Mohammed Saadon, My sister, Menar, and my best friend, Hashim; are worthy of deserving my wholehearted thanks as well.

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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December 2017

Chairman : Ishak Bin Aris, PhD
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The electric vehicle (EV) could be one of the solutions to address the issues of the environmental pollution and the depletion problems of non-renewable energy resources. EVs, which are energized by a battery storage system, are becoming attractive because it keeps the environment clean and friendly. The battery charger of EV needs to have a sufficient performance by a unity power factor and zero harmonic distortion.

This work presents the design process of a universal EV charger. The proposed charger is able to provide a controllable and constant charging voltage for a variety of EVs. It is composed of three levels of charging: (1) 650 V/100 A DC for bus or lorry, (2) single-phase 120 V/16 A AC for motorcycle, and (3) three-phase 240 V/60 A for saloon car battery charging.

The power system of this work consists of two converters: (1) the three-phase pulse-width modulated (PWM) of a bridge rectifier with an output of 650 V DC unregulated voltage, and (2) the converter is for the three-phase DC–DC converter.

To satisfy the voltage control and the isolation between Grid To Vehicle (G2V), a three-phase transformer has been exploited within the DC–DC converter. The primary output circuit achieved the charge Levels 1 and 2, while the whole circuit output can charge Level 3 or the DC charge. For efficient and secure battery charging, voltage-oriented control (VOC) technique is proposed.

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A study is conducted to investigate the use of a three-phase converter unidirectional EV battery charger. In the proposed design, the reactive and unstable active currents can be counteracted by the PWM rectifier via the input and output filters and PFC.

The current controller and DC-link voltage controller have been designed using a technique called internal model control. The unity power factor for the PWM-based rectifier and SPWM are designed and evaluated using MATLAB/Simulink 2010a block sets. The total harmonic distortion (THD) for the input current is recorded as less than 0.85 %. A prototype and simulation results are used to validate the proposed EV charger to ensure its robustness, accuracy, and application.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGECAS KENDERAAN ELEKTRIK SEMESTA TIGA ARAS BERDASARKAN KAWALAN BERHALAAN VOLTAN DAN MODULASI LEBAR DENYUT BENTUK SINUS

Oleh

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Kenderaan elektrik (EV) boleh menjadi salah satu penyelesaian untuk menangani isu-isu pencemaran alam sekitar dan masalah kesusutan tenaga. EV yang ditenagakan oleh sistem storan bateri, menjadi menarik kerana ia menjadikan alam sekitar bersih. Pengecas bateri EV perlu mempunyai prestasi yang mencukupi dengan faktor kuasa unit dan gangguan sifar herotan harmonik.

Kerja ini membentangkan proses reka bentuk pengecas EV semesta, Pengecas yang dicadangkan dapat menyediakan voltan pengecasan terkawal dan berterusan untuk pelbagai EV, yang terdiri daripada tiga tahap pengisian iaitu 650 V/100 A DC untuk bas atau lori, fasa tunggal 120 V/16 A AC untuk motosikal, dan tiga fasa 240 V / 60 A untuk pengecasan bateri kereta saloon.

Sistem kuasa kerja ini terdiri daripada dua penukar; pertama, adalah untuk modul penerus jambatan termodulat lebar denyut (PWM) tiga fasa dengan keluaran 650 V voltan DC tak diatur, manakala penukar kedua adalah untuk penukar DC-DC tiga fasa.

Untuk memenuhi kawalan voltan dan pengasingan antara Grid ke Kenderaan (G2V), pengubah tiga fasa telah dieksploitasi dalam penukar DC-DC. Litar keluaran utama mencapai cas Tahap 1 dan 2, manakala keluaran keseluruhan litar boleh mengecas Tahap 3 atau cas DC. Untuk pengecasan bateri yang cekap dan selamat, teknik kawalan berorientasikan voltan (VOC) telah dicadangkan.Satu kajian telah dijalankan dengan menyiasat penggunaan penukar tiga fasa pengecas bateri EV satu

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arah tiga fasa untuk digunakan di stesen pengecasan. Dalam reka bentuk yang dicadangkan, arus regangan dan arus aktif yang tidak stabil boleh diatasi oleh penerus PWM melalui penapis masukan dan keluaran dan PFC.

Pengawal arus dan pengawal voltan DC-link telah direka menggunakan teknik yang dikenali sebagai Kawalan Model Dalaman. Faktor kuasa unit untuk penerus berasaskan PWM dan SPWM direka dan dinilai menggunakan set blok MATLAB/Simulink 2010a. Jumlah herotan harmonik (THD) untuk arus masukan adalah kurang daripada 0.85 %. Keputusan prototaip dan simulasi mengesahkan bahawa pengecas EV yang dicadangkan adalah kukuh, tepat dan boleh guna.

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I certify that a Thesis Examination Committee has met on 21 December 2017 to conduct the final examination of Ali Saadon Mtair Al-Ogaili on his thesis entitled "Three-Level Universal Electric Vehicle Charger Based on Voltage-Oriented Control and Sinusoidal Pulse-Width Modulation" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF SYMBOLS

a	Phase A
b	Phase B
c	Phase C
d	D Frame Representation
C_{dc}	DC-link Capacitor
i_S	Source Current
L	Inductor
P	Active Power
Q	Reactive Power
q	Q Frame Representation
R	Resistor
S	Switching Signal
T	Torque
V_{dc}	DC-link Capacitor Voltage
v_S	Source Voltage
θ	Reference Angle
α	Alpha Domain Representation
β	Beta Domain Representation
0	Zero Domain / Frame Representation
ψ_R	Amplitude of rotor flux
$\overline{\Psi_r}$	Rotor flux
$\omega_{\lambda r}$	Rotor flux angular velocity

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog-to-Digital Converter
BEV	Battery Electric Vehicle
BMS	Battery Management System
CC	Constant Current
CCS	Code Composer Studio
CV	Constant Voltage
DC	Direct current
DSP	Digital Signal Processor
DPC	Direct Power Control
DTC	Direct Torque Control
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FLC	Fuzzy Logic Controller
FOC	Field-oriented Control
GPC	Generalized Predictive Control
GPIO	General Purpose Input / Output
G2V	Grid to Vehicle
IC	Integrated Circuit
ICE	Internal Combustion Engine
IGBT	Insulated Gate Bipolar Transistor
IMC	Internal Model Control
IPM	Intelligent Power Model
KVL	Kirchhoff's Voltage Law

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MIMO	Multi-input Multi-output
MPC	Model Predictive Control
NN	Neural Network
NNGVE	Neural Network Grid-Voltage Estimator
NNIPI	Neural Network Interfacing Parameters Identifier
SISO	Single Input Single Output
SM	Sliding Mode
SPWM	Sinusoidal Pulse-width Modulation
SVPWM	Space Vector Pulse-width Modulation
THD	Total Harmonic Distortion
PEV	Plug-in Electric Vehicle
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
P	Proportional
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PLL	Phase-locked loop
PWM	Pulse-width Modulation
VOC	Voltage-oriented Control
VSS	Variable Structured Systems
VSI	Voltage Source Inverter
V2G	Vehicle to Grid

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CHAPTER 1

INTRODUCTION

1.1 Background

There is a growing concern on the issues of the non-renewable energy resources depletion and other environmental issues all over the world. The concerns are largely focusing on replacing the fuel based automobiles with electric vehicles (EVs) with no emission and low noise. Motorbike vehicles – salon cars and vans – generate about 15% of the EU's emissions of CO_2 as shown in Figure 1.1. Consequently, various countries have taken their own initiatives in developing their own EV industry, aiming to de-carbonize their transport sectors. In setting the timeframe for the Malaysia Automotive Technology Roadmap (MART), the most appropriate policy adopted is the forecasted advancement of the Energy Efficient Vehicle (EEV) from Internal Combustion Engine (ICE) to Electric Vehicles (EV) as description in Figure 1.2. For instance, China has brought forward a conservative development plan that aimed to increase number of EVs ownership to five millions by 2020 [1]. However, the availability and convenient of EVs charging infrastructure are the key factors that affects the future development and popularization of the EVs. In addition, EV charging infrastructure insufficiency will hinder the widespread use of EVs. Therefore, all necessary advice and guidance have been provided to develop a convenient EV charging infrastructure network, especially, fast charging stations on the freeways, which can significantly enhance travel distance of EV [2].

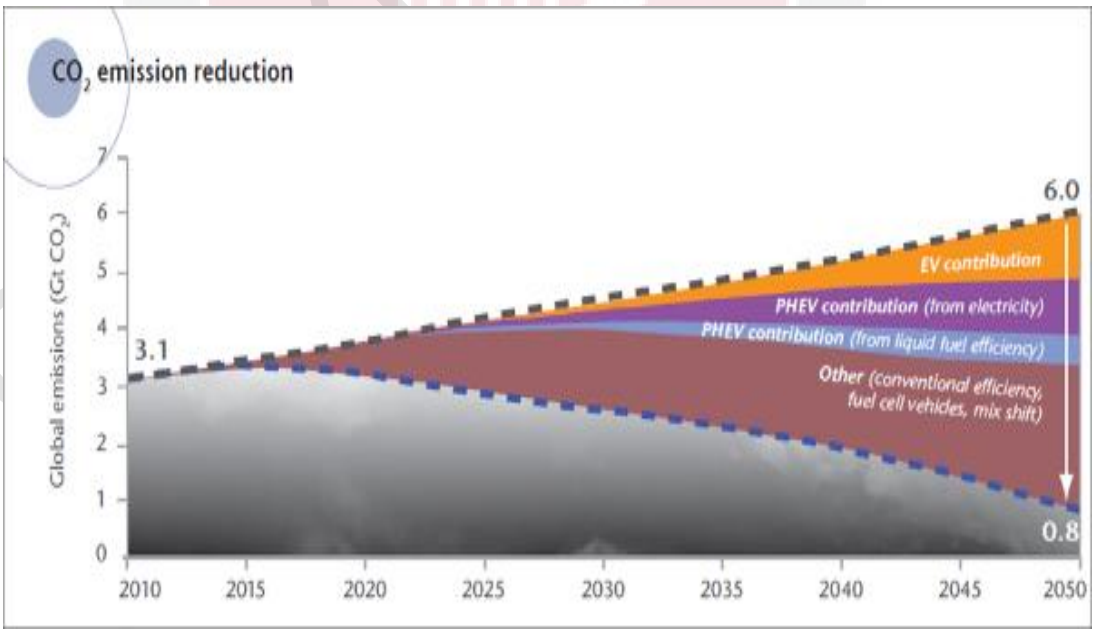

Figure 1.1 : Global CO2 emission reduction

Figure 1.2 : Malaysia automotive technology projection (2013-2025)

Regardless of the environmental and economic benefits, the substantial scales of grid-connected EVs impose incredible difficulties to the power grid. The main issues that are caused by EV charging on the power grid include harmonics, voltage drop, system instability, system losses, and grid overloading [3, 4]. Particularly, the effect of EV charging which leads to voltage drop of power grid has broadly been investigated and reported in the previous literatures [5-7]. In spite of the fact that EV charging has caused many difficulties to the operation of power grid, the development of EV can actually convey another prospect to the power grid. This is due to the fact that EV is considered as mobile energy storage. The energy in EV battery can be used to support the grid in different circumstances. With the bidirectional communication framework integrated in the power grid, the exchange of energy between the power grid and EV battery can plausibly be managed.

EVs are operated by an electric motor which receives power from a rechargeable battery. The performance qualities required for some EVs specifications greatly surpass the capabilities of traditional battery systems. Unfortunately, when the battery technology advances, the charging of these batteries turns out to be exceptionally complicated. This is due to the involvement of high voltage and currents flow in the system; as well as the necessity of complex charging techniques. This imposes great distortions in the connected ac power system, and thus, an efficient and low-distortion charger is highly required. With respect to the issues stated above, battery charging technology faces a great deal of challenges. The technology of battery varies in different ways. The commonly applied charging techniques are the constant-current and constant-pressure charging techniques. Since AC voltage of the charger fluctuates most of the time, it requires a tributary constant-current power supply for the charging process; which is known as constant-current charger.

1.1.1 Types of Vehicles in Use Today

Ideas that were developed during the 19th century are now being utilized to develop a new collection of vehicles. Vehicles can be classified into four basic types. First type is the internal combustion engine (ICE) vehicle. It runs on liquid fuels such as, gasoline, diesel, ethanol or biodiesel. The ICE vehicle is the most common type and majority of the vehicles on the road today belong to this category.

The second type is the traditional battery electric vehicle (BEV). This battery relies fully on batteries to obtain their energy. The BEV can be charged either by being plugged into a charger, or by exchanging or replacing the depleted battery with a charged one. BEVs do not have the usual conventional engine or a tailpipe or even a fuel tank. This is because of the type of vehicle is fully operated on battery energy, whereas the commercial vehicles run on fossil fuels. The distance range and performance of the BEVs is fairly limited, however, they are adequate for their planned purpose. It is essential to remember that the electric car is a major performer in this field, and there is still room for an improvement. Nevertheless, the technology of electric cars is developing and improving continuously in order to compete with their biggest competitors; the internal combustion engine cars.

A hybrid vehicle uses a combination of electric power and fossil fuel; it has two energy systems for the engines to operate. The furthermost public type of hybrid vehicle is comprised of: an internal combustion engine with a battery, and an electrical motor and generator. The two basic measures for hybrid vehicles consist of the series called the hybrid vehicle and the parallel hybrid. A hybrid vehicle series is driven by one or more electric motors, which is provided either from the ICE driven generator unit (EVT book) or the battery or both. In either system, the electric motor fully supplies the driving force. However, in the parallel hybrid series, both the electric motor and internal combustion engine provide the driving force. In this system, the generator and engine recharges the battery itself while moving. Both types possess a regenerative braking mechanism, whereby, the drive motor works as a generator while slowing down the vehicle and simultaneously recharging the battery.

The fueled electric vehicle comprises of the same basic principles of an electric vehicle, where the battery is the power source. However, instead of a rechargeable battery, a metal air battery or fuel cell is used. Hydrogen gas is used to power an electric motor, which is kept in liquid system. Even though it can be kept on the board, it is not an easy task. Alternatively, hydrogen is produced from a fuel such as methanol. A variation of fuel cells is the metal air batteries that are refueled by substituting the metal electrodes, which can be easily recycled. The most common type metal that can be categorized to this class are the zinc air batteries.

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1.1.2 On / Off Board Charging System

Presently, there are two charging techniques for electric vehicles (EVs) namely AC and DC charging [8, 9]. For AC charging, single-phase and three-phase AC power is supplied via on-board AC–DC converter of the EV. Meanwhile, DC charging is performed by direct supplying DC power to the battery of EV via off-board AC–DC converter supplies. There are three types of chargers that are widely applied [10-14]:

1. Type 1 SAE J1772 – single-phase charger applied in US
2. Type 2 Mennekes – single-phase and three-phase charger applied in Europe,
3. Tesla dual charger – single-phase AC and DC.

The use of on-board chargers definitely will increase charging accessibility of the vehicle and meanwhile, off-board chargers allow the use of higher rating circuits. Thus, it completes charging in shorter period of time.

Figure 1.3 shows the off-board charger [15]. It is actually available as an outside unit, rather than being a part of the EV. A typical off-board charger is able to produce a higher DC voltage. As a result, the internal battery management system (BMS) should have the ability to charge the battery by supplying this voltage. Nevertheless, the main weakness of this type of design is that the charger is not installed as a part of the EV. Therefore, charging of EV battery can only be done with a specific charger that is capable of providing the required higher amount of DC voltage.

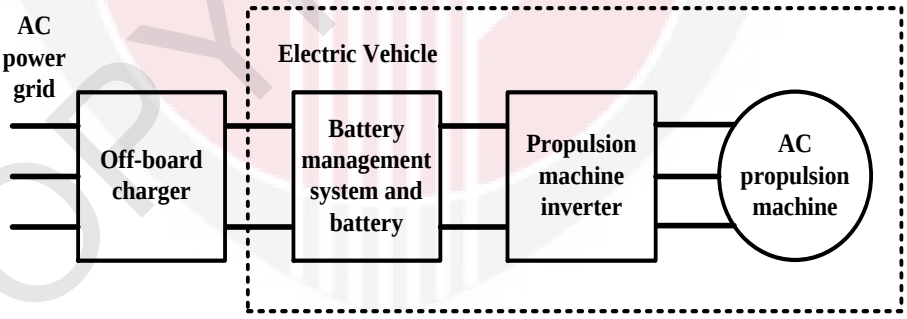

Figure 1.3 : Block diagram of off-board charger [15]

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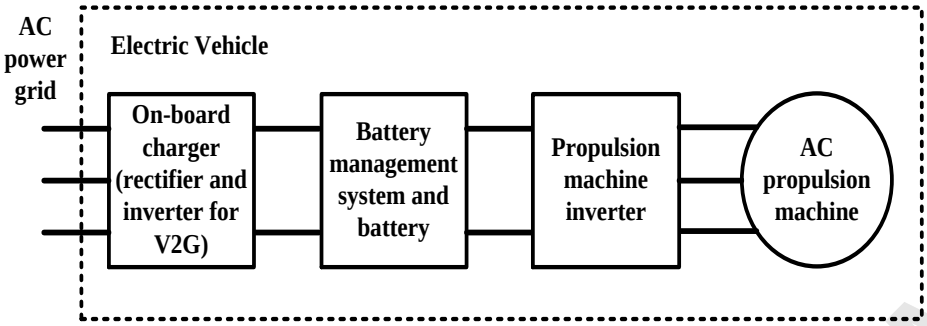

Figure 1.4 : Figure 1.4: Block diagram of on-board charger [16]

On the other hand, Figure 1.4 depicts the on-board charger [16]. In contrast to off-board charger, on-board charger is made as a part of EV, which allows charging at almost every location possible. As long as there is a single-phase and three-phase supply is available. However, the main disadvantage of this design is that an additional DC–AC inverter is essential.

1.1.3 Overview about the Planning of EV Charging Facilitates

Lately, plug-in electric vehicles (PEVs) have acquired a noteworthy awareness as they provide significant advantages both economically and financially. From environmental point of view, effective utilization of PEVs can greatly reduce the consumption of conventional energy sources especially gasoline. This is because PEVs powered by battery that can be completely recharged by electricity. Thus, fewer discharges are generated. From the literature [17], battery powered PEVs has reported to have a reduced discharge from transport sector, with up to 70 %, hence, it essentially minimizes environmental contamination. Financially, from previous literature [18], a TESLA PEV prices only 30$/km, meanwhile, a gasoline-fueled premium sedan prices 173$/km, respectively.

Due to the results of benefits mentioned above, there is a large number of PEVs operating in various nations among the world [19]. Additionally, high PEV infiltration levels are estimated to reach about 35 % by the year 2020, 51 % by the year 2030, and 62 % by year 2050 [20]. Generally, PEVs can be recharged by electricity while they are being parked at industrial, residential, and commercial as well as parking areas [21]. Moreover, mobile PEVs can fully be recharged within the time duration of 30 minutes at fast charging stations [22].

Generally, there are two main directions of research which are linked to these charging facilities (fast charging stations and parking lots). Firstly, it focuses on the process techniques of these charging services to prevent problems of overload charging [23, 25- 30]. Secondly, diverse development models are examined for these charging facilities [31, 32]. Therefore, this work focuses on the future research

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direction. Charging facility planning for PEV [33] must include the charger numbers to be installed in the charging facility. This corresponds to the degree of power drawn from the grid, and the space of waiting area for the uncharged PEVs. Literature has rarely discussed on the main factors that influence waiting duration of PEVs at the charging services and the proportion of PEVs with forbidden charging orders, which happens once all chargers and waiting areas are fully occupied for a new PEV [34, 35].

Besides, the research on charging facilities is limited to few factors that are discussed in literature. One factor is that an optimization for performance improvement only involves the number of chargers installed. Nevertheless, the space of waiting area for uncharged PEVs is also important due to the fact that fast charging stations are more commonly installed in areas that are based in real estate such as business districts and city centers. Thus, it becomes expansive at cost. However, oversized waiting area may reduce the profit of operator for charging facility because of the associated high investment cost. In contrast, an insufficient size of waiting area may reduce the request probability in term of PEV charging, and it will eventually contribute to loss in profit. Moreover, the current planning models only target to enhance a single criterion such as rejected requests, charger utilization, and waiting time. However, an effective charging facilities plan must consider implementing a multiple criteria, which includes the electricity cost, price of charging service, waiting queue length of PEVs, and percentage of rejected PEV charging requests. This is because these are all the critical aspects that greatly influence the amount of profit earned.

1.1.4 Charger Power Levels and Infrastructure

The power level of charger reflects towards its power, location and charging time, equipment, the impact on the grid, and cost. Charging infrastructure and EV supply equipment (EVSE) installation requires critical considerations due to many issues that should be considered: the regulatory procedures, demand policies, distribution, extent, charging time, and charging stations standardization. The availability of charging infrastructure can be utilized to lessen the requirements. Thus, the cost of on-board energy storage is applied. The significant segments of EVSE include EV charge cords, attachment plugs, power outlets, vehicle connectors, charge stands (public or residential), and protective [36, 37]. Generally, they are available in two distinct designs: (1) a dedicated cord set, and (2) a pedestal or wall mounted box. The detailed setup is differs in different locations and countries subjected to electrical grid connection, voltage, frequency, and the applied standards [38].

1.1.5 Level 1 Charging

Level 1 charging is installed for slow charging. In United States (US), a standard 120 V/15 A single-phase grounded outlet is dedicated for Level 1 charging. For example, a NEMA 5-15 R. A typical J1772 connector may be applied into the AC port of EV

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[39]. Meanwhile, no addition substructure is compulsory for sites such as home and business. Low off-peak rates are probably accessible during the night time.

1.1.6 Level 2 Charging

Level 2 charging is preferred to be used for public and home facilities. This type of charging infrastructure can likewise be installed on-board to prevent excessive power through electronic devices. The current Level 2 devices provide charging from 208 V or 240 V (at up to 80 A, 19.2 kW). It could need specific tool and a joining installation for home or public units [42]. In spite of the fact that vehicles especially Tesla has on-board power electronics, it requires just the outlet. Most homes in the US have 240 V service accessibilities, and Level 2 equipment can charge a typical EV battery overnight. Level 2 technologies are very much preferred by consumers as they provide standardized connection between the vehicle and charger, and a fast charging time. However, billing meter is installed differently.

1.1.7 Level 3 Charging

Level 3 charging system is installed for fast charging (within 60 minutes) and it is suitable to be installed at city refueling areas, corresponding to petrol stations, and also in highway rest areas. Normally, the charging system works with three-phase circuit of 480 V or higher [46] and it would require an off-board charger to ensure effective AC–DC rectification procedure. DC joining may directly be applied to the vehicle.

1.1.8 Charging Features and Infrastructures of Some Manufactured PHEVs AND EVs

Charging via Level 3 is less appropriate for residential areas. CHAdeMO is a Japanese protocol that has received an international acknowledgment [47]. It is reported to have an issue on the installation cost. However, it has been reported in [48, 49], that the installation costs between $30 000 and $160 000 is required for Level 3 charging infrastructure. Meanwhile, an additional cost is needed for maintenance of the charging stations, respectively [50]. It is stated in standard SAE J1772 [51] that Levels 1 and 2 EVSE must be situated on the vehicle, while Level 3 should be situated at the external to the vehicle [52, 53]. Generally, it is expected that public stations apply either Levels 2 or 3 charging in order to achieve fast charging in public places [72]. A lower charge power is beneficial for functions seeking to reduce on-peak effect [54]. High-power fast charging can build request and possibly over-burden local distribution equipment at peak times [55, 56]. Level 2 and 3 charging contributes greatly to harmonic distortion, increment to transformer losses, peak demand, voltage deviations, and thermal loading on the power system. These difficulties encountered may affect the transformer's operational life, efficiency, security, reliability, and the market of smart grids development caused by

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degraded transformer operation life [57]. Nevertheless, a controlled smart charging scheme [58] can be applied to minimize the likelihood of typical distribution equipment from degrading. Subsequently, a robust communication network and public charging control system is expected to successfully ensure the large-scale development of EVs [59]. Charging features and infrastructure aspects for five types of vehicles is summarized in Table 1.1.

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Table 1.1 : Charging characteristic and infrastructures of some manufactured PHEVS and EVS

	Battery Type and Energy	Connector Type	All-Electric Range	DC Fast Charging		Level 1 Charging		Level 2 Charging	
				Demand	Charge Time	Demand	Charge Time	Demand	Charge Time
Chevrolet Volt PHEV	Li-Ion 16 kWh	SAE J1772	40 miles	N / A	N / A	0.96 – 1.4 kW	5 – 8 hours	3.8 kW	2 – 3 hours
Mitsubishi i-MiEV EV	Li-Ion 16 kWh	SAE J1772 JARI/TEPCO	96 miles	50 kW	30 Minutes	1.5 kW	7 hours	3 kW	14 hours
Toyota Prius PHEV (2012)	Li-Ion 4.4 kWh	SAE J1772	14 miles	N / A	N / A	1.4 kW (120 V)	3 hours	3.8 kW (240 V)	2.5 hours
Nissan Leaf EV	Li-Ion 24 kWh	SAE J1772 JARI/TEPCO	100 miles	50 + kW	15 – 30 minutes	1.8 kW	12 – 16 hours	3.3 kW	6 – 8 hours
Tesla Roadster EV	Li-Ion 53 kWh	SAE J1772	245 miles	N / A	N / A	1.8 kW	30 + hours	9.6 – 16.8 kW	4 – 12 hours

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1.1.9 Typical Battery Charging Profile

Battery is simply an electrochemical galvanic cell or a combination of these cells, which is capable of storage chemical energy. It is commonly referred to as an invention that converts chemical energy into electrical energy in a direct manner. Battery is highly preferred to be utilized in vehicles, and most EV manufacturers apply specific traction batteries such as Nickel, Nickel and Cadmium, Lead Acid, Sodium and Nickel Chloride, Lithium ion/polymer, and Zinc. Besides that, the design of batteries must fulfill certain requirements in expressions of power density and energy, safety matters, and operational life with a specific end goal; so that they can be applied in EVs and PHEVs. Hence, in 2006, the United States Advanced Battery Consortium (USABC) and Electrochemical Energy Storage Tech Team (EESTT) have worked together to create requirements for PHEV end of life battery [60]. The EV's battery should perfectly afford a high independence (refer to the distance coverage of vehicle in one whole discharge of the battery) to any vehicle and have the necessary specific amount of energy and power. In other words, the batteries should be compact, lightweight, and accomplished of storage and providing extraordinary amounts of energy and power correspondingly. Moreover, they should also have a extended operational life, where they should be able to fully discharge to an empty state and fully recharge again as many times as possible. This also needs to ensure that there is no exhibiting of any obvious performance degradation and it can be fully recharged in shortest time. Furthermore, they must also be able to function properly over a substantial temperature range and safely handle and recycle with a minimum costs. In contrast to batteries that are applied in conventional low power/energy applications, batteries apply in EV require additional care regarding safety issues. This is due to a continuous fast charging or discharging cycles and a high power transfer may generate excessive heat. The choices of a proper chemistry, cell balancing and advanced thermal management are the factors that influence losses in the cell. One passive solution to those losses is by using phase alteration materials to eliminate large amounts of heat by means of latent heat of fusion [61].

A common charging profile of Li-ion battery cell [62] is shown in Figure 1.5. In industry, constant voltage (CV) and constant current (CC) charging are the two typical charging profiles applied for Li-ion batteries. Throughout CC charging, the current is controlled, whilst maintaining a constant fix value until the voltage of battery cell scopes the desired level. Consequently, the charging will switch to CV charging, and the battery will be charged with the applied trickle current supplied by constant output voltage of the charger.

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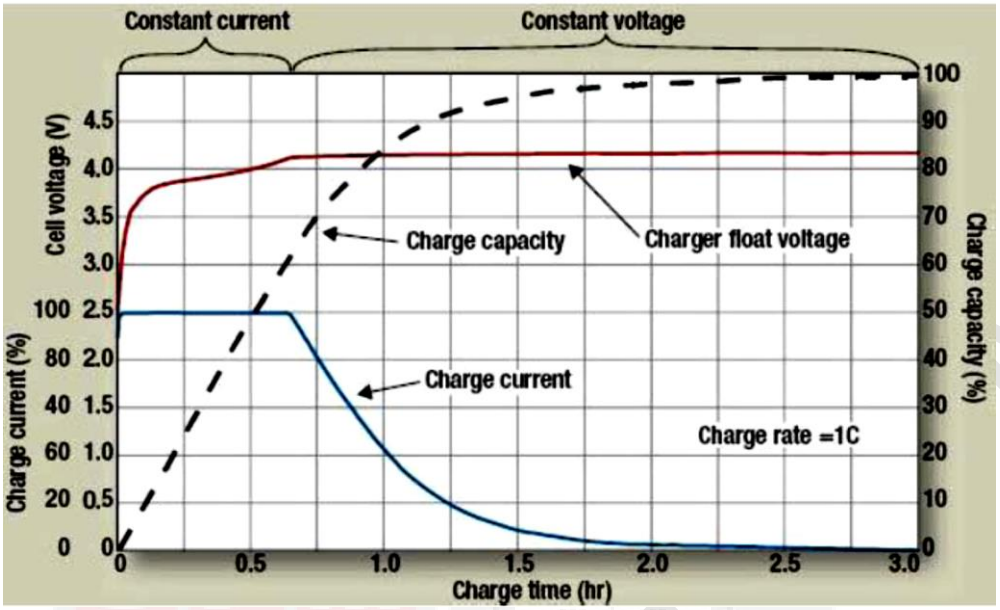

Figure 1.5 : Typical charging profile of Li-ion cell [62]

1.2 Problem statement

Electric vehicle (EV) development is one of the effective approaches in reducing fuel consumption and greenhouse emissions, and battery charging system is the most critical part of its development. Owing to the advancement in EV technologies, the design of a reliable, efficient and high power density charger has become a great challenge. Its operation is fully dependent on components, control, and switching technique.

As described in Sections 1.1.5 – 1.1.7, there are three levels of charging mode. However, the existing battery chargers are designed only to charge one level of charging mode [19], and thus lack of flexibility to provide charging for the other modes. Besides, the chargers also suffer from high ripples of DC-link voltage which can damage the battery.

The input current of the EV charger with high total harmonic distortion (THD) can subsequently cause many problems to the other electronic devices that are used in the charger station. Hence, it is crucial to maintain the THD of the input current within the acceptable limits of 5 % as stated in IEEE 519 standard.

Numbers of control algorithms have been introduced to reduce the harmonic distortion of the current drawn from the input power line by the rectifiers, such as Direct Power Control (DPC) and Virtual Flux Oriented Control (VFOC). The application of control systems is accomplished through the following components: (1)

analog controllers, (2) microcontrollers, (3) digital signal processors, and (4) integrated circuits particularly reliant on the rating, and (5) category of converters.

Studies recommended that DPC control algorithm provides an improved power factor when compared with other algorithms [7, 22]. Although, there is a greater power factor can be achieved with Variable Flux Direct Power Current (VF-DPC), the drawback is that it requires microprocessors and A/D converters. To avoid this, voltage oriented control VOC should be selected.

1.3 Aim and Objectives

This work aims to present the design and fabrication process of a three levels universal electric vehicle charger. The proposed charger is capable of providing a controllable and constant charging voltage for various EVs. The objectives of this work are as follows:

1. To develop three levels of electric vehicle charging system, it composes 650V/100A DC for bus or lorry, three-phase 240V/60A AC for saloon car and single-phase 120V/16A AC for motorbike.
2. To propose and design a new control algorithm for three-phase PWM rectifier, based on concepts of voltage oriented control (VOC), and three-phase PWM inverter based on SPWM technique.
3. To validate and compare experimental results of the charging system with the simulation results by developing a laboratory prototype of the charging system with integration of VOC and SPWM algorithms.

1.4 Scope and Limitations of Work

This work is divided into two sections, namely, software and hardware sections. In the software section, the work begins with the design of three levels charger followed by simulation of the proposed design in MATLAB/Simulink software program. The three levels charger covers both the on board and off board charging: Levels 1 and 2 for on board charging, while, Level 3 is for off board charging. The input source voltage is set to be 600 Vrms (line to line) for Level 1 charger testing, and 850 Vrms (line to line) for Level 2 charger testing. Both Levels 1 and 2 chargers are tested with resistor load. On the other hand, for Level 3 charger, the input source voltage is set to be 1700 Vrms (line to line) and it is tested with three types of batteries (Li – ion, Lead – acid and Nickel Cadmium).

Performance evaluation with the actual EV is not within the scope of this work, as this work only focuses on power system. In order to work with EV, BMS and PLC or CAN communication system must be installed. Furthermore, this work does not consider unbalanced and distorted input voltage in the evaluation process. The input

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voltage serves as a reference to ensure proper synchronization between voltages and current, hence, an effective charging can be achieved. Therefore, this work only considers balanced three-phase three-wire system with sinusoidal source voltage.

In the hardware section, a laboratory prototype is constructed where the controller and power circuits are assembled to function as three levels charger, similar to the one that is modeled in MATLAB/Simulink. In the experimental work, for safety purposes and due to limitations of available resources, the maximum input supply voltage for the battery charger is set to be 180 Vrms (line to line). Meanwhile, a high performance digital signal processor (DSP) is programmed to perform all the control algorithms of the battery charger. In the experiment work, Levels 1 and 2 chargers are tested with resistor load ranging from 20 Ω to 70 Ω. Meanwhile, for validating performance of Level 3 charger, 15 cells 12 V lead-acid batteries are applied.

1.5 Thesis Layout

This thesis is organized into five chapters. Chapter 1 provides an overview of the research work which includes research background, related study, main problems to be solved, aim and objectives, and scope and limitations of the work.

Chapter 2 provides a comprehensive review on the technology of Electric Vehicle Supply Equipment (EVSE). A survey on the charger requirements for different vehicles and classification based on charging times are also provided. Next, a comprehensive review on the power converters and the existing control method is presented. Lastly, the related works on electric vehicle charger are highlighted.

Chapter 3 describes the design and development of the electric vehicle (EV) charger, detailing its operating principle and design considerations. Moreover, the newly proposed control algorithms are clearly described. This chapter also provides complete details on simulation model and laboratory setup of the proposed EV charger as well as implementation of the proposed control algorithms in a high performance DSP.

Chapter 4 presents the findings and results obtained in simulation and experimental works. In the simulation, the findings are presented according to the level of charger which includes Levels 1, 2, and 3. Meanwhile, in the experimental work, the findings are presented according to power rating which include low and medium powers.

Chapter 5 concludes the work, significant contributions of the work and recommends possible future works.

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