UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF OPTIMAL ENERGY MANAGEMENT TOPOLOGY FOR BATTERY ELECTRIC VEHICLE WITH LOAD SEGMENTATION

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By

TENGKU AZMAN TENGKU MOHD

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

August 2020

DEDICATION

To my wife, Nor Suraya Aini, and my beloved children; Tengku Adam Qaeis, Tengku Zara Adlieya, Tengku Hajar Aemilya and Tengku Umar Qawweim for their love, unfaltering support, patience and sacrifices…

To my parents, siblings, and in-laws for their prayers, encouragements and understanding…

To the memory of my father in law…

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

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Chairman : Associate Professor Mohd Khair Hassan, PhD, Ir.
Faculty : Engineering

Sustainable transportation has been widely explored as a result of fossil fuels depletion and pollution emissions released by conventional vehicles. Among the alternatives, hybrid and plug-in hybrid electric vehicles manage to reduce but incompletely remove the carbon impacts. Battery electric vehicles (BEVs) instead, offer zero carbon footprint solution with outstanding drivetrain performance and energy efficiency, however they are confined by the driving range due to constraints in batteries capacity and volume. The increase in power requirement and number of electrical loads on-board, due to the transportation electrification has complicated the situation further. Primarily, the challenges in BEV having batteries as the only energy storage but multiple loads to be fulfilled lie in eliminating the 'range anxiety' by developing stringent control rules and management strategy that could further extend the driving range. In this thesis, an attempt has been made to modularly design a power and energy management system (PEMS) for BEV by modelling the plant that comprises the modules of energy management system (EMS) and power management system (PMS). Several simulation tests performed on BEV model have verified its control robustness, effectiveness in satisfying the targeted performances and suggested load distribution profiles for the corresponding driving cycles. The area of PEMS in the application field of BEV is relatively new and incorporates several different disciplines. Two levels of control; low level component control (LLCC) and high level supervisory control (HLSC) have been implemented, adapting load segmentation strategy from large scale power distribution systems. Four auxiliary load segments have been modelled and ranked for prioritization task via energy distribution strategy algorithm, operated within three distribution regions of battery state-of-charge (SOC). The incorporation of load segmentation into EMS topology has significantly improved the organization of energy flow management between supply and load. The simulation tests in New European urban and extra urban driving (NEDC) has successfully verified the optimal energy consumption with a saving of 18.6% in energy or an increase of 28.5% (17.22 km) in driving range cumulatively. Subsequently, the development of three driving modes in PMS via power scheme management has successfully represented the diversity in driving between the most-comfortable-driving with highest-power-usage (Comfort

Mode) and the least-comfort-driving with lowest-power-usage (Economic Mode). The combination of PMS-EMS has been proven in satisfying all cost functions during simulation tests. An integrated driving mode i-FUZZY has also been proposed using fuzzy logic control to overcome the manual mode selection in PMS. The simulation tests have verified the robustness of i-FUZZY in making quick decision on selecting the best adaptive driving mode while satisfying the predefined cost functions. In conclusion, the simulation results with the proposed PEMS strategy have proven the effectiveness and potential of BEV as the future sustainable transportation.

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

PEMBANGUNAN TOPOLOGI PENGURUSAN TENAGA OPTIMAL UNTUK KENDERAAN ELEKTRIK BERBATERI DENGAN SEGMENTASI BEBAN

Oleh

TENGKU AZMAN TENGKU MOHD

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Fakulti : Kejuruteraan

Pengangkutan lestari telah diterokai secara meluas akibat pengurangan bahan api fosil dan pelepasan pencemaran yang dikeluarkan oleh kenderaan konvensional. Antara kenderaan alternatif yang ada, kenderaan hibrid dan hibrid berpalam-masukan berjaya mengurangkan tetapi tidak menghapuskan kesan karbon sepenuhnya. Kenderaan elektrik berbateri (BEV) sebaliknya, menawarkan penyelesaian tapak sifar karbon dengan prestasi pemacuan dan kecekapan tenaga yang luar biasa, tetapi dihadkan oleh jarak pemanduan disebabkan kekangan kapasiti bateri dan isipadu ruang. Peningkatan keperluan kuasa dan bilangan beban elektrik di dalam kenderaan, disebabkan oleh elektrifikasi pengangkutan turut merumitkan keadaan. Cabaran utama BEV yang mempunyai bateri sebagai simpanan tenaga tetapi pelbagai beban yang perlu dipenuhi, terletak pada menghapuskan 'kebimbangan jarak' dengan membangunkan peraturan kawalan ketat dan strategi pengurusan yang dapat memanjangkan jarak perjalanan. Dalam tesis ini, satu rekabentuk sistem pengurusan kuasa dan tenaga (PEMS) dibangunkan secara modular untuk BEV dengan memodelkan loji yang merangkumi modul sistem pengurusan tenaga (EMS) dan sistem pengurusan kuasa (PMS). Beberapa ujian simulasi yang dilakukan pada model BEV mengesahkan keteguhan kawalan dan keberkesanannya mencapai prestasi sasaran serta mencadangkan profil pengagihan beban untuk kitaran memandu sepadan. Ruang lingkup PEMS dalam bidang aplikasi BEV agak baru dan menggabungkan beberapa disiplin berbeza. Dua peringkat kawalan; kawalan komponen peringkat rendah (LLCC) dan kawalan penyeliaan peringkat tinggi (HLSC) dilaksanakan, dengan mengadaptasi strategi segmentasi beban dari sistem pengagihan kuasa berskala besar. Empat segmen beban tambahan dimodelkan dan disenaraikan mengikut keutamaan melalui algoritma strategi pengedaran tenaga, yang dikendalikan dalam tiga kawasan tahap-pengecasan bateri (SOC). Penggabungan segmen beban ke dalam topologi EMS meningkatkan organisasi pengurusan aliran tenaga antara bekalan dan beban dengan lebih baik. Ujian simulasi semasa kitaran pemanduan Eropah baru bandar raya dan bandar raya tambahan (NEDC) mengesahkan penggunaan tenaga optimum dengan penjimatan sebanyak 18.6% dalam tenaga atau peningkatan 28.5% (17.22 km) dalam jarak memandu secara kumulatif. Selepas itu, pembangunan tiga mod pemanduan PMS melalui pengurusan

skim kuasa berjaya menunjukkan kepelbagaian pemanduan daripada paling selesa dengan penggunaan kuasa tertinggi (Mod Selesa) kepada kurang selesa dengan penggunaan kuasa terendah (Mod Jimat). Kombinasi PMS-EMS terbukti dapat memenuhi semua fungsi kos semasa ujian simulasi. Mod pemanduan bersepadu i-FUZZY juga dicadangkan menggunakan kawalan logik kabur untuk mengatasi pemilihan mod manual dalam PMS. Ujian simulasi telah mengesahkan keteguhan i-FUZZY membuat keputusan pantas dalam memilih mod pemanduan adaptif terbaik sambil memenuhi fungsi kos yang ditetapkan. Kesimpulannya, keputusan simulasi dengan cadangan strategi PEMS telah membuktikan keberkesanan dan potensi BEV sebagai pengangkutan lestari pada masa depan.

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First and foremost, my highest gratitude to Allah, the Most Merciful, for His Blessing, for giving me health, patience and strength to complete my study. The writing of this thesis has been one of the most significant academic challenges I have ever experienced in my life. Without the support, patience and guidance from special people around me, the journey of this study would not be completed.

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Alhamdulillah, I have finally accomplished my PhD journey.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date: 08 October 2020

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LIST OF ABBREVIATIONS

AC	Alternating Current
AEV	All Electric Vehicles
AMPS	Advanced Mobile Integrated Power System
BEV	Battery Electric Vehicle
CL	Comfort Limit Distribution
COMF	Comfort Driving Mode
DC	Direct Current
DOD	Depth-of-discharger
EM	Electrical Motor / Machine
EMR	Energetic Macroscopic Representation
EMS	Energy Management System
ECO	Economic Driving Mode
EV	Electric Vehicle
EVD	EV Driving Mode
FCEV	Fuel Cell Electric Vehicle
FIS	Fuzzy Inference System
FRGS	Fundamental Research Grant Scheme
FTP-75	US Urban Driving
GHG	Greenhouse gases
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
HF	Hybridization Factor
HLP	Hadiah Latihan Persekutuan
HLSC	High Level Supervisory Control

HV	High Voltage
HWFET	US Highway Driving
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
i-FUZZY	Integrated Fuzzy Driving Mode
LEV	Low Emission Vehicle
LLC	Low Level Control
LLCC	Low Level Component Control
LS	Load Shedding / Shifting
LV	Low Voltage
MESS	Multiple Energy Storage System
ND	Normal Distribution
NEDC	New European Urban and Extra Urban Driving
PCU	Power Control Unit
PEMS	Power and Energy Management System
PES	Power Electronic Shell
PEV	Pure Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PMAC	Permanent Magnet AC Motor
PMC	Power Management Controller
PMS	Power Management System
RB	Rule based
RTO	Real-Time Optimization
SC	Super-capacitor
SL	Safety Limit with Load Scheduling Distribution

SOC	State-of-charge
TPES	Total Primary Energy Supply
UC	Ultra-capacitor
ZEV	Zero Emission Vehicle

LIST OF SYMBOLS

a	Linear acceleration
v_{max}	Top cruising speed
t_a	Acceleration time
k_p	Proportional gain
k_i/s	Integrator gain
T_r	Reset time
$C(s)$	Controller
$P(s)$	Plant
$e(t)$	Error
v_{ref}	Reference speed
v_{ev}	EV speed
F	Force
M	Vehicle mass
F_t	Traction force
F_r	Resistive force
F_{rr}	Rolling resistance force
F_{ad}	Aerodynamic drag force
F_{hc}	Hill climbing force
g	Gravitational acceleration
C_r	Tire rolling resistance coefficient
α	Slope or incline angle of the road
ρ	Air density
A_f	Vehicle frontal area

C_d	Aerodynamic drag coefficient
v	Vehicle speed
P_t	Traction power
P_b	Braking power
P_{bat}	Battery output power
P_{DC}	DC-DC converter output power
i_a, i_b, i_c	3-Phase stator currents
T_e	Electromagnetic torque
N_e	Electromagnetic rpm speed
T_v	Vehicle torque
N_v	Vehicle rpm speed
g_{ratio}	Gear ratio
F_v	Vehicle tractive force
r_w	Wheel radius
$SOC(t)$	Battery state of charge
$SOC(t_0)$	Battery initial SOC level
$i_{bat}(t)$	Battery current
C_n	Battery rated or nominal capacity
V_o	Output voltage
V_i	Input voltage
I_o	Output current
I_i	Input current
η_{DCDC}	Efficiency of DC-DC conversion
D	Duty cycle
I_{inv}	Inverter current

I_p	Peak current (stator)
P_{out}	Inverter output power
η_{inv}	Efficiency of inverter
V_{bus}	Bus input voltage
θ	Inverter phase angle
k_t	Torque constant
T_{actual}	Actual torque produced
T_e	Electromagnetic torque
θ_r	Rotor angle
ω_r	Rotor angular speed
T_{e_max}	Maximum motor torque
F_{v_max}	Maximum tractive force
P_{e_max}	Maximum motor power
ω_{base}	Base angular speed
P_{mot_in}	Input power during motoring (positive torque)
P_{mot_out}	Output power during motoring (positive torque)
η_{mot}	Motoring efficiency
η_{gear}	Gear efficiency
η_t	Transmission efficiency
P_{regen_in}	Input power during regenerating (negative torque)
P_{regen_out}	Output power during regenerating (negative torque)
T_{wheel}	Wheel torque
V_{nom}	Nominal voltage
τ_{s_limit}	Shaft torque limit
P_{s_limit}	Shaft power limit

P	Power
E	Energy
T	Trip time
dE	Rate of change in energy
dt	Rate of change in time
E_{bat}	Battery energy
I_{bat}	Battery output current
V_{bat}	Battery terminal voltage
E_{cons}	Energy consumption
P_{bat_out}	Out-flow power to driving wheels
P_{prop}	Power consumed for propulsion/traction
P_{aux}	Power consumed by auxiliary loads
P_{bat_in}	In-flow (recuperated) power to the battery
P_{regen}	Regenerative braking power
β	Regenerative braking power coefficient
P_{hvac_HV}	Power consumed by HVAC connected to high voltage bus-bar
P_{aux_LV}	Power consumed by auxiliary loads connected to low voltage bus-bar
J	Cost function
J_E	Energy cost function
P_{cons}	Power consumption
P_{avg}	Average power
n	Number of load
A_{1n}	Initial load
A_{2n}	Safety load
A_{3n}	Comfort load

A_{4n}	Luxury load
b	Pattern type
B_{1n}	Constant load
B_{2n}	Slow varying load
B_{3n}	Pulsed load
c	Operational type
C_1	Continuously operational
C_2	Periodically high
C_3	Periodically medium
C_4	Periodically low
$P_{\max\_n}$	Peak power for load n
P_{avg_cons}	Average power consumption
P_{AC}	Power for air conditioner
P_{heat}	Power for heater
P_{max}	Maximum power
T_{comf}	Comfort temperature
T_{max}	Maximum temperature
T_{min}	Minimum temperature
LD1	Propulsion load
LD2	Initial load
LD3	Safety load
LD4	Comfort load
LD5	Luxury load
SOCA	High voltage battery state of charge
SOCB	Low voltage battery state of charge

BATT_A	High voltage battery
BATT_B	Low voltage battery
P_{comf}	Comfort power
acc_{limit}	Performance (acceleration) limit
J_{P_COMF}	Comfort cost function
J_{P_ECO}	Economic cost function
J_{P_EVD}	EV driving cost function
E_{prop}	Propulsion load energy
E_{comf}	Comfort load energy
E_{batc}	Battery charging energy
E_{init}	Initial load energy
E_{safe}	Safety load energy
E_{luxu}	Luxury load energy
E_{gen}	Regenerative energy

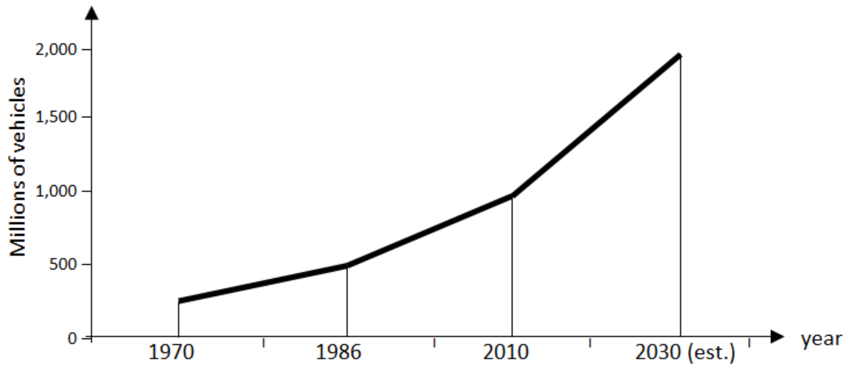
CHAPTER 1

INTRODUCTION

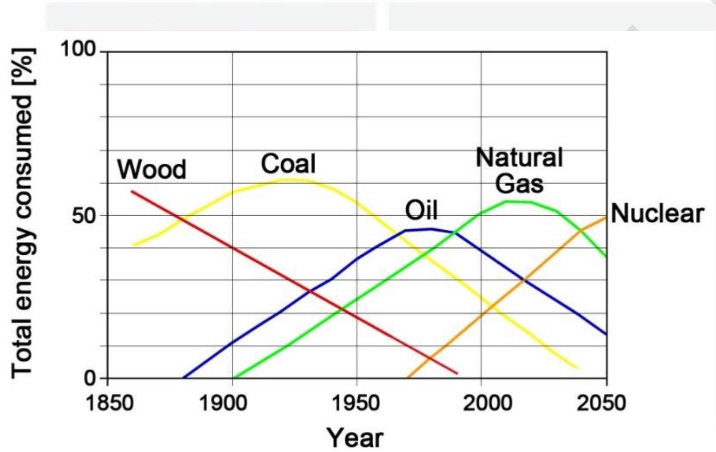
1.1 Preface

Two major concerns in transportation sector nowadays are the energy conservation and environmental protection. Both concerns are resulted from massive production of conventional internal combustion engine vehicles (ICEV) in worldwide vehicle population. The former is related to the depletion fear of world number one energy supplier (fossil fuels) whereas the latter, fears against the consequences of pollution emissions released by ICEV such as, extreme global warming and harmful air pollution.

Energy consumption in industrialized countries has projected a continuous growth in transportation due to increase in the world vehicle population. Based on Ward's Auto report in [1], as presented in Figure 1.1 (a), the number of vehicles reached approximately 250 million units in 1970, before it rapidly increased to 500 million units in 1986. The number surpassed the one-billion-unit mark in 2010. Considering the current trends, researchers and industry experts generally agree that, the number of vehicles in operation is expected to reach two billion units worldwide in the next 20 years. Regarding this huge increased numbers of vehicles, the impact to the total energy demand in transportation is anticipated to be dramatically amplified. However, based on the study on energy demand and availability for the 21st century conducted by World Energy Council in [2, 3], the increasing in demand only matched the energy consumption of oil until around 1980 as shown in Figure 1.1 (b). The trend of oil consumption is estimated to decline after 1980 which reflects the reduction in worldwide oil reserves. This is conflicting to the growth in transportation demand, which means the transportation sector needs to search for new alternatives to replace oil.



(a)



(b)

Figure 1.1: (a) World vehicle population between 1970 to 2030 (personal and commercial vehicles) [1] **(b) Energy consumption between 1850 to 2050** [3]

According to World Energy Outlook 2011, International Energy Agency (IEA) forecasts an average annual increase in global transport energy demand of 1.6% between 2007 and 2030 [4], or by one-third between 2010 and 2035 [5]. The world Total Primary Energy Supply (TPES) which consist of nearly 87% of fossil fuels in 2009 has to satisfy this demand. However, only 69% of TPES is available for consumption while the rest was spent during energy transformation. If the trend continues, sooner or later, this will result to deficiency of energy supply in the world. The following Figure 1.2 illustrates the percentage of oil demand worldwide as calculated by Organization of the Petroleum Exporting Countries (OPEC) secretariat [6]. The chart points out, transportation is the largest oil energy consumer which accounts for 59% in 2011 and expected of 4% rise in 2040. This increasingly fuel consumption and conflicts in the Middle East, crude oil supplier countries have led to oil shortage fear and price escalation as during 2008 economic crisis [5].

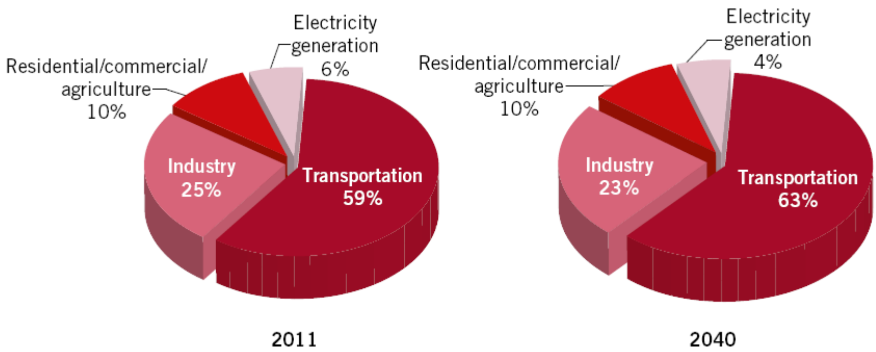


Figure 1.2: Percentage of oil demand worldwide by sector in 2011 and 2040 [6]

Another issue in transportation sector is the environmental consequences due to massive deployment of ICE vehicles. The combustion of fuel to provide mechanical energy produces pollution emissions; (1) greenhouse gases (CO2, NOX, CH4) and (2) harmful smog (particulate matters, NOX, SO, SO2). Transportation has been one of the top contributors in the GHG emission globally. Greenhouse gases trap heat in the atmosphere due to greenhouse effect, leading to climate change, particularly global warming. Melting glaciers, rising sea levels, flood, gully erosion, desertification, and extreme weather conditions can happen in worse situation [7] which must be strictly prevented. The increasing in emission restriction is established worldwide, for instance, European Council has targeted to reduce GHG emission by 20%, to increase renewable energy by 20% and to improve energy efficiency by 20% by 2020. In December 2011, European Commission in its Energy Roadmap 2050 has targeted to reduce carbon emission on transport by 60% by 2050 [5].

In urban area, transportation is one of the major sources of traffic congestion, disturbing noise, air pollution, and closely related to health problem such as respiratory problems, allergies, asthmatics and some cancers. Based on a study in [5, 8] to estimate the impact of traffic-related and outdoor air pollution, it has concluded that 6% of total mortality (40,000 cases per year) is caused by air pollution, whereby half is due to motorized traffic. Other cases are; beyond 25,000 new cases of chronic adults bronchitis, beyond 290,000 series of children bronchitis, beyond 0.5 million asthma attacks, and beyond than 16 million person-days of restrictive activities.

The aforementioned issues have raise a general public awareness on the importance of heading towards a sustainable alternative transportation in term of; (1) reducing emissions, and (2) reducing dependency on fossil fuels. Both the first and the latter require comprehensive actions from automakers and researchers to gradually improve the vehicle drivetrain efficiency and fuel economy; shifting from conventional high emission vehicle to low emission vehicle (i.e. hybrid electric vehicle (HEV) and plug-in hybrid (PHEV)) and finally zero emission vehicle (i.e. battery electric vehicle (BEV)). The study by C. P. Lawrence in 2007 in [9], has agreed that; in order to moving forward, automotive industry needs to achieve three main goals; (1) reducing energy consumption, (2) finding alternative energy sources, and (3) reducing environmental impact.

At present state, the viable energy sources for EV applications are batteries, fuel cells (FCs), super-capacitors (SCs) or ultra-capacitors (UCs) and ultrahigh-speed flywheels [5, 7, 10]. Relatively, batteries are the most dominant electrical energy source in BEV due to their technologies is maturing and developing with acceptable performance cost. Figure 1.3 demonstrates three stages development in battery technologies subject to the increases in performance [11]. Among newly introduced technology, Lithium-ion is the most preferable option for EV battery due to its high power or energy density characteristics. However, it is still high in cost.

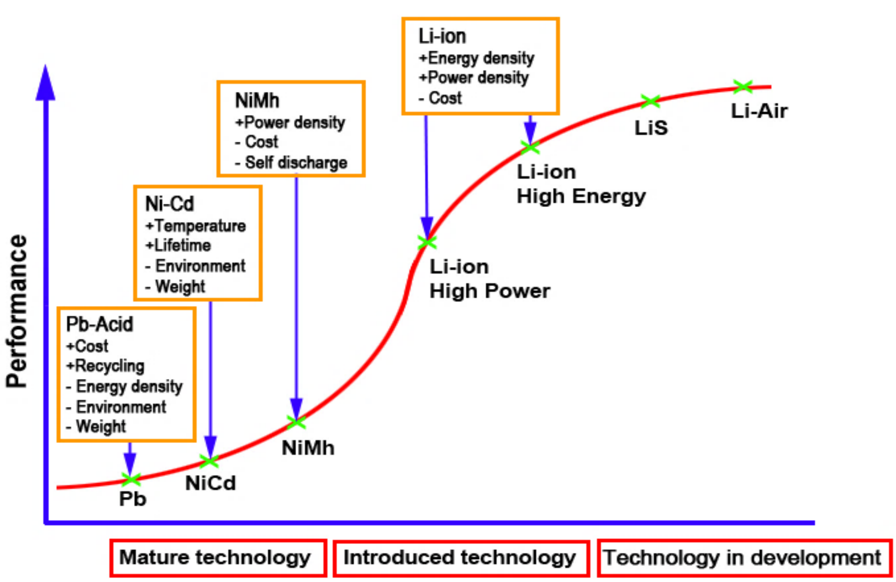


Figure 1.3: Battery technologies roadmap (adapted from [11])

According to data from U.S. Department of Energy (U.S. DOE), battery costs are coming down rapidly, surpassing halve in four years; from USD 1,000 per kilowatt hour (kWh) in 2008 to USD 485/kWh at end of 2012. It is very much expected that based on IEA, U.S. DOE, and Deutsche Bank data in Figure 1.4, the EV cost will achieve ICE vehicle parity by 2020 [12]. The World Resources Institute in [13] has also agreed that the EVs will be cost competitive with conventional vehicles in 2020.

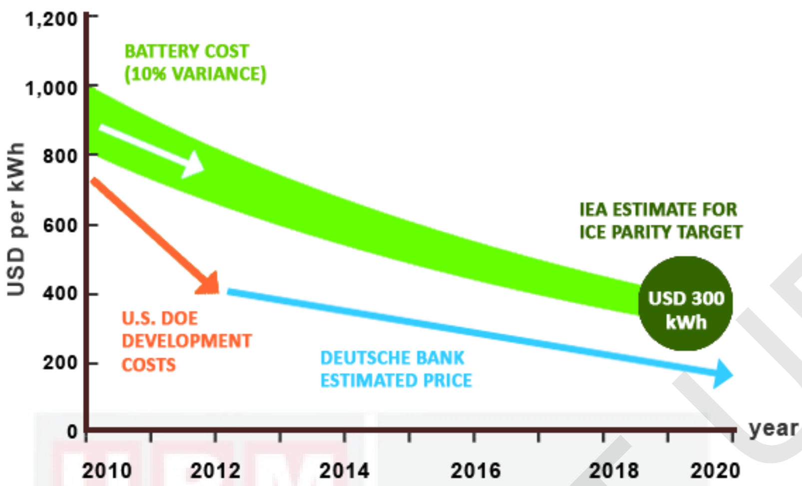


Figure 1.4: Projected costs of EV batteries (adapted from [12])

The decreasing in battery cost is one of the achievements from vast research and development efforts in EV technology. The results will be; lower in initial cost, and extend of driving range by marginally increase the size of the battery. However, it is unwise to simply increase the battery size in order to extend the range due to the constraint in vehicle weight and volume. A promising way is by implementing PEMS to manage the power and energy efficiently [14]. Figure 1.5 summarizes of the issues, the EV development, the advantages and drawbacks in EV, and the problem that needs attention.

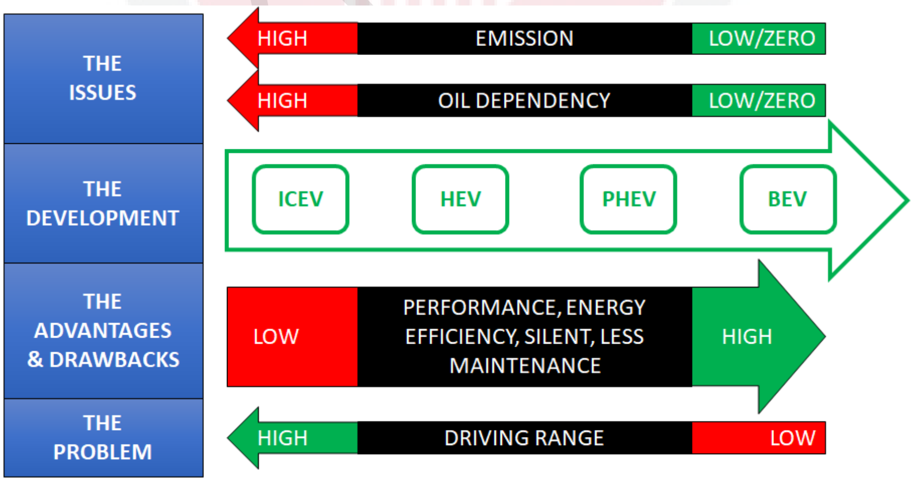


Figure 1.5: Summary of the issues, the EV development, the advantages and drawbacks in EV, and the problem that needs attention.

In search of sustainable transportation; new alternative, high efficiency and environmentally friendly propulsion have been widely explored. These include electric, hybrid, natural gas, liquid petroleum gas, bio-diesel and hydrogen fuel-cell technologies. Alternative fuels such as natural gas, liquid petroleum gas (propane and butane), biodiesel, and hydrogen have the potential to reduce fossil fuel dependency and emissions. However, the vehicles operating costs are cost-effective only in some territories, especially where their price is largely determined by government policies on the price and tax. In addition, alternative fuels possessed common drawbacks such as limitation in design technology, fuel availability, storage, fuel infrastructure, lower energy content and driving range [7]. Pereirinha and Trovão [5] in their study emphasized that the problem is not the replacement of fossil fuels by biofuels, but the replacement of inefficient ICE by efficient electric motors. Electric propulsion by electrical motor is much more efficient (70-90% efficiency) than the internal combustion engine (10-30%). Although electrical preparation for battery electric vehicle (BEV) imposed lower well-to-tank efficiency (~38%) than petroleum preparation for ICE vehicle (~83%), however BEV (~30%) is still superior on a well-to-wheel basis as compared to ICEV (~17%) [15] as illustrated in Figure 1.6.

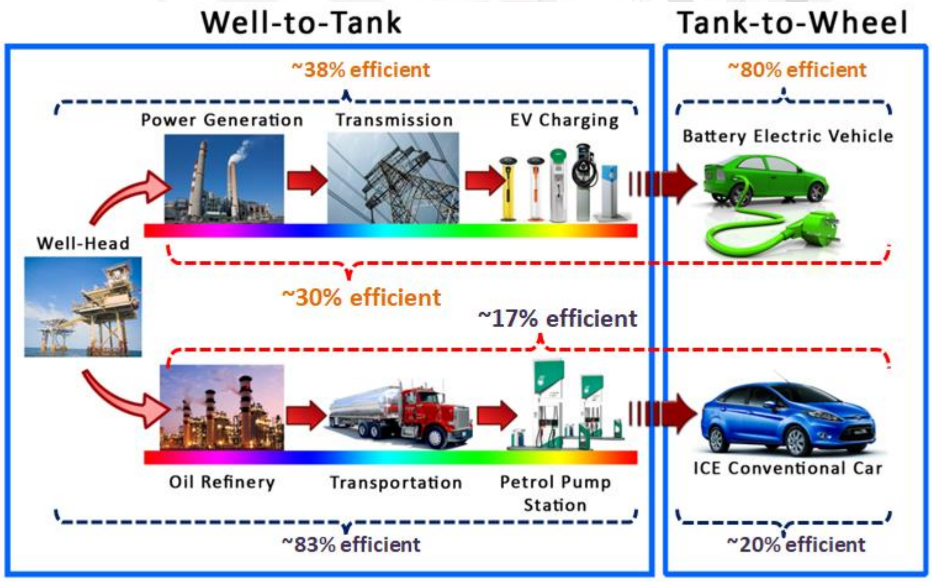


Figure 1.6: Well-to-wheel efficiency between BEV and ICEV (adapted from [15])

As a future key sustainable transportation, electric vehicle technology has been massively explored, hence paving way to the development of hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and battery powered electric vehicle (BEV) or pure EV. Tie and Tan (2013) in [16] have classified vehicles into three groups; (1) internal combustion engine vehicle (ICEV), (2) hybrid electric vehicle (HEV) and (3) all electric vehicles (AEV) as shown in Figure 1.7. Considering the hybridization factor (HF) to calculate the ratio of hybrid or electric vehicle, HEV is divided into mild-HEV and full-HEV, while AEV consists of BEV and fuel cell EV (FCEV). Another type of classification is by emissions level; (1) low emissions vehicle (LEV) comprise of HEV and PHEV, and (2) zero emissions vehicle (ZEV) include of BEV and FCEV [5].

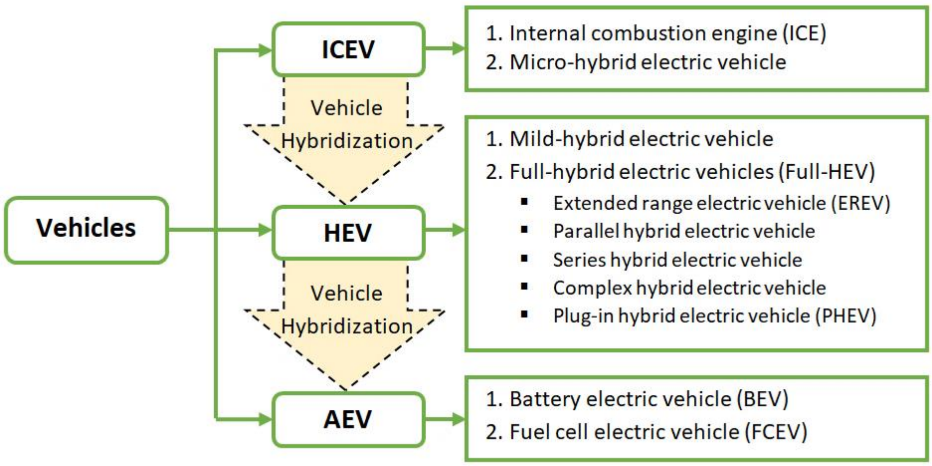


Figure 1.7: Classification of vehicles (adapted from [16])

Figure 1.8 illustrates the typical drivetrain for HEV, PHEV and BEV [17]. HEV consists of a battery pack and a small internal combustion engine (ICE). The battery pack is typically smaller and lighter since most of power supply for the EV comes from the ICE. The battery pack is important so as to store recuperated energy from braking. Later the energy is used for quick acceleration. The HEVs system has two configurations; parallel and series. The former uses ICE coupled to an electric motor in a pre-transmission configuration. The summation of power generated from ICE and motor generated from batteries will turn the vehicle wheels. The ICE will be the main contributor of this power ratio. The batteries also act as storage for energy generated from braking, when the motor becomes generator [18]. In the latter topology, ICE does not directly power up the vehicle. The power summation is an electrical summation because it is obtained from the electric motor. ICE acts as generator and battery as storage.

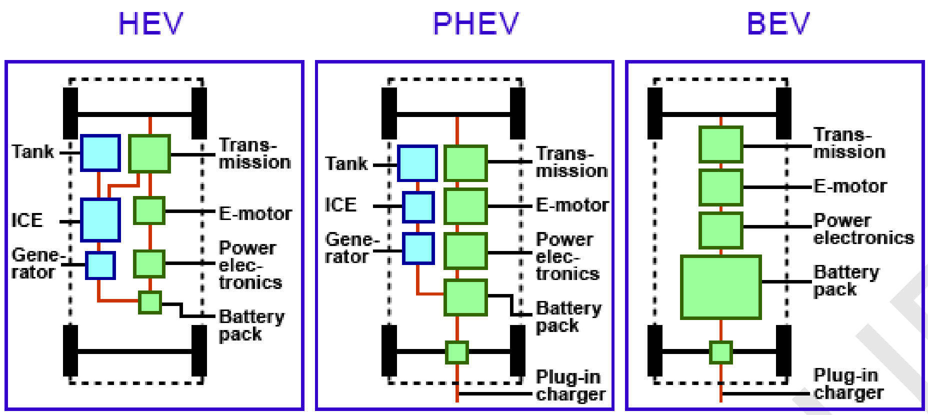


Figure 1.8: Typical drivetrain of HEV, PHEV and BEV (adapted from [17])

A PHEV is similar to the HEV except for; it has a larger battery size but smaller ICE as shown in Figure 1.8. The battery pack is charged by the ICE and from plugging into a standard 110/120 V electrical outlet. Thus, PHEVs require on-board/off-board charger which involve a large battery size, heavy and costly. Nevertheless, it offers better mileage [19]. Due to the removal of mechanical ICE components, a BEV completely depends on the battery capacity, the selection of traction motors as well as the weight distribution ratio of the vehicle.

HEV and PHEV are the first two important steps in reducing emissions and dependency of fossil fuels. Although PHEV offers a better mileage, efficiency and produces lower emission than HEV, these two options however unable to completely solve emissions problem. Eventually, BEV relies on battery as the only energy source [14] possesses the best in efficiency and produces absolutely zero tail pipe emission. In addition to transportation sector, BEV adoptions is the answer to the drawbacks of mechanical ICE-driven vehicle, in terms of performance, energy efficiency, noise, maintenance and can be regulated by the power grid operator [5, 20]. However, the main concern in BEV are battery-related issues; the high initial cost, limited driving range, and long charging time of its battery [11, 21-23].

1.2 Problem statements

Researchers put numerous efforts on power electronics in developing advanced batteries. The efforts have resulted to the increased in energy and power capability, prolonged the life, and reduced the battery costs. The declining of battery cost is one of the achievements that will reduce vehicle initial cost, and extend of driving range by marginally increasing the battery size. However, the battery must contain sufficient energy to drive in certain range, provide enough power during accelerations and supply all loads; propulsion and auxiliary loads. The increasing number of electrical auxiliary loads in vehicles due to the transportation electrification has led to further increase (from about 1 kW to 5 kW) in auxiliary on-board power requirement, and propulsion loads will exceed 100 kW [1, 7, 23]. The massive capacity of vehicle power requirement further complicates the concern for suitable power and energy management. Enlarging the energy capacity by simply increasing the battery size will only imply a penalty to the vehicle weight and volume. Therefore, employing power and energy management system (PEMS) is perceived to be a promising way to appropriately manage and distribute the power and energy in BEV.

Power management and energy management are two different terms that often been inaccurately applied interchangeably. Fundamentally, the energy management refers to the accumulation of power over a given time period, dealing with energy consumption and recuperation over a trip. Instead, power management refers to instantaneous power distribution and power flow control between electrical and mechanical powertrain components to satisfy the power demands [7, 23]. The development of control strategies to achieve the optimal energy management system (EMS) and appropriate power management system (PMS) for BEV is one of the biggest challenges among automakers because it has been disclosed (as a trade secret) and always commercially known as a black box.

Currently, PEMS plays an important role in HEV, as it has several degree-of-freedoms that provide room for optimizations. This is due to the existing of multiple or hybrid energy and power generation sources onboard. Similarly, for a single source BEV with numerous loads, PEMS can be very much favorable. However, typical PEMS topology for BEV still preserves the PEMS trend of HEV, such as adopting super-capacitor (SC) as secondary energy storage device. This configuration has been well implemented in various state-of-the-art strategies in PEMS by previous researchers and was remarkably proven to improve the vehicle energy efficiency as well as the lifetime of the battery.

Nevertheless from different angle of view, PEMS itself can be employed to eliminate the presence of SC which in effect, reduces the cost and complexity of the BEV system. The nature of BEV topology with single energy source and numerous loads are very similar to the electrical power distribution network. This study will put an effort to venture on PEMS topology for BEV with battery only storage and electrical propulsion and auxiliary loads in reverse approach.

There are three key issues being investigated and discussed throughout this study; (1) characterizing the energy distribution and power flow between powertrain components of electric vehicle architecture, (2) develop an optimal energy management system for BEV, and (3) strategize an integrated driving mode which able to automatically adapt with the deviations in external (environment) and internal (battery state of charge, performance and comfort) parameters changing during the trip. These three issues are the main concern of this study since many of technical reports related to BEV only described the surface level of information; specifically on the application features, without development data. Although current trend in PEMS studies for EV are showing a prominent increase, most of the studies however focus on the hybrids (HEV and PHEV) rather than BEV. This is based on smaller number of research publications and reading materials available on PEMS application in BEV.

The fundamental study of power flow and energy distribution will provide a better insight in characterizing supply-load topology model of BEV that able to satisfy pre-set performances of speed, acceleration and range. Batteries are the only energy source in BEV, but they have multiple loads to satisfy. Hence, reverse management strategy will be implemented by considering two levels of controls; low level component control (LLCC) and high level supervisory control (HLSC). The distribution strategy will be strictly equipped with the most economical rules due to the constraint in available energy source, adapting load segmentation management based on large scale power distribution, demand management strategy and smart grid systems.

EV driving modes are basically designed based on 4 aspects; appropriate driving environments, driver driving styles, vehicle types and its power management strategy. HEV benefits a wide option in driving mode from high performance to high efficiency, as it possesses secondary propulsion power source. Unlike HEV, the priority in BEV is given to energy sustainability for a better range; conflicting between standard driving mode (high comfort, low efficiency) to aggressively energy recuperative braking mode (low comfort, high efficiency). For instance, three driving modes are available in BMW i3; comfort, eco pro, and eco pro+ [24]. During any trip, it is imperative for the driver to manually switch into the best driving mode at the right time, condition and place. Improper handling of the modes will prevent the driving from fully utilizing its driving potential at highest efficiency (optimized driving). Therefore, an adaptive integrated driving mode is proposed as a solution to above problem using fuzzy-rule-based control which able to automatically decide the best driving based on internal and external inputs.

1.3 Research objectives

This research aims to develop an optimal energy management system (EMS) and an adaptive power management system (PMS) for BEV using low level component control (LLCC) and high level supervisory control (HLSC). In order to achieve these aims, four research objectives are specifically formulated as follows:

1. To develop mathematical model of BEV drivetrain and auxiliary loads topology using white-box modelling.
2. To validate the BEV model with the performances of speed, acceleration and range of commercial's BEV and proposes the energy distribution profiles.
3. To design energy management system (EMS) for BEV, using low level component control via load segmentation strategy and high level supervisory control via energy distribution strategy for optimized driving.
4. To verify power management system (PMS) for BEV, using high level supervisory control via power scheme management strategy and fuzzy logic for adaptive integrated driving mode.

1.4 Scopes of research

The scopes of the research are listed as below;

1. This work only considers battery powered electric vehicle (BEV) as the subject plant, whereby battery is the only energy source on-board of vehicle.

2. The BEV technical specifications are adopted from a Malaysian local car, Proton IRIZ manufactured by Proton, classified as a B-segment car (subcompact/super-mini).

3. The modelling is specifically based on Malaysia environmental and social requirements. The effect of different weather setting will be excluded in the study. A constant tropical weather is retained for all simulation tests; normal temperature, day driving and clear (not raining).

4. The effect of incline angle of the road to the vehicle model is also excluded in the study. The road incline angle is set to zero throughout the study.

5. Vehicle supply-load topology comprises; (1) the high voltage battery and low voltage battery, (2) the DC-DC boost converter, DC-DC buck converter and DC-AC inverter, (3) the high voltage power bus and low voltage power bus, (4) the permanent magnet AC motor (PMAC) as propulsion load connected to high voltage power bus, (5) the comfort load connected to high voltage power bus, and (6) the initial load, safety load and luxury load connected to low voltage power bus through low voltage battery.

6. The size of single cell high voltage battery is 183 mm x 116 mm x 46 mm (length x width x height). The effect of physical size of battery is excluded in the study.

7. All modelling and simulation works are performed in MATLAB/Simulink workspace environment.

1.5 Research contributions

This study implements EMS and PMS into BEV and is carried out as an effort to inspire the automakers and encourage potential consumers to continuously improve and choose pure electric vehicle as the way to support and promote green vehicle for sustainable environment. The original contributions of this thesis can be notified as follows;

1. A new design of BEV supply-load topology in simulation environment considering battery only storage, both propulsion and auxiliary loads with analysis of their power and energy impacts on vehicle range efficiency.

2. A new segmentation of electrical auxiliary loads using LLCC that has improved the organization of loads.

3. A new EMS algorithm for energy distribution strategy using HLSC that has ensured optimal energy distribution. Applying such techniques has successfully optimized the energy consumption as much as 6.4% (18.1% driving range increment) during comfort limit distribution and another 12.2% (10.4% driving range increment) during safety limit. For a full cycle of battery usage, the energy saving would be as much as 18.6%, with total increase in driving range of 28.5% (17.22 km).

4. A new PMS algorithm for power scheme management using HLSC that has satisfied all driving mode cost functions.

1.6 Thesis outline

The thesis writing scheme has been outlined based on the steps taken in the development of the vehicle model, energy management and power management strategies for battery electric vehicle. It consists of six chapters; (1) Introduction, (2) Literature Review, (3) Methodology, (4) Results and Discussion, and finally (5) Conclusion and Recommendations.

Chapter 1 is the background and overview of this research. This chapter highlights numerous efforts by researchers and automakers regarding worldwide concerns of energy conservation and environmental protection in transportation sector. The advantages and limitations of BEV as potential sustainable transportation have been briefly described. A promising solution to BEV drawbacks has been proposed by implementing power and energy management strategies. On top of that, the aims, objectives, scopes and research contribution are also included in the chapter.

Chapter 2 presents a review on the energy management and power management strategies related to BEV. The gaps and techniques proposed from past researchers were investigated. A few control layers of energy management system based from previous researches are also presented and discussed.

Chapter 3 comprises three key sections of the research methodology. The first section describes a comprehensive modelling of battery electric vehicle and its auxiliary loads. Each component was modelled based on its mathematical equations and the actual components data to construct the vehicle entire model. The second section elaborates the utilization of two level control strategies; low level component control (LLCC) and high level supervisory control (HLSC) in the development of BEV energy management system. The energy in auxiliary loads has been managed via load segmentation strategy in LLCC, while new EMS algorithm was defined in HLSC via energy distribution strategy. The third section presents the development of three PMS driving modes for BEV via power scheme management strategy. Subsequently, fuzzy logic was employed to develop an additional mode by integrating previous driving modes into a single adaptive mode.

Chapter 4 presents the simulation results and discussion according to sections in previous chapter. Initially, the proposed BEV model was tested in a few speed conditions to verify the control robustness and the effectiveness in accomplishing the targeted performances. The data from energy validation was then utilized to form the energy distribution profiles for each driving cycle. In EMS simulation test during NEDC (New European urban and extra urban driving), the coordination between LLCC and HLSC has ensured optimal energy consumption up to 28.5% cumulative increase in driving range. The collective work between PMS driving modes and EMS has effectively satisfied the individual driving cost function. Further development of integrated driving mode using fuzzy logic rule-based has enabled an adaptive driving mode which has been verified in simulation test.

Chapter 5 consists of the review of research achievement (objectives and aim) and overall conclusion. The chapter also includes future work directions and some suggestions for further development.

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BIODATA OF STUDENT

The student was born in February 25, 1978, in Kampung Pulau Rusa, Kuala Terengganu, Malaysia. He started his primary and secondary education at Sekolah Kebangsaan Wakaf Mempelam (1985-1990) and Sekolah Menengah Kebangsaan Sultan Sulaiman (1991-1995), Kuala Terengganu, Terengganu, Malaysia. Next, he continued his study at the Universiti Teknologi Malaysia, Skudai, Johor (1996-2000) for his bachelor degree in Electrical Engineering and started his career as a lecturer at Kolej Komuniti Kuala Terengganu (2001-2012) and Politeknik Kuala Terengganu (2012-2013). During service, he managed to compete Diploma Perguruan (2002-2003) from Maktab Perguruan Teknik Kuala Lumpur and MSc in Electrical Engineering (2009-2010) from The University of Nottingham, UK under Hadiah Latihan Persekutuan (HLP) Scheme, Ministry of Higher Education Malaysia. Under the same scheme, he now pursue for Doctor of Philosophy (PhD) in Control and Automation in Universiti Putra Malaysia (UPM). Currently, he is a member of BEM, IEM, MBOT and MACE IFAC Malaysia.

LIST OF PUBLICATIONS

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